Vol.13 Iss.1 pp.21-37 International Journal of Control, Energy and Electrical Engineering (CEEE)

IoT-Based Intelligent Monitoring and Adaptive Control for High-Efficiency Fault-Tolerant Solar PV Systems

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Abstract— Solar photovoltaic (PV) systems are critical to renewable energy adoption, yet their efficiency is often compromised by environmental fluctuations and undetected faults. This paper introduces a novel solar PV system that integrates adaptive Maximum Power Point Tracking (MPPT) technology with IoT-driven real-time monitoring to maximize energy yield and ensure operational resilience. Central to the system is an Arduino Uno microcontroller, which orchestrates data acquisition from voltage, current, and temperature sensors, while a Bluetooth module enables wireless communication with the custom-developed mobile application Sun Scope. This IoT framework allows users to remotely monitor performance metrics, including voltage (23.34 V), current (2.64 A), and power output (61.38 W), and receive instant alerts for anomalies. Proteus simulations validated the system's design, including boost converter efficiency and MPPT algorithms, while hardware implementation demonstrated robust fault detection capabilities under partial shading (reducing output to 25.07 W), total panel occlusion, and component failures (e.g., diode burnout). Experimental results highlighted the system's ability to maintain 85% efficiency during faults, with real-time diagnostics enabling rapid corrective action. By combining adaptive energy optimization with proactive IoT-based monitoring, this work advances solar energy systems toward higher reliability, sustainability, and user-centric control, setting a benchmark for intelligent renewable energy management.

Keywords— Solar PV Systems, MPPT Technology, IoT Monitoring, Fault Detection, Energy Efficiency, Arduino Microcontroller, Real-Time Diagnostics, Renewable Energy Optimization.

I. INTRODUCTION

Solar photovoltaic (PV) systems have emerged as a linchpin in global efforts to decarbonize power generation, offering scalable and modular electricity production with a negligible carbon footprint [1]. Groundbreaking analyses of the theoretical efficiency limits of p–n junction cells have provided essential benchmarks, guiding both material and system-level research toward higher conversion efficiencies [2]. Modern implementations leverage sophisticated Maximum Power Point Tracking algorithms to dynamically adjust PV array operating points, thereby ensuring optimal energy extraction in the face of fluctuating irradiance and temperature [3]. In parallel, real-time monitoring architectures enable continuous acquisition of electrical and environmental parameters, offering enhanced visibility into system performance, component health, and degradation trends [4][5]. The convergence of embedded controllers with mobile and IoT frameworks facilitates user-centric interfaces for data visualization, alerts, and remote control, driving more informed, data-driven decision-making for energy management [6]. Recent advances in edge-based AI methodologies further augment fault detection capabilities, identifying anomalies in power and voltage profiles within milliseconds to seconds [7]. Tailored system adaptations for harsh environments have demonstrated robust operational reliability, validating the resilience of PV solutions under extreme conditions [8]. Building on these technological pillars, the present study introduces a comprehensive platform that integrates an Arduino Uno–based MPPT controller, a suite of precision sensors, Bluetooth communication, and a dedicated mobile application to deliver a seamless, high-efficiency PV energy management solution.

II. SYSTEM DESIGN

A. Overview of the System

The innovative solar photovoltaic system designed in this study integrates Maximum Power Point Tracking (MPPT) technology and real-time monitoring capabilities to optimize energy production from solar panels. The

ISSN: 1737-9288

system aims to enhance the efficiency of energy harvesting while providing users with valuable insights into energy generation and consumption patterns [6][7].

The MPPT technology used in this system continuously adjusts the electrical operating point of the photovoltaic (PV) panels to maximize their output power. By utilizing advanced algorithms, the system is capable of responding dynamically to varying environmental conditions, such as temperature and solar irradiance, ensuring optimal performance under different operational scenarios [9].

Moreover, the real-time monitoring application allows users to track key performance metrics—including voltage, current, and power generation—from their mobile devices. This functionality not only aids in timely decision-making regarding energy usage but also facilitates predictive maintenance, thereby enhancing the longevity and reliability of the solar power system [10][11].

B. Key Features

The Arduino Uno microcontroller, built on the ATmega328P architecture, serves as the central processing unit in the proposed photovoltaic monitoring system. Renowned for its open-source platform and ease of integration, the Arduino Uno supports a wide range of peripheral devices, making it highly adaptable for energy systems that require real-time data acquisition and control. Its low power consumption and capacity to manage multiple digital and analog input/output channels enable seamless communication with sensors and actuators, which is crucial for accurate monitoring of electrical parameters such as voltage, current, and temperature in solar PV systems [12]. Moreover, the extensive community support and availability of development resources, such as the Arduino IDE and related libraries, further streamline implementation and troubleshooting, ensuring greater system reliability and ease of deployment for field applications [13].

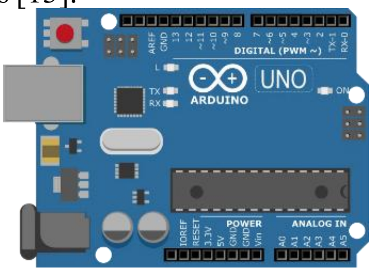

Fig. 1. Arduino Uno.

To enhance wireless communication capabilities, the HC-06 Bluetooth Module is integrated into the design of the photovoltaic system. This module provides a reliable interface for remote data transfer and real-time monitoring by establishing seamless communication between the system and user mobile devices. The inclusion of Bluetooth technology allows users to remotely access system data and control parameters such as voltage, current, and power output, significantly improving the operational efficiency and flexibility of the system. By enabling wireless interaction, this integration minimizes the need for physical connections, reducing the complexity of installations and facilitating real-time decision-making for energy optimization and fault management in remote or distributed photovoltaic installations [14].

