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Embedded MPPT for Photovoltaic Systems: Low-Cost Microcontrollers, P&O and Incremental Conductance Algorithms, and IoT-Based Monitoring - A Systematic Review

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ABSTRACT

This survey offers an embedded-oriented view of MPPT applied to PV systems, with specific attention devoted to low-cost microcontroller-based implementations and classical P&O and INC algorithms for application in IoT-supervised smart PV infrastructures. This paper synthesizes 83 recent peer-reviewed articles published from 2023 to 2025. It highlights how embedded MPPT controllers are increasingly implemented using low-cost hardware, such as Arduino , ESP32 and STM32, that support real-time duty-cycle control, remote monitoring, and PV supervision at a large scale. These results confirm that although classical P&O and INC dominate lower-memory embedded hardware, they are inherently limited by steady-state oscillations, poor adaptability to rapid irradiance transitions, and practical constraints such as finite ADC resolution and sampling delays. To address these limitations, robust and hybrid strategies for enhancement (among which Active Disturbance Rejection Control – ADRC/LADRC, sliding-mode-and super-twisting Sliding-mode or Super-twisting controllers controllers, as well as hybrid approaches such as INC–SMC and LADRC–metaheuristic optimization) always tend to outperform conventional ones by reducing ripple magnitude , decreasing the settling time while guaranteeing a higher tracking efficiency under conditions of partial shading ranging from partially clouded to dynamic operating conditions. Additionally, enables embedded MPPT systems with intelligent cyber-physical infrastructures and with predictively supervised, adaptively operated systems, using secured wireless IoT monitoring layers (WiFi, LoRaWAN, XBee, MQTT). There are still important research gaps, such as the lack of an end-to-end, unified, IoT-robust co-design, insufficient real-time resilience, and insufficient cybersecurity integration. Thus, this review suggests that the secure cyber-physical embedded MPPT model, based on ESP32 edge control, is adopted with ADRC-based stability improvement and secure IoT communication, for highly relevant PV farm installations in harsh Iraqi weather, such as Basra and desert areas.

Introduction

Photovoltaic (PV) technology has grown to become one of the most installed renewable energy technologies for its sustainability and falling cost year by year. Unfortunately, PV arrays with nonlinear V-I characteristics and significant power losses under complex operating conditions, such as partial shading or fluctuating irradiance, require advanced MPPT techniques. Some recent work has shown that metaheuristic search algorithms, such as the Salp Swarm Algorithm (SSA), can improve MPPT stability in partial shading conditions [1]. In addition to algorithmic advancements, current PV systems are transitioning towards centralized MPPT schemes enabled by wireless communication (e.g., XBee networks), which also facilitate coordinated power extraction from PV arrays [2].

Also, the incorporation of IoT monitoring layers has enabled low-cost supervisory platforms that can perform real-time sensing and remote visualization of PV behavior [3]. In addition to conventional MPPT techniques, AI controllers were also studied for enhanced solar energy harvesting and improved tracking performance in varying environments [4]. At the converter-controller level, an integrated MPPT with a sliding-mode controller for a buck–boost–type converter has been introduced to enhance system stability and minimize steady-state oscillations [5].In addition, some robust control strategies, such as ADRC, have shown potential to improve PV inverter dynamics and grid-connected stability under disturbances [6] . Also, high-order sliding-mode MPPT controllers based on super-twisting algorithms have been presented to achieve fast convergence and ripple-free tracking [7] .Classical algorithms, including Perturb and Observe (P&O), despite their simplicity and widespread industrial use, still exhibit poor performance during rapid changes in irradiance. As a result, P&O methods, along with advanced nonlinear controllers such as backstepping , were developed to improve tracking robustness [8].

Additionally, for grid-connected PV systems operating under partial shading conditions, dynamic global MPPT schemes are necessary to extract the global peak, as suggested in IEEE studies [9].In addition, to address complex solar irradiance fluctuations, bio-inspired optimization approaches such as the Marine Predator Algorithm have been proposed, which proved highly efficient for MPP tracking under very severe variations [10] .Therefore, this work includes a systematic approach to the low-cost implementation of MPPTs, focusing on microcontroller-based systems and the classical P&O and Incremental Conductance algorithms, culminating in their development as IoT-supervised, cyber-physical photovoltaic storage systems. Unlike previous MPPT survey research, which is mainly algorithm-performance-comparison-oriented, this study adopts a systematic analysis approach and presents a multidimensional evaluation scheme for embedded MPPT systems.

These are the very contributions of this paper:

1- Embedded-Oriented Taxonomy:

However, to the best of our knowledge, no classification of MPPT techniques considers embedded feasibility, computational complexity, and hardware implementation.

