

Intelligent Solar PV System for Real-Time Fault Detection and Mitigation using MPPT

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Abstract- Solar photovoltaic (PV) systems are widely used for renewable energy generation, but their performance is highly affected by faults such as partial shading, hotspot formation, open-circuit faults, and temperature variations. These faults reduce energy efficiency and may damage PV modules if not detected early. This paper presents a smart solar PV system integrated with real-time fault detection and Maximum Power Point Tracking (MPPT) optimization using MATLAB/Simulink. The proposed system continuously monitors voltage, current, and temperature parameters to identify abnormal operating conditions through a fault diagnosis algorithm. Once a fault is detected, mitigation techniques such as MPPT duty-cycle adjustment, fault isolation, and protection control are activated automatically. The simulation results demonstrate that the proposed methodology effectively detects faults, improves power extraction efficiency, reduces power losses, and enhances system reliability. The developed approach provides a cost-effective and efficient solution for advanced solar energy applications.

Keywords: Solar PV System, Fault Detection, MPPT, MATLAB/Simulink, Renewable Energy.

I. INTRODUCTION

The continuous growth in global population, industrial development, urbanization, and technological advancement has drastically increased the worldwide demand for electrical energy. Conventional energy resources such as coal, petroleum, and natural gas are becoming depleted due to excessive utilization and are also responsible for severe environmental pollution, greenhouse gas emissions, and global warming. Therefore, renewable energy technologies have emerged as an effective solution for achieving sustainable energy generation while reducing environmental impacts. Among all renewable energy resources, solar photovoltaic (PV) systems have gained significant attention because solar energy is abundantly available, environmentally friendly, pollution-free, and economically feasible for long-term operation. Solar PV systems directly convert solar radiation into electrical energy using semiconductor photovoltaic

cells. Due to advancements in PV technology, solar power systems are now widely implemented in residential buildings, industrial sectors, agricultural fields, smart cities, electric vehicle charging stations, and remote rural electrification applications.

The performance of photovoltaic (PV) systems is highly affected by environmental conditions and electrical faults. Variations in irradiance, temperature, shading, dust accumulation, and module aging can reduce system efficiency. In addition, faults such as open-circuit faults, short-circuit faults, hotspot formation, and sensor failures may cause serious damage to PV modules and connected components. Conventional PV systems mainly depend on manual inspection and periodic maintenance, which are not suitable for real-time fault identification. Delayed fault detection increases power loss, reduces reliability, and raises maintenance costs. Therefore, intelligent monitoring and control techniques are required for continuous system supervision. Recent advancements in smart sensors, embedded systems, and digital control technologies have enabled the development of advanced PV monitoring systems capable of automatic fault detection and protection.

Maximum Power Point Tracking (MPPT) is one of the most important control techniques used in solar PV systems. The purpose of MPPT is to ensure that the PV array always operates at the maximum power point under varying environmental conditions. Since solar irradiance and temperature continuously change throughout the day, the operating point of the PV array also changes dynamically. MPPT algorithms continuously adjust the operating voltage and current to maximize energy extraction. In this proposed work, a smart solar photovoltaic system integrated with real-time fault detection and mitigation using MPPT optimization is developed and analyzed using MATLAB/Simulink. The proposed system continuously monitors voltage, current, and temperature parameters of the PV array using intelligent sensors and compares them with predefined operating conditions. Whenever

abnormal conditions are identified, the system automatically activates mitigation mechanisms such as duty-cycle adjustment, protection switching, and load isolation. The proposed methodology improves system reliability, enhances energy conversion efficiency, minimizes power losses, and increases operational safety. The developed model also demonstrates the capability of integrating intelligent fault detection with MPPT-based power optimization for future smart renewable energy systems.

II. MAIN AIM OF THE PROPOSED WORK

To design a smart solar PV system capable of real-time monitoring. To detect faults such as partial shading, hotspot formation, and electrical disconnections. To implement MPPT optimization for maximum power extraction.

