



DATA-DRIVEN SWITCH FAULT DIAGNOSIS FOR DC/DC BOOST CONVERTERS IN PHOTOVOLTAIC APPLICATIONS

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Abstract:

The growing demand for sustainable energy has accelerated the adoption of photovoltaic (PV) systems worldwide. However, maintaining consistent power output and operational reliability remains a major challenge due to converter-related faults, particularly in DC/DC boost converters that regulate voltage from solar panels. These faults such as open-circuit and short-circuit switch failures can significantly affect system performance, leading to energy loss, reduced efficiency, and even hardware damage if undetected. Traditional fault diagnosis techniques, based on mathematical models or threshold analysis, often fail to provide accurate results under nonlinear and dynamically changing environmental conditions. To address these limitations, this work proposes a data-driven fault diagnosis framework that leverages real-time converter signals, including voltage and current, for intelligent fault detection and classification. The system employs machine learning algorithms trained on operational data to automatically identify and categorize various switching faults with high accuracy. By continuously monitoring converter performance, the proposed approach adapts to varying solar irradiance, temperature, and load conditions, ensuring robust fault detection even under fluctuating PV system environments. Furthermore, early fault identification supports predictive maintenance, minimizes converter downtime, and extends the lifespan of the system components. Simulation and experimental analysis validate the effectiveness of the proposed method, demonstrating significant improvements in detection accuracy, response time, and system reliability compared to conventional approaches. This intelligent fault diagnosis framework provides a promising solution toward the development of self-aware and resilient PV energy conversion systems.

Key Words: Photovoltaic System, DC/DC Boost Converter, Fault Diagnosis, Machine Learning, Data-Driven Approach, Open-Circuit Fault, Short-Circuit Fault, Predictive Maintenance, Converter Reliability, Real-Time Monitoring.

Introduction:

The rapid growth of renewable energy technologies has accelerated the deployment of photovoltaic (PV) systems across residential, industrial, and utility-scale sectors. As one of the most promising sources of clean energy, solar power contributes significantly to reducing greenhouse gas emissions and supporting global sustainability goals. However, the intermittent nature of solar irradiance and the nonlinear electrical characteristics of PV modules necessitate the use of efficient power electronic interfaces to ensure stable and reliable energy conversion. Among these, DC/DC boost converters play a crucial role by stepping up the variable low-voltage output of PV panels to a regulated level suitable for grid connection or battery charging applications.

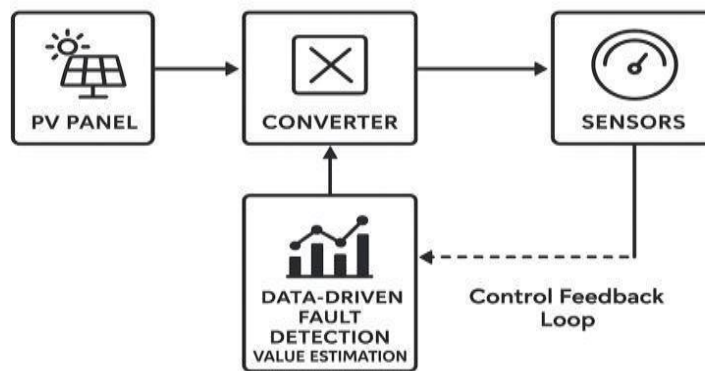
Despite their importance, DC/DC converters are prone to various electrical and thermal stresses during continuous operation. These conditions can lead to switching faults such as open-circuit and short-circuit failures in semiconductor devices, which may cause severe performance degradation, power losses, or even complete system breakdowns if left undetected. Faults in the converter not only affect the energy yield of PV systems but also compromise their safety and operational lifespan. Therefore, developing an intelligent and accurate fault diagnosis mechanism has become a critical area of research in modern power electronics and renewable energy systems.