2- Comparative Analytical Framework:

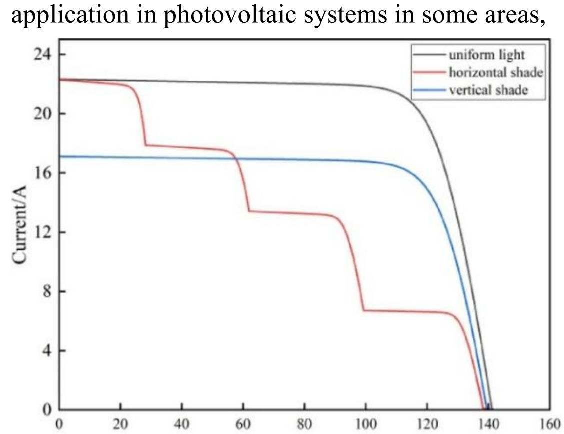
A multi-criteria assessment of MPPT techniques based on tracking efficiency, ripple suppression, speed of convergence, IoT compatibility, and cyber-physical system maturity.

3-Cyber-Physical Embedded MPPT Architecture:

A unified architecture for ESP32 edge control, ADRC/LADRC robust stability improvement, and secure IoT-based supervisory communication.

4 - Practical Deployment Perspective:

Identification of limitations and future work for implementing an embedded MPPT system under harsh environmental conditions, especially its application in photovoltaic systems in some areas,



such as Iraq.

Figure(1):I–V characteristic plots for a PV array under various irradiation conditions, such as full

uniform illumination, horizontal shading, and vertical shading [11].

The IV characteristic of photovoltaic arrays is very sensitive to the radiation profile. Under uniform solar illumination, PV modules generate only one maximum power point; however, partial shading gives rise to multiple local peaks, rendering the MPPT process complex. This phenomenon is evident in Figure 1, which shows the I–V curves of a PV array under uniform shading and under horizontal and vertical shading conditions. [11].

1. Fundamentals of Embedded MPPT Systems

1.1 PV Characteristic and Requirements of MPPT

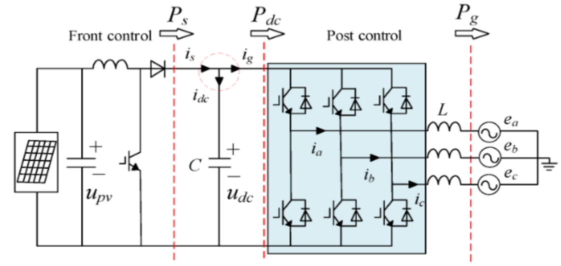
The nonlinear current–voltage (I–V) and power–voltage (P–V) curves of photovoltaic (PV) systems change with both irradiance and temperature. Moreover, under dynamic atmospheric conditions, the operating point of a PV array varies continuously over time, and significant efficiency drops are observed when MPPT is not employed. According to recently developed adaptive MPPT methods, it has been proven that approaching the optimal point quickly is important for reducing ripple and increasing the energy harvesting ratio[11].

This latter aspect is supported by global MPPT validation analysis under dynamic solar irradiance profiles, and it has been indicated that a preliminary algorithm (as the conventional ones analyzed here) could not ensure tracking under high perturbations, advocating the engineering of advanced embedded MPPT solutions that achieve real-time operation [12].

1.2 Embedded Operation Loop (ADC --> Control --> PWM)

MPPT algorithms are primarily based on embedded control in practical photovoltaic applications. The classical embedded MPPT loop includes voltage and current readings, ADC sampling, algorithmic duty-cycle implementation, and PWM control of the DC–DC converter stage. Centralized embedded MPPT architectures, such as PV string systems, also proliferate, referring once more to the control loop, which can extend to power optimization via coordinated operation through a single inverter-level controller, thereby providing better scalability and less hardware redundancy [13].

Moreover, the popularity of low-cost embedded systems such as ESP32 has risen, offering the perfect combination of real-time MPPT implementation and wireless IoT-based monitoring (remote management/cloud-based PV visualization) [14]. In Figure 2 shows an example of a photovoltaic power conversion structure regulated by an embedded MPPT algorithm, comprising a DC–DC converter stage, a DC-link, and a grid-connected inverter .This



architecture demonstrates where the voltage and current signals are sensed and how they impact the power flow through control loops managed by the embedded controller [6][15].

Figure(2): Typical embedded-controlled photovoltaic power conversion system consisting of a DC–DC converter, DC-link capacitor, and grid-connected inverter [6].

1.3 Disadvantages of Conventional Embedded MPPT

Although they are simple and widely implemented, classical MPPT techniques (e.g., P&O and Incremental Conductance) are still limited by oscillations around the maximum power point (MPP) in steady-state conditions and under rapid irradiance perturbations. Low-cost embedded processors and controllers, in particular, may suffer performance degradation because of low-resolution ADCs, sampling jitter, and steady-state ripple.

IoT-based monitoring frameworks have been proposed as an efficient enabler that can provide continuous performance monitoring, fault diagnosis, and situational awareness for independent PV plants [15].Extensive reviews also reinforce the need for second-future embedded MPPT systems to address classical limitations for quicker convergence, stronger control embedding, and adaptable IoT-tracked cyber-physical infrastructures [16].