Fig. 2. Module Bluetooth HC-06.

The monitoring subsystem incorporates the DSI-0301 Voltage Sensor, engineered to deliver precise analog voltage readings within a measurement range of ±30V. Such accuracy is paramount for effective management of electrical parameters, contributing to the overall performance and stability of the system [15].

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Fig. 3. Voltage Sensor DSI-0301.

Real-time data visualization is achieved through the use of a Liquid Crystal Display (LCD). This component effectively communicates both textual and graphical information, thus enabling users to perform data analysis and system evaluations promptly [16].

Temperature monitoring is facilitated by the DS18B20 Temperature Sensor, which operates across a measurement range of -55°C to +125°C, exhibiting a high degree of precision. The ability to monitor temperature variations is critical for ensuring the operational integrity of the photovoltaic system under diverse environmental conditions [17].

Fig. 4. Temperature Sensor DS18B20.

A high-capacity Battery is incorporated into the system to provide essential energy storage and management capabilities. This component plays a crucial role in ensuring a stable and reliable power supply, particularly during periods of low solar irradiance [18].

Fig. 5. Battery

The system is equipped with Solar Panels (Model: SPM040901200), which convert solar energy into electrical energy through photovoltaic technology. This integration underscores the system's commitment to sustainable energy production [19].

To regulate power delivery effectively, the system employs a Pulse Width Modulation (PWM) Regulator. This component optimizes energy efficiency by dynamically adjusting the duty cycle, thereby minimizing power loss during operation [20].

Fig. 6. Régulateur PWM.

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Lastly, the inclusion of the XL6009 Boost Converter facilitates efficient voltage amplification, enabling the system to meet diverse power requirements across various components, thereby enhancing the overall functionality and performance of the photovoltaic system [21].

Fig. 7. Convertisseur Boost.

C. *System Architecture*

The architecture of the innovative solar photovoltaic system is designed to facilitate optimal energy conversion and efficient real-time monitoring through a modular layout that enhances functionality and user experience.Central to this design is the Arduino Uno microcontroller, which gathers data from various sensors and manages system components, while the Bluetooth module (HC-06) enables wireless communication with a mobile application, allowing remote access to vital information on energy production, voltage levels, and temperature readings[22]. Power generated by the solar panel array is regulated by a PWM controller, optimizing energy flow to the battery and load. Additionally, a boost converter (XL6009) increases output voltage to meet device demands, while an LCD display provides real-time visualization of system performance, including voltage, current, and temperature[23]. The battery serves as a critical energy storage component, ensuring reliability by utilizing energy generated during peak sunlight hours for use during low-sunlight periods [24].

III. Software Development

A. *Proteus Development Environment*

The development environment for the photovoltaic system incorporates Proteus, a powerful simulation tool that allows for the design and testing of embedded systems before physical implementation. This software enables engineers to create virtual prototypes of their circuits, offering a platform to simulate microcontroller behavior, sensor interactions, and overall system functionality. With its intuitive graphical interface, Proteus facilitates the visualization of circuit connections and components, allowing for efficient debugging and optimization. In practice, this approach significantly reduces the risk of errors during physical assembly and enables comprehensive testing of various scenarios, enhancing the reliability of the final product [25].

B. *Arduino Development Environment*

Complementing the simulation capabilities of Proteus, the Arduino IDE serves as the primary platform for software development in the photovoltaic system. Using the Arduino Uno microcontroller—or an alternative suitable microcontroller tailored to project needs—this environment allows for embedded programming in C/C++. The programming language supports efficient coding practices while leveraging libraries specifically designed for sensor interfacing and communication protocols. This seamless integration ensures real-time data acquisition from solar panels and effective interaction with connected devices. In practice, the Arduino IDE's extensive community resources, libraries, and example codes enable developers to streamline their workflows, reduce development time, and enhance both functionality and reliability in the final implementation [26].

IV. Simulation and Programming of a Photovoltaic (PV) System Using Proteus

A. *Simulation of the Solar Panel:*

The simulation of a solar panel allows us to predict its performance under various factors such as sunlight, temperature, and the connected load. Tools like Proteus enable the modeling of the electrical behavior of the solar panel using mathematical models and characteristic data. This type of simulation helps in understanding how the panel would operate in real-world conditions, allowing for adjustments and optimizations before actual implementation.

- Power Output (Ppv) vs. Voltage (V): The graph shows the power output of the panel as a function of voltage. The curve typically forms a bell shape, with a peak at the Maximum Power Point (MPP), indicating the optimal operating point for energy generation.

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- Current (Ipv) vs. Voltage (V): This graph illustrates the relationship between current and voltage under various irradiance and temperature conditions. It shows that the current starts at the short-circuit current (Isc) and decreases as the voltage increases, reaching zero at the open-circuit voltage (Voc).

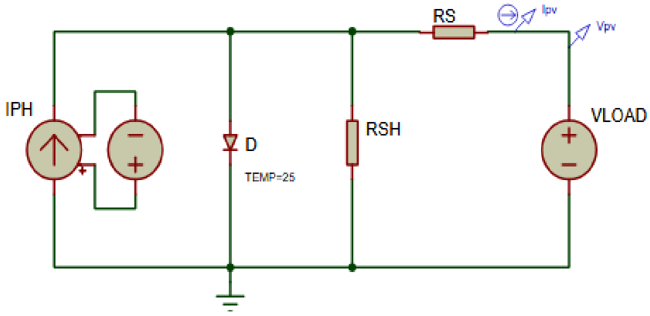

Fig. 8. Simulation of the Solar Panel.