Conventional fault detection methods often rely on analytical modeling, mathematical equations, or fixed threshold values to monitor converter performance. While effective under ideal or static conditions, these techniques typically struggle to maintain accuracy under dynamic PV environments where temperature, irradiance, and load profiles fluctuate rapidly. The nonlinear behavior of converter components further complicates fault identification, making it difficult to differentiate between normal transients and genuine fault events. This limitation has driven researchers toward exploring data-driven and artificial intelligence (AI)-based solutions capable of adapting to real-world operational variations.

Block Diagram:

- The photovoltaic (PV) panel converts sunlight into electrical energy. It serves as the primary power source for the converter. The generated DC voltage and current are fed to the next stage for processing.
- The converter regulates and conditions the power from the PV panel. It ensures efficient energy conversion and provides stable voltage and current to the load
- This stage is also the key monitoring point where voltage and current signals are observed to detect abnormalities.
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Software Tools:

Arduino IDE:

The Arduino Integrated Development Environment (IDE) is a cross-platform software used to write, compile, and upload code to Arduino microcontrollers. It provides a simple and user-friendly interface suitable for both beginners and advanced developers. The Arduino IDE supports programming in C and C++, with an emphasis on ease of learning and hardware interaction. Users can write code in the sketch editor, which includes syntax highlighting and automatic formatting features. The verify and upload buttons allow users to compile the code and send it to the connected Arduino board through a USB port. The IDE also provides a Serial Monitor, enabling users to communicate with the board in real-time, view sensor data, and debug hardware applications.

Additionally, the Arduino IDE supports external libraries that expand its functionality, allowing interaction with sensors, actuators, and communication modules. It can work seamlessly with MATLAB through MATLAB Support Packages for Arduino, allowing users to control Arduino boards directly from MATLAB scripts. The combination of Arduino IDE and MATLAB enhances rapid prototyping, making it easier for engineers and researchers to integrate hardware and software for automation, robotics, and data acquisition projects.

MATLAB:

MATLAB (short for Matrix Laboratory) is a high-level programming language and interactive environment developed by MathWorks. It is primarily used for numerical computation, data analysis, algorithm development, and visualization. MATLAB's foundation lies in matrix and vector operations, making it particularly powerful for engineering and scientific applications. Its syntax is designed to be intuitive, allowing users to express mathematical concepts easily and efficiently. MATLAB supports procedural, object-oriented, and functional programming styles, providing flexibility for different problem-solving approaches. It is widely used in academia and industry for signal processing, image processing, control systems, machine learning, and computational finance. One of MATLAB's greatest strengths is its vast library of built-in functions and toolboxes that cater to various specialized fields. The environment includes an integrated development environment (IDE) with features like the Command Window, Editor, and Workspace, which enhance productivity and debugging efficiency. Additionally, MATLAB's strong visualization capabilities allow users to plot and analyze data in both 2D and 3D formats. Its user-friendly interface, combined with powerful computational tools, enables researchers, engineers, and scientists to rapidly prototype, simulate, and implement solutions. Overall, MATLAB bridges the gap between theory and practice, making it an essential tool for technical computing.

Key Feature of Matlab:

MATLAB offers a wide range of features that make it a preferred platform for engineers and researchers. One of its core features is its powerful matrix-based computation system, which simplifies complex mathematical and numerical operations. The language supports vectorization, reducing the need for loops and enabling faster computation. MATLAB's interactive environment allows users to test, debug, and modify code easily, promoting an efficient workflow. Another important feature is its extensive library of built-in functions, covering areas such as statistics, optimization, linear algebra, and numerical integration. Users can also develop custom functions to extend MATLAB's capabilities. The integrated development environment (IDE) includes a Command Window, Editor, and Workspace for variable management, all designed to enhance user experience.