2- Classical Embedded MPPT Algorithms P&O and INC

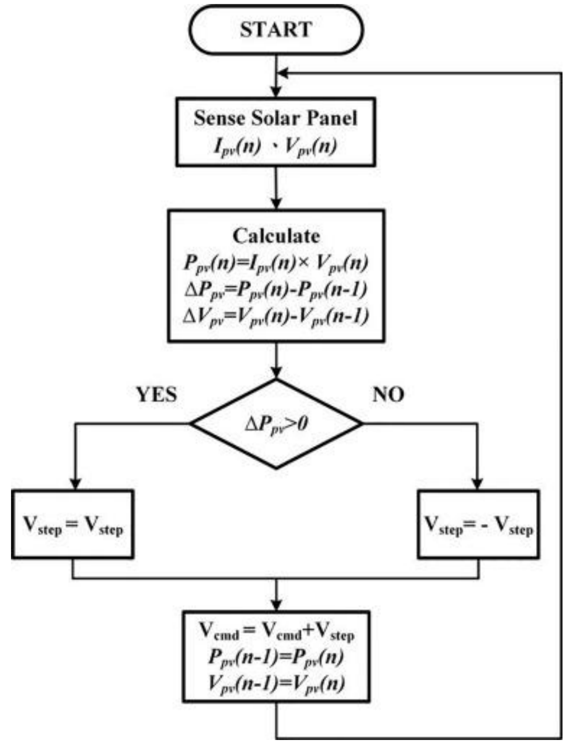
2.1 Perturb and Observe (P&O) Algorithm

For determining the maximum power point (MPP) of a PV module, the P&O algorithm perturbs the operating voltage and observes the resulting power change until the MPP condition is reached. The Perturb and Observe (P&O) technique is one of the most widely used MPPT algorithms in low-cost embedded PV controllers, thanks to its simplicity and low computational cost. But classical P&O has weaknesses in steady state oscillations around the MPP, especially at fast-changing irradiance and partial shading conditions. It has recently been proposed that dynamic and adaptive P&O improvements, in conjunction with sliding-mode and artificial intelligence assistance, improve the transient behaviour of the PV system [17].On the other hand, nonlinear control interconnection has also been investigated to enhance embedded P&O performance, and backstepping-based controller structures have been found to increase convergence rate and insensitivity to environmental variations. These methods are more robust than the fixed step P&O methods in grid-connected PV systems[18].

In addition, strong hybrid MPPT approaches, such as LADRC-based optimization integrated with metaheuristic tracking, have demonstrated enhanced transient performance and reduced oscillations compared to classical P&O, highlighting that conventional embedded techniques require supplementary control layers for future PV systems [19].The implementation of the embedded P&O algorithm is shown in Figure 3, where a controller samples the PV current-voltage curve and iteratively adjusts the duty-cycle command based on power variance to attain an operating point that maximizes power. This chart demonstrates the ease of P&O for low-cost microcontroller-based systems, though it is prone to steady-state oscillations when irradiance changes rapidly [16][20].

2.2 Incremental Conductance (INC) Algorithm

The Incremental Conductance (INC) method is considered more accurate than P&O for rapid irradiance variations, as it directly computes the slope dP/dV = 0 at the MPP. Advanced global tracking studies show that the INC-based embedded MPPT is more reliable in partial shading conditions than classical controllers, which converge to local maxima. [20]In addition, some IoT-supervisory embedded MPPT architectures adopt INC as a base algorithm because it is a trade-off between computational complexity and tracking accuracy. Recent IoT PV monitoring and control systems validate that INC loops implemented on networked infrastructures allow PV plants to operate adaptively or proactively through predictive maintenance, as well as to provide continuous, real-time performance assessment. [21] Similarly, IoT-based supervisory monitoring studies for photovoltaic utility plants emphasize that INC remains a feasible embedded solution, with wireless communication layers, to improve the controllability and visibility of large-scale PV systems [22].



Figure(3): Flowchart of the embedded P&OMPPT algorithm implemented in feeding photovoltaic systems [16][20].

2.3 Disadvantages of Classical Embedded P&O and INC Techniques

However, these P&O and INC methods may have shortcomings in real-time embedded applications, though they are widely used. Classical P&O is inherently prone to steady-state oscillations, while INC becomes computationally intensive, and sensor noise and ADC sampling limitations become dominant factors. Strong control-based techniques such as Linear Active Disturbance Rejection Control (LADRC) have been proposed to enhance dynamic tracking capability and maintain embedded MPPT in grid-forming PV systems [23].Furthermore, some backstepping techniques have been integrated to address distributed PV (DPV) problems in the microgrid-connected process, resulting in better stability margins and lower power ripples compared with direct classical MPPT control[24].To conclude, available adaptive backstepping MPPT designs provide evidence that classical embedded algorithms are not sufficient for next-generation PV systems subject to variable and erratic irradiance changes, which motivates the development of robust embedded architectures. Hybrid architecture for global power extraction[25].

