Comprehensive Review Of Embedded Control And Remote Monitoring For Solar PV Energy Harvesting Systems

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Abstract: The growing global demand for clean and sustainable energy has intensified research into efficient solar photovoltaic (PV) energy harvesting systems. Embedded control and remote monitoring have emerged as key enablers for enhancing the performance, reliability, and autonomy of PV systems. This paper presents a comprehensive review of embedded solutions for solar PV energy harvesting, drawing insights from two major research directions. First, microcontroller-based solar tracking systems are examined, highlighting their role in optimizing the orientation of PV panels through feedback control, stepper motor actuation, and sensor integration to maximize solar irradiance capture [1]. Such systems demonstrate cost-effectiveness, stability, and improved energy yield compared to fixed collectors. Second, advances in embedded monitoring and control frameworks are explored, where modern embedded processors, wireless sensor networks, Internet of Things (IoT) technologies, and cloud connectivity enable real-time data acquisition, performance analysis, and fault detection in decentralized PV plants [2]. These systems not only improve operational robustness but also reduce maintenance costs while supporting large-scale deployment. The review synthesizes design methodologies, hardware platforms, communication protocols, and control strategies reported in literature, while discussing trade-offs between cost, scalability, and energy efficiency. Finally, future perspectives are outlined, emphasizing the integration of artificial intelligence, cybersecurity, and hybrid renewable energy systems for advancing embedded control and monitoring in PV energy harvesting.

Index Terms - Solar Photovoltaic (PV) Systems, Embedded Control, Remote Monitoring, Microcontroller-Based Solar Tracking, Wireless Sensor Networks (WSN), Maximum Power Point Tracking (MPPT), Fault Detection and Diagnosis, Artificial Intelligence (AI) in PV Systems, Cloud-Based Monitoring.

I. Introduction

The depletion of fossil fuels and the rise of climate concerns have necessitated a shift towards renewable energy sources. Solar photovoltaic (PV) systems have gained prominence due to their abundance, scalability, and declining cost. However, to achieve higher efficiency and reliability, advanced embedded control and remote monitoring technologies are required. Embedded systems play a vital role in enhancing PV performance by providing autonomous control, intelligent decision-making, and remote accessibility.This review paper focuses on two critical aspects of embedded PV systems: (i) microcontroller-based solar tracking systems and (ii) embedded monitoring and control frameworks for remote supervision. Together, these advancements ensure maximized solar energy harvesting and sustainable long-term operation.

II. Literature Review

Research on embedded control and monitoring of solar PV systems has expanded significantly over the last two decades. Early works focused on microcontroller-based tracking mechanisms to improve energy capture. Bingol et al. [3] and Kehinde et al. [1] demonstrated that single-axis and dual-axis trackers could substantially increase the efficiency of PV panels compared to fixed installations. Subsequent studies emphasized intelligent control, with Koutroulis et al. [10] implementing microcontroller-based MPPT systems to further enhance energy yield.

On the monitoring side, IoT-based solutions have gained traction in recent years. Adhya et al. [4] developed an IoT-enabled smart monitoring system for PV arrays, while Pereira et al. [5] introduced a Raspberry Pi–

based platform for decentralized renewable energy supervision. Similarly, Rahman et al. [9] reviewed global PV monitoring solutions, highlighting the role of cloud integration and low-cost microcontrollers. These studies revealed how wireless sensor networks and embedded devices can transform PV management into an intelligent, automated process.

Several review-oriented studies, including Chang et al. [2], have consolidated recent developments in embedded frameworks for monitoring PV plants. These works highlight the importance of wireless sensor networks, cloud storage, and AI-enabled analytics for predictive maintenance and energy optimization. Mellit et al. [6] presented an extensive review of fault detection techniques in PV systems, demonstrating the importance of embedding intelligent diagnostic algorithms into monitoring platforms. Engin [12] also discussed open-source embedded data loggers as cost-effective solutions for small-scale PV installations.

