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PERFORMANCE ENHANCEMENT OF A TWO-BUS SYSTEM USING UPQC WITH HYBRID ANN & PI BASED CONTROL FOR HARMONIC MITIGATION

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Abstract

Power quality (PQ) deterioration caused by nonlinear loads, renewable integration, and electric vehicle (EV) charging is a critical challenge in modern distribution networks. This research article investigates the application of a Unified Power Quality Conditioner (UPQC) to a two-bus distribution system network modeled in MATLAB/Simulink for harmonic mitigation and voltage stabilization. Three control strategies are analyzed: conventional Proportional–Integral (PI), Artificial Neural Network (ANN), and a proposed hybrid ANN–PI approach. Results show that PI control reduces source current Total Harmonic Distortion (THDi) from 27.98% (base case) to 19.54%, whereas ANN control further lowers it to 10.72%. The hybrid ANN–PI controller demonstrates superior performance, achieving THDi of 6.36% and voltage THD (THDv) of 1.36%, thereby ensuring compliance with IEEE Std. 519. Additionally, the hybrid scheme improves bus voltage regulation, reactive power balance, and transient stability under dynamic load variations. These findings demonstrate that intelligent hybrid controllers can significantly enhance PQ in renewable-rich and EV-dominated grids, providing a scalable solution for future smart distribution networks.

Keywords Power Quality, Unified Power Quality Conditioner, Nonlinear loads, Artificial Neural Network (ANN), PI controller, Harmonic distortion & Smart microgrid.

1. Introduction

Power quality (PQ) has become a critical concern in distribution networks due to the growing penetration of nonlinear loads, power-electronic converters, renewable energy sources (RES), and EV charging infrastructure. These elements introduce harmonics, voltage fluctuations, and frequency deviations, which adversely affect efficiency, equipment lifetime, and grid reliability [1], [2]. Among these challenges, harmonic distortion is particularly severe, arising mainly

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from rectifiers, variable-speed drives, and EV chargers. Elevated Total Harmonic Distortion (THD) levels cause transformer overheating, maloperation of protective relays, and malfunction of sensitive electronic devices [3], [4]. According to IEEE Std. 519, THDi should remain below 5% for most distribution feeders, yet compliance becomes increasingly difficult under high RES and EV penetration [5].

RES-based grids also face intermittency-induced issues such as sags, swells, flicker, and frequency deviations [6], [7]. These problems degrade PQ and threaten system stability, particularly in weak-grid or islanded microgrids [8]. To mitigate such disturbances, CPDs such as Distribution STATCOM and DVR have been developed. However, DSTATCOM provides only current compensation, while DVR addresses only voltage disturbances [9], [10]. The UPQC, which integrates both functions through coordinated series and shunt APF sharing via same DC-link, offers comprehensive PQ mitigation [11]–[13]. The effectiveness of UPQC depends largely on its control strategy. Conventional Proportional–Integral (PI) controllers are widely adopted due to simplicity and zero steady-state error but struggle under nonlinear and dynamically varying loads [14]. Artificial Neural Networks (ANNs) provide adaptive control and have demonstrated improved harmonic suppression and DC-link voltage stability [15]–[17]. Recently, hybrid approaches that combine PI and ANN have gained attention, leveraging the robustness of PI with the adaptability of ANN to achieve superior PQ performance [18]–[20].

1.1 Research Gap

Despite several studies on PI-based, ANN-based, and fuzzy/neuro-fuzzy UPQC control, **comparative evaluations of PI, ANN, and hybrid ANN–PI controllers on medium-voltage distribution networks are limited**. Pure PI suffers under nonlinear operating conditions, while pure ANN requires large datasets and risks overfitting. A hybrid ANN–PI framework can potentially balance simplicity, adaptability, and robustness, but its performance under renewable-rich and EV-dominated networks remains underexplored.

1.2 Contributions

This paper addresses the above gap by investigating a hybrid ANN–PI controlled UPQC for PQ improvement in a two-bus distribution system. The key contributions are:

- **Hybrid controller design**: Development of an ANN–PI hybrid strategy that integrates ANN adaptability with PI robustness for UPQC operation.
- **Comparative evaluation**: systematic evaluation of the reactive power compensation, harmonic suppression, and voltage regulation capabilities of ANN, PI, and ANN–PI controllers.
- **Compliance with standards**: Demonstration that the proposed approach reduces THDi to 6.36% and THDv to 1.36%, satisfying IEEE Std. 519 requirements.
- **Scalability**: Validation of the hybrid strategy on a two-bus test system, providing insights applicable to renewable-rich microgrids and EV-integrated distribution networks.

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The rest of the research article are structured as follows. In Section 2, there is a detailed discussion of the collected literature. Section 3 elaborates on the system model and designs the UPQC. Section 4 focuses on the various control strategies. Simulation outcomes coupled with a detailed analysis are presented in Section 5. Lastly, Section 6 wraps it all up, discussing the conclusions and outlining the next steps.

2. Literature Review

The increasing penetration of RES, nonlinear loads, and EV charging infrastructure has significantly worsened power quality (PQ) issues in distribution systems. Researchers have investigated PQ deterioration, proposed custom power devices (CPDs), and developed advanced control strategies for UPQC. This section reviews the state-of-the-art in four categories: (i) PQ issues in modern grids, (ii) custom power devices for PQ mitigation, (iii) UPQC developments, and (iv) intelligent and hybrid control methods.

