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Metaheuristic Optimization of ANN-Based MPPT Controller Using Modified Water Cycle Algorithm for Standalone Photovoltaic Application

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ABSTRACT: The escalating global demand for electricity, coupled with the environmental implications associated with the utilization of fossil fuels, has catalysed the adoption of non-conventional energy technologies, with a specific importance on photovoltaic systems. Standalone PV systems are instrumental in providing electrical power to isolated and rural locales; nevertheless, their efficacy is profoundly influenced by the nonlinear current–voltage characteristics as well as the continual fluctuations in solar irradiance and ambient temperature. These elements render the precise execution to tracking the Maximum Power Point is the formidable challenge under real-time operational scenarios. Traditional MPPT methodologies frequently encounter issues related to sluggish convergence and persistent steady-state oscillations, whereas intelligent control systems necessitate meticulous parameter optimization to guarantee dependable performance. This manuscript introduces a Modified Water Cycle Optimization tuned Artificial Neural Network controller aimed at optimizing MPPT in standalone PV implementations. The ANN is specifically engineered to predict the optimal PV voltage, with its weights and biases being systematically fine-tuned through the MWCO algorithm to enhance convergence precision and circumvent local minima. The suggested methodology is substantiated through MATLAB/Simulink models and is juxtaposed with five pre-existing MPPT strategies under variable environmental conditions. The findings reveal a notable enhancement in tracking efficiency, expedited response times, and minimized power fluctuations, thereby affirming the efficacy of the MWCO-based ANN controller in achieving superior performance in PV systems.

1. Introduction

The modern electric power system faces radical restructuring due to surging global demand, depleting fossil fuels, and environmental concerns. Traditional fossil-based generation struggles with emissions, price volatility, and sustainability, driving a shift to renewables like photovoltaic (PV) systems. PV excels in modularity, scalability, low cost, and off-grid applications but suffers from nonlinear I-V/P-V curves, irradiance/temperature variability, shifting maximum power points (MPP), and partial shading creating multiple local maxima.

Conventional MPPT methods like Perturb & Observe (P&O) and Incremental Conductance (IC) falter under dynamic or shaded conditions. Intelligent methods (ANN, Fuzzy Logic) improve adaptability but face training issues or tuning complexity. Metaheuristics (GA, PSO, ACO, GWO) offer global search but risk premature convergence and high computation.

This paper proposes a Water-Cycle Optimization (WCO)-tuned ANN MPPT controller for standalone PV systems. WCO mimics river flows for efficient exploration/exploitation, optimizing ANN weights/biases for superior tracking accuracy, fast convergence, minimal oscillations, and robustness to partial shading.

Primary Contributions:

- Modified WCO (MWCO)-tuned ANN controller for PV MPPT.
- Enhanced convergence, local minima avoidance, and dynamic response.
- Reduced steady-state oscillations and higher efficiency.

Structure: Section 2 details system architecture and controls; Section 3 covers configuration, case studies, and simulations; Section 4 concludes.

2. Objectives

To design and develop a high-gain DC–DC converter that efficiently boosts the low-voltage PV output to a stable DC bus with reduced component stress and improved conversion efficiency under varying solar and load conditions.

To implement a Water Cycle Optimization–tuned Artificial Neural Network (WCO-ANN) based MPPT algorithm for achieving ultra-fast tracking speed, minimal steady-state oscillations, and maximum energy extraction from the PV source.
To integrate an IoT-enabled monitoring and control layer for real-time data acquisition, remote supervision, and predictive decision-making to ensure reliable and optimized operation of the DC microgrid in remote power-deficient regions.

3. Related work

Traditional MPPT methods like Perturb and Observe (P&O) and Incremental Conductance (IC) form the baseline for PV systems but suffer limitations. P&O perturbs voltage to track power changes, offering simplicity yet causing steady-state oscillations and failure under rapid irradiance or partial shading shift.

IC enhances accuracy by comparing incremental and instantaneous conductance, though it requires precise sensors and complex computations, faltering in dynamic environments.

