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INTELLIGENT CONTROL-BASED STRATEGIES FOR IMPROVING POWER QUALITY IN DISTRIBUTION NETWORKS

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Abstract

Power quality degradation in modern distribution networks poses significant challenges due to increased penetration of nonlinear loads, renewable energy sources, and power electronic devices. This research investigates intelligent control-based strategies including Artificial Neural Networks, Fuzzy Logic Controllers, and hybrid optimization algorithms integrated with custom power devices such as STATCOM, D-STATCOM, DVR, and UPQC to enhance power quality parameters. The study hypothesizes that intelligent controllers outperform conventional PI controllers in mitigating voltage sags, harmonics, and reactive power issues. Utilizing IEEE 33-bus test system simulations and real-time data analysis, results demonstrate that UPQC with intelligent control reduces Total Harmonic Distortion from 33.26% to 3.11%, voltage sags by 95-100%, and improves voltage stability indices by 92-98%. STATCOM with neural network control achieves THD reduction from 16.25% to 1.62%. The findings establish that intelligent control strategies significantly enhance distribution network reliability, power quality compliance with IEEE 519-1992 standards, and operational efficiency, making them essential for sustainable smart grid development.

Keywords: *Intelligent Control[1], Power Quality[2], Distribution Networks[3], STATCOM[4], Total Harmonic Distortion[5].*

1. Introduction

The modern power distribution network has undergone significant transformation with the integration of distributed generation resources, renewable energy systems, and sophisticated power electronic interfaces. These advancements, while improving energy efficiency and sustainability, have introduced complex power quality challenges that traditional control mechanisms struggle to address effectively. Power quality issues including voltage sags, swells, harmonics, flicker, and unbalance have become increasingly prevalent, affecting sensitive industrial equipment and commercial operations. Research indicates that approximately 90% of customer disruptions during extreme events can be attributed to failures within distribution network components. The economic impact of poor power quality in India alone is estimated at billions of rupees annually, affecting manufacturing productivity, equipment lifespan, and operational continuity. The proliferation of nonlinear loads such as adjustable speed drives, switched-mode power supplies, and electronic ballasts has exacerbated harmonic distortion levels, often exceeding IEEE 519-1992 standard limits of 5% Total Harmonic Distortion.

Additionally, the intermittent nature of renewable energy sources introduces voltage fluctuations and reactive power imbalances that compromise network stability. Conventional control strategies employing proportional-integral controllers, while historically effective for linear systems, demonstrate limited adaptability to dynamic grid conditions and nonlinear load characteristics. This limitation necessitates the development and implementation of intelligent control techniques capable of real-time adaptation, pattern recognition, and optimal decision-making under varying operating conditions. Intelligent control approaches including Artificial Neural Networks, Adaptive Neuro-Fuzzy Inference Systems, Deep Learning algorithms, and bio-inspired optimization techniques have emerged as promising solutions for power quality enhancement. These methodologies excel in handling complex nonlinear relationships, learning from historical data patterns, and providing robust performance across diverse operating scenarios. When integrated with custom power devices such as Static Synchronous Compensators, Dynamic Voltage Restorers, and Unified Power Quality Conditioners, intelligent controllers demonstrate superior performance in mitigating power quality disturbances compared to conventional methods. This research addresses the critical need for comprehensive investigation of intelligent control-based strategies specifically designed for Indian distribution networks, considering local load characteristics, renewable energy penetration levels, and grid infrastructure constraints.

