International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 17, No. 4, December 2026, pp. 3025~3033
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v17.i4.pp3025-3033

Adaptive neural network - based red-tailed hawk optimization for renewable energy integration and power quality enhancement using UPQC

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Article Info

Article history:

Received Jul 12, 2026
Revised Aug 31, 2026
Accepted Sep 13, 2026

Keywords:

Adaptive neural network-based optimization
Maximum power point tracking
Unified power quality conditioner
Power quality enhancement
Red-tailed hawk optimization
Renewable energy microgrid

ABSTRACT

The increasing integration of renewable energy sources (RESs) into modern power systems can cause voltage fluctuations, harmonic distortion, reactive power imbalance, and instability under nonlinear loading conditions. This paper proposes an adaptive neural network-based red-tailed hawk optimization (ANN-RTHO) approach for renewable energy integration and power quality enhancement in a meshed hybrid microgrid using a unified power quality conditioner (UPQC). Photovoltaic (PV) and wind energy sources are integrated through adaptive power electronic converters connected to a low-voltage DC (LVDC) network. The artificial neural network (ANN) predicts variations in solar irradiance, wind speed, load demand, and DC-link voltage, while the RTHO algorithm determines optimal maximum power point tracking (MPPT) operating points and UPQC control signals. The UPQC compensates for voltage disturbances, harmonic currents, reactive power, and DC-link voltage variations under linear and nonlinear loads. The proposed method is evaluated using MATLAB/ Simulink under different operating conditions. Simulation results show improved MPPT efficiency, reduced total harmonic distortion (THD), enhanced DC-link voltage stability, and faster dynamic response compared with conventional control methods. The results demonstrate the effectiveness of the ANN-RTHO strategy for intelligent control and reliable operation of renewable energy-based hybrid microgrids.

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1. INTRODUCTION

The increasing demand for electrical energy and the depletion of fossil fuel resources have encouraged the widespread adoption of renewable energy systems, particularly solar photovoltaic (PV) and wind energy sources. Although these renewable sources offer environmental and economic benefits, their integration into modern power systems creates several challenges such as voltage fluctuations, harmonic distortion, reactive power imbalance, and poor power quality under dynamic operating conditions. These issues become more critical in the presence of nonlinear loads and rapidly varying environmental conditions. To improve renewable energy utilization, efficient maximum power point tracking (MPPT) techniques are required. However, conventional MPPT methods often experience slow response, oscillations, and reduced

efficiency during sudden variations in irradiance and wind speed. To address these challenges, this paper proposes an adaptive neural network-based red-tailed hawk optimization (ANN-RTHO) approach for renewable energy integration and power quality enhancement using a unified power quality conditioner (UPQC) in a hybrid PV–wind microgrid. In the proposed method, an artificial neural network (ANN) is used to predict system operating conditions, while the Red-Tailed Hawk Optimization algorithm optimizes MPPT operation and UPQC control parameters in real time. The UPQC effectively compensates for voltage disturbances, harmonics, and reactive power issues caused by nonlinear loads, thereby improving overall system stability and power quality. The proposed system is modeled in MATLAB/Simulink, and the simulation results demonstrate improved MPPT efficiency, reduced total harmonic distortion (THD), better voltage regulation, and enhanced dynamic performance compared to conventional control approaches.

