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New Approach for Tracking, Monitoring, and Diagnosing Faults in a Photovoltaic System in Real Time: An Experimental and Case Study

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Abstract

Photovoltaic installations have emerged as a cornerstone of sustainable energy production, playing a pivotal role in the global transition towards renewable sources of electricity. As the demand for clean energy surges, so too does the need for robust monitoring and diagnostic strategies to ensure the efficient operation of these systems. This study presents a novel methodology for the real-time tracking, monitoring, and diagnosing of faults in photovoltaic systems (PVSs), emphasizing their crucial role in sustainable energy production amid the global shift to renewable energy. The study was conducted in Guelma, Algeria, during the spring and summer seasons. The investigation utilized WatchPower simulation software over a 24-hour performance analysis of the photovoltaic system. On June 19, 2023, with a high temperature of 32°C, the system achieved a peak output power of 600W under optimal conditions, validating its efficiency in energy generation. The study also analyzed the effects of shading on energy output by comparing data from a shaded day on May 14, 2023, at 25°C, to an unshaded day on June 21, 2023, at 32°C, during peak sunlight hours from 9:00 AM to 2:15 PM, the period when sunlight is at its strongest. The results showed a significant drop in output power from 600W to 450W due to shading, underscoring the importance of real-time monitoring to detect performance inefficiencies. This research not only enhances operational

reliability and maintenance strategies for PV systems but also demonstrates the effectiveness of integrating real-time data analytics to support decision-making in similar environments.

Keywords: Renewable energy, Photovoltaic installations, Real-time monitoring, Fault diagnosis, Energy yield, Anomaly detection.

1. Introduction

Photovoltaic panels, commonly known as solar panels, are a transformative technology that convert sunlight directly into electricity through the photovoltaic effect. These panels harness solar energy, providing a renewable and sustainable power source that significantly reduces greenhouse gas emissions and dependence on fossil fuels (Hansen *et al*., 2019; Qusay *et al*., 2024; Dmitrii *et al*., 2021). Widely used in residential, commercial, and industrial applications, photovoltaic systems not only lower energy costs (Neacsa *et al*., 2022) but also enhance energy independence and grid stability. Continuous advancements in technology have improved efficiency and reduced costs, making the adoption of photovoltaic panels increasingly viable, paving the way for a cleaner and more sustainable energy future. Dust accumulation is a major factor affecting the efficiency of PV panels; a study has shown that in the El-Oued region, the performance of dusty panels is reduced by up to 34.67% compared to clean ones (Largot *et al*., 2024).

The global shift towards renewable energy has heightened interest in photovoltaic (PV) technology due to its efficiency in harnessing solar energy (Ofélia de Queiroz *et al*., 2024; Irmak *et al*., 2023). Growing demand for renewable energy in residential and commercial sectors has driven a global surge in PV installations, underscoring the need for effective monitoring and maintenance strategies (Abdulla *et al*., 2024) to ensure the reliability and performance of PV systems (Ahmadizadeh *et al*., 2024). Efficient tracking, monitoring, and diagnosis are essential for maintaining optimal operational efficiency and ensuring the long-term sustainability of PV installations (Mellit *et al*., 2018). However, traditional monitoring and diagnostic systems often fall short in identifying issues, leading to energy losses and increased operational costs (Sarang *et al*., 2024; Hind *et al*., 2024; Peinado Gonzalo *et al*., 2020). Additionally, optimizing the tilt angle of PV panels is critical for maximizing efficiency; a study determined that the optimal tilt angles in the El-Oued region are 33° in March and 28° in April, directly impacting energy production (Ghodbane *et al*., 2023).

The Algerian government has prioritized harnessing solar energy for electricity generation, recognizing the necessity of diversifying its energy sources. To achieve this goal, it has committed to investing in advanced technologies and infrastructure to optimize the use of this renewable resource. Consequently, many installations—including businesses, schools, and homes—have integrated photovoltaic (PV) panels to reduce electricity consumption. As the adoption of photovoltaic systems (PVS) continues to expand (Lazaroiu *et al*., 2023), ensuring their optimal performance and reliable operation is becoming increasingly critical (Orosz *et al*., 2024; Patil *et al*., 2024). This paper proposes a new approach for monitoring and diagnosing PV installations to efficiently detect performance issues and malfunctions, utilizing WatchPower, a sophisticated surveillance tool specifically designed for energy systems (WatchPower user manual, 2023).

The integration of photovoltaic systems for irrigation, as exemplified by the solar pumping systems in Terifaoui, demonstrates how photovoltaic technologies can enhance agricultural production and strengthen the economic resilience of the region (Rehouma *et al*., 2024; Zakaria *et al*., 2024).

In recent years, the rapid proliferation of solar energy within the renewable energy sector has underscored the need for effective surveillance and diagnostic tools to enhance the performance and longevity of photovoltaic (PV) systems. Various methods have been proposed to monitor and assess the operational efficiency of PV installations, ranging from traditional manual inspections to advanced automated monitoring systems (Alam *et al*., 2015; Chine *et al*., 2014). Traditional methods relied primarily on manual checks and periodic maintenance, which were often resource-intensive and susceptible to human error (Platon *et al*., 2015; Daliento *et al*., 2017; Muñoz-García *et al*., 2011; Mgonja & Saidi, 2017). Most traditional approaches involve time-consuming and complex procedures, including physical inspections and remote monitoring (Lakshmi *et al*., 2023). With advancements in sensor networks and data analytics, the PV monitoring landscape has shifted toward more automated solutions. Research in this area has largely focused on specific topics, such as PV system (PVS) installation types, monitoring methods, sensor integration, input parameters, data acquisition, applied techniques, and system integration (Triki-Lahiani *et al*., 2018; Hong & Pula, 2022). Numerous reviews have examined fault detection and classification methods in PVSs; however, most have focused only on particular aspects, such as PVS connectivity, related electrical techniques, specific PVS components, and the advantages and limitations of various approaches (Department for Business, Energy & Industrial Strategy, 2021).

Innovation in hybrid photovoltaic-thermal (PV/T) systems is another promising avenue. Studies have shown that these systems can produce both electrical and thermal energy, thereby improving overall efficiency through the use of appropriate working fluids such as nanofluids (Ghellab *et al*., 2021).

Many modern monitoring systems leverage Internet of Things (IoT) frameworks to collect real-time data, enhancing both responsiveness and accuracy in tracking photovoltaic (PV) system performance (Hamied *et al*., 2018). A significant advancement in this area is the integration of machine learning algorithms, which have improved fault detection and performance forecasting capabilities for PV systems (Liang *et al*., 2021; Vicente-Gabriel *et al*., 2021). These algorithms analyze extensive datasets from PV operations to identify anomalies, predict malfunctions (Amiri *et al*., 2024; Al-Mashhadani *et al*., 2021; Sonawane *et al*., 2023; Parenti *et al*., 2024), and suggest timely interventions. Research has shown substantial improvements in the early detection of performance degradation, leading to increased operational reliability (Livera *et al*., 2022).

