People`s Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

University of Echahid Hamma Lakhdar - El Oued

Faculty of Technology

Department of Process Engineering & Petrochemistry

Dissertation

ACADEMIC MASTER

Domain: Science and Technology

Division: Mechanical Engineering

Specialty: Electromechanical

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Entitled:

Online Diagnostics and Optimization of Photovoltaic Panel Arrays for Enhanced System Efficiency

Dissertation Submitted in Partial Fulfillment of the Requirements for the Master

MEM

Degree in : Master

Publicly defended in: 29 /05 /2025 Board of Examiners:

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Academic Year: 2025/2024

Dedication

To those who granted us life and hope...

To the heartbeat of our souls and the light of our eyes...

To our dearest parents,

We dedicate this humble work to you, in appreciation and love for your invaluable efforts and sacrifices. You have always been our source of support and inspiration, and without you, we would not have reached this stage.

Every moment of your hard work and every sincere prayer was a reason behind this achievement.

We hope we have made you as proud of us as we are proud to be your children.

To the one who has been our steadfast support...

To the one who provided us with guidance and encouragement with heartfelt sincerity...

To our esteemed professor and mentor, Dr. Labiod Chouaib,We dedicate this humble work to you, in deep gratitude and appreciation for your crucial role in the completion of this thesis. You have always been our source of inspiration and motivation, generously giving your time, effort, and invaluable advice.Through your wise guidance and unwavering support, we were able to achieve this success.We hope that we have made you as proud of your efforts and dedication as we are proud to be your students.Thank you from the depths of our hearts.

Additionally, we would like to extend our sincere thanks to our co-supervisor, Mr. Abdelmoumene Hechifa, whose valuable insights, guidance, and unwavering support have greatly contributed to the completion of this work. Your encouragement and expertise have been instrumental in shaping this thesis. We are deeply grateful for your time and dedication

To our companions and lifelong friends...

To those who have been our support, our laughter, and our comforting hands...

To our dear friends,We dedicate this humble work to you, in appreciation and gratitude for every moment we spent together and for all the support and encouragement you provided us throughout this journey.You have always stood by our side, in difficult times and joyful moments, and without you, this journey would not have been as beautiful or successful.

We hope we have succeeded in achieving what you wished for us, and that we can all take pride in this accomplishment just as we take pride in our friendship

Acknowledgments

First and foremost, we extend our heartfelt gratitude to Almighty God – Allah – who granted us the strength and patience to persevere through many years of study.

All praise is due to God, who guided us and assisted us in completing this thesis. By His grace, good deeds are accomplished. May peace and blessings be upon the most noble of creation, our Prophet Muhammad (peace and blessings be upon him), his family, and all his companions.

It is truly one of God's greatest blessings that He endowed us with the ability and patience to complete this work.

To our dear parents, who spared no effort in supporting and encouraging us throughout our academic journey, we offer our deepest gratitude and appreciation. You are the light that illuminated our path to knowledge and learning. Without you, we would not be where we are today.

We extend our special thanks to our supervising professor, who generously dedicated his time and effort to provide us with valuable advice and guidance. He illuminated our path during difficult times, and his continuous support was a powerful motivation that helped us overcome many challenges.

What he imparted to us in terms of knowledge, patience, and wisdom will remain in our hearts, and we pray that God rewards him abundantly on our behalf.

We are also deeply grateful to the esteemed members of the defense committee for their participation in evaluating this work—an honor that we deeply cherish.

Abstract

This master's project aims to design an online diagnostic and optimization platform for photovoltaic (PV) panel systems using Internet of Things (IoT) technology. The idea stemmed from observed challenges in monitoring performance and ensuring the efficiency of PV systems. These challenges include energy losses due to partial shading, dirt accumulation, undetected faults, and the lack of real-time system feedback.

The project seeks to enhance overall system efficiency through real-time fault detection and performance analysis using IoT-based monitoring. This helps reduce downtime, improves maintenance scheduling, and ensures stable energy output, especially in remote or large-scale installations.

The project is divided into two main parts: hardware and software. On the hardware side, sensors for voltage, current, irradiance, and temperature were deployed across the PV array. A custom PCB was designed to process and wirelessly transmit the data.
On the software side, a cloud-based platform was developed to analyze the data, along with an Android application to display performance metrics and send alerts in case of anomalies. Optimization algorithms such as Maximum Power Point Tracking (MPPT) and intelligent cleaning suggestions were implemented to boost performance.

The system was tested on a small-scale PV installation, where it successfully identified faults and optimized power output, aligning with the project's core objectives.

Keywords:

Photovoltaic Systems, Online Diagnostics, IoT Monitoring, AC/DC Voltage and Current Sensors, Maximum Power Point Tracking (MPPT), Renewable Energy Optimization

الملخص :

يُقدم هذا العمل حلً تقنيًا متقدمًا لمراقبة وتشخيص أداء الألواح الشمسية في محطات الطاقة الكهروضوئية واسعة النطاق، حيث تتوزع آلاف الألواح على مساحات كبيرة، ما يزيد من احتمالية حدوث أعطال تؤثر على كفاءة النظام ككل، مثل الغبار، التظليل، وتقلبات الطقس، إضافة إلى التوصيلات الضعيفة يعتمد النظام المصمم على بنية " master - slave " موزعة، حيث تقوم وحدات محلية (slave) بجمع بيانات الجهد والتيار بشكل لحظي وترسلها لاسلكيًا إلى وحدة مركزية (master)، تقوم بدورها بتحليل البيانات، عرضها، وتنفيذ أوامر تحكم تلقائية مثل عزل اللوح المتعطل مع التركيز على خفض استهلاك الطاقة وتقليل EasyEDA تم تطوير المنصة الإلكترونية للجهاز باستخدام بيئة التداخل الكهرومغناطيسي، كما تم اعتماد تصميم معياري يسهل صيانته وتطويره مستقبلً. من أبرز خصائص هذا النظام الذكي دعمه لبروتوكول إعادة تشكيل مصفوفات الألواح الكهروضوئية، والذي يُعيد توجيه التيار حول الألواح المتعطلة، مما يحسن من موثوقية النظام ويقلل من الخسائر الناتجة عن الأعطال

ما يتيح مراقبة مستمرة، تحليلً ذكيًا للأداء، وتشغيلً مرنًا (IoT) يعتمد النظام أيضًا على تقنيات إنترنت الأشياء في حالات ضعف أو انقطاع الاتصال بالشبكة. يُساهم هذا التكامل في رفع كفاءة الطاقة وتحقيق أقصى استفادة ممكنة من النظام في مختلف الظروف البيئية والتشغيلية

الكلمات المفتاحية:

الطاقة الشمسية، الألواح الكهروضوئية، المراقبة الذكية، التشخيص الفوري، النظام الموزع، إعادة تشكيل المصفوفات، إنترنت الأشياء، كفاءة الطاقة، التحكم الذاتي، .EasyEDA

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List of Abbreviations

PV: Photovoltaic

MPP: Maximum power point

MPPT: Maximum power point tracking

P&O: Perturb and observe

INC : Incremental Conductance

ANN : Artificial neural network

PWM Pulse Width Modulation

LED : Light Emitting Diode

MOSFET: Metal Oxide Semiconductor Field Effect Transistor

DC : Direct Current

AC: Alternating Current

IV :Current-Voltage

IoT : Internet of Things

EMS : Energy Management System

List of Acronyms

D	The duty cycle
T	The total time period (S)
CH	The chopper
$f_{switching}$	The switching frequency (kHz)
G	The conductance value (1000 W/m^2)
R_{opt}	The optimal value of the load resistance (Ω)
R_c	The load resistance (Ω)
V_{oc}	Open circuit voltage (V)
I_{oc}	Open circuit current (A)
Rs	Series resistance (Ω)
Rsh	Shunt resistance (Ω)
L	Inductance (mH)
C	Capacitance (µF)
I_{sc}	The short circuit current (A)
Pmax	The value of the maximum real power (W)
η	The energy efficiency of the solar cell (%)
$P\gamma$	The incident light power on the surface of the cell
V_L	The voltage across the inductor (V)
W_{on}	The energy input provided by the source to the inductor when CH is on
W_{off}	The energy that the inductor releases to the load when CH is off

General Introduction

General Introduction

Today, solar energy aligns with ecological concerns. Technologies that harness the sun's rays to produce energy have significantly evolved in recent years. The sun is an infinite source of energy, from which we can benefit abundantly. This passive energy is simply captured by photovoltaic solar panels (PV) [1]. Photovoltaic energy is obtained from sunlight. More precisely, its principle is to transform the energy carried by light photons into electricity [2].

This is why photovoltaic panels, which collect this energy, are often installed on rooftops, with the best possible orientation. This is where the photovoltaic cell comes into play. Made of silicon, it absorbs the energy of light photons when exposed to light. This process generates direct current electricity, which is then converted into alternating current by an inverter. The electricity produced can be immediately used to power light-consuming devices. Any solar installation thus requires three main components to ensure the capture of solar radiation and its conversion and distribution as electricity [3, 4]:

- Photovoltaic panels,
- An inverter to convert the generated electricity into alternating current; its output is regulated by a Maximum Power Point Tracker (MPPT) to ensure the system always operates at optimal capacity,
- Batteries for storing electricity, with a charge controller to ensure battery longevity.

The number of solar systems is increasing rapidly each year, raising the need for technicians who know how to efficiently operate photovoltaic systems. Troubleshooting PV systems generally focuses on four main parts of the system: photovoltaic modules, batteries, inverters, and junction boxes [5]. To enable precise diagnostics, the detection and localization of faults in a PV installation help reduce maintenance costs and, most importantly, increase productivity [6].

This thesis is structured into four interrelated chapters, each addressing a key aspect in the development of an intelligent monitoring system for photovoltaic energy. The work progresses from exploring technical challenges, through integration with Industry technologies, to the design and testing of the proposed system.

Chapter One provides a technical background on photovoltaic systems, explaining their working principles and the main factors affecting their efficiency. It also emphasizes the importance of electrical protection components and their role in enhancing system safety and stability.

Chapter Two examines the impact of the Fourth Industrial Revolution particularly the Internet of Things (IoT) across various sectors, including energy. This chapter highlights the role of IoT in enhancing solar energy monitoring by enabling real-time data collection, performance analysis, and automatic fault response.

Chapter Three outlines the technical aspects of designing an intelligent monitoring unit using the EasyEDA platform. It discusses the selection and arrangement of system components, ensuring both electrical and functional compatibility. The chapter also focuses on a modular and scalable design philosophy that facilitates maintenance and future upgrades.

Chapter Four presents the proposed real-time smart monitoring system for solar panel performance based on a MASTER-SLAVE architecture. It explains the mechanism of local data acquisition and analysis, followed by transmission to a central unit responsible for system-wide management and corrective actions, such as isolating underperforming panels or reconfiguring connections. The chapter also includes the results of system testing and its effectiveness in enhancing overall performance.

This thesis represents a comprehensive effort toward designing and implementing a smart and efficient monitoring system for photovoltaic energy, leveraging modern technologies such as the Internet of Things and advanced electronic design. The results demonstrate that such systems can significantly improve performance, increase reliability, and reduce losses caused by environmental and operational conditions. In the future, this system could be expanded to cover broader applications and integrated with artificial intelligence algorithms to predict failures and enhance autonomous decision-making, thereby contributing to the advancement of smart and sustainable energy solutions.

Fundamentals and Challenges in Photovoltaic (PV) Systems

1.1. Introduction

A photovoltaic (PV) solar energy system is a clean and reliable renewable energy solution that converts sunlight into electricity using photovoltaic cells. This electricity can be used directly, stored, or integrated with the grid and other energy sources, making it suitable for various applications such as residential, industrial, and agricultural use [7].

Despite the integration of system components aimed at maximizing efficiency, several natural and operational factors like weather, pollution, shading, and poor electrical connections can prevent the system from reaching its maximum power point. These issues negatively affect energy yield and overall performance.

Understanding and addressing these challenges is crucial to maintaining optimal PV system operation. In addition, protective devices like circuit breakers, motor controllers, and leakage detectors play a key role in enhancing system safety, efficiency, and reliability

1.2. Solar Energy in Algeria:

Algeria is among the richest countries in solar resources worldwide, thanks to its geographical location and high solar radiation levels. Despite this potential, the contribution of renewable energy particularly solar remains limited in the national energy mix, mainly due to the country's heavy reliance on hydrocarbons as the primary source of energy and revenue.

With declining oil and gas reserves, Algeria has initiated reforms since 2019 to promote a shift toward clean energy. These include the establishment of a dedicated Ministry of Renewable Energy, national support institutions, and the launch of major projects such as the Hassi R’Mel Integrated Solar Combined Cycle plant and photovoltaic power stations in various provinces.

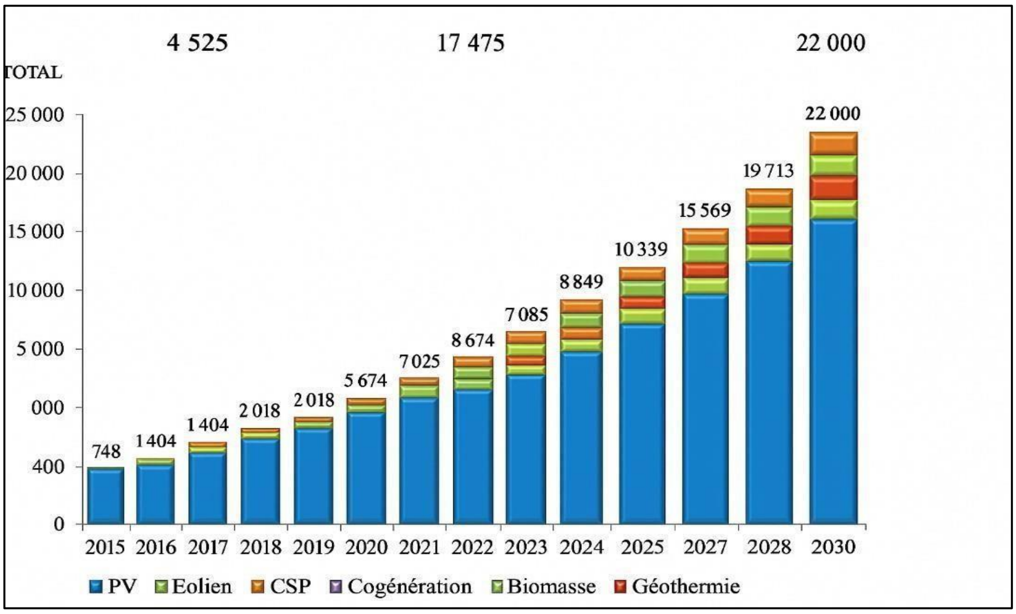


Figure 1.1. Solar radiation distribution map of Algeria

These initiatives reflect the country's strategic direction toward diversifying its energy sources, ensuring energy security, and achieving long-term economic and environmental sustainability.

1.3. Components of a PV System

A photovoltaic (PV) solar energy system consists of several components that must be carefully selected based on the system type, location, and intended applications. These components will be mentioned later, along with an explanation of the role each one plays in ensuring efficient system operation [8].

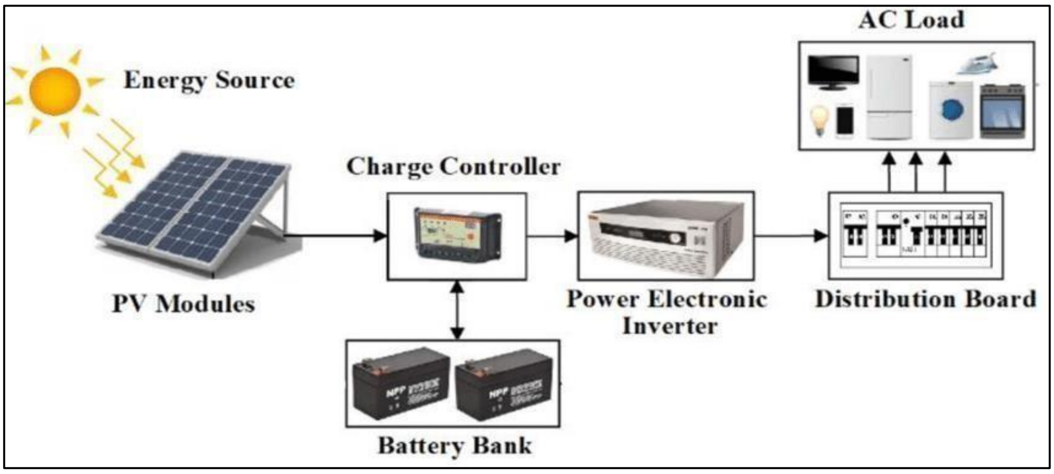


Figure 1.2. General Diagram of a Photovoltaic (PV) Solar Energy System

1. Photovoltaic Module
2. Solar Charge Controller
3. Inverter
4. Battery Bank
5. Load
6. Auxiliary Power Sources

1.3.1. Photovoltaic Module:

Photovoltaic (PV) modules consist of interconnected solar cells encapsulated between glass or a glass-Tedlar sheet. These modules are typically framed in anodized aluminum, though frameless designs are used in building-integrated applications.

The module's power output depends on its surface area and solar irradiation, measured in peak watts. The voltage is determined by the number of cells connected in series, with higher outputs achieved by adding more cells in series or parallel. The dimensions of the modules vary, and multiple modules form a panel, while several panels make up a photovoltaic array, allowing for customized voltage and power configurations [8].

Figure 1.3. Engineering Diagram of a Solar Panel Assembly

1.3.1.1 Operating Mechanism of a Photovoltaic:

In a photovoltaic cell, sunlight is converted into electricity through three main stages:

The cell absorbs photons with sufficient energy, releasing electrons.

These electrons and the resulting holes move due to the internal electric field at the P-N junction, generating an electric current.

When the cell is connected to an external circuit, electrons flow through the wires, producing current and voltage from the movement of charges and the internal electric field [9].

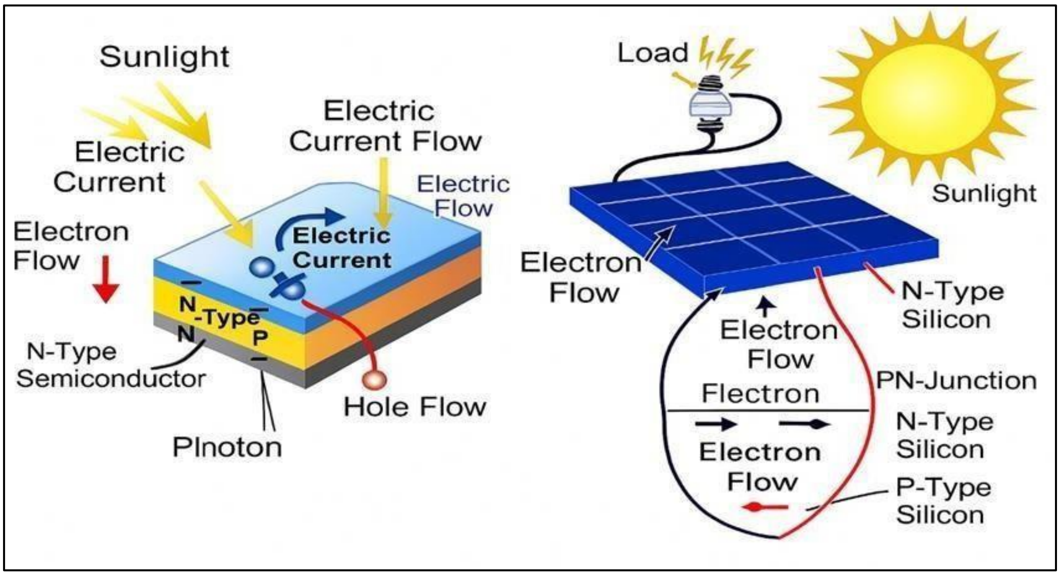


Figure 1.4. Illustrative Diagram Showing the Operating Mechanism of a Solar Panel Using Artificial Intelligence

1.3.1.2 Types of Photovoltaic Cells

- **Monocrystalline Cells:**

Monocrystalline silicon results from the cooling of molten silicon. Once solidified, it transforms into a uniform crystal that is cut into thin slices to form the photovoltaic cell. The colour of this material is blue, without any trace of crystals or other impurities [10].

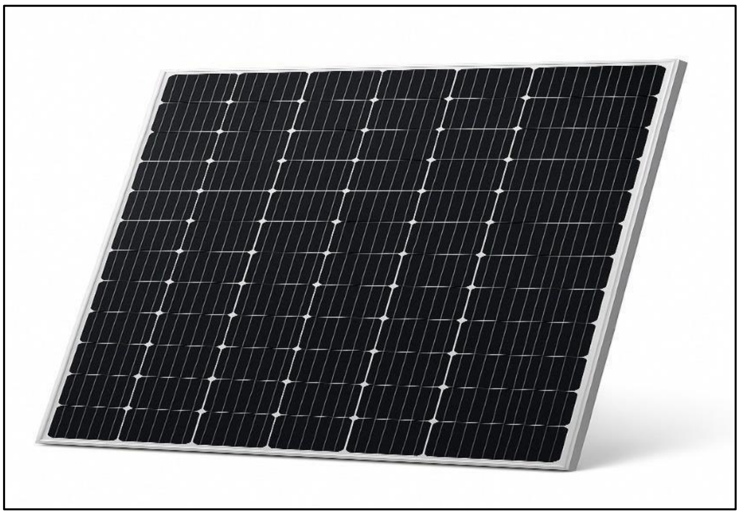


Figure 1.5. Example of Monocrystalline Solar Cells

- **Polycrystalline Cells:** Polycrystalline silicon is obtained by melting silicon in a square and elongated metal mold, called an ingot. The color of this type of cell is blue and speckled with patterns left by the crystals. This characteristic allows us to easily recognize this photovoltaic cell.

Figure 1.6. Example of Polycrystalline Solar Cells

1.3.2 Solar Charge Controller:

is the second main component after solar panels in a solar energy system, along with batteries and inverters. Its primary function is to regulate the voltage and current coming from the solar panels to deliver electrical energy with output voltage and current compatible with the battery voltage and inverter input. In addition to this main role, it performs several other functions:

- It prevents the batteries from being completely discharged, and usually includes a display showing the battery charging status.

- It protects the solar cells and other components of the system from short-circuit currents.

- It disconnects the solar panels from the system when there is no sunlight, ensuring that current does not flow back from the battery to the panels.

- It can be programmed to suit the specific parameters of your solar energy system by setting the voltage range of the controller to protect both batteries and loads [10].

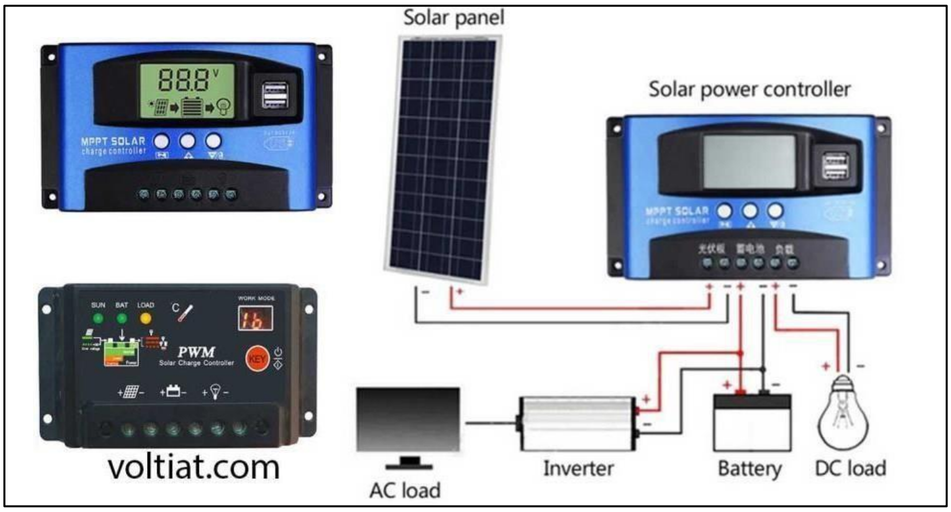


Figure 1.7. Examples of Solar Charge Controllers with Connections

1.3.3 Inverter:

When installing a solar power system, the solar panels are just one component of the overall system. The solar inverter is another essential component that plays a critical role in making the generated electricity usable. The inverter's function is to convert the direct current (DC) generated by the photovoltaic modules into alternating current (AC), which is the type used to power appliances and devices. There are several types of solar inverters, each differing in their operating mechanisms and efficiency. Therefore, understanding how solar inverters work and distinguishing between their types is crucial in selecting the most suitable model to ensure optimal performance of the photovoltaic system [11] .

1.3.3.1 Working Principle:

Alternating current (AC) constantly changes direction and follows a sinusoidal wave pattern, making it suitable for powering household appliances.

Solar panels generate direct current (DC) electricity when exposed to sunlight. This DC power flows to an inverter, which converts it into AC electricity. Inside the inverter, a transformer adjusts the voltage, and transistors switch the current’s direction rapidly, effectively transforming DC into AC.

The resulting AC electricity is then delivered to the home’s electrical panel. If not immediately used, the electricity is sent to the grid or stored in a battery if available, ready to power household needs.

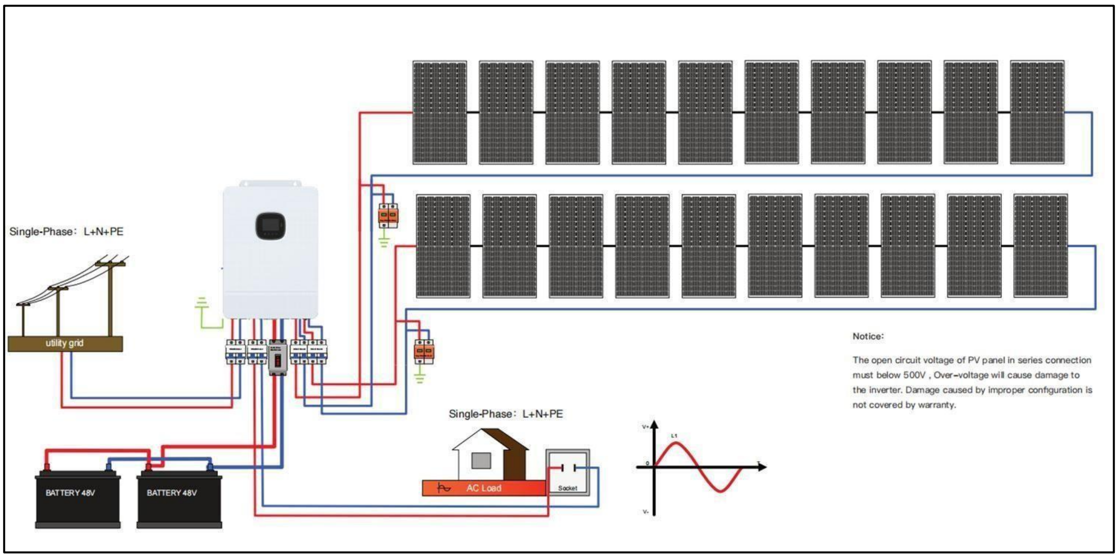


Figure 1.8. Examples of Inverters with Connections

1.3.3.2 Types of solar inverters:

The three main types of solar inverters are:

Grid-Tied Inverter:

Used in systems connected to the public electricity grid. It converts the electricity generated by solar panels to be used directly or fed into the grid.

