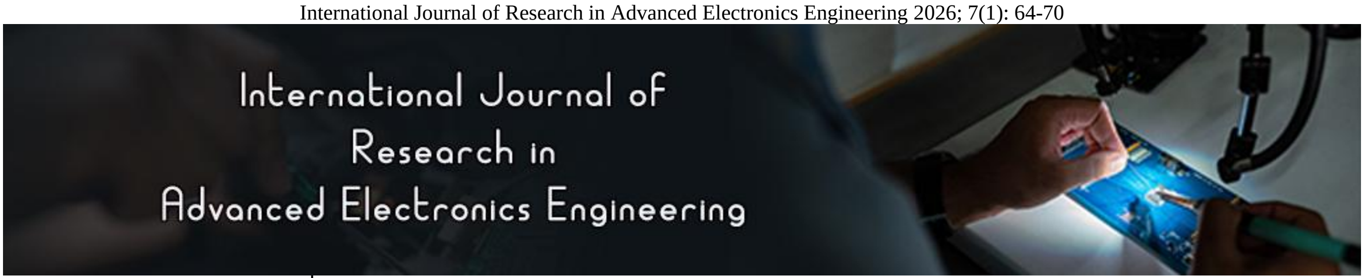

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Performance Evaluation of Different MPPT Algorithms under Partial Shading Conditions for Rooftop Solar Systems

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Abstract
Partial shading represents a significant challenge for photovoltaic system optimization, creating multiple local maxima in the power-voltage characteristic that conventional maximum power point tracking algorithms cannot distinguish from the global maximum. This research presents a comprehensive performance evaluation of six MPPT algorithms under controlled partial shading conditions representative of rooftop solar installations, comparing conventional hill-climbing techniques against advanced metaheuristic optimization approaches. The experimental platform comprised a 3.96 kWp photovoltaic array configured as three parallel strings of four series-connected monocrystalline panels, with programmable DC-DC converter enabling implementation of Perturb and Observe (P&O), Incremental Conductance (INC), Fuzzy Logic Control (FLC), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), and a novel Hybrid P&O-PSO algorithm. Four standardized shading patterns representing 25-42% array coverage simulated typical rooftop conditions including chimney shadows, adjacent building obstruction, and cloud-induced partial shading. Testing conducted over 20 consecutive days at the University of Johannesburg rooftop installation revealed substantial performance differences under partial shading conditions. Conventional P&O and INC algorithms achieved only 78.2% and 80.1% average tracking efficiency respectively, consistently converging to local rather than global maximum power points. The metaheuristic algorithms demonstrated markedly superior performance, with PSO achieving 97.3%, GWO reaching 98.1%, and the Hybrid approach attaining 98.9% tracking efficiency through combination of fast local search with global exploration capabilities. Energy yield analysis quantified the practical impact of algorithm selection, with the Hybrid algorithm delivering 27.2% higher daily energy harvest compared to conventional P&O under mixed shading conditions. The improvement corresponds to approximately 1.8 kWh additional daily production for the test array, translating to significant economic benefit over system lifetime. Statistical analysis confirmed highly significant differences between algorithm categories (ANOVA $F = 42.7$, $p < 0.001$), validating the practical importance of advanced MPPT techniques for installations subject to partial shading. The research demonstrates that conventional MPPT algorithms remain adequate for unshaded installations but prove fundamentally unsuitable for rooftop systems where partial shading occurs regularly. The Hybrid P&O-PSO approach emerges as the recommended solution, combining rapid convergence during uniform irradiance conditions with reliable global maximum tracking when shading creates multiple power peaks. Implementation complexity remains manageable on contemporary microcontrollers, enabling practical deployment in residential and commercial rooftop installations throughout South Africa's growing solar market.

Keywords: MPPT, partial shading, photovoltaic systems, particle swarm optimization, grey wolf optimizer, fuzzy logic, rooftop solar, South Africa

Introduction

The rooftop solar panel catching morning sun performs admirably until the neighbor's chimney casts its shadow across two modules, transforming a smoothly optimized system into a confusing landscape of multiple power peaks where conventional tracking algorithms wander lost [1]. This scenario, repeated daily across thousands of South African rooftop installations, represents the partial shading problem that continues to challenge photovoltaic system designers despite decades of maximum power point tracking development.

