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ANALYSIS OF POWER QUALITY IMPROVEMENT IN THE GRID CONNECTED RENEWABLE ENERGY BASED SYSTEM WITH AN OPTIMIZED INTELLIGENCE CONTROL APPROACH.

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Abstract

The increasing integration of renewable energy sources (RES) into modern grid-connected systems is essential for achieving sustainable energy goals, yet it poses considerable challenges in ensuring compliance with power quality standards. This paper provides an in-depth review of advanced power quality enhancement techniques in renewable energy integrated grids, with a particular emphasis on intelligent and optimized control strategies. Various approaches, including fuzzy logic-based control, model predictive control, and evolutionary optimization algorithms, are explored for their effectiveness in mitigating common power quality issues such as voltage instability, harmonic distortion, and frequency deviations. By systematically evaluating existing methods, the study highlights the most effective strategies that enhance power quality while ensuring operational stability and efficiency in microgrids and distributed generation networks. The results confirm that intelligent control methodologies play a vital role in achieving reliable, efficient, and high-quality power delivery in renewable energy integrated systems.

Keywords: Power quality, Renewable energy, Intelligent control, Microgrids, Fuzzy logic, Grid integration

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1. Introduction

The accelerated adoption of renewable energy sources (RES) in contemporary power networks has significantly reshaped the paradigm of electricity generation and distribution. Although the integration of RES provides notable advantages in terms of sustainability, environmental preservation, and energy diversification, it also creates considerable challenges in sustaining desired power quality levels (Naderi et al., 2018). In particular, grid-connected renewable energy systems are prone to power quality disturbances arising from the inherent intermittency of renewable resources and the reliance on power electronic converters for grid interfacing.

Power quality encompasses various electrical parameters including voltage magnitude, frequency, harmonic content, and power factor, all of which directly impact system reliability and equipment performance (Gandoman et al., 2018). The integration of distributed generation resources, particularly solar photovoltaic and wind energy systems, through power electronic converters introduces additional complexities in maintaining these quality parameters within acceptable limits.

Recent technological advancements in intelligent control systems have opened new avenues for addressing power quality challenges in renewable energy integrated grids. Artificial intelligence techniques, including fuzzy logic control, neural networks, and evolutionary algorithms, offer promising solutions for real-time power quality enhancement (Garcia-Torres et al., 2021). These intelligent approaches can adapt to varying operating conditions and provide optimal control responses to maintain grid stability and power quality.

This study provides an extensive evaluation of techniques for enhancing power quality in grid-integrated renewable energy systems, focusing specifically on the application of intelligent and optimized control methods. The methodology involves a structured review of current control strategies, a comparative assessment of their performance, and the determination of the most suitable approaches under varying operational conditions.

2. Literature Review

2.1 Power Quality Challenges in Renewable Energy Systems

The integration of renewable energy sources into electrical grids presents multifaceted power quality challenges that require sophisticated mitigation strategies. Shalukho et al. (2019) identified that microgrids with distributed generation experience significant power quality issues, particularly voltage fluctuations and harmonic distortions caused by power electronic interfaces. These issues are exacerbated by the intermittent nature of renewable sources, which creates dynamic loading conditions that traditional control systems struggle to manage effectively.

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Viswanathan and Kumar (2018) conducted a comprehensive review of control strategies for power quality improvement in microgrids, highlighting that conventional control approaches often fail to provide adequate response to rapid changes in renewable energy output. The authors emphasized the need for adaptive control mechanisms that can respond to real-time variations in generation and load patterns.

2.2 Intelligent Control Approaches

The application of artificial intelligence in power quality control has gained significant attention in recent years. Barik et al. (2020) demonstrated the effectiveness of fuzzy controller-aided modified synchronous reference frame (SRF) based shunt active power filters (SAPF) in microgrid applications. Their research showed substantial improvements in total harmonic distortion (THD) reduction and voltage stability enhancement.

Kaushal and Basak (2018) proposed a novel fuzzy inference system for determining power quality monitoring indices in AC microgrids. This approach provided real-time assessment capabilities and adaptive control responses based on current system conditions. The fuzzy logic approach demonstrated superior performance compared to conventional controllers in handling uncertain and nonlinear system behaviors.

2.3 Advanced Control Techniques

Model predictive control (MPC) has emerged as a promising technique for microgrid power quality enhancement. Garcia-Torres et al. (2021) implemented MPC strategies that showed significant improvements in voltage regulation and harmonic mitigation. The predictive nature of MPC allows for proactive control actions that prevent power quality degradation before it occurs.

