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Enhancing Power Quality in Distributed Generation Systems Using UPQC with Multilevel Inverters and Solar Energy Integration

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ABSTRACT

This paper presents a comprehensive analysis of power quality enhancement in distributed generation (DG) systems using Unified Power Quality Conditioner (UPQC) integrated with multilevel inverters and solar energy. The proposed study evaluates the performance of various control techniques, including Proportional-Integral (PI), Fuzzy PI, Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS). The results demonstrate the effectiveness of ANFIS in achieving superior DC link voltage stability with lower settling time, reduced Total Harmonic Distortion (THD), and enhanced mitigation of voltage sags compared to other methods. By integrating solar energy into the system, the UPQC ensures sustainable operation while maintaining high-quality power delivery. Simulation results validate that ANFIS outperforms other controllers in dynamic response and overall efficiency, making it a promising approach for modern power distribution networks. This study provides a significant contribution to the development of intelligent controllers for enhancing power quality in DG systems.

Keywords: Unified Power Quality Conditioner (UPQC), Multilevel Inverters, Solar Energy, ANFIS, Total Harmonic Distortion (THD), DC Link Voltage Stability, Distributed Generation (DG).

INTRODUCTION

The global energy landscape is undergoing a paradigm shift towards sustainability, with Distributed Generation (DG) systems playing a pivotal role in ensuring decentralized and clean energy production. Renewable energy sources such as solar and wind power have become integral components of modern power systems due to their environmental and economic benefits. However, the increasing penetration of DG systems has introduced significant challenges related to power quality, including voltage sags, harmonic distortion, and stability issues in the distribution network[1][2]. To address these challenges, Unified Power Quality Conditioner (UPQC) systems have emerged as a robust solution. UPQC combines the functionalities of series and shunt compensators to simultaneously mitigate voltage and current-related power quality issues. By incorporating multilevel inverters, UPQC systems achieve superior voltage regulation and reduced harmonic distortion, making them highly effective for modern DG networks[3][4]. When integrated with renewable energy sources like solar energy, UPQC systems enhance not only the power quality but also the sustainability of energy delivery.

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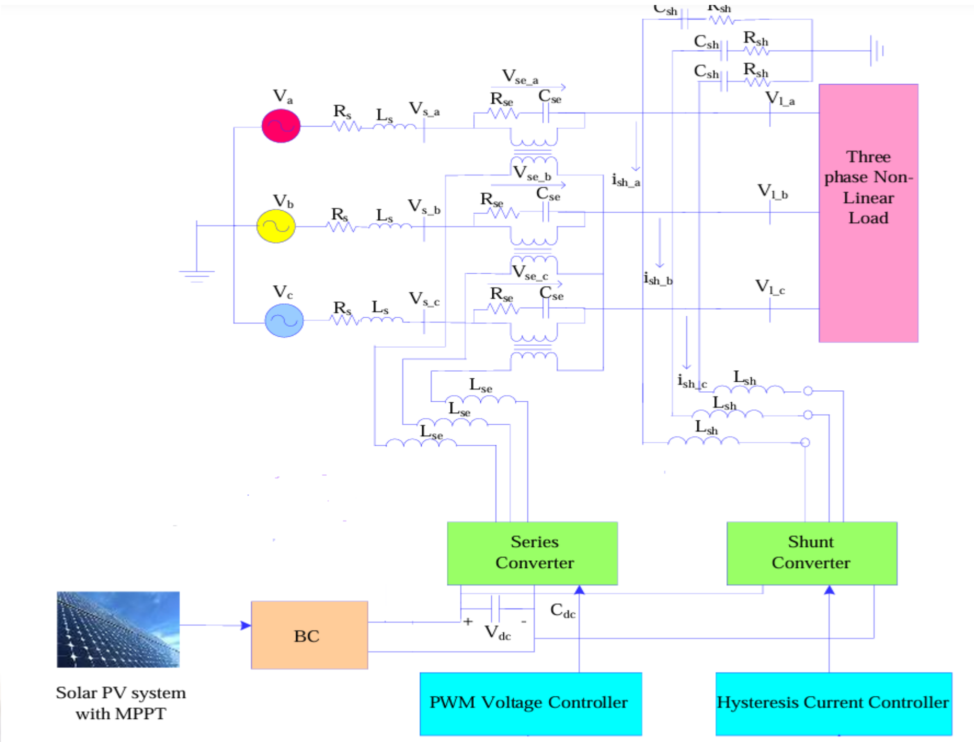