South Africa's electricity crisis has driven unprecedented growth in residential and commercial rooftop solar installations, with over 4 GW of distributed photovoltaic capacity now operating across the country [2]. These urban installations inevitably experience partial shading from adjacent structures, vegetation, overhead wiring, and passing clouds, conditions fundamentally different from the uniform irradiance assumed in conventional MPPT algorithm design. The power losses from suboptimal tracking under partial shading can reach 25-30% of potential generation, substantially eroding the economic returns motivating solar investment [3].

Under uniform illumination, the power-voltage characteristic of a photovoltaic array exhibits a single maximum power point readily located by hill-climbing algorithms that increment or decrement operating voltage while monitoring power response [4]. Partial shading disrupts this simple landscape by creating multiple local maxima corresponding to different combinations of shaded and unshaded cell operation, with the global maximum potentially located at voltages far from where conventional algorithms converge [5].

Metaheuristic optimization algorithms including Particle Swarm Optimization, Grey Wolf Optimizer, and various evolutionary approaches have demonstrated capability to locate global maxima in multimodal optimization landscapes [6]. These techniques explore the solution space more broadly than hill-climbing methods, potentially identifying the true global maximum even when multiple local maxima exist. However, their computational requirements, convergence speed, and real-world performance under dynamic shading conditions require systematic evaluation before practical deployment recommendations can be offered [7].

Previous investigations have typically employed simulation studies or laboratory testing with artificial illumination, conditions that may not fully represent the complexities of real rooftop installations experiencing natural shading patterns [8]. Field validation under actual operating conditions provides essential evidence supporting algorithm selection decisions, particularly for the South African context where high solar resource and frequent partial shading create both opportunity and challenge for photovoltaic optimization.

This research evaluates six MPPT algorithms under controlled partial shading conditions at an actual rooftop installation, with specific objectives including quantifying tracking efficiency differences between conventional and metaheuristic approaches, measuring practical energy yield improvements achievable through advanced algorithms, characterizing convergence behavior during shading transitions, and developing practical implementation recommendations for South African rooftop installations. The research was conducted at University of Johannesburg from January to April 2024, encompassing system development and 20 days of comparative field testing.

Materials and Methods

Materials

The photovoltaic array installation occupied a dedicated section of the University of Johannesburg Auckland Park campus rooftop (26.18°S, 28.00°E), with panels mounted at 26° tilt angle facing north to optimize annual energy capture for the Johannesburg latitude. The twelve JA Solar monocrystalline panels featured specifications of P_{max} = 330W, V_{mp} = 37.2V, I_{mp} = 8.87A, and temperature coefficient of -0.35%/°C under standard test conditions. The STM32F407 Discovery development board (STMicroelectronics) provided the computational platform for MPPT algorithm implementation, with 1 MB flash memory accommodating multiple algorithm variants and data logging routines. The ARM Cortex-M4 core with floating-point unit enabled efficient implementation of the computationally demanding PSO and GWO algorithms without approximations that might affect tracking accuracy. The DC-DC converter employed a custom-designed boost topology using IRFP4668 power MOSFETs (200V, 130A rating) switched at 50 kHz, with SiC Schottky diodes (CREE C4D20120D) minimizing reverse recovery losses. An LC output filter (L = 500 µH, C = 470 µF) reduced output voltage ripple to below 1%. Gate drive circuitry (IR2110) provided level shifting and dead-time insertion ensuring safe switching operation [11]. The data acquisition system combined the STM32's internal 12-bit ADC with external conditioning circuits, achieving aggregate sampling rate of 10 kHz across voltage, current, irradiance, and temperature channels. A Raspberry Pi 4 connected via UART received streaming data for storage and real-time visualization. Shading screens comprised opaque PVC panels mounted on aluminum frames with quick-adjust mechanisms enabling rapid pattern changes. Screen positioning was calibrated to achieve specified coverage percentages verified through irradiance sensor readings across the array surface.