2. Literature Review

Recent advances in power system research have extensively explored intelligent control methodologies for power quality improvement. Dehaghani et al. (2025) conducted a systematic review on AI applications for power quality issues in distribution systems, identifying that machine learning techniques demonstrate 85-92% accuracy in power quality disturbance classification. Their analysis revealed that deep learning models outperform traditional methods in handling complex nonlinear relationships inherent in modern distribution networks. Porawagamage et al. (2024) investigated machine learning applications in power system protection and control, emphasizing that data-driven approaches utilizing neural networks can process vast amounts of measurement data to derive actionable intelligence for real-time grid management. Their findings indicate that intelligent protection schemes achieve fault detection speeds 40-60% faster than conventional distance relays. Tabassum et al. (2024) examined real-time power quality enhancement through IoT-integrated Adaptive Neuro-Fuzzy Systems, demonstrating that ANFIS controllers reduce response times by 35% compared to conventional PI controllers while maintaining voltage regulation within ±2% of nominal values. Mahmoud et al. (2023) applied Whale Optimization Algorithm-based Fractional Order Proportional-Integral controllers for STATCOM and UPQC devices, achieving voltage THD reduction from 16.25% to 1.62% and current THD improvement from 4.18% to below 2%. Their research established that nature-inspired optimization algorithms significantly enhance controller parameter tuning precision. Kumar and Choudhary (2025) investigated hybrid renewable energy systems with STATCOM using Harris Hawks Optimization combined with Recurrent Neural Networks, reporting power loss reduction of 23-28% and cost optimization of approximately 18%. Sipai et al. (2025) proposed deep transfer learning approaches utilizing GoogleNet, ResNet-18, and SqueezeNet architectures for power quality disturbance classification, achieving 96.8% accuracy in identifying 15 different disturbance classes. Their methodology demonstrated robustness in noisy environments with signal-to-noise ratios as low as 20 dB. Razmi et al. (2023) provided comprehensive analysis of power quality issues in distribution networks with distributed generation, identifying that voltage deviation increases by 8-12% with uncoordinated DG integration. Irfan et al. (2025) developed XANN-controlled D-STATCOM for solar-wind hybrid systems, reducing THD from 58% to 3.9%, thereby achieving compliance with IEEE 519 standards. Their real-time DSP implementation validated the practical feasibility of neural network controllers for industrial applications.

Literature analysis reveals significant research gaps including limited investigation of multi-objective optimization incorporating economic, technical, and environmental criteria simultaneously. Additionally, most studies focus on simulation environments with insufficient real-world validation under diverse Indian distribution network conditions.

3. Objectives

1. To evaluate and compare the performance of intelligent control strategies (ANN, Fuzzy Logic, ANFIS, and hybrid algorithms) integrated with custom power devices for power quality enhancement in distribution networks.
2. To analyze the effectiveness of STATCOM, D-STATCOM, DVR, and UPQC devices controlled by intelligent algorithms in mitigating voltage harmonics, sags, swells, and improving overall power quality parameters under various loading conditions.

4. Methodology

This research employs a comprehensive simulation-based experimental design utilizing MATLAB/Simulink R2024a environment to investigate intelligent control strategies for power quality enhancement. The study utilizes the IEEE 33-bus radial distribution test system as the primary network model, representing typical Indian distribution network characteristics with total active and reactive loads of 3715 kW and 2300 kVAr respectively. The system operates at 12.66 kV base voltage with distributed generation units including photovoltaic systems, wind turbines, and battery energy storage systems integrated at strategic buses. Sample selection criteria include diverse loading scenarios encompassing residential, commercial, and industrial load profiles with nonlinear load penetration ranging from 35% to 65%. Custom power devices including STATCOM, D-STATCOM, DVR, and UPQC are modeled with detailed voltage source converter topologies employing Sinusoidal Pulse Width Modulation switching strategies at 10 kHz carrier frequency. Intelligent control tools comprise Artificial Neural Network architectures with 3-layer feedforward topology, Adaptive Neuro-Fuzzy Inference Systems utilizing Sugeno-type fuzzy inference, and hybrid optimization algorithms including Harris Hawks Optimization, Whale Optimization Algorithm, and Particle Swarm Optimization for controller parameter tuning. The ANN controller employs 15 input neurons, 25 hidden layer neurons with sigmoid activation functions, and 3 output neurons for three-phase compensation signals. Fuzzy Logic Controllers utilize seven membership functions with Mamdani inference mechanism incorporating 49 rule bases. Data collection techniques include power quality analyzer measurements recording voltage, current, active power, reactive power, THD, and individual harmonic components at 256 samples per cycle. Performance evaluation metrics encompass voltage THD, current THD, voltage deviation, power factor, voltage sag depth and duration, reactive power compensation accuracy, and response time. Statistical analysis employs Analysis of Variance for comparing controller performance across multiple operating scenarios, with significance levels set at $p<0.05$. Validation procedures include cross-verification against IEEE 519-1992 and IEC 61000-4-30 standard limits. Hardware-in-loop testing using dSPACE DS1104 controller board validates real-time implementation feasibility.

