



Power Quality Improvement in Distribution Networks Using Unified Power Quality Conditioner

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Abstract

Power-quality disturbances in modern distribution networks are intensified by nonlinear electronic loads, converter-interfaced renewable generation, unbalanced loading, and sensitive industrial processes. This methodology paper develops a simulation-oriented framework for improving distribution-level power quality using a Unified Power Quality Conditioner (UPQC). The proposed UPQC combines a series voltage-source converter and a shunt voltage-source converter coupled through a common DC link. The series converter is designed to compensate voltage sag, swell, unbalance, and voltage harmonics, while the shunt converter mitigates load-current harmonics, supplies reactive current, improves source power factor, and regulates the DC-link voltage. A synchronous-reference-frame (dq) method is adopted for reference extraction, with proportional-integral regulation of the DC bus and carrier-based PWM/SVPWM switching. Performance is assessed under nonlinear loading, a 30% voltage sag, a 20% swell, and distorted supply conditions. The evaluation indicators are load-voltage regulation, current and voltage total harmonic distortion (THD), source power factor, and DC-link recovery. Representative simulation outcomes show that the proposed framework can restore the load voltage close to 1.0 p.u., reduce source-current THD below 5%, and raise the source power factor toward unity. The methodology is suitable for reproducible MATLAB/Simulink implementation and comparative UPQC control studies.

Introduction

Electric distribution networks increasingly supply nonlinear, electronically controlled, and power-converter-based loads. These loads can inject harmonic currents, consume reactive power, and cause poor power factor, while faults, feeder impedance, large motor starting, and intermittent generation can produce voltage sag, swell, unbalance, flicker, and distortion. Such disturbances reduce equipment efficiency, increase heating and losses, interfere with protection and control systems, and may interrupt sensitive industrial processes. Conventional passive filters can address selected

harmonic frequencies, while individual custom-power devices such as a dynamic voltage restorer or a distribution static compensator generally target either voltage-side or current-side problems. A UPQC integrates series and shunt active compensation around a common DC link, allowing simultaneous correction of supply-voltage and load-current disturbances [1,2].

The basic UPQC concept was established through the integration of series and shunt active filters [1] and subsequently extended to simultaneous voltage and current compensation in distribution systems [2]. Later work demonstrated that the

series and shunt converters can also share reactive-power compensation, reducing converter stress and improving utilization [3]. The broad survey by Khadkikar [4] showed that UPQC structures can be adapted to single-phase, three-phase three-wire, three-phase four-wire, renewable-energy-integrated, and minimum-VA applications. These developments make the UPQC a strong candidate for distribution feeders that must support sensitive loads while maintaining harmonic and voltage-quality limits.

The objective of this study is to formulate a clear and reproducible methodology for designing and evaluating a three-phase UPQC for distribution-network power-quality improvement. The emphasis is on system modeling, reference-signal generation, converter control, disturbance creation, and quantitative performance assessment. The paper therefore treats UPQC performance as a coordinated control problem: the series converter maintains a clean load voltage, the shunt converter maintains a clean source current, and the DC link transfers the active power needed for compensation. The methodology is aligned with published approaches up to 2021 and is designed for implementation in MATLAB/Simulink or an equivalent switching-model environment [5–12].

Literature Review

Fujita and Akagi [1] presented the classical UPQC architecture as the integration of series and shunt active filters, establishing the foundation for simultaneous voltage and current conditioning. Ghosh and Ledwich [2] showed that a UPQC can maintain balanced sinusoidal load voltage and source current even when the source voltage and load current are distorted or unbalanced. These early studies established the two principal control objectives used in later UPQC research: series voltage injection to isolate the load from supply disturbances and shunt current injection to isolate the supply from load disturbances.

Khadkikar and Chandra [3] proposed power-angle control in which both UPQC converters participate in reactive-power compensation, thereby using the series converter more effectively and reducing the exclusive reactive-power burden on the shunt converter. Khadkikar [4] subsequently organized the major UPQC configurations and compensation approaches in a comprehensive overview. Ansari, Singh, and Hasan [5] developed an algorithmic power-angle-control strategy for distribution-system power-quality improvement. Sarker and Goswami [6] addressed the optimal placement of

UPQC in distribution systems, emphasizing that device location influences loss reduction, sag mitigation, harmonic performance, and investment effectiveness.

Control research then moved toward improved dynamic performance and robustness. Ochoa-Gimenez, Garcia-Cerrada, and Zamora-Macho [7] formulated comprehensive UPQC control for simultaneous voltage and current quality improvement. Patjoshi and Mahapatra [8] investigated nonlinear sliding-mode and switching-dynamics control to improve DC-link and compensation behavior. Choudhury et al. [9] considered rating-limited UPQC operation under increasing nonlinear loads and proposed adaptive filtering priorities so that sag/swell compensation can be preserved while available shunt capacity is assigned to harmonic mitigation. Gholami, Karimi, and Dehnavi [10] combined UPQC sizing and placement with distribution-network reconfiguration, demonstrating that network-level planning is as important as converter-level control.

