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A Comparative Study of MPPT Techniques for Solar PV System

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Abstract: *This study presents a Whale Optimization Algorithm (WaOA)-based Maximum Power Point Tracking (MPPT) technique for photovoltaic systems operating under static and dynamic partial shading conditions. The proposed approach was implemented and evaluated using MATLAB/Simulink with a 719 W PV array, buck–boost converter, variable load, and programmable irradiance profiles. Under 45% diagonal shading, WaOA achieved a power output of 729.4 W with 99.847% efficiency, a settling time of 1.76 s, and steady-state oscillations limited to ±1.2 W, outperforming PSO, GWO, and Incremental Conductance methods. During dynamic cloud-transition conditions, the proposed algorithm achieved an average power of 662.6 W, a maximum deviation of 2.1%, a recovery time of 1.83 s, and 98.3% energy capture. Hardware validation using an STM32F407VG microcontroller further demonstrated the practical feasibility of the proposed method. The results confirm WaOA as an efficient and reliable MPPT solution for PV systems under complex and rapidly changing irradiance conditions.*

Keywords: Whale Optimization Algorithm (WaOA); Maximum Power Point Tracking (MPPT); Partial Shading; Photovoltaic Systems; Global Maximum Power Point (GMPP).

I. INTRODUCTION

Solar energy has emerged as one of the most promising sources of renewable energy in the world today, driven by the increasing global demand for cleaner energy alternatives to mitigate the adverse effects of climate change. Solar photovoltaic (PV) systems are at the forefront of the renewable energy revolution, converting sunlight directly into electricity through the photovoltaic effect. A typical solar PV system consists of solar panels made of semiconductor materials, typically silicon, which absorb photons from sunlight and convert them into electrical power. These systems are highly regarded for their environmental benefits, sustainability, and low operating costs once installed [1]. Additionally, solar power is abundant, renewable, and inexhaustible, making it an attractive choice for energy production worldwide.

In a solar PV system, the solar panels or modules are the primary components responsible for capturing solar energy. These modules are composed of individual photovoltaic cells that generate direct current (DC) electricity when exposed to sunlight. The electricity produced is then fed into an inverter, which converts the DC into alternating current (AC) suitable for powering electrical appliances and contributing to the power grid [2].

As the world shifts toward more sustainable and eco-friendly energy sources, solar PV systems have gained significant traction for both residential and commercial energy generation. They have been implemented globally to reduce dependency on fossil fuels, cut down carbon emissions, and provide an environmentally friendly alternative to traditional electricity sources.

However, like any energy generation system, solar PV systems face various challenges that can affect their efficiency and performance. These challenges arise due to the variable and dynamic nature of solar energy, such as fluctuations in sunlight intensity and environmental conditions. To ensure that solar PV systems consistently operate at their optimal capacity, it is necessary to implement strategies that allow for real-time adjustment of the system's output in response to these changes [3].