Off-Grid Inverter:

Used in standalone systems that are not connected to the electricity grid. It works with batteries to store and supply energy when needed.

Hybrid Inverter:

Combines the features of both grid-tied and off-grid inverters. It can operate with the grid and batteries simultaneously, offering flexible energy management.

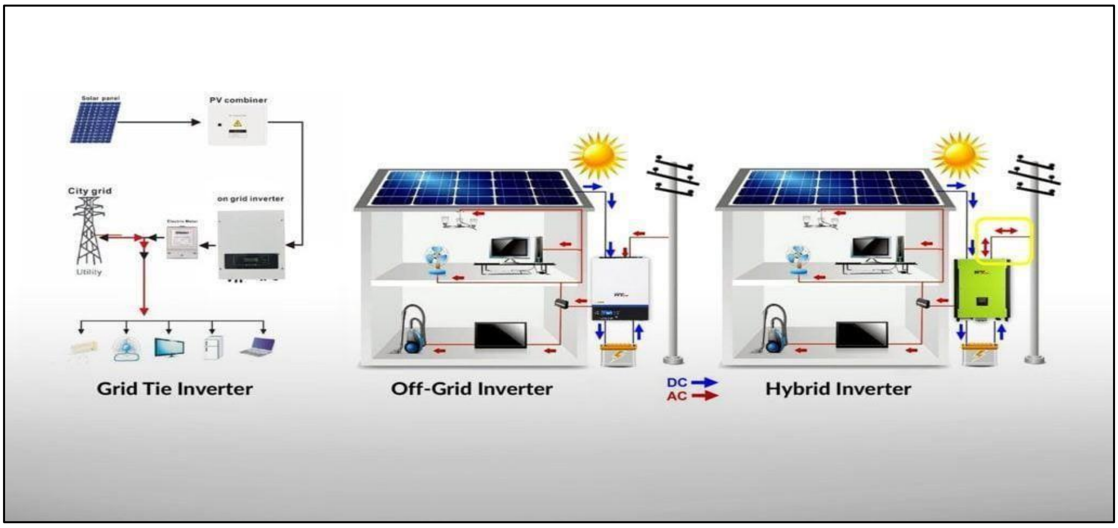


Figure 1.9. Types of Inverters with Connections

1.3.4 Batteries:

Batteries in solar energy systems are used to store the energy generated by solar panels. During periods without sunlight, such as at night or on cloudy days, these batteries supply power to electrical loads. The duration of the system's autonomy, meaning the ability to operate independently from sunlight, depends on the battery capacity. The capacity of the battery determines the amount of energy that can be stored, and it can be increased by connecting batteries in series or parallel, depending on the requirements [12].

Figure 1.10. Example of Batteries with Connections

1.3.4.1 Connection Methods:

There are three basic ways to connect batteries in a solar system, depending on the desired voltage and capacity:

Series Connection: The positive terminal of one battery is connected to the negative terminal of another. This increases the total voltage while the capacity (Ah) remains the same.

Parallel Connection: All positive terminals are connected together, and all negative terminals are connected together. This increases the total capacity, while the voltage stays the same.

Series-Parallel Connection: A combination of both series and parallel to increase both voltage and capacity as needed [13].

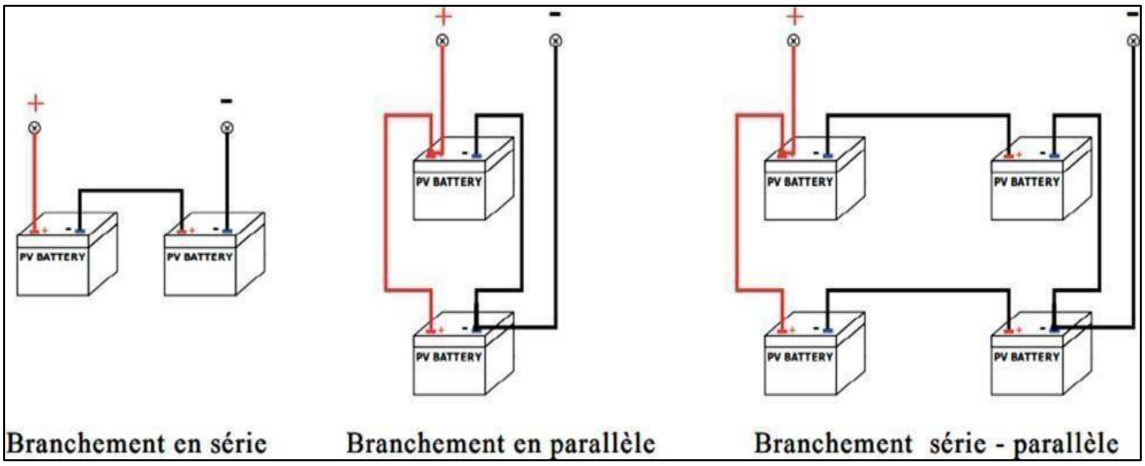


Figure 1.11. Connection Methods for Batteries

1.4 Impact of Environmental Factors on Solar Panel Performance:

The performance of solar panels experiences noticeable fluctuations due to the influence of various environmental factors, leading to a decline in their efficiency and stability in energy production. High temperatures, dust accumulation, variations in solar irradiance, and humidity levels are among the most significant factors affecting this performance. Such fluctuations present a real challenge to achieving optimal operation of photovoltaic systems, especially in regions characterized by extreme or variable climatic conditions. Therefore, it is essential to study and analyze these factors in order to propose effective technical solutions that contribute to enhancing the efficiency and continuity of solar energy production [14].

Figure 1.12. Symbols of Environmental Factors Affecting Solar Panel Performance

1.4.1 The Impact of Solar Radiation on Solar Panel:

Figure (I.11) show the influence of radiation on the I=f(V) and P=f(V) characteristics at a constant temperature. We maintained a constant temperature (25°C) at different radiation levels (200 ,400 ,600 ,800 ,1000 W /m2).

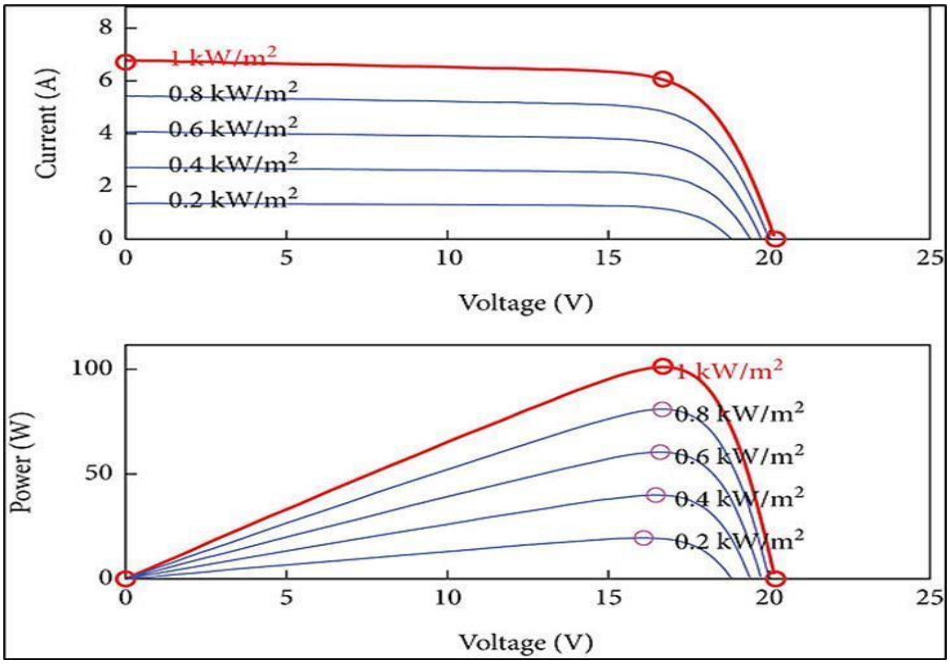


Figure 1.13. The Impact of Solar Radiation on Solar Panel Performance

1.4.2 The Impact of Temperature on Solar Panel:

The effect of temperature can be summarized as shown in the following figure:

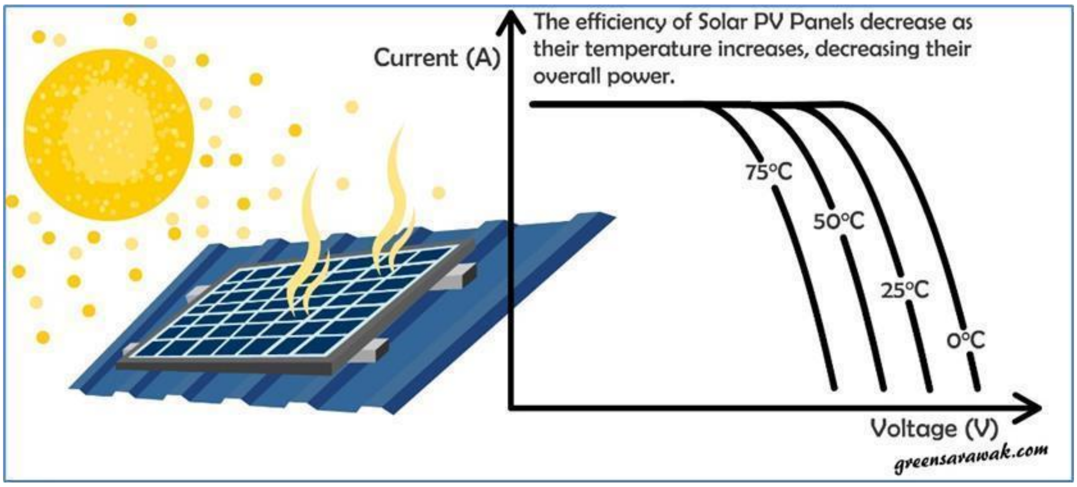


Figure 1.14. The Impact of Temperature on Solar Panel Performance

1.4.3 Impact of Humidity on Voltage:

The graph shows that as humidity increases, the voltage decreases. This indicates an inverse relationship. High humidity can reduce the efficiency of electronic systems, such as solar panels, by absorbing light or causing surface conductivity, which lowers the output voltage.

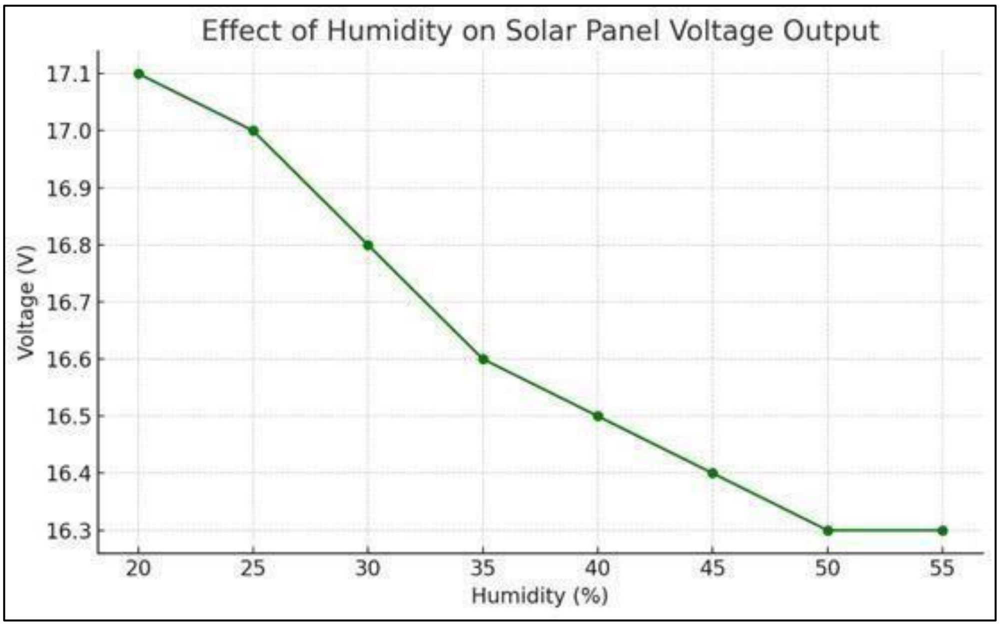


Figure 1.15. Impact of Humidity on Voltage in Solar Panels

1.5. Performance Indicators:

Performance indicators in photovoltaic systems are essential tools for assessing the efficiency of converting solar energy into electrical energy. These indicators are used to evaluate the effectiveness of a solar cell under specific operating conditions, allowing for performance analysis, design optimization, and comparison with other systems in the field. The following section highlights the most relevant indicators used to evaluate solar cell performance [15].

1.5.1 IV and PV Curve:

The current-voltage (IV) curve of a solar cell shows the relationship between output current and voltage under various lighting conditions. In the dark, the cell behaves like a conventional diode. When exposed to light, photons generate charge carriers, producing a photocurrent that shifts the IV curve into the fourth quadrant, where the cell delivers electrical power.

From the IV curve, the power-voltage (PV) curve is derived, indicating the power output at different voltages. The Maximum Power Point (MPP) is the point where the cell delivers the highest possible power, serving as a key performance indicator.

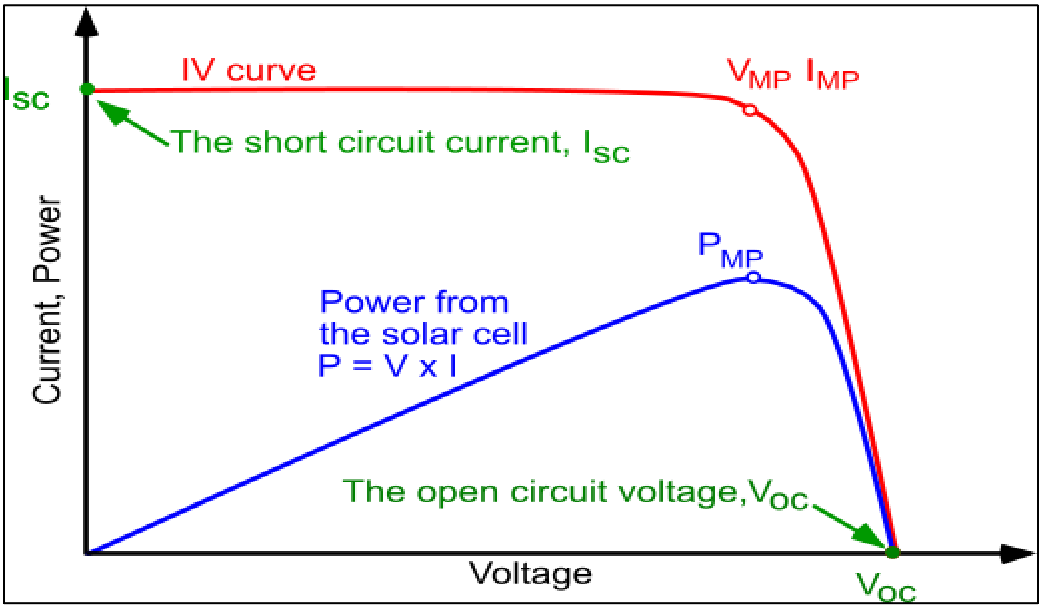


Figure 1.16. Current-Voltage (I-V) Characteristic Curve

1.5.2 Solar Cell Efficiency:

Efficiency is the most commonly used parameter to compare the performance of solar cells, defined as the ratio of energy output from the cell to the energy input from sunlight. Efficiency depends on the spectrum, intensity of light, and the cell's temperature, which requires controlled conditions during measurement. Terrestrial solar cells are measured under AM1.5 conditions at 25°C, while space cells are measured under AM0 conditions. Recent solar cell efficiency results are presented on the "Solar Cell Efficiency Results" page [16].

1.5.3 Fill Factor:

The short-circuit current (Isc) and open-circuit voltage (Voc) represent the maximum current and voltage of a solar cell, but no power is generated at these points. Therefore, the fill factor (FF) is used to determine the maximum extractable power. It is defined as the ratio of the maximum output power to the product of Voc and Isc, making it a key indicator of the cell's efficiency

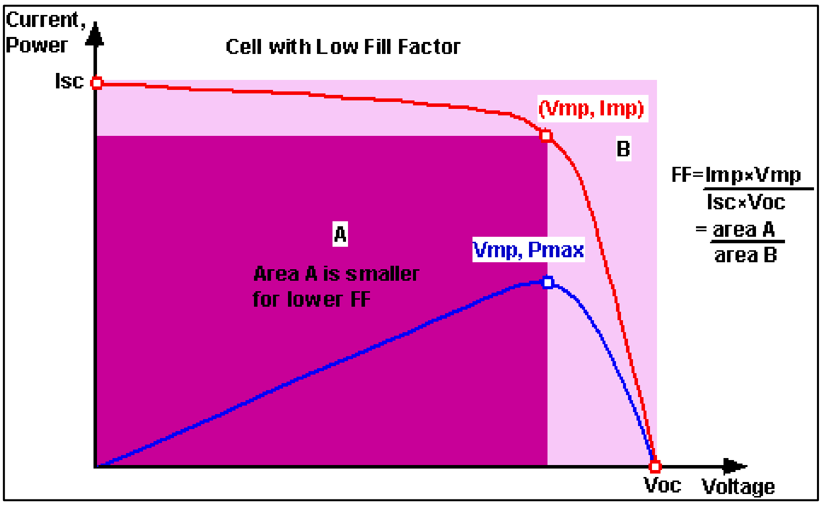


Figure 1.17. Fill Factor (FF) Indicator

1.6 Conclusion :

In this chapter, we addressed the fundamental aspects of photovoltaic (PV) systems, discussing their main components such as PV modules, charge controllers, inverters, and energy storage units, along with the role each plays in energy conversion and ensuring system stability. We also analyzed the influence of various environmental factors namely solar irradiance, temperature, and humidity on the system's efficiency and operational continuity.

Additionally, we reviewed a set of technical indicators used to evaluate PV system performance, which serve as essential tools for efficiency assessment and identifying areas for improvement.

These foundational concepts establish the necessary knowledge base for the following chapters, which will focus on intelligent control strategies, real-time performance optimization, and the integration of advanced electronic solutions and IoT technologies.

IoT Applications in Photovoltaic Systems: Diagnosis and Monitoring

2.1 Introduction :

The world is currently undergoing a broad digital transformation known as the Fourth Industrial Revolution. This transformation has led to the integration of advanced technologies such as Artificial Intelligence (AI), robotics, 3D printing, and the Internet of Things (IoT) into various aspects of human life. These technologies have become essential components across multiple sectors, including agriculture, industry, healthcare, commerce, economy, and public administration, and have deeply permeated everyday life [17].

The impact of this revolution has also extended to educational institutions, causing a radical shift in teaching practices and communication methods between students, teachers, and other educational stakeholders [18]. Among the most influential technologies of this era is the Internet of Things, which has enabled the emergence of innovative teaching methods and non-traditional learning environments. These tools enhance interaction between people and systems, whether physical or virtual, resulting in a significant transformation of the educational process.

IoT technologies play a central role in supporting interactive and collaborative learning, developing intelligent educational content, and facilitating the preparation of personalized lesson plans. They also help in tracking student performance, and enable students to access academic support anytime and anywhere, both inside and outside the educational institution [19].

Several previous studies have demonstrated that integrating IoT into education contributes significantly to achieving learning outcomes aligned with the demands of the digital era [20]. Moreover, other studies have recommended embedding IoT technologies into educational systems to equip students with the skills necessary to manage and process information and digital experiences effectively [21].

In this context of widespread IoT adoption, its use is not limited to education. Its applications extend to smart agriculture, flexible manufacturing, smart buildings, transportation, and healthcare. Notably, in the energy sector particularly solar energy IoT is used to monitor and optimize photovoltaic (PV) system performance, aiming to increase efficiency in managing energy resources.

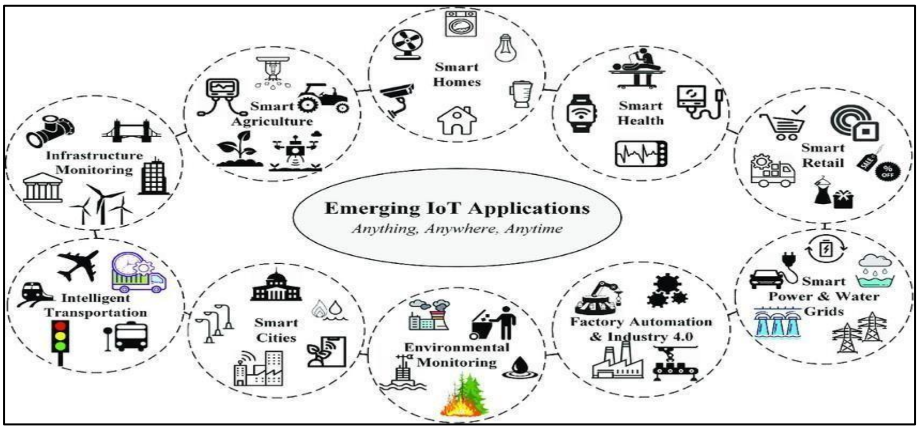


Figure 2.1. Emerging IoT Applications Across Sectors – From Smart Homes to Industry 4.0

1.2 IoT in the Energy Sector .

The Internet of Things (IoT) has brought transformative capabilities across various industries, including agriculture, manufacturing, health, and transportation. However, one of the most impactful domains where IoT is driving change is the energy sector. With increasing global demand for sustainable and intelligent energy systems, IoT provides tools for efficient resource management, real-time monitoring, and enhanced automation, as widely discussed in recent IoT research [22]. This chapter narrows the focus from general IoT applications in energy to more specific uses within smart grids, solar energy systems, and wind power.

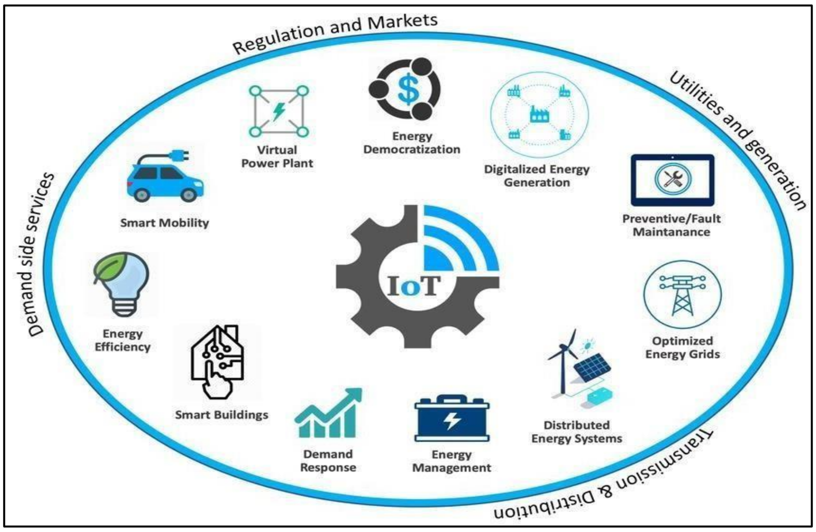


Figure 2.2. Integrated Applications of the Internet of Things (IoT) in Smart Energy Systems

2.2.2 Smart Grid Applications:

One of the most widespread applications of IoT in the energy industry is within smart grids. A smart grid leverages intelligent communications to collect data from each node of the power grid. This data collection occurs at various stages and is utilized to predict power consumption. The system can then automatically adjust the usage of electricity to achieve intelligent peak shaving. This approach helps consumers lower their electricity consumption during peak hours and reduces the overall power generation demand during such periods [23].

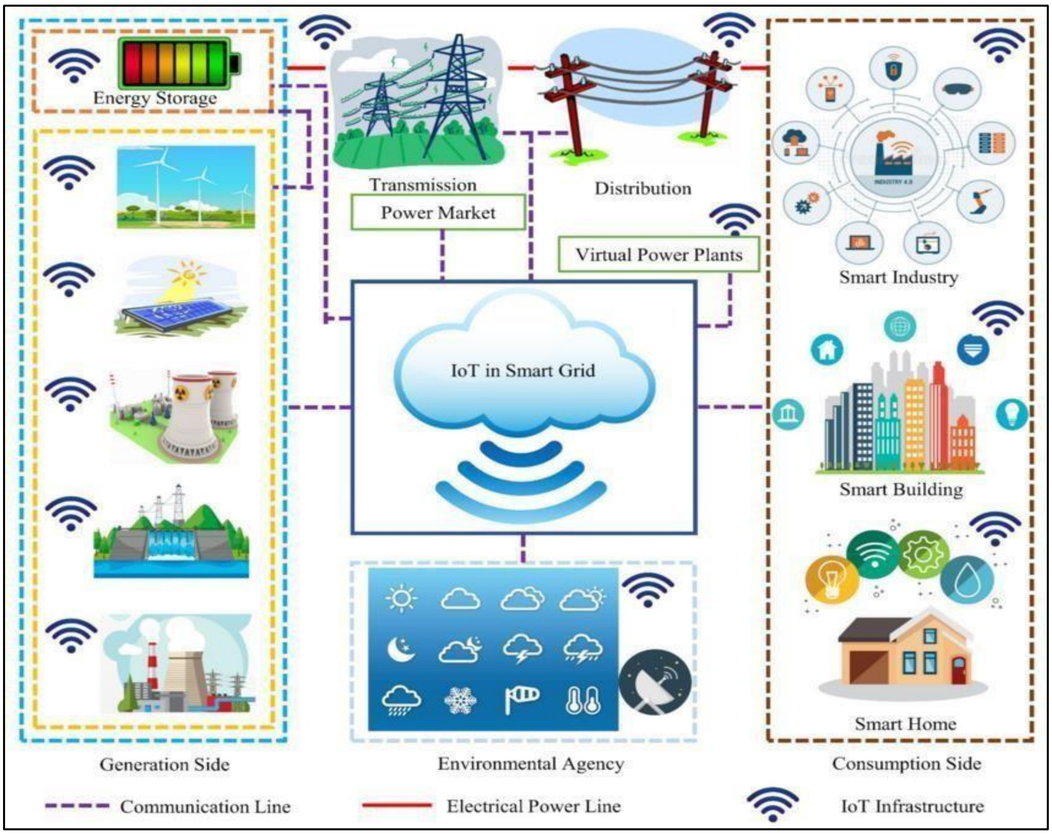


Figure 2.3. IoT-Enabled Smart Grid Architecture Integrating Generation, Transmission, and Intelligent Consumption Sectors

2.2.3 Solar Energy Systems:

Another significant example of IoT application is in solar energy systems, particularly solar photovoltaic (PV) power stations. These systems incorporate intelligent monitoring and control frameworks powered by IoT technologies. Such systems allow for remote querying and tracking of solar panel data. They can also issue alerts related to system faults and status updates, helping to detect and even predict issues in the operation of solar PV power stations. These smart energy management systems are essential for promoting efficient and sustainable energy transitions [24].