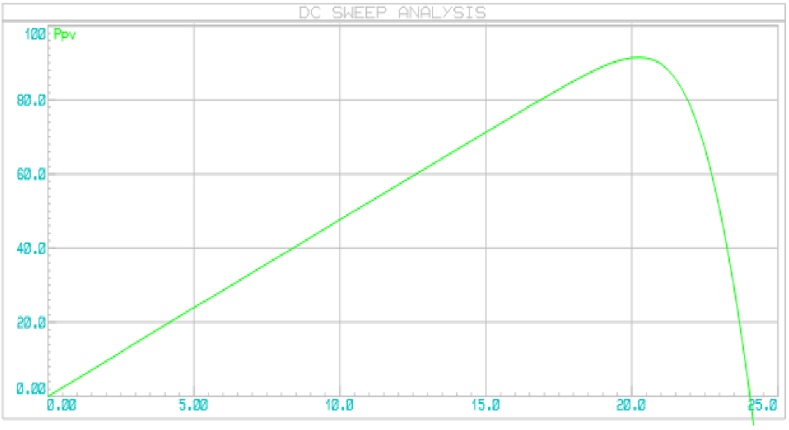

Fig. 9. Power vs. Voltage (Ppv) Graph.

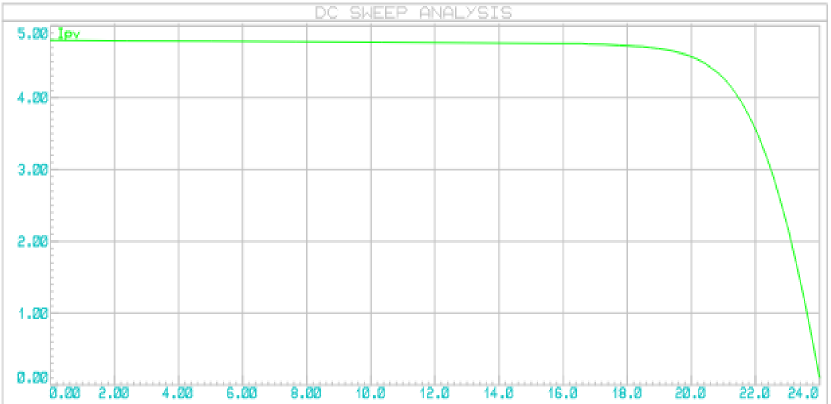

Fig. 10. Current vs. Voltage (Ipv) Graph.

B. Simulation of the Boost Converter:

The boost converter is a crucial component in a PV system, as it steps up the voltage from the solar panel to supply the battery or the connected load. Simulating the boost converter helps verify its efficiency and stability under varying load and sunlight conditions.

- Input and Output Voltage: The simulation results indicate that the output voltage of the boost converter is higher than the input voltage, which confirms the correct functioning of the converter. Initially, there is a transient period where the output voltage gradually increases until it stabilizes, after which it remains constant.

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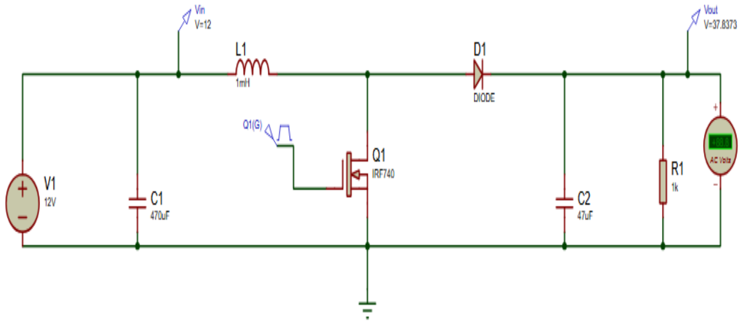

Fig. 11. Simulation of the Boost Converter.

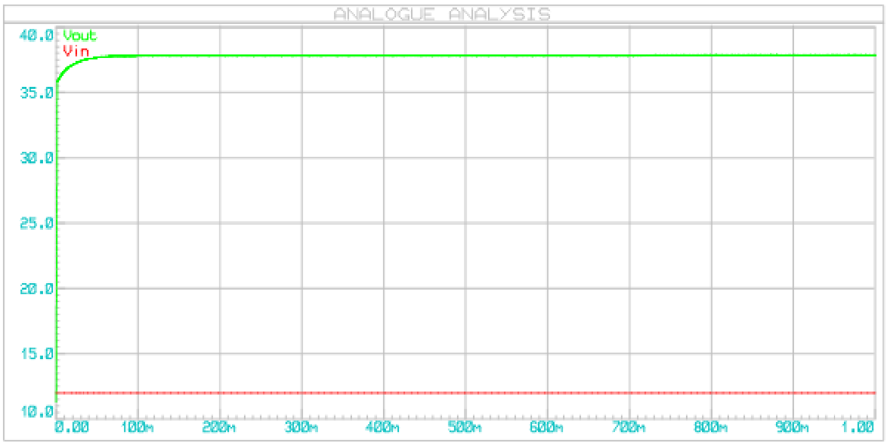

Fig. 12. Input and Output Voltage of the Boost Converter.