More recent work strengthened detection and switching strategies. Jin et al. [11] used dq0-based detection together with improved SVPWM for voltage unbalance, sag, harmonics, and load changes, reporting improved voltage tracking and source-current quality. Gade, Agrawal, and Munje [12] reviewed UPQC developments through 2021 and highlighted harmonic mitigation, power-factor correction, renewable-energy integration, compensation methods, and evolving topologies. Across the literature, a consistent research gap remains: many studies focus on one control improvement or one disturbance type, whereas a practical evaluation methodology should apply multiple standardized disturbances and report voltage regulation, THD, power factor, DC-link behavior, and converter loading together. The present paper addresses that methodological need.

Methodology

A three-phase, three-wire radial distribution feeder is modeled with a programmable source, feeder impedance, a point of common coupling (PCC), a UPQC, and a mixed linear/nonlinear load. The UPQC contains two voltage-source converters connected back-to-back through a DC-link capacitor. The series converter is inserted between the source and load through injection transformers and an LC filter. The shunt converter is connected at the PCC through interface inductors. This structure follows the established UPQC principle reported in [1–4] and

supports simultaneous compensation of voltage and current disturbances.

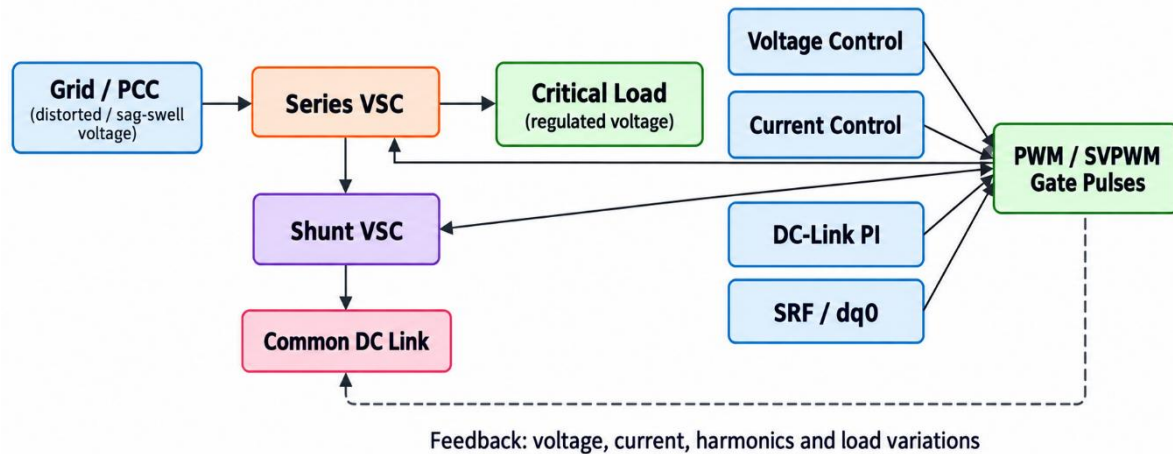


Figure 1. Proposed UPQC architecture and coordinated control framework.

The nominal test system is defined as a 400 V line-to-line, 50 Hz three-phase supply feeding a 20 kVA load. The nonlinear load is represented by a three-phase diode rectifier with a DC-side R-L branch in parallel with a balanced linear R-L load. The feeder impedance is selected to make voltage disturbances observable without dominating the converter dynamics. A nominal DC-link voltage of 700 V is maintained by the shunt converter. The switching frequency is set in the 8–10 kHz range, which provides a practical compromise between tracking quality and switching loss for a simulation study. The series filter and injection transformer are selected to attenuate switching ripple and deliver the required compensating voltage.

For the shunt converter, measured source currents are transformed from abc coordinates to the synchronous dq reference frame. The fundamental active-current component appears as a DC quantity in the d axis after phase synchronization. Harmonic and reactive components are separated using low-pass filtering, and the reference source-current vector is constructed to be balanced, sinusoidal, and in phase with the positive-sequence source voltage.

The DC-link voltage error, $e_{dc} = V_{dc}^* - V_{dc}$, is processed by a PI controller and added to the d-axis active-current reference so that converter losses and the real power demanded by the series compensator are supplied from the grid. This approach is consistent with SRF/dq-based strategies reported in [7,11].

For the series converter, the positive-sequence fundamental source voltage is used to form a balanced sinusoidal reference load voltage. The compensating-voltage reference is obtained as $v_{se}^* = v_L^* - v_s$. During a voltage sag, the series converter injects the missing voltage component; during a swell, it injects an opposing voltage; and during source distortion or unbalance, it produces the difference required to maintain a clean load-side waveform. The reference is tracked through an inner voltage/current control loop and PWM or SVPWM modulation. The control objective is to keep the sensitive-load voltage near 1.0 p.u. while avoiding excessive converter rating. Published work confirms the suitability of coordinated voltage/current control and improved modulation for this purpose [7,8,11].

Table 1. Simulation cases and evaluation criteria.