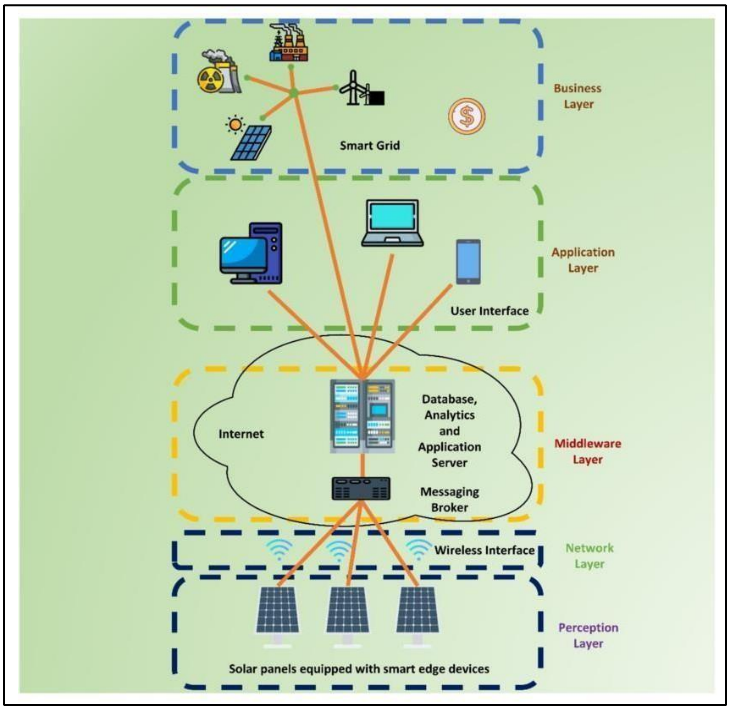


Figure 2.4. IoT-Based Monitoring and Control Architecture for Photovoltaic (PV) Solar Power Systems

2.2.3.1 Intelligent Monitoring System

Intelligent monitoring systems play a crucial role in observing the performance of solar PV systems. They adjust the angle and direction of solar panels according to environmental conditions to maximize energy output. In harsh conditions, they also protect panels from damage. These systems enable administrators to set thresholds for power output triggering alerts when these limits are breached.

Remote monitoring is particularly vital for solar power plants located in remote areas. Managers can view energy data such as load and production metrics in real-time via a remote monitoring platform. This platform not only collects and uploads data from sensors to databases but also integrates and visualizes it for user-friendly access. Overall, IoT-based smart control systems offer a reliable and cost-effective solution for solar power management [25].

2.2.3.2 Benefits of IoT for Solar Energy System

IoT serves as a cornerstone technology for the energy transition, offering intelligence, security, efficiency, and operational stability. For solar energy systems, IoT enables real-time monitoring, predictive analytics, and flexible communication. These features collectively reduce operational costs and enhance the performance of solar power stations.

Furthermore, IoT systems can forecast weather patterns and power generation rates, which contribute to the stability and efficiency of the overall power network [26].

2.3 Photovoltaic Module Architecture

Wind energy is another vital area within clean energy that benefits significantly from IoT integration. Companies operating wind farms are increasingly turning to IoT to enhance operational efficiency and reduce maintenance expenditures.

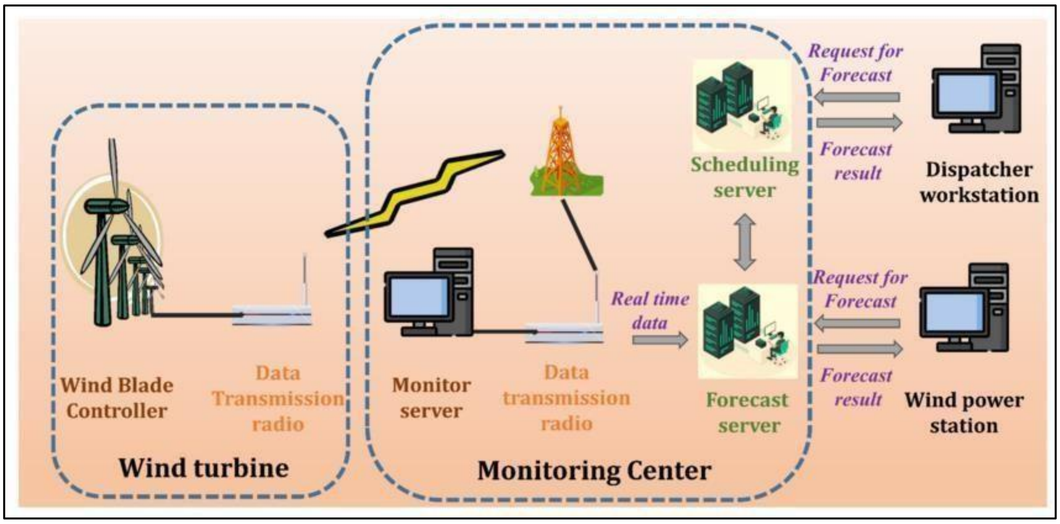


Figure 2.5. IoT-Based Smart Monitoring and Forecasting Architecture for Wind Power Systems

2.3.1 Monitoring, Control, and Analysis

- **Equipment Monitoring:** IoT-enabled sensors can track parameters such as rotation speed, temperature, and humidity of wind turbine blades. These sensors enable early fault detection, minimizing equipment damage and downtime.
- **Data Analysis:** Collected data is uploaded to the cloud, where big data analytics are employed to uncover trends and improve system efficiency. This analysis aids in evaluating the operational status of wind farms.

- **Intelligent Control**: IoT facilitates automated adjustments of turbine blade angles and rotation speeds based on real-time wind data. This optimizes power output and ensures energy efficiency [26].

2.3.2 Advantages of IoT in Wind Power System

IoT introduces numerous benefits to wind energy systems:

- **Enhanced O&M Efficiency**: IoT enables remote monitoring, reducing the need for manual inspection and cutting down operational costs.
- **Reduced Energy Costs:** Smart control systems dynamically adjust turbine output for optimal efficiency.
- **Improved Generation Stability:** Real-time data monitoring ensures stable and efficient energy generation [27].

2.3.3 Challenges of IoT in Wind Power System

Despite the benefits, several challenges remain:

- **Data Security:** Handling sensitive operational data requires robust security and privacy mechanisms.
- **Skills Gap:** There is a shortage of technical experts in IoT systems for wind energy.
- **Standardization Issues:** Inconsistent technical standards across devices and platforms hinder compatibility and integration. Unified standards are essential for seamless IoT implementation [28].

2.3 Applications of IoT in the Energy Sector

2.3.1 Architecture of a photovoltaic module

2.3.1.1 Grouping cells in series

An elementary photovoltaic cell constitutes a.low-power electrical generator, insufficient on its own for most domestic or industrial applications. Photovoltaic.generators are, therefore, made by connecting a large number of elementary cells.in series.and/or parallel.

A series connection of (Ns) cells increases the voltage of the photovoltaic generator. The cells are traversed by the same current, and the resulting characteristic of the series connection is obtained by adding the voltages of the individual cells, as represented in Figure 2.6.

Equation (1.3) summarizes the electrical characteristics of a series connection of (Ns) cells:

$$V_{oc_{N_s}} = N_s \times V_{oc}; I_{cc_{N_s}} = I_{cc} \quad 1.1$$

$V_{oc_{N_s}}$: The sum of the open-circuit voltages of the (Ns) cells in series.

$I_{cc_{N_s}}$: The short-circuit current of the (Ns) cells in series.

This connection system is generally.the most commonly used for commercial photovoltaic modules.

As the surface area of the cells increases, the current produced.by a single cell steadily increases with technological advancements, while its voltage remains very.low. The.series connection thus allows.for an increase.in the overall voltage, thereby enhancing the total power output.

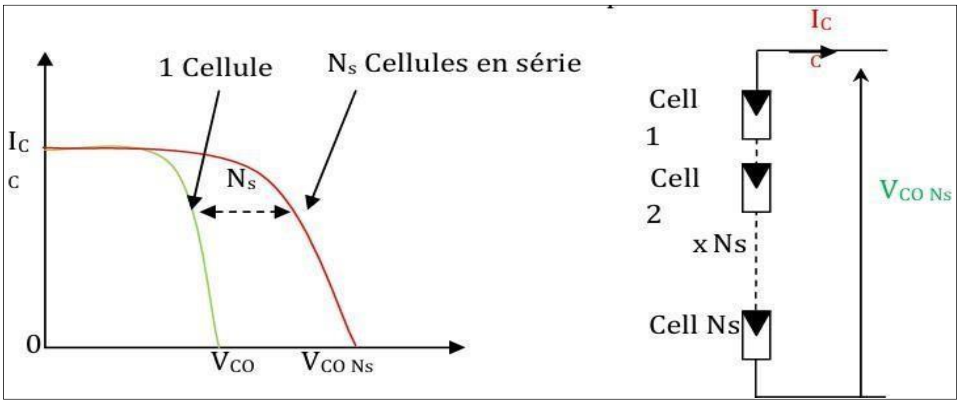


Figure 2.6. Resulting characteristic of a series connection of (Ns) cells.

2.3.1.2 Parallel Connection of Cells

A parallel connection of (Np) cells is possible and allows.for an increase in the output current of the generator thus created. In a grouping of identical cells connected.in parallel, the cells are subjected to the same voltage, and the resulting characteristic of the grouping is obtained by adding the currents.

Figure 2.5 summarize the electrical characteristics. of a parallel connection of (Np) cells.

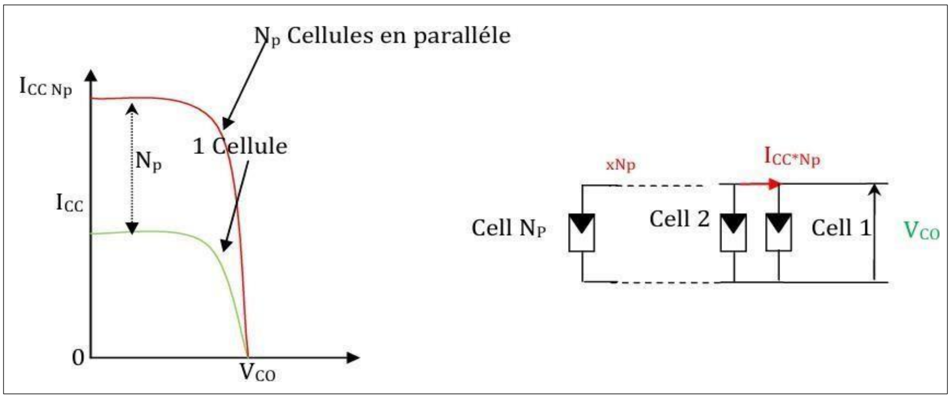


Figure 2.7. Resulting characteristic of a parallel connection of (Np) cells [29, 30].

$$I_{cc_{N_p}} = N_p \times I_{cc} \qquad 1.2$$

$$V_{oc_{N_p}} = V_{oc} \qquad 1.3$$

$I_{cc_{N_p}}$: The sum of the. short-circuit currents of (Np) cells connected in parallel.

$V_{oc_{N_p}}$: The open-circuit voltage of (Np) cells.connected.in parallel.

2.3.1.3 Hybrid Connection of Cells (Series & Parallel)

Depending on the series and/or parallel connection of these cells, the values of the total short-circuit current and the total open-circuit voltages are given by.the following relations:

$$I^t{}_{cc} = N_p \times I_{cc} \qquad \text{II.4}$$

$$V^t{}_{oc} = N_c \times V_{oc} \qquad \text{II.5}$$

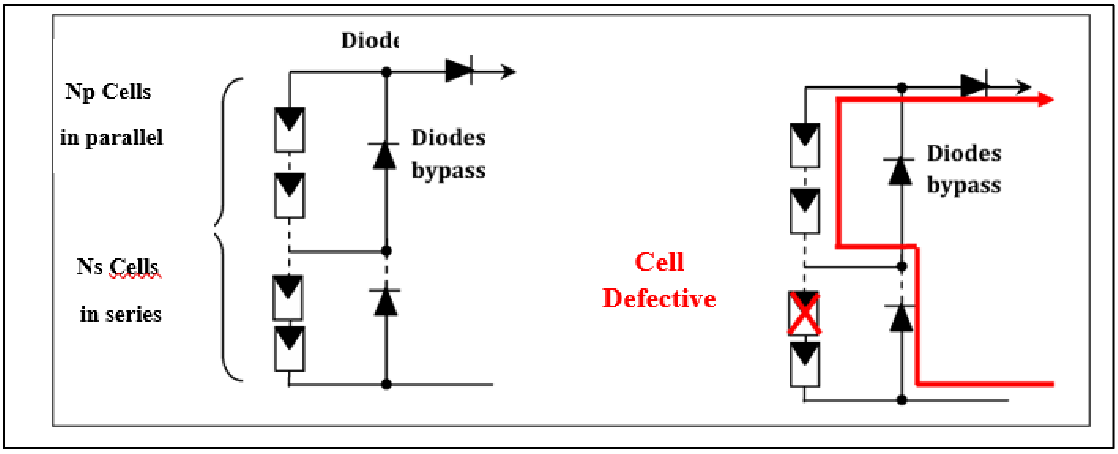


Figure 2.8. Resulting characteristics of a hybrid connection of $(Ns\ x\ Np)$ cells [29, 30].

Where:

N_c: Number of. cells connected.in. parallel.

N_p: Number of. cells connected. in series.

$I^t{}_{cc}$: Total.short-circuits. current.

$V^t{}_{oc}$: Total open-circuit. voltage.

Thus, the characteristic $Ip\ Vp$ of a photovoltaic generator can be considered the result of a network of $Ns\ x\ Np$ cells connected.in series/parallel. The.overall characteristic.can also vary depending on illumination, temperature, cell aging, shading effects, or illumination inhomogeneity. Furthermore, even single shading or degradation of a cell in a series connection can cause a significant reduction in the current produced by.the photovoltaic module.

When the current drawn exceeds the current produced by the poorly illuminated cell, the voltage of that cell becomes negative, turning it into a receiving element. The cell then dissipates an excessive amount of electrical power, which could lead to its destruction if the fault persists for too long. This phenomenon.is known as the "hot spot effect".

To address this issue, photovoltaic panels are equipped with bypass diodes, which serve to protect cells that become passive. When the bypass diode activates, it short-circuits a part of the module, thereby preventing reverse currents within defective cells. However, this effective solution reduces both the power output.and the voltage across.the module terminals. The degradation of a cell renders.the group of cells associated with the defective cell, and protected by the bypass diode, incapable of producing power.

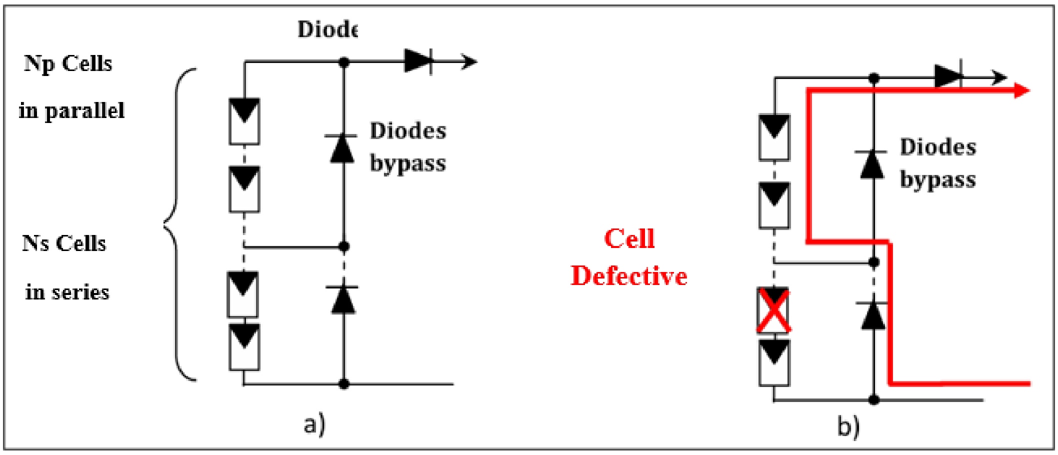


Figure 2.9. a) Classical architecture of a photovoltaic module with protective diodes.

b) Failure of one of the PV. module cells and activation of the bypass diode,the circulation current Ipv.

This phenomenon. of partial power loss should be compared to the total loss of a module in the event of a problem with a single cell in a module operating without protections.

2.4 Terminology Related to Diagnosis

According to the standardization by the SAFEPROCESS technical committee of the International Federation of Automatic Control (IFAC) [31, 32], the following terms commonly encountered in the field of diagnosis and their meanings are presented below:

2.4.1 Fault

A fault is any deviation or discrepancy in at least one observed characteristic of the monitored system compared to its required reference characteristic, which corresponds to the normal and standard operating condition. A fault does not usually cause a complete shutdown of the system but may lead to a potential failure. A fault may originate from physical causes such as hardware malfunction, design errors, operational misuse, or errors during maintenance actions. As a result of a fault, the system may become unable to perform the primary function for which it was designed.

2.4.2 Failure

A failure is the inability of a physical system to perform its main function or one of its functions. A failure can result from a fault. However, a fault does not necessarily lead to a failure. This means that the system can still perform its main function as long as the fault does not affect that task. A failure may be partial if the system retains the ability to perform some of its required functions, or performs them in a limited manner; it may also be total if the system is unable to perform any of the required functions.

2.4.3 Breakdown

A breakdown is the inability of a device to perform a required function. When a failure occurs, characterized by the shutdown of the device in fulfilling its function, the device is said to be in a state of breakdown. Consequently, a failure is always the result of a malfunction.

2.4.4 Degradation

Degradation is a process of gradual decline in the performance of a functional entity within a device.

2.4.5 Disturbance

A disturbance is any uncontrolled input originating from the external environment that negatively influences a physical system.

2.4.6 Anomaly

An anomaly is a behavior of the physical system that does not conform to a reference condition.

2.4.7 Symptom

A symptom is a distinctive sign that enables the detection of a malfunction in the monitored system.

Figure 2.10 illustrates the transition from a normal operating state to a breakdown state, passing through degradation and failure.

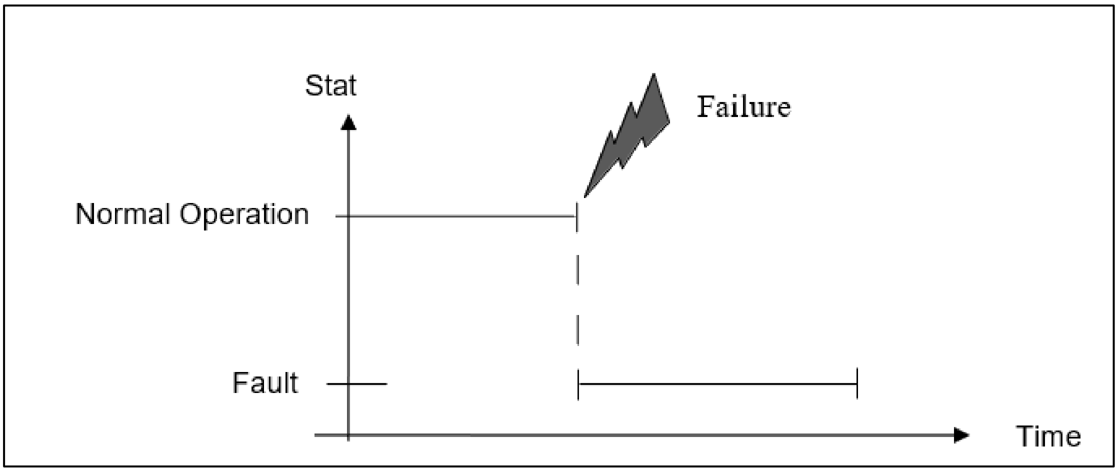


Figure 2.10. Transition from a normal operating state to a failure state caused by a fault

2.5 Diagnostic System

Diagnosis was originally used in the medical field. The term refers to the reasoning process leading to the identification of the cause (origin) of a failure, problem, or disease based on observed characteristics or symptoms through observation, monitoring, or testing (i.e., acquiring knowledge through observable signs).

As in the medical context, the diagnosis of industrial systems is a procedure that consists of detecting and locating a faulty component or element in a dynamic system. Its purpose is to determine the cause of a failure.

We adopt the definition established by standardization bodies: the French Standardization Association (AFNOR) and the International Electrotechnical Commission (IEC) have precisely defined the vocabulary to be used across different industrial sectors [33]:

" Diagnosis is the identification of the probable cause(s) of failure(s) through logical reasoning based on a set of information obtained from inspection, monitoring, or testing. "

This concise definition summarizes the two essential tasks in diagnosis:

Observing the symptoms of the failure;

Identifying the cause of the failure using logical reasoning based on observations.

2.5.1 Diagnosis Steps

The procedure for diagnosing failures and degradations that may affect various entities in an industrial process revolves around the following steps [34]:

2.5.2 Data Acquisition

This function must provide a representation of the process. The following tasks must be performed:

- Signal conditioning and preprocessing;
- Validation of the measurement signal.

2.5.3 Detection

Detection is the first level of diagnosis. It consists of making a binary decision: either the system is operating correctly, or a fault has occurred. The outcome of the detection procedure is an alarm indicating that the actual behavior of the system no longer matches the model of healthy operation

2.5.4 Localization

This is the second level of diagnosis, triggered by a detection procedure. It involves determining in more detail the faulty components: sensor, actuator, process, or control unit.

2.5.5 Identification

Fault identification consists of estimating the magnitude and temporal evolution of the fault in order to best explain the system's behavior. This identification stage is the final phase of the diagnostic procedure.

2.5.6 Decision-Making

Once a malfunction in the system is observed, it is essential to act in a way that maintains the desired performance or minimizes degradation of the real system. The decision-making process involves choosing between several options, such as shutting down the system for maintenance or accepting a degraded mode of operation. If possible, it may also involve reconfiguring or reorganizing the system.

2.5.7 Performance of a Diagnostic Procedure

In general, a diagnostic system is characterized by four main attributes: detectability, isolability, sensitivity, and robustness. Based on these four characteristics, we can compare different diagnostic approaches and determine the most suitable method for our system [35].

2.5.8 Detectability

Detectability is the ability of the diagnostic system to detect the presence of a failure in the process. It is closely related to the concept of fault indicators (residuals): the residual generator must, in some way, be sensitive to the specific failure intended to be detected.

2.5.9 Isolability

Isolability refers to the diagnostic system’s ability to trace the fault back to its origin. Often, one alarm triggers other alarms, making it difficult to identify the actual faulty component. Isolability is directly related to the structure of the residuals and the detection procedure itself.

2.5.10 Sensitivity

Sensitivity characterizes the system's ability to detect faults of a certain magnitude depends not only on the structure of the residuals but also on the ratio between the measurement noise amplitude and that of the fault.

2.5.11 Robustness

Robustness determines the system's ability to detect faults regardless of modeling errors (i.e., the residual's sensitivity to faults and insensitivity to disturbances). In general, robustness is defined with respect to all unknown inputs.

In practice, other criteria must also be considered. During the industrialization phase, ergonomic and economic constraints are essential. The speed of detection can be a determining factor. Similarly, economic costs will influence the diagnostic strategy: does the system require overly expensive components for its implementation Is the development time too long

2.6 Classification of Diagnostic Methods

Previous works reveal a wide variety of diagnostic methods. Nevertheless, they can be classified into two major categories depending on the type of knowledge used to detect faults [35] Figure 2.11 provides a general overview of the main diagnostic methods.

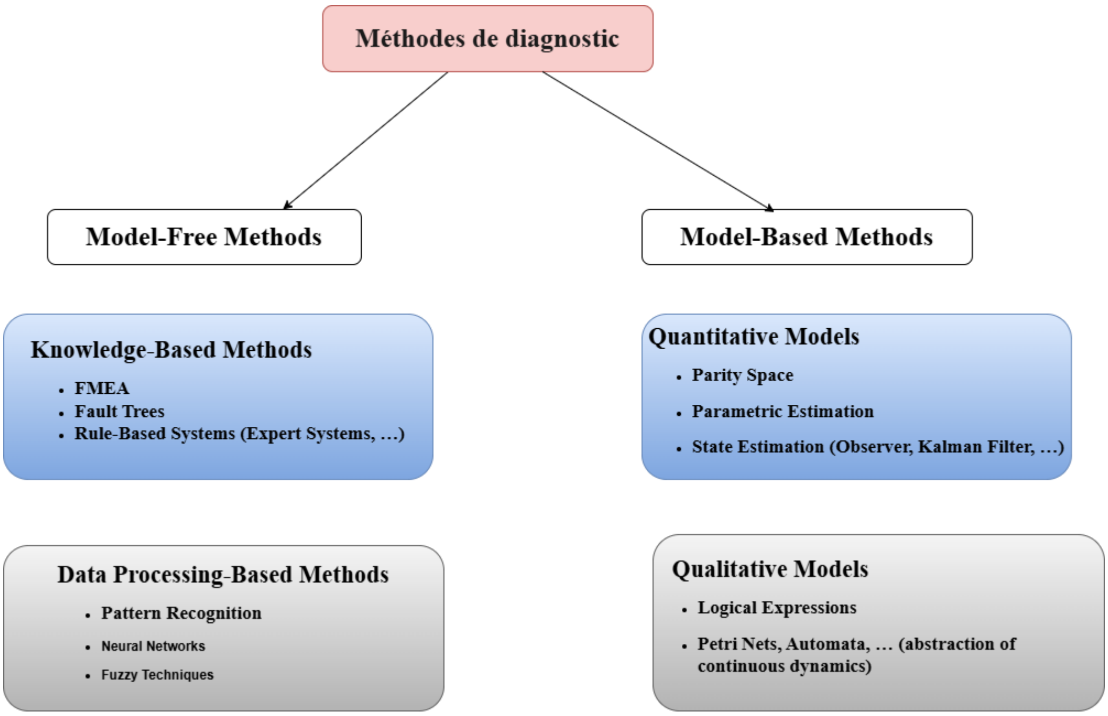


Figure 2.11. A classification of diagnostic methods.

As shown in the previous figure, two main categories of diagnostic methods can be considered.

The first category, known as model-free methods, is characterized by the fact that the system model is not involved in the diagnostic process. Only information from the controller and sensors is used.

- **This category is further divided into two subtypes:**

Knowledge-based methods

Data-driven methods

- **The second category includes:**

Quantitative model-based methods, and Qualitative model-based methods

As is well known, the models of industrial systems—when they exist—are generally complex.

From this perspective, the remainder of this thesis will focus on the first category of methods, specifically those based on data processing, due to the numerous advantages they offer compared to knowledge-based methods.

2.7 Faults in Photovoltaic Systems

In the previous sections of this thesis, we described the various components of a photovoltaic power generation system, followed by an overview of diagnostic methods in industrial systems in general. This current section is dedicated to identifying faults in our specific case study: the photovoltaic system.