Studies have shown that using machine learning algorithms can enhance fault detection in photovoltaic systems, demonstrating detection rates of 95% when analyzing real-time operational data and allowing for better forecasting of malfunctions (Haffaf *et al*., 2022). Furthermore, it has been observed that photovoltaic systems are known to degrade over time, which can adversely affect their overall performance. A study revealed that the durability of photovoltaic systems, particularly in arid environments, requires special attention to maintain their operational efficiency in the long term (Zine *et al*., 2024).

Additionally, extreme temperatures in desert regions, such as those observed in Algeria, impact the performance of photovoltaic panels. Research indicates that high temperatures can significantly reduce the energy output of photovoltaic panels, with some panels achieving only 52% of their rated power under elevated temperatures (Medekhel *et al*., 2022).

This study explores the innovative use of Watch Power software for real-time tracking, monitoring, and fault diagnosis in photovoltaic (PV) systems, aiming to enhance system efficiency and minimize downtime. By utilizing advanced data analysis and visualizations, the study investigates the effects of diverse climatic conditions on solar panel performance, with a specific focus on improving energy output and reducing operational costs. This work is novel in its comprehensive approach, integrating real-time monitoring with automated fault diagnosis, enabling proactive maintenance strategies that adapt to varying environmental factors. Ultimately, this research aspires to establish best practices for optimizing PV systems, contributing to the advancement of sustainable solar energy management and offering valuable insights for future innovations in the field.

2. Methodologies

This study presents an innovative approach for tracking, monitoring, and diagnosing photovoltaic (PV) systems using WatchPower software. The method was tested in a real-world experiment conducted in Guelma, Algeria. In the initial experiment, we monitored the health and fault status of a PV system through real-time analysis over a 24-hour period on June 19, 2023, when the maximum temperature reached 32°C. A second experiment investigated the impact of shading on system performance by comparing data from a shaded day on May 14, 2023, with a maximum temperature of 25°C, to an unshaded day on June 21, 2024, when the maximum temperature also reached 32°C. The comparison was conducted within a specific timeframe from 9:00 AM to 2:15 PM, the period of peak sunlight.

The paper is organized as follows: we first introduce the WatchPower software, highlighting its main features and advantages. We then outline the proposed methodology for PV system surveillance and diagnostics, followed by a discussion of the case study's application and context. Finally, we describe the experimental validation process and present a detailed analysis of the results obtained from the study.

2.1.WatchPower software

The WatchPower software is a specialized monitoring and diagnostic tool designed specifically for managing and analyzing photovoltaic systems (PVSs) (Sosnovsky, *et al*, 2023, Akpolat *et al.*, 2021; and Agrawal & Gupta, 2016). It offers comprehensive solutions for monitoring and diagnosing renewable energy systems, particularly solar installations. With its user-friendly interface, WatchPower enables users to effortlessly analyze real-time data and performance metrics, allowing them to monitor energy production, consumption, and overall system efficiency. The software also delivers detailed visualizations of power generation trends, along with operational notifications and alerts for any detected abnormalities or inefficiencies. Additionally, its comprehensive reporting tools enable users to swiftly diagnose issues and optimize performance, enhancing the longevity of their renewable energy investments. By leveraging advanced analytics, WatchPower empowers users to make informed decisions, ensuring systems operate at peak efficiency while maximizing energy yield.

2.1.1 Power Flow and Modes

The system includes five main device icons: solar panel, battery, inverter, load, and utility. Dynamic power flow is displayed across these five device modes.

- **Power-On and Standby Mode**: In this mode, the inverter does not supply power to the load until the "ON" switch is activated. The battery remains in standby mode, which can be charged by either a qualified utility source or a photovoltaic (PV) source (refer to Figures 1 and 2).

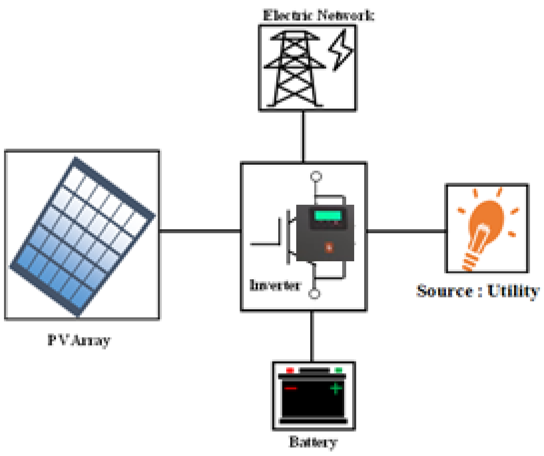

Figure 1 - Power-On Mode

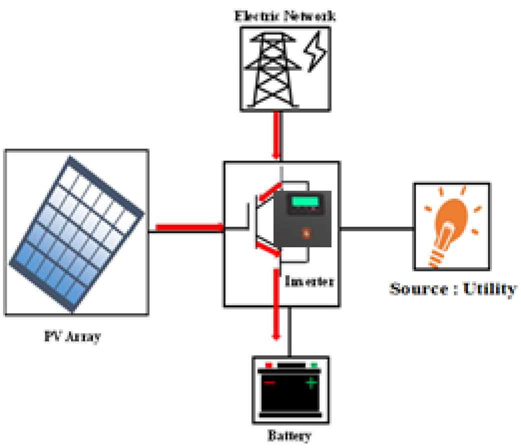

Figure 2 - Standby Mode

- **Line Mode**: In this mode, the inverter supplies power to the load using utility power. A photovoltaic source or suitable utility can charge the battery in this mode (Figure 3).
- **Battery Mode**: In this mode, the inverter supplies power from either the photovoltaic (PV) panel or the battery. However, the battery can only be charged by the PV source (Figure 4).

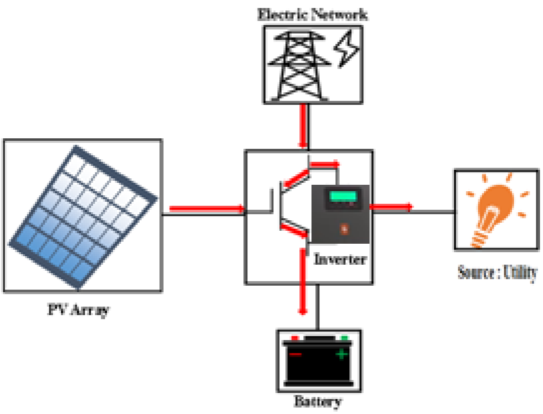

Figure 3 - Line Mode

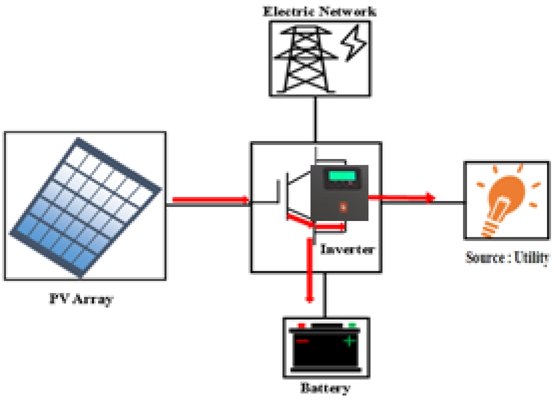

Figure 4 - Battery Mode

-Fault Mode: If the inverter encounters any faults, it may be unable to deliver the full output power. Nonetheless, the qualified grid or the PV source (as shown in Figure 5) can still charge the battery.

