

MPPT in Solar Photovoltaic Systems with AI Modules for Partial Shading Conditions

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Abstract - This paper introduces an AI-driven MPPT framework designed to address real-time power optimization challenges caused by PSCs. The system consists of five interconnected modules: contextual hierarchical transfer graph embedding (CHTGE) is used for transfer learning across various environmental conditions through policy graphs based on shading history and weather context. The spatio-temporal feature attention-based indexing (STFAI) module aids in detecting transient phenomena by using attention maps that are temporally synchronized and derived from real-time multimodal sensor data. In the third module, differential contextual residual optimization (DCRO) corrects inaccuracies and achieves rapid stabilization by applying residual corrections in highly variable environments. Outputs from conventional MPPT methods are enhanced with multi-agent decision fusion using quantum-inspired adaptive logic (MADF-QAL). Evolution-based causal disentanglement networks (ECDN) offer fault localization and explainability through latent representation. The proposed framework offers an interpretable, resilient, and intelligent MPPT control suitable for real-world operating conditions.

Keywords - Photovoltaic systems, Partial shading, Maximum power point tracking, Artificial intelligence, Causal inference.

1. Introduction

The power output of photovoltaic (PV) energy systems is significantly impacted by changing operating conditions, with partial shading being a major factor influencing the energy harvested. Partial shading can occur due to various reasons, such as shadows from nearby buildings, trees, cloud cover, or seasonal weather changes. These elements lead to multiple local peaks in the power-voltage curve of PV arrays. Consequently, traditional Maximum Power Point Tracking (MPPT) methods struggle to identify the global maximum power point, resulting in suboptimal use of PV resources. Classical MPPT algorithms, including Perturb and Observe (P&O), Incremental Conductance (IC), and various fuzzy logic and neural network-based controllers, are limited in adapting to such conditions when faced with dynamic and uncertain environments. They rely heavily on instantaneous measurements and heuristic decisions, which cannot be universally applied across different settings or distinguish between temporary anomalies and consistent patterns in system behaviour. Additionally, these

methods often operate independently and fail to leverage multiple tracking modalities or integrate environmental context, domain knowledge, or passively gathered historical data.

The challenges of resilience, efficiency, and interpretability of MPPT controllers in partial shading conditions remain unresolved in current PV energy research. To overcome these challenges, this study introduces a novel AI Integrated MPPT architecture designed for joint learning, reasoning, and control [4, 5, 6], providing the system with real-time adaptability and enhanced interpretability under complex partial shading scenarios. This framework includes advanced components such as Contextual Hierarchical Transfer Graph Embedding (CHTGE) for facilitating knowledge transfer, Spatio-Temporal Feature Attention Indexing (STFAI) for identifying transient phenomena, Differential Contextual Residual Optimization (DCRO) for improving adaptive convergence, Multi-Agent Decision Fusion using quantum-inspired adaptive logic (MADF-QAL) for achieving consensus control, and Evolutionary Causal Disentanglement Networks (ECDN) to ensure post-hoc explainability.

1.1 Motivation and Contribution

The impetus for this work stems from the swift and unpredictable environmental changes that cause partial shading and diminish the operational efficiency of solar PV arrays. Traditional approaches struggle with overcoming multiple local maxima, exhibit slow tracking speeds, and suffer from energy losses due to steady-state oscillations around the maximum power point. Additionally, the absence of context awareness complicates the differentiation between transient disturbances and systemic variations, posing an extra challenge for conventional algorithms. In applications critical to grid and safety, current methods fall short in providing explainability and fault traceability.

2. Review of Existing Models used for MPPT in PV Analysis

RPV research employs smooth and IMPI techniques in the hybrid training of a three-phase interleaved boost converter to stabilize tracking during Load Poise Shading transitions, though it relies significantly on deterministic switch control. Kanth et al. [2] applied Sovereign Butterfly Optimization to a flyback converter designed for optimizing challenges presented by more intense irradiance gradients. Nonetheless, the system's capacity

to adjust to long-term context drift remains notably constrained. Aron and Louis [3] implemented the controller using intelligent optimization, yet parameter tuning complicates static options and limits adaptability across different seasons and locations. Siddique et al. [4] expanded on this work by validating global MPPT strategies under complex PSCs within a comparative framework, but the aspect of real-time transferability was not thoroughly addressed. In their research, Wang et al. [5] introduced an enhanced White Shark Optimizer for MPPT, achieving faster convergence rates, although it still demands substantial computational resources during initialization. El Iysaouy et al. [6] modeled PV panel configurations under shading, providing some physics-based insights but lacking adaptable control sets.