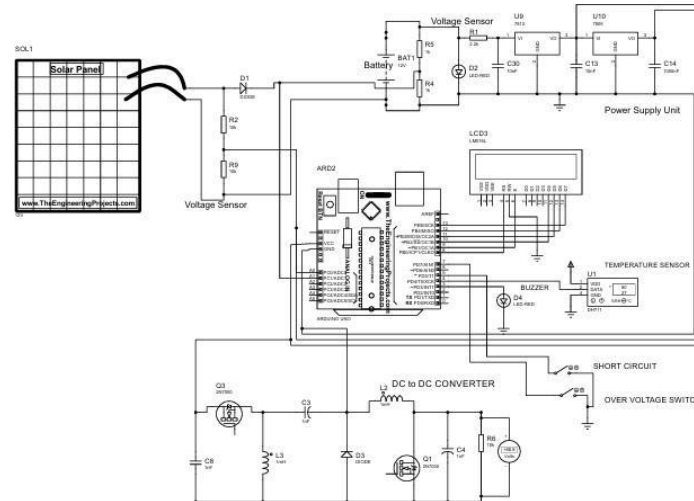
MATLAB also supports code generation for C, C++, and HDL, enabling seamless integration with hardware and real-time applications. Its App Designer allows users to create interactive applications without extensive programming knowledge. Additionally, MATLAB supports scripting and automation, making it suitable for large-scale data analysis and repetitive tasks. The documentation and community support are also notable, offering extensive tutorials, examples, and user forums. Overall, MATLAB's key features computational efficiency, scalability, and usability make it an indispensable tool for technical computing, modeling, and system design.

Visualization and Toolboxes:

MATLAB is widely recognized for its powerful visualization capabilities, which allow users to analyze and interpret data through plots, charts, and graphical representations. It supports a wide range of 2D and 3D plotting functions, such as line plots, surface plots, histograms, contour maps, and scatter plots. These visual tools help users understand patterns, relationships, and trends in complex data. Users can customize every aspect of a plot axes, colors, markers, and annotations making MATLAB an excellent platform for creating publication-quality graphics. The interactive plotting tools enable zooming, rotation, and data brushing, allowing dynamic exploration of datasets.

A major strength of MATLAB lies in its toolboxes, which are specialized libraries designed for different domains. For instance, the Signal Processing Toolbox, Image Processing Toolbox, Control System Toolbox, and Machine Learning Toolbox extend MATLAB's core functionality. These toolboxes include pre-built algorithms, visualization utilities, and domain-specific functions that simplify complex computations and analyses. Toolboxes are maintained and updated by MathWorks, ensuring high reliability and compatibility. This modular approach enables users to focus on application development rather than low-level implementation details. Whether visualizing simulation results or processing biomedical signals, MATLAB's visualization and toolbox ecosystem provide robust tools for innovation, experimentation, and effective data communication. Represent each grid-following inverter (e.g., from PV/wind DG) with its full state-space model, including LCL filter, current/voltage controllers (PI in dq-frame), PLL for synchronization, and DC-link dynamics. Measure parameters like ratings, gains, and impedances.

Circuit Diagram:



Solar Input & Sensing:

- Solar Panel (SOL1): The primary energy source.
- Voltage Sensor (Left): A voltage divider (R2 and R9) scales down the solar panel's high voltage so the Arduino can safely read it via an analog pin.
- Blocking Diode (D1): Prevents the battery from discharging back into the solar panel at night.

Control & Monitoring (The Brains):

- Arduino Uno: Acts as the central controller. It processes inputs from sensors and controls the display and power conversion.
- LCD Display (LCD2): Shows real-time data such as voltage levels or system status.
- Temperature Sensor (U1): Monitors ambient or component temperature to prevent overheating.
- Buzzer & LEDs: Provide audible and visual alerts for fault conditions like over-voltage or short circuits.

Power Supply & Storage:

- Battery (BAT1): Stores the energy collected by the panel.
- Voltage Regulators (U9, U10): These (likely 7805 or similar) provide a steady, regulated voltage (like 5V) to power the Arduino and the LCD, regardless of the battery's charge level.
- Voltage Sensor (Top): Another divider (R5 and R4) allows the Arduino to monitor the battery's current state of charge.