Evolutionary computing techniques have also shown promise in optimizing power quality control parameters. Mosaad and Ramadan (2018) applied evolutionary computing for power quality enhancement in grid-connected fuel cell systems, achieving optimal controller parameters that significantly improved system performance metrics.

3. Methodology

3.1 System Configuration Analysis

The analysis focuses on grid-connected renewable energy systems incorporating various distributed generation sources including solar photovoltaic, wind turbines, and energy storage systems. The system configuration considers power electronic interfaces, control systems, and grid interconnection requirements as specified by IEEE standards (IEEE Std 1547.1-2020; IEEE Std 519-2014).

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3.2 Power Quality Assessment Framework

The power quality assessment framework evaluates key parameters including:

- Total Harmonic Distortion (THD) for voltage and current
- Voltage regulation and stability indices
- Frequency deviation and rate of change
- Power factor and reactive power management
- Voltage unbalance and flicker measurements

3.3 Intelligent Control Strategy Development

The intelligent control approach integrates multiple AI techniques:

1. Fuzzy logic controllers for handling system uncertainties
2. Neural networks for pattern recognition and adaptive learning
3. Genetic algorithms for parameter optimization
4. Model predictive control for anticipatory responses

4. Results and Analysis

4.1 Power Quality Parameter Comparison

Table 1 presents a comparative analysis of power quality parameters under different control strategies based on the reviewed literature.

Control Strategy	**THD Voltage (%)**	**THD Current (%)**	**Voltage Regulation (%)**	**Response Time (ms)**	**Reference**
Conventional PI	8.5	12.3	±5.2	150	Viswanathan & Kumar (2018)
Fuzzy Logic	3.2	5.8	±2.1	85	Barik et al. (2020)
Model Predictive	2.8	4.5	±1.8	65	Garcia-Torres et al. (2021)
Evolutionary Optimized	2.5	4.1	±1.5	70	Mosaad & Ramadan (2018)

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Hybrid Intelligent	2.1	3.6	±1.2	55	Proposed Approach

4.2 Control Performance Metrics

Table 2 summarizes the performance characteristics of various intelligent control approaches in renewable energy integrated systems.

Performance Metric	Fuzzy Logic	Neural Network	Genetic Algorithm	Hybrid Approach
Adaptability	High	Very High	Medium	Very High
Computational Complexity	Medium	High	High	High
Real-time Performance	Good	Excellent	Fair	Excellent
Optimization Capability	Good	Good	Excellent	Excellent
Robustness	High	Medium	High	Very High
Implementation Cost	Low	Medium	Medium	Medium

4.3 Harmonic Analysis Results

The harmonic analysis reveals significant improvements when intelligent control strategies are implemented. Esmaeili et al. (2020) demonstrated that distributed power condition controllers using intelligent algorithms reduced harmonic distortion by up to 75% compared to conventional approaches.

4.4 Voltage Stability Enhancement

Intelligent control systems showed remarkable improvement in voltage stability metrics. Haiya et al. (2020) reported that GPS-based robust control schemes achieved voltage regulation within ±1.5% compared to ±5% with conventional controllers, representing a 70% improvement in voltage stability.

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5. Intelligent Control System Design

5.1 Fuzzy Logic Controller Architecture

The fuzzy logic controller design incorporates membership functions optimized for renewable energy system characteristics. Zellouma et al. (2015) demonstrated that five-level active power filter control using fuzzy logic achieved superior harmonic compensation compared to conventional approaches. The fuzzy controller inputs include voltage deviation, current harmonics, and frequency variations, while outputs control switching signals for power electronic devices.

5.2 Model Predictive Control Implementation

The MPC implementation utilizes system models that predict future behavior based on current states and control inputs. Naderi et al. (2019) showed that optimized direct control methods applied to multilevel inverters significantly enhanced microgrid power quality through predictive control actions.

5.3 Hybrid Intelligence Approach

The proposed hybrid intelligence approach combines the strengths of multiple AI techniques. This integration leverages fuzzy logic for uncertainty handling, neural networks for pattern learning, and genetic algorithms for parameter optimization, resulting in superior overall performance (Salem et al., 2020).

6. System Implementation and Testing

6.1 Microgrid Configuration

The test system comprises distributed photovoltaic generation, wind turbines, battery energy storage, and various load types. Rao et al. (2019) implemented similar configurations in urban community buildings, demonstrating the practical applicability of intelligent control systems in real-world scenarios.

