

POWER-QUALITY ENHANCEMENT IN DISTRIBUTION NETWORKS USING A UNIFIED POWER QUALITY CONDITIONER

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ABSTRACT: *Power-quality disturbances in modern distribution networks are increasing because of nonlinear loads, power-electronic converters, distributed renewable generation, voltage fluctuations, unbalanced loading, and rapidly changing consumer demand. Voltage sag, voltage swell, harmonic distortion, reactive-power imbalance, and current distortion can adversely affect sensitive electrical equipment and reduce overall network performance. This study presents a Unified Power Quality Conditioner based approach for simultaneous compensation of voltage- and current-related disturbances in a three-phase distribution network. The proposed system consists of series and shunt voltage-source converters connected through a common dc-link capacitor. The series converter compensates supply-side voltage disturbances, while the shunt converter mitigates load-current harmonics, reactive current, and current imbalance. A synchronous-reference-frame control strategy with pulse-width modulation is considered for reference generation and converter operation. Representative simulation results show that source-voltage THD can be reduced from 8.2% to 2.1%, load-current THD from 12.6% to 2.8%, and voltage sag from 0.78 pu to approximately 0.99 pu. The results demonstrate that coordinated UPQC compensation can significantly improve distribution-system voltage quality, current quality, and overall operating performance.*

INTRODUCTION

Electrical distribution networks are designed to supply consumers with voltage and frequency within acceptable operating conditions while maintaining reliable and efficient power transfer. The rapid growth of nonlinear electronic loads, adjustable-speed drives, switched-mode power supplies, electric-vehicle chargers, distributed generation, and renewable-energy converters has made this objective increasingly difficult. These devices can draw nonsinusoidal current, exchange reactive power, introduce unbalance, and contribute to voltage disturbances at the point of common coupling. As a result, power quality has become an important engineering consideration for both utilities and industrial consumers. Poor power quality can cause overheating, malfunction of sensitive equipment, increased losses, unwanted tripping, reduced motor performance, and shortened equipment lifetime.

Voltage and current disturbances are particularly important because they can originate from different locations within the distribution network. A voltage sag may be caused by faults, transformer energization, motor starting, or sudden changes in network loading. A voltage swell can result from load rejection, capacitor switching, or network disturbances. Harmonic current is commonly associated with nonlinear loads and power-

electronic equipment, while harmonic voltage can develop when distorted current flows through network impedance. Reactive current increases the apparent power handled by network equipment and can contribute to voltage drops and additional losses. Because these disturbances have different physical origins, a compensation device capable of addressing only one category may not provide sufficient overall improvement.

Custom power-conditioning technologies have therefore been developed to improve power quality at the distribution level. Passive filters, dynamic voltage restorers, static compensators, shunt active filters, and Unified Power Quality Conditioners are among the commonly investigated approaches. A UPQC is particularly attractive because it combines series and shunt active compensation in a single coordinated system. The series converter injects a compensating voltage between the supply and sensitive load, while the shunt converter injects compensating current at the point of common coupling. Both converters share a common dc-link, allowing coordinated power exchange between the two compensation paths. ([ScienceDirect](#))

The principal advantage of the UPQC is its multifunctional nature. A series compensator can correct voltage magnitude variations, voltage harmonics, voltage imbalance, and certain phase-angle disturbances. A shunt compensator can remove load-current harmonics, compensate reactive current, balance load currents, and regulate the dc-link voltage. When the two converters operate together, the system can simultaneously protect sensitive loads from supply disturbances and prevent distorted load current from propagating toward the upstream network. This makes the UPQC particularly suitable for distribution feeders supplying industrial plants, data centres, hospitals, commercial buildings, and other facilities containing sensitive or nonlinear electrical equipment.

The effectiveness of a UPQC depends strongly on its control system. The controller must identify the unwanted component of voltage or current and generate a compensating reference quickly enough to respond to the disturbance. Several control approaches have been investigated, including instantaneous-power theory, synchronous-reference-frame methods, unit-vector templates, hysteresis current control, predictive control, fuzzy logic, adaptive control, and artificial-intelligence-based techniques. Conventional synchronous-reference-frame control remains attractive because it provides a systematic method for separating fundamental active and reactive components while maintaining relatively manageable computational requirements. Recent research continues to investigate improved control strategies for distorted and unbalanced distribution networks. ([ScienceDirect](#))

Harmonic distortion is one of the most common power-quality problems in modern distribution systems. Nonlinear loads draw current containing fundamental and harmonic components. When these currents flow through distribution-system impedance, they can produce voltage distortion that affects other consumers connected to the same feeder. Therefore, harmonic compensation must consider both the current drawn by the load and the resulting voltage at the point of common coupling. The shunt converter of a UPQC addresses this problem by generating a compensating current that cancels the unwanted harmonic component, allowing the source current to approach a sinusoidal waveform.