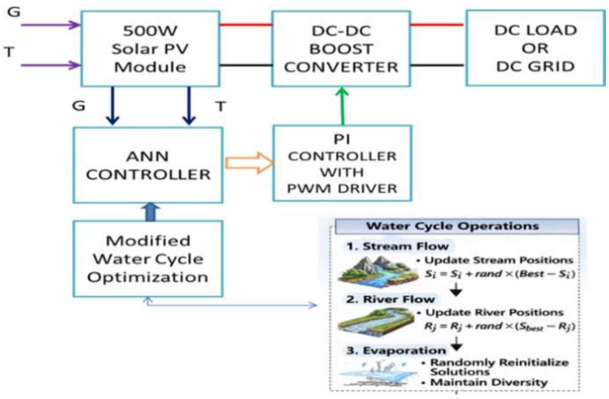
Intelligent approaches such as Fuzzy Logic Controllers (FLC) and Artificial Neural Networks (ANN) address nonlinearity without rigid models. FLCs use rule-based inference for adaptability to environmental uncertainty, but demand expert-designed membership functions and rules, risking suboptimal tuning. ANNs learn mappings from irradiance, temperature, and voltage to optimal operating points, enabling fast tracking, yet rely heavily on quality training data and risk local minima during weight initialization.

Metaheuristic techniques like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Grey Wolf Optimization (GWO), and Water Cycle Optimization (WCO) provide global search capabilities ideal for multimodal P-V curves under shading. PSO optimizes FLC parameters in PV water pumping, yielding 96.5% efficiency versus 85% for P&O. WCO, inspired by river flows to seas, excels in fast convergence and low ripples for boost converter MPPT and PV parameter estimation, though sensitive to population size and iteration counts.

Recent hybrids advance robustness: WCO-tuned P&O minimizes errors in solar E-vehicles; improved WCO swiftly locates global MPPs amid shading. These evolutions underscore the need for your MWCO-ANN innovation, which fine-tunes ANN weights/biases for superior convergence speed, oscillation reduction, and standalone PV efficiency under varying conditions.

4. System Architecture

The photovoltaic energy conversion system utilizes a 500 W PV module rated at 12 V and 41.8 A under standard test conditions. The PV array is the primary energy source, with its electrical characteristics modelled to account for variations in irradiance and temperature. A conventional boost converter is integrated to regulate and elevate the output voltage, accommodating environmental fluctuations.



This boost converter improves power transfer efficiency and facilitates impedance matching between the PV source and the load. For optimal power extraction, a MWCO tuned ANN controller is employed for (MPPT). This controller processes solar irradiance and temperature inputs to generate an optimal PV reference voltage (Vref) that corresponds to the determined power point.

5. Results and Discussion

This study prototyped a 500 W PV-boost converter system and validated it via MATLAB/Simulink under realistic conditions to assess the MWCO-tuned ANN MPPT controller. MWCO optimized ANN weights and biases, outperforming GA and standard WCO in MSE convergence precision and stability. PV performance was evaluated across varying irradiance and temperature, analyzing tracking behavior, duty cycle response, voltage regulation, and steady-state oscillations, where MWCO-ANN demonstrated superior efficiency and faster response compared to traditional MPPT methods. This section details the controller design, comparative analysis, and real-time performance results.

6. MWCO-ANN

MWCO optimizes ANN weights and biases by minimizing prediction MSE without gradient backpropagation, where each raindrop represents a full parameter set initialized randomly alongside population size, iterations, flow coefficient, evaporation threshold, and ANN architecture constraints. Fitness ranked by MSE designates the best as sea, top candidates as rivers, and others as streams, which update toward superiors via controlled equations to iteratively reduce error. Evaporation triggers raining or Cauchy mutation on stagnation for diversity and global search, halting at termination to deploy the optimal sea parameters in the controller for accurate, robust MPPT performance