C. Simulation of the PV System with Boost Converter:

By combining the simulated models of the solar panel and the boost converter, a comprehensive simulation of the entire PV system can be achieved. This enables the evaluation of the system's performance under different sunlight and load conditions.

- Output vs. Input Voltage: The simulation shows that the output voltage (Vout) is greater than the input voltage (Vin), indicating that the boost converter is functioning correctly by increasing the voltage supplied by the solar panel.
- Current Behavior: The input current (Iin) is observed to be higher than the output current (Iout) due to the boost converter increasing the output voltage, which requires a higher input current to maintain the power balance.

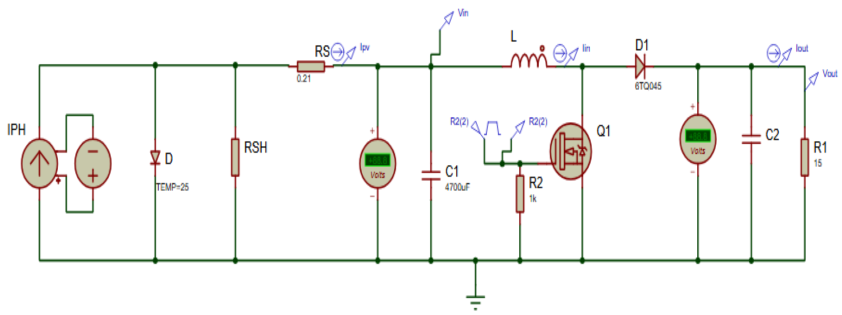

Fig. 13. Simulation of the Solar Panel with Boost Converter.

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Fig. 14. Input and Output Voltage Over Time.

Fig. 15. Input and Output Current Over Time.

D. Simulation of the Photovoltaic System:

Simulating a photovoltaic (PV) system in Proteus is an effective method for studying and optimizing system performance. Using the Proteus model, it is possible to simulate real-time operation of the PV system, varying solar radiation intensity and visualizing the I-V characteristics of the solar panel. This simulation also allows testing of Maximum Power Point Tracking (MPPT) algorithms, crucial for maximizing the conversion of solar energy into electrical energy.

- System Configuration: The simulated PV system includes three distinct parts: a control circuit based on an Arduino UNO, a power circuit comprising a Boost converter and load, and a results display on an LCD screen.
- Power Output Over Time: The simulation demonstrates the power output of the PV system over time. The graph reveals that power varies due to factors such as solar radiation intensity, panel temperature, and overall system efficiency. The initial constant phase in the curve corresponds to the simulation's start with stable conditions, followed by a gradual increase due to rising solar radiation intensity, after which the system stabilizes.

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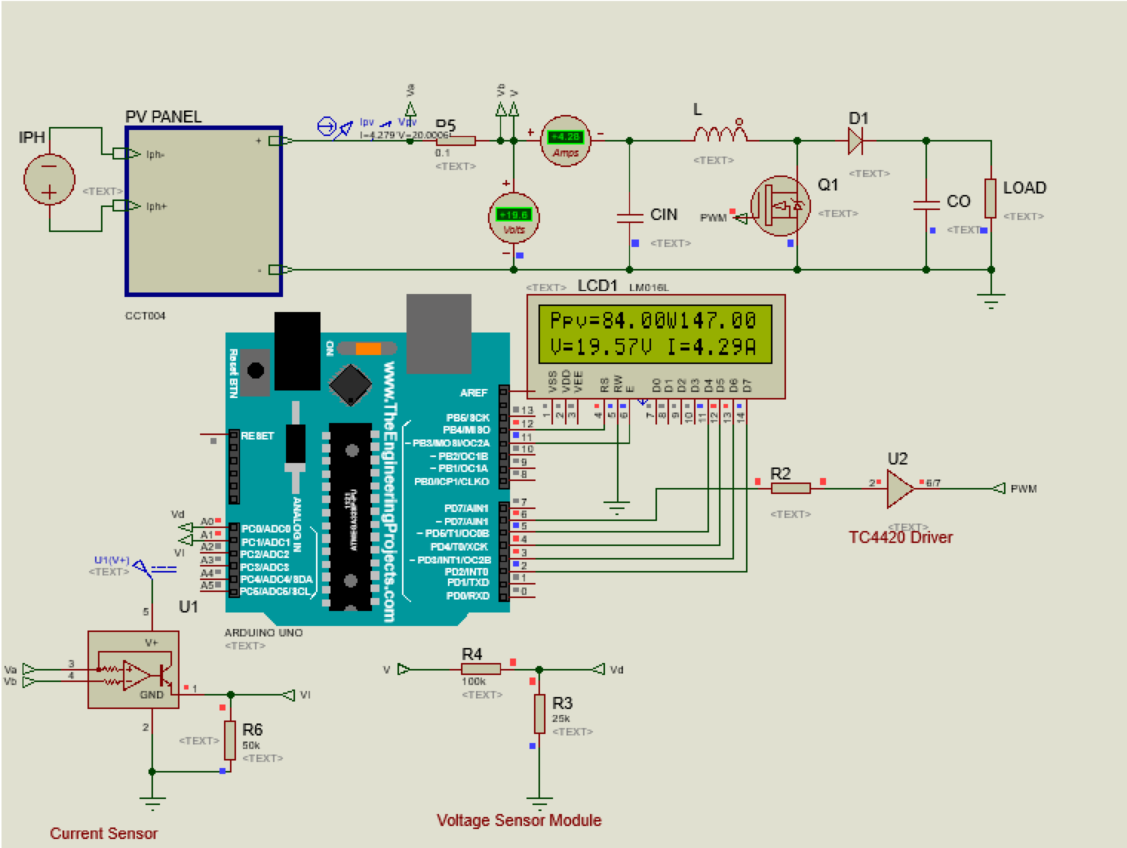

Fig. 16. Simulation of the PV System.