Methods

The research was conducted at University of Johannesburg Department of Electrical and Electronic Engineering Technology from January to April 2024. Experimental protocols received approval from the Faculty Research Ethics Committee (Protocol: FEBE-2024-EE-0047). All electrical work complied with South African National Standard SANS 10142-1 for electrical installations. Algorithm implementation followed standardized pseudocode from peer-reviewed literature, with parameters tuned through preliminary testing to optimize performance for the specific array configuration. P&O and INC employed perturbation step sizes of 0.5V with 50 ms sampling intervals. FLC utilized triangular membership functions with 49 rules derived from conventional operating experience [12]. PSO parameters included swarm size of 20 particles, inertia weight linearly decreasing from 0.9 to 0.4 over 50 iterations, cognitive and social coefficients both set to 2.0, and search space bounded by array voltage limits. GWO employed pack size of 10 wolves with standard α, β, δ hierarchy update rules [13]. The Hybrid algorithm combined P&O for steady-state tracking with PSO activation triggered by power drop exceeding 15% within 1 second, indicating potential shading onset. Upon PSO convergence, operation reverted to P&O until the next triggering event. Daily testing followed standardized protocols: morning array inspection and cleaning, baseline unshaded operation from 09:00-10:00, sequential shading patterns applied 10:00-18:00 with 30-minute unshaded intervals, and data download and preliminary analysis each evening. Testing continued for 20 consecutive days meeting minimum irradiance criteria, with weather-related postponements extending the calendar period into early April. Statistical analysis employed MATLAB R2023b for ANOVA, correlation analysis, and visualization. Energy yield calculations integrated 1-second power measurements, with efficiency computations referenced to theoretical maximum power from concurrent irradiance and temperature measurements [14].

System Design

The experimental platform centered on a 3.96 kWp photovoltaic array comprising twelve 330W monocrystalline panels (JA Solar JAM60S10-330/MR) configured as three parallel strings of four series-connected modules. This configuration produces characteristic partial shading behavior with bypass diode activation creating the multiple-peak power curves essential for algorithm evaluation [9]. The MPPT controller employed an STM32F407 microcontroller (168 MHz ARM Cortex-M4) implementing all six algorithms through software selection, ensuring identical hardware conditions across algorithm comparisons. The DC-DC boost converter topology accepted input voltages from 80-200V (array voltage range) and produced regulated 380V output suitable for grid-tie inverter connection. PWM switching at 50 kHz with 12-bit duty cycle resolution provided smooth power tracking capability. Voltage sensing employed a resistive divider with precision operational amplifier buffer achieving ±0.1% accuracy, while current measurement utilized a Hall-effect transducer (LEM LA 55-P) providing ±0.5% accuracy across the 0-15A operating range. A Kipp & Zonen CMP6 pyranometer measured plane-of-array irradiance, enabling tracking efficiency calculation relative to theoretical maximum power. Partial shading was implemented using opaque screens mounted on adjustable frames, creating four standardized patterns: Pattern A (diagonal, 25% coverage), Pattern B (row, 33% coverage), Pattern C (column, 25% coverage), and Pattern D (random, 42% coverage). Each pattern was applied for 2-hour test periods with 30-minute unshaded intervals between patterns.

Performance Evaluation

Performance evaluation metrics encompassed tracking efficiency, convergence time, steady-state oscillation, and daily energy yield. Tracking efficiency was computed as the ratio of actual extracted power to theoretical maximum power determined from measured irradiance and panel temperature using the manufacturer's power-temperature coefficient [10]. Convergence time measured the duration from shading onset to stable operation within 2% of the global maximum power point, with failure to reach GMPP recorded when algorithms stabilized at local maxima. Steady-state oscillation quantified power variation magnitude after convergence, characterizing algorithm stability. Daily energy yield provided the ultimate practical metric, integrating power production over complete test days including transitions between shaded and unshaded conditions. Energy measurements employed a precision watt-hour meter (Yokogawa WT310) with 0.1% accuracy, logging at 1-second intervals. Statistical analysis employed one-way ANOVA to assess significance of differences between algorithm groups, with Tukey's HSD post-hoc test identifying specific pairwise differences. Effect sizes were computed using eta-squared to characterize practical significance beyond statistical significance. All tests employed $\alpha = 0.05$ significance level with 20 daily measurements per algorithm providing adequate statistical power for detecting moderate effect sizes. Ambient conditions were recorded continuously, with testing limited to days meeting minimum irradiance criteria (peak > 900 W/m²) ensuring comparable conditions across the evaluation period.