Furthermore, studies have addressed challenges of environmental conditions on PV systems. Bhol et al. [14] and Zlatov et al. [15] analyzed how temperature, irradiance variations, and climatic degradation affect PV efficiency. Embedded monitoring solutions have been developed to capture and compensate for such conditions in real time. Gad [13] also proposed advanced temperature acquisition systems for optimizing PV thermal management.

Beyond hardware and IoT integration, Industry 4.0 concepts such as edge computing and cognitive embedded systems are being explored. Barsocchi et al. [7] emphasized the role of IoT devices in smart city infrastructure, which can be extended to PV system monitoring. Teng et al. [8] further demonstrated the potential of hybrid renewable energy monitoring (PV-wind-storage), reinforcing the need for embedded systems capable of managing multi-source integration.

In summary, the literature indicates a transition from hardware-centric tracking designs to hybrid frameworks integrating IoT, AI, and embedded processors for both control and monitoring. The evolution of these systems has led to more autonomous, reliable, and cost-efficient PV solutions. This review builds upon prior research by synthesizing these developments into a structured framework, highlighting trends, limitations, and opportunities for future work.

III. Microcontroller-Based Solar Tracking Systems

Solar tracking systems enhance PV performance by orienting panels to maximize exposure to sunlight throughout the day. Microcontroller-based designs are cost-effective and versatile solutions that automate solar tracking.

i) *Design Methodology*

Microcontrollers, such as the PIC16F877, are widely used in solar tracking systems. They provide programmable flexibility, low cost, and compactness [1]. Single-axis and dual-axis tracking mechanisms are implemented, with stepper motors controlled by pulse sequences to adjust PV panel orientation. Sensor-based feedback, often using light-dependent resistors (LDRs), enables real-time optimization.

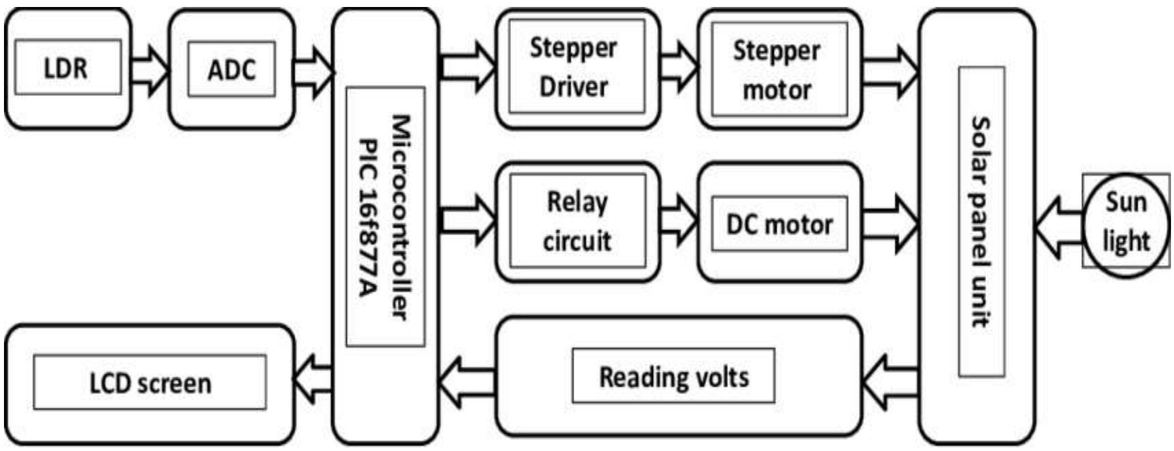

Fig 1: Block Diagram of a Microcontroller-Based Solar Tracking System

ii) Performance Improvements

Compared to fixed solar panels, microcontroller-based trackers yield significantly higher energy capture by maintaining near-normal incidence of solar irradiance [1]. Automatic reset mechanisms and error correction improve reliability and reduce manual intervention.

iii) Case Studies

Several experimental prototypes demonstrate the efficiency of such systems. Kehinde et al. [1] implemented a single-axis tracker that successfully increased PV efficiency while maintaining cost-effectiveness. Bingol et al. [3] also presented microcontroller-based solar tracking with practical improvements in rural electrification projects.

iv) Challenges

Despite their advantages, solar trackers increase mechanical complexity and may require higher maintenance. Cost-benefit trade-offs must be considered, especially for small-scale residential applications.

