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ANALYSIS OF IOT APPLICATION IN SOLAR PHOTOVOLTAIC SYSTEM

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***Abstract*— The integration of Internet of Things (IoT) technology into Solar Photovoltaic (PV) systems has emerged as an effective approach for improving energy harvesting efficiency, operational reliability, and efficient system monitoring and management. This review paper provides a comprehensive analysis of multi-layered IoT applications in PV infrastructures, ranging from panel-level monitoring to intelligent power conversion. As global solar capacity surpassed 1,400 GW in 2024, the demand for real-time data acquisition and efficient system management has become critical. This study explores IoT implementation in solar PV arrays, conventional boost converters, Maximum Power Point Tracking (MPPT) units, inverters, and specialized sensor networks. It highlights the transition from conventional monitoring to IoT-enabled real-time monitoring and data-driven analysis using communication protocols such as MQTT and NB-IoT to address challenges such as partial shading, thermal variations, and power quality. Recent studies indicate that AI-integrated IoT frameworks improve system performance through predictive maintenance, anomaly detection, and performance forecasting. This review identifies key challenges such as system complexity, communication latency, and scalability, and outlines potential directions for improving IoT-based PV system performance. Overall, IoT integration represents a significant step toward efficient, reliable, and sustainable next-generation renewable energy systems.**

Keywords*— *Internet of Things (IoT); Solar Photovoltaic; MPPT; Boost Converter; Smart Inverter; Real-time Monitoring; Renewable Energy

I. INTRODUCTION

Solar photovoltaic (PV) systems convert incident solar radiation directly into electrical energy through the photovoltaic effect. When photons strike the semiconductor p–n junction of a PV cell, electron-hole pairs are generated and separated by the built-in electric field, thereby producing direct current (DC) power. Since the output of an individual PV cell is relatively low, multiple cells are interconnected to form a module or panel capable of delivering usable power. A practical solar PV system typically consists of solar panels, a power conditioning unit incorporating an MPPT-controlled DC–DC boost converter, regulated DC output paths for battery or DC loads, inverters, and connected AC loads or grid systems, as illustrated in Fig. 1.

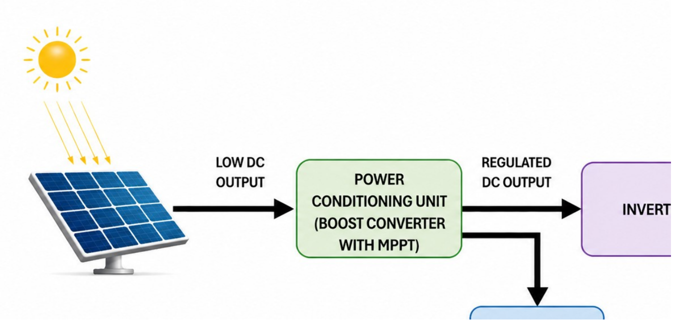

Fig. 1. Block diagram of a solar photovoltaic system with MPPT-controlled DC–DC converter.

The global energy landscape is undergoing a radical shift toward decarbonization, with Solar Photovoltaic (PV) technology leading the transition. As of early 2026, cumulative global solar capacity has surpassed 1,500 GW, with annual additions exceeding 350 GW. Solar PV installed capacity is expected to exceed 2,350 GW by 2027, making it one of the dominant power generation technologies worldwide. The global cumulative power capacity by source from 2010 to 2027(GW) is illustrated in Fig. 2.