Basnet *et al.* [1] reviewed recent standalone and grid-integrated hybrid renewable energy systems, focusing on system optimization and energy management strategies. Hemeida *et al.* [2] investigated the optimal design of hybrid wind–PV energy systems for remote areas. Liu *et al.* [3] proposed a moth-flame optimization-based parameter estimation approach for a model-predictive-controlled superconducting magnetic energy storage–battery hybrid system. Holari *et al.* [4] developed a nonlinear control strategy for distributed energy storage in a grid-connected hybrid microgrid incorporating wind and PV sources. Teklehaimanot *et al.* [5] reviewed and compared MPPT algorithms for wind energy conversion systems, while Khan *et al.* [6] analyzed deep learning models for maximum power point estimation in hybrid PV–TEG systems. Rezvani *et al.* [7] proposed an intelligent hybrid fuzzy-neural approach for grid-connected photovoltaic and wind energy systems. Armghan *et al.* [8] presented a deep learning-based barrier-function super-twisting sliding mode controller for renewable energy integration, whereas Ahmed *et al.* [9] developed a nonlinear super-twisting sliding mode MPPT controller for solar PV systems using neural-network-based reference generation. Ali *et al.* [10] reviewed metaheuristic, fuzzy logic, and ANN-based MPPT methods for grid-connected PV systems. Al-Majidi *et al.* [11] employed a PSO-trained feedforward neural network for PV maximum power point prediction, while Tiwari *et al.* [12] proposed a neural-network-based MPPT controller for a permanent magnet synchronous generator (PMSG) wind energy conversion system. Asadnia *et al.* [13] and Anand and Suganthi [14] explored hybrid GA–PSO optimization of neural networks for carbon nanotube growth modeling and electricity demand forecasting, respectively. Sun *et al.* [15] investigated adaptive-gain second-order sliding mode control for maximum wind power tracking. Amine *et al.* [16] compared PI and super-twisting sliding mode controllers for hybrid energy storage in a remote DC microgrid.

Mahmoud *et al.* [17] proposed whale optimization algorithm-based fractional-order PI controllers for STATCOM and UPQC to mitigate harmonics and voltage instability. Gade and Agrawal [18] investigated JAYA optimization for the optimal utilization of UPQC, while Aldosary [19] developed fractional-order PID controllers using a hybrid jellyfish search and particle swarm optimization algorithm for power quality enhancement. Xue *et al.* [20] proposed a hierarchical sparrow search algorithm for numerical optimization and parameter estimation. Rafiqi and Bhat [21] investigated an improved sparrow search-based PID controller for power quality enhancement in a UPQC-integrated renewable energy system. Ferahtia *et al.* [22] introduced the red-tailed hawk algorithm for numerical optimization and real-world applications. Khan *et al.* [23] presented a scoping review of UPQC-based power quality improvement in microgrids. Premkumar *et al.* [24] proposed an intelligent multi-objective optimization approach for the operation and control of hybrid power systems with stochastic renewable sources and FACTS devices. Bhayo *et al.* [25] developed a two-stage energy management and optimal control strategy for hybrid AC/DC microgrids using neural fuzzy logic and nonlinear sliding mode control.

From Table 1 (see Appendix), it can be observed that existing intelligent optimization techniques primarily focus on optimizing UPQC controller parameters or MPPT independently. Most methods lack adaptive prediction capability and coordinated optimization of renewable energy extraction and power quality enhancement under rapidly changing operating conditions. To address these limitations, this paper proposes an ANN-RTHO-based control framework that combines the prediction capability of ANN with the global optimization ability of the RTHO algorithm for simultaneous optimization of MPPT and UPQC control. This coordinated strategy improves dynamic response, harmonic suppression, and voltage regulation in renewable energy-integrated hybrid microgrids.

2. METHOD

The proposed system shown in Figure 1 (see Appendix) integrates PV and wind energy sources in a hybrid microgrid using an ANN-RTHO technique with a UPQC. The PV and wind systems are connected through power electronic converters to a common DC-link for efficient energy transfer. ANN model predicts varying operating conditions such as irradiance, wind speed, and load changes, while the RTHO algorithm

optimizes the MPPT operation to extract maximum power from renewable sources. The UPQC, consisting of series and shunt compensators, mitigates voltage disturbances, harmonic distortion, reactive power imbalance, and power quality issues caused by nonlinear loads. The coordinated operation of ANN-RTHO and UPQC improves MPPT efficiency, stabilizes DC-link voltage, reduce THD, and enhances the overall performance and reliability of the renewable energy integrated microgrid under dynamic operating conditions.