IV. EMBEDDED CONTROL AND REMOTE MONITORING FRAMEWORKS

Monitoring and control frameworks ensure the reliable operation of PV systems by collecting, transmitting, and analyzing system parameters.

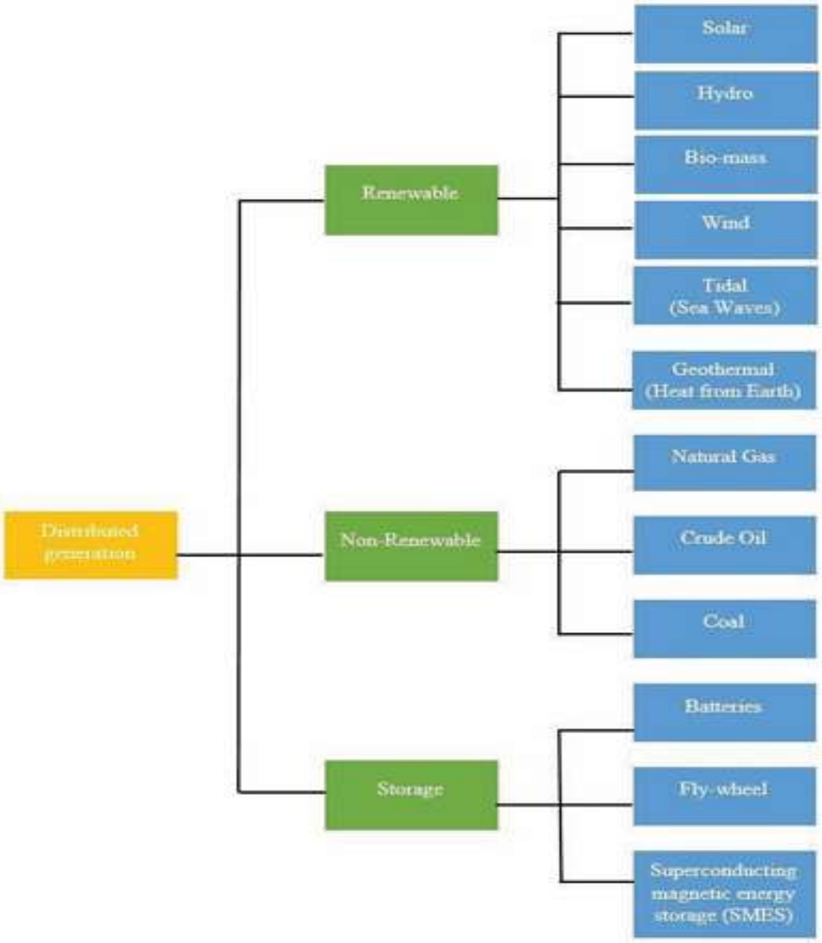

Fig 2: Distributed Generation Framework for Renewable Energy Systems [2]

i) IoT and Embedded Processors

Recent advancements leverage embedded processors, wireless sensor networks (WSNs), and IoT technologies to monitor decentralized PV plants [2]. Devices such as Arduino, Raspberry Pi, and ARM Cortex controllers integrate sensors to capture voltage, current, irradiance, and temperature data.

ii) Remote Accessibility

Through cloud platforms and wireless communication (Wi-Fi, GSM, ZigBee), PV performance data can be transmitted to centralized servers. This enables real-time fault detection, predictive maintenance, and optimization [2].

iii) Data Processing and Reliability

Embedded monitoring systems employ digital storage, local data logging, and remote access. Low-power designs and modular sensor integration enhance cost-effectiveness and scalability. However, challenges remain in ensuring cybersecurity, data integrity, and standardization.

iv) Case Studies

Adhya et al. [4] demonstrated IoT-enabled PV monitoring using PIC18F46K22 microcontrollers, integrating temperature and irradiance sensing for real-time supervision. Pereira et al. [5] developed an

ADCES-based Renewable Energy Monitoring System using Raspberry Pi for both analog and digital data handling. Such studies prove the scalability of embedded monitoring solutions in real-world applications.