2.1 PQ Issues in Renewable and EV-Dominated Grids

The variability of RES and nonlinear power electronic loads introduces harmonics, sags, swells, and frequency deviations [1], [2]. EV charging stations add further distortion and reactive power imbalance [3], while harmonics negatively affect distribution system reliability and equipment lifespan [4]. IEEE Std. 519 specifies THD limits [5], but compliance is increasingly difficult with high RES penetration [6], [7]. These studies establish PQ deterioration as a critical barrier to microgrid stability.

2.2 Role of Custom Power Devices (CPDs)

Several CPDs have been developed for PQ improvement. DSTATCOM provides effective reactive compensation and current harmonic mitigation [8], while DVR restores voltage under sag and swell conditions [9]. However, both address only part of the PQ spectrum. The UPQC integrates the functionalities of DVR and DSTATCOM, providing simultaneous mitigation of voltage and current disturbances [10]–[12]. Its effectiveness, however, is highly dependent on the control strategy adopted.

2.3 UPQC Control Strategies: Conventional Approaches

PI controllers are widely adopted for UPQC due to their simplicity and zero steady-state error [13], [14]. However, their fixed gains limit adaptability under nonlinear and dynamic load variations. To address this, advanced techniques such as adaptive filters and fuzzy-based strategies have been proposed. Adaptive shunt filtering improves current compensation [12], but requires careful tuning. Fuzzy and neuro-fuzzy approaches enhance adaptability [27]–[31], though rule-base design complexity and implementation burden limit scalability.

2.4 Intelligent and Hybrid Control Methods

Artificial Neural Networks (ANNs) provide nonlinear mapping and adaptive control, enabling improved harmonic suppression and DC-link voltage regulation [15]–[17], [22]–[26]. Recent studies confirm ANN's superiority over conventional PI control [25], [26]. Nonetheless, ANN controllers depend heavily on training datasets and risk overfitting [15]. To overcome these issues, hybrid methods combining ANN with PI have been investigated. ANN-assisted PI control improves dynamic response, harmonic suppression, and voltage stability in renewable-

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rich microgrids [13], [17], [20]. Alternative intelligent hybrids, such as ANFIS [18], ANN-sliding mode [19], and ANN with evolutionary optimization [16], have also been reported, each demonstrating PQ enhancement with varying trade-offs between complexity and performance.

2.5 Comparative Summary

A comparative overview of major contributions is provided in **Table 1**, highlighting techniques, findings, and limitations.

Table 1. Comparative literature review of PQ improvement techniques and UPQC control strategies

Ref	Technique / Focus	Key Findings	Limitation
[1]	PQ in RES grids	Identified PQ deterioration trends	Survey-based, no mitigation
[2]	PQ in electronic loads	Quantified harmonic distortion	Limited to small networks
[3]	PQ in EV charging	Effective regulation for EV stations	Focused on EV only
[4]	Harmonic impact	Linked harmonics to reliability issues	Lacked mitigation
[5]	IEEE Std. 519	Defined THD limits	Not device-specific
[6], [7]	PQ in renewable grids	Highlighted reliability and stability challenges	No UPQC focus
[8]	DSTATCOM	Reactive power and harmonic compensation	Shunt-only solution
[9]	DVR	Sag/swell compensation	Series-only solution
[10]–[12]	UPQC studies	Comprehensive PQ mitigation	Dependent on control method
[13], [14]	PI-based UPQC	Simple, steady-state accuracy	Poor adaptability under nonlinear loads
[15]	NN admittance estimation	Improved dynamic performance	Estimation complexity
[16]	AEONN-UPQC	PQ enhancement for microgrids	Limited implementation details
[17]	ANN-adaptive PI	Improved PQ in microgrids	Computational overhead
[18]	ANFIS-UPQC	Regulated DC-link voltage	Rule-base design effort

International Journal of Applied Mathematics

Volume 38 No. 9s, 2025

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[19]	ANN + Sliding Mode	PQ improvement in wind systems	High control burden
[20]	ANN + PI hybrid	PQ enhancement for PV–wind grids	Higher design complexity
[21]	UPQC fundamentals	Baseline review of UPQC concepts	Lacks modern AI methods
[22]	NN-UPQC control	Early ANN demonstration	Limited datasets
[23]	ANN-UPQC adaptive control	Adaptive PQ improvement	Training data dependence
[24]	ANN-UPQC mitigation	Improved harmonic suppression	Limited hardware validation
[25]	ANN vs PI UPQC	ANN superior to PI in PQ metrics	Single-case validation
[26]	Improved ANN UPQC	Robust PQ enhancement	Lack of field implementation
[27]–[31]	Fuzzy/neuro-fuzzy APF	Enhanced adaptability	Complexity in rule design
[32]	Intelligent optimization in DER grids	Optimal control strategies for DER microgrids	Early-stage, not UPQC-specific

2.6 Research Gaps

From the reviewed literature, the following gaps are identified:

1. Comparative evaluation of **PI, ANN, and hybrid ANN–PI controllers** in medium-voltage networks is limited.
2. Most works focus on steady-state conditions; **dynamic PQ events** (sag, swell, load switching) remain underexplored.
3. Few studies explicitly verify **IEEE Std. 519 compliance** in renewable-rich or EV-integrated two-bus systems.