Table 1. Classical Embedded MPPT Algorithms in Recent Literature

Author (Year) [Ref]	Technique	Advantages	Limitations
Odat et al. (2023) [17]	Sliding-Mode + Adaptive P&O MPPT	Improved stability and reduced ripple	Higher complexity than classical P&O
Bendé et al. (2023) [18]	P&O with Backstepping Support	Faster convergence and enhanced performance	Requires nonlinear parameter tuning
Ibrahim et al. (2025) [19]	LADRC-HHO Robust MPPT Scheme	Superior tracking efficiency, low oscillations	Increased computational burden
Zheng et al. (2025) [20]	INC-Based Global Peak MPPT	Accurate tracking under partial shading	Sensitive to sensor noise
He et al. (2025) [21]	IoT-Supervised Embedded INC MPPT Framework	Real-time monitoring and adaptive supervision	Communication latency issues
Ferrite et al. (2024) [22]	IoT-Based Supervisory Monitoring Framework	Scalability for utility PV applications	Cybersecurity not addressed
Liu et al. (2024) [23]	LADRC-Assisted Embedded MPPT	Improved robustness under disturbances	Parameter tuning required
Debdouche et al. (2023) [24]	Integral Backstepping MPPT Control	Reduced power fluctuations and stable operation	Complex implementation
Manna et al. (2023) [25]	Adaptive Backstepping MPPT	Ripple-free and fast settling response	Sensitive to tuning

3 - Low-Cost Microcontroller-Based Platforms for Embedded MPPT

Low-cost microcontroller-based systems have been the fundamental building blocks for realistic embedded MPPT, as they are available at low cost, capable of real-time processing, and equipped with standard interfaces to sensing and communication layers. Contrary to their expensive DSP-based MPPT counterparts, Arduino and other prosumer controllers like the ESP32 or STM32 open up low-cost possibilities for form-fit PV MPPT (Fit PV MPPT) units in stand-alone and IoT applications. are increasingly combined with wireless transceivers to turn PV plants into smart cyber-physical systems[26].

3.1 Arduino -Based MPPT Systems

Though using Arduino microcontrollers is a popular choice in academia and for prototyping MPPT designs for being cheap, simple, and well supported by the community, classical methods like P&O and INC have been successfully tested using experimental and simulation approaches, so that these algorithms can be effectively implemented on Arduino-based platforms for low-power PV systems. Comparative assessments also demonstrate that the Arduino MPPT is a successful starting-point solution when compared side by side; however, it may suffer from aggressive resolution and poor performance during rapid irradiance variations[50][53][67].

3.2 ESP32 IoT MPPT Systems

The ESP32 is arguably one of the most powerful budget embedded controllers available to modern MPPT systems. This advantage comes from its dual-core real-time control execution and built-in WiFi/Bluetooth connectivity. El-Khozondar et al. also presented ESP32-based monitoring systems that enable MPPT tracking, real-time monitoring, and cloud-based visualization of PV [27][28].Furthermore,

IoT-supervisory architectures have been embedded at the level of ESP32 controllers, enabling the photovoltaic array to become an intelligent, networked infrastructure with adaptive monitoring and predictive inspection. These frameworks enhance the ESP32's suitability for future-generation smart PV systems[29]. By enhancing PV security using IoT (LoRaWAN + ESP32-based) & edge intelligence in monitoring, ESP32 has become a better fit for next-generation smart PV deployments [30][31].

3.3 Intelligent MPPT for the Embedded controller: STM32 and PIC

More generally, outside Arduino/ESP, industrial-grade MCUs like STM32 or PIC have been more frequently used for higher-performance MPPT, faster sampling, higher PWM resolution, and enhanced robustness as target features. Recent literature highlights that these platforms are of particular interest for grid-connected and utility-scale PV systems, where the integral MPPT capability must effectively interact with embedded MPPT algorithms in the presence of disturbances and dynamic irradiance shifts[32][70].

In general, the selection of a microcontroller platform is crucial to MPPT efficiency, IoT scalability, and real-time adaptability for photovoltaic embedded control systems