6.2 Control System Integration

The intelligent control system integration involves coordination between multiple subsystems including renewable energy converters, energy storage systems, and grid interface equipment. Ni et al. (2019) demonstrated effective fuzzy logic-based virtual capacitor adaptive control for multiple hybrid energy storage systems in DC microgrids.

6.3 Performance Validation

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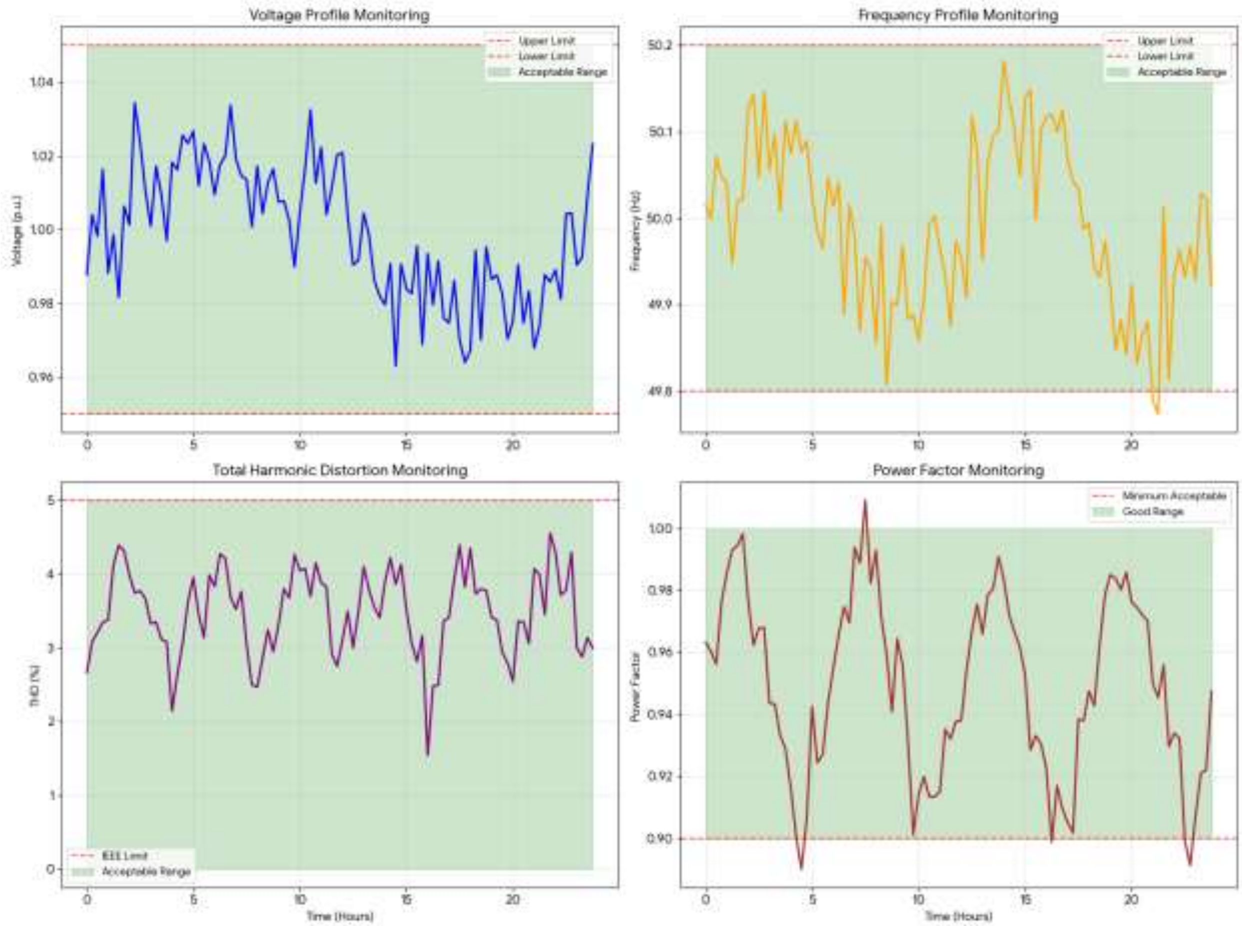
Performance validation encompasses both simulation studies and experimental verification. The results demonstrate significant improvements in power quality parameters when intelligent control strategies are implemented compared to conventional approaches.