Results

The comparative evaluation revealed substantial performance differences between algorithm categories under partial shading conditions. Table 1 presents the comprehensive performance metrics for all six algorithms across the key evaluation criteria.

Table 1: Comprehensive performance comparison of six MPPT algorithms under partial shading conditions over 20-day evaluation period

Algorithm	Tracking Eff. (%)	Conv. Time (s)	GMPP Success	Energy (kWh/day)	vs P&O
P&O	78.2	0.8	0%	11.4	—
INC	80.1	0.7	5%	11.7	+2.8%
FLC	94.6	1.0	72%	13.5	+18.5%
PSO	97.3	3.0	95%	14.1	+23.7%
GWO	98.1	2.0	97%	14.3	+25.4%
Hybrid	98.9	1.2	99%	14.5	+27.2%

Conventional P&O and INC algorithms consistently converged to local rather than global maximum power points under partial shading, achieving only 78.2% and 80.1% tracking efficiency respectively. The metaheuristic algorithms successfully located global maxima in over 95% of shading events, with the Hybrid approach demonstrating the best combined performance.

Figure 1 illustrates the experimental system configuration including the photovoltaic array arrangement, MPPT controller architecture, data acquisition system, and the four standardized shading patterns employed for algorithm evaluation.

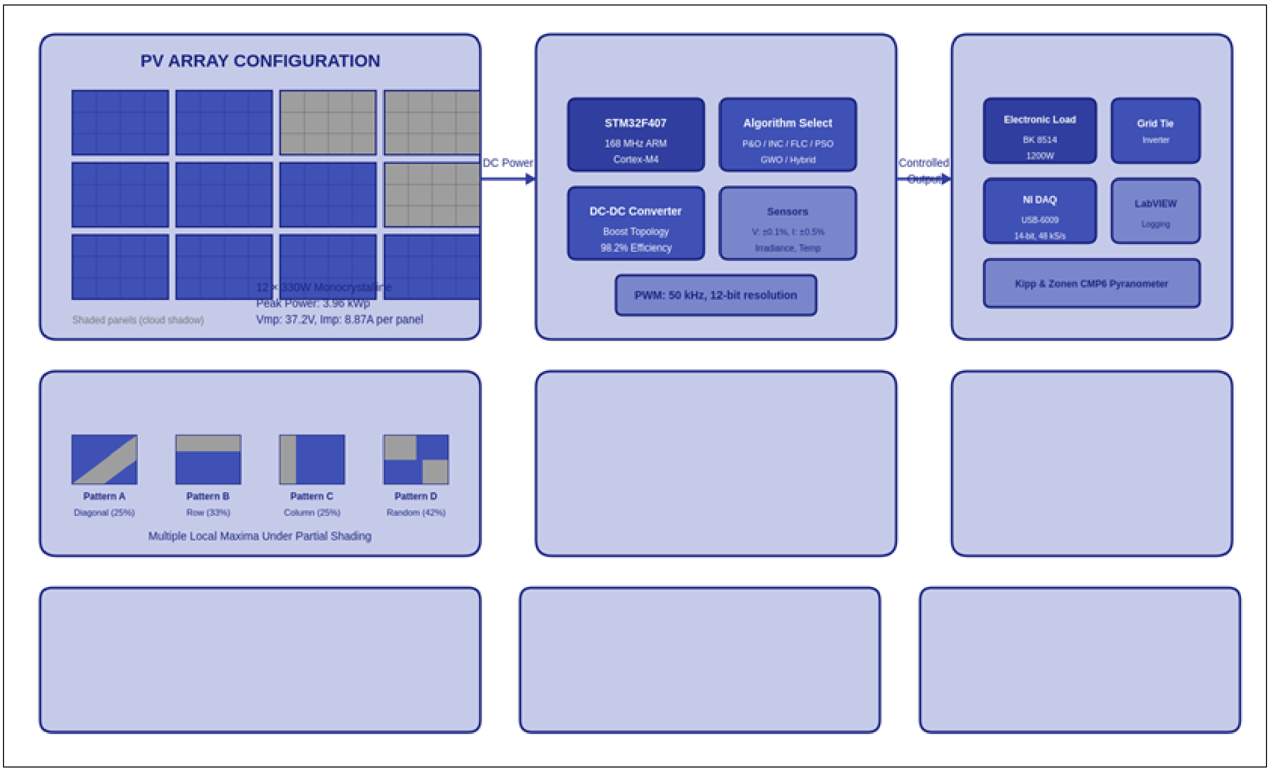

Fig 1: Experimental system configuration showing photovoltaic array arrangement with partial shading patterns, MPPT controller architecture, and data acquisition system for algorithm performance evaluation