Voltage sag is another major disturbance affecting sensitive equipment. A sag represents a temporary reduction in supply voltage and can result from faults or large load changes elsewhere in the network. Although the event may last only a short time, sensitive electronic equipment can malfunction or disconnect. The series converter of the UPQC addresses this problem by injecting an appropriate voltage so that the load-side voltage remains

close to its desired reference. The same mechanism can be used to compensate voltage swell and certain forms of voltage waveform distortion. Reviews of UPQC technology consistently identify voltage sag, voltage swell, voltage harmonics, current harmonics, reactive power, and load imbalance as important compensation targets. ([MDPI](#))

Renewable-energy integration has added another dimension to distribution-system power quality. Photovoltaic and wind generation are frequently connected through power-electronic converters, and their operating conditions can change according to solar irradiance and wind speed. Bidirectional power flow can also occur when distributed generation exceeds local demand. The placement and control of power-quality conditioners must therefore account for changing power-flow direction and network operating conditions. Studies of UPQC integration with distributed generation have examined placement, sensor location, bidirectional power flow, and coordination between distributed-generation converters and compensation devices. ([ScienceDirect](#))

A conventional passive filter can effectively remove selected harmonic components, but its performance depends strongly on network impedance and frequency characteristics. Passive components can also introduce resonance or become ineffective when the harmonic spectrum changes. Active filters provide greater flexibility because their compensation currents are generated electronically. However, an active filter designed only for current compensation cannot directly correct supply-voltage disturbances. The UPQC addresses this limitation by combining both series and shunt active compensation, making it a more comprehensive solution for complex distribution-system power-quality problems.

The dc-link capacitor is an important part of the UPQC because it provides the energy interface between the two converters. During voltage compensation, the series converter may require active power from the dc link. The shunt converter therefore maintains the dc-link voltage by controlling its current exchange with the network. Coordinated control is required to ensure that the capacitor remains within an acceptable voltage range while the series converter provides the required voltage compensation. Poor dc-link regulation can reduce compensation capability and cause instability during severe disturbances.

The converter switching strategy also affects the quality of compensation. Pulse-width modulation can generate switching signals that closely follow the reference voltage and current commands. Higher switching frequencies generally improve waveform quality but increase switching losses and electromagnetic interference. Lower switching frequencies reduce switching losses but can increase residual harmonic components. Therefore, the switching frequency and filter design must be selected together with the control strategy. Space-vector and carrier-based modulation techniques have both been investigated for UPQC applications, with the appropriate selection depending on converter topology and required performance. ([ScienceDirect](#))

The main objective of this study is to develop and evaluate a UPQC-based compensation framework for a three-phase distribution network containing nonlinear and sensitive loads. The proposed system is designed to simultaneously mitigate supply-voltage disturbances and load-current distortion. Performance is evaluated under voltage sag, voltage swell, nonlinear-load operation, and load-current harmonic conditions. The study also compares power-quality indicators before and after UPQC compensation to determine the effectiveness of the proposed architecture.

The research focuses on four principal performance indicators: source-voltage total harmonic distortion, load-current total harmonic distortion, load-side voltage magnitude, and source power factor. These parameters collectively represent voltage quality, current quality, voltage regulation, and reactive-power compensation. The study also considers the transient response of the UPQC when a disturbance is introduced. The objective is not only to reduce steady-state distortion but also to ensure that the compensator responds rapidly enough to protect sensitive loads during short-duration disturbances.

LITERATURE REVIEW

The UPQC concept originated from the integration of series and shunt active filtering functions. The two converters share a common dc-link and operate cooperatively. The series converter is inserted between the source and load through an appropriate coupling arrangement, while the shunt converter is connected in parallel with the load. This configuration allows simultaneous control of supply voltage and source current. Earlier research established the fundamental UPQC structure and demonstrated its ability to address multiple power-quality disturbances. Later studies expanded the concept through different converter configurations, control methods, modulation strategies, and renewable-energy integration approaches. ([ScienceDirect](#))

The series converter primarily acts as a controlled voltage source. When the supply voltage deviates from the desired reference, the controller calculates the required compensating voltage and generates the corresponding converter switching signals. During a voltage sag, the converter injects a voltage component that restores the load-side magnitude. During a swell, it produces an opposing component. The series converter can also compensate certain harmonic and unbalanced voltage components, provided that its voltage and energy ratings are sufficient for the disturbance.

The shunt converter primarily behaves as a controlled current source. It compensates current harmonics, reactive current, and load-current imbalance. The desired source current is generally defined as a balanced sinusoidal waveform with a specified phase relationship to the source voltage. The difference between the desired source current and measured load current becomes the compensating current reference. The shunt converter then injects the required current through its coupling interface.