2.7.1 Common Faults in Photovoltaic Systems

The operation of a photovoltaic system can experience various malfunctions and anomalies that lead to a decrease in system performance or even its unavailability. Figure 2.12 presents the classification of the most common types of faults in PV systems

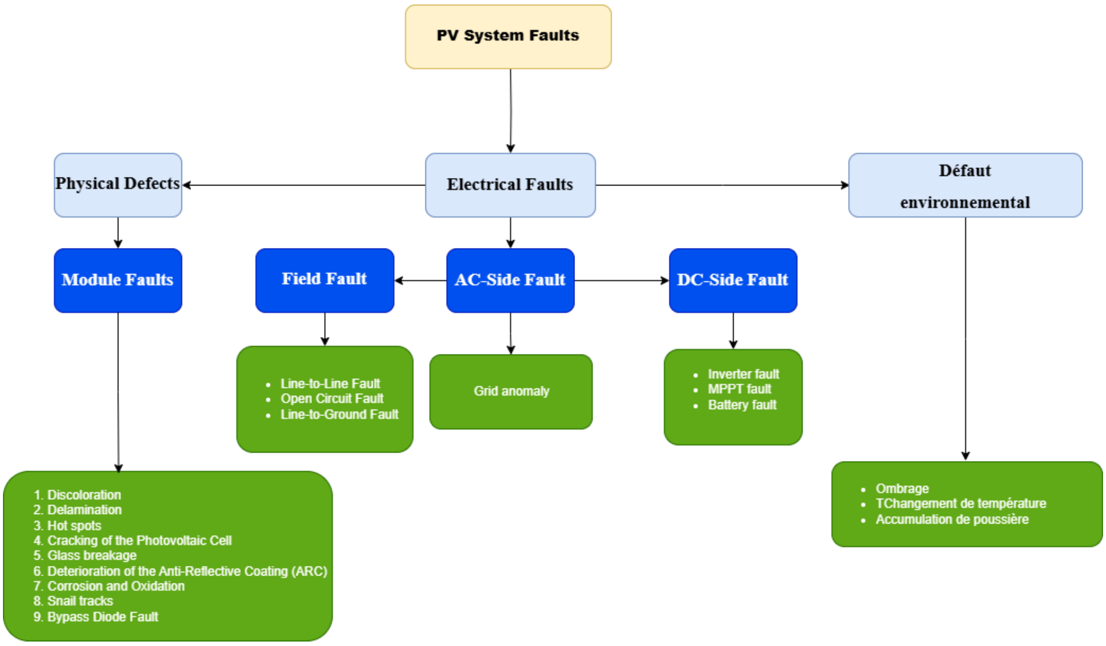


Figure 2.12. Photovoltaic System Faults

2.7.1.1 Physical Defects

This section provides an overview of the drawbacks of photovoltaic systems in order to present useful information to readers and scientific researchers. We focus on the drawbacks of photovoltaic modules

2.7.1.1.1 Discoloration

Discoloration, caused by external factors such as prolonged exposure to ultraviolet rays and high temperatures exceeding 50°C—more frequent in hot and dry areas—is one of the most common defects in photovoltaic panels.

On the other hand, discoloration can be divided into two main types: grid (finger) discoloration and the yellowing and browning of EVA. This imbalance occurs in the photovoltaic sector, leading to a loss of output power due to a reduction in light flux. The light energy is intense when it reaches the surface of the solar cell [36]. Figure 2.13illustrates an example of this defect.

Figure 2.13. Discoloration on the Cell Surface

2.7.1.1.2 Delamination

One of the main modes of degradation is delamination, which includes the loss of adhesion between the different layers (glass/encapsulant), (encapsulant/cell), and the poor adhesion of sensitive and material photovoltaic layers. This defect exists in photovoltaic modules.

Due to the increased reflection of sunlight reaching the surface of the module, the short-circuits generated by the module are reduced [37]. This deterioration is more prevalent in hot and humid regions. An example of these defects is illustrated in Figure 2.14

Figure 2.14. Delamination on the cell surface

2.7.1.1.3 Hot Spots

When the photovoltaic solar cells of the modules produce less current than the module strings, hot spots occur. This defect, which affects the performance of the solar cell, can be caused by various factors such as partial shading of the cell, damage, or electrical imbalance.

Factors include p-n junction deformation, local shunting, impurities, and wafer resistance [38]. Figure 2.15 illustrates how hot spots can damage a cell

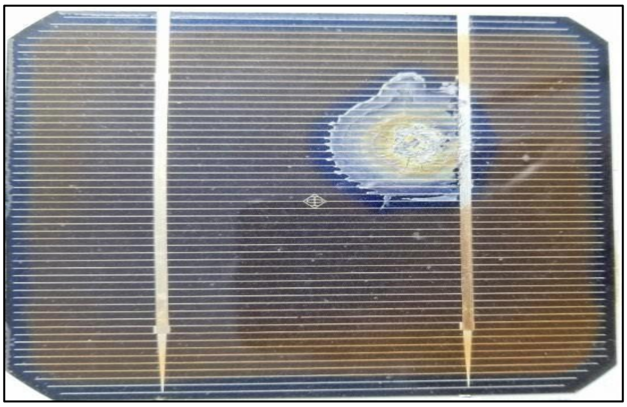


Figure 2.15. Hot spot on the cell surface

2.7.1.1.4 Cracking of the Photovoltaic Cell

When exposed to outdoor conditions, mechanical or thermal stress can lead to visible cell cracks. Micro[39]cracks can also be caused by the same stresses generated during the manufacturing process [40]. Figure 2.16 presents a photograph of these defects.

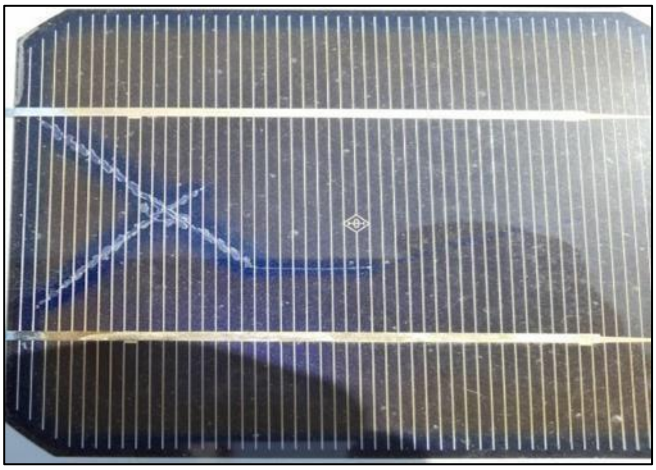


Figure 2.16. Cracking on the cell surface

2.7.1.1.5 Glass Breakage

Glass breakage is generally caused by external factors such as poor packaging during transport, installation, maintenance, handling, wind, thermal stress, and stone impacts [39]. An example of this defect is presented in Figure 2.17.

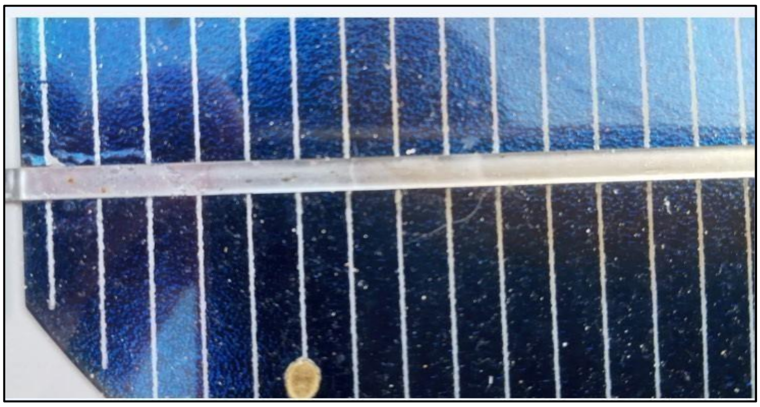


Figure 2.17. Glass breakage on the cell surface

2.7.1.1.6 Deterioration of the Anti-Reflective Coating (ARC)

The amount of reflected light must be reduced in order to improve the optical performance of solar cells, which is why anti-reflective coatings (ARC) are used.

However, they lose this property when they become degraded [41]. This defect is presented in Figure 2.18.

Figure 2.18. Détérioration du revêtement antireflet (ARC)

2.7.1.1.7 Corrosion and Oxidation

The combination of moisture penetration, increased encapsulant absorption, and system voltage can cause corrosion and oxidation of metallic contacts such as fingers, busbars, bus lines, ribbon and string connections, soldered joints, and output terminals. This defect leads to an increase in series resistance, a decrease in the fill factor, and a reduction in output power [42]. Figure 2.19 shows an example of busbar and cell connection corrosion

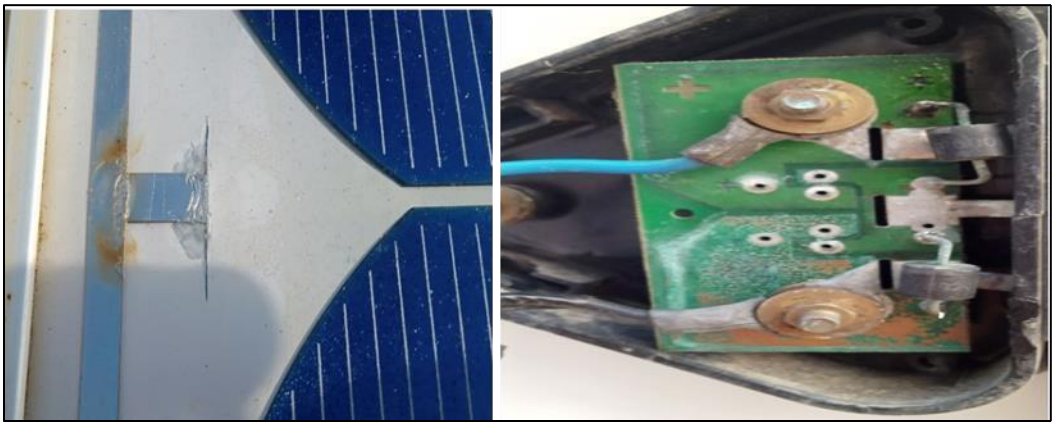


Figure 2.19. Corrosion et oxydation de l'interconnexion des chaînes et de la boîte de jonction

2.7.1.1.8 Snail Tracks

This defect is a microcracking or discoloration of the silver grid lines along the edges of the cell. Various module manufacturers have observed snail tracks (see Figure 2.20) after solar panels have been installed in the field for months or years [43].

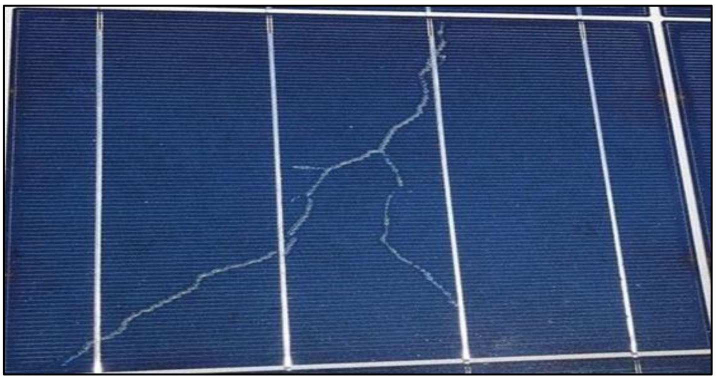


Figure 2.20. Snail tracks on the cell surface

2.7.1.1.9 Bypass Diode Fault

Overheating is a major cause of bypass diode failure due to forward voltage triggering, reverse heat leaks, shadow-to-shadow changes, and even high current transients caused by nearby lightning [44]. See Figure 2.21.

Figure 2. 21. Bypass diode fault.

2.7.1.2 Electrical Fault

2.7.1.2.1 Field Fault.

A photovoltaic generator generally has multiple parallel photovoltaic strings, and each string contains several modules connected in series. Each module, string, and complete assembly, whether normal or defective, has its own I-V characteristics and a unique maximum power point (MPP). When PV modules are connected together, their overall I-V curve is determined by their interactions. Consequently, photovoltaic modules operate together as a string, only as strong as its weakest link.

For the performance of a photovoltaic generator, the weakest link is the module or string with the lowest efficiency under normal conditions [45]. The same applies to photovoltaic panels in power failure scenarios. A photovoltaic generator failure can damage photovoltaic modules and cables, and cause risks of electric shock and fire. The fire risk in photovoltaic generators is caused by line-to-line faults, open circuits, l

2.7.1.2.1.1 Line-to-Line Fault

A line-to-line fault is an accidental low-resistance connection established between two points of different potential in an electrical network or system. In PV systems, a line-to-line fault is generally defined as a short-circuit fault between PV modules or network cables with different potentials (see Figure 2.22). Line-to-line faults in photovoltaic generators can be caused by the following reasons:

- Cable insulation failure, such as an animal gnawing on the cable insulation.
- Accidental short circuit between current-carrying conductors, such as a nail driven into unprotected wiring.
- Line-to-line faults in the DC junction box, caused by mechanical damage, water penetration, or corrosion [46].

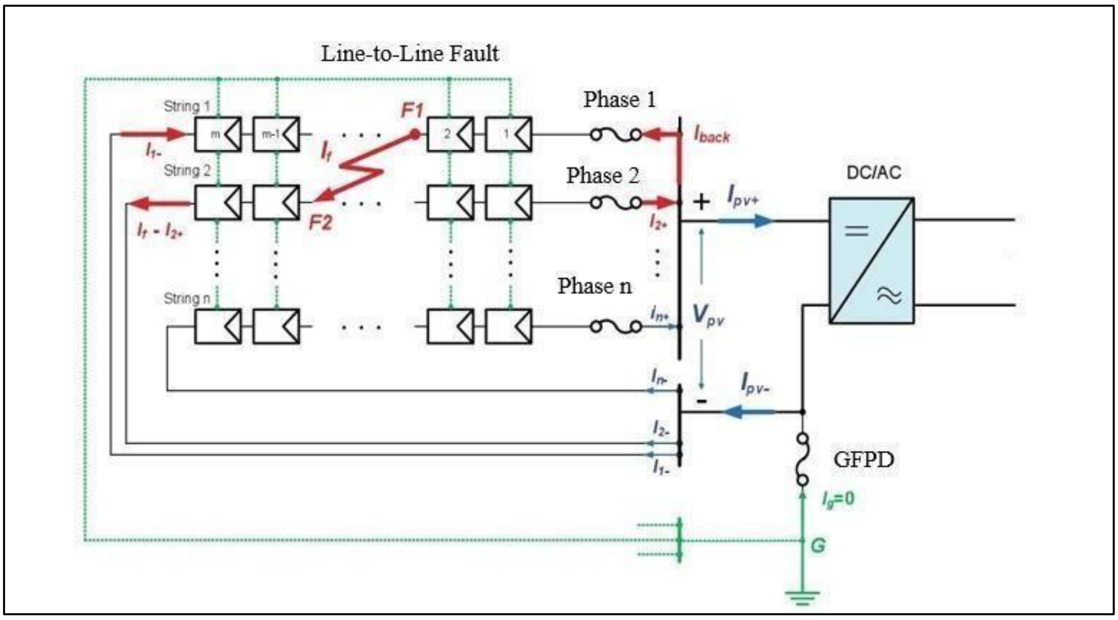


Figure 2.22. Schematic diagram of the PV system under a line-to-line fault [47].

2.7.1.2.1.2 Open Circuit Fault

The open circuit fault is an accidental disconnection in the current-carrying conductor, cracking of PV modules/cells, or connections between modules, with a significant effect on the series and parallel resistance of the PV generator [48]. This fault is shown in Figure 2.23.

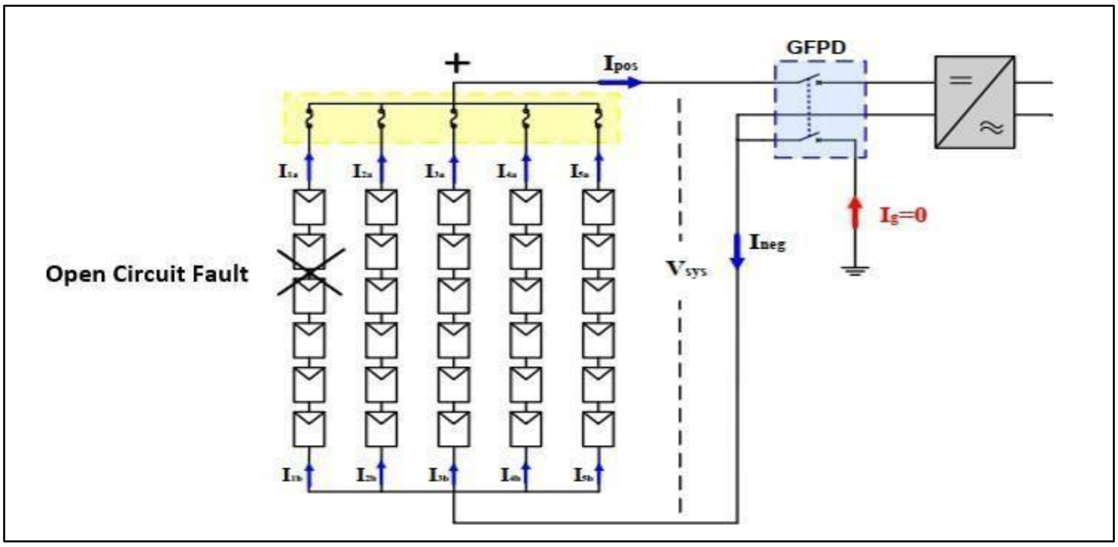


Figure 2.23. Schematic diagram of an open-circuit fault in the photovoltaic generator.

2.7.1.2.1.3 line-to-ground fault

An accidental electrical short circuit between the ground and one or more current-carrying conductors is called a ground fault. The magnitude of the ground fault current depends on the fault location, fault impedance, and geographic factors. If a ground fault is not resolved by appropriate fault protection, the fault connection can start to generate and sustain a DC arc, which may become a fire hazard. This fault is illustrated in the diagram in Figure 2.24..

- Typical ground faults are generally caused by the following reasons [49]:
- An accidental short circuit between the ground and a normal conductor occurs when a cable in the unit's junction box accidentally touches a grounded conductor.
- Cable insulation failure, such as an animal gnawing on the cable insulation causing a ground fault.
- Ground faults in solar modules, i.e., a short circuit between a solar cell and the grounded module frame due to degradation of the solar module encapsulation, water corrosion, or impact

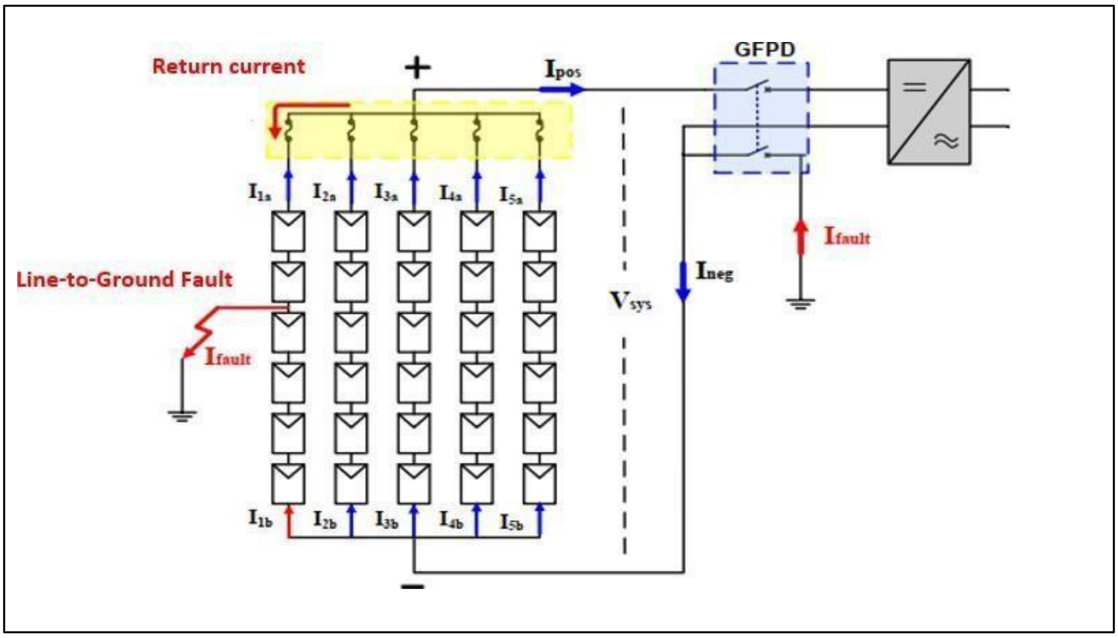


Figure 2.24. Schematic diagram of a line-to-ground fault in the photovoltaic generator

2.7.1.2.2 AC-Side Fault

- The risk of an event occurring on the network is related to many random parameters. Thus, short circuits can have multiple causes [50]:
- Electrical cause: This includes changes such as the insulation degradation of network equipment. Indeed, the electrical equipment of a network or substation contains insulators (solid, liquid, or gaseous) made of more or less complex components placed between the live parts and the ground. These insulators degrade over time, causing insulation failure and consequently short circuits.
- Atmospheric: Overhead lines are sensitive to external disturbances such as lightning, storms, or freezing.
- Mechanical cause: For example, falling objects on conductors or conductors mechanically degraded by external damage from excavation machinery.
- Human cause: This involves operational errors, such as opening a switch under load.

2.7.1.2.3 DC-Side Fault

2.7.1.2.3.1 Converter Fault

Like all power converters, multilevel converters include active semiconductor components such as diodes, MOSFETs, IGBTs, and GTOs, as well as energy storage elements such as inductors and capacitors. Although few studies have been conducted, it is common for the initial switches, especially the controlled ones, to be the most vulnerable to failures.

The internal temperature of the power switch can increase due to a thermal issue caused by an overload from an overvoltage that leads to avalanche breakdown, which may be caused by their control [51].

2.7.1.2.3.2 MPPT Fault

In a typical solar system, the energy from the solar panels is delivered to the battery via a solar charge controller. However, this does not always function correctly. If the solar energy does not reach the battery, it could be a wiring issue, possibly indicating a problem with the solar charge controller (Figure 2.25) [52].

To determine if there is an issue with the solar charge controller, it is necessary to understand the most common problems with these devices in order to perform proper diagnostics. Generally, there are five common issues with solar charge controllers, the main one being that solar charge controllers have [53, 54]:

1. Low battery voltage: When the battery voltage drops, the controller shuts down. To resolve this, an AC charger is used to keep the battery fully charged.

2. Overcurrent at the load output: The charge controller stops charging when an overcurrent occurs at the load output. The solution is to reduce the load.

3. Short circuit due to the load: If the load causes a short circuit, the controller stops charging. The solution is to fix the short circuit issue.

4. Excessive battery voltage: The charge controller will stop charging if the battery voltage is too high. Simply check if the battery connector cable is loose. Additionally, verify whether the battery is too weak or if another charger is connected to it.

5. Panel output current exceeds rated current: When the solar panel's output current exceeds the rated current, the charge controller shuts down.

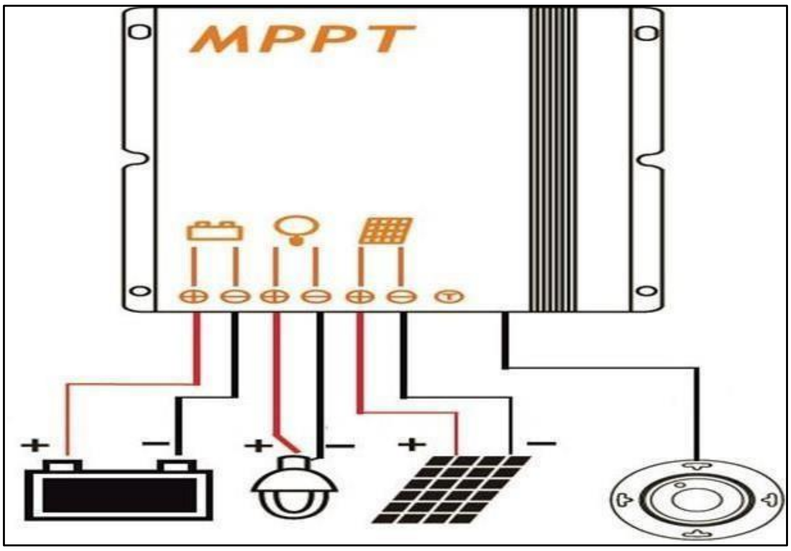


Figure 2.25. Typical diagram of the solar system connected to a solar charge controller

2.7.1.2.3.3 Battery Fault

Battery faults are classified into internal and external faults. Lyu et al. [55] presented a detailed review of the failure modes and mechanisms of rechargeable batteries. Figure 2.26 provides a summary of various faults in a battery system and briefly presents some causes and mechanisms of these faults. It is crucial to understand the mechanisms of these faults, as this helps in establishing appropriate fault diagnosis methods to ensure the safety of battery applications (Figure 2.26).

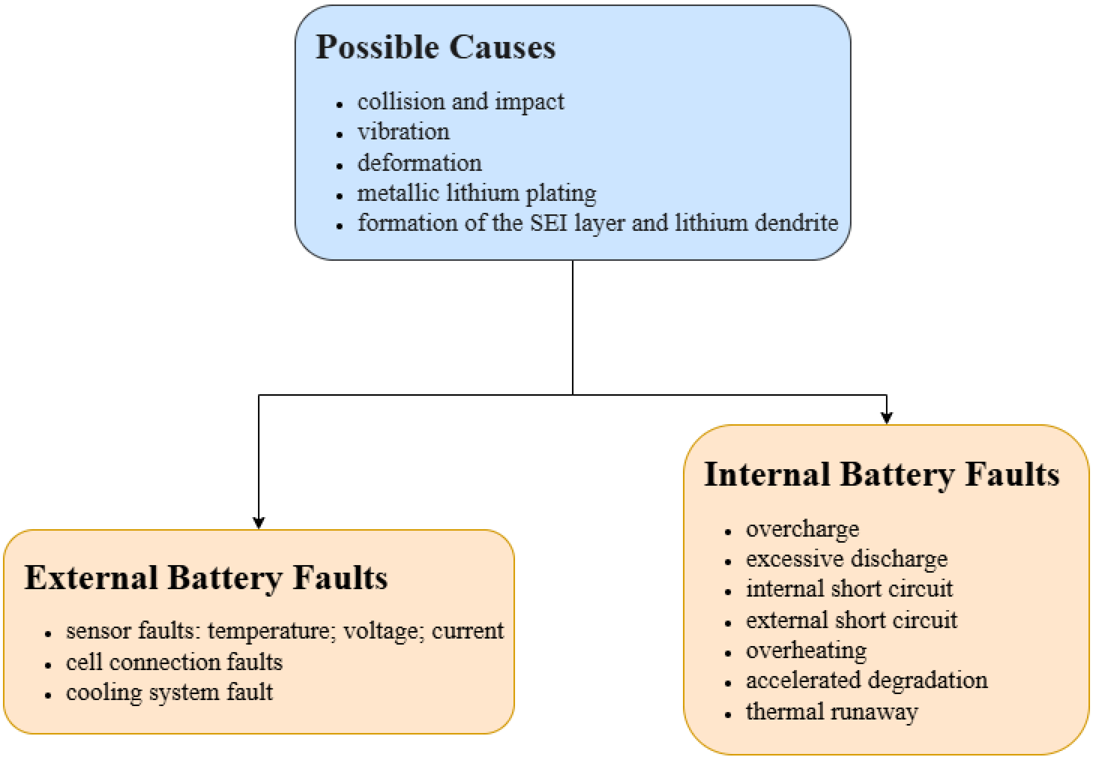


Figure 2.26. Internal and external battery faults and their causes [56] .

2.7.1.3 Environmental Defect

2.7.1.3.1 Shading

In photovoltaic modules, shading represents a major issue, as it can significantly reduce the system's output power. Indeed, the individual cells in a module are connected in series, so if even a single cell is shaded, it can limit the current throughout the entire string, potentially causing a complete loss of power generated by the affected module.