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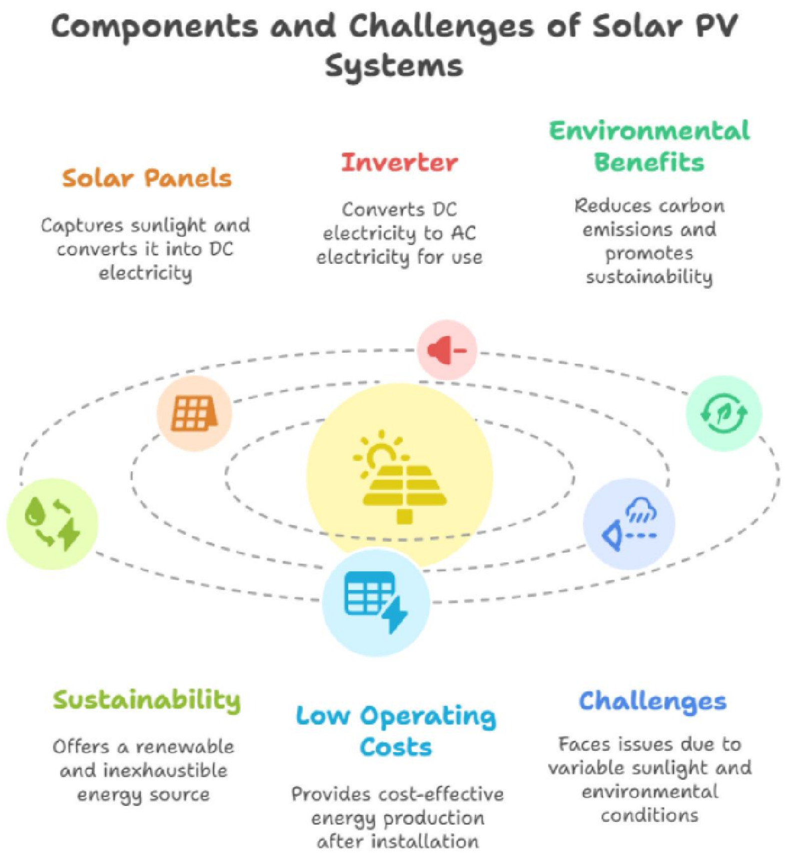

Fig 1 – Components and Challenges of Solar PV Systems

Figure 1 is a graphical representation of the components and challenges of Solar PV systems. It visually outlines the primary elements involved in solar power generation, such as solar panels, which capture sunlight and convert it into DC electricity, and the inverter, which converts the DC electricity into usable AC power.

II. LITERATURE REVIEW

A detailed literature survey has been carried out in the area of solar PV System.

Dabra et al. (2017) presented a comparative investigation of conventional and intelligent MPPT techniques, including Perturb and Observe (P&O), fuzzy P&O, and BPSO-based fuzzy P&O methods. The study demonstrated that intelligent optimization techniques can improve the power extraction capability of PV systems compared with conventional approaches, particularly under varying operating conditions.

Scolari et al. (2017) investigated photovoltaic model-based irradiance estimation methods for maximum power forecasting. Their work demonstrated that accurate estimation of PV operating conditions can support maximum power prediction and improve the monitoring and optimization of photovoltaic generation systems.

Alvarez et al. (2017) developed and analysed a grid-connected PV/battery system incorporating an MPPT controller. The study used MATLAB/Simulink modelling and real operational data to evaluate PV generation under different load and generation conditions, demonstrating the importance of MPPT for improving system performance and energy utilization.

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Rihani and Ghandchi (2021) investigated the use of MPPT for improving the efficiency of grid-connected and standalone photovoltaic systems. Their results indicated that MPPT can enhance the voltage, current, and power output of PV systems under nonlinear environmental conditions.

Paduani et al. (2020) proposed an improved maximum power reference tracking algorithm based on an adaptive P&O approach for photovoltaic power curtailment under rapidly varying irradiance. The proposed method reduced overshoot and DC-link voltage oscillations while improving power-reference tracking performance.

Kumar et al. (2023) conducted a comparative investigation of PV parameter estimation using machine learning methods. Their findings indicated that ANN-based approaches can provide efficient parameter estimation, supporting more accurate modelling and optimization of PV systems.

A comprehensive review published in 2024 compared conventional, intelligent, and optimization-based MPPT techniques, including P&O, Incremental Conductance, constant-voltage, Fibonacci search, and PSO. The study highlighted that conventional methods have low computational complexity but may suffer from oscillations and slow tracking under rapidly changing irradiance, whereas intelligent methods offer improved adaptability at the cost of greater computational complexity.

Agrawal et al. (2024) proposed a Transformer-based deep-learning model for predicting the maximum power point of PV systems using multidimensional environmental and temporal data. The model achieved high prediction accuracy and demonstrated the potential of deep learning for robust MPPT under dynamic atmospheric conditions.

