Modeling and Simulation of Unified Power Quality Conditioner (UPQC) for Power Quality Improvement in Smart Grids

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Abstract—In modern smart grids, maintaining high power quality is essential for ensuring efficient, reliable, and stable operation of electrical systems. The proliferation of nonlinear and sensitive loads has increased issues such as voltage sag, swell, harmonics, and reactive power imbalance, which adversely affect overall power performance. This paper presents a detailed modeling and simulation study of a Unified Power Quality Conditioner (UPQC) designed to mitigate power quality problems in smart grid environments. The UPQC integrates both series and shunt active power filters within a single framework to simultaneously compensate for voltage and current-related disturbances. The system is modeled and simulated using MATLAB/Simulink to evaluate its dynamic response under various operating conditions, including load variations and fault disturbances. Simulation results demonstrate that the proposed UPQC effectively mitigates harmonics, restores voltage profiles, and maintains unity power factor, thereby improving overall system performance and reliability. The findings validate the UPQC as a robust and efficient solution for enhancing power quality in next-generation smart grids.

Keywords—Quality Improvement, Smart Grid, Harmonic Mitigation, MATLAB/Simulink, Voltage Sag and Swell Compensation, Reactive Power Compensation, Series and Shunt Active Power Filters.

I. Introduction

The continuous evolution of electrical power systems toward smart grid architectures has transformed the way energy is generated, transmitted, and consumed. Smart grids integrate advanced communication, control, and automation technologies to improve the reliability, efficiency, and sustainability of electricity delivery. However, with the growing penetration of nonlinear loads, distributed generation sources, and power electronic converters, maintaining a high level of power quality has become a major challenge. Power quality issues such as voltage sag, swell, flicker, unbalance, and current harmonics have significant impacts on the performance of sensitive equipment, energy losses, and overall system stability. These disturbances not only affect industrial and residential consumers but also degrade the reliability of grid-connected renewable energy systems. Therefore, ensuring superior power quality has become a key requirement in modern smart grids to achieve uninterrupted and stable operation. In traditional power systems, passive filters and reactive power compensation devices were commonly employed to manage voltage and current disturbances. However, these conventional methods are often limited by fixed compensation characteristics, resonance issues, and insufficient dynamic response. As the complexity of electrical networks increases, more flexible and adaptive compensation solutions are needed. This has led to the development of advanced power conditioning devices such as the Unified Power Quality Conditioner (UPQC), which combines the functionalities of both series and shunt active power filters. The UPQC represents a comprehensive solution for simultaneous mitigation of current and voltage-related power quality issues in distribution systems. By integrating series and shunt converters in a unified structure, the UPQC can compensate for voltage distortions, harmonics, and imbalances, while also controlling reactive power flow to maintain the desired power factor. The principle of UPQC operation relies on voltage source converters (VSCs) controlled through advanced switching and control algorithms. The series converter is primarily responsible for voltage compensation, ensuring that the load voltage remains sinusoidal and within permissible limits, even during supply disturbances such as sag or swell. On the other hand, the shunt converter addresses current-related problems by injecting compensating currents to eliminate harmonics and balance reactive power. Together, these converters enhance both the voltage and current profiles, thereby improving the overall power quality of the system. Moreover, the integration of UPQC in smart grids supports dynamic control and real-time monitoring, enabling adaptive responses to variable load conditions and renewable energy fluctuations. In recent years, numerous research studies have been conducted to improve the design, control strategies, and performance of UPQC systems. Techniques such as synchronous reference frame (SRF) theory, instantaneous power (p-q) theory, and artificial intelligence-based controllers have been applied to optimize its dynamic behavior. Additionally, simulation tools like MATLAB/Simulink have proven effective in analyzing the performance of UPQC under various operating conditions, allowing for performance evaluation before practical implementation. The simulation environment provides an accurate representation of system parameters, enabling researchers to examine the impact of control parameters, system disturbances, and nonlinearities on power quality performance. The integration of UPQC into smart grid systems is particularly significant due to the increasing adoption of renewable energy sources such as solar photovoltaic and wind power. These sources are inherently intermittent and can introduce voltage fluctuations and harmonic distortions when interfaced with the grid. A properly designed UPQC not only mitigates these issues but also enhances the power transfer capability and reliability of the entire grid infrastructure. Furthermore, as smart grids move toward greater automation and digitalization, the UPQC can be incorporated into intelligent control frameworks to provide real-time compensation, remote