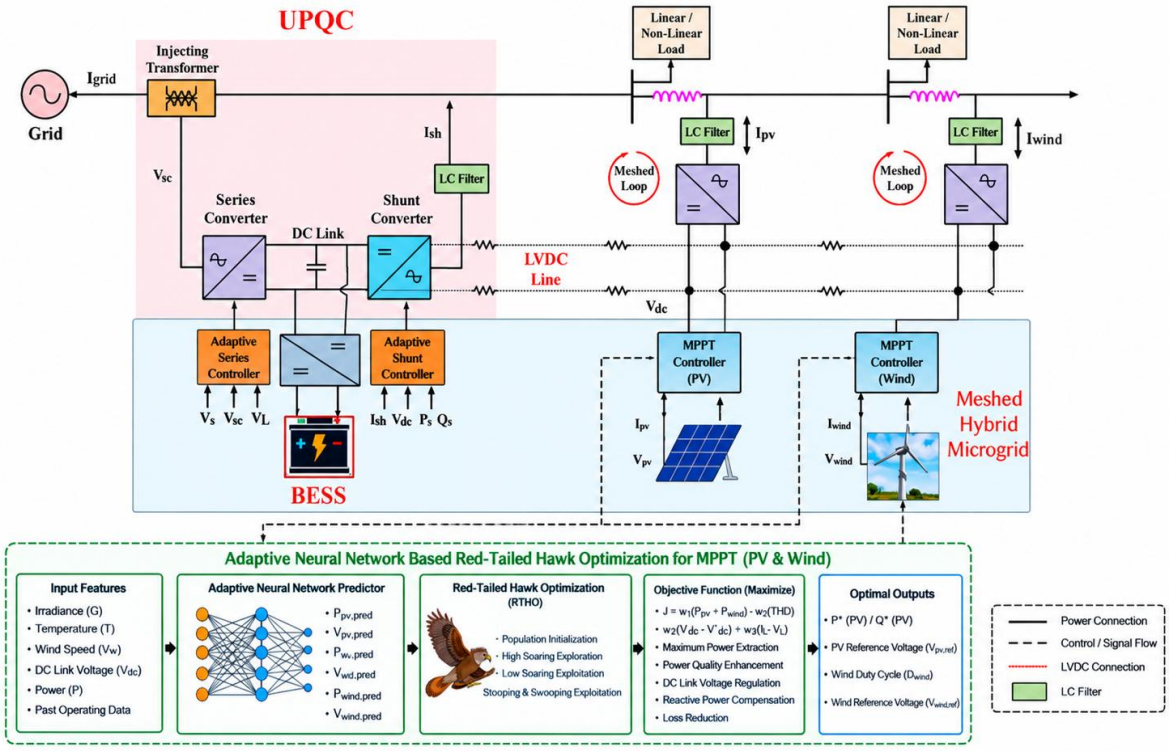


Figure 1. Proposed system with ANN-RTHO

3. RED TAILED HAWK OPTIMIZATION

The Red-Tailed Hawk (*Buteo jamaicensis*) is a widely distributed bird of prey found throughout North America, extending from Alaska and Canada to Central America and the Caribbean. It is highly adaptable and thrives in a variety of habitats, including forests, grasslands, deserts, agricultural lands, and urban environments. As a carnivorous predator, the hawk primarily feeds on small mammals, particularly rodents, which account for the majority of its diet. Depending on seasonal and geographical availability, it also preys on birds, reptiles, amphibians, fish, and invertebrates. One of the remarkable characteristics of the Red-Tailed Hawk is its energy-efficient flying strategy. It spends much of its time soaring with minimal wing flapping by holding its wings in a slight V-shaped (dihedral) position. This flight mechanism enables the bird to cover long distances while conserving energy. During normal flight, the hawk typically travels at speeds ranging from 32 to 64 km/h. When attacking prey or defending its nest, however, it can rapidly dive at speeds approaching 190 km/h, demonstrating exceptional agility, precision, and striking capability.