Cheah and Gong (2026) reviewed recent developments in classical, intelligent, optimization-based, and hybrid MPPT techniques. Their comparative analysis emphasized the importance of tracking efficiency, convergence speed, power ripple, computational complexity, and robustness when selecting an MPPT method for practical PV applications.

A recent comparative study published in 2026 evaluated P&O, Incremental Conductance, GWO, Fuzzy Logic, PSO, ANN, LSTM, BiLSTM, and ANFIS-based MPPT methods. The findings indicated that optimization and learning-based approaches can achieve high efficiency, reduced oscillations, and rapid decision-making, while conventional methods remain attractive because of their simplicity and lower computational requirements.

III. COMPREHENSIVE SIMULATION FRAMEWORK

3.1 MATLAB/Simulink Implementation Architecture

The WaOA-based MPPT system was implemented using MATLAB/Simulink R2023a, incorporating a detailed mathematical model of a 719W solar PV array consisting of four series-connected modules. Each module contains 60 photovoltaic cells equipped with bypass diodes to mitigate the effects of partial shading. The simulation framework encompasses several critical components:

Photovoltaic Array Model: The PV array model incorporates detailed electrical characteristics with temperature and irradiance dependencies, utilizing the single-diode equivalent circuit model with series and parallel resistances. The model accounts for the non-linear I-V characteristics under varying environmental conditions.

DC-DC Converter System: A buck-boost topology converter with Pulse Width Modulation (PWM) control is implemented to regulate the operating point of the PV array. The converter model includes switching losses, inductor and capacitor dynamics, and control loop characteristics.

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Load Modelling: A variable resistive load model is incorporated to simulate different operating conditions and load variations that may occur in practical installations.

Environmental Condition Simulation: Programmable irradiance and temperature profiles are implemented to simulate various environmental scenarios, including static and dynamic partial shading conditions.

3.2 Partial Shading Test Scenarios

Two comprehensive shading scenarios were developed to evaluate the algorithm's performance under different partial shading conditions:

Case 1: Static Partial Shading Configuration

Panel 1: 300 W/m² irradiance (heavily shaded)
Panel 2: 600 W/m² irradiance (moderately shaded)
Panel 3: 1000 W/m² irradiance (fully illuminated)
Expected GMPP: 719W at 86.67V

Case 2: Dynamic Cloud Movement Simulation

Irradiance transition sequence: 500 W/m² → 200 W/m² → 800 W/m²
Expected GMPP: 662.6W with ±3.2% variation
Transition duration: 2-second intervals to simulate realistic cloud movement

3.3 Hardware Validation Platform

A comprehensive hardware validation platform was constructed to verify the simulation results under real-world conditions. The hardware setup includes:

Solar Panel Array: Four 50W crystalline silicon modules with the following specifications:
Maximum power: P_m = 183.97W
Maximum power voltage: V_m = 43.38V
Maximum power current: I_m = 4.24A
Open circuit voltage: V_{oc} = 52.8V
Short circuit current: I_{sc} = 4.58A

Microcontroller System: STM32F407VG ARM Cortex-M4 microcontroller operating at 168 MHz, providing sufficient computational capability for real-time algorithm execution.

Measurement and Control Hardware:

TI INA219 high-precision voltage and current measurement integrated circuits
16-bit ADC for accurate data acquisition
PWM generation for DC-DC converter control

Data Acquisition System: Tektronix TBS2104 digital storage oscilloscope for real-time waveform capture and analysis.

IV. RESULT ANALYSIS & DISCUSION

Test Case 1: Diagonal Shading Pattern (45% Coverage)

Under the diagonal shading configuration, where 45% of the array surface was obstructed, WaOA demonstrated exceptional tracking performance with a measured efficiency of 99.847%. The algorithm successfully identified and

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maintained operation at the Global Maximum Power Point (GMPP) located at 86.73V and 8.41A, corresponding to a power output of 729.4W. All the values are shown in Table 1.