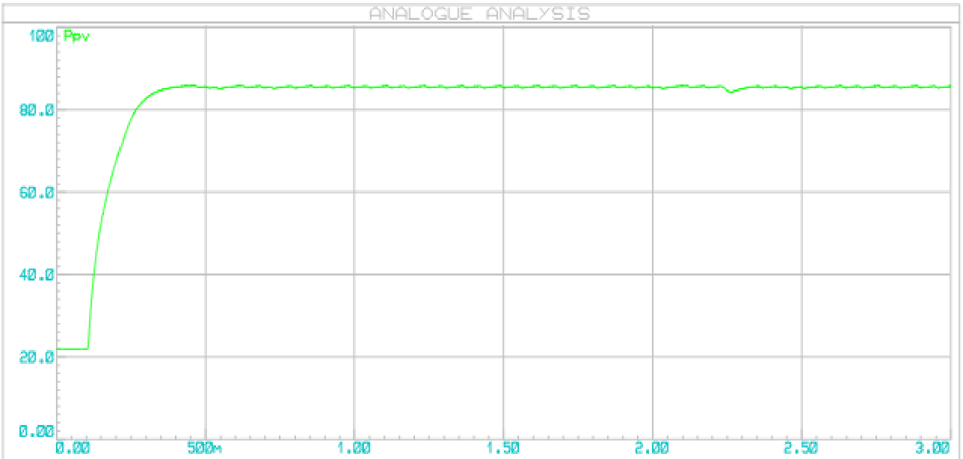

Fig. 17. Power vs. Time Graph.

E. MPPT Programming with Arduino Uno:

Programming an MPPT (Maximum Power Point Tracking) controller with an Arduino Uno optimizes the power extracted from the solar panel by ensuring it operates at its maximum power point. The MPPT adjusts the load using Pulse Width Modulation (PWM) to maintain optimal power output.

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```
if (Power_now > Power_anc)
{ if (voltageValue > voltage_anc)
    pwm = pwm - delta;
  else
    pwm = pwm + delta;
}
else
{
  if (voltageValue > voltage_anc)
    pwm = pwm + delta;
  else
    pwm = pwm - delta;
}
Power_anc = Power_now;
voltage_anc = voltageValue;
if (pwm < 20)
  pwm = 20;
if (pwm > 150)
  pwm = 150;