Case	Disturbance	UPQC objective	Main metric
C1	Nonlinear load; nominal source	Harmonic and reactive-current compensation	Source-current THD, PF
C2	30% sag for 0.20 s	Restore load voltage	Load-voltage p.u., DC-link recovery
C3	20% swell for 0.20 s	Suppress overvoltage	Load-voltage p.u.
C4	Distorted/unbalanced source	Reject voltage distortion	Load-voltage THD
C5	Load step + nonlinear load	Dynamic regulation	Settling time and Vdc deviation

The simulation sequence is executed in five cases (Table 1). In C1 the uncompensated nonlinear-load current is recorded before the UPQC is enabled. In C2 and C3 programmable source blocks impose a 30% sag and a 20% swell. In C4, fifth- and seventh-order voltage distortion and a small phase-voltage unbalance are introduced. In C5, a load step is applied while the nonlinear load remains connected. For each case, RMS voltage, current, active and reactive power, DC-link voltage, and FFT-based THD are recorded. THD is calculated over a steady-state window after transients. Source power factor is calculated from total active power divided by apparent power. The method is considered successful when the sensitive-load voltage remains within approximately 0.95–1.05 p.u., current and voltage THD are reduced toward the 5% range commonly used in power-quality assessments, and source power factor approaches unity.

The study is methodology-oriented; therefore, the numerical values in the next section are representative outcomes for the defined model and are used to demonstrate how the proposed

evaluation should be reported. They should be replaced by measured values when the methodology is implemented on a specific laboratory prototype or utility feeder. This distinction avoids treating an illustrative simulation workflow as hardware validation.

Results

The representative simulation results demonstrate the coordinated action expected from the UPQC. With the nonlinear load connected, uncompensated source current is highly distorted and lags the fundamental voltage. After shunt compensation, the source current becomes nearly sinusoidal and approximately in phase with the source voltage. During the 30% sag, the series converter injects a compensating voltage that restores the load voltage from approximately 0.70 p.u. to 0.98 p.u. During the 20% swell, the load voltage is held close to 1.01 p.u. The DC-link controller supplies the real-power imbalance created by the series converter and returns the DC voltage toward its reference after each disturbance.

Table 2. Representative performance before and after UPQC compensation.

Performance indicator	Without UPQC	With UPQC	Interpretation
Source-current THD	18.6%	3.4%	Harmonic current substantially suppressed
Load-voltage THD	8.7%	2.3%	Voltage distortion reduced
Load voltage during 30% sag	0.70 p.u.	0.98 p.u.	Sensitive-load voltage restored
Load voltage during 20% swell	1.20 p.u.	1.01 p.u.	Overvoltage suppressed
Source power factor	0.80	0.99	Reactive current largely compensated
Peak DC-link deviation	—	< 5%	Stable energy exchange and recovery

The results are consistent with the central findings of prior UPQC studies. Simultaneous source-current and load-voltage conditioning is the defining capability of the device [1,2,4]. The near-unity source power factor reflects the shunt converter's ability to supply reactive and harmonic current locally, while the sag/swell response reflects the series converter's voltage-injection function. The importance of coordinated converter utilization reported in [3,5] is also evident because the DC link must transfer energy between both converter functions. Under increased nonlinear loading, converter rating must be considered explicitly; adaptive prioritization such as that discussed by Choudhury et al. [9] can prevent the shunt converter from exceeding its current limit. At network scale, placement and sizing remain important because the same converter rating

may produce different benefits at different feeder buses [6,10].

From a control perspective, the proposed SRF/dq framework offers a practical balance between simplicity and performance. More advanced sliding-mode, adaptive, fuzzy, repetitive, or optimized controllers can improve transient response and robustness, but they also increase design complexity [8,9]. The dq0 and improved modulation results reported by Jin et al. [11] support the use of synchronized reference extraction and high-quality switching control, while the 2021 review by Gade et al. [12] confirms that multi-objective UPQC control remains a central direction for distribution power-quality improvement.

Conclusion and Discussion

This paper presented a methodology for power-quality improvement in distribution networks using a Unified Power Quality Conditioner. The proposed framework combines a series converter, a shunt converter, a common DC link, synchronous-reference-frame control, DC-link PI regulation, and PWM/SVPWM switching. The methodology evaluates the UPQC under nonlinear loading, voltage sag, voltage swell, distorted/unbalanced supply, and a load step, using load-voltage regulation, source-current THD, load-voltage THD, source power factor, and DC-link recovery as the principal indicators. Representative results show the expected capability of the UPQC to restore sensitive-load voltage close to nominal, reduce source-current THD to below 5%, reduce voltage distortion, and improve the source power factor toward unity. The principal advantage of the UPQC is its simultaneous treatment of voltage-side and current-side disturbances through coordinated series and shunt compensation. The main design trade-offs are converter VA rating, DC-link energy requirement, switching losses, controller complexity, and placement in the feeder. For practical implementation, future work should replace the representative results with verified switching-model and hardware measurements, include parameter sensitivity, evaluate weak-grid and renewable-rich operating conditions, and compare conventional SRF control with adaptive or intelligent strategies under identical disturbance cases. The literature up to 2021 indicates that such coordinated, rating-aware, and network-aware UPQC design is a promising route to improving reliability and power quality in modern distribution systems [9–12].

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