Shading leads to the dissipation of excess power from unshaded cells as heat within the shaded cells, which can result in the formation of hot spots and premature degradation of the module. Bypass diodes are often employed to circumvent shaded cells and minimize these negative effects [45].

- **Shading of a single cell:**

The output of a cell decreases when it is partially or fully shaded, for example by a tree branch, dust, or an opaque object such as a leaf. The reduction in current is proportional to the area of the cell affected by the shadow.

- **Shading of a cell within a module:**

Since the cells in a module are connected in series, the current is the same for all of them. Consequently, shading a single cell lowers the current of the entire string of cells to the level of the shaded cell. For example:

- A cell that is 50% shaded can reduce the module's output power by half.
- A completely shaded cell can reduce the power of the entire module to zero, regardless of the module's size or the number of connected cells.
- The unused power from the other cells is then dissipated in the affected cell, leading to local overheating. This is illustrated in Figure 2.27.

Figure 2.27. Building shading on the panels

2.7.1.3.2 Temperature Variation

Temperature is one of the most critical environmental factors affecting the performance and longevity of photovoltaic modules. The encapsulation of solar cells, although essential for their protection, alters the thermal flow by preventing efficient heat dissipation. This leads to an increase in the operating temperature of photovoltaic cells.

Effects on performance:

When the module temperature increases:

• The output voltage decreases, leading to a reduction in delivered power.

• The conversion efficiency is negatively affected, particularly for crystalline silicon-based cells.

• For every 10 °C increase, the degradation rate can double, exacerbating internal failures.

Effects on reliability:

High temperatures promote:

• Thermal expansion of materials (glass, encapsulant, cell, etc.), which can cause cracks or delamination.

• Accelerated degradation of materials such as EVA (ethylene-vinyl acetate) or the anti-reflective coating.

• The emergence of hot spots when certain cells or areas heat abnormally compared to the rest of the module.

Illustration:

Figure 2.28 presents a thermographic image of a photovoltaic module containing sixteen cells with integrated bypass diodes, subjected to reverse bias. The color variations indicate temperature differences of approximately 4 °C between different areas of the module, clearly illustrating the thermal heterogeneity that can occur during operatio [57].

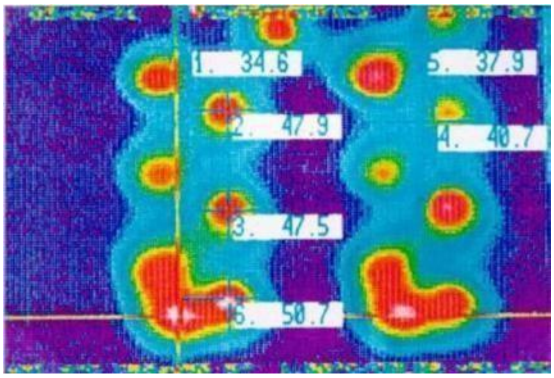


Figure 2.28. Image thermographique d'un module de seize cellules avec changement de température[57] .

2.7.1.3.3 Dust Accumulation

Dust accumulation on photovoltaic modules constitutes a major source of performance loss, particularly in arid, semi-arid, or industrial areas. This phenomenon, although sometimes underestimated, has both direct and indirect effects on solar energy production..

Negative effects:

• Reduction of received irradiation: Dust forms a partially or fully opaque layer, which decreases the amount of light incident on the solar cells.

• Local temperature increase: By blocking light, dust causes localized heating of the module, intensifying the effects of hot spots.

• Alteration of electrical characteristics: This includes a reduction in short-circuit current (Isc) and open-circuit voltage (Voc), thereby affecting the maximum power point (MPP).

Importance of cleaning:

• Regular maintenance through module cleaning is essential to:

  • Maintain optimal energy efficiency.
  • Extend the system's lifespan.
  • Prevent the buildup of corrosive chemical deposits mixed with moisture.

Influence of ambient temperature:

It is important to note that solar panels perform less efficiently at high temperatures. Thus:

A sunny but hot day may produce less energy than a cloudy day with cool winds.

This is due to the negative temperature effect on cell voltage.

Illustration:

Figure 2.29 shows the combined impact of dust accumulation and high ambient temperature on the overall efficiency of a photovoltaic system, highlighting the importance of preventive maintenance [58].

Figure 2.29. Dust accumulation on the panels

2.8 Fault Detection and Diagnostic Methods in a PV System

Climatic conditions (shading effects, module soiling), operational conditions (aging of PV modules), and manufacturing defects are the primary causes of anomalies appearing at various stages of the photovoltaic system, including the module, wiring, protection, and finally power converters.

Similar to all industrial systems, monitoring systems play an essential role in photovoltaic installations because they perform the tasks of fault detection and control [59].

In this context, researchers have proposed several diagnostic methods dedicated to photovoltaic plants.

Three basic features distinguish one method from another: the speed of anomaly detection, the optimization of input data, and selectivity (i.e., the ability to distinguish between different faults).

Overall, these methods can be classified into two main categories [60]:

- Visual and thermal methods [44, 61] (non-electrical), which can be used to detect discoloration, browning, surface soiling, hot spots, cracks, and delamination.
- Electrical methods that can be used to detect and diagnose defective PV modules, strings, and arrays, including arc faults, ground faults, diode faults, etc.
- The following graph presents the different diagnostic methods

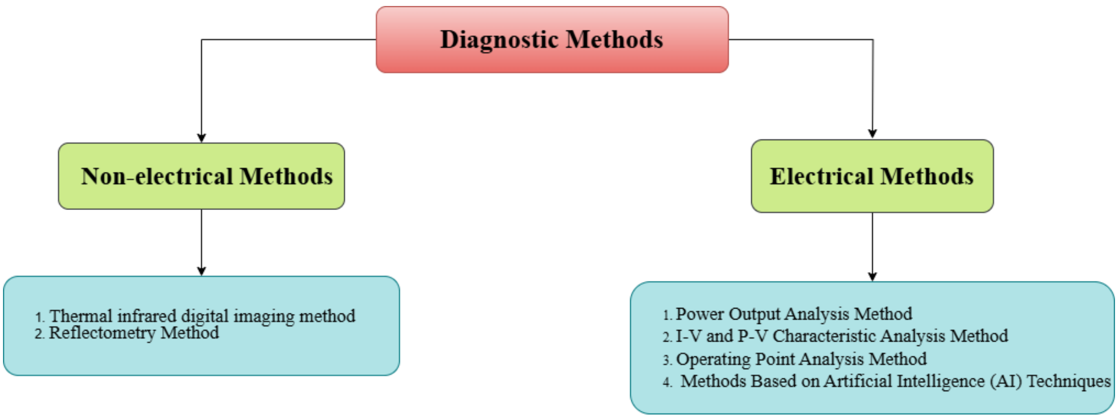


Figure 2.30. Fault diagnosis methods for a PV generator.

2.8.1 Non-electrical methods

This category of methods is mainly intended for detecting cracks. Examples include mechanical bending tests, photoluminescence imaging, and electroluminescence. In our case (diagnosis of PV modules), infrared imaging and reflectometry are the most widely used [62].

2.8.1.1 Thermal infrared digital imaging method

Visual inspections and infrared and thermal imaging analysis for detecting and locating faults are classified as non-electrical methods. These methods do not require electrical data measured from the PV system. Visual and thermal methods are specifically used to detect discoloration, browning, soiling, hot spots, cracks, and delamination of PV modules [59, 63]. Visual inspection of modules is time-consuming and unsuitable for large-scale PV systems.

Thermal and infrared fault detection methods generally rely on equipment such as thermal or infrared cameras, drones, etc., and the detection speed depends on the frequency of plant monitoring. These methods have proven to be effective [44, 61] [64]but they are not suitable for small-scale photovoltaic installations.

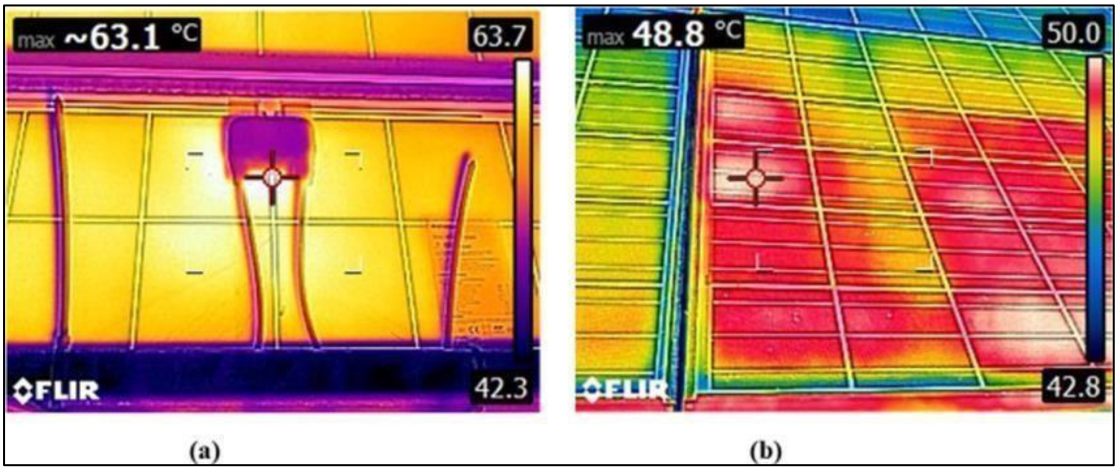


Figure 2.31. Infrared thermal images of PV modules showing fault indications.

2.8.1.2 Reflectometry Method

Reflectometry operates on the same principle as radar: a pulse or signal is transmitted into the PV field to be diagnosed. Any discontinuity (crack, fault, short circuit, open circuit) acts as an obstacle to this incident pulse and causes a reflection. The returned echoes are then measured. The delay and amplitude of the echoes are used to obtain information about the location, characterization, and potentially the prediction of the fault. It only requires a single access point, which demands precision in its determination. Nevertheless, it is well suited for networks with complex topologies. It can also be integrated into control systems. However, early fault detection in a PV field requires powerful data processing with very rapid sampling, which increases the complexity and cost of the diagnostic system.

This method has been used by [64, 65], and by T. Takashima et al. [66], aiming to detect "open circuit," "short circuit," and "increased connection impedance" faults in a photovoltaic string

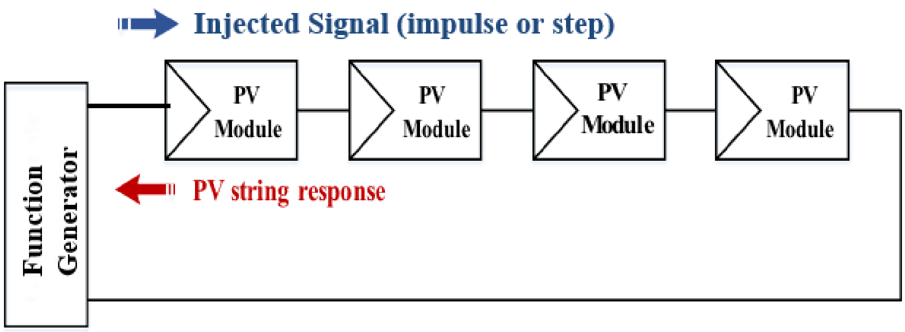


Figure 2.32. Principle of reflectometry for locating the fault in a PV string.

2.8.2 Electrical Methods

The input data for these methods are electrical parameters (current, voltage, and power). Four main types of methods are proposed in the literature, which we focus on in this section.

2.8.2.1 Power Output Analysis Method

This method is applied by [67, 68]. It is effective in determining whether a PV field is operating normally or not. It uses solar irradiation and module temperature data to predict the photovoltaic panel output with an equivalent circuit model. Two indicators corresponding to thermal losses and power losses are defined. The detection algorithm recognizes faulty system operation when measured losses are significantly higher than simulated losses. Indicators based on ratios of simulated and measured current and voltage values are then used to identify string faults or shading faults [69].

2.8.2.2 I-V and P-V Characteristic Analysis Method

Collecting measured quantities (current and voltage) at different points in the photovoltaic field allows precise detection and localization of the fault location using sensors placed in the PV field. Several studies have been conducted in this regard by various authors [70].

2.8.2.3 Operating Point Analysis Method

This method is based on analyzing and comparing the current maximum power point (MPP) of the PV installation with the expected one [71]. This method enables automatic fault detection without interrupting the system.

2.8.2.4 Methods Based on Artificial Intelligence (AI) Techniques

The diagnosis of complex physical systems containing multiple types of descriptions and elements, where purely mathematical models cannot provide an adequate methodology with the required precision, poses significant challenges. Therefore, AI methods have been developed to mimic human reasoning in decision-making. Their objective is to simplify and facilitate the diagnostic process.

Over the past decade, AI techniques have demonstrated their capability in modeling, control, prediction, and forecasting within PV systems [72].

2.9 Photovoltaic System

Photovoltaic solar systems can be classified into three main types: grid-connected, hybrid, and off-grid. Each type of solar panel system has its advantages and disadvantages, and it really depends on what the consumer wishes to gain from their solar panel installation [73].

2.9.1 Grid-Connected Solar System

A grid-connected solar system is a photovoltaic solar system that connects directly to the national grid. This type of photovoltaic solar system is the most common among homeowners and businesses. It is ideal for someone who is already connected to the grid but wants to reduce their carbon footprint and energy bills.

A grid-connected solar system does not require a battery storage system and is connected to the national grid directly via a solar or micro-inverter. One disadvantage of this photovoltaic solar system is that, because it uses a grid-tied inverter, when the national grid fails, this solar system does as well. This simply means that you will have no backup power source.

It can be upgraded to a hybrid system by adding a battery. It is necessary to install an AC-coupled control management system alongside the battery, which is called a retrofit. Adding battery storage to the photovoltaic solar system can provide solar energy even during outages. This is called a hybrid system (Figure 2.33) [74].

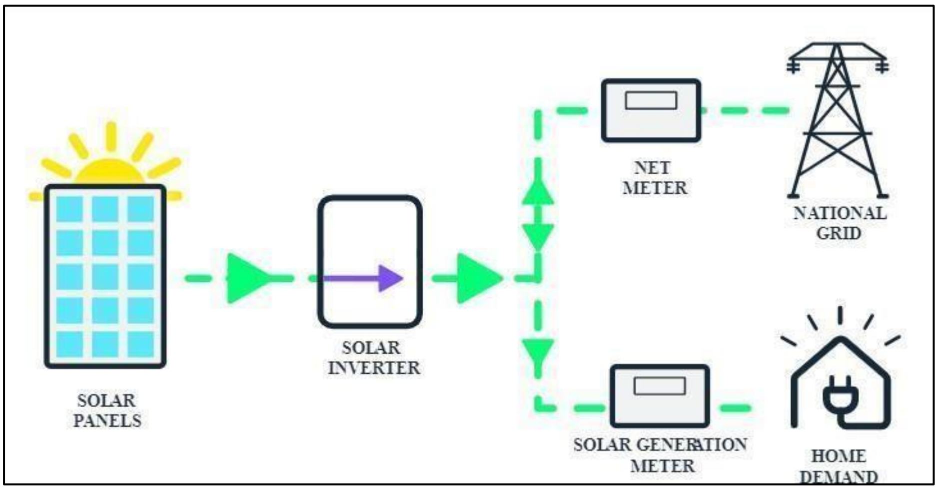


Figure 2.33. Grid-connected photovoltaic installation

2.9.2 Hybrid Solar System

Hybrid solar systems combine solar panel technology and solar batteries to create a green energy solution that provides backup power supply. Although a hybrid PV system remains connected to the national grid, any solar energy generated is first stored in a home battery solution before being routed to the grid (Figure 2.34).

The main advantage of a hybrid solar system is that by storing surplus energy in a battery, solar power can be used to supply the home during the night and less energy is exported back to the grid. Additionally, unlike a grid-tied system, when the national grid is down, energy can also be drawn from the battery. This is called islanding and is particularly ideal for homeowners living in areas prone to power outages.

Hybrid solar panel systems offer great flexibility; when all battery power is depleted, it is still possible to draw from the grid. This makes a hybrid solar system the perfect intermediate solution. As an intermediate solution, a hybrid solar system is more economical than an off-grid system but more expensive than a grid-tied system.

A significant advantage of a hybrid solar system is that the battery storage system can be expanded at any time, and because it is always connected to the grid, it can also charge batteries from cheap off-peak rates. However, since more components are involved in a hybrid solar system, it is less efficient than a grid-connected system [74].

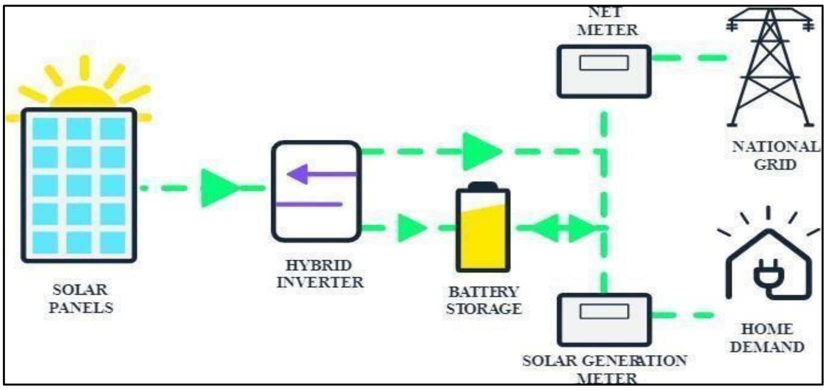


Figure 2.34. Hybrid solar system installation

2.9.3 Off-Grid (Standalone) Solar System

An off-grid system is not connected to the national grid (Figure 2.35), unlike a grid-connected solar system. This makes it desirable for those who cannot easily connect to the grid or who wish to be energy independent.

With rising energy costs, energy independence is more in demand than ever. A complete off-grid solar system contains everything needed to generate clean solar energy. Unlike hybrid systems, off-grid systems tend to have backup generators and other types of renewable sources to ensure that the battery is fully charged throughout the year. In fact, the off-grid system is the only available power supply. Off-grid solar systems have the potential to provide electricity even in remote areas.

With an off-grid solar system, one can be energy self-sufficient, having a power supply regardless of where they live [73].

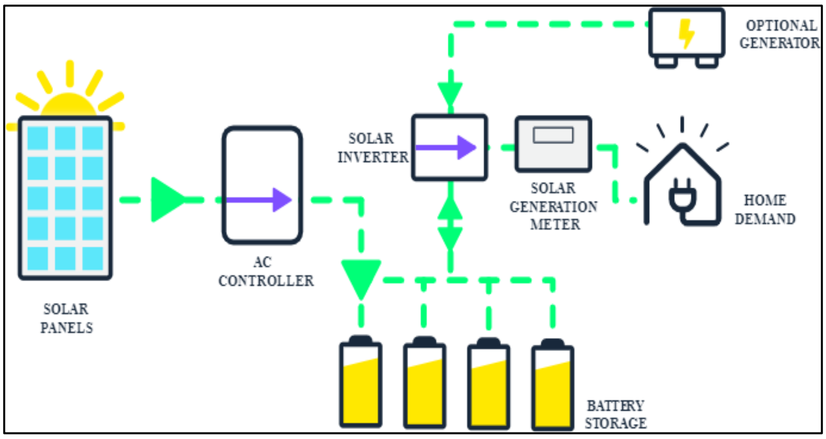


Figure 2.35. Stand-alone solar system installation

2.10 Electrical Modeling of a Photovoltaic Cell

The single PV cell is a small building block that forms the larger PV energy conversion system used to generate power. When the negative and positive wires are connected to a load, they form an electrical circuit, and electrons flow to complete the circuit.

The current generated in the PV cell is called the photonic current (Iph). In a simple single-diode model, the PV cell is composed of a photo-current source connected in parallel with a diode. The electrical behavior of this component operates like a P-N junction. The current generated by the irradiance (G) is proportional to the solar radiation directly incident on the surface.

The simple PV model does not include series and shunt resistances; this basic model can be described using Shockley's diode theory. The PV cell is not a constant current source. The single-diode simple PV model [75] is illustrated in Figure 2.36.

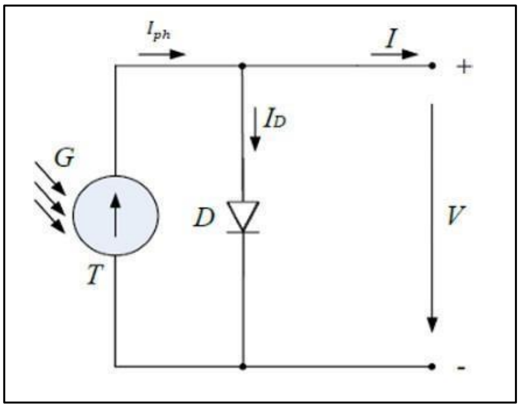


Figure 2.36. Simple PV Model with a Single Diode

This model is represented based on Shockley's diode equation . In this model, *G* is the irradiance, and the diode current is given by:

$$I_D = I_0 \left[exp\left(\frac{qv}{nkT}\right) - 1 \right] \quad (1.4)$$

According to Kirchhoff's law, the total incoming current and the sum of the outgoing current are always zero. Based on Kirchhoff's law, the current generated from the PV is given by:

$$I = I_{ph-I_D} \quad (1.5)$$

Therefore

$$I = I_{ph} - I_D = I_{ph} - I_0 \left[exp \left(\frac{qv}{nkT}\right) - 1\right] \quad (\mathbf{1.6})$$

Iph is the photocurrent, ID is the diode current, and I_0 is the dark saturation current. n is the diode ideality factor, q is the electron charge, k is Boltzmann's constant, and T is the cell junction temperature.

For the characterization of the PV cell, the short-circuit current (Isc) and the open-circuit voltage (Voc) have a considerable influence. When the voltage is zero, Isc is equal to the photocurrent (Iph). Therefore, $I = Iph$. The simple model provides the value of the PV output. A series resistance is added to the simple PV model. The four-parameter model of the PV cell is illustrated in Figure 2.37 [76].

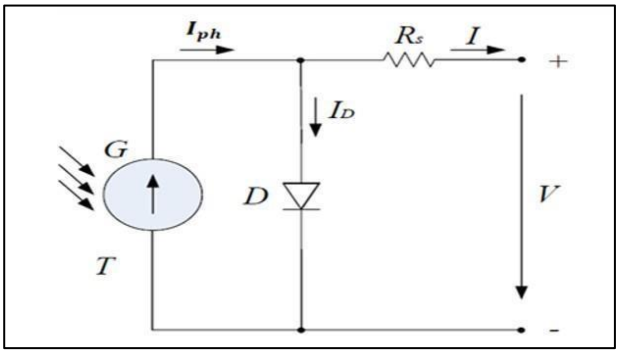


Figure 2.37. Four-Parameter Single-Diode PV Cell Model

The four-parameter mathematical model provides the current-voltage characteristics of the PV cell.

The total current is given by:

$$I = I_{ph} - I_D = I_{ph} - I_0 \left[exp \left(\frac{qv \pm qR_S I}{nkT}\right) - 1\right] \quad (\boldsymbol{I.7})$$

Rs is the internal series resistance in the equivalent PV circuit. To obtain a more accurate output, a more sophisticated model that includes both a series and a shunt resistance is required.

The five-parameter single-diode PV model is well known and the most commonly used for simulating the PV cell. This model represents the electrical equivalent of the PV cell. It exhibits behavior that closely approximates that of solar cells in a PV panel.

The shunt resistance and the series resistance are included in parallel in the equivalent PV circuit, forming the five-parameter model of the PV cell. The five-parameter model of the PV cell is illustrated in Figure 2.38. [76].

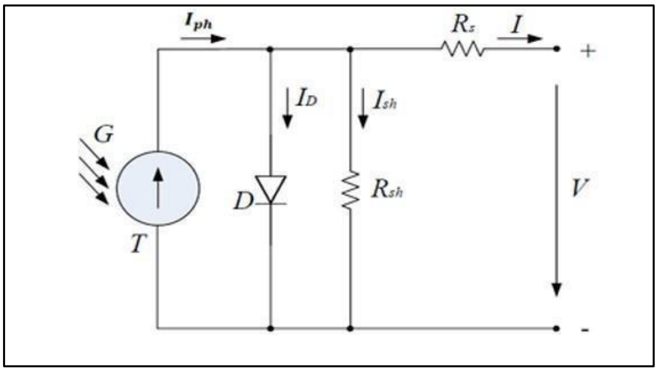


Figure 2.38. Single-Diode PV Cell Model with Five Parameters

I_{ph} is the photocurrent, which is the current source for the circuit; a single diode D with a current ID flowing through it; a series resistance R_s representing the resistance within the cell; and a shunt resistance R_{sh} connected in parallel.

The current across the shunt resistance **(I_{sh})** is given by :

$$I_{sh} = \frac{V \pm IR_S}{R_{Sh}} \quad 1.8$$

By applying Kirchhoff's current law, the total incoming current and the outgoing current sum to zero.

According to Kirchhoff's current law, the current generated by the PV is given by:

$$I = I_{ph} - I_D - I_{sh} \quad 1.9$$

After substituting all the values, the total current is given by:

$$I = I_{ph} - I_D - I_{sh} = I_{ph} - I_0 \left\{ exp\left(\frac{q(V + IR_S)}{nkT} \right) - 1 \right\} - \left(\frac{V + IR_S}{R_{Sh}} \right) \quad 1.10$$

Shunt resistance and series resistance are included and used for different simulations. If the shunt resistance is much larger than the load resistance and the series resistance is much smaller than the load resistance, then their losses within the cell can be neglected. When these losses are ignored, the shunt and series resistances can also be omitted from the model.Thus, the total current is the difference between the diode current and the photocurrent, and the equation becomes as in (I.4). This represents the ideal PV model without series and shunt resistances. The current and voltage have significantly different characteristics for the PV model.For the open circuit, the voltage (Voc) is the voltage when the current is zero, and the output power is also zero. For the short circuit, the current (Isc) is the condition where the voltage is zero and the energy output is zero. The current (Imp) corresponds to the value at which the PV module delivers the maximum output power under internal and environmental conditions. The voltage at maximum power (Vmp) is the voltage at which the PV module provides maximum power.The maximum power point (MPP) is important as it represents the point where the PV module delivers its best efficiency. This point depends on different values related to environmental parameters [76].

2.11 Conclusion

In this chapter, an overview of the Internet of Things (IoT) and its various applications was first presented, with a particular focus on its role in the energy sector and smart system monitoring. Emphasis was placed on the potential of IoT to enhance the performance of photovoltaic (PV) systems by enabling real-time data collection and analysis for effective diagnostic decision-making.Subsequently, a set of key definitions and terminology related to the field of fault diagnosis was introduced. Diagnostic methodologies found in the literature generally consist of three main stages: detection, localization, and identification.The chapter also highlighted the most common faults and anomalies that may occur in PV systems, which can broadly be categorized into manufacturing defects and those resulting from climatic or operational conditions. Furthermore, a comprehensive review of the state-of-the-art diagnostic techniques for PV systems was provided. These methods aim to monitor system performance to detect, locate, and accurately diagnose faults, thereby enhancing operational efficiency and reliability.In addition, modeling was incorporated into the diagnostic approach, as it offers a powerful tool for simulating and understanding system behavior under various fault conditions, thus improving prediction accuracy and performance analysis.