analogWrite(6, pwm);
}
```

Control Loop: The program implements a feedback control loop that adjusts the PWM signal based on comparisons between current and previous values of power and voltage. This ensures that the PWM value stays within a specified range (20 to 150) and applies the calculated PWM to the designated pin (Pin 6 in this case). This approach helps maintain efficient power conversion and adapts to changing environmental conditions.

V. User Interface Development

A. MIT App Inventor

MIT App Inventor is a visual programming environment designed to simplify mobile application development for Android devices, originally created by Google and now maintained by the Massachusetts Institute of Technology (MIT). It reduces entry barriers for individuals lacking programming experience by utilizing a graphical interface similar to Scratch, enabling users—including primary school children—to engage in programming without extensive coding knowledge. Since its release on December 15, 2010, and subsequent transition to MIT in 2011, App Inventor has fostered accessible mobile app development methodologies, encouraging innovation among novice programmers. In this exploration of MIT App Inventor, a program has been developed specifically to manage Bluetooth device control.

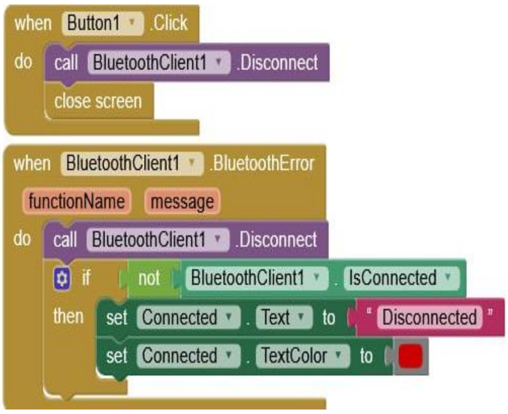

Fig. 18. Bluetooth Program Diagram in MIT App Inventor

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B. User Interface of the Application

The user interface of the "Sun Scope" application is meticulously designed to display critical parameters of a photovoltaic (PV) system in real-time.

Fig. 19. User Interface of the Application

the main screen provides users with access to the following parameters:

- Voltage: Represented in volts (V).
- Current: Indicated in amperes (A).
- Temperature: Displayed in degrees Celsius (°C).
- Power: Shown in watts (W).

Bluetooth Status: An icon that conveys the connection state to the Bluetooth device.

This user-centric interface not only facilitates effective monitoring of solar system performance but also enhances the user experience by providing intuitive access to essential data at all times. The application, aptly named "Sun Scope," is designed to support the real-time monitoring of photovoltaic system performance via Bluetooth connectivity

VI. Practical Implementation of a Solar System with Monitoring

Figures (15) and (16) depict the photovoltaic installation with mobile monitoring, illustrating a comprehensive system designed for the generation of clean and sustainable electricity while enabling remote performance tracking. Mobile monitoring confers numerous advantages, including real-time tracking, fault detection, performance optimization, and preventive maintenance.

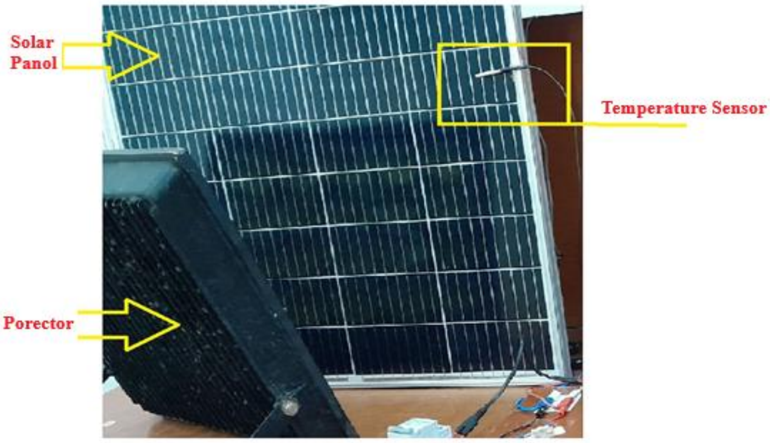

Fig. 20. System Input Equipment

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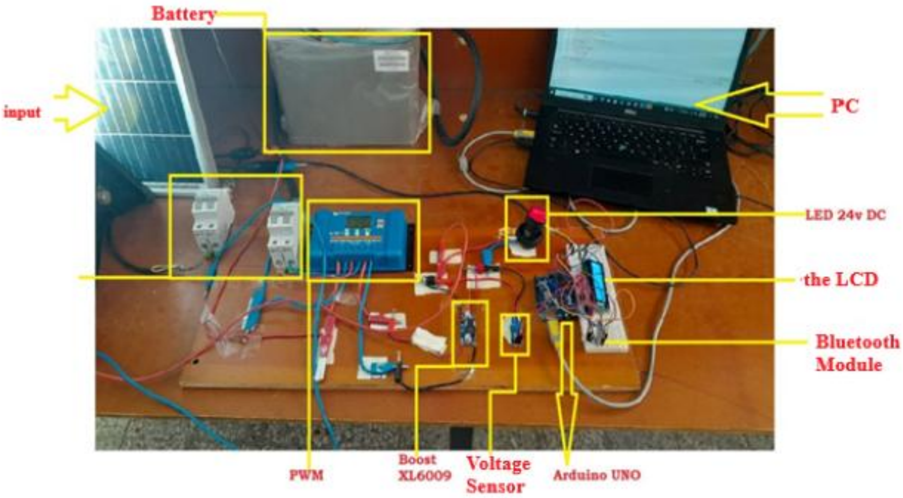

Fig. 21. Solar Photovoltaic System with Monitoring

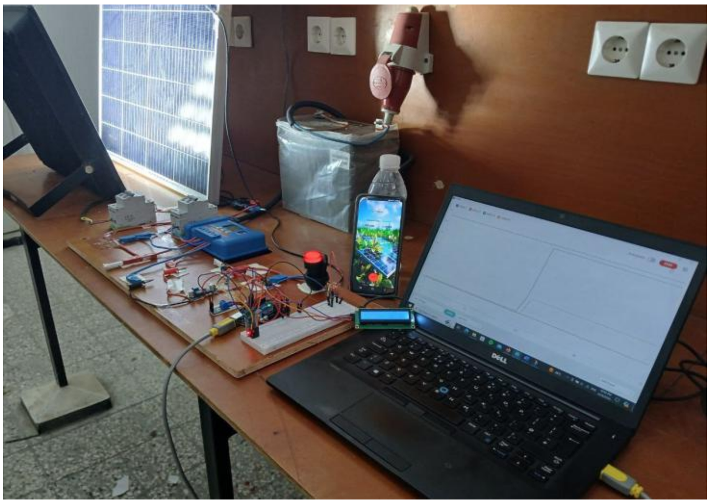

Fig. 22. System realized

A. System Operation

