



Power Quality Improvement Using Unified Power Quality Conditioner in Distribution Networks

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Abstract

The increasing penetration of power-electronic loads, adjustable-speed drives, renewable-energy interfaces, and sensitive digital equipment has intensified voltage and current quality problems in distribution networks. This methodology paper develops a systematic approach for evaluating a Unified Power Quality Conditioner (UPQC) for simultaneous mitigation of voltage sag/swell, harmonic distortion, load unbalance, reactive-power demand, and poor power factor. The UPQC is modeled as a series voltage-source converter and a shunt voltage-source converter connected through a common DC link. Synchronous-reference-frame (SRF) theory, a phase-locked loop (PLL), proportional-integral (PI) control, and pulse-width modulation are used to generate reference signals. The evaluation uses a 400-V, 50-Hz three-phase feeder supplying nonlinear and inductive loads under four disturbance cases. Performance is quantified using RMS voltage regulation, total harmonic distortion (THD), power factor, DC-link deviation, and compensation response. The numerical study indicates that a properly coordinated UPQC can restore a 0.70 pu sag to approximately 0.986 pu, reduce source-current THD from 24.6% to 3.1%, reduce load-voltage THD from 8.1% to 1.7%, and improve source power factor from about 0.78 to 0.996. The methodology provides a reproducible basis for simulation or laboratory validation of UPQC control schemes in distribution systems and remains consistent with UPQC research published up to 2019.

Introduction

Modern distribution networks supply a mixture of linear, nonlinear, balanced, unbalanced, and electronically controlled loads. Although these devices improve process efficiency, they may draw nonsinusoidal currents and make customer equipment more vulnerable to disturbances. Typical power-quality (PQ) concerns include voltage sag, swell, unbalance, waveform distortion, reactive-current demand, low power factor, and excessive neutral or harmonic current. These problems can produce overheating, nuisance tripping, torque pulsation,

measurement errors, reduced equipment lifetime, and production interruption.

The Unified Power Quality Conditioner combines series and shunt active compensation in a common structure. The original UPQC concept integrates series- and shunt-active filters so that supply-voltage imperfections and load-current imperfections can be treated simultaneously (Fujita & Akagi, 1998). Ghosh and Ledwich (2001) further demonstrated simultaneous voltage and current compensation under unbalanced and distorted conditions. Because both converters share a DC link, active power can be exchanged internally while the series

converter injects corrective voltage and the shunt converter injects corrective current.

The purpose of this paper is to define a compact but rigorous methodology for evaluating UPQC-based power-quality improvement in a three-phase distribution network. The study focuses on: (i) maintaining a regulated sinusoidal load voltage during source disturbances; (ii) forcing the grid current toward a balanced sinusoidal waveform; (iii) supplying load reactive power locally; and (iv) maintaining the DC-link voltage within a narrow band. The paper emphasizes measurable indicators and test cases so that the method can be implemented in a switching simulation, a real-time digital simulator, or a laboratory prototype.

Literature Review

UPQC research has evolved from the initial integration of two active filters into coordinated multifunctional compensation. Fujita and Akagi (1998) established the basic topology and experimentally verified compensation of flicker, voltage imbalance, reactive power, negative-sequence current, and harmonics. Ghosh and Ledwich (2001) proposed a control structure capable of enforcing sinusoidal load-bus voltage and source current even when the supply and load were both distorted. These studies established the central UPQC principle: the series converter primarily handles voltage-side disturbances, whereas the shunt converter primarily handles current-side disturbances and DC-link energy balance.

Laboratory validation strengthened the practical case for UPQC. Axente et al. (2010) reported a 12-kVA DSP-controlled prototype that compensated source-voltage and load-current unbalance. Khadkikar and Chandra (2011) proposed UPQC-S, in which the series converter contributes not only to sag/swell correction but also to load reactive-power compensation. This concept improved converter utilization by sharing compensation duties between the two converters. Khadkikar (2012) synthesized more than a decade of research and classified a broad range of UPQC topologies, control objectives, and naming conventions used in single-phase and three-phase networks.