Reference	Method	Main Objectives	Findings	Limitations
1]	Hybrid MPPT with 3-Phase Interleaved Boost	Stabilize MPPT under PSC using converter-based hybrid strategy	Improved dynamic tracking and power smoothing	Converter design complexity and limited adaptability to fast irradiance shifts
2]	Sovereign Butterfly Optimization + Flyback	Enhance MPPT resilience under shading via metaheuristics and converter control	High power extraction efficiency in lab conditions	High sensitivity to parameter tuning, lacks scalability
3]	Intelligent Optimization-Based MPPT	Introduce intelligent control for shaded PV environments	Improved performance under structured PSC	Static parameters limit adaptability
4]	Global MPPT Validation under Complex PSC	Assess GMPPT algorithms under realistic shading	GMPP T methods show higher energy yield than local MPPT	Real-time responsiveness not addressed
5]	Improved White Shark Optimizer	Increase tracking accuracy using WSO metaheuristic	Enhanced global search with better convergence	High initial overhead, not ideal for low-power systems

6]	Panel Configuration Modeling under PSC	Model PV behavior under shading for design enhancement	Improved understanding of physical mismatch loss	No integrated control strategy included
7]	Hybrid Global Search + Enhanced INC	Combine INC with global search to improve convergence	Faster tracking in multiple PSC patterns	Still trapped in local maxima under noisy conditions
8]	Zebra Optimization-Based MPPT	Apply nature-inspired ZOA for MPPT validation	Strong lab-tested performance across standard test cases	Real-world dynamic input performance not assessed
9]	Hybrid MPPT Controller	Design MPPT controller adaptable to various PSC types	Good tracking accuracy across tested PSCs	Lacks online learning or fault adaptation
[10]	Metaheuristic MPPT for Complex PSC	Enable robust tracking under severe PSC	Outperformed traditional MPPT under complex patterns	Computational load is high
[11]	Fuzzy Logic MPPT	Enhance MPPT via fuzzy rule systems	Effective in moderate PSCs, interpretable decisions	Performance degrades in high-dimensional input spaces
[12]	Fuzzy-PI + PSO MPPT	Combine fuzzy logic and PI with PSO tuning	Smooth convergence with moderate complexity	Slower training phase and moderate generalizability
[13]	War Strategy Optimization	Introduce fast global MPPT via WSO metaheuristic	Good convergence and low overshoot	No explanation mechanism or traceability
[14]	Adaptive Neuro-Fuzzy	Improve tracking with	Promising performance under	Resource-intensive and sensitive

	Inference System	adaptive NFIS learning	various PSC	to training data quality
[15]	CG FSSO MPPT	Apply swarm-based cooperative Salp Swarm logic	Good global convergence rate	Lacks causal interpretability and human-in-the-loop design

Table 1. Model's Empirical Review Analysis

Initially, according to Table 1, Zaki et al. [7] introduced a hybrid global search method that incorporates enhanced Incremental Conductance (INC) to adjust the balance between exploration and exploitation. However, it remains influenced by compensating local optima in highly stochastic shading profiles. Abdelmalek et al. [8] explored and confirmed the effectiveness of a zebra optimization algorithm under laboratory-controlled PSCs, highlighting its robustness, though its deterministic nature remains rigid and necessitates manual calibration. Hussaian Basha et al. [9] tackled this issue by suggesting hybrid MPPT controllers that adjust to shading profiles, yet they did not focus on integrating real-time feedback. Kishore et al. [10] developed metaheuristic-based controllers suitable for both simple and complex PSCs, aligning with the current trend of hybridizing search strategies. Kumar and Balakrishna [11] developed a fuzzy-logic-based MPPT system that relied heavily on rule-based structures for better interpretability, but it faced rule saturation when dealing with high-dimensional input conditions. Zaghba et al. [12] addressed this challenge by combining fuzzy logic with a PI controller and optimizing the structure using PSO, which resulted in smoother transitions but required extensive training periods. Alshareef [13] presented the War Strategy Optimization algorithm to achieve rapid MPPT convergence, yet offered limited analytical insights into environmental coupling. Mohammed et al. [14] advanced further with an adaptive neuro-fuzzy inference system, demonstrating promising results under PSCs, though its scalability in edge-deployed PV networks remains untested.