Table 2. Low-Cost Controllers and IoT Capability in Embedded MPPT Systems

Author (Year) [Ref]	Controller Platform	IoT Support	Key Contribution	Limitations
El-Khozondar et al. (2024) [14]	ESP32	Wi-Fi / Cloud Monitoring	Smart energy monitoring with real-time PV sensing and visualization	Limited cybersecurity integration
Demir (2023) [15]	Low-cost IoT MCU Platform	IoT-based Remote Supervision	Affordable PV monitoring design for stand-alone PV plants	Mainly monitoring-focused
He et al. (2025) [21]	Embedded IoT Supervisory Controller Architecture	IoT Connectivity	Real-time PV monitoring, control, and inspection architecture	Latency challenges in communication
Ferrite et al (2024) [22]	Utility-Scale Embedded IoT Monitoring Platform	IoT Utility Supervision	Utility-scale PV plant monitoring with IoT-based integration	Cybersecurity not addressed
Hameed & Kurnaz (2024) [45]	LoRaWAN + Embedded AI Module	Secure Long-Range IoT	Low-power secure PV monitoring using LoRaWAN networks	Hardware complexity increases
Livinti et al. (2024) [50]	Arduino-based MPPT Prototype	No Native IoT	Classical P&O MPPT implementation with fuzzy enhancement	Limited processing capability
Youssef et al. (2023) [56]	Embedded Multi-MPPT Structure	Optional Supervisory Layer	Evaluation of single vs multiple MPPT embedded structures	Mainly simulation-based
Liu et al. (2024) [23]	STM32-class Controller	Industrial Integration Possible	Robust LADRC-supported MPPT for grid-forming PV systems	Requires parameter tuning
Debdouche et al. (2023) [24]	PIC/STM32 Embedded Control	Not Core IoT	Integral backstepping robust MPPT for microgrid PV integration	Complex implementation

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Table 3. IoT-Based Case Studies of PV and Performance Monitoring

Author (Year) [Ref]	IoT Platform	Communication Tech	Validation	Key Outcome	Limitations
Mohammed Nafa et al. (2025) [34]	IoT-enabled PV prediction + PSO-MPPT	IoT Monitoring Layer	Experimental	Real-time irradiance prediction with smart supervision	Limited cybersecurity integration
KIU Author (2025) [35]	IoT + MPPT Integration Survey	General IoT Platforms	Review	Highlights IoT-enhanced MPPT performance improvements	Low experimental benchmarking
El-Khozondar et al. (2024) [14]	ESP32 Smart Monitoring System	Wi-Fi + Cloud Dashboard	Experimental	Low-cost real-time PV visualization and supervision	Primarily monitoring-focused
He et al. (2025) [21]	IoT-Based PV Supervisory Monitoring Architecture	IoT Connectivity	Simulation + Experimental	Real-time monitoring, inspection, adaptive PV operation	Latency challenges
Ferrite et al. (2024) [22]	Utility-Scale Embedded IoT Supervisory Framework	IoT Supervisory Network	Experimental	Scalable PV utility plant visibility and regulation	Cybersecurity not addressed
Fernandez-Bustamante et al. (2023) [2]	Centralized MPPT String Supervision	X Bee 900 MHz	Simulation	Coordinated PV string MPPT via wireless architecture	Medium-range limitation
Fernandez-Bustamante et al. (2025) [40]	Centralized MPPT via LoRa	LoRa Technology	Simulation	Long-range energy-efficient PV communication	Requires gateway infrastructure
Hameed & Kurnaz (2024) [45]	Secure PV Monitoring Module	LoRaWAN + AI Support	Simulation + Experimental	Secure low-power PV monitoring for cyber-physical systems	Hardware complexity

The communication layer is a fundamental pillar of smart PV monitoring, and technologies such as Wi-Fi, LoRaWAN, xBee, and MQTT can provide the scalability needed for embedded MPPT controllers interfacing with cloud-based platforms. Fernandez-Bustamante et al. showed that centralized MPPT architectures facilitated by XBee 900 MHz communication provide coordinated PV string control with dependable supervisory networking [38][46].Additionally, a LoRa-based centralized MPPT control has been suggested as an energy-efficient long-haul solution and as highly practical for PV farming scale-up, offering a low-power communication system [39][41].Secure IoT communication has also been an active area of research, and the use of LoRaWAN alongside artificial intelligence was presented for robust yet inexpensive monitoring applications in the future PV cyber-physical paradigm[42][43].

4.3 Illustrative Examples of IoT-MPPT PV Plants

systems that can be remotely managed at a scale of [49][51]. However, IoT integration also introduces additional challenges, such as communication delays, network security threats, and device system complexity. Recent work also emphasizes that many current IoT-enabled PV power plants do not possess secure communication and real-time cyber-resilience functionality, which could jeopardize system dependability in decentralized solar power systems [45]. In general, IoT-enabled PV monitoring layers are especially suitable for application in countries like Iraq, where high irradiance variability and environmental aging issues require the implementation of low-cost embedded supervision systems incorporated with reliable wireless communication.

5 - Classical MPPT: Supporting Approaches and Drawbacks

Classical embedded MPPT algorithms such as P&O and INC are still interesting because of their simplicity and low computational cost. Nevertheless, their behavior is not always satisfactory under partial shading conditions, abrupt irradiance changes, and real-time embedded constraints. As a result, advanced robust and hybrid control strategies have been proposed to facilitate MPPT operation by enhancing tracking efficiency, reducing steady-state ripple, and shortening settling time. The high performance of the IoT modules for real-time PV diagnostics also reinforces the idea that future MPPT systems are gradually becoming intelligent cyber-physical infrastructures with a strong cloud layer. [52][54][69].