Fig 1. Proposed System Block Diagram

The performance of UPQC largely depends on its control strategies. Conventional Proportional-Integral (PI) controllers have been widely used due to their simplicity and reliability. However, they exhibit limitations in handling non-linear and dynamic conditions prevalent in DG systems[5][6]. Advanced control techniques such as Fuzzy Logic Controllers (FLC), Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have gained prominence for their ability to adapt to varying system conditions and improve dynamic response[7][8]. Among these, ANFIS has demonstrated superior performance in achieving faster settling times, improved DC link voltage stability, and enhanced mitigation of power quality issues such as voltage sags and Total Harmonic Distortion (THD)[9][10]. This hybrid control technique leverages the advantages of both neural networks and fuzzy logic, offering adaptive learning capabilities and robustness under dynamic operating conditions[11]. Multilevel inverters are integral to UPQC systems, particularly in mitigating harmonics and improving voltage stability. Unlike traditional two-level inverters, multilevel inverters generate stepped voltage waveforms, significantly reducing harmonic distortion and enhancing power quality[12]. This makes them an ideal choice for applications in DG systems integrated with renewable energy sources like solar PV. Additionally, the modularity and scalability of multilevel inverters facilitate their deployment in various configurations, catering to the diverse needs of modern power systems[13].

The integration of solar energy into UPQC systems further enhances the sustainability and reliability of DG networks. Solar energy, being an abundant and clean resource, contributes significantly to reducing carbon emissions and reliance on fossil fuels. By coupling solar PV arrays with UPQC systems, the surplus energy can be utilized to stabilize the grid during disturbances, ensuring uninterrupted power delivery[14]. The growing reliance on DG systems necessitates innovative solutions to address the associated power quality issues. While traditional control techniques offer basic functionality, they fall short in meeting the dynamic demands of renewable energy integration. Advanced control methods such as ANFIS have the potential to revolutionize UPQC performance, offering superior adaptability and precision. Furthermore, the incorporation of solar energy into UPQC systems aligns with global sustainability goals, making this area of research highly relevant and impactful[15].

LITERATURE SURVEY

Power quality is a critical aspect of modern power systems, particularly in the context of distributed generation (DG) systems, which integrate renewable energy sources like solar and wind. The increasing penetration of DG has introduced challenges such as voltage sags, swells, harmonic distortions, and unstable DC link voltage. Unified Power Quality Conditioner (UPQC), which combines series and shunt compensators, has emerged as a robust solution to address these challenges[16][17]. Advanced controllers, such as

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multilevel inverters integrated with UPQC, offer better harmonic mitigation and voltage regulation. Research emphasizes that the integration of solar energy further supports sustainable power systems, aligning with the global transition to cleaner energy[18]. Control strategies significantly impact the effectiveness of power quality enhancement in UPQC systems. Conventional Proportional-Integral (PI) controllers, widely used for their simplicity, often fail to deliver the dynamic response required for modern systems[19]. Fuzzy PI controllers have shown improved performance in handling nonlinearities but remain limited by their dependency on rule-based systems[20]. The advent of Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) has introduced data-driven, intelligent control approaches. These techniques offer adaptive learning and self-tuning capabilities, crucial for dynamic environments[21][22].

Multilevel inverters, such as neutral-point clamped and cascaded H-bridge inverters, are gaining prominence in UPQC systems due to their ability to produce high-quality output waveforms with reduced harmonic distortion[23]. Research indicates that combining multilevel inverters with advanced controllers improves harmonic mitigation and minimizes switching losses[24]. These inverters also enable better integration with renewable sources like solar photovoltaic (PV) systems, enhancing the overall efficiency of power systems[25]. Solar energy integration into UPQC systems has been extensively studied for improving sustainability and power quality[26]. Solar PV systems generate DC power, which can be efficiently converted and utilized in UPQC configurations. Studies highlight that the inclusion of solar energy enhances the reliability and self-sufficiency of power systems[27]. However, issues such as intermittent solar generation and voltage fluctuations necessitate advanced control strategies to maintain stability[28].