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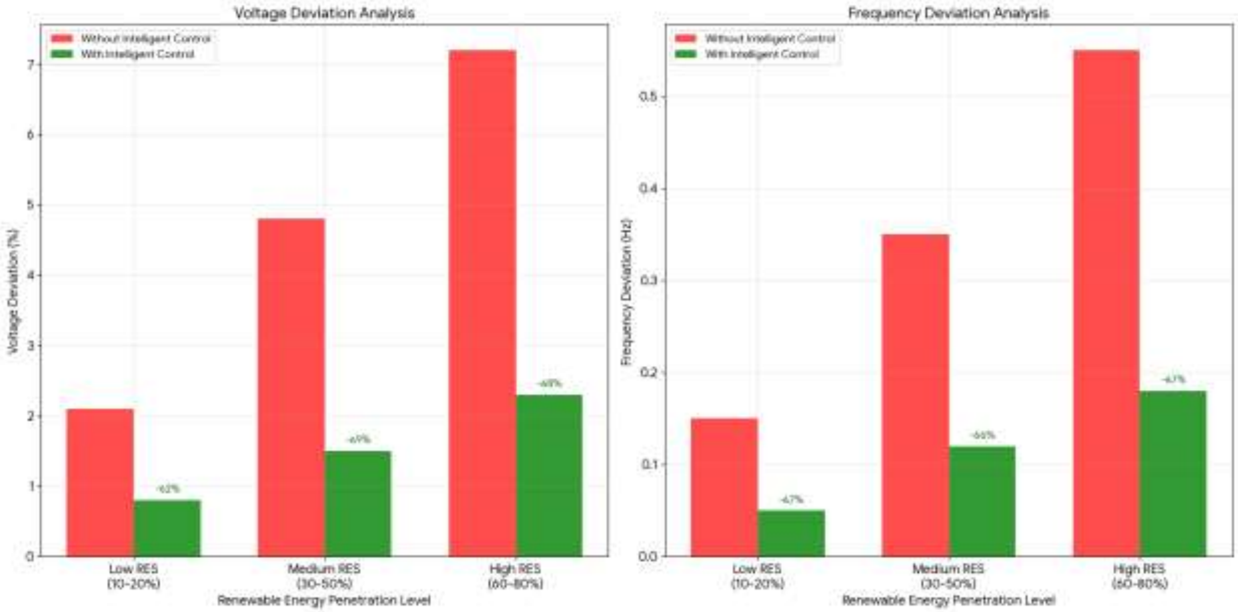