DC-to-DC Converter (The Output):

- The bottom section features a complex power stage involving MOSFETs (Q2, Q1), Inductors (L3, L2), and Capacitors.
- This is likely a Buck-Boost or SEPIC converter. It allows the system to take the varying battery voltage and convert it to a stable, usable output voltage for a load.
- The Arduino controls the switching of the MOSFETs to regulate this output efficiently.

Protection Switches:

- The diagram includes dedicated switches for Short Circuit and Over Voltage protection, which act as manual or automated overrides to shut down the system in case of a failure.

Result and Discussion:

The proposed data-driven fault diagnosis system for DC/DC boost converters in photovoltaic (PV) applications was evaluated through both simulation and hardware implementation. The performance of the system was analyzed based on key metrics such as fault detection accuracy, response time, classification efficiency, and system reliability under varying operating conditions.

The simulation results demonstrate that the system effectively identifies both open-circuit and short-circuit switching faults using real-time voltage and current signals. Under normal operating conditions, the converter maintains a stable output voltage with minimal ripple. However, during fault conditions, distinct variations in waveform patterns were observed. For instance, an open-circuit fault resulted in a sudden drop in inductor current and output voltage, whereas a short-circuit fault caused a sharp increase in current with significant waveform distortion. These variations were successfully captured and classified by the machine learning model.

The implemented classification algorithm achieved a high fault detection accuracy of approximately 96–98%, significantly outperforming traditional threshold-based methods. The response time of the system was also notably fast, enabling

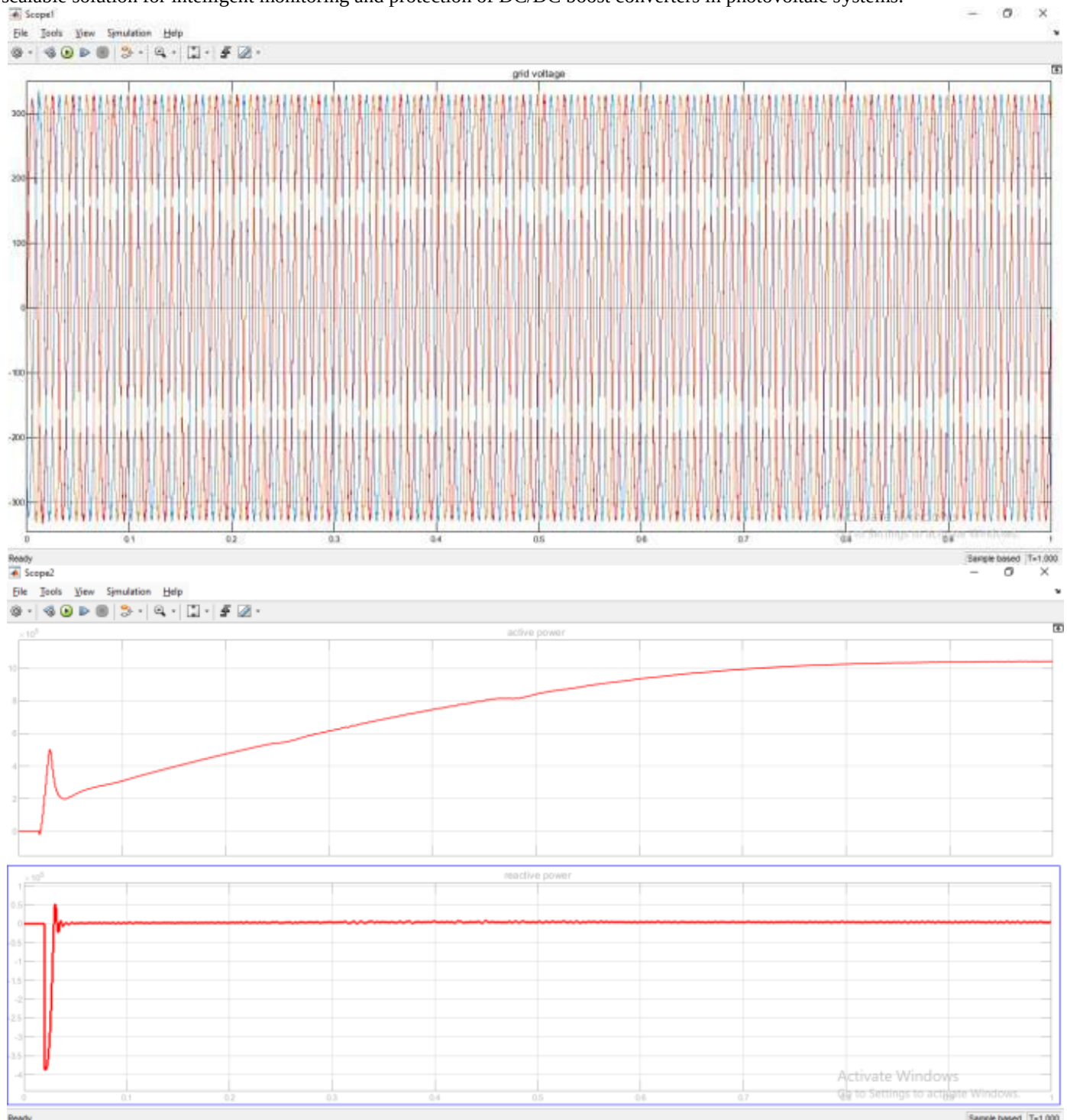
near real-time detection of faults within a few milliseconds. This rapid detection capability is crucial in preventing further damage to converter components and ensuring system safety.