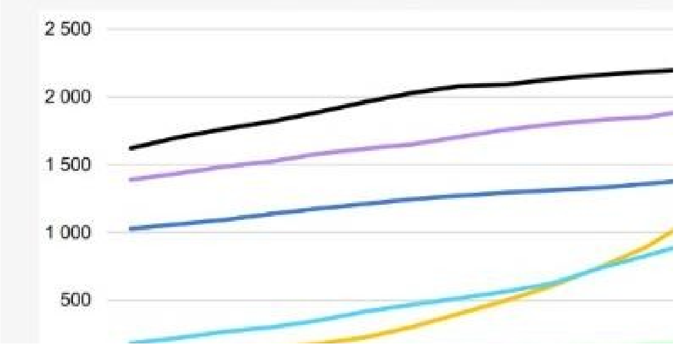

Fig. 2. Global cumulative power capacity by source from 2010 to 2027(GW) (adapted from [1]).

Despite its advantages, the performance of PV systems is significantly affected by environmental factors such as irradiance variation, temperature rise, dust accumulation, and partial shading conditions [2]. In addition, the rapid deployment of utility-scale and distributed rooftop PV systems has increased the demand for efficient monitoring, fault diagnosis, and intelligent control systems. To overcome these challenges, the Internet of Things (IoT) provides a smart bidirectional communication framework enabling real-time monitoring, predictive maintenance, remote supervision, and optimized power conversion [3].

This review paper presents a comprehensive analysis of IoT applications in solar PV arrays, conventional boost converters, MPPT techniques, inverters, and sensor networks, highlighting recent developments, comparative studies, and future research opportunities.

II. APPLICATIONS OF IOT IN SOLAR PV SYSTEMS

The practical implementation of Internet of Things (IoT) technology in solar photovoltaic (PV) systems has enabled intelligent operation through interconnected sensing, communication, and control networks. In a typical IoT-enabled PV system, data collected from sensors is transmitted through wireless or wired communication modules to local gateways or cloud platforms for storage, analysis, and automated decision-making. This digital framework allows continuous supervision of system performance under dynamic environmental and load conditions.

IoT applications are distributed across major PV subsystems, including solar PV arrays, power converters, Maximum Power Point Tracking (MPPT) units, inverters, and sensor networks. Each subsystem utilizes IoT for specific operational tasks such as panel condition assessment, converter regulation, tracking optimization, inverter diagnostics, and environmental data acquisition. Through coordinated control and data analytics, IoT enhances system reliability, response speed, and operational efficiency in both rooftop and utility-scale installations. The following subsections discuss these applications in detail.

A. IoT in Solar PV Array

The solar photovoltaic (PV) array is the primary power generation unit of a PV system and is frequently affected by faults such as hot spots, micro-cracks, dust accumulation, shading, and module degradation, which reduce energy output and reliability. The integration of Internet of Things (IoT) technology at the array level enables continuous monitoring of individual panels or strings using distributed sensing and communication networks. Key parameters such as irradiance, temperature, voltage, current, and power output are collected and analyzed to identify abnormal operating conditions at an early stage. In addition, intelligent techniques such as Artificial Neural Networks (ANN), Decision Trees, and k-Nearest Neighbor (kNN) algorithms are increasingly employed for automated fault diagnosis and predictive maintenance. Fig. 3 illustrates a layered IoT-based framework for continuous PV array monitoring, cloud analytics, and intelligent fault classification. Table I summarizes recent IoT-based PV monitoring approaches, highlighting their methods, features, performance, and limitations.

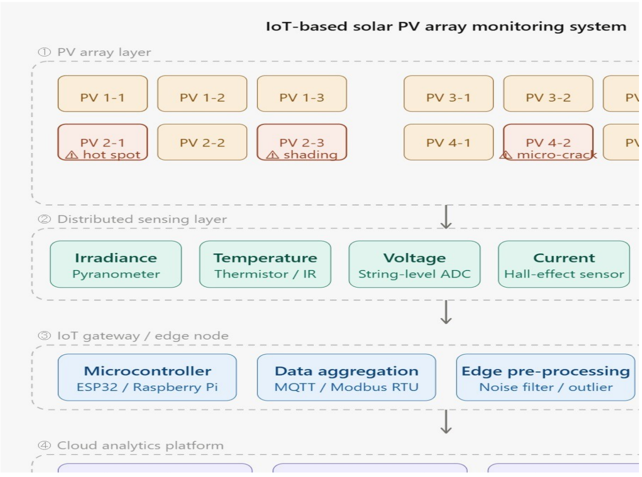

Fig. 3. IoT-based framework for PV array monitoring, fault diagnosis, and predictive maintenance.