Hardware Design of the Unit

1.1 Introduction :

The hardware design of an embedded monitoring unit involves more than the simple assembly of electronic components; it represents a deliberate and structured process aimed at translating system-level functional requirements into a physical platform that meets operational, environmental, and technical challenges. Achieving such a design demands a thorough understanding of performance criteria and real-world constraints, alongside the technical capacity to transform theoretical concepts into a robust and maintainable implementation [77, 78].

The design approach adopted for this system focuses on building a stable and adaptable hardware foundation. Development was carried out using EasyEDA, which supported the design of a clean and optimized circuit layout. The hardware integrates key subsystems such as voltage regulation, voltage and current sensing, wireless communication, and relay control circuits. The choice of components was governed by criteria such as efficiency, power consumption, and compatibility, while PCB layout optimization aimed to minimize electromagnetic interference and facilitate diagnostics and repair [79, 80].

A modular design philosophy was adopted, avoiding the permanent integration of certain components, including the microcontroller, in order to allow for future upgrades and system scalability. This approach simplifies maintenance and enhances the adaptability of the unit for evolving application needs. All design decisions were guided by a careful balance of performance, longevity, and ease of assembly, establishing a sound platform for intelligent, field-deployable systems [81].

3.1 General outline and design of the proposed model:

Here, the general outline and basic design of the proposed model are clarified, which helps in understanding the overall structure of the project. It also highlights how the model operates and contributes to evaluating its feasibility and effectiveness before implementation .

3.1.1 General outline of the proposed model

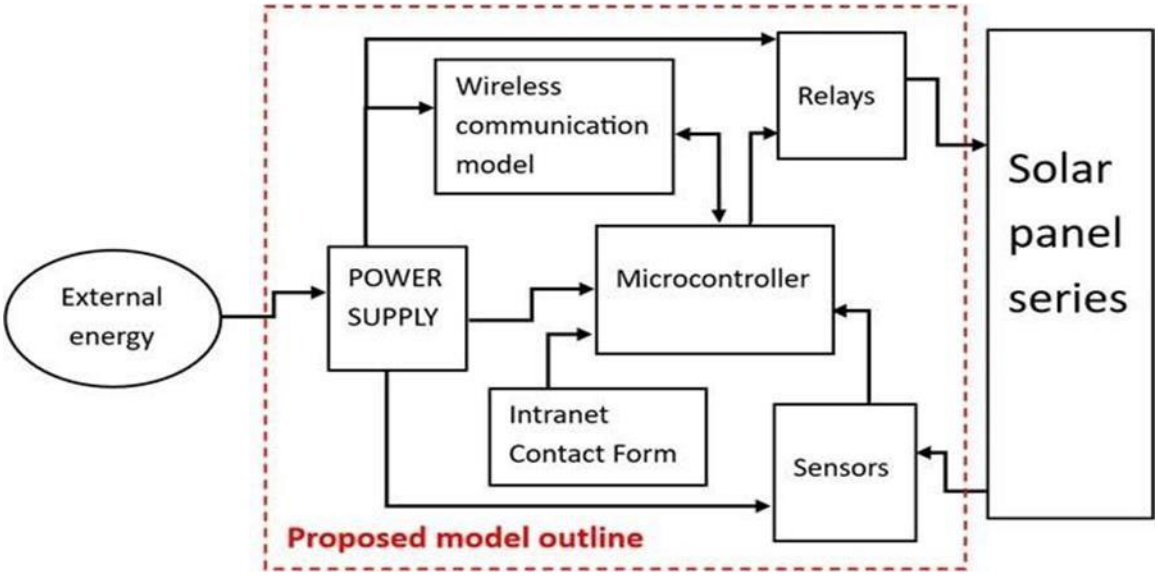


Figure 3.1. Model diagram

The figure below represents the general diagram of the proposed smart unit, which is used to intelligently and flexibly monitor and control the solar panel array. This system is based on several integrated components that collect, process, and communicate with a central control unit to make immediate and effective operational decisions.

The process begins with an external power source connected to the power regulation unit, which provides the appropriate power for the device components to operate in a stable and safe manner. This unit, in turn, supplies power to the microcontroller, the central component responsible for managing data and operations within the system.

A set of sensors is connected to the microcontroller to monitor the performance of the solar panels and collect data such as voltage and current. This data is transmitted to the microcontroller using internal communication protocols, such as serial communication protocols such as UART, I2C, and SPI, which allow data to be exchanged between the microcontroller and the device's secondary components with high efficiency and speed.

When data is collected, the controller sends it to the main unit via a wireless communication module. The main unit is connected to a display interface to show the real-time performance of the solar panels. When the data is processed and a fault is detected in one of the solar panels, the main unit issues control commands that are returned via the same wireless channel to the controller in the secondary unit.

These commands are used to turn on or off relays that control the connection or disconnection of panels within the chain, based on a carefully thought-out protocol that enables us to automatically isolate damaged panels to ensure they do not affect the system, while keeping the remaining healthy panels operating normally.

In this way, the plan provides us with an integrated and powerful system that combines data collection, effective communication, and fast and intelligent processing to make decisions that allow for enhancing and improving the efficiency of solar power plants.

3.1.2 Device design on EasyEDA

In this section, we have some custom images of the proposed device design created using the EasyEDA software, which was chosen due to the many advantages it offers :

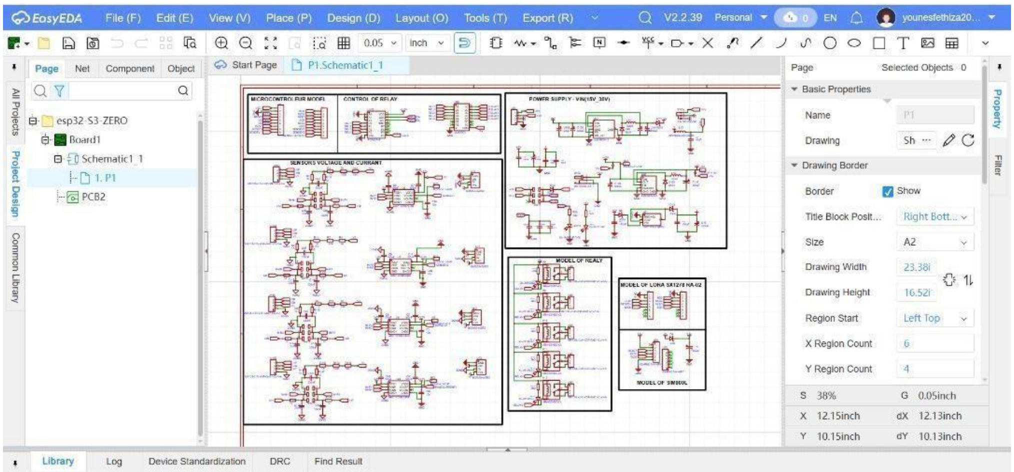


Figure 3.2. Schematic Interface in EasyEDA Software

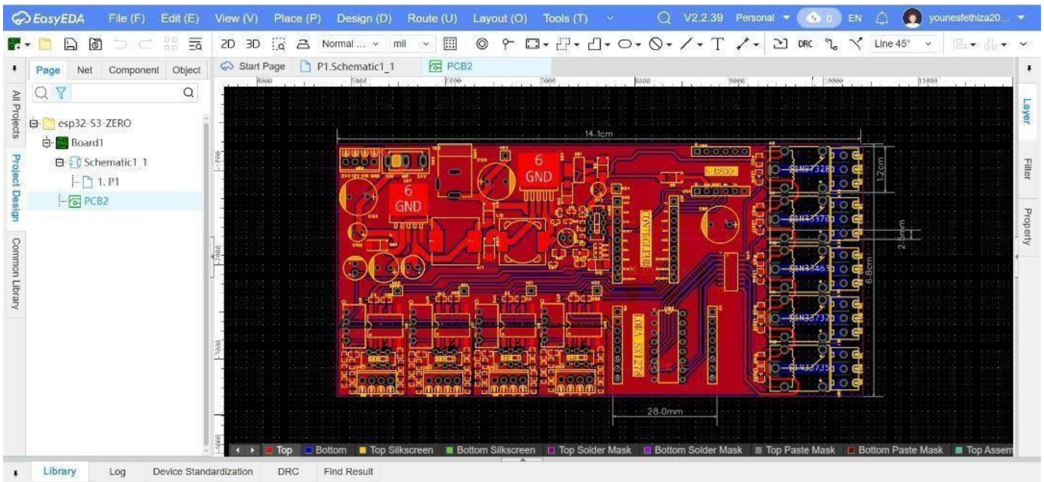


Figure 3.3. Top Layer View of the PCB Layout in EasyEDA

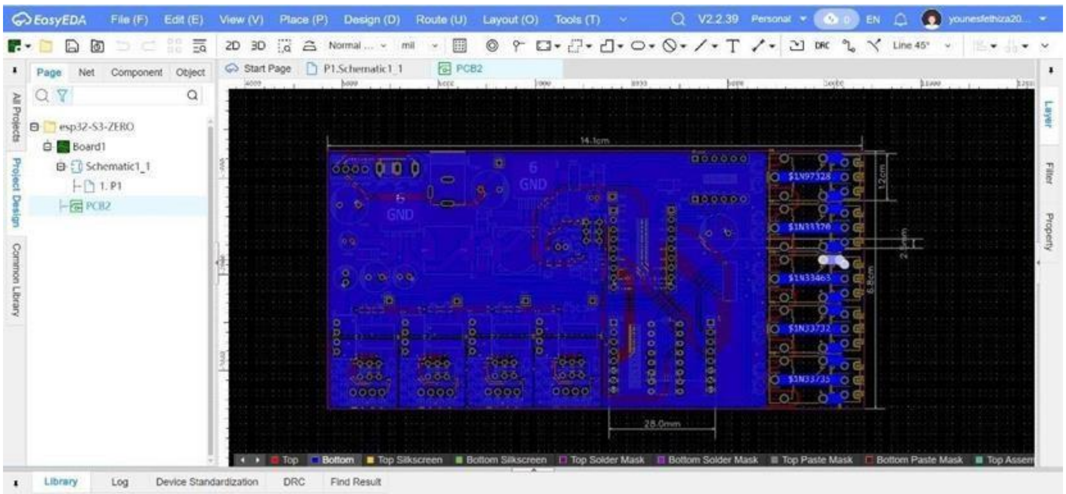


Figure 3.4. Bottom Layer View of the PCB Layout in EasyEDA

3.2 Definition of the elements in the device:

This section is dedicated to introducing all the main components of the device, which have technical names consisting of symbols and numbers. We will now briefly explain their meanings :

LM2596S-12 :

A step-down (buck) voltage regulator designed to provide a stable 12V output from a higher voltage input. It features high conversion efficiency and is suitable for powering fixed-voltage loads [82].

LM2596S-5.0 :

A buck voltage regulator that delivers a fixed 5V output from a higher input voltage. Commonly used to power microcontrollers and communication modules requiring a 5V supply [83].

LM1117-3.3 :

A linear voltage regulator that provides a stable 3.3V output from a higher input voltage. Frequently used for powering Wi-Fi and LoRa modules that require precise voltage levels [84].

ESP32-S3 Zero :

A compact embedded microcontroller module equipped with Wi-Fi and Bluetooth LE. It features a dual-core processor and support for AI and computer vision applications, making it ideal for advanced IoT systems [85].

AMC1200 :

An isolated differential amplifier used for measuring analog signals in environments requiring electrical isolation between circuits. Commonly applied in industrial measurement and power systems.

B0505S-W2R2 :

An isolated DC-DC converter that transforms a 5V input into an isolated 5V output. It is used to protect sensitive circuits by preventing electrical interference between input and output.

PCF8574P :

An I/O expander that communicates via the I2C interface. It provides 8 programmable digital I/O pins and is used to increase the number of input/output ports available on a microcontroller [86].

ULN2003 :

A driver IC containing 7 Darlington transistor arrays with open-collector outputs. It is used to drive high-current loads such as relays, motors, and LEDs, and includes internal protection diodes [87].

LoRa SX1278 RA-02 Module :

A long-range, low-power communication module based on the LoRa SX1278 chip. It is commonly used in sensor networks, tracking systems, smart agriculture, and other IoT applications [88].

SIM800L Module :

A compact GSM/GPRS communication module used for sending and receiving SMS, making voice calls, and connecting devices to mobile networks. Ideal for remote IoT solutions [89].

3.3 Circuit Design Explanation:

Here, the basic idea behind the circuit design is explained, helping to understand the device components, how it works, and the reasons behind choosing each part.

3.3.1 Power Circuit Design Explanation:

This part is extremely important in the design, as it is responsible for providing stable power to all components of the device. Any malfunction in the power supply could pose a risk to the other components. The design of this section is divided into three parts.

3.3.1.1 Linear Regulation Stage 12V:

This part of the circuit functions as a buck converter based on the LM2596S-12 voltage regulator. It steps down the input voltage from a range of 15V to 30V (as indicated by VIN) to a stable output of 12V (as specified at the U10 output), making it suitable for powering digital and analog systems that require a stable 12V supply. The converter operates in switching mode and includes in its design an inductor with a value of 47 microhenries (L14), an SS34 Schottky diode (D11), and filtering capacitors (C126 at 470 microfarads and C128 at 220 microfarads). These components work together to maintain voltage stability and reduce output ripple. The design is characterized by its compact size, thermal protection (thanks to the LM2596S features), and good performance, making it ideal for applications in embedded systems and limited-power systems.

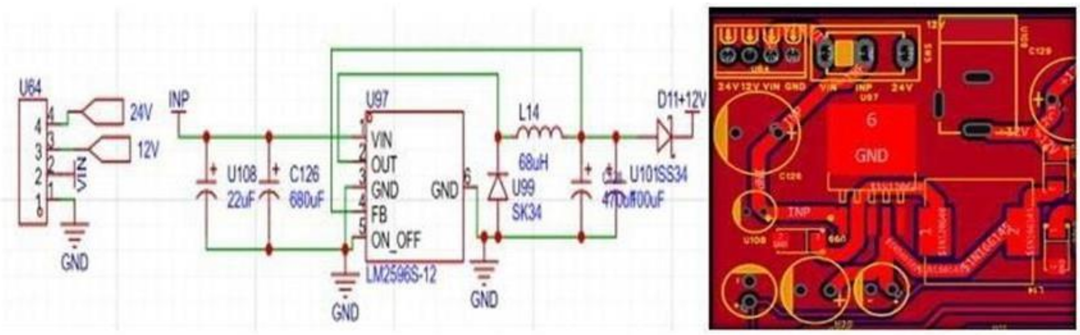


Figure 3.5. circuit of DC-DC buck converter based on the LM2596S-12

Among the reasons the LM2596S-12 was chosen are:

- **High Efficiency:** Approximately 73% when stepping down from 12V to 3V at 3A, ideal for energy conservation.
- **Fixed Output Voltage:** 12V regulated without adjustment, ensuring stable power supply.
- **Wide Input Range:** 15V-40V, supports the variable voltage of solar panels.
- **High Current:** Supports up to 3A for monitoring circuits.

- **Thermal Protection:** Includes overheat shutdown to protect the device.
- **Compact Design:** Requires only 4 external components, reducing costs.
- **Low Ripple:** Ensures stable power for digital loads.
- **Thermal Reliability:** Resistance of 2°C/W, suitable for diverse thermal conditions.

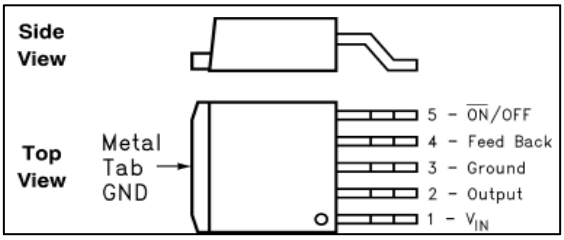


Figure 3.6. Definition of ports for LM2596S-12

*** Battery module:**

This module is designed to power the device from either a 12V or 24V battery. Each of the above battery types has a dedicated port on the board. The 12V battery is connected directly to the LM2596S-5.0, while the 24V battery is connected to the LM2596S-12. A switch is also provided to select the primary power source, which will be either the solar panel or the 24V battery.

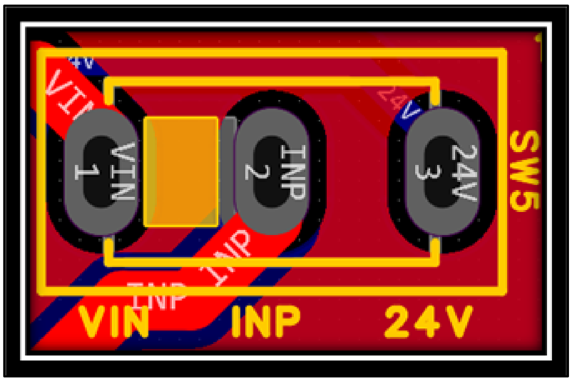


Figure 3.7. Battery switch design

3.3.1.2 Linear Regulation Stage 5V:

The opposite section of the circuit reduces the 12V voltage coming from the previous section LM2596S-12 and from the DC port U109 to a constant 5V voltage, and this is to operate some of the chips and components on the board.

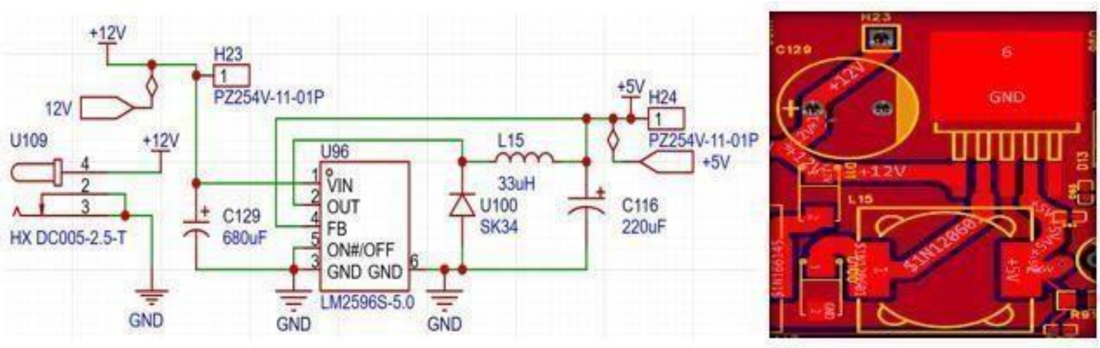


Figure 3.8. circuit of DC-DC buck converter based on the LM2596S-5.0

This chip is from the same family as the previous chip LM2596S-12 and the same reasons for choosing it apply to it.

3.3.1.3 Linear Regulation Stage 3.3V:

The circuit achieves linear voltage regulation through a low-voltage step-down (LDO) regulator (LM1117-3.3). This regulator takes the 5V input voltage from the previous chip LM2596S-5.0, and converts it to a constant 3.3V output voltage. This voltage works with low-voltage digital components.

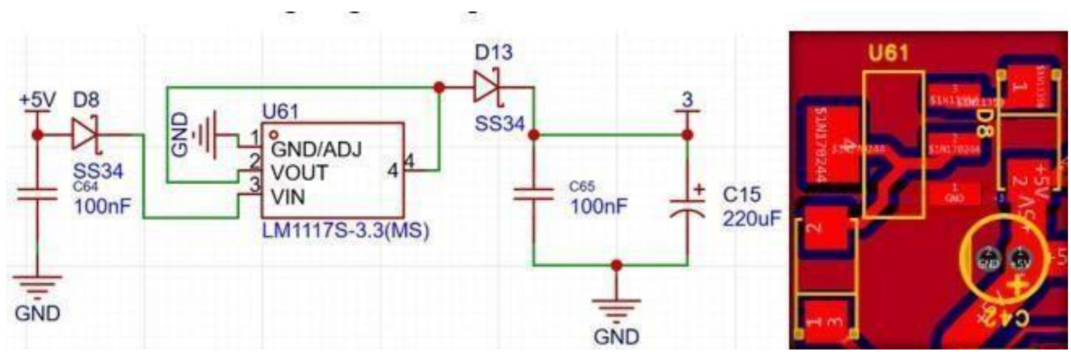
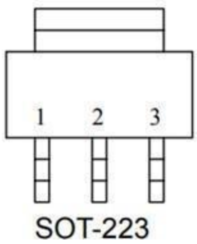


Figure 3.9. circuit of DC-DC buck converter based on the LM1117-3.3

Package Information



Pin	Function
1	ADJ/GND
2	OUTPUT
3	INPUT

Figure 3.10. Definition of ports for LM1117-3.3

The LM1117-3.3 was chosen for the solar system monitor for several reasons, including:

- **Simple Design:** Features a straightforward design with a fixed output and requires minimal components.
- **Low Dropout:** Operates efficiently with a low dropout, functioning at an input voltage close to approximately 4.5V.
- **Stable Output:** Provides reliable and clean power, ideal for microcontrollers and sensors.
- **Cost Effective:** Affordable and widely available, making it an economical choice.

3.3.2 Microcontroller Unit Design Explanation:

After in-depth study and several consultations, it was agreed that the microcontroller circuit would not be integrated into the board. This was for several reasons, including: - Reducing the cost of the board - Avoiding the loss of the entire board in the event of a microcontroller failure - The ability to test any other microcontroller or replace it in the event of a failure A place was allocated for the microcontroller on the board, and the ESP32 S3 ZERO board was chosen.

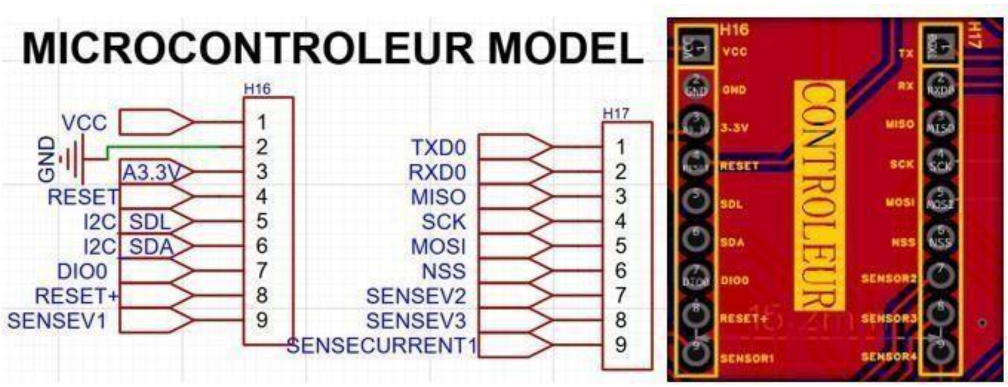


Figure 3.11. Design the location of the microcontroller and its location in the PCB

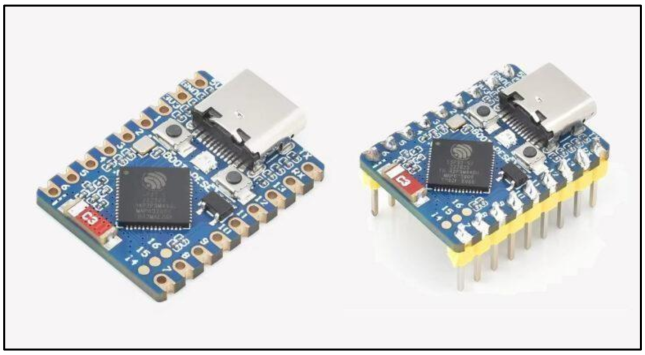


Figure 3.12. Real photos of the ESP32 S3 ZERO module

3.3.2.1 Supported Programming Environments for the ESP32-S3-Zero

Module :

The ESP32-S3-Zero module from Waveshare uses the ESP32-S3 chip from Espressif and supports multiple development and programming environments. Here are the most popular programs (environments) you can use to program it:

- **1. Arduino IDE**
- **2. PlatformIO**
- **3. ESP-IDF (Espressif IoT Development Framework)**
- **4. MicroPython**
- **5. CircuitPython**

3.3.2.2 Features and Reasons for Choosing the ESP32-S3-Zero Board:

The ESP32-S3-Zero module offers several advantages that make it suitable to serve as the control unit for our device. Among these advantages are :

- **Compact Design:** The module's small size and onboard ceramic antenna make it ideal for integration in space-constrained circuit boards.
- **Sufficient Ports:** Provides 24 configurable GPIO pins and supports multiple interfaces such as SPI, I2C, UART, and ADC for connecting various sensors and components.
- **Wireless Connectivity:** Supports 2.4GHz Wi-Fi (802.11 b/g/n) and Bluetooth 5 (LE), enabling wireless data transmission to IoT platforms or smart devices.
- **High Performance:** Equipped with a dual-core Xtensa® LX7 processor running at up to 240 MHz, enabling efficient data processing.
- **Low Power Consumption:** Offers flexible clock settings and independent module power supply control to reduce energy consumption, making it suitable for solar-powered systems.
- **Design Flexibility:** The non-integrated module design allows for easy replacement or upgrades when used in custom PCB designs.
- **Integrated Flash Memory:** Includes 4MB of onboard flash memory for storing programs and data.
- **Fast Processing and Buffer Memory:** Features 512KB SRAM and 384KB ROM along with 2MB of PSRAM for fast data handling and temporary storage.
- **Advanced Interface Support**: Supports a wide range of interfaces including

4× SPI, 2× I2C, 3× UART, 2× I2S, and 2× ADC, offering flexible sensor integration.

- **USB Programming Capability:** Integrated full-speed USB controller for easy programming and data transfer.

3.3.3 Sensors section of the device:

Sensors are an essential component of our project, as they enable us to monitor the characteristics of the solar panels (voltage and current). Their design must be accurate and efficient to ensure reliable tracking of this data.

3.3.3.1 Chip selection and sensor design

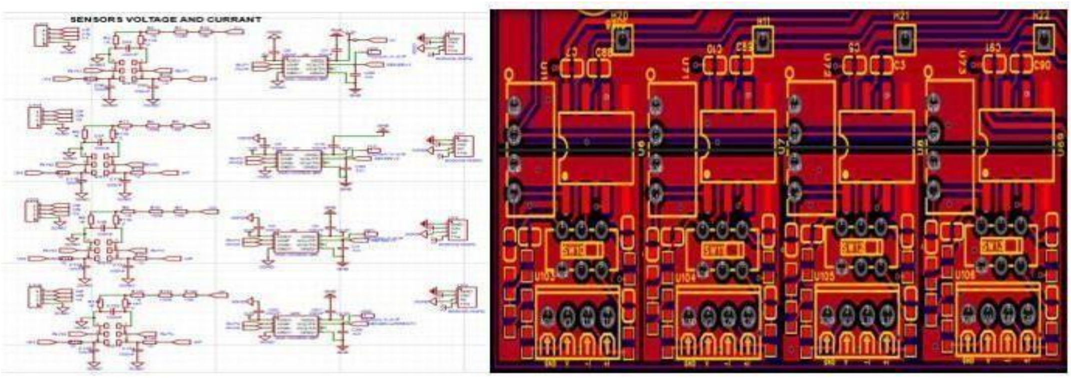


Figure 3.13. Design of voltage and current sensors

After thorough research and extensive study as part of designing cost-effective and high-quality voltage and current sensors, the AMC1200 chip from Texas Instruments was selected. It is a high-precision differential isolation amplifier that offers many features making it ideal for measurement applications, especially in industrial and energy systems. Some of the key features of this chip include:

- **Provides high electrical isolation** up to 4000 VPEAK using a silicon dioxide (SiO_2) barrier, making it ideal for isolating high-voltage circuits from sensitive electronics.
- **Offers high linearity** (nonlinearity does not exceed ±0.075%), ensuring accurate measurements.
- **Has a low offset error** (up to ±1.5 mV), reducing the need for calibration.
- Features a **small differential input range** (±250 mV), specifically designed to measure the voltage drop across shunt resistors.
- **Low high-side current consumption** (maximum 8 mA), contributing to reduced power usage.
- **Operates over a wide temperature range** (from –40°C to +105°C), making it suitable for harsh environments.