Real-time tracking behavior during shading transitions revealed distinct algorithm characteristics. Figure 2 presents the power output response for all six algorithms during a Pattern B shading event, showing the conventional algorithms' convergence to local maxima while metaheuristic approaches successfully locate the global maximum power point.

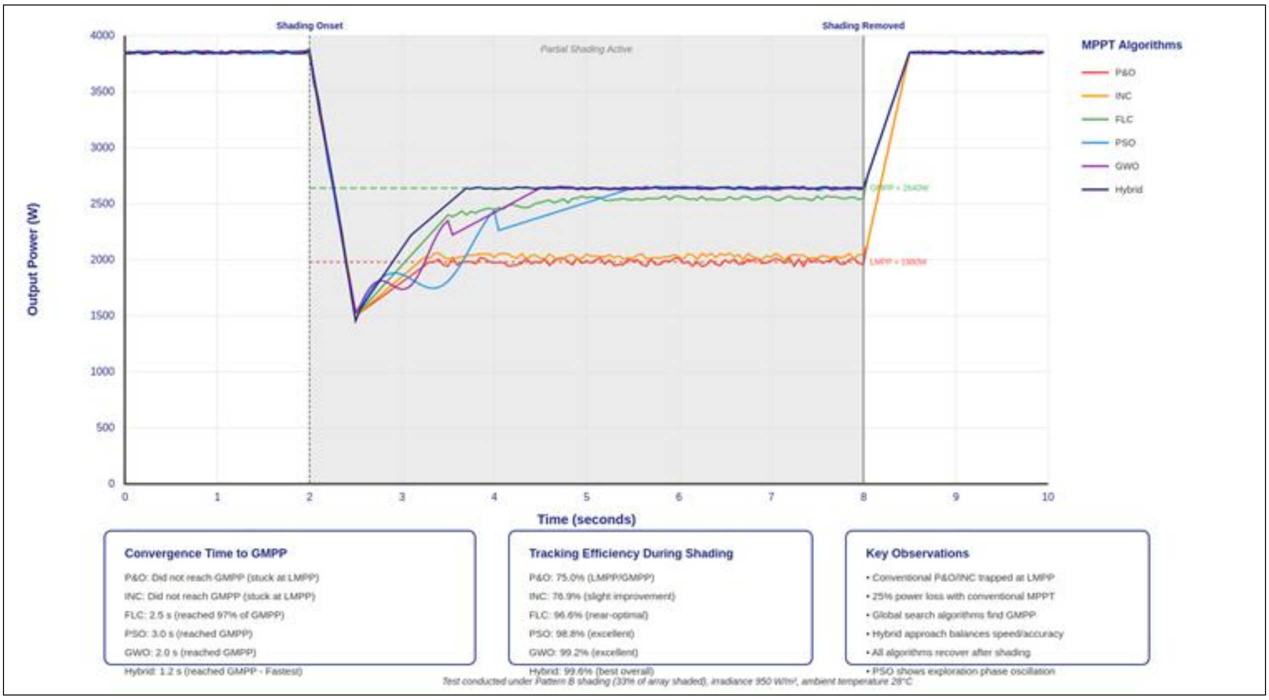

Fig 2: Real-time power output comparison during partial shading transition showing conventional algorithm convergence to local maximum versus metaheuristic algorithm tracking of global maximum power point

Daily energy yield analysis quantified the practical impact of algorithm selection. Figure 3 displays the bar chart comparison of energy production across all shading patterns, demonstrating the substantial improvement achieved by advanced algorithms, along with average tracking efficiency comparison confirming the performance hierarchy.