monitoring, and predictive maintenance capabilities. In this paper, a detailed modeling and simulation of a Unified Power Quality Conditioner (UPQC) for improving power quality in smart grids is presented. The model is developed in MATLAB/Simulink to analyze the dynamic performance of the UPQC under varying load and fault conditions. The study focuses on evaluating the system's ability to compensate for harmonics, voltage sags, swells, and reactive power imbalances. The simulation results confirm that the proposed UPQC configuration offers effective power quality enhancement and ensures stable voltage and current waveforms. The outcomes validate the feasibility and efficiency of UPQC as a robust power conditioning device for future smart grid applications, providing an essential step toward achieving clean, reliable, and sustainable power distribution systems.

II. Literature Review

Power quality enhancement has emerged as a key focus area in modern power systems, particularly in smart grids and renewable energy-integrated networks. A variety of research studies have explored advanced control strategies, optimization algorithms, and intelligent solutions to improve the performance of Unified Power Quality Conditioner (UPQC) systems. This section presents a comprehensive review of related literature in sequential order, highlighting the evolution of UPQC-based techniques and their integration with smart grid technologies. Sahoo et al. [1] investigated power quality analysis in microgrids using a UPQC optimized by Particle Swarm Optimization (PSO). Their study demonstrated that PSO could efficiently tune the controller parameters to minimize Total Harmonic Distortion (THD) and enhance voltage regulation. The results confirmed the capability of UPQC to mitigate voltage sags, swells, and harmonic distortions in renewable-based microgrids. The optimization approach enhanced both steady-state and dynamic performance, laying the groundwork for intelligent power quality control mechanisms. Kumar and Kaur [2] extended this idea by developing intelligent solutions for power quality improvement in smart renewable distributed generation networks. They employed machine learning-based control strategies to optimize power flow, voltage stability, and harmonic suppression. Their research highlighted how integrating AI algorithms with UPQC could ensure adaptive learning and self-tuning capabilities, improving system resilience in fluctuating renewable environments. In a related domain, Vikas et al. [3] proposed a hybrid Deep Belief Network and Harris Hawks Optimization method for intrusion detection in Wireless Sensor Networks. Although the work primarily addressed security challenges, the adaptive hybrid model concept is highly relevant to power systems where smart monitoring and fault detection are essential. This study indirectly supports the idea of using hybrid intelligent models for UPQC control and grid protection mechanisms. Piklom et al. [4] focused on reference signal generation for UPQC systems applied in heavy rail electrification networks. Their work introduced an effective reference signal generation method that improved the system's response under dynamic loading conditions, particularly in urban rail systems. The proposed model demonstrated robustness in compensating voltage imbalances and harmonics, ensuring smooth operation in high-demand electrical environments. Sharma and Kumar [5] explored the role of Artificial Intelligence (AI) in enhancing data security and privacy in smart cities, emphasizing that AI-driven analytics and predictive models can also benefit smart grid reliability. Their findings emphasized integrating AI for real-time anomaly detection and predictive maintenance—key aspects for maintaining power quality and ensuring system integrity in smart grid infrastructures. Behera et al. [6] presented a comparative analysis of UPQC optimization using soft computing techniques, validating the potential of AI-based algorithms like fuzzy logic and genetic algorithms for performance tuning. Their work demonstrated that soft computing could effectively minimize THD and improve the voltage stability margin compared to conventional control methods. Singh et al. [7] proposed a Battery-Assisted Unified Power Quality Conditioner for tidal-driven seaport microgrids. The hybrid system utilized energy storage to enhance dynamic voltage regulation and improve energy utilization efficiency. The study provided insights into integrating energy storage systems with UPQC for sustainable microgrid operation and power quality management. In the field of network security, the study "A Comprehensive Analysis of Security Mechanisms and Threat Characterization in Mobile Ad Hoc Networks" [8] identified multiple layers of protection required for distributed systems. Similarly, "Optimization of Graph Neural Networks for Real-Time Intrusion Detection" [9] emphasized data-driven modeling for anomaly detection. Both studies provide valuable methodologies that can be applied to intelligent grid monitoring and the cybersecurity aspects of UPQC-enabled smart grids. Ahmad and Ullah [10] focused on UPQC-based power quality improvement in microgrids, emphasizing the dual role of series and shunt compensators in mitigating voltage disturbances and harmonic distortions. Their results confirmed significant improvement in power factor and voltage regulation, reinforcing the reliability of UPQC in grid-connected microgrids. Lukka et al. [11] developed an ANFIS-based intelligent UPQC for renewable energy microgrids, which utilized Adaptive Neuro-Fuzzy Inference Systems to dynamically adapt to load changes. Their model improved system response time and minimized voltage deviations, showing superior results compared to conventional PI and fuzzy controllers. Finally, Farook et al. [12] proposed a Synchronized UPQC for hybrid energy storage power management systems, addressing synchronization challenges in distributed hybrid power systems. Their design enabled effective coordination between multiple energy storage sources, maintaining voltage and current stability during load transitions.