TABLE I. COMPARATIVE ANALYSIS OF IOT-BASED MONITORING TECHNIQUES FOR SOLAR PV ARRAYS

Ref	**Method**	**Key Features**	**Advantages**	**Limitation**
[4]	Cloud IoT platform with AI models.	Multi-site monitoring, next-day prediction, real-time anomaly alerts.	Scalable management, proactive maintenance, robust detection.	Needs cloud connectivity, high computation, retraining required.
[5]	IoT-AI hotspot detection using IRT images	RF; 0.995 sensitivity; works >300 W/m²	Accurate, automated, more inspection time	Needs IR camera; retraining needed; untested <300 W/m²
[6]	STM32-based IoT fault detection with HIL simulation	Real-time monitoring, mobile/HMI apps, automated warnings.	Accurate sensing, safe testing, user-friendly access.	Wi-Fi dependency, complex setup, limited scale validation.
[7]	ESP32 IoT PV logger with ML forecasting	Monitors PV/battery/weather; ThingSpeak dashboard;	Low-cost, remote access, early fault prediction	ThingSpeak limits; monitoring only
[8]	Arduino IoT monitoring with MPPT control.	Real-time dashboard, six-parameter sensing, seasonal validation.	Low cost, improved energy harvest, open-source design.	Small-scale prototype, internet dependency, no AI analytics.

B. IoT in Boost Converter

The boost converter is a fundamental DC–DC power electronic converter in solar photovoltaic (PV) systems, used to step up the low and variable DC voltage from the PV array to a stable higher output suitable for load and grid applications. However, its performance is affected by input voltage fluctuations, switching losses, and thermal stress, which can reduce overall conversion efficiency and reliability. To address these issues, Internet of Things (IoT) integration has been widely adopted to enable real-time monitoring and improved observability of converter operation. Recent approaches also incorporate advanced converter technologies such as CMOS-based designs and high-gain IoT-enabled architectures to improve efficiency and support smart energy applications. Fig. 4 shows an IoT-enabled boost converter framework with real-time monitoring, cloud analytics, and smart control for enhanced converter performance. Table II presents a comparative analysis of recent IoT-based boost converter techniques, highlighting their methodologies, key features, advantages, and limitations.

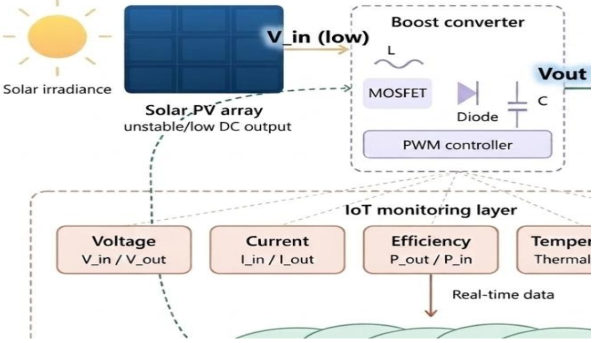

Fig. 4. IoT-enabled boost converter framework with cloud analytics and smart control.