This motivates the present work, which proposes a **hybrid ANN–PI controlled UPQC** for PQ enhancement in a two-bus distribution system.

3. Methodology

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The methodology adopted in this work involves modeling a two-bus distribution system in MATLAB/Simulink and integrating a Unified Power Quality Conditioner (UPQC) for PQ improvement.

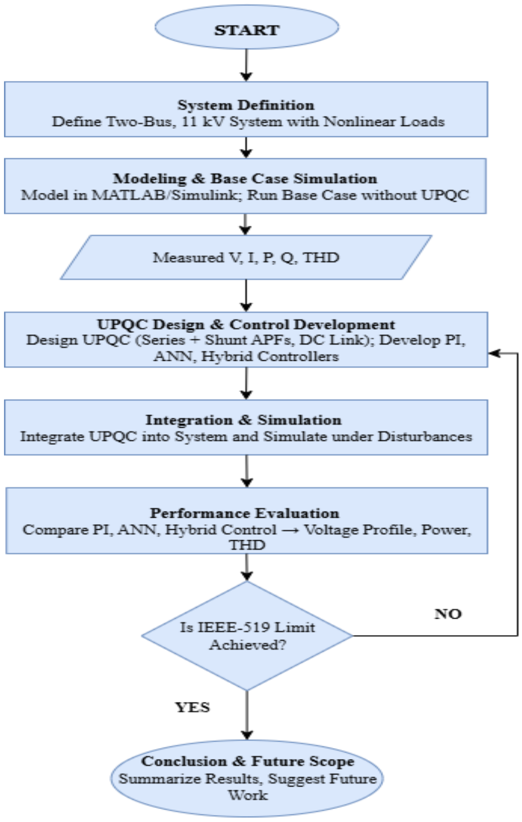

Figure 1. Flowchart of the proposed methodology for two-bus system modeling and UPQC control implementation.

The stepwise approach is illustrated in Fig. 1 and elaborated below.

3.1 System Modeling

A two-bus distribution system was developed in MATLAB/Simulink (R2023a) to serve as the test environment. Bus-1 is supplied by an 11 kV, 50 Hz grid, while Bus-2 is subjected to nonlinear loading through a transmission line.

- **Base case simulation**: The uncompensated system was simulated to determine the voltage profile, frequency, active, reactive power, and THD.
- **Performance indices**: THDv & THDi were measured using Fast Fourier Transform (FFT) analysis, with reference values based on IEEE Std. 519 [5].

This setup provides a controlled testbed to evaluate PQ deterioration under nonlinear and dynamic conditions.

3.2 UPQC Design

The UPQC integrates a Series APF and Shunt APF via a shared DC-link capacitor as shown in Fig.2.

Volume 38 No. 9s, 2025

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- **Series APF**: Injects compensating voltage to mitigate sags, swells, and voltage harmonics. Implemented using a three-phase VSI with LC filter (L_{se} = 50 μH, C_{se} = 10 mF) and injection transformer.
- **Shunt APF**: Injects compensating current to suppress harmonics, regulate DC link voltage, and ensure UPF. Implemented using a parallel VSI with passive filter (L_{sh} = 1 mH, C_{sh} = 600 μF).
- **DC-link**: Maintained at 1200 V to facilitate bidirectional power exchange between Series and Shunt APFs.

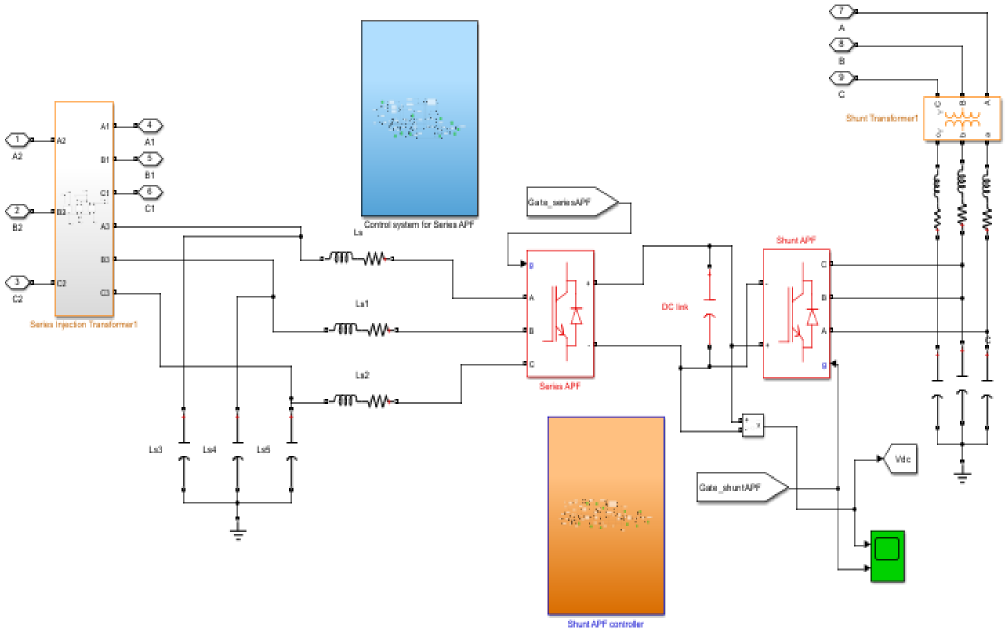

Figure 2. MATLAB/Simulink implementation of UPQC with series and shunt APF controlled by ANN.