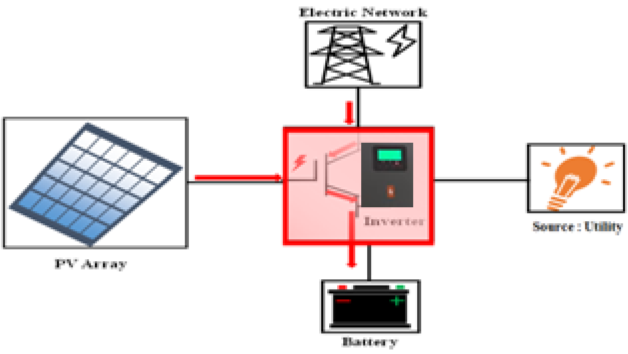

Figure 5 - Fault Mode

2.1.2 Remote monitoring of Photovoltaic installations via Android and iOS Applications

In today's renewable energy landscape, remote monitoring of photovoltaic (PV) installations via mobile applications is essential for maximizing efficiency and ensuring optimal performance. Both Android and iOS platforms (Figure 6) provide innovative solutions th*et al*low users to track energy production, assess system health, and receive real-time maintenance alerts. These applications feature intuitive dashboards displaying key metrics such as solar output, energy consumption, and weather conditions, empowering users to make informed decisions about their solar investments. Additionally, with built-in remote troubleshooting and diagnostic capabilities, users can proactively manage their PV systems from anywhere, enhancing reliability, minimizing downtime, and supporting sustainability goals.

Figure 6 - WatchPower using the mobile application

2.2 Characteristics and Benefits of Watch Power Software for the Monitoring and Diagnosis of Photovoltaic Systems

1. **Real-time Performance Monitoring**: Provides continuous tracking of solar energy generation, allowing users to instantly assess the functionality of their PV systems and detect any anomalies.
2. **Improved Diagnostics**: Facilitates early identification of system faults, inefficiencies, or underperformance through advanced analytics, which can lead to timely interventions and repairs.
3. **Enhanced Efficiency**: By analysing historical data and performance trends, the software helps optimize energy output, which can increase the overall efficiency of the photovoltaic system.
4. **User-friendly Interface**: Typically features a graphical interface that makes it easy for users, regardless of their technical expertise, to understand system performance and engage with the data.
5. **Alerts and Notifications**: Automatically sends alerts in case of system malfunctions or performance drops, helping operators address issues promptly and reduce downtime.
6. **Data Reporting and Analysis**: Offers comprehensive data reporting tools that enable users to generate insights and reports, which can assist in maintenance planning and performance evaluations.
7. **Cost Savings**: By proactively identifying issues and optimizing system performance, the software can lead to reductions in maintenance costs and improved energy yield, resulting in financial savings over time.
8. **Integration with Other Systems**: Often allows for integration with other energy management systems, enhancing overall energy management and contributing to smart grid initiatives.
9. You can remotely monitor the photovoltaic system via the WatchPower application on an Android phone, utilizing either Bluetooth or Wi-Fi connectivity.

2.3 Proposed approach for surveillance and diagnosis of PV installation using WatchPower

The proposed methodology offers a structured approach to effectively monitor and analyze photovoltaic (PV) systems, ensuring their reliable and efficient operation. This step-by-step process enables the detection of potential faults and facilitates timely interventions to maintain optimal performance:

- **Step 1 and 2:** The methodology begins by initiating the process and defining clear objectives.
- **Step 3 and 4:** Next, system information is gathered, and necessary software is installed.
- **Step 5:** Communication is then established with the PV system, enabling seamless interaction.
- **Step 6 and 7:** This allows for data collection and real-time monitoring commencing.
- **Step 8 and 9:** The collected data undergoes analysis specifically for fault detection.
- **Step 10 and 11:** Reports are generated to support decision-making, and an action plan is developed based.
- **Step 12:** The process concludes with ongoing review and long-term monitoring, ensuring efficient operation and addressing any detected faults in the PV system.