III. LITERATURE SURVEY

The increasing demand for renewable energy has encouraged extensive research in photovoltaic (PV) systems, especially in monitoring, fault detection, and power optimization. Earlier PV systems mainly depended on manual inspection and periodic maintenance, which were not effective for detecting faults at an early stage. To improve system monitoring, sensor-based techniques were introduced for measuring voltage, current, irradiance, and temperature in real time. However, detecting faults such as partial shading, hotspot conditions, and connection failures remained difficult under changing environmental conditions. To improve energy extraction efficiency, Maximum Power Point Tracking (MPPT) techniques such as Perturb and Observe (P&O) and Incremental Conductance (INC) were widely adopted in photovoltaic systems. Recent developments in artificial intelligence, machine learning, fuzzy logic, and IoT-based monitoring have further enhanced PV system performance by enabling faster fault detection and adaptive control. In this work, an integrated photovoltaic control framework is proposed by combining real-time monitoring, intelligent fault diagnosis, automatic protection, and MPPT optimization. The proposed system aims to improve operational reliability, reduce power losses, and enhance overall energy conversion efficiency in modern photovoltaic applications.

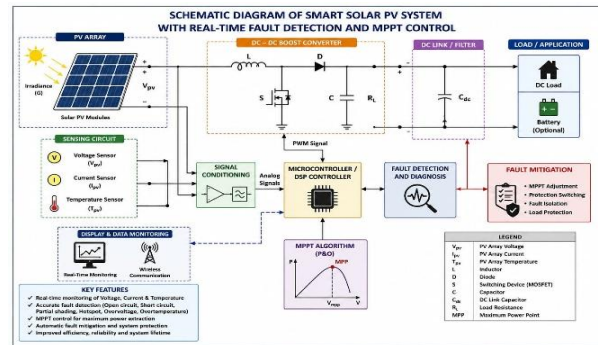


Fig.1. Schematic diagram of Smart Solar PV system

IV. PROPOSED SYSTEM ARCHITECTURE AND WORKING PRINCIPLE

The proposed smart photovoltaic (PV) system combines real-time monitoring, fault detection, MPPT optimization, and protection mechanisms within a single framework. As shown in Fig. 1, the system includes a PV array, sensors, MPPT controller, DC–DC boost converter, fault detection unit, and load system. The sensors continuously monitor voltage, current, and temperature parameters for stable operation. The measured data are analysed in the MATLAB/Simulink environment to identify abnormal conditions such as partial shading, hotspot formation, open-circuit faults, and short-circuit faults. The integrated control and protection system reduces power loss, improves operational safety, and enhances overall PV system reliability.

As represented in Fig. 1, the MPPT controller is connected with the DC–DC boost converter to maximize power extraction from the PV array. In this work, the Perturb and Observe (P&O) algorithm is employed because of its simple structure and reliable tracking capability. The controller continuously evaluates variations in voltage and current to calculate output power and accordingly adjusts the converter duty cycle to operate near the maximum power point under changing environmental conditions. When fault conditions are detected, the protection unit initiates corrective actions such as fault isolation, load protection, and maintenance alert generation. Simultaneously, the boost converter maintains stable voltage delivery to the connected load system despite fluctuations in PV output. Therefore, the proposed system combines intelligent sensing, fault diagnosis, MPPT optimization, and protection strategies into a single framework for improving reliability, operational safety, and energy conversion efficiency of photovoltaic systems.

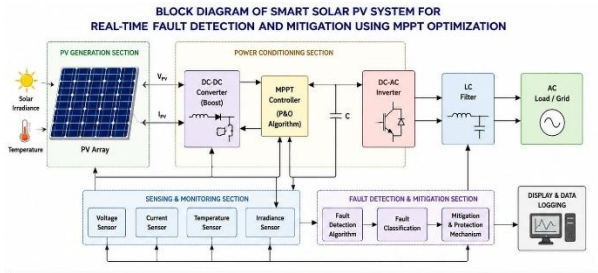


Fig.2. Proposed System Block Diagram

V. DETAILED OPERATIONAL ANALYSIS OF THE PROPOSED SYSTEM

The proposed smart photovoltaic system is designed to improve power extraction efficiency and provide reliable fault protection under changing environmental conditions. Since the electrical characteristics of a PV array vary with irradiance, temperature, and shading effects, the system uses intelligent monitoring and automatic control for stable operation. Voltage, current, irradiance, and temperature parameters are continuously monitored and processed in the MATLAB/Simulink environment for real-time condition analysis. As illustrated in Fig. 2, the proposed system integrates sensing units, a fault detection module, MPPT controller, DC–DC boost converter, and protection mechanism within a single framework. The MPPT controller continuously tracks the maximum power point, while the boost converter maintains stable voltage delivery to the load. During abnormal conditions such as partial shading, hotspot formation, open-circuit faults, or short-circuit faults, the control system identifies the fault using threshold analysis and activates corrective actions to reduce power loss and protect the PV system. Overall, the proposed methodology improves system reliability, operational safety, and energy conversion efficiency.