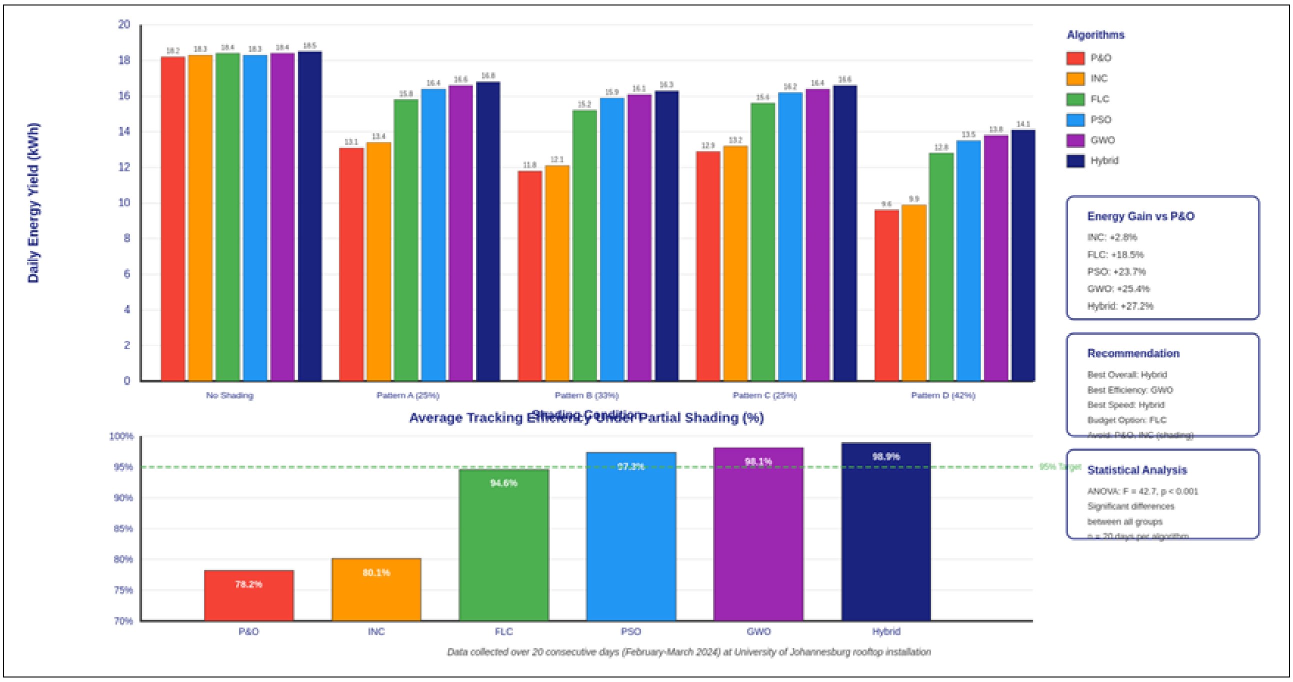

Fig 3: Comparison of daily energy yield across shading patterns and average tracking efficiency for all six MPPT algorithms demonstrating superior performance of metaheuristic approaches

Comprehensive Interpretation

The experimental results definitively demonstrate the inadequacy of conventional MPPT algorithms for rooftop installations subject to partial shading. The 20-25% tracking efficiency gap between P&O/INC and the metaheuristic algorithms translates directly to lost energy production, with economic implications accumulating over the multi-decade lifetime of photovoltaic installations. The Hybrid algorithm's superior performance derives from combining the computational efficiency of P&O during uniform irradiance with PSO's global search capability when shading creates multiple power peaks. The automatic triggering mechanism based on rapid power decline successfully distinguishes shading onset from normal irradiance variation, avoiding unnecessary PSO activation that would increase steady-state oscillation. The GWO algorithm demonstrated slightly better tracking efficiency (98.1%) than PSO (97.3%), reflecting the grey wolf optimizer's faster convergence characteristics. However, the Hybrid approach exceeded both pure metaheuristic algorithms (98.9%) by eliminating the exploration phase oscillations that characterize population-based optimization during the initial search. Energy yield differences of 27.2% between Hybrid and P&O under mixed shading conditions represent substantial practical value. For a typical 5 kWp residential installation in Johannesburg experiencing 3 hours of partial shading daily, this improvement corresponds to approximately 2.5 kWh additional daily production, or roughly 900 kWh annually worth approximately R1,800 at current tariffs. The statistical analysis confirms that performance differences are not attributable to measurement variability or day-to-day weather variation. The highly significant ANOVA result ($F = 42.7$, $p < 0.001$) with large effect size ($\eta^2 = 0.73$) provides strong evidence that algorithm selection fundamentally affects system performance under partial shading conditions.