The CGFSSO developed by Raj et al. [15] provides excellent search capabilities for multidimensional shading issues but lacks causal validation in the process.

3. Proposed Model Design Analysis

The integrated MPPT model proposed here is crafted to manage Partial Shading Conditions (PSCs) through a multi-layered framework that employs contextual learning, spatio-temporal attention, residual optimization, decision fusion, and causal disentanglement. This approach ensures control that is robust, adaptive, and interpretable. Modules are interconnected via context-aware data pipelines, culminating in a final decision function that guides the PV system to the global maximum power point (GMPP), even amidst environmental volatility. The process begins with the extraction of contextual input features and concludes with a real-time control signal derived from an optimized, fused policy with residual adjustments, all validated causally in real-time. Let $C(t) \in \mathbb{R}^n$ represent the contextual feature vector at time t , which includes irradiance $G(t)$,

temperature $T(t)$, wind speed $W(t)$, incidence angle $\theta(t)$, and historical MPPT trace embeddings $H(t)$. These features are passed as inputs to the Contextual Hierarchical Transfer Graph Embedding (CHTGE) module, which constructs a directed policy graph $G=(V,E)$, where nodes correspond to state-action pairs, and edges encode transition probabilities modulated by environmental contexts.

Subsequently, the Spatio-Temporal Feature Attention Indexing (STFAI) module processes real time IV and PV curves $V(t)$, $I(t)$, and other auxiliary sensor data to extract high-resolution attention maps. These maps were time-aligned and narrated into the CHTGE module into policy embeddings under transient disturbances. The (DCRO) loop introduces adaptive correction by minimizing the residual error between the expected power output $P_e(t)$ and actual output $P_a(t)$ in the process. Thus, the weighted punishment guarantees more aggressive penalization of larger residuals during critical high Volatile time durations. The learning rate η is adapted dynamically according to factors regarding the stability of the convergence metrics. Multi-Agent Decision Fusion Using Quantum Inspired Adaptive Logic (MADFQAL), as the name the word states, creates decisions from multiple baseline MPPT algorithms $\{\pi_1, \pi_2, \dots, \pi_k\}$. Each decision $d_i(t)$ is treated as a probabilistic quantum state $|\psi_i\rangle$, with fusion modelled as a Hilbert space projection maximizing logical entropy coherence. The ECDN further analyzes periodic system logs to extract the subsidiary causes of energy deviation in the process, thereby enhancing interpretability.

4. Comparative Result Analysis

The experimental setup designed to assess the proposed integrated MPPT framework replicates real-world partial shading scenarios using a combination of hardware-in-the-loop (HIL) emulation and synthetic data from environmental sensor networks. The primary power generation component was a PV array model consisting of polycrystalline modules arranged in a 4×6 configuration, each rated at 250 W and equipped with bypass diodes. A programmable solar emulator (Keysight N8937A) was employed to manage the characteristics of the simulated electricity, primarily by mimicking dynamic irradiance profiles. The irradiance level $G(t)$ was varied in real-time between 200 W/m² and 1000 W/m² over a 5-20 second cycle to simulate the effects of cloud movement and urban.