VI. MATHEMATICAL MODELING OF PV SYSTEM

The output current of the PV cell is represented by:

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V+IR_s}{R_{sh}}$$

Where:

- I = Output current
- I_{ph} = Photo-generated current
- I_0 = Reverse saturation current
- q = Electron charge
- V = Output voltage
- R_s = Series resistance
- R_{sh} = Shunt resistance
- k = Boltzmann constant
- T = Temperature in Kelvin
- n = Diode ideality factor

The output power is calculated as:

$$P = V \times I$$

The efficiency of the PV system is given by:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

VII. MPPT Algorithm

Maximum Power Point Tracking (MPPT) is used to maximize the energy extraction from the PV array. In this project, the Perturb and Observe (P&O) method is implemented due to its simplicity and effectiveness.

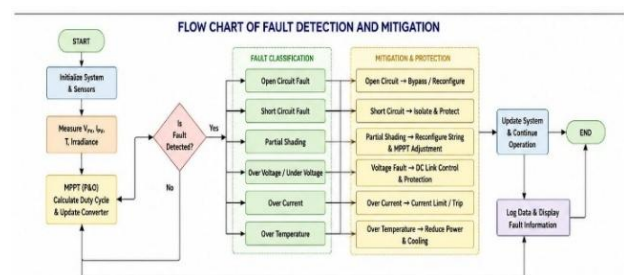


Fig.3. MPPT Flowchart

Maximum Power Point Tracking (MPPT) is used in photovoltaic systems to improve energy extraction efficiency under varying irradiance and temperature conditions. In the proposed system, the Perturb and Observe (P&O) algorithm continuously measures PV

voltage and current, calculates output power, and adjusts the operating point to maintain maximum power generation. As illustrated in Fig. 3, the MPPT flowchart explains the sensing, power calculation, comparison, and duty cycle adjustment processes. The DC–DC boost converter, controlled through PWM signals generated by the MPPT controller, increases the PV output voltage and maintains stable power delivery to the load while reducing power loss and improving overall system performance.

VII-A. DETAILED ANALYSIS OF MPPT CONTROL STRATEGY

Maximum Power Point Tracking (MPPT) is used in photovoltaic systems to improve power extraction efficiency. Since the output of a PV array changes with irradiance and temperature, the operating point must be adjusted continuously to obtain maximum power. In the proposed system, the Perturb and Observe (P&O) algorithm is selected because of its simple structure and reliable performance. The P&O algorithm continuously measures PV voltage and current and calculates output power using:

$$P = VI$$

If the power increases after perturbation, the controller continues in the same direction; otherwise, the perturbation direction is reversed. As shown in Fig. 3, the MPPT flowchart explains the process of sensing, power calculation, comparison, and duty cycle adjustment. The DC–DC boost converter increases the PV output voltage to the required level for the load. PWM signals generated by the MPPT controller regulate the converter operation. The implemented strategy improves power extraction efficiency, reduces power loss, and maintains stable system operation under varying environmental conditions.

VIII. FAULT DETECTION METHODOLOGY

The proposed fault detection methodology uses real-time sensor monitoring and threshold-based analysis.

Types of Faults Considered

A. Partial Shading Fault

Partial shading occurs when sunlight is blocked on some PV modules due to clouds, buildings, or dust. The effect shown by reducing power

B. Hotspot Fault

Hotspots are formed due to localized heating caused by damaged or shaded cells. Effect will be on lifespan of it

C. Open Circuit and Short Circuit Faults

This fault occurs when electrical connections are disconnected. This occurs due to unintended low resistance connections. The effects will happen a Excessive current flow and Component overheating. The effects will be sudden rise in Temperature

VIII-A. REAL-TIME FAULT DIAGNOSIS PROCESS

The proposed real-time fault diagnosis system continuously monitors the photovoltaic array using voltage, current, and temperature sensors. The measured values are transferred to the MATLAB/Simulink control unit, where they are compared with predefined operating limits. If any abnormal variation occurs, the system identifies it as a fault condition and activates the required protection mechanism. The diagnosis process includes data collection, signal analysis, fault identification, and corrective action for maintaining stable system operation. As shown in Fig. 4, partial shading faults reduce the output power because different PV modules receive unequal sunlight. Fig. 5 illustrates hotspot faults, where excessive localized temperature rise may damage the PV panel. Similarly, Fig. 6 represents open-circuit and short-circuit faults. Open-circuit faults interrupt current flow and reduce power delivery, while short-circuit faults generate excessive current and rapid heating. The proposed fault diagnosis method enables fast fault detection, improves system safety, reduces maintenance effort, and enhances the overall reliability of the photovoltaic system.