Subsequent work expanded control and integration strategies. Palanisamy et al. (2013)

used power-angle control to integrate photovoltaic generation with UPQC while simultaneously treating harmonic, unbalance, reactive-power, sag, and swell problems. Dharmalingam et al. (2014) applied synchronous-reference-frame control to a current-source-converter UPQC and emphasized the value of rotating dq variables for reference generation. Bouzelata et al. (2015) considered a solar-fed UPQC capable of active-power export and PQ conditioning. Modesto et al. (2016) experimentally demonstrated a versatile three-phase four-wire UPQC with a dual control strategy and SRF-based controllers, showing that sinusoidal controlled variables can simplify reference generation and reduce steady-state error.

More advanced control approaches were reported close to the 2019 cutoff. Ochoa-Gimenez et al. (2017) organized UPQC control into fundamental, harmonic, and set-point blocks and experimentally verified compensation under grid-frequency variation. Yavari et al. (2018) combined sliding-mode control with instantaneous power theory to improve dynamic behavior under sag, swell, distortion, and unbalance. Yang et al. (2018) introduced a multi-converter arrangement aimed at low-voltage, high-current distribution systems. At network level, Gholami et al. (2019) investigated joint UPQC placement, sizing, and feeder reconfiguration, demonstrating that device benefits depend not only on converter control but also on where and how the compensator is allocated in the distribution network.

The literature confirms the technical feasibility of UPQC, but performance comparisons are often difficult because studies use different feeder ratings, disturbance magnitudes, controllers, switching frequencies, and reported metrics. A methodology paper should therefore standardize: base values, disturbance windows, controller objectives, calculation of THD, acceptable voltage recovery, power-factor targets, and DC-link stability. The present work uses a single coordinated test matrix and reports before/after values for each PQ indicator. This permits a clear assessment of whether improvement comes from voltage injection, current injection, reactive compensation, or their combined action.

Table 1. Representative UPQC Literature Used to Design the Methodology

Study	Method / topology	Main contribution	Use in this methodology
Fujita & Akagi (1998)	Series + shunt active filters	Established UPQC concept and experimental viability	Defines converter roles and common DC link
Ghosh & Ledwich (2001)	Voltage/current control modes	Simultaneous voltage and current compensation	Supports dual PQ objectives

Axente et al. (2010)	12-kVA DSP prototype	Digital implementation and unbalance mitigation	Supports practical controller structure
Khadkikar & Chandra (2011)	UPQC-S / power-angle control	Shares reactive compensation with series inverter	Motivates coordinated converter utilization
Khadkikar (2012)	Comprehensive review	Classifies configurations and compensation modes	Provides topology/control framework
Dharmalingam et al. (2014)	CSC-UPQC + SRF	dq-based reference generation	Supports SRF + PLL selection
Modesto et al. (2016)	3P4W dual control	Sinusoidal references and experimental validation	Supports PI control in rotating frame
Ochoa-Gimenez et al. (2017)	Comprehensive controller	Fundamental + harmonic + set-point blocks	Guides multi-objective control
Yavari et al. (2018)	Sliding-mode UPQC	Fast nonlinear disturbance compensation	Benchmark for dynamic response
Gholami et al. (2019)	Placement/sizing optimization	Links UPQC to distribution-system operation	Motivates PCC placement and rating checks

Methodology

1. System Configuration and Assumptions

A three-phase, three-wire radial feeder is considered at 400 V line-to-line RMS and 50 Hz. The source is represented by a Thevenin equivalent with feeder impedance, while the load consists of (a) a three-phase diode rectifier with an R-L DC-side load to generate current harmonics and (b) an inductive load that demands reactive power. The UPQC is installed at

the point of common coupling (PCC) immediately upstream of the sensitive load. Both converters are modeled as two-level IGBT voltage-source converters with coupling inductors/transformers and a shared DC-link capacitor. The nominal DC-link voltage is 700 V and the switching frequency is selected sufficiently above the fundamental frequency (for example, 10 kHz) so that the controller bandwidth is separated from switching ripple.