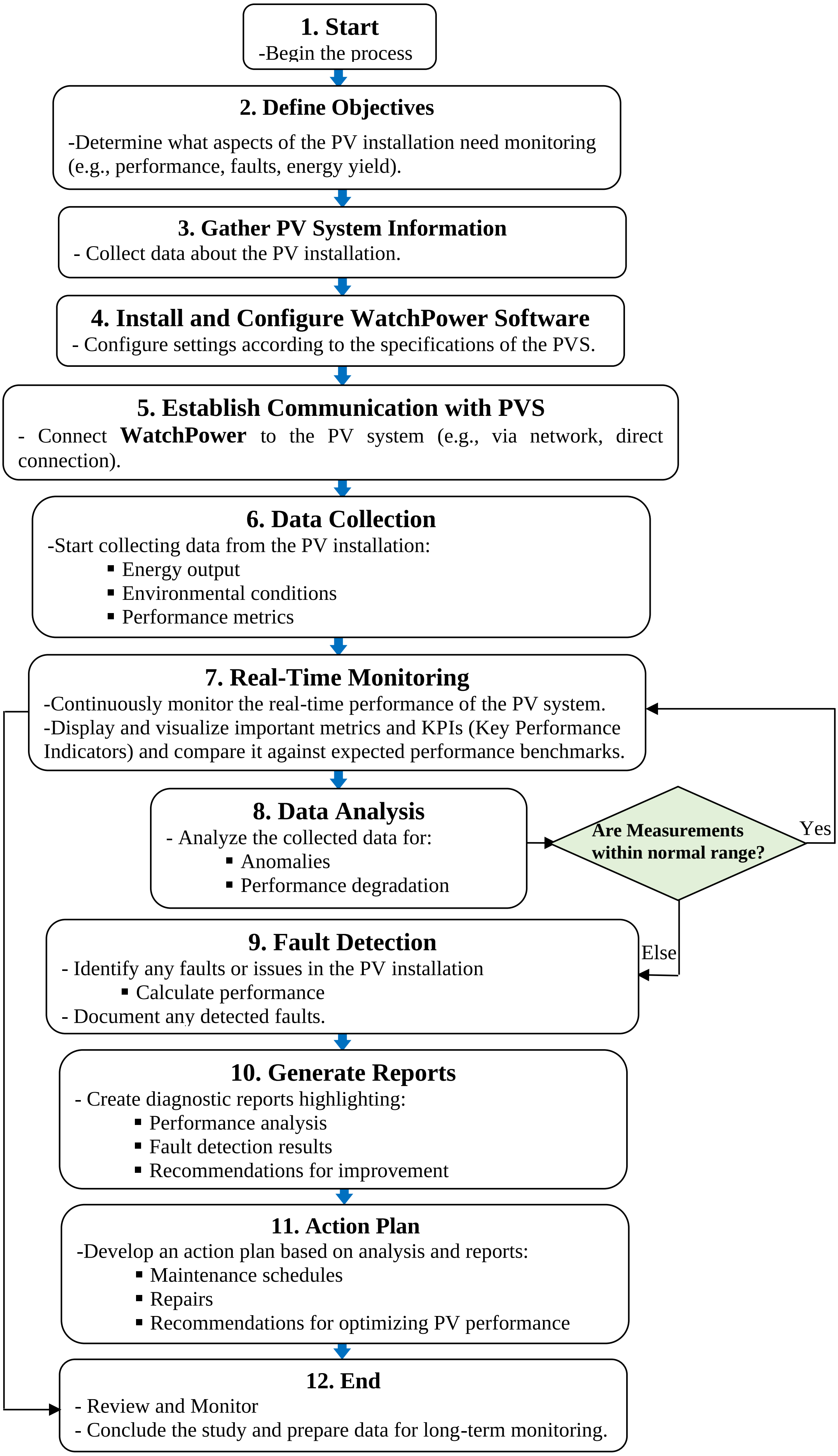

Figure 7 - Flowchart of the proposed approach

2.4. Case study application

The application of our proposed approach centers on a solar power generation configuration that employs four HD-200M 18V panels arranged in a 2x2 layout to evaluate real-time performance metrics. This configuration includes a Maximum Power Point Tracking (MPPT) controller, two 12V batteries, an inverter, and a computer equipped with WatchPower software for monitoring and diagnostic purposes (Figure 8).

The HD-200M 18V solar panel is a photovoltaic module specifically designed for converting solar energy into electrical energy. It boasts a peak power output of 200 W, an open-circuit voltage of 23.2 V, and a short-circuit current of 11.69 A. These specifications make it a suitable choice for a wide range of applications, from residential to commercial solar power systems (see Table 1).

Table1 - Electrical Characteristics of the HD-200M 18V solar module.

Electrical Characteristics	HD-200M 18V
Maximum power produced by panel (P_m)	200 W
Open circuit voltage (V_{oc})	23.2 V
Short circuit current (I_{sc})	11.69 A
Maximum power voltage (V_{mp})	18.2 V
Maximum power current (I_{mp})	10.98 A

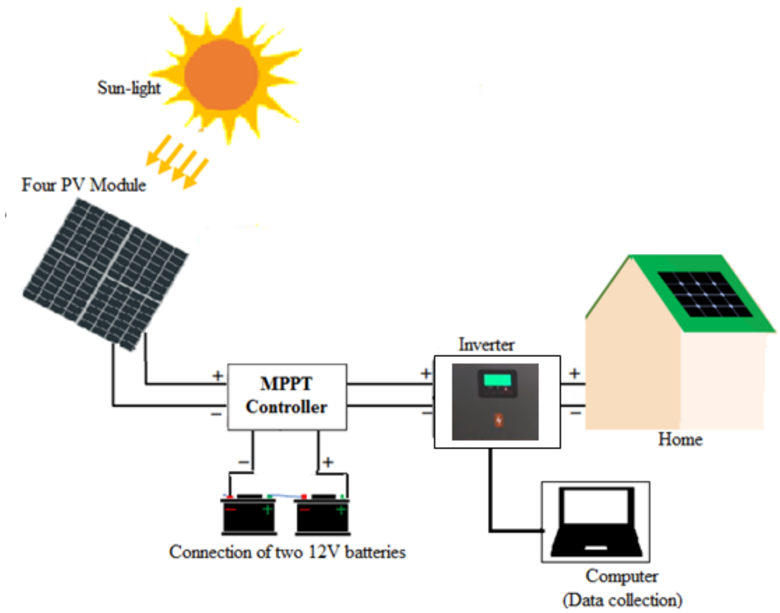

Figure 8 - PVS Case study.

The MPPT controller plays a crucial role in optimizing the power output from the solar panels by dynamically adjusting the electrical operating point of the modules. It efficiently extracts maximum energy, enhances battery charging, and contributes to system stability. The inverter then converts the DC power stored in the batteries into usable AC power. Meanwhile, a computer equipped with WatchPower software enables real-time monitoring and diagnostic capabilities for the solar installation. This software offers valuable insights into performance metrics, energy consumption, system efficiencies, and alerts for any anomalies. With this configuration, the case study application establishes a robust foundation for effectively harnessing solar energy, allowing for systematic observations and adjustments to optimize performance over time.

- **Input Current (I_{in})**: The current produced by the PV modules when exposed to sunlight.

$$I_{in} = \frac{P_{in}}{V_{in}} \tag{1}$$

Where P_{in} is the input power (in Watts) and V_{in} is the input voltage (in Volts).

- **Input Voltage of the PV System (V_{in})**: The voltage produced by the PV modules in the system configuration.

- **Input Power of the PV System (P_{in})**: The total power generated by the PV modules, calculated as the product of input voltage and input current.

$$P_{in} = \frac{V_{in}}{I_{in}} \tag{2}$$

- **Active Output Power of two connected batteries (P_battery):** The total output power from the two connected batteries operating in the system.

$$P_{battery} = V_{battery} \, . I_{battery} \tag{3}$$

Where $V_{battery}$ is the output voltage of the batteries, and $I_{battery}$ is the current drawn from the batteries.

- **Charging Current (I_{charge}):** The current flowing from the PV modules to charge the batteries.

$$I_{charge} = \frac{P_{in}}{V_{battery}} \tag{4}$$

- **Output Voltage (V_{output}):** The voltage delivered by the batteries to the load.

- **Maximum Power** (P_{MAX} or MPP): Refers to the optimal point at which the power generated by the array, connected to a load such as batteries or inverters, reaches its highest value. This can be expressed by the equation:

$$P_{max} = V_{max} \, . I_{max} \tag{5}$$

- **Output frequency (F_{out})**: The output frequency of an electrical system is typically determined by the inverter and is usually set to standard values of 50 Hz or 60 Hz.

To validate the effectiveness of the proposed approach, the following section focuses on its application to the case study presented in Section 3.4 (refer to Figure 8). This application utilizes the WatchPower software to evaluate real-time performance metrics.