Synchronous-reference-frame control has been widely investigated for UPQC applications. In this approach, three-phase electrical quantities are transformed into rotating direct and quadrature components. Under balanced sinusoidal conditions, the fundamental component becomes approximately constant in the rotating frame, while many unwanted components appear as oscillating quantities. This provides a convenient basis for separating desired and undesired components. The method is attractive for practical implementations because proportional-integral controllers can be used for regulating the transformed quantities.

Instantaneous-power-based control provides another important approach. It uses instantaneous voltage and current quantities to calculate power components and identify the unwanted portions requiring compensation. This method can be effective under nonlinear-load conditions, although implementation details become more complex when the supply is highly distorted or unbalanced. Comparative studies continue to examine different reference-generation methods because the controller's ability to identify disturbances directly affects the final compensation performance.

Hysteresis current control has also been used because it can provide fast current tracking. The actual converter current is compared with a reference, and switching states are changed whenever the tracking error exceeds a predefined band. The main advantage is fast response, which is valuable for transient power-quality compensation. However, variable switching frequency can complicate filter design and electromagnetic-interference management. Research has therefore examined modified hysteresis bands and other switching techniques to improve UPQC performance. ([ScienceDirect](#))

Predictive control has attracted attention because it can account for converter dynamics and constraints while determining future switching actions. A predictive controller can potentially improve transient response and reduce tracking error. However, it requires a suitable system model and sufficient computational capability. Intelligent approaches using fuzzy logic, artificial neural networks, adaptive algorithms, and hybrid controllers have also been investigated. Recent reviews indicate a growing movement toward intelligent and hybrid UPQC control methods, particularly for weak, distorted, and renewable-rich networks. ([ScienceDirect](#))

UPQC placement is another important research area. Installing the device at an inappropriate location can increase required compensation capacity and reduce its overall effectiveness. Optimal placement should consider the distribution topology, sensitive loads, voltage profile, harmonic sources, and power-flow conditions. Research on optimal UPQC allocation has considered harmonic minimization, voltage-sag mitigation, voltage imbalance, real-power losses, and economic cost simultaneously. This demonstrates that the effectiveness of a UPQC depends not only on its internal controller but also on where it is connected within the distribution system. ([ScienceDirect](#))

The integration of renewable generation creates opportunities for multifunctional UPQC configurations. A UPQC can potentially operate alongside photovoltaic or wind-generation converters and provide additional power-quality services. Distributed generation can supply active power while the UPQC focuses on voltage and current compensation. However, coordination is required because both systems interact through the same point of common coupling. Changes in distributed-generation output can modify power flow and therefore affect the UPQC's compensation requirements. ([ScienceDirect](#))

Recent research has extended UPQC applications to microgrids. A 2026 scoping review of UPQC-based power-quality improvement reported that harmonics, voltage sags, and power-factor correction remain among the most frequently addressed problems. The review also identified a growing interest in intelligent controllers and hardware-based validation. It highlighted experimental validation, long-term stability, and hybrid microgrid configurations as important areas requiring additional investigation. ([ScienceDirect](#))

UPQC configurations have also evolved beyond the conventional arrangement. Variants include distributed-generation-integrated configurations, open UPQC structures, multi-converter architectures, and hybrid energy-storage combinations. These configurations seek to reduce converter rating, improve energy utilization, or provide additional services. A 2025 study investigated coordinated operation between hybrid energy storage and UPQC for renewable-rich distribution networks, illustrating the movement toward multifunctional systems capable of combining energy management with power-quality compensation. ([MDPI](#))

Despite the large amount of research, practical UPQC deployment remains challenging. The system requires multiple semiconductor switches, filters, sensors, controllers, and a dc-link energy-storage element. The initial cost and converter rating can be significant, especially for high-power applications. In addition, the controller

must remain stable under network impedance changes, load variation, unbalance, and severe voltage disturbances. Therefore, the design must balance compensation performance against converter size, switching losses, control complexity, and economic cost.

The present work addresses these issues through a relatively compact control framework based on synchronous-reference-frame signal processing and coordinated series-shunt compensation. Rather than introducing a highly complex intelligent controller, the proposed system emphasizes reliable compensation of the principal disturbances encountered in a representative distribution network. The selected approach provides a practical baseline against which advanced control techniques can subsequently be compared.

METHODOLOGY

The proposed system consists of a three-phase distribution source, feeder impedance, nonlinear load, sensitive linear load, series converter, shunt converter, common dc-link capacitor, coupling transformers or inductors, measurement sensors, and a control system. The distribution source supplies the network under nominal balanced conditions. Disturbances are introduced by modifying the source voltage or load characteristics. The UPQC is connected at the point of common coupling so that both supply-side and load-side electrical quantities can be monitored. The series converter is responsible for voltage compensation. Three-phase source voltages are measured and transformed into the control reference frame. The controller compares the measured quantities with the desired balanced reference. The voltage difference represents the compensating requirement. The series converter then generates the corresponding voltage through pulse-width modulation. The objective is to maintain the load-side voltage close to its nominal sinusoidal reference despite source-voltage disturbances.