5.1 Controller platform with built-in MPPT support

Active Disturbance Rejection Control (ADRC) has been the focus of extensive research on robust control for PV systems, particularly in grid-connected inverter applications. Wang et al. showed that ADRC-based PV inverter control provides clear benefits in disturbance rejection and dynamic stability compared with traditional control techniques [60][61]. where LADRC, in combination with virtual synchronous generator (VSG) concepts, has been introduced for grid-forming PV systems to enhance robustness against disturbances and MPPT-related stability. These architectures demonstrate that ADRC systems are particularly well-suited for controlling an embedded PV plant in an uncertain environment [63][64].

MPPT controllers based on sliding mode and super-twisting Sliding mode control is a well-established technique that was proposed to address this problem due to its fast convergence and insensitivity to parameter variation. Contreras-Carmona et al. introduced a super-twisting sliding-mode MPPT method with ripple-free tracking and improved stability under non uniform irradiance conditions [55].Likewise, upper-level sliding-mode observer-based MPPT controllers have shown better performance in grid-connected PV/battery systems, with compact steady-state oscillation and fast settling, than classical INC and P&O methods[56][57].Recent optimization work confirms that, under dynamic conditions, super-twisting-based controllers offer better performance than conventional MPPT controllers, with lower ripple and greater robustness. [59]. Strong controllers, including ADRC and sliding mode methods, improve MPPT tracking stability through disturbance rejection, reduction of steady-state oscillations, and improved convergence rates [62][68]. However, such controllers increase computational load and parameter-tuning complexity, which might restrict their use in low-cost embedded microcontrollers [59].

5.2 Hybrid Embedded MPPT Enhancements

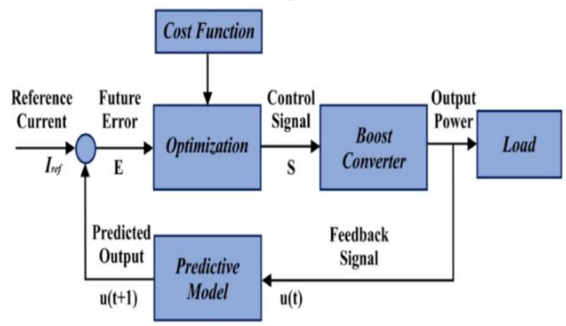
In addition to robust controllers, hybrid embedded MPPT controllers have been proposed to integrate classical and nonlinear or metaheuristic aids .For instance, the hybrid INC–SMC has been experimentally demonstrated in a grid-connected PV system to achieve much higher tracking efficiency and a quicker settling time than either of these two methods[10].Furthermore, LADRC-based hybrid optimization algorithms, such as Horse Herd Optimization (HHO) combined with LADRC, are superior to conventional MPPT, achieving faster global peak attainment and smoother steady-state ripples under partial shading[19].Also, state-of-the-art super-twisting sliding-mode controllers developed for grid-connected PV systems demonstrate that hybrid robust MPPT should be considered an important path toward future embedded PV infrastructure. [65]. Developed MPPT schemes tend to feature prediction and optimization control layers to improve tracking precision and dynamic performance. In Figure 4, a predictive control scheme is shown that employs cost-function optimization and model-based estimation to adjust the boost converter duty cycle in response to changing irradiance[12][66].

Conclusion The work presents several case studies that confirm that modern, advanced, robust, and hybrid controllers resolve classical embedded MPPT limitations by: improving tracking speed, minimizing oscillatory motion, and stabilizing operation in cyber-physical PV systems.

Comparative evaluation with other recent works proves that ADRC-based as well as hybrid MPPT offer advantageous features over traditional P&O and INC in terms of tracking ratio, ripple amplitude elimination, transient stability, especially under the conditions of partial shading/dynamic irradiance, which identifies their relevance for future implementations in a new generation embedded photovoltaic systems [6][19][71][72].

These results inspire the design of centralized cyber-physical MPPT frameworks that integrate embedded control, enhanced robustness, and IoT-connected supervisory intelligence, as described in the next section.

Figure (4): Architecture of MPPT control based on predictive optimization, which combines cost-function-based optimization with model-



based converter control [12].

6 - Proposed Cyber-Physical Embedded MPPT Architecture

Compared with what is found in the comparative summary of this review, classical MPPT techniques are found to be inadequate for future photovoltaic infrastructure.Thus, id cyber-physical, centralized MPPT implementation incorporating ADRC-based stabilization enhancement, edge-level address immediate and decentralized PV supervision requirements, this paper recommends edge-level intelligence, and secure IoT communication. According to literature analysis, traditional integrated MPPT techniques (P&O and INC) have been proven to be an applicable solution for low-cost PV systems. But present-day PV systems need comprehensive cyber-physical emulation frameworks that integrate real-time embedded control and robust stability on the one hand, and secure IoT-based supervision on the other. Recent research has shown that the lack of an end-to-end co-design approach that integrates robust control, edge intelligence, and secure communication into a scalable MPPT solution is a major drawback in state-of-the-art MPPT implementations. As such, a cyber-physical embedded MPPT framework is