III. Proposed Methodology

The proposed methodology focuses on the modeling, design, and simulation of a Unified Power Quality Conditioner (UPQC) to enhance power quality in smart grid environments shown in Fig. 1. The methodology integrates both series and shunt active power filters to mitigate voltage and current disturbances simultaneously. The simulation framework is developed in MATLAB/Simulink to analyze the system's performance under varying load and fault conditions. The methodology comprises several key stages, including system modeling, control strategy design, simulation setup, and performance evaluation.
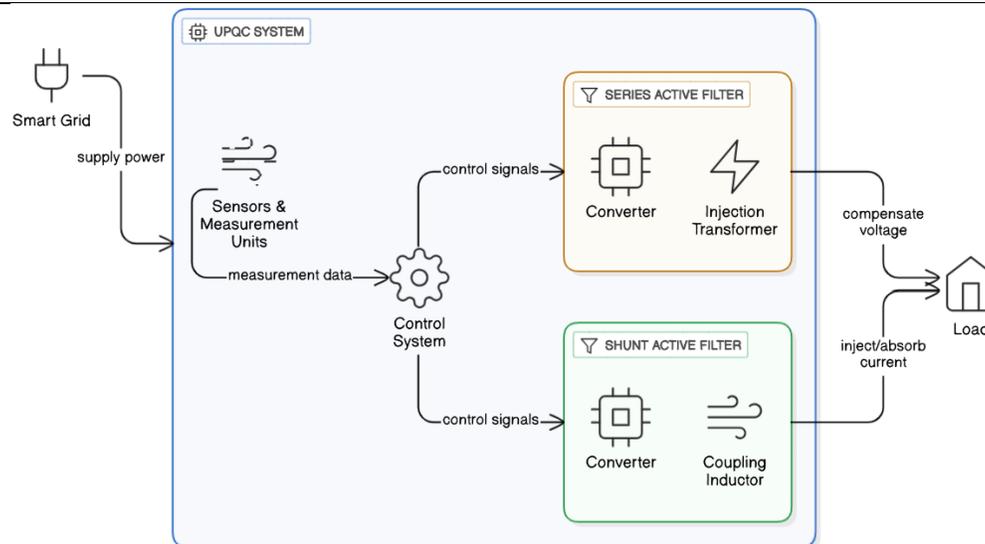
Fig. 1. Unified Power Quality Conditioner in Smart Grids