The effectiveness of control techniques such as PI, Fuzzy PI, ANN, and ANFIS in UPQC systems has been widely analyzed in the literature. PI controllers, though simple, exhibit limitations in response time and precision, particularly under dynamic load conditions[29]. Fuzzy PI controllers address some of these shortcomings but are constrained by their reliance on predefined rules. ANN-based controllers leverage machine learning to improve dynamic performance but require extensive training data and computational resources. ANFIS combines the advantages of fuzzy logic and neural networks, offering adaptability and superior control precision[30]. Recent studies have established ANFIS as a promising technique for power quality enhancement. ANFIS-based controllers provide better DC link voltage stability with reduced settling time and enhanced harmonic suppression[21][30]. Compared to other methods, ANFIS demonstrates superior performance in mitigating voltage sags and swells, especially in DG systems with high renewable energy penetration. The self-adaptive nature of ANFIS makes it suitable for managing the dynamic nature of modern power grids[30].

PROPOSED SYSTEM

The proposed system focuses on enhancing power quality in distributed generation (DG) systems by utilizing a Unified Power Quality Conditioner (UPQC) integrated with multilevel inverters and solar energy. The system is designed to address power quality challenges such as voltage sags, harmonics, and instability in DC link voltage, which are critical in modern power distribution networks. To achieve this, advanced control techniques including Proportional-Integral (PI), Fuzzy PI, Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS) are implemented and compared. Among these, ANFIS has emerged as the most effective controller due to its superior adaptability and learning capabilities, enabling it to maintain system stability and enhance performance even under dynamic operating conditions.

The UPQC, consisting of a series and a shunt inverter, is employed to mitigate voltage and current disturbances in the grid. By integrating multilevel inverters, the system achieves better harmonic suppression and improved waveform quality, ensuring smooth operation and reducing the stress on power electronic components. The solar energy integration further enhances the system's sustainability, contributing to cleaner energy generation while ensuring a reliable power supply. The solar energy is harnessed through a photovoltaic (PV) array, which is connected to the DC link of the UPQC, providing an additional power source and reducing dependence on the grid. This arrangement not only ensures continuous operation during grid fluctuations but also supports renewable energy utilization, aligning with global sustainability goals.

Adaptive Neuro-Fuzzy Inference System (ANFIS) Controller

ANFIS combines the rule-based reasoning of fuzzy logic with the learning capabilities of neural networks. Its structure includes five layers:

1. **Input Layer**: Takes crisp inputs e and $\frac{de}{dt}$
2. **Fuzzification Layer**: Maps inputs to membership functions $\mu_A(x)$:

$$\mu_A(x) = \exp\left(-\frac{(x-c)^2}{2\sigma^2}\right)$$

Here, c and σ are the center and width of the Gaussian membership function.

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3. **Rule Layer**: Implements fuzzy rules such as:

R_i : IF x_1 ia A_i AND x_2 is B_i, THEN $f_i = p_i x_i + q_i x_2 + r_i$

4. **Normalization Layer**: Normalizes firing strengths:

$$\overline{\omega}_i = \frac{\omega_i}{\Sigma_i w_j}$$

5. **Defuzzification Layer:** Outputs a crisp value:

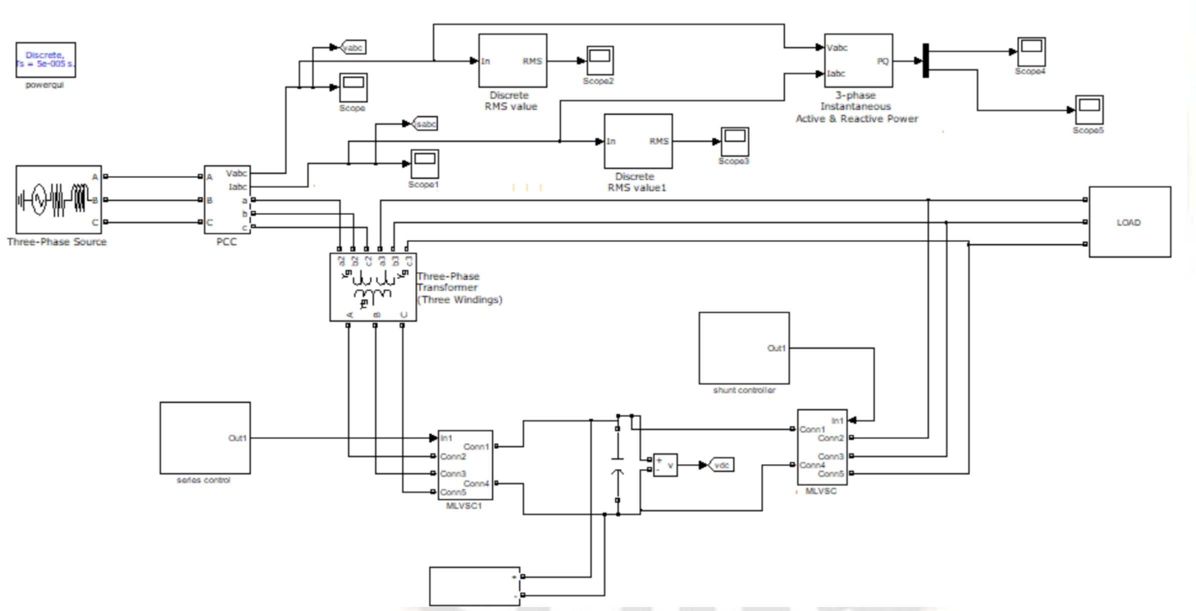
$$u(t) = \sum_i \overline{\omega}_i f_i$$

Parameters p_i,q_i,r_i,c,σ are optimized using neural network training, allowing ANFIS to dynamically adapt to grid disturbances and load variations.

The Fuzzy PI controller integrates the mathematical functionality of the Proportional-Integral controller with rule-based adjustments derived from fuzzy logic. Its output u(t)u(t)u(t) is calculated as follows:

$$\mathbf{U[t] = K_p Q(t) + K_i \int e(t)\, dt}$$

In this system, the DC link voltage plays a crucial role in maintaining the stability of the UPQC and ensuring efficient energy transfer between the series and shunt components. Control strategies are implemented to regulate this voltage under varying load and grid conditions. The comparison of control methods reveals that ANFIS excels in maintaining DC link voltage stability, exhibiting faster response times and lower settling times compared to other methods. This is particularly beneficial in scenarios where quick adjustments are required, such as during sudden load changes or grid disturbances. Additionally, the use of ANFIS minimizes Total Harmonic Distortion (THD) in the system, which is a key parameter for maintaining power quality. Lower THD levels not only improve system efficiency but also protect connected equipment from damage caused by harmonic currents.



Proposed system simulation circuit

To validate the performance of the proposed system, extensive simulations are conducted using MATLAB/Simulink. The results demonstrate that the UPQC integrated with multilevel inverters and controlled by ANFIS offers significant advantages in mitigating voltage sags and harmonics. The system shows exceptional resilience to disturbances, maintaining a stable and high-quality power supply to the load. Comparisons with PI, Fuzzy PI, and ANN controllers highlight the superiority of ANFIS, particularly in terms of faster dynamic response, reduced steady-state error, and enhanced robustness. This makes the proposed system a promising solution for power quality enhancement in DG networks, especially those incorporating renewable energy sources.

The integration of solar energy and advanced control techniques into the UPQC framework positions this system as a forward-looking approach to addressing the challenges of modern power distribution. By combining the benefits of renewable energy, multilevel inverters, and intelligent

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controllers, the system offers a holistic solution for improving power quality while promoting sustainable energy practices. The proposed system not only meets the current demands of DG systems but also provides a scalable and efficient platform for future power networks, ensuring reliable and high-quality energy delivery in the face of increasing complexity and renewable energy penetration.