Table 4. A Comparison between classical and robust embedded MPPTs in the latest literature

Author (Year) [Ref]	Method	Validation	Performance Gain	Main Limitations
Wang et al. (2024) [6]	ADRC for PV Grid-Connected Inverters	Simulation	Improved disturbance rejection and dynamic stability	Requires controller tuning
Liu et al. (2024) [23]	LADRC + VSG for Grid-Forming PV	Simulation	Enhanced robustness under disturbances, stable MPPT-linked operation	Parameter tuning complexity
Contreras-Carmona et al. (2024) [7]	Super-Twisting Sliding Mode MPPT	Simulation	Ripple-free tracking and fast convergence vs INC/P&O	Higher computational effort
Dunna et al. (2024) [47]	Higher-Order Sliding Mode Observer MPPT	Simulation + Experimental	Reduced steady-state oscillation and rapid settling time	Implementation complexity
Mohapatra et al. (2024) [48]	Optimized Super-Twisting Controller for PV	Simulation	Outperforms classical MPPT under dynamic irradiance	Not fully tested in large-scale PV
Ibrahim et al. (2025) [19]	Hybrid LADRC-HHO Global MPPT	Simulation	Fast global peak convergence and minimized ripples	Metaheuristic computation cost
Zahran et al. (2024) [51]	Hysteresis Super-Twisting MPPT Algorithm	Simulation	Improved tracking speed and reduced oscillation	Sensitive to tuning parameters
Hybrid INC–SMC Experimental Study (2024) [10]	INC + Sliding Mode Hybrid MPPT	Experimental	Higher efficiency and shorter settling time than classical INC	Requires careful hybrid design

(2) Robust Stability Layer with ADRC/LADRC

Finally, to suppress oscillations and improve tracking performance under rapid irradiance variations, a robust, stable layer is added using Active Disturbance Rejection Control (ADRC) and Linear ADRC (LADRC). These disturbance-rejection controllers provide superior transient tracking speed, minimum steady-state ripple, and improved inverter-level dynamic stability when compared to conventional MPPT methods [76][77].

(3) IoT Communication and Control Connected Securely

Robust communication: Secure communication between distributed PV monitoring nodes and supervisory dashboards is established via a secure IoT layer. Communication technologies such as Wi-Fi, LoRaWAN, and MQTT enable scalable smart PV infrastructure. Recent secure LoRaWAN-based photovoltaic monitoring solutions illustrate the need for communication, security, and cyber resilience in distributed solar energy systems [45][78].

4) Predictive monitoring and Edge Intelligence

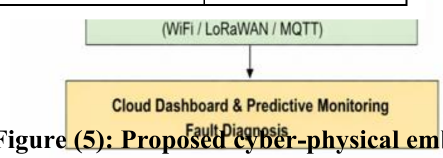


Figure (5): Proposed cyber-physical embedded MPPT architecture [21].

6.2 Practical Relevance for Iraq Deployment

The suggested CP-embedded MPPT algorithm is very practical for photovoltaic deployment in Iraq, because solar installations are subject to extreme environmental factors (dust and temperature gradients) and dramatic variability in solar irradiance. Situations like desert weather in Basra and other central Iraqi sites can induce significant operational disruptions, necessitating reliable ADRC/LADRC and IoT-enabled predictive monitoring to maximize power extraction and long-term PV plant surveillance. It follows that Iraq is proving to be a good case study in the real world to test the efficiency of IoT-supported MPPTs. systems. Such systems can improve photovoltaic reliability, predict maintenance schedules, and maintain the operational stability of a large desert solar field[21][81][82].

Table 5. Challenges and Future Research Needs for Embedded IoT-Based MPPT Systems

Challenge Category	Current Limitation	Future Research Need	Key Refs
End-to-End Co-Design Gap	MPPT control, IoT connectivity, and robust enhancement are often developed separately rather than as unified embedded architectures.	Develop integrated ESP32-based cyber-physical MPPT frameworks combining control + monitoring + edge intelligence.	[14][45]
Limited Real-Time Adaptability	Classical P&O/INC suffer from oscillations, ADC noise, sampling delays, and reduced accuracy under rapid irradiance transitions.	Design adaptive hybrid embedded controllers with fast convergence and ripple-free tracking.	[17][20] [25]
Cybersecurity Absence	IoT monitoring platforms lack secure communication layers and protection against cyber-attacks in distributed PV deployments.	Implement encryption, secure LoRaWAN/MQTT protocols, and resilience strategies for PV IoT networks.	[45]
Experimental Validation Scarcity	Many robust/AI MPPT enhancements remain simulation-based with limited hardware testing in realistic harsh climates.	Increase experimental prototypes and field deployments in environments such as Iraq (Basra deserts).	[29][43] [109]
Scalability and Cost Constraints	Advanced robust control increases computational burden for low-cost microcontrollers.	Optimize lightweight robust MPPT algorithms suitable for ESP32-class devices.	[14][19]