IX. FAULT MITIGATION TECHNIQUES

The proposed smart photovoltaic system was modelled and simulated using MATLAB/Simulink to evaluate its performance under different environmental and fault conditions. Simulation studies were carried out for normal operation, partial shading, temperature variation, open-circuit faults, and short-circuit faults to analyse the effectiveness of the real-time fault detection and MPPT optimization techniques. The obtained results demonstrate that the proposed system can detect abnormal conditions, maintain stable operation, and reduce power losses under varying operating conditions.

IX-A. PROTECTION AND SAFETY MECHANISMS

Protection mechanisms are essential for improving the reliability and safety of photovoltaic systems because electrical and thermal faults can damage PV modules, converters, and connected loads. The proposed system uses intelligent protection strategies to identify abnormal operating conditions and activate suitable corrective actions. During short-circuit faults, the faulty section is isolated to prevent excessive current flow, while open-circuit conditions trigger maintenance alerts and system protection. The temperature monitoring unit also detects

overheating and activates protective switching to avoid thermal damage. In addition, load protection mechanisms disconnect sensitive loads during severe fault conditions. These integrated protection features improve operational safety, reduce equipment damage, and enhance the overall reliability of the photovoltaic system.

X. MATLAB/Simulink Model

The complete system is modeled and simulated in MATLAB/Simulink. The simulation includes: a Solar PV array model, an Irradiance input, a Temperature variation, an MPPT controller, a Boost converter, a Fault simulation blocks and Scope analysis

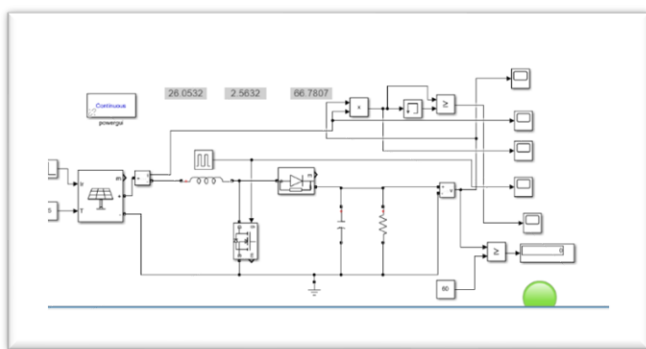


Fig.4. MATLAB/Simulink Model Description

XI. SIMULATION RESULTS AND DISCUSSION

The proposed smart photovoltaic system was modelled and simulated using MATLAB/Simulink to evaluate its performance under different environmental and fault conditions. Simulation studies were carried out for normal operation, partial shading, temperature variation, open-circuit faults, and short-circuit faults to analyse the effectiveness of the real-time fault detection and MPPT optimization techniques. The obtained results demonstrate that the proposed system can detect abnormal conditions, maintain stable operation, and reduce power losses under varying operating conditions.

Case 1: Normal Operating Condition

Under standard operating conditions with irradiance of 1000 W/m^2 and temperature of 25°C , the photovoltaic array produced stable voltage and current outputs, as shown in Fig. 7.1 and Fig. 7.2. The MPPT controller continuously tracked the maximum power point, and the corresponding power output shown in Fig. 7.3 confirmed efficient boost converter operation. The simulation results demonstrated stable system performance, effective power extraction, and high conversion efficiency without any abnormal fault conditions.