TABLE II. COMPARATIVE ANALYSIS OF IOT-ENABLED ADVANCED BOOST CONVERTER TECHNIQUES

Ref	Method	Key Features	Advantages	Limitation
[9]	Loss-optimized CMOS boost converter for RF IoT harvesting.	Peak power conversion efficiency of 98.4% at 0.4 V input; 96.5% PCE at 0.1 V;	Very high efficiency; battery-less operation.	Simulation-only; low-voltage range only.
[10]	Fully integrated capacitive charge pump with bias boosting	80.1% efficiency; fully on chip; 60 pF capacitance	No inductor; ultra-compact design	Lower efficiency; narrow voltage range
[11]	CMOS TEG boost converter with A-MPPT + I-ZCS	90 mV startup; 85.9% efficiency; 0.03 mm^2	Ultra-low startup voltage; compact design; high MPPT efficiency	Limited output power (~1 mW); temperature-dependent performance
[12]	10-component inductive boost converter for TEG IoT nodes	1.2 V output from 0.5 V input; 1.25 MHz LC oscillator;	Low-cost, simple design; good efficiency at >20 kΩ loads;	No MPPT; frequency depends on component tolerances

C. *IoT in MPPT*

The maximum power point tracking (MPPT) technique is a critical control strategy in solar photovoltaic (PV) systems, used to continuously extract the maximum possible power from the PV array under varying environmental conditions such as irradiance and temperature. However, conventional MPPT methods are affected by slow tracking speed, oscillations around the operating point, and reduced efficiency under partial shading conditions. To overcome these limitations, Internet of Things (IoT) integration has been increasingly adopted to enable real-time monitoring and adaptive control of MPPT operation. Recent approaches also incorporate intelligent and adaptive MPPT algorithms with IoT connectivity for enhanced accuracy and faster convergence under dynamic operating conditions. Fig. 5 shows an IoT-based MPPT framework integrating sensing, communication, cloud analytics, and adaptive control for PV applications. Table III presents a comparative analysis of recent IoT-based MPPT techniques, highlighting their methodologies, key features, advantages, and limitations.

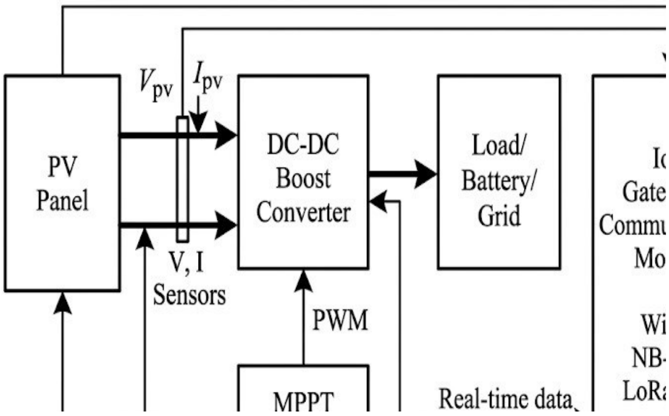

Fig. 5. IoT-based MPPT system for solar PV applications.

TABLE III. COMPARATIVE ANALYSIS OF IOT-INTEGRATED AND INTELLIGENT MPPT TECHNIQUES

Ref	Method	Key Features	Advantages	Limitation
[13]	IoT-based MPPT review (P&O, INC, Fuzzy, ANN)	Cloud monitoring of PV parameters; remote sensing	Improved monitoring and fault detection; flexible integration	Not a standalone algorithm; lacks experimental validation
[14]	MPPT + IoT cleaning/cooling + NN training	Integrates maintenance (dust removal, cooling) with tracking	Higher 24-hr energy output; better low-irradiance performance	Maintenance cost; system complexity
[15]	LSTM-based MPPT	Uses real-world irradiance data; temporal learning capability	Superior tracking in dynamic conditions; high accuracy	Requires large dataset; high training complexity

[16]	NN-assisted P&O MPPT	NN corrects duty cycle during rapid irradiance change	Faster tracking than conventional P&O; low training data need	Still depends on P&O baseline; limited adaptability in extreme cases