The system operates through several interconnected stages. Initially, the solar panels convert light from the projector into direct current (DC) electricity. This generated electricity is subsequently stored in a battery. A charge controller plays a crucial role in regulating the flow of electricity between the solar panels, the battery, and the load, ensuring that the battery is neither overcharged nor excessively discharged. Voltage and temperature sensors monitor voltage, current, power, and temperature. These data are collected by an Arduino microcontroller, which transmits the information to a Bluetooth module. This module facilitates wireless communication by relaying data to a smartphone or tablet via a mobile application. Through this application, the user can monitor the photovoltaic system's various parameters in real-time, including voltage, temperature, current, and power.

B. Measurement

Accurate measurement of a photovoltaic system's parameters is essential for assessing its efficiency and performance.

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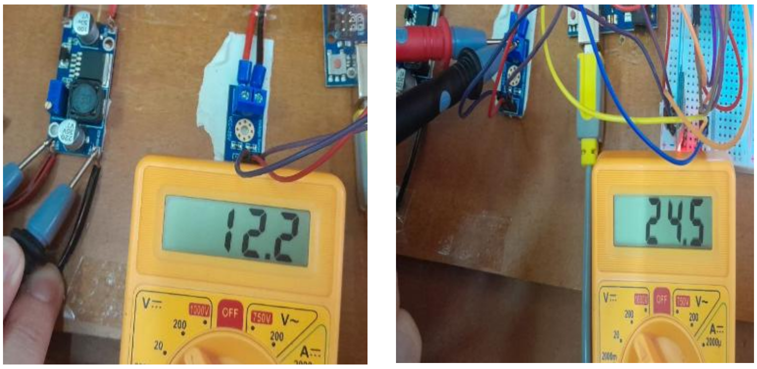

Fig. 23. Voltage Measured Before and After Boost

Fig. 24. LCD Display of Load Measurements (No Faults)

Note: The voltage displayed on the LCD screen exhibits slight increases due to the sensitivity of the sensors connected to the Arduino, which are influenced by voltage fluctuations, particularly the 5V from the Arduino itself.

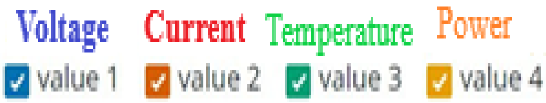

Fig. 25. Data Representation

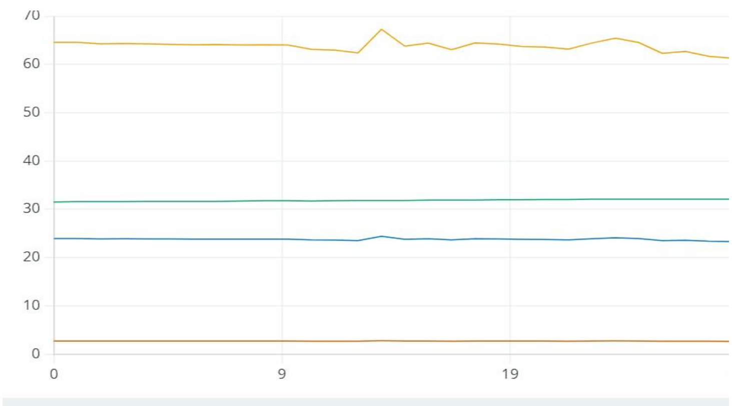

Fig. 26. Curve Displayed on Arduino Serial Plotter for Solar Panel Without Faults

VII. INTRODUCTION OF FAULTS IN THE PV MONITORING SYSTEM

To evaluate the robustness and reliability of the photovoltaic monitoring system, various types of faults were systematically introduced to analyze their impacts on system performance. The injected faults and their corresponding results were displayed on the LCD screen and in the mobile application "Sun Scope" for real-time monitoring. The following faults were introduced:

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Partial Shading: Partial obstruction of the solar panel was implemented to simulate conditions of partial shading, resulting in a moderate reduction in energy production.

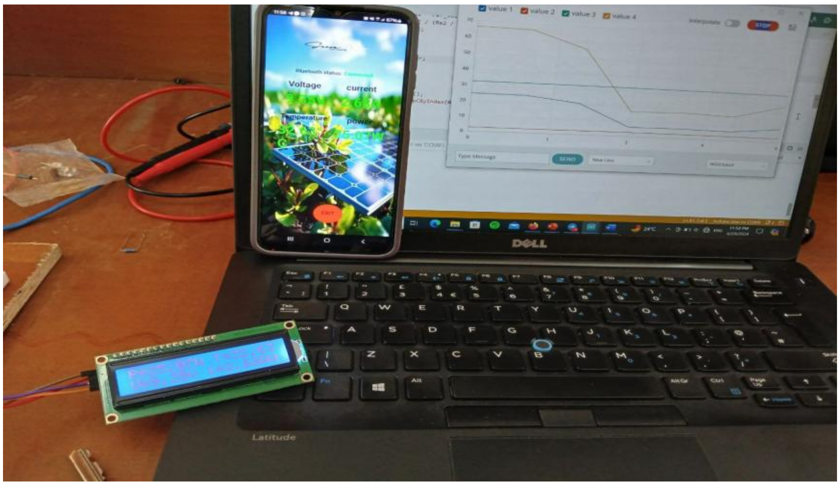

Fig. 27. Result of Partial Shading Fault (Center of Panel)

Fig. 28. Curve Displayed on Arduino Serial Plotter for Partial Shading

Total Shading: Complete coverage of the solar panel was performed to simulate total shading conditions, demonstrating a drastic decrease in energy production.

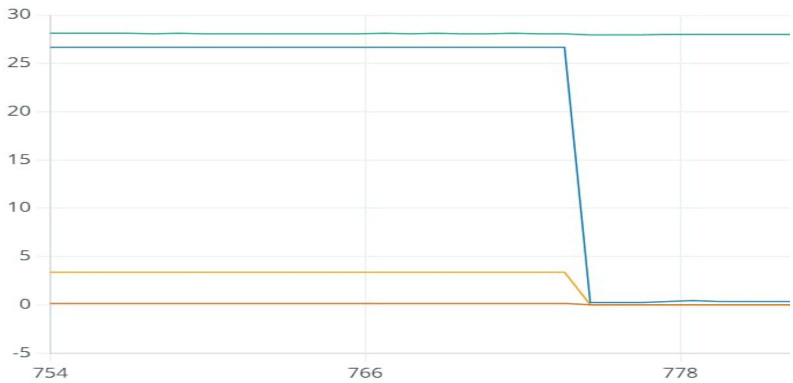

Fig. 29. Curve Displayed on Arduino Serial Plotter for Total Shading

Resistance in Parallel with Load: A resistance was added in parallel with the load to simulate energy losses, indicating power loss.

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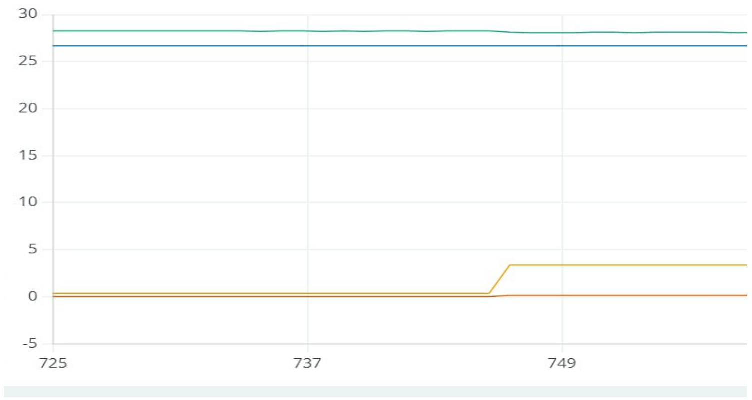

Fig. 30. Curve Displayed on Arduino Serial Plotter for Resistance in Parallel with Load

Boost Stage Fault (Burnout of Schottky Diode SS34): A fault in the boost conversion stage was simulated, leading to a decrease or complete loss of power conversion.

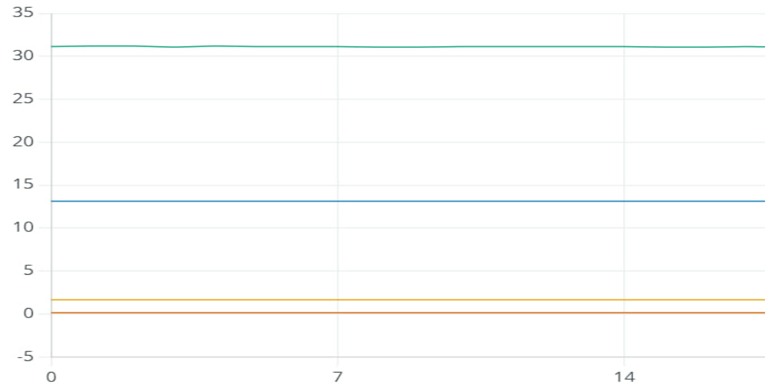

Fig. 31. Curve Displayed on Arduino Serial Plotter for Boost Fault

VIII. INTERPRET THE RESULTS

These practical tests provided valuable insights into the system's tolerances and the necessary mitigation strategies to ensure optimal performance, even in the presence of anomalies. The results of each injected fault are clearly presented on both monitoring interfaces, enabling rapid identification and informed decision-making for corrective actions.