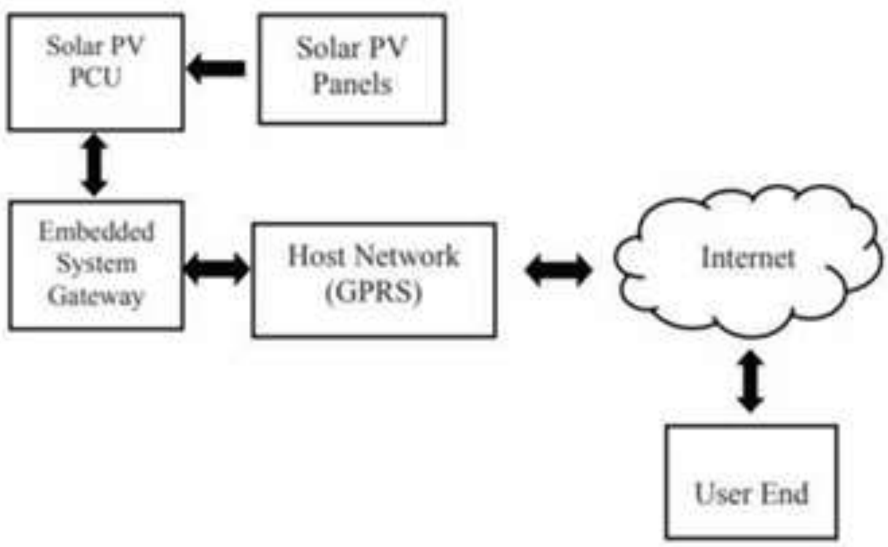

Fig 3: Block Diagram of an Embedded Monitoring System Using Arduino/PIC Controller [2]

V. Comparative Analysis of Embedded Approaches

SL.NO.	Feature	Microcontroller-Based Tracking [1,3]	Remote Monitoring Frameworks [2,4,5]
1	Primary Function	Maximize solar irradiance capture	Ensure system reliability & supervision
2	Key Technology	Microcontrollers, stepper motors, LDR sensors	IoT, WSN, cloud, embedded processors
3	Benefits	Higher energy yield, autonomy, cost-effective	Fault detection, predictive maintenance, scalability
4	Challenges	Mechanical complexity, maintenance	Cybersecurity, communication reliability

VI. Integration of Monitoring and Tracking Systems

A promising trend is the integration of solar tracking and embedded monitoring. By combining active tracking mechanisms with IoT-based supervision, PV systems can achieve both enhanced efficiency and resilience. For example, Arduino-based trackers integrated with GSM modules provide both orientation control and remote fault reporting. Such hybrid approaches are expected to become industry standards.

VII. Future Research Directions

The future of embedded PV systems lies in combining control and monitoring with advanced digital technologies:

- **Artificial Intelligence (AI):** Predictive analytics for solar irradiance forecasting and fault diagnosis [6].
- **Cybersecurity:** Secure communication protocols to protect PV data from cyber threats [7].
- **Hybrid Systems:** Integration of PV with wind and storage systems for robust energy management [8].
- **Industry 4.0 Technologies:** Cognitive embedded systems, mesh networking, and edge computing to enhance scalability [2,9].

VIII. Conclusion

Embedded control and monitoring have transformed solar PV systems into efficient, reliable, and autonomous energy solutions. Microcontroller-based solar trackers significantly enhance energy harvesting, while IoT-enabled monitoring frameworks ensure long-term stability and adaptability. This review highlights the advancements, benefits, and limitations of both approaches, while underscoring future research opportunities in AI, cybersecurity, and hybrid renewable systems.

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