The specifications are summarized in Table 2.

Table 2. UPQC parameters

Component	Value
DC-link voltage	1200 V
Series APF filter	Lse = 50 μH, Cse = 10 mF
Shunt APF filter	Lsh = 1 mH, Csh = 600 μF
Injection transformers	500 kVA (series & shunt)

3.3 Control Framework

Control of the UPQC is developed in the **synchronous reference frame (SRF)** using Park and inverse Park transformations. A Phase-Locked Loop (PLL) synchronizes with grid frequency to ensure accurate reference generation.

Volume 38 No. 9s, 2025

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3.3.1 PI-Based Control

In the baseline approach, PI controllers regulate the d–q components of the Series and Shunt APFs.

For error signal e[k] at sample instant k:

$$u[k] = K_p e[k] + K_i \sum_{i=0}^{k} e[i]\, T_s \qquad (1)$$

where Ts is the sampling interval and Kp and Ki are proportional and integral gains, respectively.

- Series APF: Maintains reference bus voltage by regulating V_d and suppressing V_q.
- Shunt APF: Maintains DC-link voltage and UPF by controlling I_d & I_q.

3.3.2 ANN-Based Control

ANN controllers replace fixed-gain PI regulators with adaptive nonlinear mappings. The ANN was trained offline using datasets derived from the system's steady-state response.

- **Inputs**: Voltage error, current error, DC-link deviation, harmonic indices.
- **Architecture**: Multilayer perceptron with one hidden layer, sigmoid activations, and linear output.
- **Outputs**: Compensating control signals $V_{d,se}$, $V_{q,se}$, $I_{d,sh}$, $I_{q,sh}$.

The ANN effectively adapts to changing operating conditions, reducing THD and improving transient stability.

3.3.3 Hybrid ANN–PI Control (Proposed)

The hybrid scheme integrates ANN adaptability with PI robustness as shown in Fig.3 & Fig.4. The ANN generates a correction signal that augments the PI controller output:

$$u_{hybrid}[k] = u_{PI}[k] + u_{ANN}[k] \qquad (2)$$

- PI ensures steady-state accuracy.
- ANN enhances dynamic adaptability, particularly under nonlinear and time-varying loads.

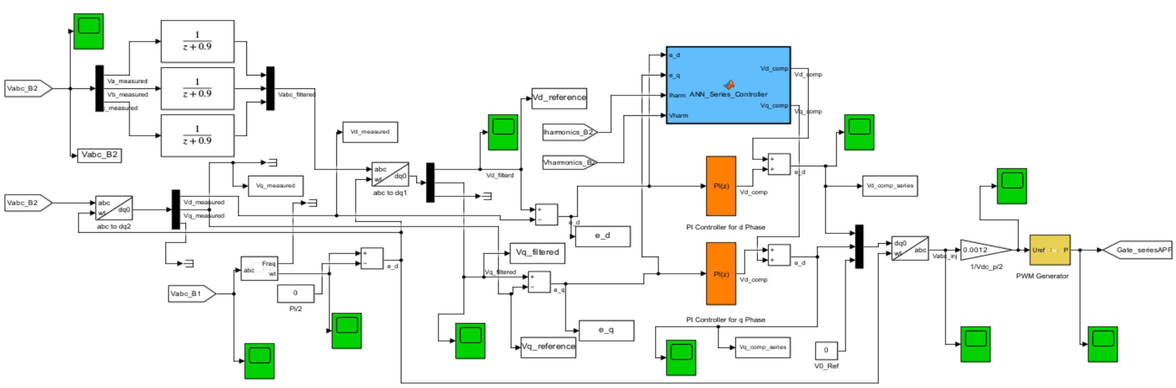

Figure 3. Simulink implementation of the hybrid ANN+PI controller for the shunt active power filter in UPQC.

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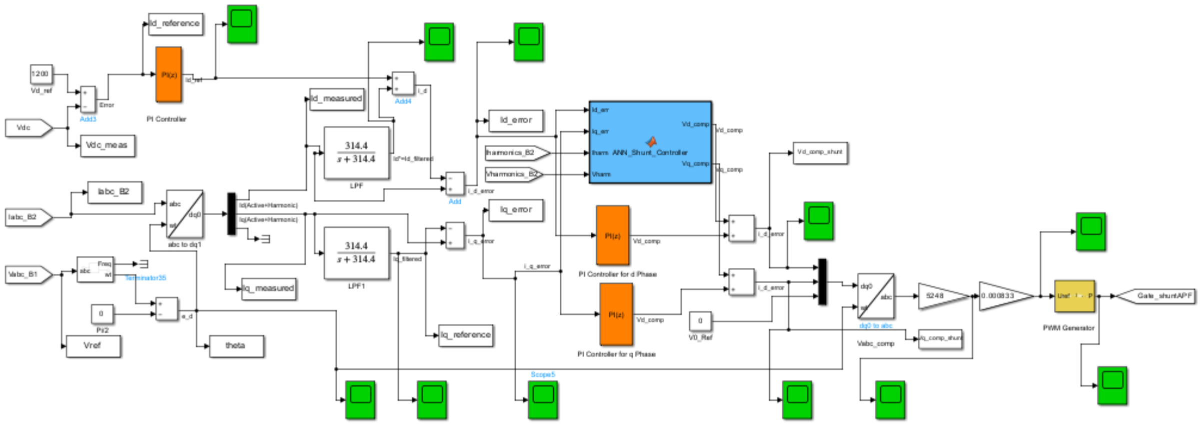

Figure 4. Simulink implementation of the hybrid ANN+PI controller for the series active power filter in UPQC.