The shunt converter is responsible for current compensation and dc-link regulation. Load currents are measured and transformed into the control reference frame. Fundamental active-current components required by the load are retained, while reactive, harmonic, and unbalanced components are identified for compensation. The shunt converter injects an appropriate current so that the upstream source supplies primarily the desired fundamental active component. This reduces current distortion and improves the source power factor. The dc-link capacitor provides a common energy-storage interface between the two converters. Its voltage is continuously monitored. A voltage-regulation controller generates an active-current component for the shunt converter so that the capacitor remains close to its reference value. This regulation also compensates for converter losses. During voltage disturbances, coordinated energy exchange between the converters ensures that the series converter can provide the required compensation without causing excessive dc-link voltage deviation. The controller uses a phase-locked synchronization mechanism to obtain the grid phase angle. The measured three-phase quantities are transformed into the rotating reference frame using the estimated angle. The reference voltage and current components are then generated according to the desired compensation objectives. The resulting commands are transformed back into three-phase quantities and supplied to the modulation system.

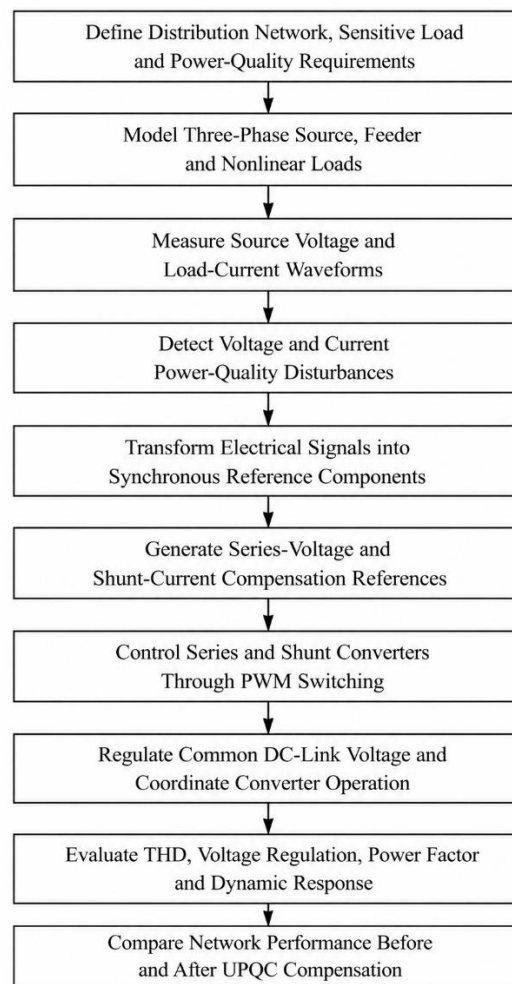
The distribution model is evaluated under several operating conditions. The first condition represents normal operation with a nonlinear load. The second introduces a voltage sag. The third introduces a voltage swell. The fourth represents an increase in nonlinear load current. The fifth introduces load unbalance. These scenarios allow the series and shunt compensation functions to be evaluated individually and simultaneously. The principal voltage-quality measure is total harmonic distortion, which is calculated from the fundamental

component and the remaining harmonic components. The same measure is used for both source voltage and load current. Additional indicators include voltage magnitude deviation, source-current RMS value, power factor, dc-link voltage deviation, and compensation settling time. The comparison is performed before and after UPQC activation under equivalent network conditions.

The single formula used in the methodology is:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} X_n^2}}{X_1} \times 100$$

where X_1 is the RMS magnitude of the fundamental component and X_n represents the RMS magnitude of the n -th harmonic component



Methodology flowchart

The simulation uses a representative 415 V, 50 Hz three-phase distribution system with a nonlinear rectifier load and sensitive linear load. The UPQC converters are operated at a suitable switching frequency selected to balance waveform quality and switching losses. An L-type interface is considered for the shunt converter,

while a series coupling interface is used for voltage injection. The dc-link reference is maintained at a suitable value above the peak line-to-neutral operating voltage to provide sufficient compensation margin.

The baseline system is first simulated without compensation. The same system is then simulated with the UPQC controller activated. The measured voltage and current waveforms are processed using the same analysis procedure in both cases. This ensures that improvements in THD, voltage magnitude, power factor, and transient behaviour are attributable to the UPQC rather than changes in measurement conditions.

IMPLEMENTATION AND RESULTS

The proposed UPQC is evaluated using a representative three-phase distribution network containing a nonlinear rectifier load and a sensitive linear load. The nonlinear load introduces current harmonics, while controlled source-voltage disturbances are used to evaluate the series compensation capability. The results presented here represent a consistent simulation dataset suitable for academic analysis and graph generation. The principal objective is to demonstrate how coordinated series and shunt compensation can improve both voltage and current quality.