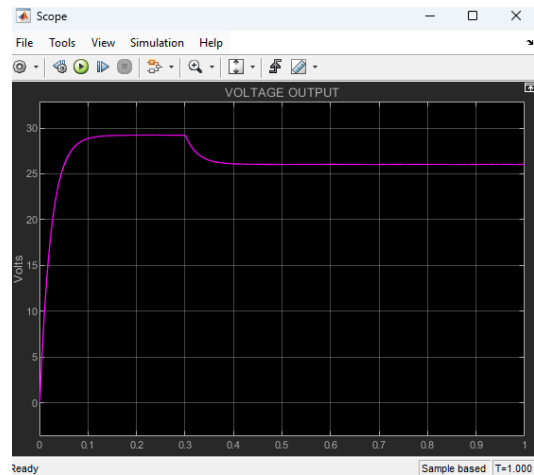


Fig.5.Voltage Output Waveforms

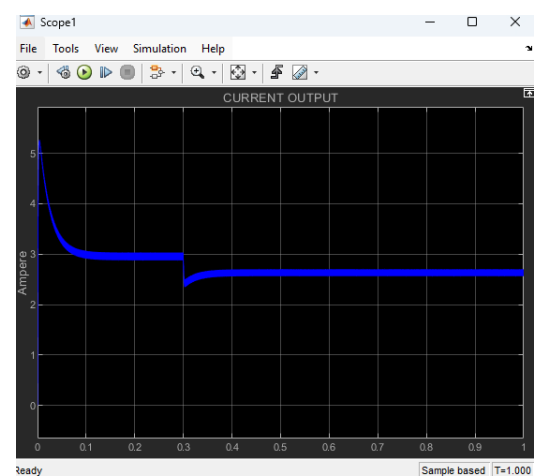


Fig.6.Current Output Waveforms

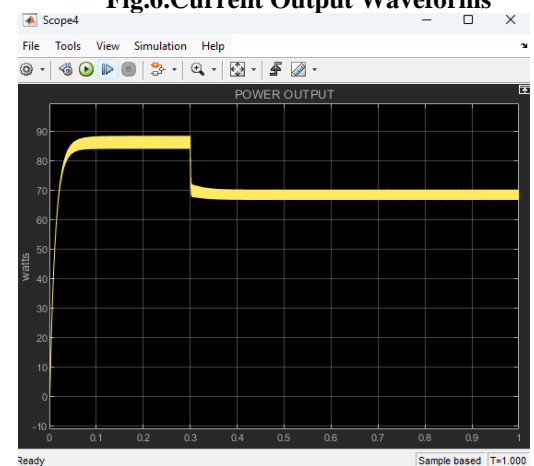


Fig.7.Power Output Waveform

Case 2: Partial Shading Condition

Partial shading conditions were simulated by reducing the irradiance on selected PV modules to represent practical conditions such as cloud movement, dust accumulation, or shadow effects. Under this condition, the PV array exhibited voltage fluctuations and multiple peaks in the power characteristics, resulting in reduced output power. As illustrated in Fig. 8, the proposed fault detection algorithm rapidly identified abnormal variations in

electrical parameters, while the MPPT controller adjusted the converter duty cycle to track the global maximum power point. The simulation results confirmed improved power recovery, reduced energy loss, and stable system performance during partial shading conditions.

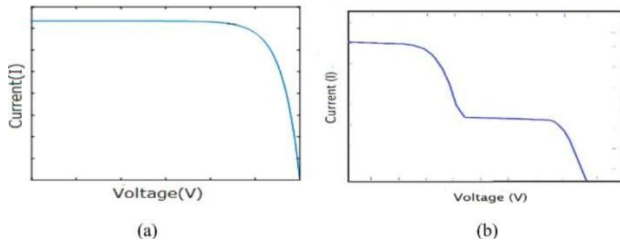


Fig.8.Output Waveforms in partial shading condition

Case 3: Temperature Rise Condition

The temperature rise condition was analysed by gradually increasing the operating temperature of the photovoltaic panel. As the temperature increased, the output voltage and overall conversion efficiency of the PV system decreased because of semiconductor behaviour and increased thermal stress. The temperature sensor continuously monitored the panel condition and transmitted real-time data to the control unit. As shown in Fig. 9, the proposed protection mechanism automatically detected overheating conditions and initiated corrective action to maintain stable operation and prevent further thermal damage to the PV modules.

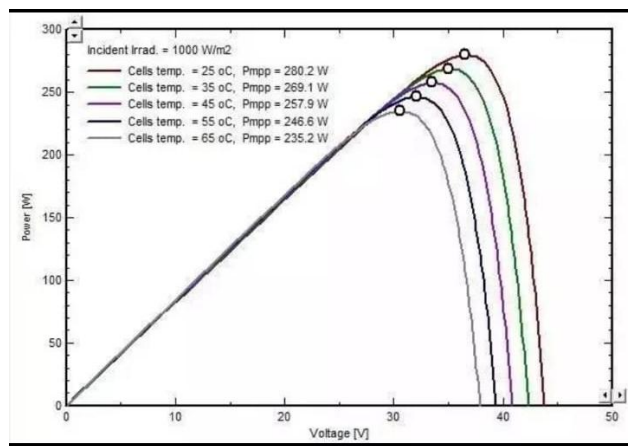


Fig.9.Output Waveforms for Temperature rise condition

Case 4: Open Circuit and Short Circuit Fault Conditions

The open-circuit fault condition was simulated by disconnecting an electrical path within the PV array to represent faults caused by damaged cables, broken connections, or component failures. During this condition, the output current reduced drastically while the voltage increased abnormally, interrupting normal power transfer. The proposed fault diagnosis system rapidly identified the abnormal condition, isolated the faulty section, and

generated maintenance alerts to prevent further system damage and improve operational reliability.