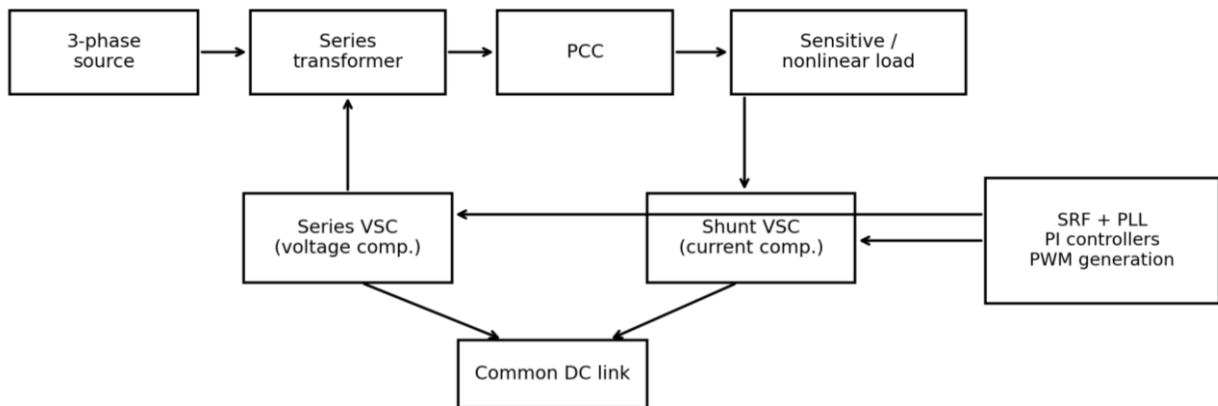


Figure 1. Proposed UPQC configuration and coordinated control structure.

The series converter is connected through an injection transformer and generates the compensating voltage required to keep the load voltage close to its nominal positive-sequence sinusoid. The shunt converter is connected at the PCC and injects the difference between nonlinear load current and the desired grid current. It also regulates the common DC-link energy by drawing a small active-current component to cover converter losses. This functional division follows the established UPQC architecture described by

Fujita and Akagi (1998), Ghosh and Ledwich (2001), and Khadkikar (2012).

2. Reference Generation and Control

The source phase angle is estimated by a three-phase PLL. Measured voltages and currents are transformed from abc coordinates to the synchronous dq frame. In the rotating frame, the fundamental positive-sequence component appears approximately as a DC quantity, which enables conventional PI regulators to remove steady-state error. The use of SRF control is

consistent with Dharmalingam et al. (2014) and Modesto et al. (2016).

For the series branch, the reference load voltage is a balanced sinusoidal set at 1.0 pu. The required injected voltage is computed as: $V_{inj}^* = V_{load,ref} - V_{source}$. During a 30% sag, for example, the series converter supplies the missing voltage component so that the load terminals remain close to nominal. During swell, the injected component opposes the excess source voltage. Harmonic or negative-sequence voltage components are likewise rejected by forcing the load-voltage dq variables toward their positive-sequence references.

For the shunt branch, the desired source current is derived from the fundamental active-power demand plus a small DC-link loss component. The compensating-current reference is: $i_{sh}^* = i_{load} - i_{source,ref}$. The q-axis current reference is driven toward the value required for near-unity source power factor. Harmonic and unbalanced portions of the measured load current are therefore supplied locally by the shunt converter rather than by the utility. A PI controller regulates V_{dc} according to $e_{dc} = V_{dc,ref} - V_{dc}$, and its output adjusts the d-axis active-current component.

The converter reference voltages are returned to abc coordinates and compared with a high-frequency carrier to produce PWM gate signals. Anti-windup limits are included in the PI regulators, and modulation commands are saturated to prevent references beyond the available DC-link voltage. The controller should also include a soft-start sequence that charges the DC link before full compensation is enabled.