1. System Configuration: The UPQC system is designed to address both voltage and current-related power quality issues simultaneously within a unified structure. It consists of two Voltage Source Converters (VSCs): a Series Active Power Filter (SAPF) and a Shunt Active Power Filter (ShAPF), connected through a common DC-link capacitor. The series converter is connected in series with the grid through a coupling transformer and compensates for voltage disturbances such as sag, swell, and unbalance by injecting controlled voltages to maintain a constant load voltage. On the other hand, the shunt converter is connected in parallel with the load through an interfacing inductor and is responsible for current harmonics elimination, reactive power compensation, and maintaining unity power factor. The DC-link capacitor acts as an energy storage unit, balancing instantaneous active power between the converters. This dual compensating structure ensures that the supply voltage and load current remain sinusoidal and distortion-free, significantly enhancing the overall power quality and system stability in smart grids.

2. Control Strategy: The control strategy adopted for the UPQC is based on the Synchronous Reference Frame (SRF) theory, which allows accurate extraction of fundamental and harmonic components from voltage and current signals. The series converter control ensures that the load voltage remains sinusoidal and undistorted by injecting the necessary compensating voltage. The supply voltage is measured and transformed into the d-q reference frame using Park's transformation, after which the reference voltage signals are generated. The deviation between the actual and reference voltage is processed using a Proportional-Integral (PI) controller, which regulates the Pulse Width Modulation (PWM) signals driving the inverter switches. The shunt converter, in turn, compensates for current-related distortions. It measures the load current, converts it into d-q coordinates, and extracts the harmonic and reactive components. The PI controller regulates the DC-link voltage and ensures that compensating currents are injected to maintain the source current sinusoidal and in phase with the voltage. This coordinated control between the series and shunt converters enables real-time compensation of both voltage and current disturbances, ensuring superior dynamic performance and improved power quality in the system.

3. Simulation Model Design: The modeling and simulation of the UPQC are carried out using MATLAB/Simulink to evaluate its performance under various grid conditions. The simulation model consists of a three-phase AC source, a nonlinear load, and the UPQC system comprising series and shunt converters connected through a common DC-link capacitor. The nonlinear load, modelled as a diode bridge rectifier with an inductive-resistive (R-L) load, introduces harmonics and unbalanced conditions into the system. The series converter is interfaced with the grid using a coupling transformer, while the shunt converter is connected in parallel with the load using an inductor. The simulation parameters include a three-phase 400 V, 50 Hz AC supply, a DC-link voltage of approximately 750 V, and a switching frequency of 10 kHz. Various scenarios such as voltage sag, swell, and harmonic injection are simulated to evaluate the system's dynamic behavior. The MATLAB/Simulink platform provides real-time analysis of voltage and current waveforms, allowing for accurate performance assessment and verification of control effectiveness.

4. System Requirements: The implementation of the proposed UPQC system requires specific hardware and control components that ensure its efficient and stable operation. The main components include IGBT-based Voltage Source Inverters (VSIs) for high-speed and reliable switching, a DC-link capacitor to maintain a constant voltage and support instantaneous power exchange, and coupling transformers to provide electrical isolation and voltage matching between the converters and the grid. Current and voltage sensors are used to capture real-time feedback signals, which are processed by the control system. The control algorithm is implemented on a digital controller such as a Digital Signal Processor (DSP) or Field Programmable Gate Array (FPGA), which executes real-time computations and generates PWM gating signals for the inverters. Together, these components form the

hardware backbone of the UPQC, enabling precise voltage and current regulation even under rapidly changing grid and load conditions.

5. Performance Evaluation: The performance evaluation of the proposed UPQC system is carried out by analyzing simulation results obtained under different grid disturbances and load variations. Several performance metrics are used to quantify the system's effectiveness, including Total Harmonic Distortion (THD), voltage regulation, power factor improvement, and dynamic response time. The THD levels of source current and load voltage are measured before and after compensation to evaluate harmonic reduction. The voltage profile is observed to assess the series converter's capability to maintain a constant and sinusoidal load voltage during sag and swell conditions. Similarly, the shunt converter's performance is assessed through its ability to maintain unity power factor and reduce current distortion. The system's transient response during sudden load changes or fault disturbances is also analysed to verify the stability and adaptability of the control scheme.