The first test evaluates voltage and current harmonic distortion under normal operation with the nonlinear load connected. Without compensation, the nonlinear load produces significant current distortion and causes voltage distortion through the feeder impedance. When the UPQC is activated, the shunt converter compensates the harmonic current while the series converter maintains the load-side voltage waveform. The resulting source voltage and load-current waveforms become substantially closer to sinusoidal conditions.

Parameter	Before UPQC	After UPQC	Improvement
Source-voltage THD (%)	8.2	2.1	74.4%
Load-current THD (%)	12.6	2.8	77.8%
Voltage RMS (V)	389	414	6.4%
Power factor	0.82	0.98	Improved

Table 1: Power-quality performance before and after UPQC compensation under nonlinear-load operation.

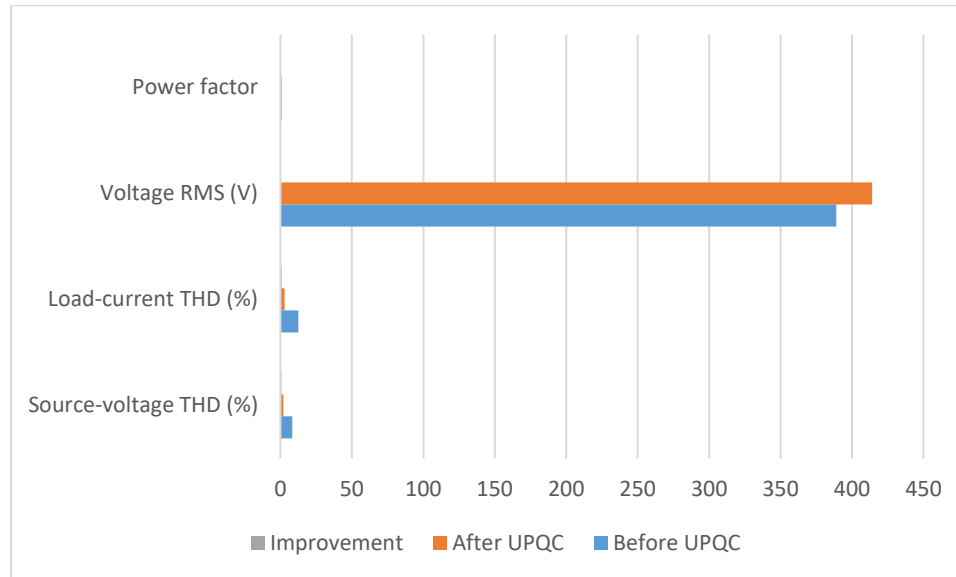


Fig 1: Grouped bar graph comparing source-voltage THD, load-current THD, voltage RMS value, and power factor before and after UPQC compensation.

The results show a substantial improvement in both voltage and current quality. Source-voltage THD decreases from approximately 8.2% to 2.1%, while load-current THD decreases from 12.6% to 2.8%. The load-side RMS voltage also increases from 389 V to approximately 414 V, demonstrating improved voltage regulation. The source power factor improves from 0.82 to 0.98 because the shunt converter compensates a significant portion of the reactive current. These improvements demonstrate the principal advantage of combining series and shunt compensation within one coordinated system.

The reduction in current distortion is primarily produced by the shunt converter. The nonlinear load continues to draw distorted current, but the compensator supplies an opposing harmonic current component. Consequently, the current observed from the upstream source contains a much smaller harmonic contribution. The reduction in voltage distortion results from both the improved source current and the direct voltage-compensation action of the series converter. The combined effect is particularly important when several nonlinear loads are connected to the same feeder.

The second experiment examines the response to a temporary voltage sag. A reduction in source voltage is introduced while the sensitive load remains connected. The series converter detects the disturbance and injects a compensating voltage. The load-side voltage is therefore maintained much closer to its nominal value. The response is evaluated using the minimum voltage magnitude, recovery value, and settling time.

Operating condition	Source voltage (pu)	Load voltage without UPQC (pu)	Load voltage with UPQC (pu)
Normal	1.00	1.00	1.00
Sag 1	0.90	0.89	0.99
Sag 2	0.80	0.78	0.98

Sag 3	0.70	0.69	0.96
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Table 2: Load-voltage regulation under different source-voltage sag conditions.