D. IoT in Sensor unit

The sensor unit is a vital component in solar photovoltaic (PV) systems, used to measure key electrical and environmental parameters such as irradiance, temperature, voltage, and current for effective monitoring and control. However, conventional sensors may experience calibration drift, measurement errors, and delayed fault detection, affecting overall system performance. To address these issues, Internet of Things (IoT) technology is widely adopted for real-time sensing, data acquisition, and remote supervision of PV systems. Recent methods include IoT-enabled wireless sensor networks with fuzzy logic compensation, sensor benchmarking techniques, and Raspberry Pi-based cloud monitoring platforms. These approaches improve sensing accuracy, reduce maintenance effort, and support faster operational decisions. The overall architecture of the IoT-enabled sensor unit for solar PV monitoring is illustrated in Fig. 6, showing the integration of measurement, processing, communication, and application layers. Table IV presents a comparative analysis of recent IoT-based sensor techniques, highlighting their methodologies, key features, advantages, and limitations.

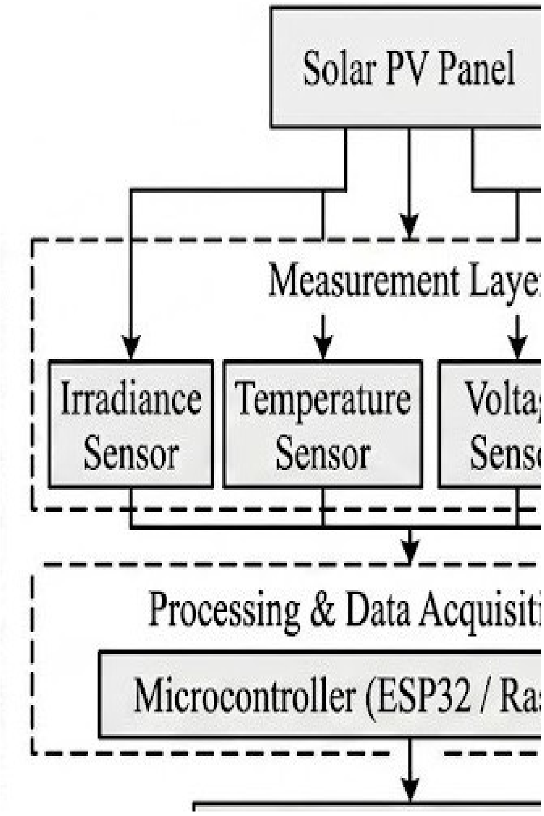

Fig. 6. IoT-based sensor unit architecture for solar PV monitoring.

TABLE IV. COMPARATIVE ANALYSIS OF IOT-BASED SENSOR MONITORING AND ENERGY MANAGEMENT TECHNIQUES

Ref	**Method**	**Key Feature**	**Advantages**	**Limitation**
[17]	IoT WSN sensors with fuzzy compensation	Irradiance and temperature sensing	Reduced sensing error; improved accuracy	Additional processing for fuzzy compensation
[18]	ESP32-based IoT sensor monitoring for PV systems	Voltage, current, power monitoring; cloud dashboard;	Low cost; real-time supervision; Built-in Wifi.	No MPPT; alert delay; limited scalability
[19]	BIPV IoT monitoring with web app	Monitor Voltage, current, temperature, battery SoC sensing	Low cost; remote web monitoring;	Single-panel prototype; no MPPT
[20]	Smart IoT energy management for PV based on Arduino and ZigBee	Multi-sensor sensing; cloud logging;	Real-time monitoring; predictive control;	Higher cost; complex implementation and data dependent.

E. IoT in Inverter

The inverter is a vital component in solar photovoltaic (PV) systems, responsible for converting DC power from the PV array into usable AC power for load or grid applications, and its performance directly affects power quality, efficiency, and system stability. IoT is increasingly required in inverter systems to enable real-time monitoring, remote supervision, and rapid fault detection, while continuously tracking parameters such as AC voltage, current, power output, and harmonic distortion for reliable operation. Recent approaches employ machine learning techniques for anomaly detection and performance forecasting, whereas NB-IoT and low-cost embedded controllers provide scalable and wide-area connectivity for distributed PV systems. Fig. 7 shows the overall architecture of an IoT-based inverter monitoring system. Table V presents a comparative analysis of recent IoT-based inverter monitoring techniques, highlighting their methods, features, advantages, and limitations.