- **Exhibits a high common-mode rejection ratio** (CMRR) up to 108 dB, helping to minimize electrical noise.

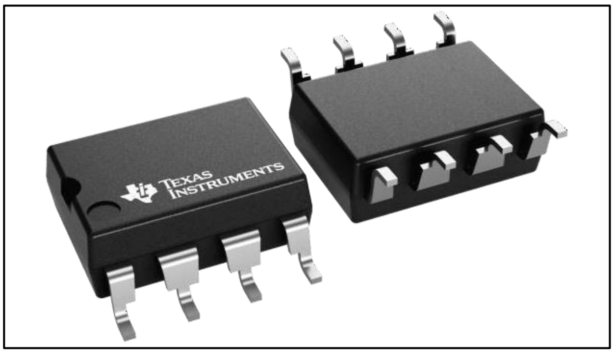


Figure 3.14. Real picture of AMC1200

3.3.3.2 Preparing the signal entering the sensor:

The AMC1200 chip is basically designed to measure the voltage between the two terminals of a current-sensing resistor, i.e. it is used as a current sensor, but in our design we also used it as a voltage sensor by reducing the voltage to be measured to the value that the chip can measure using a voltage divider.

3.3.3.2.1 Voltage Divider Configuration for the AMC1200 Voltage Sensor

To enable the AMC1200 chip to measure an input voltage up to 30V, a voltage divider was used to scale this voltage down to 250 mV the maximum differential input the chip can handle.

The lower resistor (R2) of the divider was fixed at 1 kΩ. By applying the voltage divider formula and neglecting the input impedance of the AMC1200 (as it is significantly higher than R2), the upper resistor (R1) was calculated as follows:

$$V_{out} = V_{in}.\frac{R_2}{R_2 + R_1} \Rightarrow R_1 = R_2.(1 - \frac{V_{in}}{V_{out}}) = 1\text{K}.(1 - \frac{30}{0.25}) = 119\text{k}\Omega$$

Thus, the chosen resistor values are:
R1 = 119kΩ

R2 = 1kΩ

The values 1k, 100k, and 18k were chosen in sequence instead of 119k because they are available.

This configuration provides an output of 0.25V when the input is 30V, which is perfectly suited for the AMC1200's differential input range.

3.3.3.2.2 Current Shunt Resistor Configuration for the AMC1200 Sensor

In the design of the current sensing system using the AMC1200 chip, the current shunt resistor is implemented as an external component mounted outside the PCB. This approach provides greater flexibility in selecting power ratings and improves heat dissipation.

Since the AMC1200 supports a maximum differential input voltage of ±250 mV, the shunt resistor is selected such that the voltage drop across it does not exceed this limit when the maximum current flows through it.

3.3.3.2.2.1 Shunt Resistor Value Calculation:

To determine the appropriate resistor value for a given current (e.g., 10 A), the following formula is used:

$$R_{SHUNT} = \frac{V_{MAX}}{I_{MAX}}$$

Where :

$$V_{MAX} = 0.25V \text{ (maximum voltage input allowed by the AMC1200)}$$

$$I_{MAX} = 10A$$

$$R_{SHUNT} = 25\text{m}\Omega$$

3.3.3.2.2.2 Power Rating Calculation:

To ensure the resistor can handle the power dissipation under full load, the power is calculated as:

$$P = I^2 . R = 10^2 . 0.025 = 2.5W$$

Recommended Power Rating≥4W

Final Results (for 10 A current measurement):

Resistor Value: 25 mΩ

Power Rating: ≥ 4 W

This configuration ensures that the input voltage to the AMC1200 remains within the safe operating range while maintaining accurate and stable current measurements in industrial environments.

3.3.3.3 Flexibility of the sensor

In our design, we have four ports: two for voltage and two for current. Each sensor can operate as either a voltage or current sensor using a manual switch that selects its type.

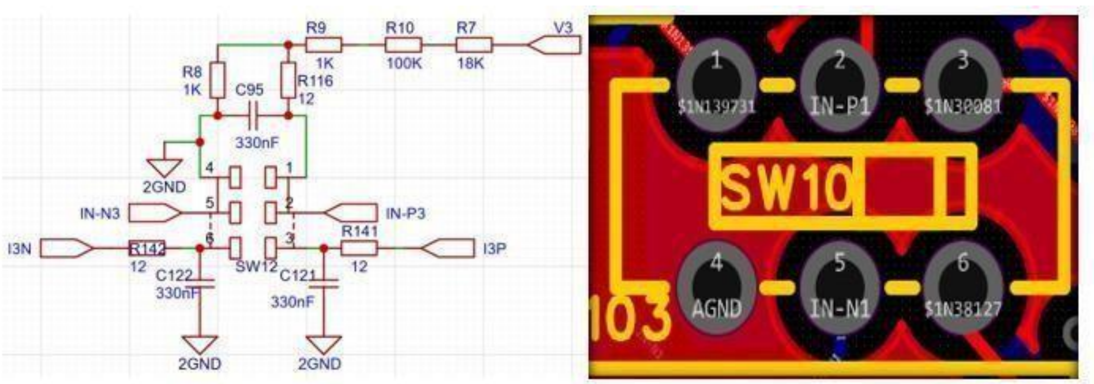


Figure 3.15. Sensor type switch design

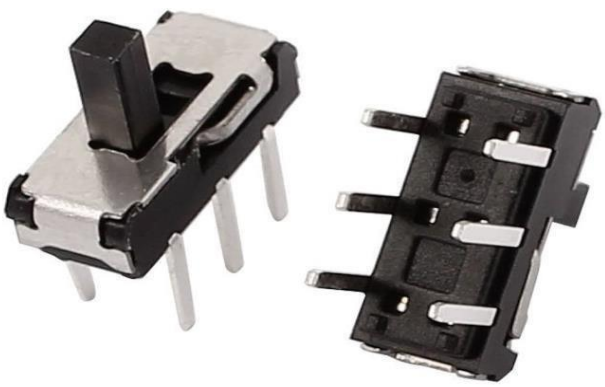


Figure 3.16. Real picture of switch

3.3.3.4 Feed part for sensors

In our current sensor design based on the AMC1200 chip, we selected the B0505S-W2R2 isolated DC-DC converter to provide power to the measurement side of the chip. The AMC1200 requires two independent, electrically isolated power supplies:

- **The first side (VDD1):** which is the measurement side, is powered with an isolated 5V generated by the B0505S-W2R2.
- **The second side (VDD2):** which connects to the microcontroller, is powered with 3.3 V from the same power source used by the microcontroller itself.

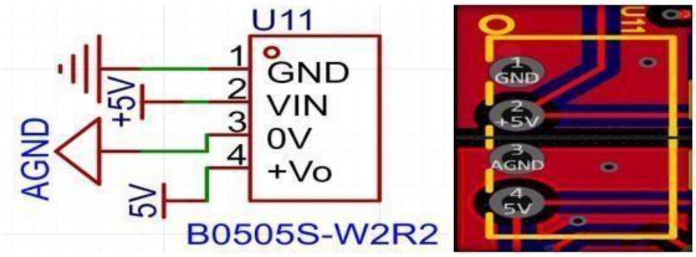


Figure 3.17. B0505S-W2R2 design

Figure 3.18. B0505S-W2R2

3.3.3.4.1 Reasons to choose B0505S-W2R2:

This particular component was chosen due to several advantages, including:

- Used to provide isolated power to the high-voltage side of the AMC1200, helping protect the microcontroller and ensure accurate signal measurements.
- Ensures full electrical isolation between the measurement and control circuits, preventing any dangerous voltage leakage.
- Good isolation helps reduce electrical noise, which improves system stability and measurement accuracy.
- Fully compatible with a microcontroller operating at 3.3V, since the output side

of the AMC1200 is powered from the same 3.3V supply as the MCU.

- This setup ensures the AMC1200's output signal stays safely within the input range of the microcontroller’s ADC or digital inputs—no level shifting required.
- The B0505S-W2R2 provides 5V input and 5V isolated output, making it a perfect match for both the AMC1200 and a 5V system.
- Offers a high isolation voltage of up to 1500VDC, which increases system safety and prevents high-voltage transfer.
- Operates at around 80% efficiency, which is more than adequate for low-power sensor circuits.
- Its compact size makes it easy to fit into the PCB layout without consuming too much space.
- Capable of delivering up to 400mA of current—more than enough to power the AMC1200 and any auxiliary components.

3.3.3.4.2 Why a direct power connection wasn’t suitable:

Using the same power supply for both sides of the AMC1200 would completely defeat the purpose of isolation. That would risk exposing the microcontroller to dangerous voltage levels and introduce noise or ground loops that could affect measurement accuracy. By using the B0505S-W2R2, I ensured full electrical separation between the sensing and control domains

3.3.3.4.3 Final Thoughts:

Choosing the B0505S-W2R2 allowed me to build a safe, reliable, and electrically isolated current-sensing system. It fits the AMC1200’s requirements perfectly and plays a crucial role in protecting both the signal integrity and the microcontroller in my design.

3.3.4 Relay Control System Design using I2C Protocol

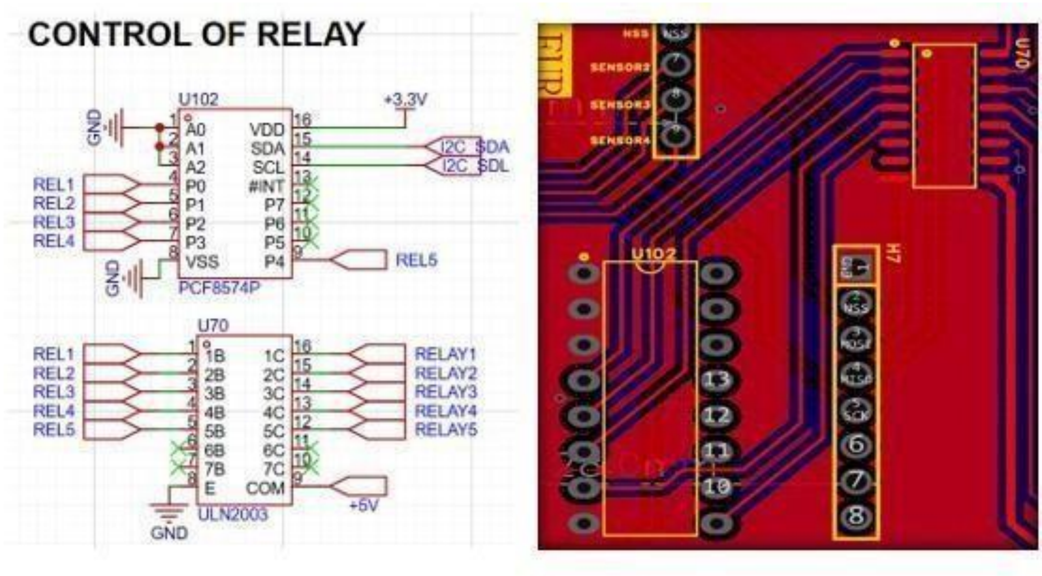


Figure 3.19. Relay Control Circuit Using PCF8574 and ULN2003 with PCB Layout

3.3.4.1 Component: PCF8574P – I2C I/O Expander

- **Function:** Expands digital output pins to control relays via I2C.
- **Features:**
  - ❖ Supports I2C protocol with only two wires (SCL and SDA).
  - ❖ Provides 8 programmable digital outputs.
  - ❖ Operates at 3.3V, compatible with microcontrollers like ESP32.
- **Reason for Selection:**
  - ❖ Minimizes the number of GPIOs used on the main microcontroller.
  - ❖ Enables system scalability and multiple output control.
- **Integration:**
  - ❖ Connected to the microcontroller via SDA and SCL lines.
  - ❖ Outputs (P0 to P4) are connected to ULN2003 inputs.

3.3.4.2 Component: ULN2003 – Relay Driver IC

- **Function:** Amplifies control signals from PCF8574 to drive the relays**.**
- **Features:**
  - ❖ Contains an array of Darlington transistors for high-current switching.
  - ❖ Includes built-in flyback diodes for protection against inductive loads.
  - ❖ Operates at 5V, suitable for relay activation.
- **Reason for Selection:**

- Protects the I/O expander and microcontroller from high currents or voltages.
- Simplifies the electrical interface with the relay coils.

- **Integration:**
  - Inputs (1B to 5B) are connected to the PCF8574 outputs.
  - Outputs (1C to 5C) drive the relay coils.
  - COM pin is tied to +5V to supply current to the relays.

3.3.4.3 Component: SRA-05VDC-CL Relays

- **Function:** Switch AC or DC electrical loads ON or OFF based on control signals.
- **Features:**
  - Operates with a 5V control signal, compatible with ULN2003 outputs.
  - Can control higher voltage loads (e.g., 12V, 24V, or 220V AC/DC).
  - Includes LED indicators for status visibility.
  - Equipped with flyback diode across the coil.

- **Reason for Selection:**
  - Matches the 5V output from the driver circuit.
  - Supports load voltages and currents required for the application.
  - Ideal for switching higher voltage loads using low-voltage control.

- **Integration:**
  - Coil connected between ULN2003 output and +5V supply.
  - Switching terminals (COM, NO, NC) wired to external AC or DC loads

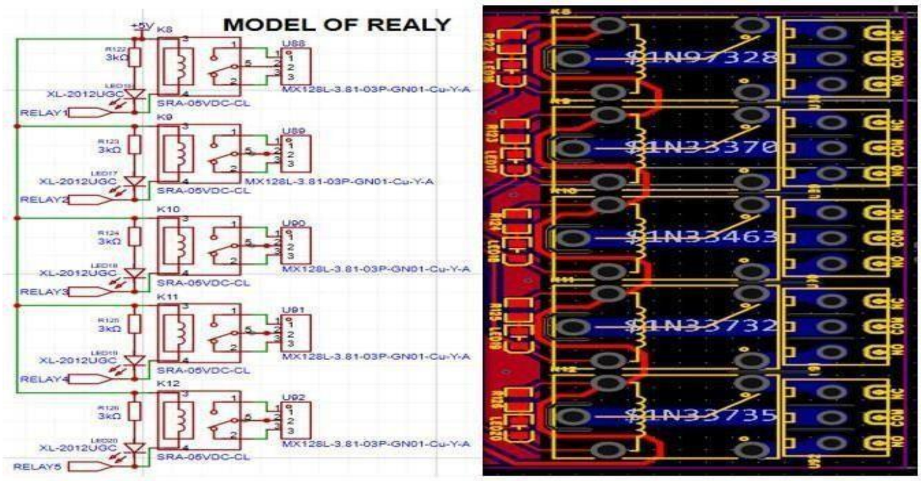


Figure 3.20. Relay diagram and design on PCB

Figure 3.21. Real picture of RELAY

3.3.5 Wireless Communication Section – Design Justification

In our proposed device, we have carefully allocated the wireless communication section to ensure optimal integration between LoRa and GSM technologies. This is achieved by using both the LoRa SX1278 RA-02 module and the SIM800L module, each connected via dedicated headers to facilitate assembly, maintenance, and testing.

3.3.5.1 LoRa SX1278 RA-02 Module

This module was selected to enable low-power, wide-range wireless communication between devices. It operates using LoRa modulation technology, which provides wide coverage while maintaining extremely low power consumption. The SX1278 module was chosen for several reasons, including:

- Ultra-low power consumption, making it ideal for battery-powered applications.
- Long communication range (up to several kilometers in open environments) thanks to LoRa technology.

- Supports both point-to-point communication and mesh network configurations.
- Compatible with SPI interface, facilitating integration with microcontrollers.
- Programmable parameters such as frequency, baud rate, and transmission power, which can be adjusted via software to suit different use cases

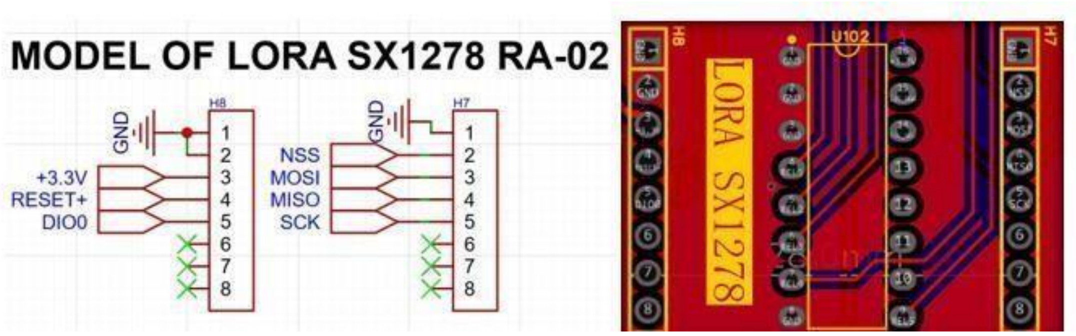


Figure 3.22. LoRa SX1278 RA-02 Module Port Design

Figure 3.23. Real picture of LoRa SX1278 RA-02 Module

As for the connection method, an 8-pin connector has been allocated for this unit, including:

- **NSS, MOSI, MISO, SCK** (SPI communication)
- **DIO0 and RESET** (event monitoring and control)
- **GND and +3.3V** (for stable power supply)

3.3.5.2 SIM800L Module:

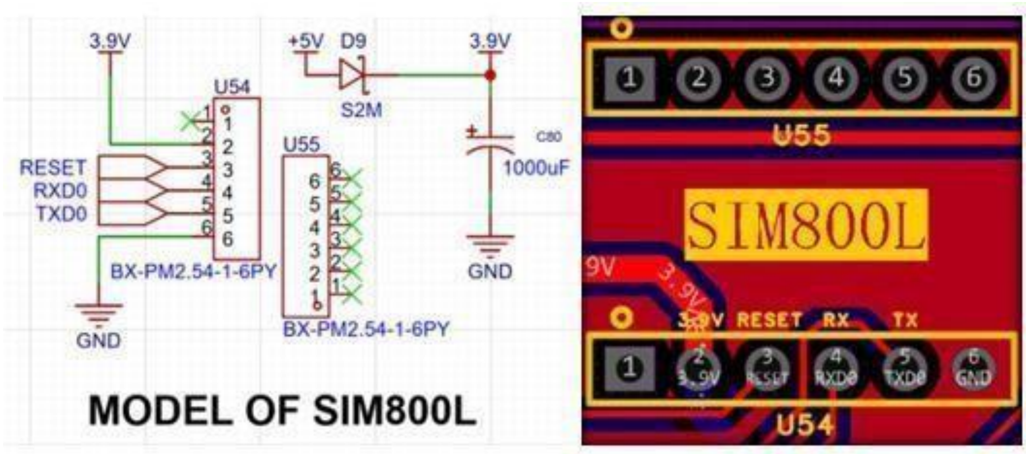


Figure 3.24. SIM800L module port design

This module enables cellular (GSM) connectivity for remote communication with servers or mobile applications via the Internet. It has many advantages that led to its selection, including:

- **Support for quad-band GSM/GPRS networks** (850/900/1800/1900 MHz), making it globally compatible.
- **Easy UART interface** for serial communication with microcontrollers.
- **Moderate power consumption**, capable of transferring data at speeds up to 85.6 kbps via GPRS.
- **Supports SMS, voice calls, and internet connectivity (TCP/IP protocol).**
- **Low cost and widely available,** making it ideal for low-cost industrial applications.

Figure 3.25. Real picture of SIM800L module

Regarding the connection details, a six-pin connector was used, which includes:

- **RXD and TXD (for serial communication)**
- **RESET** (for controlled restarts)
- **3.9V and GND** (for power input)
- **A 1000µF capacitor** is added to stabilize the voltage during startup.
- **A S2M diode** is used for input voltage protection and isolation.

3.3.5.3 Combined Operation:

By integrating these two communication technologies:

- **LoRa** is used for local or distributed communication between nearby devices without the need for cellular infrastructure.
- **SIM800L** enables global connectivity through cellular networks for real-time remote monitoring and alerting.

This hybrid setup allows the system to dynamically switch between local and wide-area communication modes, enhancing flexibility, reliability, and scalability in various deployment environments.

3.3.6 PCB Board Dimensions

The corresponding figures show the design of the proposed device, demonstrating good organization and respect for appropriate spacing between components despite the small dimensions of the board (14.1 x 8.2 cm). The track widths are also carefully considered, enhancing connection efficiency and signal stability. This design also features good cooling capabilities, a requirement for the device's operating conditions.

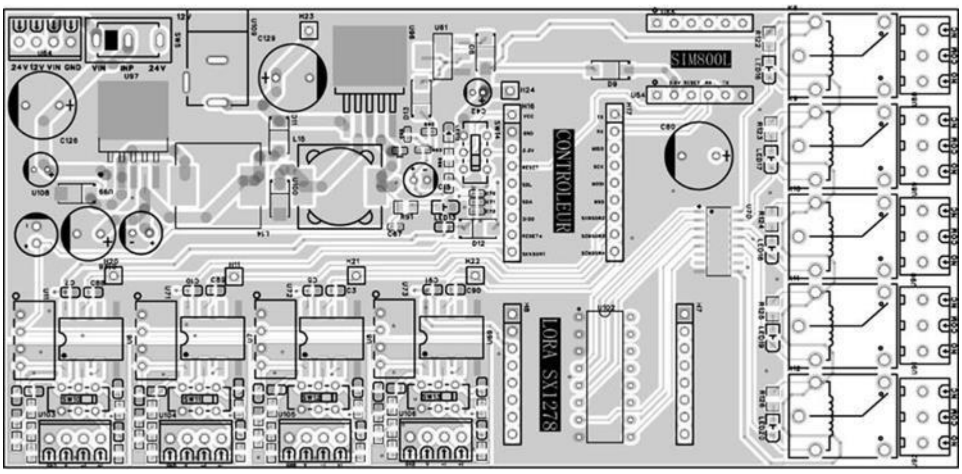


Figure 3.26. Printed Circuit Board (PCB) Layout

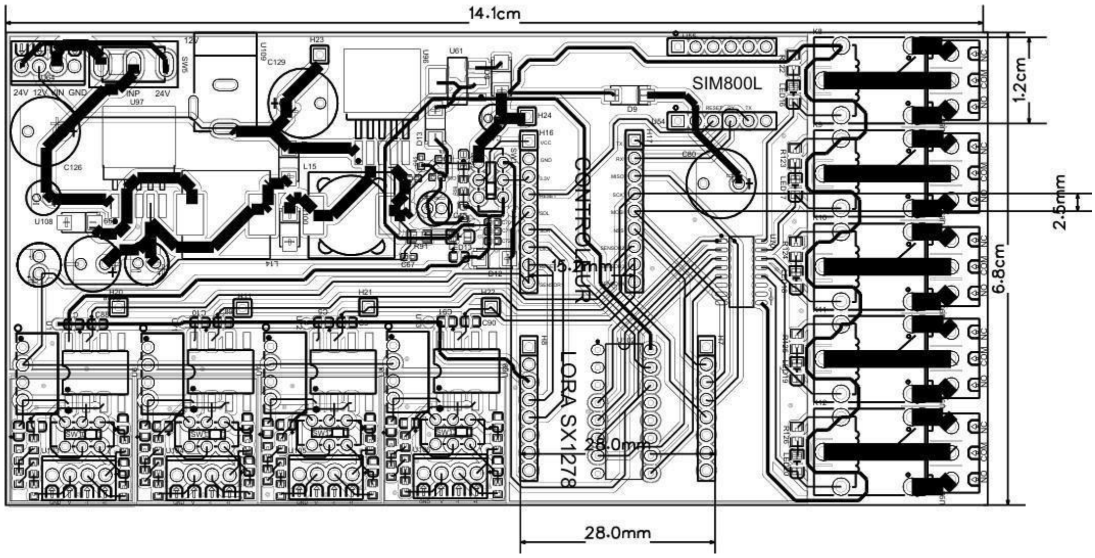


Figure 3.27. General PCB Board Dimensions

3.4 PCB Board After manufacturing

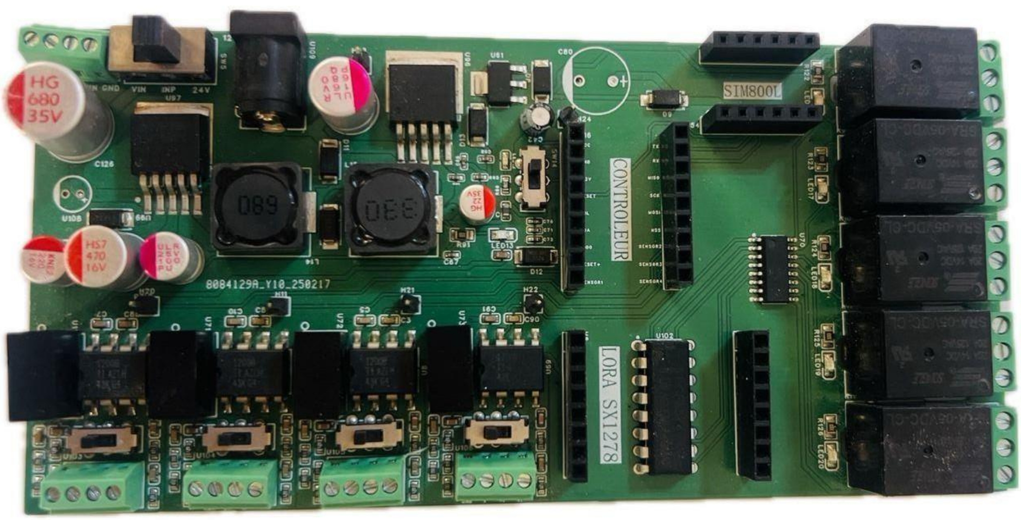


Figure 3.28. PCB Board After manufacturing

The above figure shows the printed circuit board (PCB) of our smart system after the manufacturing process is complete. The board was carefully designed with all the essential electronic components, utilizing advanced double-layer board manufacturing technology, which contributes to improving and enhancing electrical performance and ensuring optimal system stability.

3.5 Conclision

The hardware design process resulted in the development of an organized physical unit, ready for field deployment and capable of meeting the project's performance targets, while leaving ample room for future expansion. Through careful component selection and harmonious integration, we succeeded in building a stable and reliable operational platform, adaptable to changing conditions and capable of long-term operation with minimal intervention.

This systematic approach spanned from power regulation to sensor integration and communication systems, with each part designed to ensure full functional integration and efficient data handling. The final design supports monitoring, fault detection, and autonomous control mechanism essential elements in smart energy systems.

This achievement reflects not only well-considered engineering practices but also establishes a flexible infrastructure that can be built upon in the future, both in terms of hardware and software. The resulting unit is technically robust and capable of adapting to the real-world challenges of renewable energy and intelligent monitoring applications.

Implementation of the system and results

4.1 Introduction:

This section presents the implementation of an intelligent system for real-time monitoring, diagnostics, and performance optimization of photovoltaic panels, based on a distributed Master-Slave architecture. The system aims to enhance the efficiency of solar arrays by individually monitoring each panel and promptly detecting faults.