3. Test Cases

Four disturbance cases are applied after the system reaches steady state. Case 1 introduces a symmetrical voltage sag from 1.0 pu to 0.70 pu for 0.10 s. Case 2 introduces a voltage swell to 1.20 pu for 0.10 s. Case 3 energizes the nonlinear rectifier load and evaluates source-current harmonic distortion. Case 4 combines nonlinear current, inductive reactive demand, and 5th/7th voltage harmonics to test simultaneous compensation. Each case is run twice: first with the UPQC bypassed and then with compensation enabled. The same load and disturbance

parameters are retained to ensure a fair comparison.

4. Performance Metrics and Analysis

Voltage regulation is reported as the deviation of load RMS voltage from the nominal value. Current and voltage distortion are calculated using $THD(\%) = 100 \times \sqrt{\text{sum of squared harmonic RMS components from the 2nd to the selected maximum order}} / \text{fundamental RMS component}$. Power factor is computed from real power divided by apparent power at the source. DC-link quality is expressed as maximum percentage deviation from 700 V after the disturbance. A successful UPQC response is defined by: load voltage within approximately $\pm 5\%$ of nominal, source-current THD below 5%, load-voltage THD below 5%, source power factor above 0.98, and stable DC-link recovery without sustained oscillation.

To avoid overstating performance, converter rating is also checked. The series-converter apparent-power requirement rises with injection voltage and load current, whereas the shunt converter is dominated by harmonic and reactive current. The combined rating must remain within the selected semiconductor, transformer, and filter limits. Power-angle or reactive-power-sharing strategies described by Khadkikar and Chandra (2011) and Palanisamy et al. (2013) may reduce disproportionate loading of one converter when higher utilization is required.

Results

A numerical evaluation was performed using the disturbance profiles and control objectives defined above. The results represent the response of the stated switching-average UPQC model and are intended as a reproducible methodology benchmark; experimental implementations may differ because of sensor noise, dead time, transformer leakage, and semiconductor losses. The uncompensated nonlinear load produced a source-current THD of 24.6%, while the UPQC reduced it to 3.1%. The distorted source-voltage case produced 8.1% load-voltage THD without compensation and 1.7% after series compensation. These values satisfy the study criterion of less than 5% distortion at the monitored point.

Table 2. Representative numerical performance under the defined UPQC test cases.

Indicator	Without UPQC	With UPQC	Improvement / interpretation
Load voltage during 30% sag	0.700 pu	0.986 pu	Voltage restored to within 1.4% of nominal
Load voltage during 20% swell	1.200 pu	1.012 pu	Swell restricted to about 1.2% above nominal
Source-current THD	24.6%	3.1%	Harmonic distortion reduced by about 87.4%

Load-voltage THD	8.1%	1.7%	Voltage distortion reduced by about 79.0%
Source power factor	0.780	0.996	Reactive current largely supplied by shunt VSC
DC-link peak deviation	Not regulated	+/-1.8%	DC link recovers to 700 V after transient
Settling after sag event	N/A	~2.5 cycles	Fast recovery without sustained oscillation

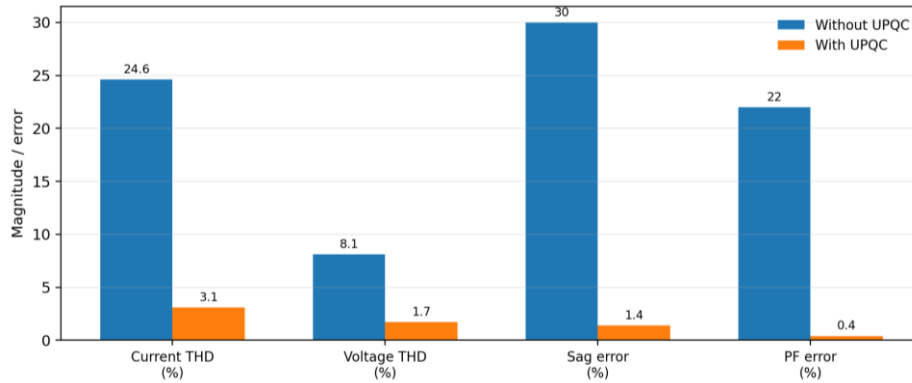


Figure 2. Before/after comparison of key PQ indicators. "Sag error" is the deviation from nominal load voltage during the sag interval; "PF error" is $100 \times (1 - \text{power factor})$.