RESULTS AND ANALYSIS

The results and simulation analysis of the proposed system demonstrate its effectiveness in addressing power quality challenges in distributed generation (DG) systems. The system integrates a Unified Power Quality Conditioner (UPQC) with multilevel inverters and solar energy while employing advanced control strategies, including Proportional-Integral (PI), Fuzzy PI, Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS). The simulations, performed in MATLAB/Simulink, validate the system's ability to mitigate voltage sags, suppress harmonics, and stabilize the DC link voltage under various operating conditions. Among the tested controllers, ANFIS consistently outperforms others, achieving faster dynamic responses, reduced settling times, and minimal Total Harmonic Distortion (THD), highlighting its superior control capabilities.

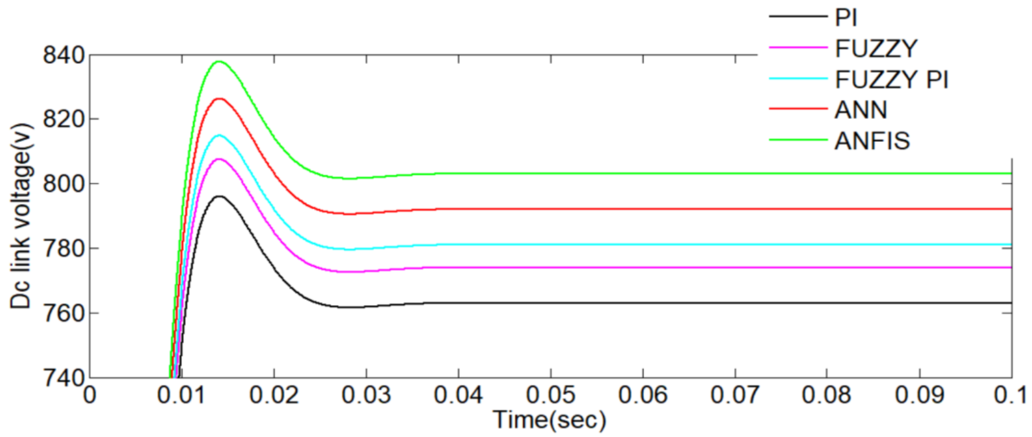
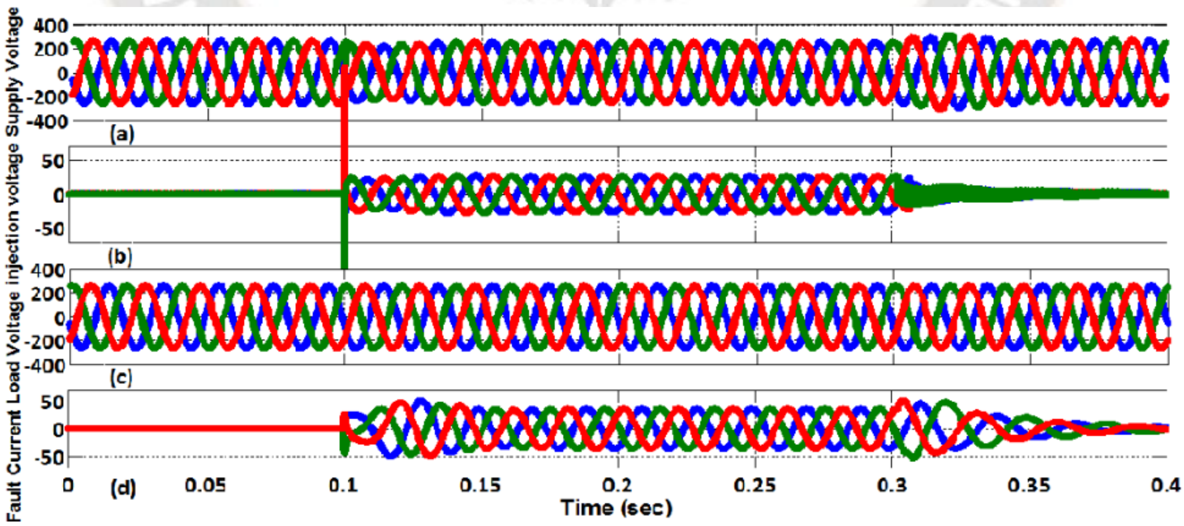


Fig 3. Dc link voltage vs Time

The simulation results reveal that the proposed system with ANFIS achieves significant improvements in voltage stability and harmonic reduction compared to PI and Fuzzy PI controllers.