The ambient temperature, $T(t)$, ranged between 15°C and 45°C, while the wind speed, $W(t)$, was artificially varied from 0 to 12 m/s to introduce variability in convective loss. Sensor data comprised sky imagery datasets (256×256 resolution, 2 fps) for estimating cloud density, infrared thermography with a thermal range up to 60°C, and IV/PV curve samplers functioning at a 1 kHz resolution. The angle of incidence, $\theta(t)$, could be adjusted by a virtual solar tracking system from 10° to 80°, mimicking the cycles of morning, noon, and evening. These conditions were aligned with historical weather data from the National Solar Radiation Database (NREL) for contextual relevance. The modules were modeled using MATLAB-Simulink software.

The simulations included real-time conditions and sampling with a contextual dataset. Five unique environmental scenarios were created from clusters of historical meteorological profiles sourced from the NSRDB and Solar Anywhere databases. For example, Context A depicted profiles with low ambient

temperatures and consistent irradiance (e.g., 950 W/m², 18°C, clear sky index >0.95). Context B simulated rapid changes in sun irradiation due to shadows (400-900 W/m² within 30 seconds) during urban edge occlusion. Context C was characterized by high-humidity coastal mornings with moderate irradiance enhanced by fog (average 650 W/m², increased aerosol optical depth). Meanwhile, Context D was designed for desert over-irradiation combined with significant convective cooling (peak irradiance reaching 1,050 W/m², 42°C, 8 m/s wind). Context E concerned overcast winter mid-latitude scenarios with diffuse irradiance (300–500 W/m², 8°C, and low sky clearness index). In each context, the policy graphs were initialized by the CHTGE module at historical trajectories and environmental embeddings, anomaly heatmaps were produced by STFAI through sky images and irradiance signals, residual weights were updated in iterative response to mismatches detected in power output by DCRO, and multiple algorithmic decisions from Perturb & Observe, Incremental Conductance, and Fuzzy Rule Sets were fused by MADF-QAL Sets. System causality is assessed with this ECDN component in periodic activities over 30-minute windows in the process. All experiments were run within a 24-hour simulation period to evaluate the performance of the power tracking accuracy, false MPPT trigger rate, convergence latency, and root-cause localization timestamp instance sets.

The datasets used in this research were obtained from the National Solar Radiation Database, which is maintained by the U.S. NREL. This resource offers detailed solar and weather data. The NSRDB dataset includes hourly and sub-hourly records of global horizontal irradiance (GHI), direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), temperature, wind speed, relative humidity, and metadata about solar positioning. For this study, data were collected from various geographical areas, specifically Denver (high altitude, less humid), San Diego (coastal), and Houston (humid subtropical), across different seasons to demonstrate diverse shading and environmental patterns. Using these 5-minute time intervals, we created comprehensive context vectors and dynamic simulations to emulate partial shading with a spatial resolution of about 4 km. Additionally, sky imagery and thermographic datasets were acquired from the Solar Forecast Arbiter (SFA), offering timestamp-synchronized sky images and thermal camera data suitable for real-time anomaly detection.

Hyperparameters for various AI modules within the programmed framework were determined through a cross-validated grid search combined with context-aware tuning methods. For the CHTGE module, graph convolutional layers were configured with hidden dimensions of [128, 64], ReLU activation, a learning rate of 0.001, and an embedding update frequency set at every 60 seconds. The STFAI attention module implemented a temporal sliding window of 20 time steps, an attention head size of 8, and a dropout rate of 0.2 to mitigate overfitting. Regarding DCRO, the residual convergence controller utilized a dynamic learning rate adjusted by volatility indices, starting with a step size of 0.005 and an update threshold at a power deviation margin of 2.5% from the baseline.

The MADF-QAL decision fusion module applies entropy-weighted majority logic with a smoothing factor of 0.1 and normalized entropy thresholds fixed at 0.3 for propagating high-

confidence decisions. Lastly, the ECDN was trained using an LSTM-based encoder-decoder with a latent size of 64, over 50 epochs, incorporating early stopping (patience = 5), and the Adam optimizer with a learning rate of 0.0005. These hyperparameter settings ensured optimal learning, adaptation, and explainability across various PSC scenarios.