3. Experimental validation and results

3.1 First experience

On June 19, 2023, we conducted a comprehensive performance monitoring of a solar energy system comprising four solar panels (Figure 8) over a full day, from 00:00 to 23:30, in Guelma, Algeria, where temperatures reached 32°C. The objective of this monitoring was to accurately track the energy production of the solar panels under optimal sunlight conditions. Throughout the monitoring period, we gathered detailed data that enabled us to analyze the system's efficiency and output in real time. The results from this experiment provide valuable insights into solar panel performance, including energy generation metrics, peak production times, and overall system effectiveness, all of which are outlined below. This data is crucial for understanding the operational capabilities of solar technologies in the region and for optimizing future installations.

According to Figures 9 and 10, the voltage begins to rise as the current starts flowing at 7:00 a.m. (as shown in Figure 10). The voltage remains elevated from 6:15 a.m. to 6:00 p.m. (refer to Figure 9). At 2:00 p.m., the voltage peaks at 43V (Voc = 46.4V), while the current reaches 20A (Isc = 23.38A). Additionally, input power peaks at 600W at this time, as illustrated in Figure 11. The solar panel system appears to be functioning effectively. The observed values for Vmax and Imax, along with their comparisons to Voc and Isc, indicate that the panel is operating within normal parameters. Specifically, the fact that Vmax (43V) is less than Voc (46.4V) and Imax (20A) is less than Isc (23.38A) suggests that the system is performing properly with no significant anomalies.

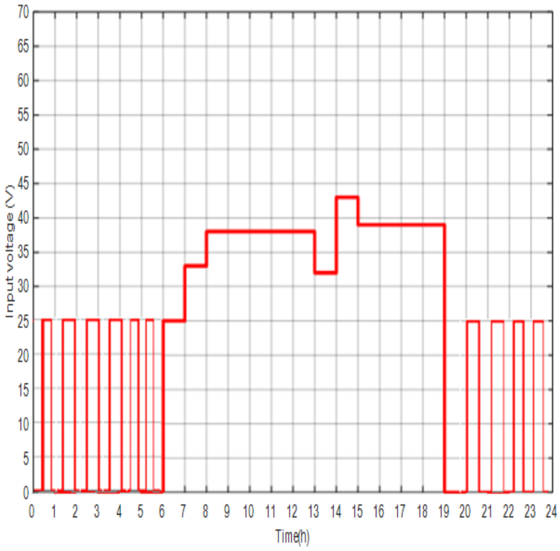

Figure 9 - Input voltage of the PV system

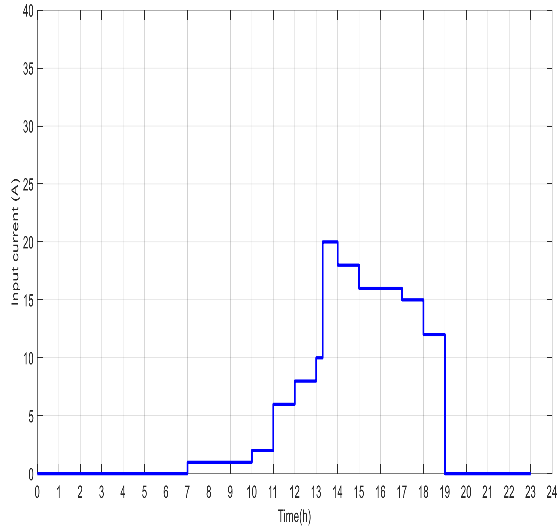

Figure 10 - Input current of the PV system

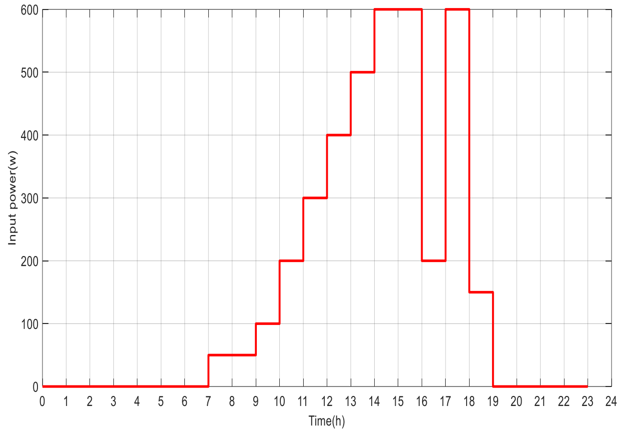

Figure 11 - Input power of the PV system

For the battery as shown in Figure 12, the capacity is at 100%, except during the periods of use of the receivers. The storage voltage is 25V, and it can reach up to 29V between 12H and 5 PM, which is when the illumination is optimal (Figure 13). Additionally, we can monitor the active power, as well as the charging and discharging currents of the battery using the Watch Power software.

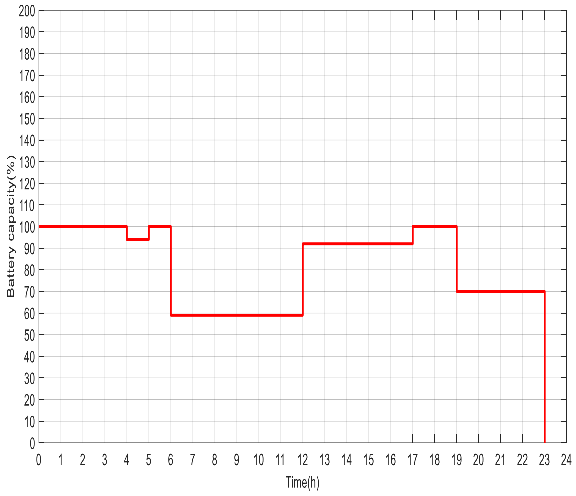

Figure 12. - Battery capacity

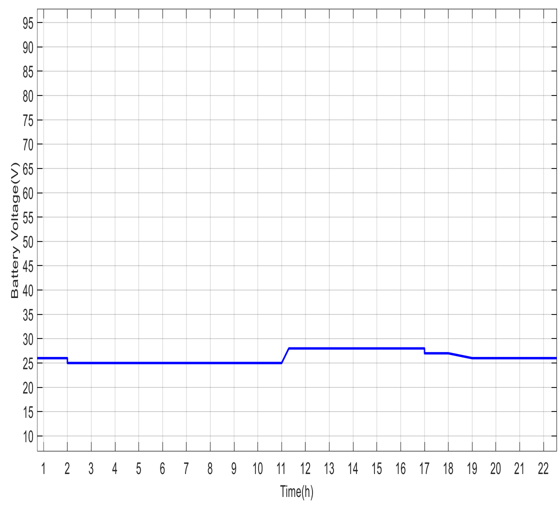

Figure 13 - Battery voltage

In Figure 14, the active output power illustrates the usable electrical power delivered by the photovoltaic (PV) installation to the electrical grid or local loads. This output is influenced by several factors, including the efficiency of the inverter, system losses, and the demand from connected devices. The graph shows how the active output power fluctuates throughout the day, highlighting peak generation times when sunlight is abundant, while also indicating periods of reduced output due to environmental conditions or shading events.