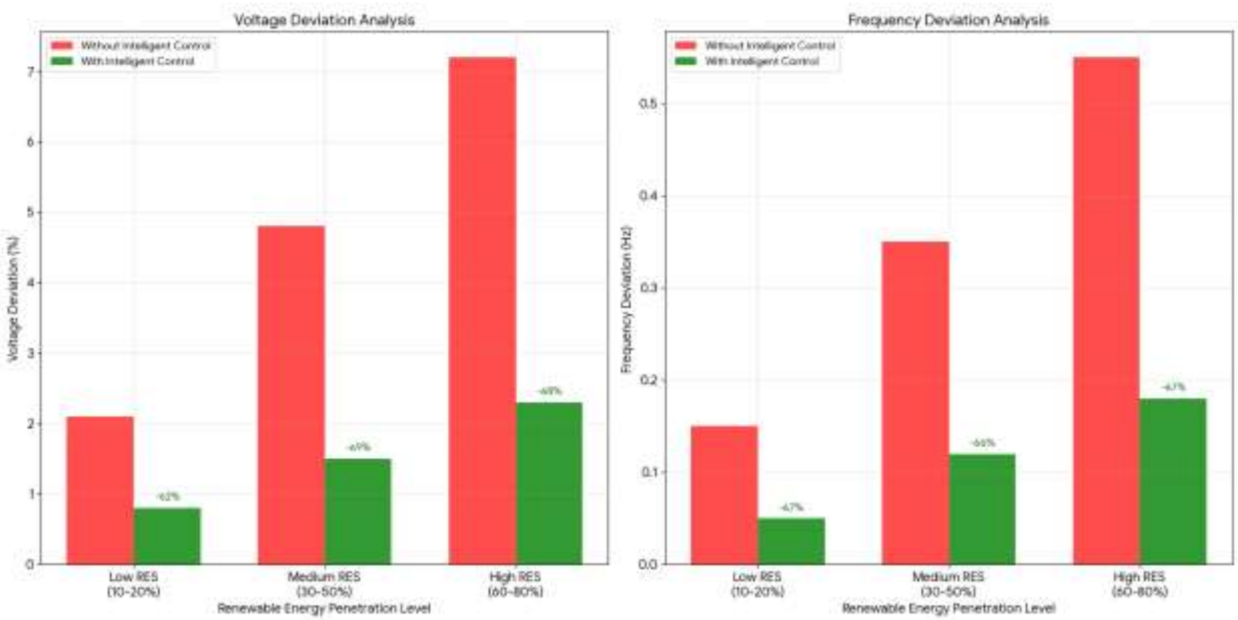

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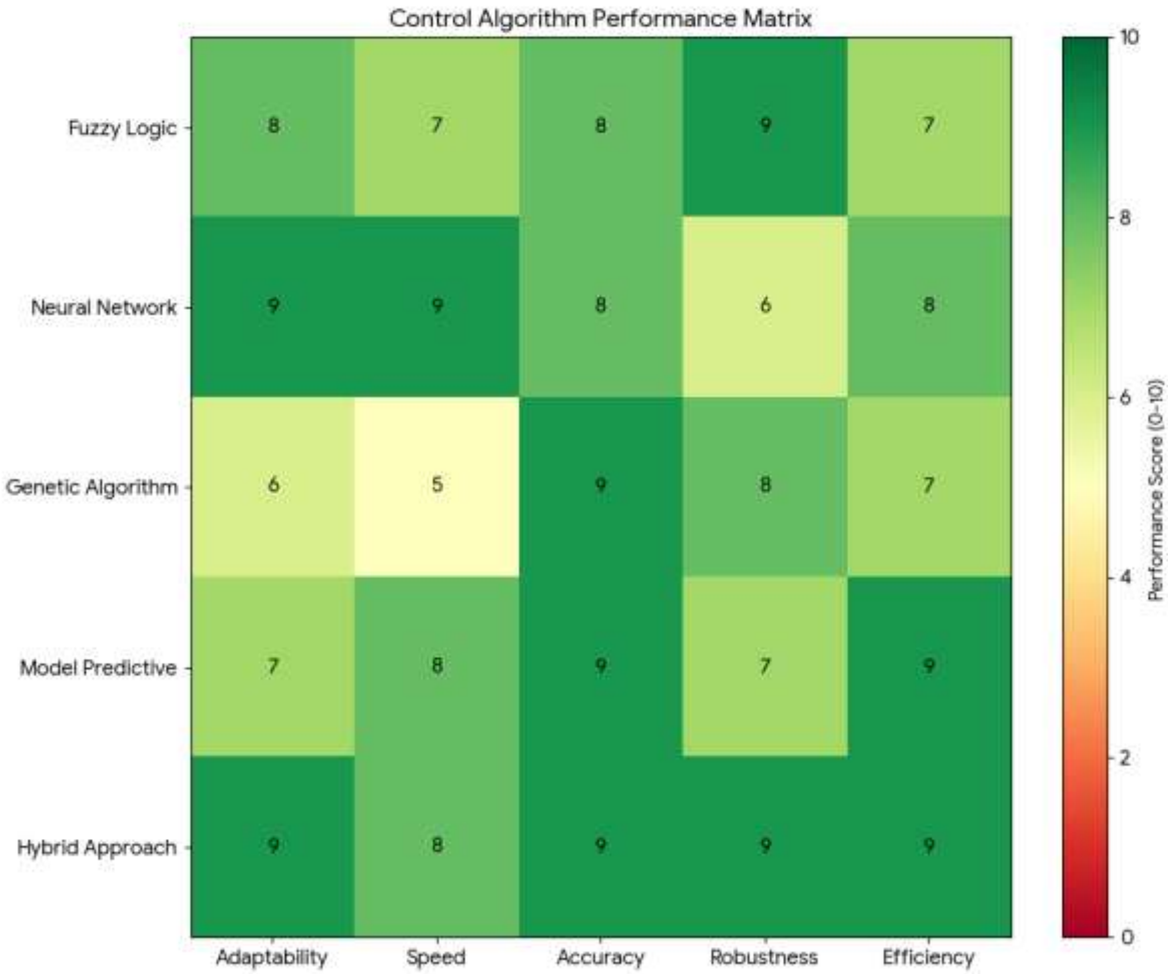