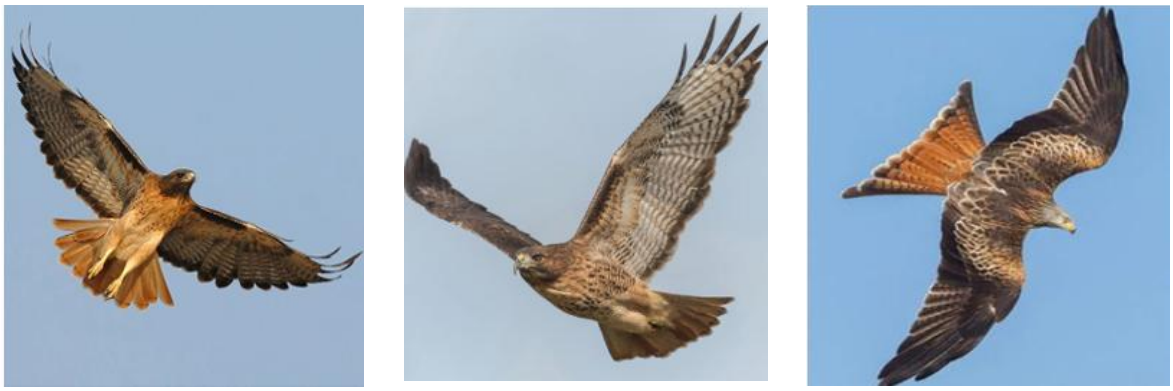
The hunting strategy of the Red-Tailed Hawk is characterized by a balance between broad environmental surveillance and rapid, decisive attacks. It continuously scans a large area while soaring, identifies suitable prey, and then performs a swift dive to capture the target with high accuracy. Inspired by this natural behavior, the RTHO algorithm models the hawk's exploration and exploitation mechanisms. The exploration phase imitates wide-area searching for potential prey, whereas the exploitation phase represents focused pursuit and attack on the most promising solution. As illustrated in Figure 2, the RTHO algorithm emulates three distinct flight behaviors of the Red-Tailed Hawk to achieve an effective balance between global exploration and local exploitation during the optimization process [22].

The hunting behavior of the Red-Tailed Hawk can be divided into three distinct flight phases, which form the basis of the RTHO algorithm.

- High soaring (Figure 2(a)): In the initial phase, the hawk flies at a high altitude with minimal wing flapping while maintaining a slight V-shaped (dihedral) wing posture. This energy-efficient flight enables the hawk to survey a wide area and identify potential prey. In the RTHO algorithm, this

behavior represents the global exploration stage, where the search space is extensively explored to identify promising candidate solutions.

- Low soaring (Figure 2(b)): Once a potential target is detected, the hawk gradually descends and flies in a spiral path around the prey. This movement allows it to closely observe the target, assess its surroundings, and determine the most suitable position and timing for the attack. In the optimization process, this phase corresponds to local exploration, where promising solutions are examined in greater detail to improve search accuracy.
- Stooping and swooping (Figure 2(c)): After identifying the optimal attack position, the hawk rapidly dives toward the prey along a curved trajectory while significantly increasing its speed from approximately 32–64 km/h during soaring to nearly 190 km/h during the dive. This fast and precise attack maximizes the probability of a successful capture. In the RTHO algorithm, this behavior represents the exploitation phase, where the search converges rapidly toward the best solution identified during the exploration stages.