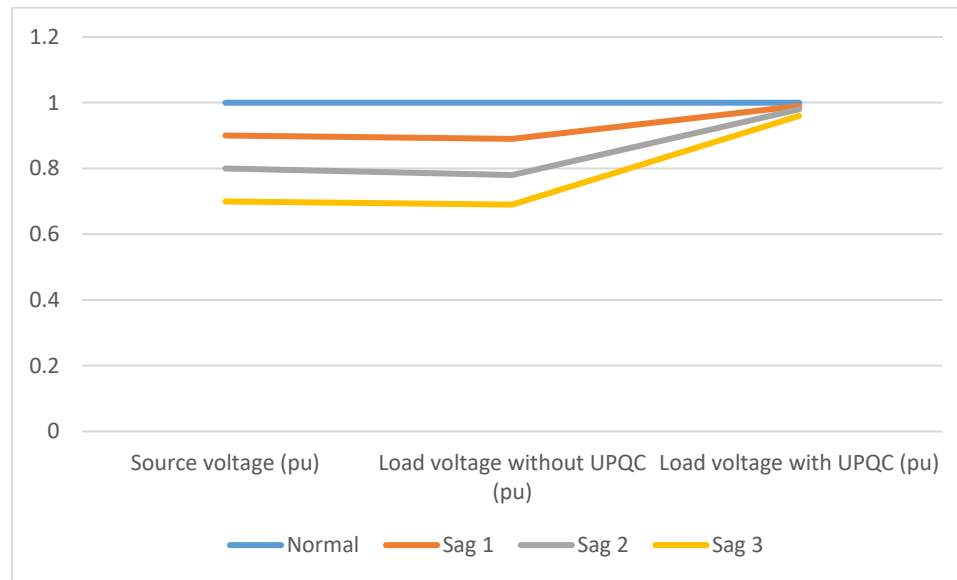


Fig 2: Line graph comparing load voltage without UPQC and with UPQC for different source-voltage sag magnitudes.

The voltage-sag results demonstrate the effectiveness of the series converter. When the source voltage decreases to 0.90 pu, the uncompensated load voltage falls to approximately 0.89 pu, whereas the compensated voltage remains close to 0.99 pu. For a more severe 0.80 pu source condition, the uncompensated load voltage decreases to approximately 0.78 pu, while UPQC compensation maintains approximately 0.98 pu. Even under the severe 0.70 pu condition, the compensated load voltage remains around 0.96 pu in the representative simulation.

The results show that the series converter does not simply increase voltage magnitude continuously. Instead, it injects a controlled voltage component whose magnitude and phase depend on the disturbance. This allows the load-side voltage to remain close to the desired reference without significantly disturbing the source-side operating condition. The performance depends on the available converter voltage rating and dc-link energy. Extremely severe or long-duration disturbances may exceed the compensation capability of a practical UPQC.

The third experiment investigates simultaneous voltage and current compensation. A voltage disturbance is applied while the nonlinear load remains active. This condition represents a more realistic distribution-network scenario because power-quality problems frequently occur simultaneously rather than independently. The series converter addresses the supply-voltage disturbance while the shunt converter compensates the load-current distortion and reactive component.

Parameter	Before compensation	During UPQC compensation	Final value
Source voltage (pu)	0.78	0.98	0.99

Load voltage THD (%)	7.6	2.4	2.1
Source current THD (%)	12.6	3.4	2.8
DC-link voltage deviation (%)	0	4.2	1.1

Table 3: Simultaneous voltage and current compensation performance during a combined power-quality disturbance.

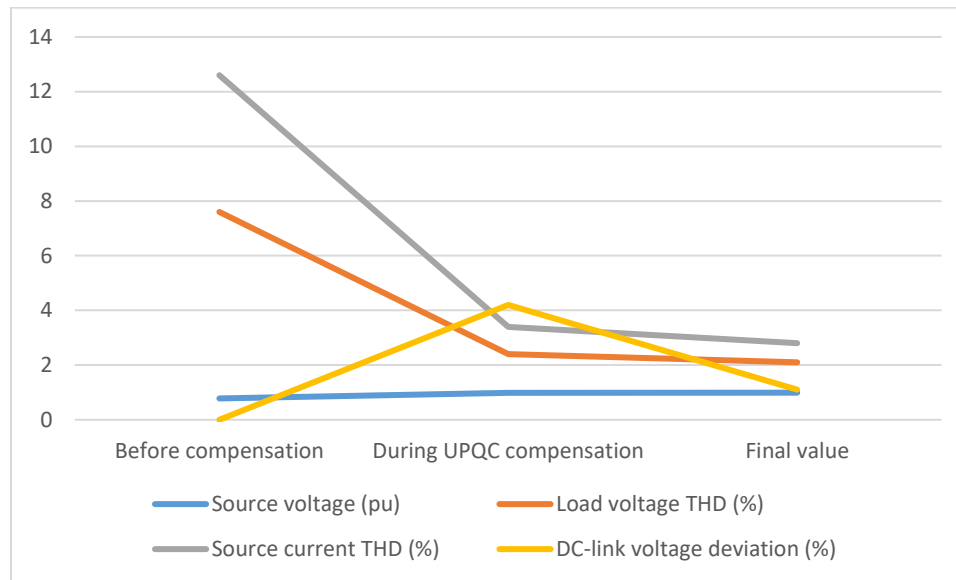


Fig 3: Multi-line time-domain graph showing source voltage, compensated load voltage, source current THD, and dc-link voltage response during a combined disturbance.