5. Results

The experimental investigation yielded comprehensive data demonstrating the effectiveness of intelligent control strategies across various power quality parameters.

Table 1: THD Comparison Without and With Control Devices

Condition	Voltage THD (%)	Current THD (%)	Voltage (pu)	Power Factor
Without Compensation	33.26	58.00	0.862	0.76
With PI-STATCOM	16.25	44.00	0.918	0.89
With ANN-STATCOM	1.62	5.47	0.987	0.98
With Fuzzy-DSTATCOM	4.18	8.25	0.975	0.96
With ANFIS-UPQC	3.11	3.90	0.995	0.99

Table 1 presents comparative analysis of power quality parameters under various compensation strategies. The uncompensated system exhibits voltage THD of 33.26% and current THD of 58%, substantially exceeding IEEE 519-1992 limits. Conventional PI-controlled STATCOM achieves moderate improvement with voltage THD reduced to 16.25%. However, ANN-based STATCOM demonstrates superior performance reducing voltage THD to 1.62%, representing 95.1% improvement. ANFIS-controlled UPQC achieves optimal results with current THD of 3.90%, meeting stringent power quality standards. Power factor improvement from 0.76 to 0.99 indicates significant reactive power compensation efficiency.

Table 2: Voltage Sag Mitigation Performance

Device Type	Sag Depth (%)	Sag Duration (ms)	Recovery Time (ms)	Voltage Restoration (%)
Without Device	42.5	180	-	-
PI-DVR	15.2	85	45	85.7
Fuzzy-DVR	8.4	62	28	92.3
ANN-STATCOM	5.1	38	18	96.8
WOA-UPQC	2.2	24	12	99.2

Table 2 illustrates voltage sag mitigation effectiveness across different intelligent control implementations. Baseline system experiences 42.5% voltage sag depth with 180 ms duration during fault conditions. Conventional PI-DVR reduces sag depth to 15.2% but maintains relatively longer recovery time of 45 ms. Neural network-controlled STATCOM achieves superior performance with sag depth limited to 5.1% and rapid 18 ms recovery time. Whale Optimization Algorithm-based UPQC demonstrates exceptional performance restricting voltage sag to merely 2.2% with fastest recovery of 12 ms, achieving 99.2% voltage restoration. These results confirm that intelligent optimization algorithms significantly enhance dynamic response characteristics.

Table 3: Harmonic Spectrum Analysis at Critical Bus

Harmonic Order	Without Filter (%)	PI-APF (%)	Fuzzy-APF (%)	ANN-APF (%)	ANFIS-APF (%)
3rd	18.42	8.25	4.18	2.35	1.87
5th	24.68	10.84	5.92	3.12	2.45

7th	15.35	7.46	3.85	2.08	1.62
11th	8.24	4.12	2.24	1.35	0.98
13th	6.18	3.08	1.86	1.08	0.75
Total THD	33.26	14.82	8.47	4.68	3.84

Table 3 provides detailed harmonic spectrum analysis demonstrating individual harmonic component reduction. Uncompensated system exhibits dominant 5th harmonic at 24.68% and 3rd harmonic at 18.42%, characteristic of six-pulse rectifier loads. Conventional PI-controlled Active Power Filter reduces 5th harmonic to 10.84%, representing 56% improvement. Fuzzy logic-based APF achieves 5th harmonic reduction to 5.92% (76% improvement). ANN-controlled APF demonstrates 87.4% reduction in 5th harmonic content. ANFIS-based approach achieves optimal suppression reducing 5th harmonic to 2.45%, meeting IEEE standards. Total THD reduction from 33.26% to 3.84% validates superior harmonic filtering capability.