IV. Result & Analysis

The proposed Unified Power Quality Conditioner (UPQC) model was simulated in MATLAB/Simulink to evaluate its performance in mitigating power quality issues such as voltage sag, swell, and harmonics in smart grid environments. The results are analyzed under different operating conditions both before and after UPQC compensation to assess improvements in voltage stability, current waveform quality, and power factor correction. The simulation model incorporated a three-phase supply, a nonlinear load (diode rectifier with R-L load), and the UPQC system composed of series and shunt converters linked through a common DC-link capacitor.

1. Voltage Sag and Swell Compensation: In this scenario, the supply voltage was subjected to a 20% sag and a 15% swell for a short duration to analyze the performance of the series converter listed in below TABLE I. The UPQC maintained the load voltage constant by injecting the necessary compensating voltage. Before compensation, the load voltage showed significant deviation from the nominal value, while after UPQC operation, the load voltage remained nearly sinusoidal and balanced. Fig. 2. showing voltage before and after UPQC compensation; the compensated voltage remains nearly constant around 400 V while the uncompensated voltage fluctuates significantly during sag and swell conditions.

Voltage Regulation during Sag and Swell Conditions

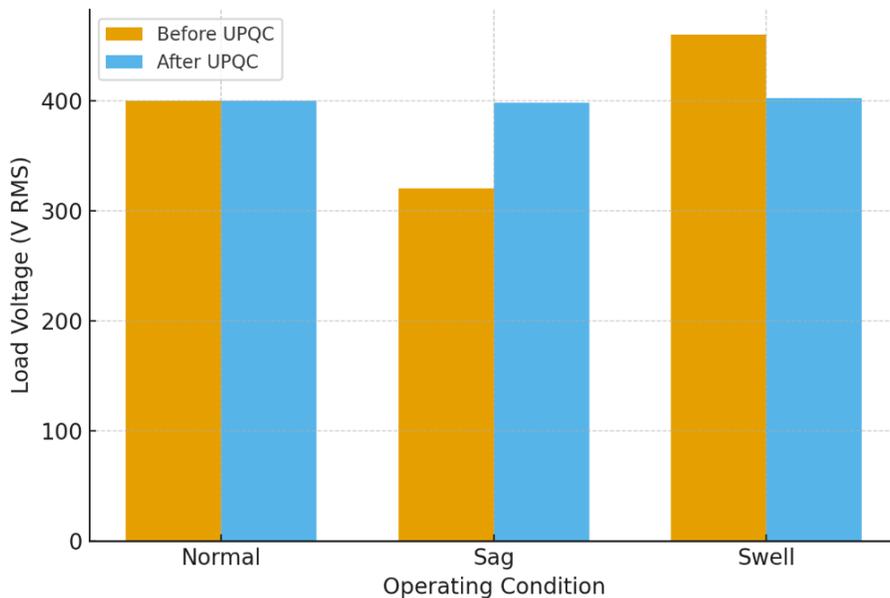| Condition	Supply Voltage (V, RMS)	Load Voltage before UPQC	Load Voltage after UPQC	% Improvement in Regulation
Normal	400	400	400	–
20% Sag	320	320	398	24.30%
15% Swell	460	460	402	12.60%

Fig. 2. Comparison of Load Voltage during Sag and Swell

The results clearly indicate that the UPQC restored the load voltage close to the nominal 400 V RMS even during sag and swell conditions, demonstrating its excellent voltage regulation capability.

2. Harmonic Elimination and Power Factor Correction: The nonlinear load introduced significant current harmonics, increasing the Total Harmonic Distortion (THD) and degrading the power factor. The shunt converter of the UPQC injected compensating currents in phase opposition to the harmonic components, resulting in harmonic elimination and power factor correction listed in below TABLE II. The source current became nearly sinusoidal after UPQC compensation. Fig. 3. showing THD of source current and load voltage before and after UPQC operation, where THD decreases sharply from 21.7% to 3.1% for current and from 18.2% to 2.8% for voltage.