Figure 15 displays the charging current, which represents the flow of current into the battery during the charging phase. This current is directly influenced by the active power generated from the PV installation and the state of charge of the battery. An efficient charging process is crucial to ensure that the battery reaches its optimal capacity and performance.

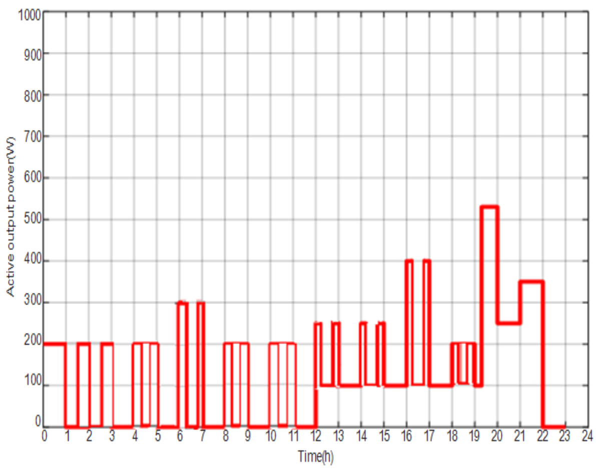

Figure 14 - Active output power

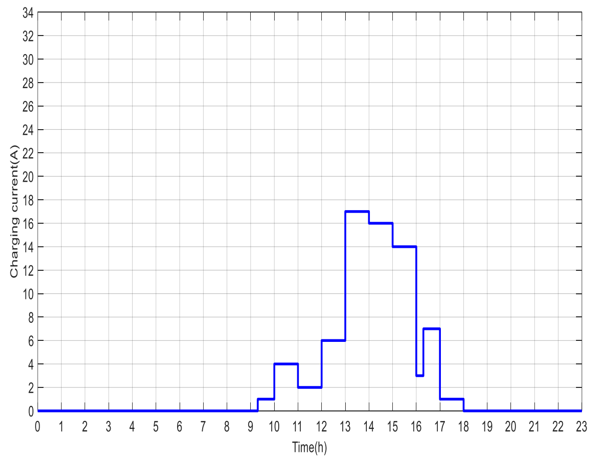

Figure 15 - Charging current

The battery discharging process involves releasing stored energy back into the system for use when the demand exceeds the power generated by the photovoltaic (PV) installation or when sunlight is not available. The discharge rate is crucial for maintaining a balance between energy supply and demand and must be carefully managed to prevent the battery from depleting too quickly.

Additionally, the results indicate that the photovoltaic system is performing within the expected operational parameters for voltage and frequency throughout the continuous 24-hour monitoring period. Below is a breakdown of Figures 16 and 17:

- **Output Voltage of 230V (Figure 16)**: A consistent output voltage of 230V suggests that the PV system effectively converts solar energy into electrical energy and delivers it at a stable voltage level. This voltage is standard in many regions, especially in areas that utilize similar voltage standards for residential and commercial electrical systems.

- **Frequency of 50 Hz (Figure 17)**: Maintaining a frequency of 50 Hz throughout this period indicates that the inverter within the PV system is functioning correctly. The inverter is responsible for converting the direct current (DC) generated by the solar panels into alternating current (AC), which is required for use in homes and for grid connection. A stable frequency is essential for synchronizing the output with the electrical grid and ensuring the safe and reliable operation of electrical appliances.

The continuous 24-hour monitoring period suggests that the system was observed throughout a typical day. The results indicate no fluctuations in output voltage or frequency, reflecting stable and reliable system performance.

These findings affirm the reliability and efficiency of the PV system, with the output voltage at 230V and the frequency at 50Hz serving as positive indicators of system health. This suggests that the system is well-designed and capable of operating effectively under the given conditions, which is crucial for both integration into the electrical grid and direct use with related electrical loads. Regular monitoring is vital for early diagnosis of potential issues and ensuring long-term operational efficiency.

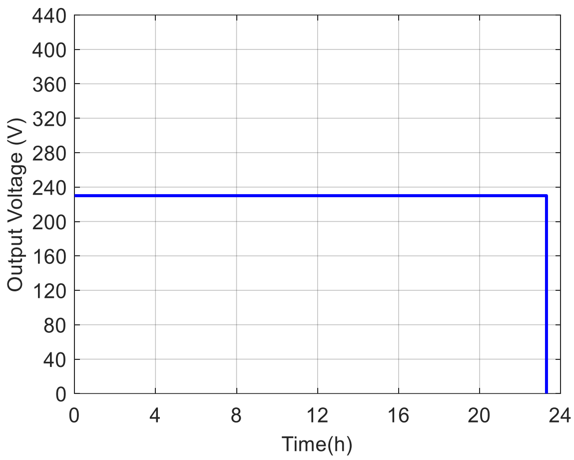

Figure 16 - Output voltage

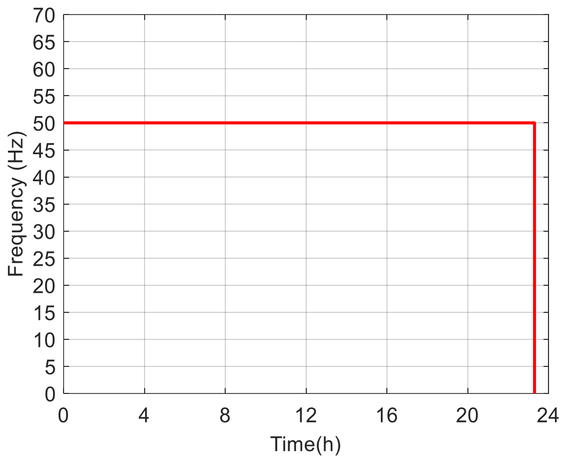

Figure 17 - Output frequency

3.2. Second experience

In our second experiment, we examined the impact of shading on the performance of the solar system by comparing data collected on a shaded day, May 14, 2023, at 25°C, with data from an unshaded day, June 21, 2023, at 32°C. This comparison focused on peak sunlight hours from 9:00 AM to 2:15 PM. We systematically monitored various parameters, including voltage, power, and current, to gain insights into how shading influences overall system efficiency.

3.2.1. Shading Defect

The curves produced during a time interval from 9:00 AM to 2:15 PM, indicate some fluctuations in electricity production, primarily due to shading effects that impact the solar panels efficiency. Notably, the peak voltage (V_{max}) recorded is 35V at 14H00 (refer to Figure 18), while the highest current (I_{max}) reaches 15A at 12:30 PM (Figure 19). This results in a maximum power output (P_{max}) of 450W, achieved at 12H, as shown in Figure 20.