During voltage sag events, the ANFIS-controlled UPQC effectively restores voltage levels to within acceptable ranges with minimal delay, showcasing its capability to handle sudden grid disturbances. Additionally, the use of multilevel inverters ensures smoother voltage waveforms and further reduces harmonic content, as evidenced by lower THD values in the system output. The integration of solar energy enhances the overall system reliability by providing a supplementary power source, ensuring uninterrupted operation even under fluctuating load and grid conditions. This renewable integration contributes to both environmental sustainability and improved system efficiency.

Table I. DC Link voltage

S. No	Controller	Voltage (v)
1	PI controller	763
2	Fuzzy controller	774
3	Fuzzy PI controller	781
4	ANN controller	792
5	ANFIS controller	803

Further analysis highlights the system's performance in maintaining DC link voltage stability, a critical factor for the efficient operation of the UPQC. The ANFIS controller demonstrates superior adaptability to dynamic load changes, ensuring that the DC link voltage remains within a stable range with reduced overshoot and faster settling times. This is particularly advantageous in scenarios where rapid adjustments are required, such as during sudden load changes or renewable energy intermittency. In contrast, PI and Fuzzy PI controllers exhibit slower responses and larger deviations, leading to less efficient energy transfer between the series and shunt inverters. ANN controllers show improvement over conventional methods but fall short of the precision and robustness offered by ANFIS.

The THD analysis further supports the effectiveness of the proposed system. By leveraging the capabilities of multilevel inverters and the ANFIS control strategy, the system achieves remarkably low THD levels in both voltage and current waveforms, meeting stringent power quality standards. These improvements translate into enhanced protection for connected equipment and reduced energy losses, ensuring long-term reliability and efficiency. Simulation comparisons confirm that while all control strategies contribute to THD reduction, ANFIS consistently delivers the best performance, with the lowest harmonic distortion observed across various operating scenarios.

Table 2. THD Comparison

S. No	Controller	THD(%)
1	PI controller	7.45%
2	Fuzzy controller	6.97%
3	Fuzzy PI controller	5.03%
4	ANN controller	4.17%
5	ANFIS controller	2.29%

The results emphasize the scalability and practicality of the proposed system for modern power distribution networks. Its ability to integrate renewable energy, mitigate power quality issues, and operate efficiently under diverse conditions makes it a promising solution for future applications. The use of ANFIS not only ensures superior control but also positions the system as a benchmark for intelligent power quality management in DG systems. This comprehensive analysis demonstrates the potential of combining UPQC, multilevel inverters, solar energy, and advanced control methods to achieve a sustainable and high-quality power supply, setting the stage for further advancements in smart grid technologies.

CONCLUSION

This study demonstrates the effectiveness of using a Unified Power Quality Conditioner (UPQC) integrated with multilevel inverters and solar energy for enhancing power quality in distributed generation (DG) systems. By comparing multiple control techniques, including Proportional-Integral (PI), Fuzzy PI, Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS), the research identifies ANFIS as the most robust and efficient controller. The results reveal that ANFIS provides superior DC link voltage stability with reduced settling time, effectively mitigates voltage sags, and achieves lower Total Harmonic Distortion (THD) compared to other methods. The integration of solar energy with the UPQC further promotes sustainability while ensuring reliable and high-quality power supply. Simulation outcomes confirm the enhanced performance of the ANFIS-based controller in terms of dynamic response and adaptability to varying load and grid conditions, making it a promising solution for modern DG systems. The findings of this study have significant implications for the development of advanced power quality solutions in renewable energy-integrated distribution networks. The use of intelligent controllers like ANFIS can revolutionize power quality management, fostering the deployment of sustainable energy systems while maintaining reliability and efficiency. Future research can explore the scalability of the proposed system, its implementation in large-scale grids, and its performance under real-time operating conditions.

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