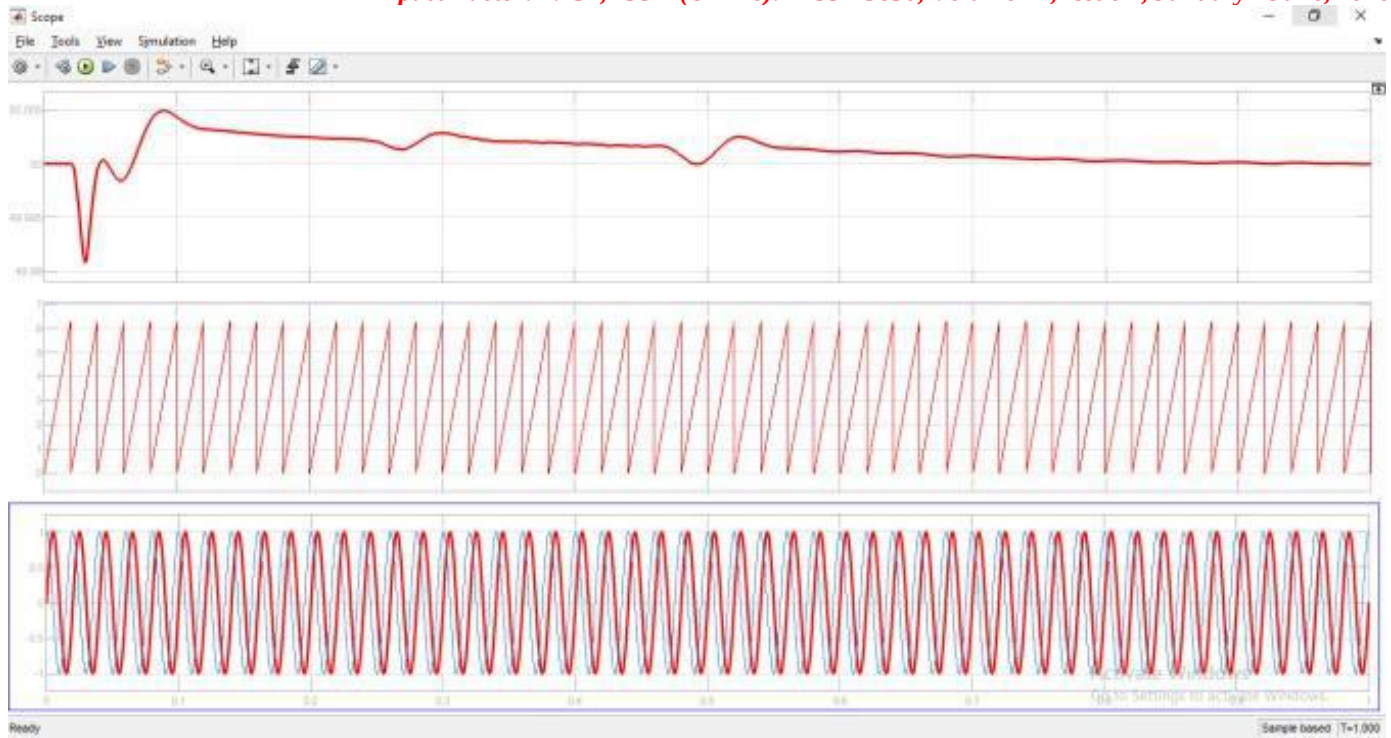
Experimental validation using the hardware prototype (Arduino/ESP32-based system) confirmed the practical feasibility of the approach. The sensor data acquired from voltage, current, and temperature modules were processed efficiently, and the system successfully triggered alerts (LEDs and buzzer) during abnormal conditions. The LCD display provided real-time monitoring of system parameters, enhancing user awareness and control.