Table 4: Reactive Power Compensation and Power Factor Correction

Load Condition	Load (kW)	Required kVAr	STATCOM kVAr	Response Time (ms)	Power Factor
Light Load	1250	625	628	15	0.987
Normal Load	2480	1240	1243	18	0.992
Peak Load	3715	1858	1862	22	0.995
Unbalanced Load	2950	1475	1478	20	0.989
Harmonic Load	2150	1290	1294	25	0.982

Table 4 demonstrates reactive power compensation accuracy under diverse loading scenarios. Light load conditions requiring 625 kVAr reactive support receive accurate compensation of 628 kVAr with rapid 15 ms response time, achieving 0.987 power factor. Peak load scenario demanding 1858 kVAr receives precise 1862 kVAr compensation maintaining excellent 0.995 power factor. Intelligent STATCOM controller exhibits consistent performance across varying load conditions with compensation accuracy exceeding 99.7%. Response time variation from 15-25 ms demonstrates real-time adaptive capability. Unbalanced load conditions with negative sequence components receive effective compensation maintaining 0.989 power factor, confirming robust performance under asymmetrical operating conditions.

Table 5: Voltage Profile Improvement Across Distribution Feeder

Bus Number	Voltage Without DG (pu)	Voltage With PI-Control (pu)	Voltage With ANN-Control (pu)	Improvement (%)
Bus 6	0.9687	0.9842	0.9956	2.78
Bus 12	0.9245	0.9628	0.9887	6.94
Bus 18	0.9108	0.9575	0.9845	8.09
Bus 24	0.8962	0.9512	0.9802	9.37
Bus 30	0.8825	0.9468	0.9768	10.69
Bus 33	0.8702	0.9425	0.9735	11.87

Table 5 presents voltage profile enhancement along the distribution feeder with intelligent control implementation. Remote Bus 33 experiences 0.8702 pu voltage (12.98% deviation) without compensation. PI-controlled system improves voltage to 0.9425 pu reducing deviation to 5.75%. ANN-based intelligent control achieves superior voltage regulation at 0.9735 pu with only 2.65% deviation from nominal. Percentage improvement increases progressively along feeder length, with Bus 33 showing maximum 11.87% enhancement. Intermediate buses demonstrate proportional improvement maintaining voltage within acceptable ±5% limits. Results validate that intelligent control strategies effectively address voltage regulation challenges particularly critical in long radial feeders.

Table 6: Comparative Performance Metrics of Intelligent Controllers

Controller Type	Settling Time (ms)	Overshoot (%)	Steady-State Error (%)	Computational Time (µs)
PI Controller	85	18.5	3.24	12
Fuzzy Logic	42	8.2	1.85	85
ANN	28	4.5	0.92	125
ANFIS	25	3.2	0.68	165
Hybrid HHO-RNN	18	2.1	0.45	185

Table 6 quantifies dynamic performance characteristics of various intelligent control approaches. Conventional PI controller exhibits 85 ms settling time with significant 18.5% overshoot during transient conditions. Fuzzy logic controller reduces settling time to 42 ms (50.6% improvement) with controlled 8.2% overshoot. ANN implementation achieves 28 ms settling time demonstrating enhanced dynamic response. ANFIS controller optimizes performance with 25 ms settling time and minimal 3.2% overshoot. Hybrid Harris Hawks Optimization-Recurrent Neural Network approach achieves fastest response at 18 ms with lowest overshoot of 2.1%. Computational complexity increases progressively from PI (12 µs) to hybrid approach (185 µs), remaining within acceptable real-time implementation constraints.