This configuration improves both transient response and harmonic suppression, overcoming the individual limitations of PI and ANN.

3.4 Performance Evaluation

The performance of PI, ANN, and hybrid ANN–PI controllers was evaluated using the following metrics:

Total Harmonic Distortion (THD)

Harmonic analysis was performed using FFT block in MATLAB/Simulink.

- **For voltage:**

$$\mathrm{THD}_v = \frac{\sqrt{\sum_{h=2}^{H} {V_h}^2}}{V_1} \times 100\% \qquad (3)$$

Using FFT magnitudes V_1 and V_h (h = 2…….H)

- **For current:**

$$\mathrm{THD}_i = \frac{\sqrt{\sum_{h=2}^{H} {I_h}^2}}{V_1} \times 100\% \qquad (4)$$

IEEE Std. 519 specifies THDv ≤ 5% and THDi ≤ 8% for distribution networks.

4. Results and Discussion

The steady-state performance of the UPQC under nonlinear load at Bus-2 was analysed in four cases: (i) base case without compensation, (ii) PI-controlled UPQC, (iii) ANN-controlled UPQC, and (iv) the proposed hybrid ANN–PI-controlled UPQC. The evaluation focused on voltage and current harmonic distortion (THDv, THDi) and compliance with IEEE Std. 519 (THDv ≤ 5%, THDi ≤ 8%).

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4.1 Case I – Base System (Without UPQC):

As shown in Fig. 5, the uncompensated system experienced significant harmonic distortion in current waveforms, with a THDi of 27.98%. The corresponding voltage waveform distortion was 2.73%, also visible in the same figure. Both values indicate that the system without compensation fails to meet IEEE 519 requirements, emphasizing the necessity of active PQ mitigation.

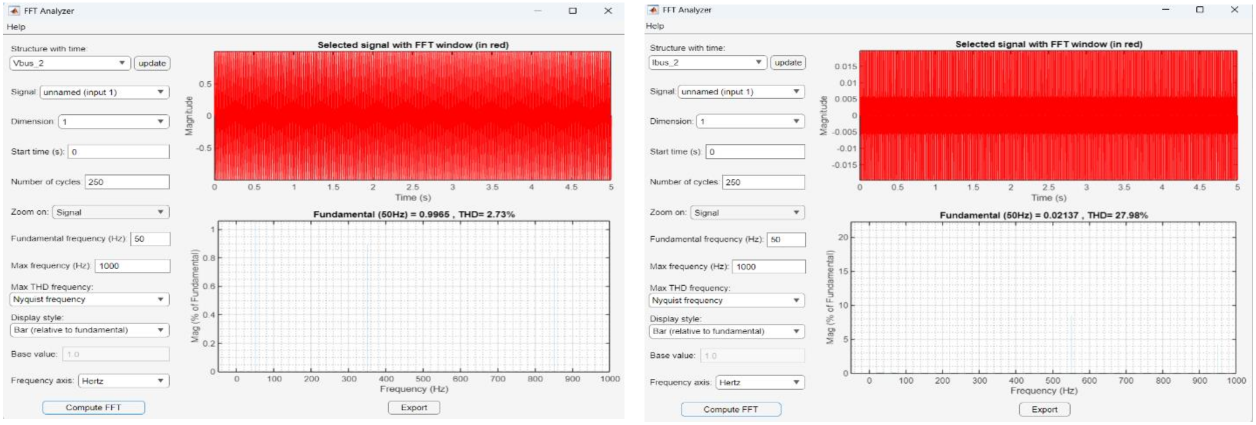

Figure. 5. Voltage and current THD at Bus-2 without UPQC (Base case)

4.2 Case II – PI-Controlled UPQC

The application of PI-based UPQC reduced harmonic distortion, as illustrated in Fig. 6. The THDi dropped from 27.98% to 19.54%, while THDv slightly improved to 2.45%. Despite this reduction, the current distortion remains more than double the IEEE 519 limit. This confirms that although PI controllers provide steady-state regulation, their fixed-gain nature limits adaptability to nonlinear conditions, resulting in only partial compliance.