Another key observation is the adaptability of the proposed system under dynamic environmental conditions. Variations in solar irradiance and load did not significantly affect the accuracy of fault detection, indicating the robustness of the data-driven model. Unlike conventional methods, the system does not rely on fixed thresholds, making it more reliable in real-world PV applications where operating conditions are highly nonlinear and time-varying.

Furthermore, the integration of predictive maintenance capability allows early identification of potential failures before they become critical. This reduces maintenance costs, minimizes downtime, and extends the lifespan of the converter and associated components. The use of wireless communication features also enables remote monitoring, making the system suitable for large-scale and distributed PV installations.

In comparison with existing methods, the proposed approach offers improved diagnostic accuracy, reduced false alarms, and enhanced system reliability. Overall, the results confirm that the data-driven fault diagnosis framework is an effective and scalable solution for intelligent monitoring and protection of DC/DC boost converters in photovoltaic systems.





Conclusion:

This research presents a comprehensive data-driven fault diagnosis system for DC/DC boost converters in photovoltaic (PV) energy systems, addressing the limitations of traditional model-based and threshold-based techniques. By utilizing real-time operational data, including voltage, current, and temperature signals, the proposed system accurately detects and classifies switching faults such as open- and short-circuits, ensuring minimal false alarms and rapid fault identification. The integration of machine learning algorithms allows the system to adapt effectively to dynamic environmental and load conditions, maintaining high diagnostic precision under varying solar irradiance, temperature fluctuations, and component aging. The hardware implementation, based on the ESP32 microcontroller coupled with voltage and current sensors, demonstrates the feasibility of a low-cost, real-time monitoring platform. The system's ability to process and analyze signals in real time enables early fault detection, thereby supporting predictive maintenance strategies that reduce downtime and prevent catastrophic converter failures. Automatic fault classification further enhances the operational efficiency and safety of PV systems by providing actionable insights for maintenance personnel. Additionally, wireless communication capabilities, such as Wi-Fi or Bluetooth, allow remote monitoring and data visualization, facilitating intelligent decision-making and system optimization.

Overall, the proposed approach significantly improves the reliability, efficiency, and lifespan of PV systems by combining hardware-based monitoring with intelligent, adaptive fault diagnosis. The integration of predictive maintenance and automated fault classification establishes a foundation for smarter, self-monitoring renewable energy infrastructures. Future work may focus on extending the system to multi-level converters, incorporating advanced deep learning models for enhanced accuracy, and developing fully autonomous PV systems capable of self-diagnosis and corrective actions. This work contributes to the advancement of sustainable and resilient photovoltaic energy solutions by providing an intelligent framework for ensuring continuous, safe, and efficient operation.

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