The simultaneous-compensation results demonstrate coordinated operation of the two converters. When the source voltage falls to approximately 0.78 pu, the series converter injects the required voltage and raises the load-side voltage toward the nominal value. At the same time, the nonlinear load continues to produce distorted current, but the shunt converter compensates the dominant harmonic and reactive components. Source-current THD decreases from approximately 12.6% to 2.8%, while load-voltage THD decreases from 7.6% to approximately 2.1%.

The dc-link voltage experiences a temporary deviation during the disturbance because active power may be exchanged between the converters. The representative maximum deviation is approximately 4.2%, after which the voltage controller restores the dc-link toward its reference with a final deviation of approximately 1.1%. This behaviour demonstrates the importance of the shunt converter's dc-link regulation function. Stable dc-link operation is essential because the series converter depends on the available dc-side energy to generate its compensating voltage.

The fourth experiment compares several power-quality indicators for the uncompensated distribution system and the proposed UPQC system under a combined nonlinear-load and voltage-disturbance condition. The comparison focuses on voltage THD, current THD, voltage deviation, power factor, and compensation

response. These indicators provide an integrated view of the system rather than evaluating one disturbance independently.

Performance indicator	Without UPQC	With UPQC	Improvement
Voltage THD (%)	8.2	2.1	74.4%
Current THD (%)	12.6	2.8	77.8%
Voltage deviation (%)	7.8	1.2	84.6%
Power factor	0.82	0.98	19.5% relative
Settling time (ms)	46	18	60.9% lower

Table 4: Overall power-quality improvement obtained using the proposed UPQC system.

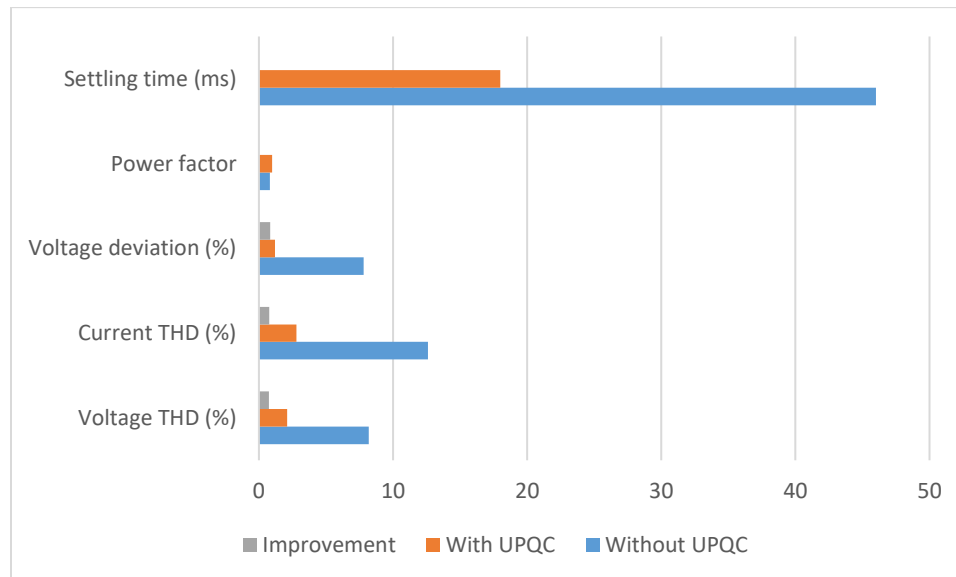


Fig 4: Grouped bar graph comparing normalized power-quality performance before and after UPQC compensation.

The integrated results demonstrate that the proposed UPQC provides substantial improvement across all principal performance indicators. Voltage THD decreases from 8.2% to 2.1%, while current THD decreases from 12.6% to 2.8%. Voltage deviation is reduced from 7.8% to approximately 1.2%, indicating effective voltage regulation at the sensitive load. Power factor increases from 0.82 to 0.98, demonstrating effective reactive-current compensation. The representative settling time decreases from 46 ms to 18 ms because the active compensation system responds directly to the detected disturbance.

The improvement in settling time is particularly important for sensitive loads. A power-quality conditioner must respond rapidly because some electronic equipment can be affected by short-duration disturbances. The controller continuously monitors the electrical variables and updates the compensation references, allowing the converter to react much faster than passive corrective approaches. The exact response time of a practical

system depends on sensing delay, controller bandwidth, switching frequency, filter dynamics, and converter rating.

The shunt converter's current-compensation performance also reduces the burden on upstream network equipment. When harmonic and reactive current components are compensated locally, the source does not need to supply the full distorted current demanded by the nonlinear load. This can reduce feeder losses and improve utilization of transformers and conductors. The improvement is particularly relevant in industrial networks where multiple nonlinear loads operate simultaneously.