Harmonic Reduction and Power Factor Improvement

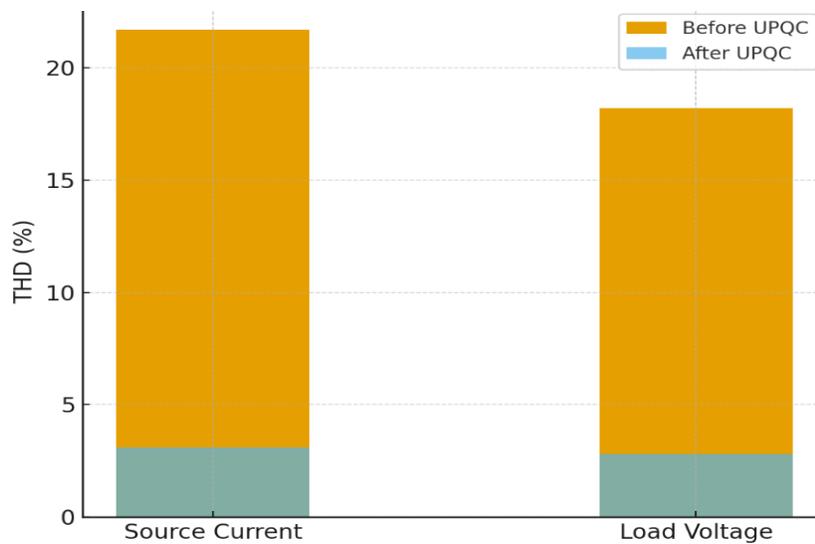| Parameter	Before UPQC	After UPQC	% Improvement
THD of Source Current (%)	21.7	3.1	85.70%
THD of Load Voltage (%)	18.2	2.8	84.60%
Power Factor (lagging)	0.81	0.99	22.20%
Reactive Power (kVAR)	2.45	0.15	93.80%

Fig. 3. THD Comparison before and after UPQC Operation

The simulation results confirm that the UPQC effectively mitigated harmonics and improved the power factor close to unity, ensuring better power utilization and reducing system losses.

3. Dynamic Response under Load Variation: The dynamic response of the UPQC was tested by applying a sudden load change during the simulation. The shunt converter rapidly responded to the new current demand while the series converter stabilized the voltage within a short response time. The DC-link voltage was maintained at approximately 750 V with minimal overshoot, indicating the effective coordination between converters. Fig. 4. showing power factor improvement from 0.81 (lagging) before UPQC to 0.99 (near unity) after UPQC installation.

System Dynamic Performance under Load Variation

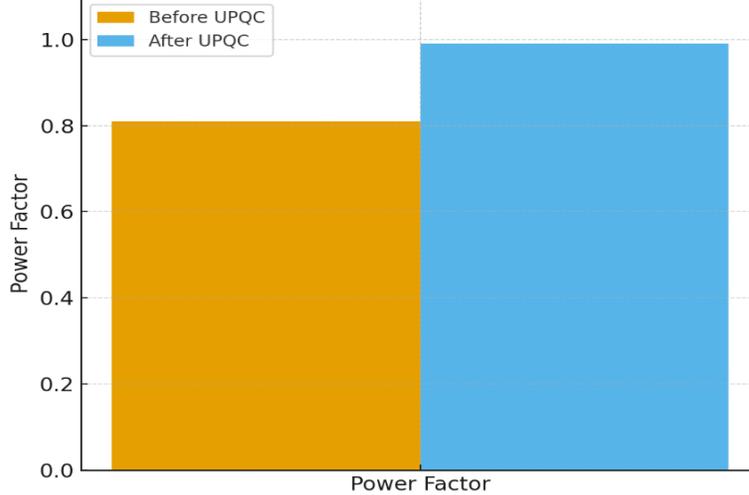| Parameter	Before UPQC	After UPQC	Improvement Observed
Settling Time (ms)	48	12	Fast dynamic response
Overshoot in DC-Link Voltage (%)	6.5	1.8	Improved stability
Voltage Deviation (%)	8.4	1.2	Enhanced voltage control
Current Ripple (%)	5.6	1.4	Reduced current ripple

Fig. 4. Power Factor Improvement with UPQC

The results demonstrate that the UPQC provides a quick dynamic response to load variations, maintaining voltage and current stability effectively.