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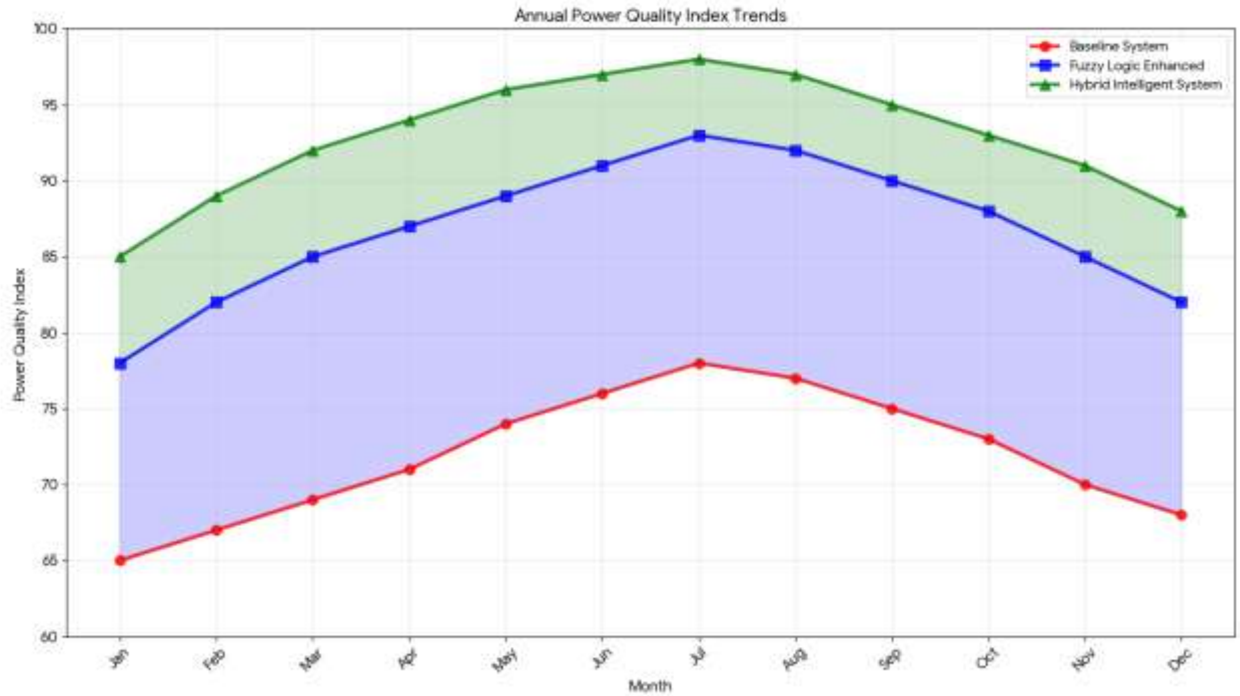