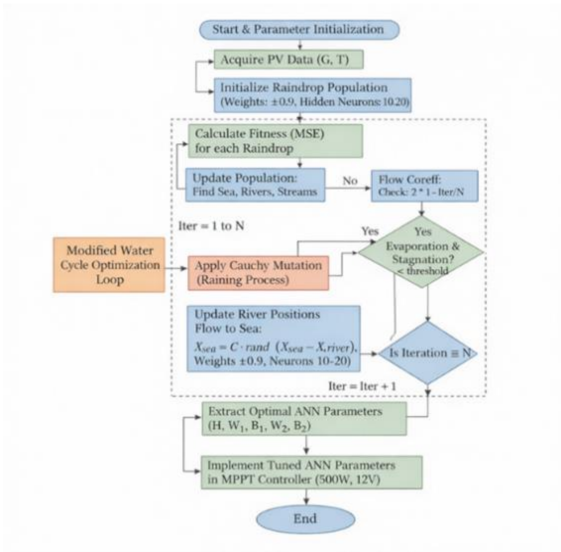


Figure 1: *Block Diagram*

7. An ANN algorithm optimized for MWCO-initialization of hidden layer parameters and weights:

The Modified WCO tuned ANN algorithm is implemented toward optimally initialize and adjust ANN weights and hidden layer parameters for precise MPPT control. Instead of random initialization, the WCO algorithm performs global optimization within a bounded search space to enhance convergence reliability and avoid local minima entrapment. In this method, each search agent represents a complete ANN parameter vector, including input-to- hidden weights, hidden-to-output weights, and bias values. The weight coefficients are initialized within the range of −0.9 to +0.9 to maintain activation function stability and prevent saturation. The hidden layer size is selected between 10 and 20 neurons, ensuring sufficient nonlinear mapping capability while avoiding overfitting and excessive computational burden.

The optimization objective is formulated using the Mean Square Error (MSE) between the ANN-generated reference voltage (Vref) and the theoretical maximum power point voltage. The algorithm targets an MSE convergence threshold in the range of $10^{-}3$ to 10^{-6} for high tracking accuracy.

For implementation, the WCO algorithm is configured with a population size of 30 search agents, 4 rivers plus 1 sea (best solution), and a maximum iteration limit of 100 iterations. The stream–river–sea updating mechanism, along with adaptive evaporation conditions, ensures balanced exploration and exploitation. The best optimized parameter set is selected as the final ANN configuration, resulting in faster convergence, minimized steady- state error, and improved robustness under active photovoltaic operating circumstances. The search progression of the algorithm is illustrated in Fig. 3, where it is compared with the conventional GA, standard WCO, and the proposed MWCO approach.

Fitness values of proposed controllers

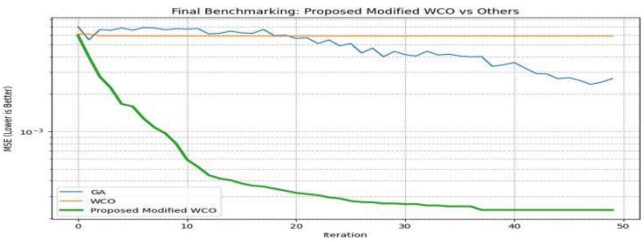


Table 1: *presents the initial statistical evaluation of the proposed method, demonstrating its promising effectiveness and performance potential.*

S.No	|Algorithm	Final MSE	Hidden Neurons
1	GA	0.00266947	16
2	WCO	0.00587566	13
3	Proposed Modified WCO	0.00023314	10

8. Conclusion

This research work introduced a MWCO based ANN controller for Maximum Power Point Tracking (MPPT) in standalone PV systems. The proposed controller was validated under dynamically varying irradiance conditions (1000–700–800–900–1000 W/m²) while maintaining a 25 °C constant temperature to assess its robustness. The convergence analysis confirms the efficiency of the proposed optimization framework. The MWCO-ANN achieved a minimum Mean Square Error (MSE) of 0.00023314, significantly outperforming the Genetic Algorithm (GA) with 0.00266947 and conventional Water Cycle Optimization (WCO) with 0.00587566. This corresponds to an improvement of approximately 91.27% over GA and 96.03% over conventional WCO. Notably, the optimized ANN required only

10 hidden neurons, compared to 16 for GA and 13 for WCO, indicating reduced computational complexity with enhanced prediction accuracy. Under standard irradiance of1000 W/m², the proposed controller achieved an output power of approximately 499.5 W, exceeding the performance of conventional ANN (495 W), Incremental Conductance (492 W), Fuzzy Logic Controller (490 W), and Perturb & Observe (478 W). Additionally, the MWCO-ANN exhibited faster dynamic response and minimal steady-state oscillations around the MPP, demonstrating superior tracking efficiency and stability during irradiance transitions. Overall, the results confirm

that the MWCO-tuned ANN controller provides improved convergence accuracy, reduced steady-state error, enhanced power extraction capability, and lower structural complexity, making it a promising solution for high- performance PV applications.

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