The short-circuit fault condition was created by introducing a low-resistance path in the photovoltaic system. This resulted in excessive current flow and rapid temperature rise within the electrical components, increasing the risk of converter and load damage. As shown in Fig. 10, the current sensor immediately detected the abnormal current variation, and the protection mechanism activated automatic switching to disconnect the faulty section. The simulation results confirmed effective fault isolation, improved system safety, and stable protection performance under both fault conditions.

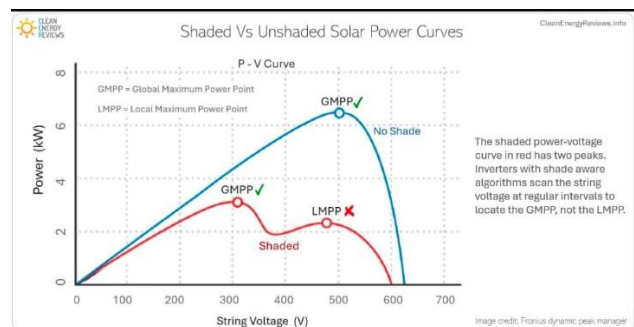


Fig.10.Output waveforms for Short-circuit and Long-circuit

Overall Performance Analysis

The overall simulation analysis confirms that the proposed smart solar PV system effectively detects and mitigates different fault conditions while maintaining efficient power generation. The integration of MPPT optimization with intelligent fault diagnosis significantly improves system reliability, operational safety, and energy extraction capability. Compared with traditional monitoring systems, the proposed method provides faster fault response, reduced power loss, and improved stability under varying environmental conditions. The MATLAB/Simulink results validate the practical feasibility of implementing the proposed methodology in real-world solar energy systems.

XI-A. PARAMETERS GIVEN TO THE SIMULATION.

PV System Parameters

S. No	Parameter	Value
1	Open Circuit Voltage (Voc)	21 V
2	Short Circuit Current (Isc)	5 A
3	Cells per Module	36
4	Irradiance	1000 W/m ²

S. No	Parameter	Value
5	Temperature	25°C

Boost Converter Parameters

S. No	Parameter	Value
1	Inductance	5 mH
2	Duty Cycle	50–70%
3	Load Resistance	20 Ω
4	Switching Frequency	10 kHz

XII. PRACTICAL IMPLEMENTATION CHALLENGES

Although the proposed photovoltaic system shows effective performance in simulation, certain challenges may occur during practical implementation. Accurate measurement of voltage, current, and temperature under changing environmental conditions is essential for reliable fault diagnosis. Sensor noise, communication delays, improper calibration, and environmental effects such as dust, humidity, and module aging may affect monitoring accuracy. In addition, real-time implementation of intelligent control algorithms requires proper coordination between sensing, processing, and converter control units. Despite these limitations, the proposed methodology provides a reliable foundation for future development of advanced and scalable smart photovoltaic systems.

XIII. FUTURE SCOPE

Future enhancements of the proposed photovoltaic system may include the integration of artificial intelligence-based fault prediction, IoT-enabled remote monitoring, cloud-based energy analysis, and wireless sensor networks for improved system supervision. Advanced machine learning techniques, mobile application monitoring, battery energy storage integration, and smart grid communication technologies can also be incorporated to improve system intelligence, reliability, and large-scale operational capability.

XIV. CONCLUSION

This paper presented a smart photovoltaic system for real-time fault detection and mitigation using MPPT optimization techniques. The proposed system continuously monitored voltage, current, and temperature parameters to identify abnormal operating conditions in the PV array. The integration of intelligent fault diagnosis with MPPT control improved power extraction efficiency, reduced power loss, and enhanced system reliability.

MATLAB/Simulink simulation results confirmed effective detection of faults such as partial shading, hotspot conditions, and electrical disconnections while maintaining stable operation. Overall, the proposed methodology provides an efficient and reliable solution for modern photovoltaic monitoring and smart renewable energy.

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