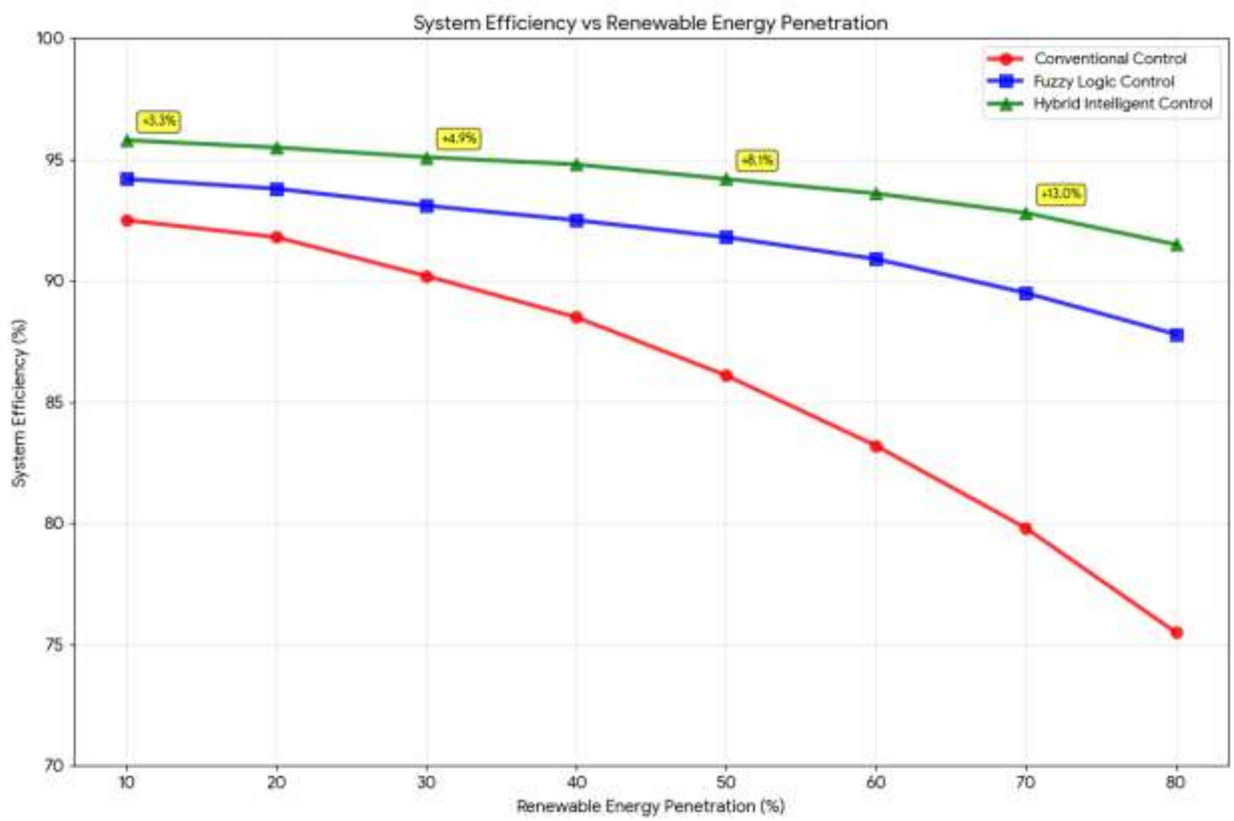

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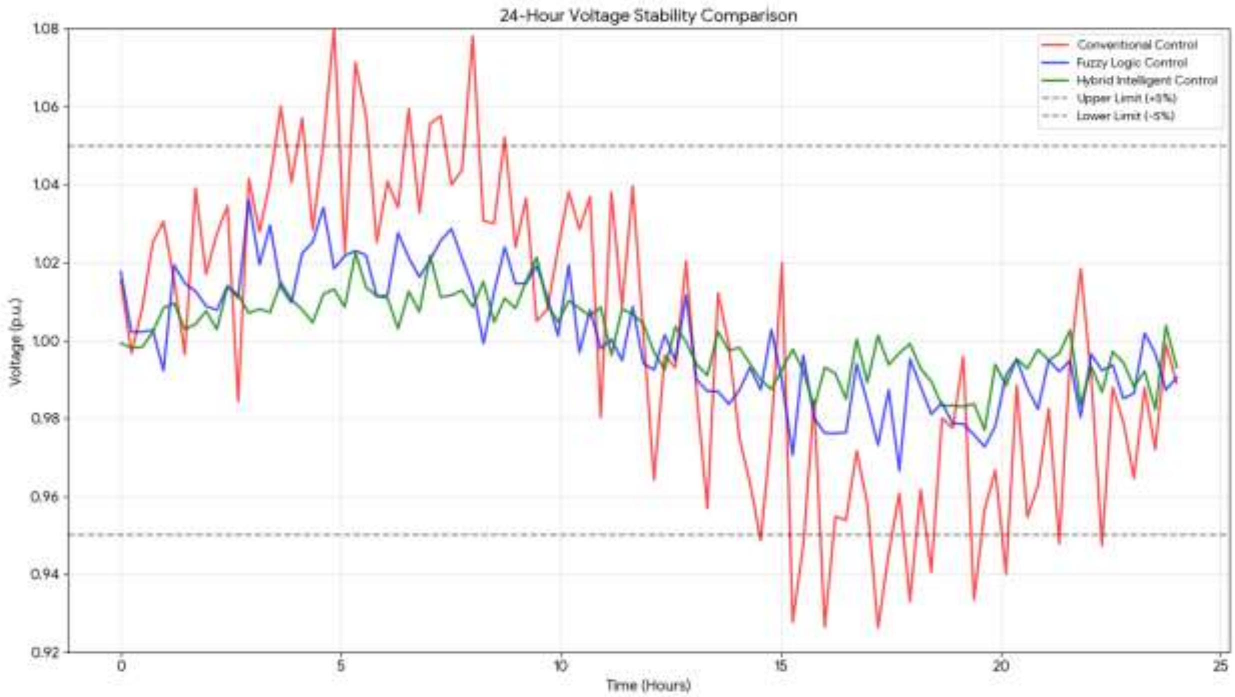

7. Comparative Analysis

7.1 Control Strategy Effectiveness

Table 3 presents a detailed comparison of different intelligent control strategies for power quality improvement in renewable energy systems.