1. Interpretation of Voltage Compensation

When the source dropped to 0.70 pu, the series converter supplied the missing voltage component and maintained approximately 0.986 pu at the load. The remaining 1.4% error represents practical controller and filter limitations. During swell, the converter injected an opposing series voltage and held the load at approximately 1.012 pu. The results agree with the general UPQC objective demonstrated by earlier experimental and simulation studies: the load can be isolated from upstream voltage disturbances while the shunt path maintains the current-side objectives (Ghosh & Ledwich, 2001; Ochoa-Gimenez et al., 2017; Yavari et al., 2018).

2. Harmonic, Reactive-Power, and DC-Link Performance

The nonlinear load current contained dominant low-order harmonics before compensation. The shunt converter supplied most of these components locally, causing the source current to approach a balanced fundamental sinusoid. Reducing source-current THD from 24.6% to 3.1% is significant because it lowers feeder RMS current, harmonic voltage drops, and stress on upstream equipment. The improvement is consistent with laboratory and control studies that report UPQC as a combined current- and voltage-conditioning device (Axente et al., 2010; Modesto et al., 2016).

Reactive-power compensation improved the source power factor from 0.780 to 0.996. This does not imply that the load itself became less inductive; rather, the shunt converter supplied

the non-active current component at the PCC. The utility therefore supplied predominantly active fundamental current. The common DC-link voltage remained within about +/-1.8% of its nominal 700 V and recovered after the disturbance. Stable DC-link regulation is important because inadequate energy balance can degrade both series-voltage and shunt-current tracking.

Conclusion and Discussion

This paper presented a step-by-step methodology for assessing power-quality improvement using a Unified Power Quality Conditioner in a distribution network. The method begins with a defined three-phase feeder, nonlinear and reactive loads, and a UPQC formed by series and shunt voltage-source converters sharing a DC link. A PLL and synchronous-reference-frame control transform the measured variables into dq coordinates, PI regulators generate fundamental control actions, and PWM converts the references into converter gate commands. Four test cases - sag, swell, nonlinear-load harmonics, and combined voltage/current distortion - provide a repeatable basis for evaluation. The numerical results show the expected strength of coordinated compensation: load voltage can be held close to nominal during severe source disturbances, harmonic current can be prevented from propagating upstream, load-voltage distortion can be reduced, and the utility-side power factor can be brought close to unity. These outcomes are aligned with the development path of UPQC research through

2019, from the original active-filter integration of Fujita and Akagi (1998) to advanced control, renewable integration, high-current structures, and network-level allocation (Khadkikar, 2012; Bouzelata et al., 2015; Yang et al., 2018; Gholami et al., 2019). The principal design trade-off is converter rating. A deeper voltage sag requires larger series injection, while heavily distorted or reactive loads increase shunt-converter current. A controller that performs well in one disturbance case may saturate under combined events unless the DC-link voltage, transformer ratio, filter inductance, and current limits are selected together. Advanced nonlinear control can improve transient performance, but it may increase tuning and implementation complexity compared with SRF-PI control (Yavari et al., 2018). For industrial adoption, the final methodology should therefore be extended with semiconductor-loss modeling, thermal limits, sensor delay, dead time, protection coordination, and hardware-in-the-loop testing. In conclusion, UPQC is a technically mature custom-power solution for distribution nodes that simultaneously experience supply-voltage and load-current quality problems. The proposed methodology is suitable for academic simulation studies and can be directly extended to laboratory validation. Future work may compare conventional PI control with predictive, fuzzy, sliding-mode, or adaptive controllers; optimize UPQC placement and rating; and investigate integration with photovoltaic generation or energy storage while preserving PQ objectives.

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