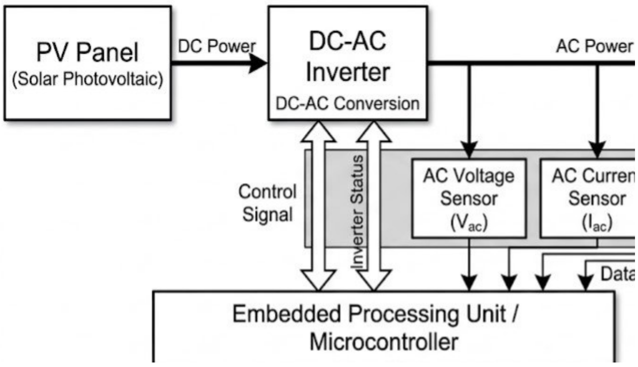

Fig. 7. The Overall architecture of an IoT-based inverter monitoring system for solar PV applications.

TABLE V. COMPARATIVE ANALYSIS OF IOT-BASED INVERTER MONITORING TECHNIQUES

Ref	**Method**	**Key Features**	**Advantages**	**Limitation**
[21]	IoT smart grid-tied inverter monitoring	Measures AC output, PF, THD, energy yield, PR	High system availability; THD < 5%	No predictive control
[22]	IoT + ML(BiLSTM) inverter monitoring	Forecasting; anomaly detection	95% detection accuracy	High complexity
[23]	NB-IoT-based inverter monitoring	Direct cloud communication via LPWA-based cellular IoT (NB-IoT)	Low power; long-range communication;	Higher latency limits real-time control
[24]	Arduino + Bluetooth	Three-phase voltage /current sensing; Android app via MIT App Inventor	Wireless local monitoring; user-friendly interface	Bluetooth dependency; no cloud support mentioned

III. DISCUSSION AND FUTURE SCOPE

The reviewed studies indicate that the integration of IoT in solar photovoltaic (PV) systems significantly enhances real-time monitoring, fault detection, and overall operational efficiency across PV arrays, converters, MPPT units, sensor modules, and inverter systems. Continuous measurement of key parameters such as irradiance, temperature, voltage, current, and power improves system observability, while cloud-based platforms enable remote supervision and data-driven decision-making. The incorporation of machine learning techniques further strengthens system performance through accurate anomaly detection and performance forecasting. However, challenges related to computational complexity, data dependency, communication latency, and scalability remain critical. Although communication technologies such as Wi-Fi and NB-IoT support flexible deployment, trade-offs between coverage, latency, and power consumption must be carefully managed for large-scale applications.

Future research should focus on integrating edge computing for low-latency processing and real-time control, along with advanced AI techniques to enhance predictive maintenance and energy forecasting. The development of hybrid communication frameworks combining NB-IoT, LoRaWAN, and 5G can further improve system scalability and reliability. Additionally, secure and standardized architectures will be essential to enable robust and large-scale deployment of IoT-based PV systems.

IV. CONCLUSION

This review presents a comprehensive analysis of IoT applications in solar photovoltaic systems, covering PV arrays, converters, MPPT techniques, sensor units, and inverter monitoring. The study highlights that IoT integration significantly enhances system performance by enabling real-time monitoring, remote supervision, and intelligent control. The incorporation of machine learning techniques further improves system reliability through predictive analytics and fault detection.

Comparative evaluations reveal that IoT-based approaches provide improved efficiency, accuracy, and operational flexibility compared to conventional methods, although challenges such as complexity, communication limitations, and scalability persist. Overall, IoT-enabled PV systems represent a key advancement toward smart, efficient, and sustainable energy solutions, with strong potential for future development in intelligent power management and smart grid integration.

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