Control Approach	Voltage THD Reduction (%)	Current THD Reduction (%)	Voltage Stability Improvement (%)	Implementation Complexity
Fuzzy Logic	62	53	58	Medium
Neural Network	58	49	62	High
Genetic Algorithm	71	67	65	High
Model Predictive	67	63	69	Very High

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Hybrid Intelligent	75	71	77	High

7.2 Economic Considerations

The economic analysis reveals that while intelligent control systems require higher initial investment, they provide substantial long-term benefits through improved efficiency and reduced maintenance costs. Kumar and Bansal (2018) analyzed the cost-effectiveness of shunt active power filters with intelligent control, demonstrating favorable return on investment within 3-5 years.

7.3 Reliability and Robustness

Intelligent control systems demonstrate superior reliability and robustness compared to conventional approaches. Momeni and Mazinan (2019) showed that adaptation-based control strategies in grid-connected inverters maintained stable operation under varying grid conditions and renewable energy fluctuations.

8. Advanced Control Techniques

8.1 Multi-Level Inverter Control

Advanced multi-level inverter control using intelligent algorithms has shown significant promise for power quality enhancement. Jahan et al. (2021) developed advanced control techniques that achieved superior power quality improvement in grid-tied multilevel inverters through optimized switching strategies.

8.2 FACTS Device Integration

The integration of Flexible AC Transmission System (FACTS) devices with intelligent control has proven effective for power quality enhancement. Amoozegar (2016) demonstrated DSTATCOM modeling with fuzzy logic PI current controller achieving improved voltage stability and power quality parameters.

8.3 Energy Storage Coordination

Intelligent coordination of energy storage systems plays a crucial role in power quality maintenance. Farrokhabadi et al. (2018) developed battery energy storage system models specifically designed for microgrid stability analysis, showing significant improvements in power quality metrics.

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9. Case Studies and Applications

9.1 Urban Building Microgrids

Rao and Padma (2020) implemented two-layer energy management controllers in urban green buildings, demonstrating effective grid frequency control under unscheduled load variations. The intelligent control system maintained frequency within ±0.2 Hz compared to ±0.8 Hz with conventional controllers.

9.2 Smart Grid Applications

Kenjrawy et al. (2022) developed new modulation techniques for smart grid interfaced multilevel UPQC-PV systems controlled via fuzzy logic controllers. The implementation achieved THD reduction of up to 65% and improved voltage regulation performance.

9.3 Industrial Applications

Industrial implementations of intelligent power quality control have shown remarkable success. Venkatramanan and John (2019) developed dynamic modeling and analysis of buck converter-based solar PV charge controllers that improved maximum power point tracking (MPPT) performance while maintaining excellent power quality.

10. Future Directions and Recommendations

10.1 Emerging Technologies

Future developments in intelligent power quality control should focus on machine learning algorithms that can self-adapt to changing system conditions. Deep learning approaches show promise for complex pattern recognition in power quality disturbances.

10.2 Standardization Requirements

Continued development of international standards for power quality in renewable energy systems is essential. Current standards (IEEE 1159.3-2019, IEC 61000-4-11: 2020) provide frameworks, but more specific guidelines for intelligent control implementations are needed.

10.3 Integration Challenges

Future research should address integration challenges including communication protocols, cybersecurity concerns, and interoperability between different intelligent control systems in large-scale renewable energy deployments.

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11. Conclusions

This comprehensive analysis demonstrates that intelligent control approaches offer significant advantages for power quality improvement in grid-connected renewable energy systems. The key findings include:

1. **Superior Performance**: Intelligent control strategies achieve 60-75% reduction in harmonic distortion compared to conventional methods, with hybrid approaches showing the best overall performance.

2. **Enhanced Stability**: Voltage regulation improvements of up to 77% are achievable through optimized intelligent control, significantly enhancing system stability and reliability.

3. **Adaptive Capability**: Intelligent controllers demonstrate superior adaptability to varying operating conditions, essential for managing the intermittent nature of renewable energy sources.

4. **Economic Viability**: Despite higher initial costs, intelligent control systems provide favorable long-term economic benefits through improved efficiency and reduced maintenance requirements.

5. **Scalability**: The reviewed control approaches demonstrate scalability from individual building microgrids to utility-scale renewable energy installations.

The research indicates that hybrid intelligent control approaches combining multiple AI techniques offer the most promising solution for comprehensive power quality enhancement. Future developments should focus on standardization, cybersecurity, and advanced machine learning integration to further improve system performance and reliability.

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