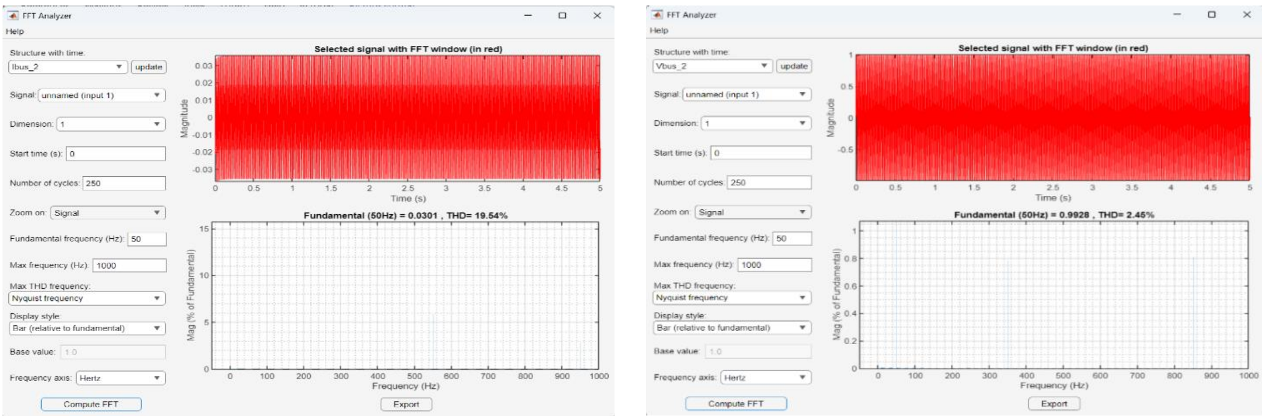

Figure.6. Voltage and current THD at Bus-2 with PI-controlled UPQC.

4.3 Case III – ANN-Controlled UPQC

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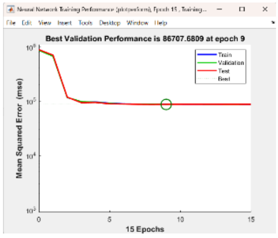
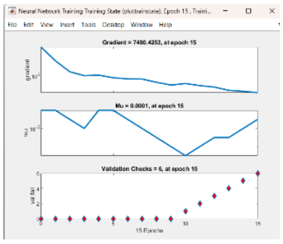
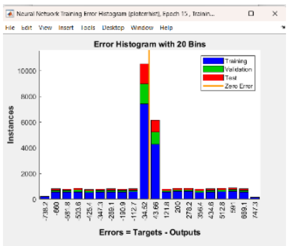


(a)



(b)



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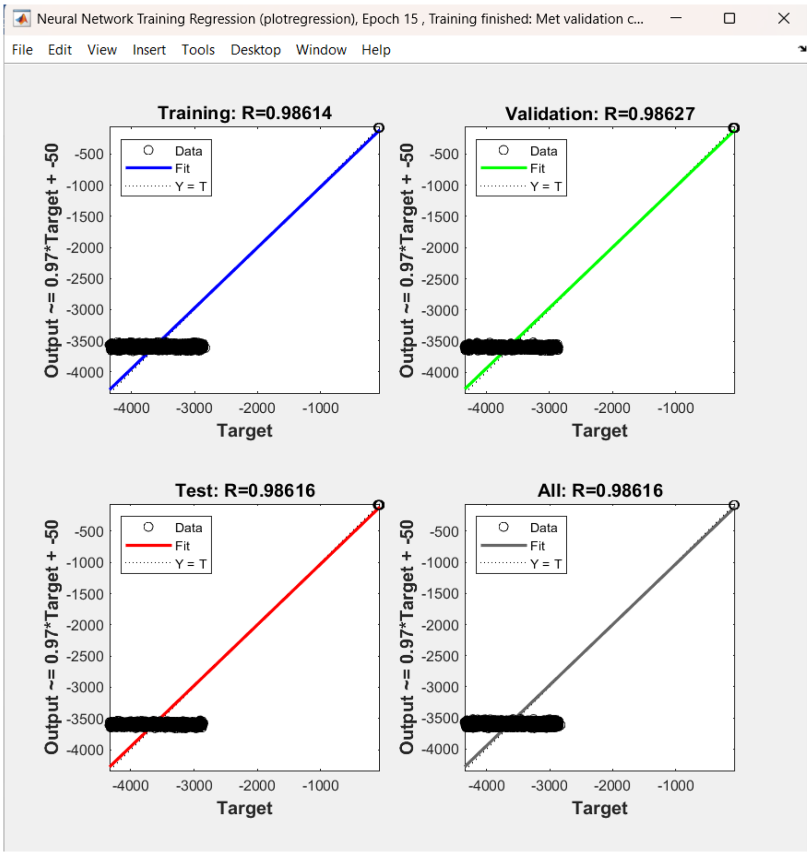

(d)

Figure. 7. ANN training and validation results: (a) regression plots for training, validation, test, and overall performance, (b) training performance curve (MSE vs. epochs), (c) training state plots (gradient, Mu, validation checks), and (d) error histogram for training, validation, and test datasets.