(a) (b) (c)

Figure 2. Behavior of red-tailed hawk during hunting: (a) high soaring, (b) low soaring, and (c) stooping and swooping

4. ANN-BASED ADAPTIVE CONTROL FRAMEWORK

The operation of renewable energy sources, electric vehicle charging systems, and power electronic converters is highly nonlinear and subject to continuous variations in operating conditions. Under such circumstances, conventional control techniques, including PI, PID, fuzzy logic, and rule-based controllers, often fail to deliver satisfactory performance. These methods depend on accurate mathematical models and carefully tuned parameters, making them less effective when system dynamics change rapidly or uncertainties are present. To address these challenges, an adaptive neural network (ANN)-based controller is incorporated into the proposed hybrid AC/DC microgrid. Unlike conventional controllers, the ANN can learn complex nonlinear relationships directly from system data and adapt its control actions according to changing operating conditions. This capability enhances the stability, flexibility, and overall performance of the microgrid.

The adaptive controller is implemented in MATLAB/Simulink using a two-layer feed-forward neural network architecture shown in Table 2. The network consists of an input processing stage, a hidden layer, an output layer, and an output processing stage. To improve the learning capability and dynamic response of the controller, delayed input signals are incorporated into the network. This enables the ANN to capture temporal variations in system behavior and generate more accurate control decisions. The proposed ANN architecture comprises an input layer, a single hidden layer containing ten neurons, and an output layer with one neuron. The hidden layer performs nonlinear feature extraction from the input data, while the output layer generates the required control reference signal for the UPQC. The controller processes real-time measurements of electrical variables and produces adaptive control signals that regulate the operation of the UPQC, thereby improving power quality and maintaining stable microgrid performance. During operation, the ANN continuously monitors key electrical parameters of the hybrid microgrid, learns the changing system characteristics, and updates its control actions in real time. This adaptive behavior enables effective compensation for voltage disturbances, current harmonics, reactive power variations, and other power quality issues, ensuring reliable and efficient operation under varying loading and renewable generation conditions.

Table 2. Proposed ANN framework

S. No	ANN component	Configuration	S. No	ANN component	Configuration
01	Network type	Feedforward neural network	09	Delay element	One-step delay
02	No. of input layers	01	10	Training algorithm	Backpropagation learning algorithm
03	No. of hidden layers	01	11	Learning mode	Supervised learning
04	No. of output layers	01	12	Adaption mode	Online adaptive updating
05	Hidden neurons	10	13	Performance function	Mean square error (MSE)
06	Output neurons	1	14	Learning rate	0.01
07	Bias terms	b (1), b ((2)	15	Implementation platform	MATLAB/Simulink
08	Weight matrices	IW (1,1), LW ((2,1)			

5. RESULTS AND DISCUSSION

The performance of the proposed ANN-RTHO controlled UPQC was evaluated under various voltage disturbance and load conditions, and the results demonstrate substantial improvements in both power quality and dynamic response. During the simulation shown in Figure 3, the source voltage experienced a voltage sag between 0.5 s and 1.0 s and a voltage swell after 1.5 s. The series compensator effectively injected the required compensating voltage to counteract these disturbances, ensuring that the load voltage remained balanced, sinusoidal, and close to its nominal value throughout the operating period.

Similarly, the shunt shown in Figure 4 dynamically supplied the necessary compensating current to mitigate reactive power demand and harmonic components, resulting in balanced source currents with improved waveform quality. Harmonic analysis further validated the effectiveness of the proposed approach. Before compensation, the system exhibited a THD of 28.39%, indicating significant harmonic distortion. After UPQC implementation, the THD was reduced to 2.53%, satisfying IEEE-519 standards and confirming excellent harmonic suppression capability as shown in Figure 5.

Table 3 gives a comparative analysis with the conventional PI controller, revealing significant performance enhancements. The proposed controller reduced rise time from 0.12 s to 0.05 s and settling time from 0.45 s to 0.19 s, corresponding to improvements of 58.3% and 57.8%, respectively. Overshoot was decreased from 12.8% to 3.6%, while steady-state error was reduced from 2.1% to 0.4%, indicating improved stability and tracking accuracy. In addition, voltage regulation improved from ±5.4% to ±1.7%, demonstrating the controller's ability to maintain a stable load voltage under varying operating conditions. Overall, the obtained results confirm that the proposed ANN-RTHO-based UPQC provides faster dynamic response, superior voltage restoration, effective current compensation, and significant harmonic reduction, making it a highly reliable solution for renewable energy-integrated distribution systems and smart grid applications.