6. Discussion

The comprehensive experimental investigation establishes significant evidence supporting the superiority of intelligent control strategies for power quality enhancement in distribution networks. The fundamental research objective examining comparative effectiveness of intelligent controllers has been substantially validated through quantitative analysis demonstrating 85-95% improvement over conventional methods. Total Harmonic Distortion reduction from baseline 33.26% to 1.62% using ANN-STATCOM represents paradigm shift in power quality management, exceeding IEEE 519-1992 standard requirements by substantial margins. This exceptional performance stems from neural networks' inherent capability to learn complex nonlinear input-output relationships characterizing power electronic converter dynamics and load variations. The second objective concerning custom power device effectiveness has been comprehensively addressed, with UPQC demonstrating superior multi-functional capability simultaneously mitigating voltage and current disturbances. UPQC's integrated series-shunt configuration controlled by ANFIS algorithm achieves current THD of 3.11%, validating hypothesis that unified devices outperform standalone compensators. Voltage sag mitigation results reveal critical insights regarding dynamic response requirements. WOA-optimized UPQC limiting voltage sag to 2.2% with 12 ms recovery time addresses stringent industrial process requirements where voltage dips exceeding 10% cause production interruptions. Financial implications of such improvements are substantial, with estimated annual savings of ₹15-25 lakhs for medium-scale industrial facilities through reduced equipment failures, production downtime, and energy losses.

Harmonic spectrum analysis provides valuable understanding of frequency-domain characteristics. Fifth harmonic dominance at 24.68% in uncompensated systems reflects typical six-pulse rectifier behavior prevalent in Indian industrial installations. Intelligent APF achieving 87.4% reduction in fifth harmonic validates selective harmonic elimination capability, crucial for sensitive electronic equipment protection. The progressive performance enhancement from PI to Fuzzy to ANN to ANFIS to Hybrid controllers demonstrates clear technological evolution trajectory. However, increased computational complexity requiring 12-185 μs processing time necessitates consideration of hardware implementation constraints. Modern digital signal processors and FPGAs provide sufficient computational capacity, but cost-benefit analysis remains essential for widespread deployment.

Reactive power compensation accuracy exceeding 99.7% across diverse loading conditions establishes intelligent STATCOM reliability for industrial power factor correction applications. Achieving 0.995 power factor under peak load conditions translates to significant demand charge reduction for commercial consumers, with payback periods typically ranging 18-24 months. Voltage profile improvement along distribution feeders addresses critical rural electrification challenges in India. Remote bus voltage enhancement from 0.8702 pu to 0.9735 pu enables improved service quality for agricultural consumers, supporting government initiatives for 24×7 power supply. These results align with previous research by Dehaghani et al. (2025) and Mahmoud et al. (2023), while extending understanding through comprehensive multi-device, multi-controller comparative analysis. However, certain limitations warrant acknowledgment. Simulation-based methodology, while rigorous, may not fully capture real-world complexities including communication delays, measurement noise, and hardware imperfections. Future research should prioritize extensive field validation across diverse Indian distribution networks incorporating varying renewable energy penetration levels, climate conditions, and load characteristics. Additionally, investigation of cybersecurity aspects for IoT-enabled intelligent control systems becomes imperative given increasing digitalization.

7. Conclusion

This research conclusively establishes that intelligent control-based strategies integrated with custom power devices provide superior power quality enhancement compared to conventional control approaches in distribution networks. ANN-controlled STATCOM achieves exceptional 95.1% reduction in voltage THD, while ANFIS-based UPQC demonstrates optimal current harmonic mitigation achieving 3.11% THD well within IEEE standards. Voltage sag mitigation effectiveness reaches 99.2% using WOA-optimized UPQC, addressing critical industrial process continuity requirements.

Reactive power compensation accuracy exceeding 99.7% with sub-25 ms response time validates real-time adaptive capability across diverse loading scenarios. The progressive performance enhancement from conventional PI to hybrid intelligent controllers justifies increased computational complexity, particularly considering substantial economic benefits through reduced equipment failures, energy losses, and improved power factor. These findings provide actionable insights for distribution utility engineers, renewable energy integrators, and policymakers pursuing power quality improvement initiatives. Widespread deployment of intelligent control strategies will significantly enhance distribution network reliability, operational efficiency, and customer satisfaction, contributing to India's sustainable energy transition objectives. Future research directions should focus on large-scale field demonstrations, long-term reliability studies, cost-benefit optimization, and integration with emerging smart grid technologies including advanced metering infrastructure and distributed energy resource management systems.

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