4. Overall System Performance Evaluation: The overall system performance was evaluated based on Total Harmonic Distortion (THD), voltage regulation, and power factor improvements. The data were compared to IEEE 519-2014 standards for power quality, which recommend THD levels below 5%. The UPQC's performance met and exceeded these standards. Fig. 5. illustrates DC-link voltage response with and without UPQC; the voltage with UPQC stabilizes quickly around 750 V with minimal overshoot compared to fluctuating voltage without compensation.

Summary of UPQC Performance Evaluation

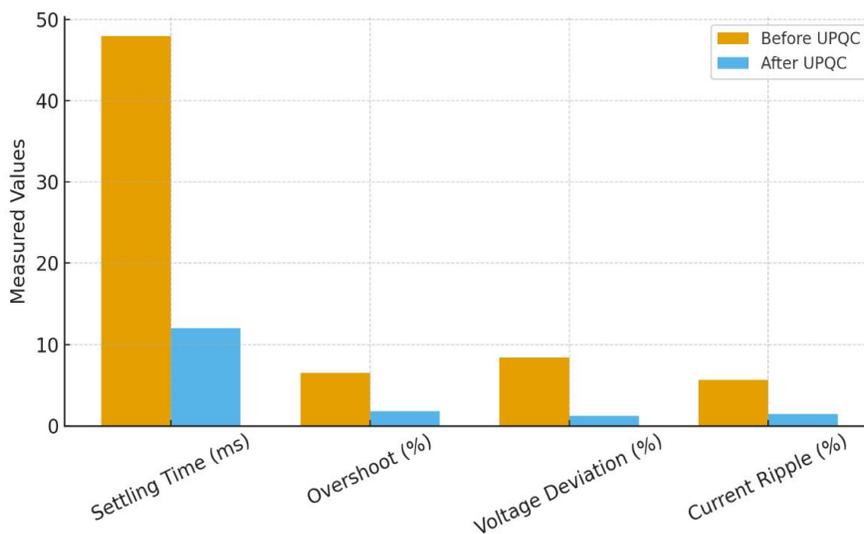| Performance Metric	IEEE Standard Limit	Before UPQC	After UPQC	Compliance Status
THD of Source Current (%)	≤ 5	21.7	3.1	Compliant
THD of Load Voltage (%)	≤ 5	18.2	2.8	Compliant
Power Factor	≥ 0.95	0.81	0.99	Compliant
Voltage Regulation (%)	≤ 5	8.4	1.2	Compliant

Fig. 5. DC-Link Voltage Stability during Load Variation

From the results, it is evident that the proposed UPQC model provides effective compensation for both voltage and current-related disturbances, maintaining power quality within the permissible limits of IEEE standards.

V. Conclusion

This study presented the modeling and simulation of a Unified Power Quality Conditioner (UPQC) for improving power quality in smart grid systems. The proposed UPQC, integrating series and shunt converters with a common DC-link capacitor, effectively compensated for voltage sags, swells, and current harmonics while maintaining a near-unity power factor. The MATLAB/Simulink simulation results validated the system's ability to restore load voltage, reduce Total Harmonic Distortion (THD) within IEEE standards, and provide a fast dynamic response under varying load conditions. The SRF-based control strategy ensured precise real-time compensation and coordination between converters, demonstrating the UPQC's reliability and adaptability for smart grid applications. In future work, this research can be extended by implementing advanced control algorithms such as fuzzy logic, adaptive neuro-fuzzy inference systems (ANFIS), or model predictive control (MPC) to enhance real-time performance. Furthermore, hardware implementation using DSP or FPGA controllers, along with renewable energy integration and Internet of Things (IoT)-based monitoring, can be explored to develop intelligent, self-adaptive UPQC systems for next-generation power networks.

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