TABLE I. RESULTS OF FAULTS ON THE PHOTOVOLTAIC SYSTEM

	Measurement		
	Power (P)	***Voltage (V)***	***Current (I)***
Panel Without Fault	**61.38 W**	**23.34 V**	**2.64 A**
Panel Fault			
Partial Shading	**25.07 W**	**9.35 V**	**2.68 A**
Total Shading	**0**	**0.38 V**	**0**
Load Without Fault	**6.73 W**	**26.67 V**	**0.25 A**
Component Fault			
Parallel Resistance	**6.73 W**	**26.67 V**	**0.25 A**
Boost Fault (Burnout)	**36.30 W**	**13.54 V**	**2.68 A**

The PV panel under nominal conditions delivered 61.38 W (±0.5 W) at 23.34 V (±0.1 V) and 2.64 A (±0.1 A), reflecting optimal irradiance-to-energy conversion with instrumentation uncertainty within industry standards (±0.1 V for voltage, <1 % for current) . Under partial shading, bypass diode conduction and current mismatch in series strings precipitated a voltage collapse to 9.35 V (±0.1 V) while current remained at 2.68 A (±0.1 A), resulting in a 59.2 % power reduction to 25.07 W (±0.5 W)—consistent with shading-loss models demonstrating power loss often exceeds proportional shading area due to string-level mismatch and corroborated by comparative performance assessments showing relative energy losses up to 60 % under medium

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shading . Total shading conditions yielded near-zero generation (0 W ± 0.5 W) with a residual, diode-bypassed panel voltage of 0.38 V (±0.1 V) and zero current, the characteristic phenomenon of full-irradiance obstruction in PV arraysn the load side, baseline measurements of 6.73 W (±0.5 W) at 26.67 V (±0.1 V) and 0.25 A (±0.1 A) aligned with expected system draw profiles under nominal operation ; intriguingly, parallel resistance faults produced indistinguishable signatures (6.73 W ± 0.5 W, 26.67 V ± 0.1 V, 0.25 A ± 0.1 A), underscoring the challenge of detecting moderate shunt-path anomalies absent granular sensor data . Conversely, a boost-converter burnout—likely precipitated by capacitor or switch degradation—manifested as a reduced DC-link voltage of 13.54 V (±0.1 V) at sustained current of 2.68 A (±0.1 A), outputting 36.30 W (±0.5 W) and unequivocally signaling DC–DC conversion failure, as documented in converter fault literature emphasizing voltage deviation as a primary diagnostic criterio.

IX. CONCLUSIONS

This article has detailed the design, implementation, and performance evaluation of a solar photovoltaic system with integrated real-time supervision using mobile technology. The system demonstrated the ability to monitor key parameters such as voltage, current, and power, allowing for proactive detection of faults and optimization of energy output. Practical tests introduced various fault scenarios such as shading, resistive losses, and component failures to assess system resilience. The results confirmed the system's robustness and reliability in maintaining operational efficiency under adverse conditions. This integration of renewable energy generation with intelligent monitoring offers a scalable and efficient solution for improving solar energy systems. It highlights the growing importance of combining sustainable energy technologies with advanced data-driven supervision, ultimately contributing to greater efficiency and resilience in energy management.

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ISSN: 1737-9288