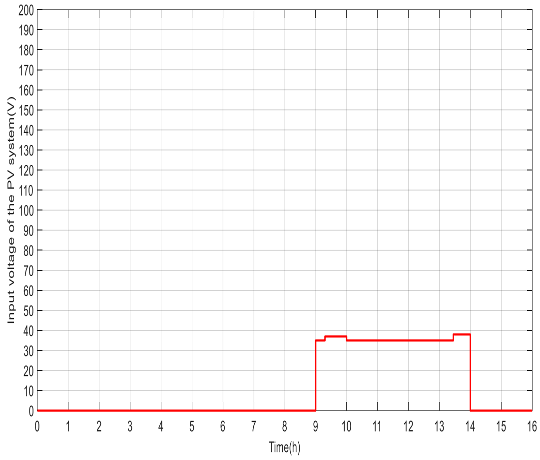

Figure 18 - Input voltage of the PV system

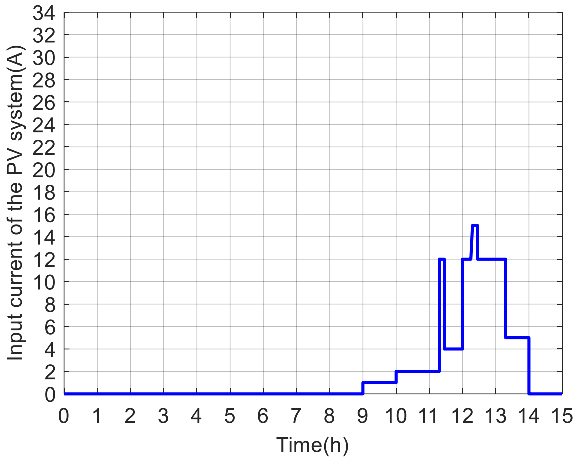

Figure 19 - Input current of the PV system

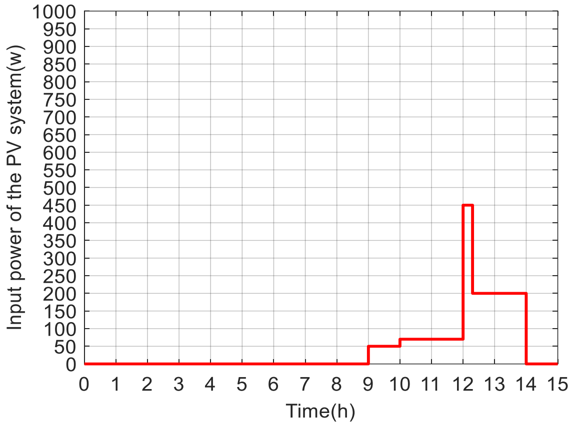

Figure 20 - Input power of the PV system

3.2.2. Normal day without defects

By analyzing the data collected under shaded conditions compared to optimal conditions, we aim to illustrate the adverse effects of shading on solar panel performance. This comparison deepens our understanding of the complexities associated with solar energy generation and is essential for enhancing the reliability and effectiveness of solar technologies. Our comprehensive analysis seeks to provide insights that can guide improved design and operational strategies for solar installations, particularly in areas susceptible to shading.

Description: The generated curves for the time interval from 9:00 AM to 2:15 PM demonstrate a significant increase in energy production from the solar panels, attributed to higher solar radiation levels and the absence of malfunctions that could hinder panel performance and power flow. The maximum voltage (Vmax) reaches 42V at 11:00 AM (Figure 21), the maximum current (Imax) is 20A at 2:00 PM (Figure 22), and the maximum power output (Pmax) peaks at 600W at 2:00 PM (Figure 23).

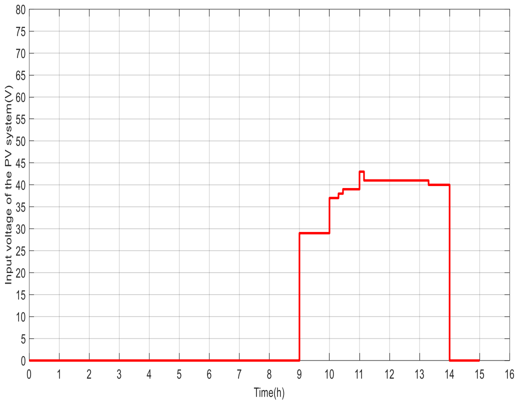

Figure 21 - Input voltage of the PV system

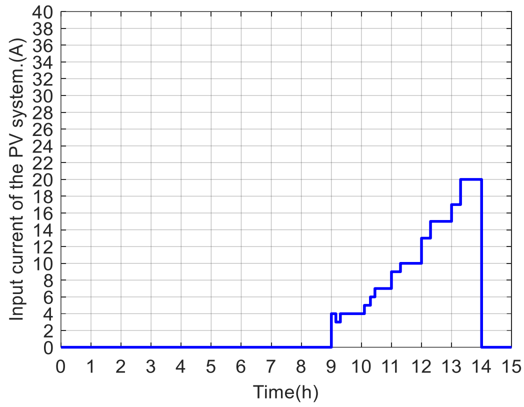

Figure 22 - Input current of the PV system

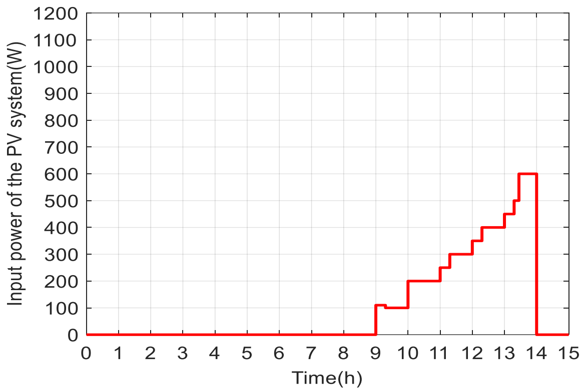

Figure 23 - Input power of the PV system

In this experiment, we investigated the performance of solar panels under conditions of shading from 9:00 AM to 2:15 PM. The results revealed significant differences in energy production between shaded and unshaded scenarios. During the shading defect conditions, fluctuations in electricity production were evident, with a peak voltage (Vmax) of 35V recorded at 2:00 PM, a maximum current (Imax) of 15A at 12:30 PM, and a peak power output (Pmax) of 450W at noon.

In contrast, the performance on a normal day without defects showed notable improvements, driven by optimal solar radiation and unobstructed panel functionality. On this day, the maximum voltage surged to 42V at 11:00 AM, the current peaked at 20A by 2:00 PM, and the power output reached an impressive 600W at the same time.

These findings underscore the detrimental impact of shading on the overall efficiency of solar panels, with the absence of defects directly correlating with enhanced energy production metrics. The analysis emphasizes the critical role of effective monitoring and diagnosis in optimizing photovoltaic (PV) system performance.

4. Discussion

The comparison between the normal day performance on June 21, 2023, and the Shaded Condition Performance (SCP) on May 14, 2023, reveals a significant degradation in performance due to shading (Figure 24). The maximum voltage decreased from 42V to 35V, reflecting a reduction of 7V (Figure 25). The maximum current also experienced a considerable decline, dropping from 20A to 15A, which corresponds to a decrease of 5A. Additionally, the maximum power output fell from 600W to 450W, representing a reduction of 150W (Figure 25). These results highlight the negative impacts of shading on solar energy systems and underscore the necessity of minimizing shading to optimize energy harvesting.