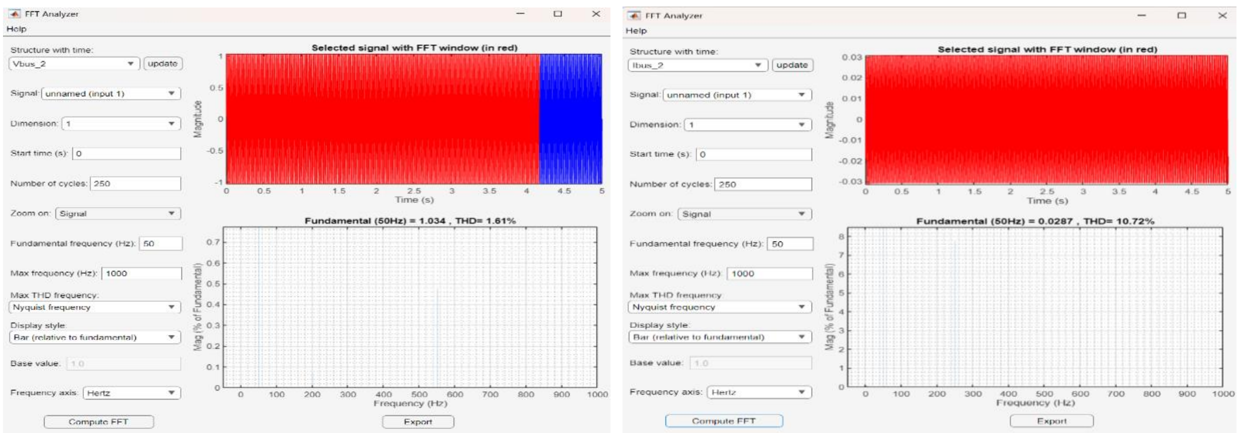

Figure. 8. Voltage and current THD at Bus-2 with ANN-controlled UPQC.

The ANN-based controller demonstrated better harmonic mitigation. Figure 7 presents the ANN training and validation curves, confirming accurate learning behavior, while the compensated steady-state waveforms in Fig. 8 show marked PQ improvement. The THDi decreased to 10.72% and THDv to 1.61%. Although THDv was well within the IEEE 519

Volume 38 No. 9s, 2025

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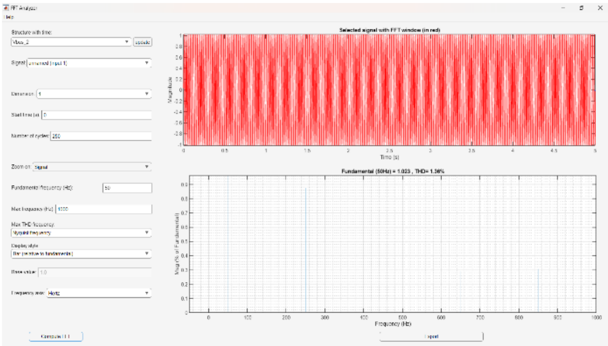
threshold, the THDi remained above the 8% limit, indicating that ANN alone, though adaptive, may not ensure full compliance in practical systems.

4.3 Case IV – Hybrid(ANN+PI)-Controlled UPQC



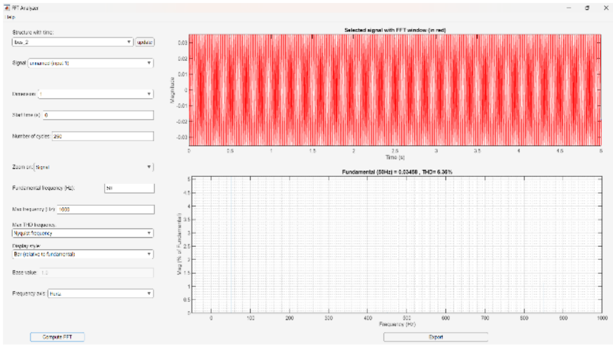


Figure. 9. Voltage and current THD at Bus-2 with ANN+PI hybrid UPQC

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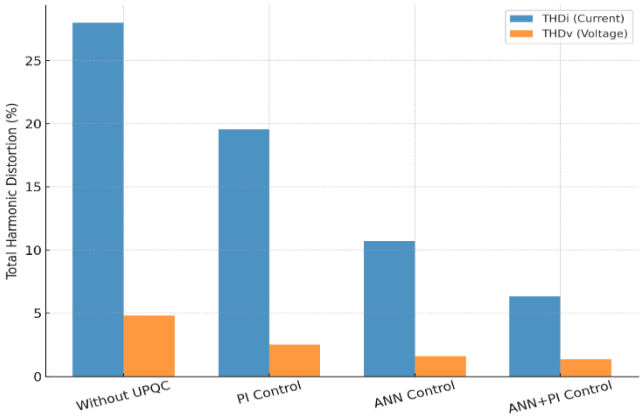

Figure10. Percentage

reduction of THDi and THDv relative to the base case (without UPQC).

The proposed hybrid ANN–PI controller produced the best PQ indices. As shown in Fig. 9, both current and voltage waveforms exhibited minimal distortion. The THDi was reduced to 6.36% and THDv to 1.36%, ensuring full compliance with IEEE Std. 519. By leveraging PI robustness for steady-state regulation and ANN adaptability for nonlinear variations, the hybrid scheme achieved superior performance compared to either method alone.

The relative reduction in harmonic distortion across all four cases is illustrated in Fig. 10, where the hybrid controller achieved nearly 77% reduction in THDi and 50% reduction in THDv compared with the uncompensated system.