The system relies on local units to collect and analyze data, wirelessly transmitting it to a central unit that displays the information and executes automatic control actions, such as isolating faulty panels. It operates in both offline and online modes to ensure continuous functionality across various environments.

This section details the system architecture, components, and operation, along with an analysis of results demonstrating its effectiveness in improving performance and stability

4.2 Proposed Solutions to Improve the Performance of Power Generation System:

In the solar panel monitoring system, both hardware and software components work together to ensure efficient and accurate tracking of panel performance and fault detection.

The hardware includes physical units such as the Slave Nodes, which are equipped with sensors to measure voltage and current, a microcontroller for initial data processing, and wireless communication modules based on LoRa technology to transmit data to the Master Node. The system also includes relays to control the connection or disconnection of faulty panels.

On the software side, it handles system operation and control through precise programming for both nodes. In the Slave Node, the software activates sensors, reads the values, and formats the data before transmission. In the Master Node, the software receives the data, analyzes it to determine the operational status of each panel, and makes appropriate decisions such as isolating faulty panels or alerting the user via an HMI screen or computer interface.

This integration of hardware and software ensures accurate and efficient monitoring of the solar panels, with real-time responsiveness to any faults, thereby enhancing the overall reliability and performance of the system.

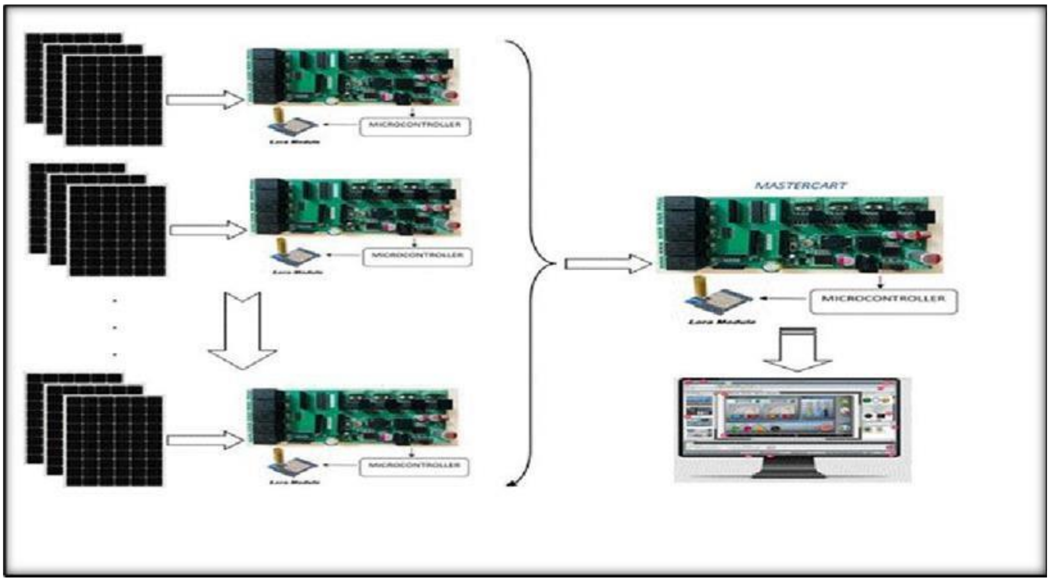


Figure 4.1. Solar Panel Monitoring and Control System via LoRa

4.2.1 Hardware System:

From the hardware perspective, the system includes the installation of slave nodes near the photovoltaic panel groups. Each node is equipped with an ESP32 microcontroller, sensors for measuring current and voltage, a relay for executing control commands, and a LoRa communication module for long-range, low-power wireless data transmission—making it ideal for distributed solar systems.

The master node is installed at a central location and includes a LoRa receiver module, a processor, and a display interface such as an HMI screen or a computer.

4.2.2 Software System:

From the software perspective, the microcontroller in both the slave and master nodes is programmed to ensure automated operation and seamless communication. The slave node software is responsible for initializing the sensors, reading and formatting the data, and transmitting it. It also receives control commands and executes them to switch the relays on or off.

In contrast, the master node software continuously listens for incoming data, analyzes it to detect faults or performance degradation, and makes appropriate control decisions. It then sends commands to the slave nodes accordingly. Additionally, it manages data display and storage through a user-friendly interface.

4.2.3 Server:

Role of the IoT Server in PV Monitoring and Control

In the context of photovoltaic (PV) system monitoring and control, the IoT server serves as a critical intermediary that facilitates seamless communication between hardware devices and software interfaces. Specifically, this server is responsible for collecting real-time electrical data such as current and voltage measured by sensors or embedded microcontrollers installed within the PV system. Once acquired, this data is transferred through the server to a client-side application, typically installed on a computer or smartphone, where it can be visualized, monitored, and analyzed. The IoT server ensures reliable, continuous, and secure data transmission, enabling end-users or operators to perform remote diagnostics, make informed decisions, and execute control commands when necessary. Hence, the server not only bridges the physical and digital layers of the system but also supports efficient and intelligent energy management.

The system is based on a Master-Slave architecture designed for real-time diagnostics and optimization of photovoltaic (PV) panel arrays to enhance overall system efficiency. Each Slave unit is equipped with an ESP32 microcontroller and sensors to measure current and voltage, enabling real-time monitoring and local analysis of each solar panel's performance.

The collected data is transmitted wirelessly to the Master unit using LoRa communication, ensuring reliable, low-power connectivity even in remote or off-grid environments. The Master processes the incoming data to identify panels exhibiting faults or reduced performance and displays the results on a Human-Machine Interface (HMI) or computer screen for further action.

In addition to diagnostics, the system incorporates automatic control mechanisms. Faulty panels are isolated in real time using integrated electronic relays, preventing their negative impact on the rest of the array and thus improving overall system stability and efficiency.

The system is designed to operate effectively in both online and offline modes, ensuring uninterrupted monitoring and control regardless of internet availability

4.3 Implemention of Hardware system and software system:

The system integrates hardware and software for real-time monitoring and control of solar panels. Slave Nodes collect voltage and current data using sensors and an ESP32 microcontroller, then transmit it via LoRa to the Master Node. The Master Node analyzes the data, detects faults, and sends control commands. This setup ensures efficient operation and quick response.

4.3.1 Hardware System:

4.3.1.1 Main Components

- ESP32 Microcontroller (in each Slave):
- Acts as the local processing unit.
- Reads data from sensors and controls the relays.
- Current and Voltage Sensors:
- Measure the electrical parameters of each solar panel.
- Enable real-time diagnostics for each panel.
- LoRa Communication Modules:
- Provide long-range, low-power wireless communication between Slave units and the Master.

Electronic Relays:

- Installed between the solar panels to automatically disconnect faulty ones.
- Master Unit (ESP32 or equivalent):
- Receives data from all Slave units.
- Analyzes system performance.
- Sends control commands when necessary.
- Displays data on an HMI screen or a monitoring dashboard.
- Power Supply Units:

- Ensure stable power delivery to microcontrollers and communication modules

4.3.1.2 The slave Node:

The Slave Node functions as a distributed monitoring unit within the photovoltaic panel system. Each Slave Node is installed near a group of solar panels and is responsible for collecting real-time data on voltage, current, and operational status from its assigned panels. Equipped with sensors and a microcontroller, it accurately measures electrical parameters and detects any faults or performance issues.

Data collected by the Slave Node is transmitted wirelessly to the Master Node using LoRa technology, which ensures reliable, long-range communication with minimal power consumption. This allows the system to monitor large solar arrays efficiently.

While the Slave Node primarily focuses on data acquisition and local fault detection, it also supports initial processing of the data before transmission. This distributed approach reduces communication load and enhances the overall system's responsiveness and reliability.

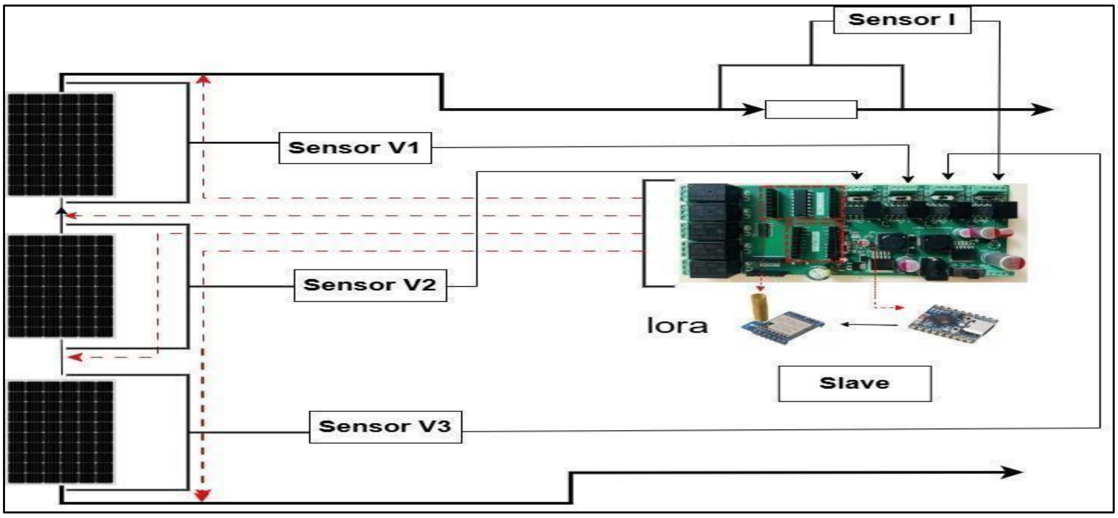


Figure 4.2. Selave Node for Solar Monitoring via LoRa

4.3.1.3 The master Node:

The Master Node serves as the central control unit in the photovoltaic panel monitoring system and is typically located in the control room. This node receives data from the Slave nodes distributed across the solar panel array, including measured voltage, current, and operational status for each individual panel. Data is transmitted wirelessly using LoRa technology, which provides reliable, long-range communication with low power consumption, thereby enhancing system performance and monitoring efficiency. Connected to an HMI screen or a computer, the Master Node's software provides a clear and real-time display of the entire solar array's performance. Through this software interface, users can monitor system health, receive immediate alerts about faulty panels, and oversee automatic control actions such as issuing commands to isolate malfunctioning panels.

The software analyzes incoming data from the Slave nodes, identifies faults or performance degradation, and automatically triggers appropriate responses, thereby improving the system's responsiveness and real-time effectiveness.

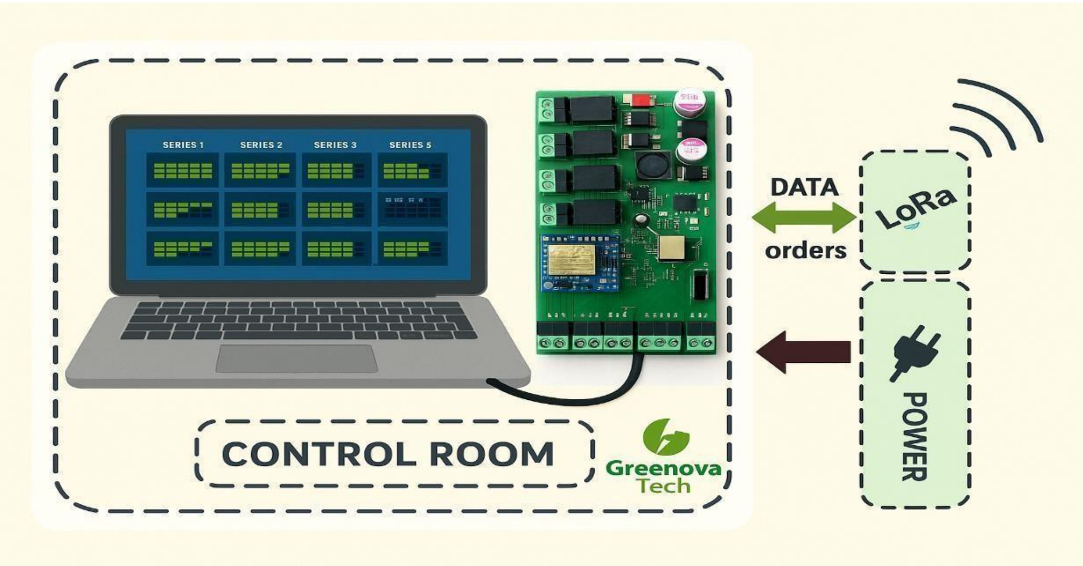


Figure 4.3. Master Node for Solar Monitoring via LoRa

4.3.2 Software System

4.3.2.1 Slave Device (Left Side):

Initialize system

Set up all system components and prepare for operation.

Providing the relay with its initial state

Assign an initial ON/OFF state to the relay before starting.

Read sensors

Collect voltage and current values from the connected sensors.

Transmit 'd=ID:V1:V2:V3:I'

Send the collected data in the format:

'd=ID:V1:V2:V3:I'

ID: Device identifier

V1, V2, V3: Voltage readings

I: Current value

Receiving the command

Wait for a control command from the Master (e.g., turn relay ON or OFF).

Command Execution

Execute the received command (e.g., switch the relay).

Specifying the state of the relay

Update the relay status based on the executed command.

4.3.2.2 Master Device (Right Side):

Initialize system

Prepare the system to receive data and perform operations.

Wait for data

Wait for incoming data from the Slave device.

Data Analyze

Analyze the received sensor data to assess system status.

Determining the appropriate configuration

Decide the appropriate control settings based on the analysis.

Specifying the state of the relay

Determine whether the relay should be turned ON or OFF.

Send commands

Send the corresponding command to the Slave device.

Print values and status

Display the sensor readings and relay status for monitoring

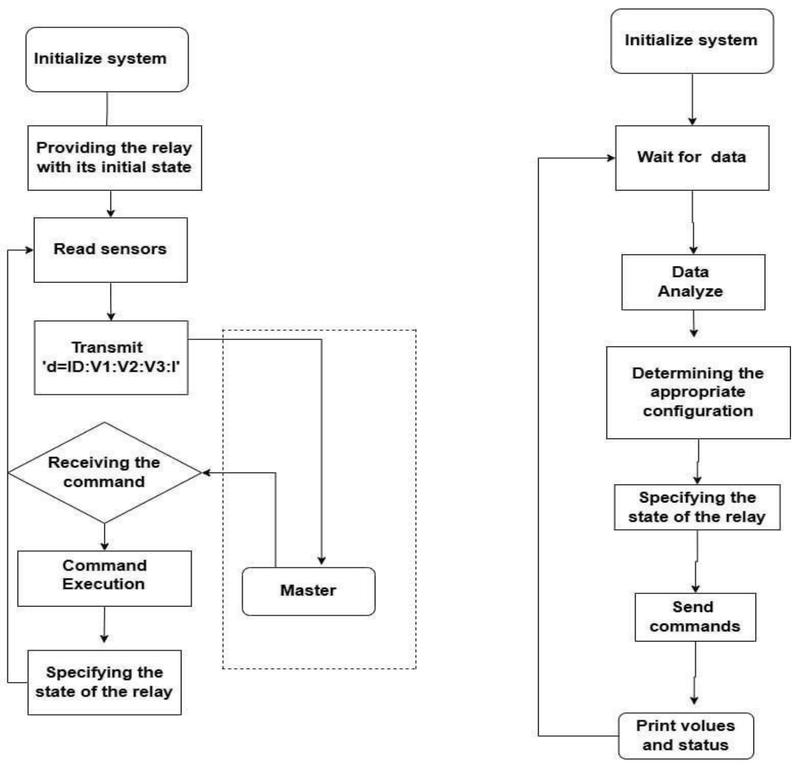


Figure 4.4. Flowchart of MASTER and SLAVE Unit Operation Algorithms

4.4 Communication Protocol:

In the implementation of our system, we adopted two distinct communication protocols corresponding to the interaction between the different units involved: the Master unit and the Slave units, and the Master unit and the HMI (Human-Machine Interface).

4.4.1 Communication between Slave and Master units:

Communication between the Slave units and the Master is carried out via LoRa SX1278 RA-02 modules, using wireless transmission in the 433 MHz frequency band. This method was chosen for its long-range capability, low power consumption, and reliability in outdoor environments.

Each Slave unit periodically sends sensor readings to the Master unit. These readings include:

Voltages from three solar panels (using analog sensors),

One current measurement (using an AMC1200-based sensor on the fourth analog input).

The transmitted data follows a custom string-based protocol structured as:

d=ID:V1;V2;V3;I;

Where:

- ID represents the Slave identifier,
- V1, V2, V3 are voltages in volts,
- I is the measured current in amperes.

For example:

d=2:14;13;12;2.345

The Master listens for incoming packets, parses the data, and stores it for processing. In response to detected faults or based on predefined conditions, the Master sends command messages back to the respective Slave unit to control relays, isolating the affected solar panels. These control messages follow the format:

ID:R1,R2,R3,R4,R5

Where R1 to R5 are binary values (0 or 1) representing the ON/OFF state of relays connected via a PCF8574 I/O expander.

4.4.2 Communication between Master and HMI:

The connection between the Master unit and the HMI screen is based on a UART Serial communication interface. This wired connection is used to transmit processed system data for visualization purposes.

Every second, the Master compiles and sends a string that includes:

The voltages of all solar panels,

The current measurements from each Slave,

The operational status of each panel (healthy or faulty).

An example of the transmitted serial format is:

1:12;13;0;14;15;13;7;6;8;2.345;2.334;2.400;1;1;0;1;1;1;1;1;1;

Here:

The number before the first colon represents the Master's identifier,

The following values represent: voltages (first 9), currents (next 3), and panel statuses (last 9), with 1 indicating healthy and 0 indicating a fault.

This structure ensures that the HMI always displays real-time, synchronized information reflecting the current electrical state of the system and the reconfiguration status.

4.5 Test of unite:

The proposed system consists of four slave devices in addition to a master device. It operates based on three strings of solar panels. The system utilizes sensors to measure current and voltage, along with relays for switching and control. An ESP32 microcontroller is used as the core processing unit.

To test the system and achieve realistic simulation, three resistors were connected in series to mimic the behavior of solar panels, and three electrical strings were connected in parallel.

The device includes four sensors dedicated to measuring both current and voltage. Voltage sensors are connected across the resistors, while the current sensors are connected in line with the strings to measure the electrical current.The values from the sensors are read and sent to the ESP32 microcontroller, which then transmits the data to the slave devices via LoRa wireless communication.

The master device receives the data from the slave devices, processes and analyzes it to make appropriate decisions. Subsequently, it sends commands back to the slave devices to perform the required actions based on the analysis results.

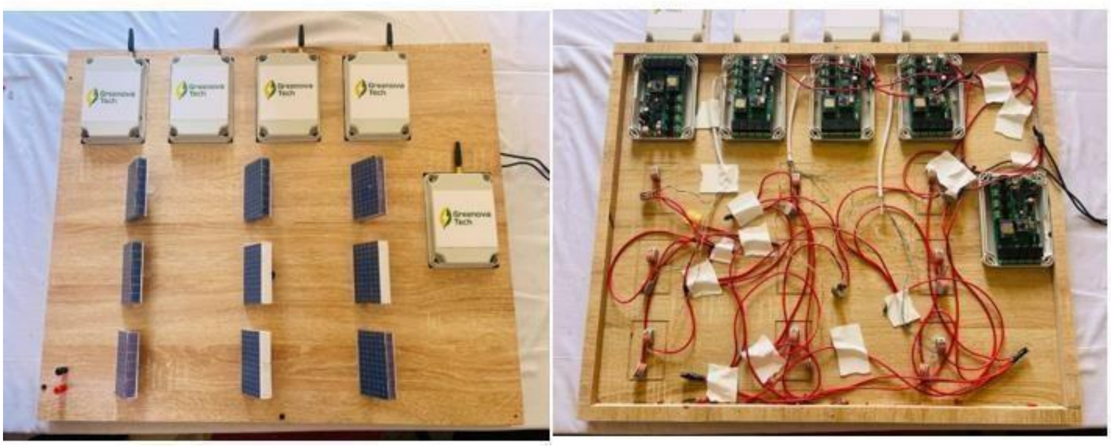


Figure 4.5. Real photos of the system simulation.

4.6 Simulation Results:

The simulation of the proposed system for monitoring and improving the performance of solar panels yielded the following results:

4.6.1 Ideal Operating Conditions (Normal System Operation):

Under ideal conditions, the system operates with high efficiency and performs all its functions as expected.

Current and voltage values for each solar panel are independently measured using accurate sensors installed at each connection point.

These readings are sent to the central processing unit, where they are analyzed and displayed on the system's main screen.

Each solar panel is shown in green on the display, indicating it is functioning within normal operational limits.

Real-time current and voltage values are continuously displayed, allowing for live monitoring of each panel's performance.

The configuration of the panels reflects an optimal setup, with panels connected in parallel or series as designed, without any interruptions or inconsistencies.

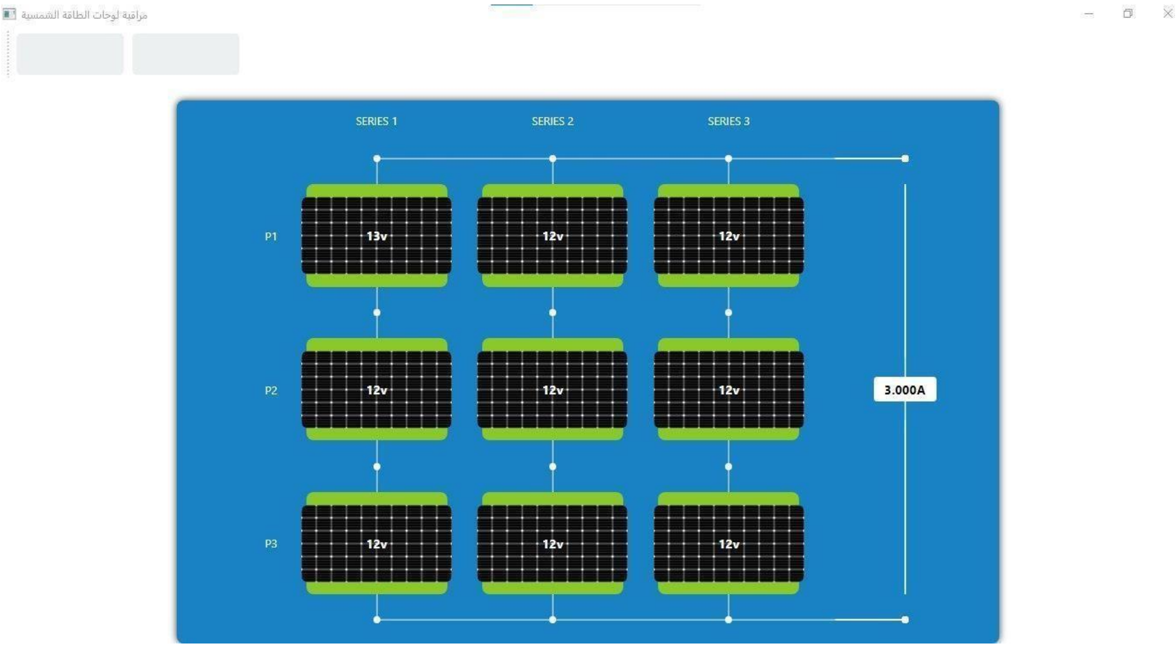


Figure 4.6. Image of the application working on the display interface

4.6.2 Fault or Malfunction in One of the Panels:

In the event of a fault in any solar panel (due to abnormal drops in voltage or current, or performance degradation), the system responds automatically using a programmed intelligent detection mechanism.

The sensors capture actual readings from the affected panel and compare them to predefined standard thresholds.

If a significant deviation is detected, the affected panel is shown in red on the display to indicate a fault.

An audible and visual alarm is triggered to alert the user.

The system activates the auto-isolation mechanism to disconnect the faulty panel from the photovoltaic string without affecting the remaining panels.

After isolation, the system performs automatic reconfiguration of the remaining panels to maintain optimal system performance and reduce energy loss.

Figure 4.7. Connecting the panel array in case of failure on the HMI interface

4.7 Conclusion:

Through this project, an integrated system was developed that combines hardware and software components to monitor and enhance the efficiency of solar panels in real time. The system is based on a Master-Slave architecture, enabling precise monitoring of each individual panel using high-accuracy sensors, ESP32 microcontrollers, and LoRa wireless communication technology, which offers wide coverage and low power consumption.

This system significantly contributes to the reliability and stability of solar power networks by enabling early fault detection and automatic isolation of malfunctioning panels, thereby preventing any negative impact on the rest of the array. Additionally, it provides real-time monitoring through an HMI interface that clearly displays data and alerts.

Simulation tests have demonstrated the system's effectiveness under both ideal and faulty conditions. It was able to identify defective panels, isolate them, and reconfigure the remaining setup to maintain optimal performance.

In conclusion, this system represents a practical and efficient step toward smart and sustainable management of solar energy systems. It helps reduce energy losses, increases overall efficiency, and supports the broader transition toward reliable and intelligent renewable energy solutions.

General Conclusion

General Conclusion

In conclusion, this report presented a comprehensive study on the design and implementation of an intelligent system for monitoring and enhancing the efficiency of solar panels, with the ability to detect and track faults in real-time. The chapters of this work addressed various theoretical and practical aspects necessary to achieve this goal.

The study began with the chapter on the fundamentals and challenges of photovoltaic (PV) systems, analyzing system components such as solar panels, charge controllers, inverters, and batteries. It also examined the impact of environmental factors such as solar radiation, temperature, and humidity on performance, and introduced key indicators for evaluating system efficiency, such as the current-voltage (I-V) curve, fill factor, and overall efficiency.

In **the second chapter**, dedicated to the Internet of Things (IoT), the focus was on the importance of integrating smart communication technologies into modern energy systems. It provided an overview of architectures based on microcontrollers (ESP32) and long-range, low-power wireless communication technology (LoRa), highlighting their effectiveness in data transmission within distributed environments.

The third chapter, focused on hardware design, covered the technical aspects of assembling the system's physical components, including the selection of sensors, control units, and communication modules, ensuring their integration into a reliable and scalable setup.

In the final chapter, which presented the system implementation and results, the installation and testing steps of the system were detailed. Real-world simulations demonstrated its capability to detect faults early, isolate damaged panels, and reconfigure the system to maintain efficient operation. Additionally, a Human-Machine Interface (HMI) was developed to facilitate real-time monitoring and data visualization.

In summary, this project represents a practical step towards enhancing the reliability and sustainability of solar systems, leveraging intelligent and self-monitoring technologies that contribute to reducing energy losses and improving operational efficiency.

Possible Future Developments:

This system can be further developed in the future through several avenues, most notably:

Integrating artificial intelligence technologies (such as neural networks or machine learning algorithms) to enhance the system's ability to predict faults before they occur.

Expanding the system's operational scope to support larger-scale solar stations in terms of the number of panels or production capacity, while maintaining efficiency and responsiveness.

Adding predictive maintenance functions that rely on historical data analysis to determine the optimal timing for preventive maintenance activities.

Supporting cloud storage for system data, enabling remote access and long-term analysis.

Designing a mobile application that allows users to monitor the system status and receive alerts directly from their smartphones.

These prospects open the door to transforming the system into a comprehensive platform for smart and sustainable solar energy management, in line with the global trend toward digital transformation in the field of renewable energy.

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