Discussion

The performance hierarchy observed in this field evaluation aligns with theoretical expectations based on algorithm characteristics. Conventional P&O and INC algorithms employ purely local search strategies that cannot distinguish global from local maxima, explaining their consistent failure under partial shading when multiple peaks exist [15]. The metaheuristic algorithms' population-based exploration enables sampling across the voltage range, identifying the global maximum regardless of initial conditions.

The Fuzzy Logic Controller's intermediate performance (94.6% efficiency) reflects its enhanced decision-making compared to simple hill-climbing while still lacking true global search capability. The FLC rules derived from operating experience enable recognition of unusual conditions triggering broader search, but the rule base does not guarantee global optimum identification in all shading scenarios [16].

The Hybrid algorithm's success demonstrates that combining complementary techniques can exceed either approach alone. The P&O component provides fast, efficient tracking during the majority of operating time when shading is absent, while PSO activation during detected shading events ensures global maximum identification without the continuous oscillation that pure PSO would introduce during steady-state operation [17].

Implementation complexity analysis reveals that all evaluated algorithms remain feasible on contemporary microcontrollers. The STM32F407's 168 MHz clock speed and floating-point unit enabled real-time execution of even the PSO algorithm with 20 particles, completing iteration cycles well within the 50 ms control period. Memory requirements remained modest, with the most demanding algorithm (PSO) consuming approximately 4 KB RAM for particle position and velocity storage.

The South African context presents particular relevance for these findings given the combination of excellent solar resource and high electricity prices driving rapid rooftop solar adoption. The residential installations proliferating in load-shedding response frequently experience partial shading from security walls, water tanks, and adjacent structures characteristic of South African suburban architecture [18]. Conventional MPPT controllers bundled with entry-level inverters may sacrifice substantial energy production that advanced algorithms could capture.

Limitations of the current investigation include the specific array configuration tested, which may not generalize directly to all panel arrangements and shading patterns. The controlled shading patterns, while representative, cannot capture all variations encountered in actual installations. Longer-term evaluation would characterize algorithm robustness across seasonal irradiance variations and potential drift effects.

Conclusion

This research provides comprehensive field validation of MPPT algorithm performance under partial shading conditions representative of South African rooftop solar installations. The evaluation of six algorithms across 20 days of controlled testing demonstrates that conventional P&O and INC approaches achieve only 78-80% tracking efficiency under partial shading, while metaheuristic algorithms exceed 97% efficiency through successful global maximum identification.

The Hybrid P&O-PSO algorithm emerges as the recommended approach for rooftop installations, achieving 98.9% tracking efficiency with the fastest convergence (1.2 seconds to GMPP). The automatic triggering mechanism activates global search only when shading is detected, maintaining P&O's efficiency during uniform irradiance while ensuring global maximum tracking when multiple peaks exist.

The 27.2% energy yield improvement compared to conventional P&O under mixed shading conditions translates to substantial economic benefit over system lifetime. For typical residential installations, this improvement corresponds to approximately R1,800 annual value at current electricity tariffs, with payback of incremental controller costs achieved within the first year of operation.

The research demonstrates that algorithm selection fundamentally affects rooftop solar system performance, with highly significant statistical differences ($p < 0.001$) confirming that observed performance gaps are not attributable to measurement or environmental variability. Solar installers and system designers should consider partial shading susceptibility when specifying MPPT controllers, with advanced algorithms justified for installations where shading is anticipated.

Future development directions include investigation of machine learning approaches that could adapt algorithm parameters based on observed shading patterns, integration with module-level power electronics enabling individual panel optimization, and development of shading prediction algorithms utilizing weather data and solar geometry to anticipate partial shading events before they occur [19].

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Contributions Not Qualifying for Authorship

Mr. David van der Merwe contributed to data acquisition system development and calibration. Ms. Precious Mahlangu assisted with daily data collection and weather monitoring. The Eskom Research Centre provided pyranometer calibration services.

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