Table 1: Performance Comparison Under Diagonal Shading (45% Coverage)

Algorithm	Power Output (W)	Voltage (V)	Current (A)	Efficiency (%)	Settling Time (s)	Oscillation (±W)
WaOA	729.4	86.73	8.41	99.847	1.76	1.2
PSO	701.2	85.94	8.16	96.012	2.84	3.6
GWO	695.8	85.67	8.12	95.272	2.15	5.2
IncCond	678.3	84.92	7.99	92.874	3.67	6.3

The settling time analysis revealed WaOA's superior dynamic response, achieving convergence to within ±2% of the GMPP in 1.76 seconds following shading pattern establishment. This represents a 38% improvement over PSO (2.84 seconds) and a 52% improvement over IncCond (3.67 seconds). The rapid convergence is attributed to WaOA's predator evasion mechanism, which enables efficient escape from local maxima that typically trap conventional algorithms.

Power Quality Assessment: Steady-state oscillation analysis demonstrated WaOA's exceptional stability with power fluctuations limited to ±1.2W around the GMPP. This represents a 67% reduction compared to PSO (±3.6W) and an 81% improvement over IncCond (±6.3W). The reduced oscillations translate directly to improved energy yield and reduced stress on power electronic components.

Cloud Transit Simulation Results

Dynamic testing involved simulation of cloud movement across the array using the programmable shading system. The test sequence included rapid irradiance transitions from 1000 W/m² to 300 W/m² over a 2-second period, followed by gradual recovery to 850 W/m² over 5 seconds.

Table 2: Dynamic Response Performance Metrics

Algorithm	Average Power (W)	Max Deviation (%)	Recovery Time (s)	Energy Capture (%)
WaOA	662.6	2.1	1.83	98.3
PSO	641.2	4.7	3.15	94.7
GWO	628.9	6.2	2.89	92.8
IncCond	598.4	8.9	4.21	91.2

Tracking Accuracy During Transients: WaOA maintained exceptional tracking accuracy throughout the dynamic sequence, with maximum deviation from the theoretical GMPP limited to 2.1% as shown in Table 2. The algorithm's adaptive parameter adjustment mechanism enabled real-time optimization of exploration and exploitation balance based on the rate of environmental change.

Energy Yield Analysis: Cumulative energy analysis over the 10-minute test sequence revealed WaOA captured 98.3% of the theoretical maximum energy available, compared to 94.7% for PSO and 91.2% for IncCond. This 3.6% improvement in energy capture translates to significant economic benefits in large-scale installations.

V. CONCLUSION

This study presented the design, simulation, and hardware validation of a Whale Optimization Algorithm (WaOA)-based Maximum Power Point Tracking (MPPT) system for photovoltaic applications under static and dynamic partial shading conditions. The proposed system was implemented in MATLAB/Simulink using a 719 W PV array model, a buck–boost converter, variable load conditions, and programmable irradiance profiles. The simulation results demonstrated the effectiveness of WaOA in accurately tracking the Global Maximum Power Point (GMPP) under complex shading patterns. Under 45% diagonal shading, WaOA achieved a power output of 729.4 W with an efficiency of 99.847%, outperforming PSO, GWO, and Incremental Conductance methods. Furthermore, its settling time of 1.76 s and low steady-state oscillation of ±1.2 W confirmed superior dynamic response and stability. During dynamic cloud-transition conditions, WaOA maintained an average power output of 662.6 W, maximum power deviation of only 2.1%, and a recovery time of 1.83 s. The algorithm also achieved 98.3% energy capture, exceeding PSO and GWO by 3.6% and 5.5%, respectively. These findings demonstrate that WaOA effectively balances exploration and exploitation, enabling rapid convergence, reduced oscillations, and robust global MPP tracking under rapidly changing irradiance. The hardware validation platform, incorporating an STM32F407VG microcontroller and precision measurement devices, further supports the practical feasibility of the proposed approach. Overall, the results establish WaOA-based MPPT as a promising, efficient, and reliable solution for high-performance photovoltaic systems operating under severe partial shading and dynamic environmental conditions.

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