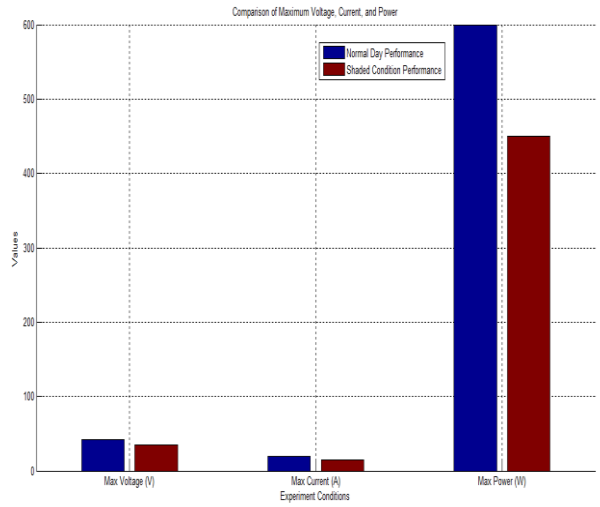

Figure 25 - Comparative performance analysis

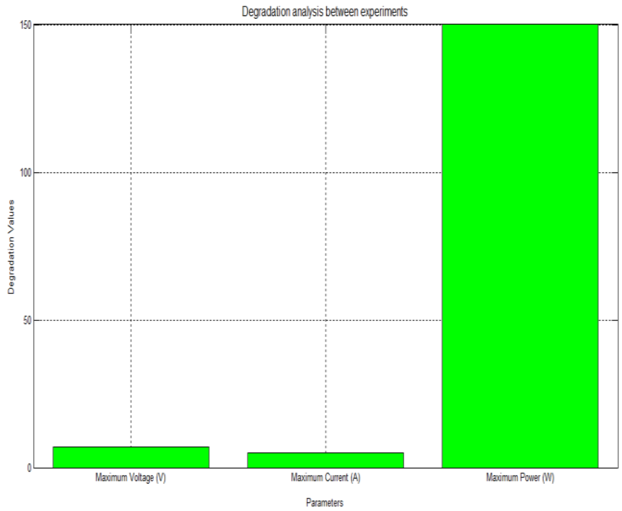

Figure 26 - Degradation analysis of the PVS across experiments

3.3. Discussion

The case study focused on the real-time tracking, monitoring, and diagnosis of faults in a photovoltaic system (PVS), effectively evaluating energy production across two distinct experiments. The first experiment, conducted on June 19, 2023, involved comprehensive data tracking, which revealed that the solar panel voltage and current peaked under optimal conditions, with the highest output power reaching 600W at 2 PM. A subsequent experiment on June 21, 2023, was carried out under the same climatic conditions (at a temperature of 32°C) during the time interval from 9:00 AM to 2:15 PM. This second experiment yielded consistent results, indicating remarkable convergence in panel productivity. The values for maximum voltage (Vmax), maximum current (Imax), and maximum power (Pmax) were aligned, demonstrating the system's reliability and efficiency, with no significant anomalies detected.

The capabilities of the WatchPower software enabled real-time monitoring of critical parameters, including active power, charging current, and battery discharging throughout the day. Notably, the battery maintained a full charge at 100% capacity during peak sunlight hours, while the output voltage was recorded at 230V with a frequency of 50Hz, indicating overall system health.

The second experiment focused on analyzing the impact of shading defects (anomaly detection) during the same time interval of 9:00 AM to 2:15 PM. This analysis revealed instability in energy production and reduced efficiency in the solar panels, as evidenced by significant drops in both maximum voltage and power output. Conversely, on a day without shading defects, the panels exhibited their full potential during the same time frame, reinforcing the effectiveness of the proposed approach in identifying performance issues.

Overall, these findings underscore the importance of regular monitoring to detect operational deviations and enhance long-term system efficiency. Collectively, the results highlight the efficacy of the proposed approach in advancing the tracking, monitoring, and diagnostic processes within the case study application, paving the way for informed decision-making and optimized operational strategies.

5. Conclusion

This study presents a comprehensive analysis of a photovoltaic system (PVS) through meticulous monitoring and diagnostic processes, aimed at optimizing solar energy production and understanding the impacts of environmental factors such as shading on performance. The experiments were conducted under varying environmental conditions, such as different levels of sunlight and shading, to evaluate the system's performance, providing valuable insights into its operational efficiency.

In the first experiment conducted on June 19, 2023, the solar panels achieved a maximum voltage (Vmax) of 42 V at 11:00 AM, a peak current (Imax) of 20 A at 2:00 PM, and a maximum power output (Pmax) of 600 W at the same time. The measurements were taken at specific times during the day. These values indicate the optimal performance of the system under ideal sunlight conditions, with the output voltage consistently maintaining a stable 230 V and a frequency of 50 Hz throughout the monitoring period.

The second experiment, conducted on May 14, 2023, focused on assessing the impact of shading defects and revealed significant performance degradation. Under shaded conditions, the maximum voltage dropped to 35 V, the current decreased to 15 A, and the maximum power output was reduced to 450 W. This decline represents a reduction of 7 V in voltage, 5 A in current, and a loss of 150 W in power output compared to the optimal unshaded conditions observed on June 21, 2024. The data underscores the detrimental effect of shading on solar energy systems, emphasizing the necessity of minimizing shading to enhance energy harvesting efficiency. Thus, under optimal conditions, the PVS operates efficiently, but suffers a significant drop in performance due to shading. Regular monitoring and analysis are crucial for identifying operational deviations and enhancing long-term system efficiency. The integration of the WatchPower software facilitated real-time insights into the system's health, ensuring effective management of energy production and battery charging. This study demonstrates the efficacy of systematic monitoring and diagnostics in photovoltaic systems, paving the way for informed decision-making and optimized operational strategies. These findings are crucial for enhancing the design and management of solar installations, especially in areas prone to shading.

Future work will focus on using the results obtained from the WatchPower software to create a comprehensive database for artificial intelligence applications, with the aim of developing automated diagnostic protocols and integrating machine learning algorithms to optimize photovoltaic (PV) system performance. This comprehensive database will serve to facilitate predictive maintenance and enhance the identification of potential faults, ultimately extending the lifespan of solar panel components. Moreover, expanding research to include diverse geographical locations and varying climatic conditions will provide deeper insights into PV system performance across different scenarios. In conclusion, the effective use of WatchPower for real-time tracking, monitoring, and fault diagnosis demonstrates its significant benefits, enabling the implementation of advanced AI-driven maintenance techniques that ensure optimal solar panel performance under fluctuating conditions while enhancing energy production, system reliability, and operational longevity.

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