The performance of the proposed integrated MPPT model was evaluated under a broad spectrum of environmental conditions. Multiple datasets representing these diverse scenarios were sourced from the NSRDB and Solar Forecast Arbiter. The outcomes were also compared with the performances of three representative state-of-the-art MPPT methods from the literature, referred to as Method [2], Method [8], and Method [11]. These correspond to the Incremental Conductance, Particle Swarm Optimization, and Fuzzy Logic MPPT techniques, respectively. Each experimental setup was crafted to represent a specific type of partial shading behavior, including very rapid transients, structured occlusions, diffuse scattering, and extreme environmental volatility

The following tables present a summary of the findings, emphasizing crucial metrics like tracking efficiency, convergence time, false trigger rate, energy yield, stability index, and causal fault traceability within the process. Table 2 displays the MPPT tracking efficiencies across five distinct contextual scenarios. In every situation characterized by swiftly changing irradiance and complex shading patterns, the proposed model consistently surpassed the reference methods. Additionally, the incorporation of spatiotemporal attention and residual correction plays a crucial role in minimizing local minima entrapment and achieving more optimal tracking in most instances.

Table 2: MPPT Tracking Efficiency (%) Across Contextual Environments

Cont ext Type	Propo sed Model	Meth od [2]	Meth od [8]	Meth od [11]
Clear Sky	99.1	96.5	95.3	94.8
Rapid Cloud Drift	96.8	88.2	90.5	91.1
Urba n Occlusio n	95.6	87.7	85.3	86.5
Coast al Fog	93.5	82.9	84.6	85.1
Wint er Overcast	94.3	83.5	80.1	81.9

Table 3: Average MPPT Convergence Time (Seconds)

Cont ext Type	Propo sed Model	Meth od [2]	Meth od [8]	Meth od [11]
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Clear Sky	0.8	1.6	2.0	2.3
Rapid Cloud Drift	1.2	3.4	2.9	3.1
Urban Occlusion	1.4	2.8	3.2	3.5
Coastal Fog	1.7	3.5	3.8	4.0
Winter Overcast	1.3	2.9	3.3	3.6

The energy harvested by the PV array over 24 hours of the cycle for each context shows that the proposed model performs well in that process. Integrated frameworks reduce overall energy consumption while improving the results from 8% to 18% in different contexts against the best baselines.

This shows how the system stays operational during normal steady-state operations using the usual measure of the standard deviation of the power output sets. The diminished values for the proposed model indicate that transitions are smoother as well as fewer oscillations, which occur owing to fusion and residual correction mechanisms that eliminate reactive decision bouncing in uncertain contexts.

Table 4: False MPPT Trigger Rate (%)

Context Type	Proposed Model	Method [2]	Method [8]	Method [11]
Clear Sky	0.3	1.4	1.9	2.2
Rapid Cloud Drift	1.1	4.8	3.5	3.7
Urban Occlusion	1.4	5.2	4.3	4.6
Coastal Fog	1.7	5.8	5.1	5.5
Winter Overcast	1.2	4.3	4.0	4.4

Table 5: Daily Energy Yield (kWh)

Context Type	Proposed Model	Method [2]	Method [8]	Method [11]
Clear Sky	6.84	6.55	6.42	6.37

Rapid Cloud Drift	5.92	5.11	5.36	5.48
Urban Occlusion	5.74	5.03	4.85	4.92
Coastal Fog	5.31	4.51	4.66	4.73
Winter Overcast	5.44	4.60	4.39	4.51

5. Conclusion and Future Scope

The study introduces a detailed AI-enhanced framework for maximum power point tracking (MPPT) designed specifically for photovoltaic systems operating under conditions of partial shading. The efficiency of MPPT tracking reached up to 99.1% in completely clear weather and 96.8% when tracking fast-moving clouds. The tracking times were reduced to under 2.5. The rate of false MPPT activations decreased by more than 70%, particularly in environments with significant variability, leading to smoother system operation and enhanced reliability. Depending on the conditions, daily energy yields increased by 8% to 18%, while power stability in a steady state showed significant improvement.

Enhancements can be made by expanding dataset coverage to include tropical, high-altitude, and desert climates, which would improve the model's ability to generalize. Additionally, further research could explore applications related to intelligent microgrids and rural electrification. The method could also be advanced to enable autonomous MPPT decision-making through the integration of federated learning techniques.

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