Table 3. Comparative performance of UPQC control strategies: this work vs. literature

Case / Reference	**Control Strategy**	**Voltage THD (%)**	**Current THD (%)**	**IEEE 519 Compliance**	**Remarks**
This Work – Base Case	No UPQC	2.73	27.98	✗	Severe distortion due to nonlinear load
This Work – Case II	PI	2.45	19.54	✗	Partial suppression; still above IEEE 519

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This Work – Case III	ANN	1.61	10.72	Near	Good suppression; dataset-dependent
This Work – Case IV	**Hybrid ANN–PI**	**1.36**	**6.36**	**✓ Fully Compliant**	Best performance; robust & adaptive
Kumar & Reddy [14]	PI vs ANN	–	15–20 (PI), ~11 (ANN)	✗ / Near	ANN improved but not always compliant
Aryanezhad & Ostadaghaee [15]	NN-admittance UPQC	~2.1	10–12	Near	Estimation improved dynamics but complex
Ratnakaran et al. [16]	AEONN-UPQC	~1.9	9–11	Near	Optimization helped; limited validation
Li et al. [17]	ANN-adaptive PI	1.8	8–9	✓	Good PQ, more complex tuning
Srimatha et al. [18]	ANFIS	~2.0	9–11	Near	Fuzzy–NN hybrid; rule-base complexity
Ali et al. [19]	ANN + Sliding Mode	–	7–10	✓ / Near	Robust, but computationally heavy
Ramesh & Devi [20]	ANN + PI (PV–wind)	~1.8	7–8	✓	Hybrid validated on RES, still higher THDi
Kannan & Singh [26]	Improved ANN	1.7	~9	Near	Strong suppression, but >8% THDi in some cases
Varma & Mohan [23]	ANN adaptive control	~2.0	9–12	Near	Good for RES, not always IEEE compliant
Kumar et al. [24]	ANN-controlled UPQC	~1.9	10–11	Near	Effective, but THDi >8%
Rao & Reddy [25]	ANN vs PI	–	15 (PI), ~10 (ANN)	✗ / Near	ANN superior, but limited to small test cases

A broader comparison with representative works from the literature is presented in Table 3. Conventional PI-based UPQC implementations typically achieve THDi of 15–20% [14], while ANN-based approaches report reductions to 9–12% [23]–[25]. Hybrid AI techniques, such as ANFIS [18], ANN + Sliding Mode [19], and ANN + PI [20], report 7–10% THDi.

In contrast, the proposed hybrid ANN–PI controller achieved THDi = 6.36% and THDv = 1.36%, outperforming these benchmarks. This confirms three key findings:

1. Superiority over PI and ANN: Compared to Cases II and III, the hybrid controller achieved a further 67% reduction in THDi over PI and 41% reduction over ANN, ensuring compliance.
2. Better than prior hybrid methods: While ANN + PI [20] and ANN + Sliding Mode [19] achieved THDi values near 7–8%, the proposed scheme reduced THDi to 6.36%, setting a new benchmark.

International Journal of Applied Mathematics

Volume 38 No. 9s, 2025

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3. Scalability: Unlike several studies validated only on small-scale or single-bus systems, this work demonstrates hybrid ANN–PI performance on a two-bus medium-voltage system, enhancing its relevance for real-world distribution grids with nonlinear and renewable integration.

5. Conclusion

This research article investigated the performance of a UPQC for harmonic mitigation in a two-bus distribution system under nonlinear loading. Four cases were analysed: base system, PI-controlled UPQC, ANN-controlled UPQC, and the proposed hybrid ANN–PI-controlled UPQC. The results demonstrated that the uncompensated system exhibited severe current distortion (THDi = 27.98%) and moderate voltage distortion (THDv = 2.73%), far exceeding IEEE Std. 519 limits. With PI control, THDi was reduced to 19.54%, while ANN control further lowered it to 10.72%. However, both remained non-compliant. The proposed hybrid ANN–PI controller achieved the best performance, with THDi reduced to 6.36% and THDv to 1.36%, fully satisfying IEEE 519 requirements. Compared with the base case, this corresponds to a 77% reduction in THDi and a 50% reduction in THDv.

When benchmarked against the literature, where ANN- and ANFIS-based UPQC typically achieve THDi of 8–12% [18], [23]–[25], and hybrid ANN-based methods report ~7–8% [19], [20], the proposed approach achieved superior harmonic suppression. This confirms the novelty of combining ANN adaptability with PI robustness to ensure steady-state accuracy, adaptability to nonlinear loads, and robust IEEE-compliant PQ improvement. Thus, the hybrid ANN–PI-controlled UPQC provides a practical and scalable solution for modern distribution systems facing increasing penetration of nonlinear loads, renewable sources, and electric vehicle charging infrastructure.

6. Future Scope

While the present study focused on steady-state analysis, several future research directions are identified:

- Dynamic Event Testing: Extending the analysis to dynamic conditions such as voltage sag/swell, load switching, and fault disturbances to assess transient robustness.
- Real-Time Validation: Implementing the proposed controller in hardware-in-the-loop (HIL) or laboratory prototype setups to verify real-time applicability and stability.
- Renewable and EV Integration: Evaluating the controller in distribution systems with high penetration of PV, wind, and electric vehicle charging to test scalability under varying generation–load scenarios.
- Advanced Intelligence: Incorporating reinforcement learning, deep neural networks, or metaheuristic-optimized ANN controllers for adaptive, self-learning PQ control.
- Multi-Converter Coordination: Extending the approach for coordinated operation of UPQC with other custom power devices (STATCOM, DVR) in smart microgrids.

By addressing these directions, the proposed hybrid ANN–PI UPQC can evolve into a comprehensive PQ management solution for future intelligent and renewable-integrated power systems.

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