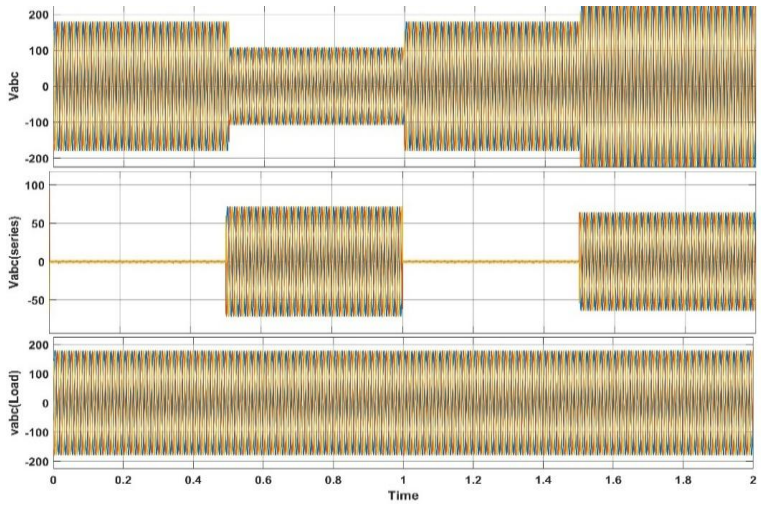


Figure 3. Three-phase voltages with UPQC

Table 3. Dynamic performance comparison between PI and ANN-based controller

S. No	Performance metric	PI controller	ANN-based controller	Improvement (%)
01	Rise time (s)	0.12	0.05	58.3
02	Settling time (s)	0.45	0.19	57.8
03	Overshoot (%)	12.8	3.6	71.9
04	Steady-state error (%)	2.1	0.4	80.9
05	Voltage regulation (%)	±5.4	±1.7	68.5
06	THD (%)	4.82	2.53	52.4