7-Challenges and Research Gaps

However, some crucial issues remain unsolved, including embedded MPPT control and IoT-supervised photovoltaic infrastructure. Existing solutions have yet to provide a complete end-to-end solution with reinforced control, embedded cognition, and secure IoT communication, which constitutes an obstacle to the realisation of next-generation MPPT architectures in practice [21][45].It does face one big challenge, however: under rapid fluctuations in irradiance, classical embedded algorithms such as P&O and INC have very low real-time adaptability. Internal constraints such as finite ADC resolution, sampling time delays, and transducer noise enhance steady-state oscillations and diminish tracking accuracy in dynamic situations [17][25].Another chronic deficiency remains the lack of cybersecurity embedded in IoT-based PV monitoring systems. Though communication network technologies such as WiFi, LoRaWAN, and MQTT support intelligent monitoring, most current research lacks secure protocols and encryption methods, or reliable security measures against adversarial attacks, which leads to the destruction of PV systems in distributed installations[45].Last but not least, experimental verification remains poor, and many sophisticated, robust, and AI-based MPPT techniques are only demonstrated in pristine simulation setups with little to no large-scale real-world application, especially under very severe conditions such as those in Iraq [29][10][83].

8-Future Directions and Iraq Deployment

The direction of embedded MPPT development is increasingly moving toward real-world cyber-physical photovoltaic systems, unifying low-cost microcontroller-based control with secure IoT-based monitoring and adaptive intelligence. This is especially significant for areas like Iraq, where there is a rapidly growing deployment of large PV systems in severe climatic conditions with high solar radiation variability and high air and dust temperatures .Photovoltaic plants in Iraq need cost-effective, flexible monitoring systems to validate maximum power point tracking and monitor system operation. Low-cost embedded systems, like the ESP32, are a cost-effective option because they can perform MPPT in real time and include wireless connectivity, allowing remote visualization of PV parameters and supervising data via cloud implementation [14].Furthermore, future PV systems in Iraq should incorporate robust IoT communication technologies (e.g., LoRaWAN and secure wireless protocols) to ensure the cyber-secure operation of distributed PV systems. Recent secure monitoring studies on low-cost PV emphasize the need to incorporate communication security and robustness components into smart PV installations [45][83].Moreover, the introduction of edge-level intelligence and predictive monitoring is also important for in-depth insights. Enhanced tracking efficiency, reduced ripple factor, and stronger adaptability to erratic isolation transition can be achieved by the hybrid embedded MPPT scheme with robust controller (e.g., ADRC/LADRC), as well as lightweight AI-based forecasting[6].Therefore, the implementation of integrated embedded MPPT–IoT platforms in Iraq, specifically in the desert region such as Basra, is a key focus for future experimental measurements and the establishment of scalable PV farm monitoring. Such initiatives will contribute to the provision of robust, stable, and smart photovoltaic installations that are responsive to local geographic conditions.

Conclusion

This systematic review delivered a unifying bottom-up perspective on maximum power point tracking (MPPT) for photovoltaic systems from an embedded systems standpoint, focusing on low-cost microcontroller platforms and analyzing the classical Perturb & Observe (P&O) and Incremental Conductance (INC) algorithms, tracing their evolution toward IoT-enabled smart PV deployments. The review also acknowledged that classical embedded MPPT methods are still interesting for their simplicity and low computational cost, but are nevertheless severely limited by steady-state oscillations (lack of smooth tracking), poor adaptability to transient, rapid irradiance changes, and hardware limitations such as finite ADC resolution and sampling lags. Furthermore, modern robust and hybrid-based enhancement techniques such as ADRC/LADRC and sliding mode controllers were found to outperform traditional methods, with reduced ripple magnitude, improved settling time, and better performance under dynamic operating conditions. Moreover, IoT-based monitoring layers using ESP32 and LoRaWAN, coupled with wireless cloud dashboards, have turned embedded MPPT power systems into smart cyber-physical infrastructures with real-time supervision, predictive monitoring, and scalable deployment. Finally, this review proposed an integrated, secure, cyber-physical, embedded MPPT architecture comprising ESP32-based edge control, robust ADRC-based stability improvement, secure IoT communication, and predictive monitoring. This approach is especially appropriate when deploying PV systems in extreme climates such as those in Iraq, whose desert terrain and variations in irradiance levels require stable, low-cost, and adaptive photovoltaic monitoring tools. More generally, embedded MPPT research is evolving toward next-generation smart PV systems with stringent control, secure IoT communications, and edge intelligence as core elements for constructing resilient and efficient PV energy infrastructures.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Waleed Abdulazeez Ahmed: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Visualization. **Montassar Aidi Sharif:** Supervision, Writing – review & editing, Validation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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