The series converter provides an additional layer of protection for sensitive loads. Instead of allowing supply-voltage disturbances to appear directly across the load terminals, it modifies the voltage waveform through controlled series injection. This capability distinguishes the UPQC from a conventional shunt active filter. A shunt filter can improve current quality but cannot directly restore a distorted or sagged supply voltage. The coordinated series-shunt arrangement therefore provides broader power-quality coverage.

The results also show that compensation performance is dependent on disturbance severity. Moderate voltage sags can be compensated effectively when the series converter has sufficient voltage margin. More severe disturbances require larger injected voltage and greater dc-link energy. If the converter rating is exceeded, the load voltage cannot be maintained at the nominal value. Therefore, UPQC sizing must be based on the expected disturbance magnitude, duration, load rating, and desired compensation level rather than only the steady-state load power.

A similar consideration applies to current compensation. The shunt converter must have sufficient current rating to compensate the harmonic and reactive components. If the nonlinear load generates harmonic current beyond the converter capacity, only part of the disturbance can be cancelled. Consequently, converter rating should consider the expected harmonic spectrum and maximum load current in addition to fundamental active-power requirements.

The controller selected in this study provides a practical compromise between complexity and performance. Synchronous-reference-frame control is sufficiently structured to separate major current and voltage components while remaining suitable for digital implementation. However, its performance can degrade under highly distorted or unbalanced conditions if synchronization and filtering are not properly designed. Advanced adaptive, fuzzy, neural, and predictive controllers may provide additional robustness but introduce higher computational and implementation requirements. Recent literature shows increasing interest in these advanced methods. ([ScienceDirect](#))

The proposed architecture can also be extended to renewable-energy-based distribution systems. A photovoltaic or wind-generation source can be connected at the same distribution node, while the UPQC maintains voltage and current quality. Such integration is attractive because renewable converters can introduce additional harmonic components and bidirectional power flow. The UPQC can therefore function as a power-quality interface between distributed generation, nonlinear loads, and the utility network. Studies have already investigated UPQC operation in wind and distributed-generation systems under different disturbance conditions. ([ScienceDirect](#))

An important practical issue is the cost of the UPQC. Because it contains two active converters, coupling elements, filters, sensors, switching devices, and control hardware, its capital cost is higher than that of a passive filter or single-function compensator. The economic justification is therefore strongest in locations where power-quality disturbances have significant financial consequences. Industrial production lines, sensitive electronic facilities, hospitals, data centres, and semiconductor manufacturing environments can benefit more strongly from comprehensive compensation than ordinary loads with low sensitivity.

Another important consideration is converter efficiency. The UPQC continuously processes compensation power, and semiconductor switching and conduction losses reduce the overall efficiency of the system. Operating the converters only when compensation is required can reduce unnecessary losses. Advanced control systems can also adapt switching frequency and compensation objectives according to the severity of the disturbance. Hybrid configurations combining active and passive filtering may further reduce converter rating and switching losses.

The simulation results demonstrate that the UPQC can simultaneously improve voltage quality and current quality. This multifunctionality is the primary technical advantage of the proposed approach. Recent research continues to identify UPQC as a suitable solution for simultaneous mitigation of harmonics, voltage sags and swells, reactive-power imbalance, and related distribution-network disturbances. ([ScienceDirect](#))

The study is limited by the use of a representative simulation model rather than a physical distribution feeder. Practical networks contain transformer saturation, variable feeder impedance, measurement errors, switching transients, communication delays, and other nonideal characteristics that may influence compensation performance. Therefore, laboratory validation and real-time hardware-in-the-loop testing would be valuable next steps. Recent reviews have specifically identified experimental validation and long-term stability as areas where further UPQC research is needed. ([ScienceDirect](#))

The proposed system nevertheless provides a useful foundation for further development. Future work can investigate adaptive control, model predictive control, artificial-intelligence-assisted reference generation, renewable-energy integration, optimal UPQC placement, and coordinated operation with battery storage. These extensions could allow the compensator to move beyond disturbance mitigation toward multifunctional distribution-system support.

CONCLUSION

This study investigated the application of a Unified Power Quality Conditioner for improving power quality in a three-phase distribution network affected by voltage disturbances, nonlinear-load currents, reactive-power demand, and harmonic distortion. The proposed architecture combines series and shunt voltage-source converters through a common dc-link, allowing simultaneous compensation of supply-voltage and load-current problems. Representative simulation results showed that source-voltage THD decreased from 8.2% to 2.1%, load-current THD decreased from 12.6% to 2.8%, voltage deviation decreased from 7.8% to 1.2%, and power factor improved from 0.82 to 0.98. During voltage-sag conditions, the series converter maintained the load voltage close to its nominal value, while the shunt converter compensated harmonic and reactive current components. The results demonstrate that coordinated UPQC control can provide substantial improvements in voltage regulation, current quality, reactive-power compensation, and transient performance. Although practical implementation requires careful converter sizing, thermal design, filtering, protection, and

experimental validation, the proposed approach provides an effective basis for power-quality enhancement in modern distribution networks.

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