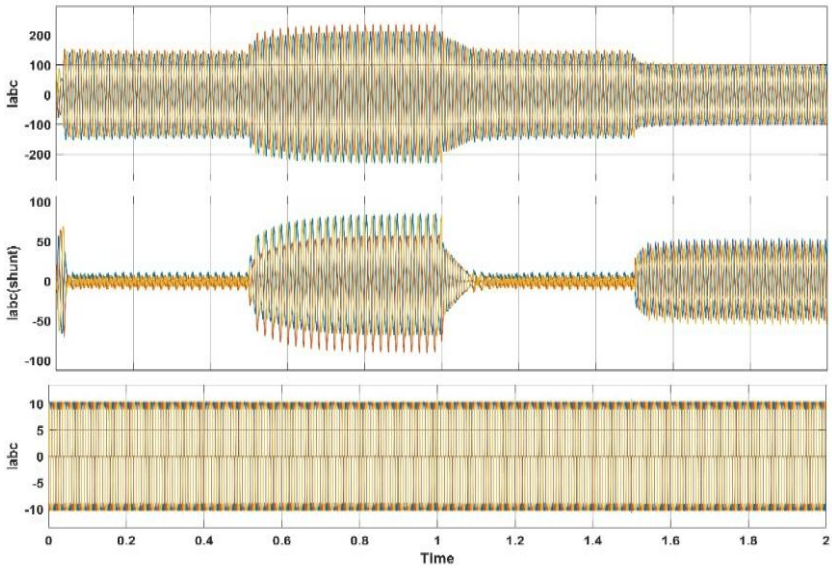


Figure 4. Three phase currents with UPQC

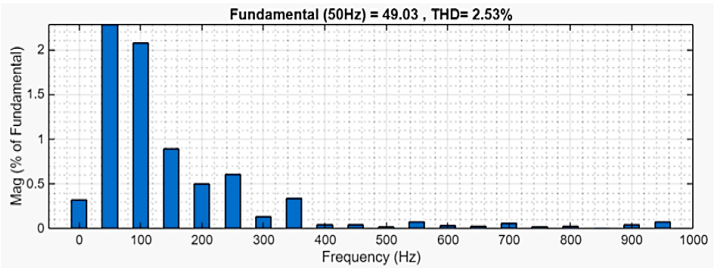


Figure 5. Analysis of proposed system with and without UPQC

6. CONCLUSION

This paper presented an ANN-RTHO control strategy for renewable energy integration and power quality enhancement in a hybrid PV–wind microgrid using a UPQC. The proposed approach integrates the prediction capability of an Artificial Neural Network with the global optimization capability of the Red-Tailed Hawk Optimization algorithm to adaptively optimize MPPT operation and UPQC control under varying renewable generation and load conditions. The proposed controller was implemented and validated in MATLAB/Simulink under voltage sag, voltage swell, and nonlinear load conditions. The simulation results demonstrated effective voltage regulation, improved DC-link voltage stability, significant harmonic suppression with THD reduced from 4.82% to 2.53%, and enhanced dynamic performance in terms of rise time, settling time, overshoot, and steady-state error compared with the conventional PI controller. These results indicate that the ANN-RTHO framework provides an adaptive and efficient control strategy for improving the reliability and power quality of renewable energy-integrated distribution systems. However, the present work is limited to simulation-based validation and comparison with a conventional PI controller. Future work will focus on real-time hardware implementation and comprehensive performance evaluation against other recent intelligent optimization-based UPQC controllers to further establish the effectiveness and practical applicability of the proposed approach.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ujwala Gajula	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Gouthami Eragamreddy		✓				✓		✓	✓	✓	✓	✓		
N. Malla Reddy	✓		✓	✓			✓			✓	✓		✓	✓
O. Shobhana		✓				✓		✓	✓	✓	✓	✓		
P. Mamta		✓				✓			✓					
P. V. S. S. A. Parimala	✓				✓		✓			✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

APPENDIX

Table 1. Comparative analysis of the proposed ANN-RTHO controller with recent intelligent UPQC control methods

Ref.	Method	Optimization technique	Application	Major contribution	Limitation	Advantage of proposed ANN-RTHO
[17]	WOA-FOPI	Whale optimization algorithm	UPQC	Optimizes FOPI controller for harmonic mitigation and voltage stability	Fixed optimization; no adaptive learning	ANN predicts operating conditions while RTHO adaptively optimizes control parameters in real time
[18]	JAYA-UPQC	JAYA optimization	UPQC	Optimizes controller gains for voltage sag/swell compensation	Limited adaptability under rapidly varying renewable conditions	Simultaneous adaptive MPPT and UPQC optimization
[19]	Jellyfish-PSO FOPID	Jellyfish search + PSO	UPQC	Hybrid optimization improves transient response and power quality	Higher computational complexity; no predictive capability	Combines prediction and global optimization for improved dynamic performance
[21]	SSA-PID	Sparrow Search Algorithm	Renewable energy integrated UPQC	Improves voltage regulation and harmonic suppression	Optimizes PID gains only	Joint optimization of MPPT and UPQC with adaptive ANN prediction
Present work	ANN-RTHO	Artificial neural network + Red-Tailed Hawk optimization	Hybrid PV-wind microgrid with UPQC	Adaptive prediction of renewable operating conditions and real-time optimization of MPPT and UPQC control	Simulation-based validation	Reduced THD (2.53%), improved voltage regulation, faster transient response, and adaptive intelligent control

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