



Enhancement of Power Quality Using Unified Power Quality Conditioner in Distribution Networks

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Abstract

The increasing use of power-electronic loads, variable-speed drives, rectifiers, distributed generation interfaces, and sensitive digital equipment has intensified voltage- and current-related power-quality problems in distribution networks. This methodology paper develops a structured approach for evaluating a Unified Power Quality Conditioner (UPQC) as an integrated compensator for voltage sag, voltage swell, supply distortion, load-current harmonics, reactive-power demand, and poor power factor. The proposed study uses a three-phase distribution feeder with a common-DC-link series and shunt voltage-source converter. A synchronous-reference-frame control structure is adopted: the series converter regulates the load-side voltage, while the shunt converter shapes the source current, supplies compensating reactive/harmonic current, and maintains the DC-link voltage. Test cases include a 30% voltage sag, 20% swell, distorted supply, and nonlinear load. Performance is evaluated using per-unit load voltage, total harmonic distortion (THD), power factor, and DC-link stability. A representative simulation dataset shows the expected trend: load voltage remains close to 1.0 p.u. during disturbances, source-current THD can be reduced from about 18.6% to 3.1%, voltage THD from 9.4% to 2.2%, and input power factor from 0.78 to 0.99. These values are illustrative model-based results, not laboratory measurements. The methodology provides a reproducible framework for validating UPQC control in MATLAB/Simulink or an equivalent power-system simulation environment.

Introduction

Power quality is a central operating requirement in modern distribution networks because sensitive loads may malfunction when the supply contains voltage magnitude variations, waveform distortion, phase unbalance, or short-duration disturbances. At the same time, nonlinear loads draw non-sinusoidal currents that can propagate harmonics through feeder impedances and distort the point-of-common-coupling (PCC) voltage. The UPQC addresses both sides of this problem by combining a series active filter and a

shunt active filter through a common DC link. The original integrated concept established that the series converter can correct supply-voltage disturbances while the shunt converter can compensate reactive, harmonic, and negative-sequence load currents (Fujita & Akagi, 1998). Later research expanded the UPQC from a basic conditioner into a flexible family of topologies and control philosophies. Interline configurations were proposed to support two feeders (Jindal et al., 2007), power-angle control enabled sharing of reactive-power compensation

between converters (Khadkikar & Chandra, 2008), and three-phase four-wire arrangements improved unbalance and neutral-current compensation (Khadkikar & Chandra, 2009). The comprehensive review by Khadkikar (2012) shows that the UPQC can be adapted for diverse voltage, current, harmonic, and distributed-generation objectives. For a distribution utility or industrial user, the practical research question is therefore not whether a UPQC can compensate disturbances, but how its topology, control, test conditions, and evaluation metrics should be organized to demonstrate repeatable improvement.

The objective of this paper is to present such a methodology. The proposed procedure models a three-phase feeder supplying a nonlinear and reactive load, introduces controlled voltage sag/swell and distortion, operates a two-converter UPQC using synchronous-reference-frame control, and compares uncompensated and compensated conditions. The emphasis is on a clear experimental/simulation sequence, measurable performance indices, and literature-grounded parameter selection. All cited references were published in 2018 or earlier, in accordance with the requested literature cut-off.

Literature Review

Fujita and Akagi (1998) provided the foundational UPQC formulation by integrating series- and shunt-active filters and demonstrating simultaneous compensation of voltage and current disturbances. Jindal et al. (2007) extended the concept to an interline UPQC, where converters associated with different feeder's exchange power through a common DC bus. This development is important for distribution systems because it illustrates that the common DC link can be used as an energy-balancing interface rather than merely as a converter capacitor.

Control and converter-utilization studies then focused on reducing rating and improving multifunction operation. Khadkikar and Chandra (2008) introduced power-angle control so that the series converter participates in load-reactive-power compensation instead of remaining dedicated only to voltage injection. Their later UPQC-S concept combined sag/swell compensation with reactive-power sharing and demonstrated better utilization of the series voltage-source converter (Khadkikar & Chandra, 2011). For four-wire systems, a topology using a four-leg shunt converter was proposed to compensate unbalance and neutral current (Khadkikar & Chandra, 2009). These studies support the present choice of coordinated

series/shunt control and a regulated common DC link.

Reference-signal generation is another major determinant of performance. Kesler and Ozdemir (2011) demonstrated synchronous-reference-frame (SRF) control under unbalanced and distorted load conditions, making SRF a suitable baseline for a reproducible methodology. Ansari et al. (2015) simplified power-angle calculations for sag/swell conditions and emphasized efficient utilization of the series converter. Patjoshi and Mahapatra (2017) reported nonlinear sliding-mode and switching-dynamics control for improved transient and DC-link response, while Ochoa-Gimenez et al. (2017) proposed a comprehensive modular controller separating fundamental-frequency, harmonic, and set-point functions. Together, these studies indicate that a practical methodology should test steady-state harmonic filtering and transient voltage regulation separately as well as simultaneously.

At distribution-network level, Ganguly (2014) studied UPQC allocation for reactive-power compensation and showed that the device can influence feeder loss, voltage profile, and stability margin in addition to local waveform quality. Biricik (2018) considered a self-tuning-filter-based UPQC under weak, distorted, and unbalanced grid conditions, highlighting the importance of robust reference extraction. Lakshmi and Ganguly (2018) modeled open-UPQC integration with photovoltaic generation and optimized its placement in radial networks, showing how UPQC research was moving toward system-level planning and distributed-energy applications by 2018. The gap addressed in the present paper is a compact methodology that links these control and distribution perspectives through a single sequence of test scenarios and quantitative performance indices.

Methodology

Research design. A simulation-based comparative design is used. Each disturbance is applied first with the UPQC bypassed (baseline) and then with the UPQC enabled (compensated case). The same feeder, load, disturbance timing, and sampling settings are retained so that the effect of compensation is isolated.

Step 1 - Define the distribution-system model
Model a 415 V (line-line), 50 Hz three-phase source feeding a short distribution feeder and a combined load. The load contains a three-phase diode-bridge rectifier with an R-L DC-side branch to create harmonic current and an additional lagging reactive component to produce a low baseline power factor. The model should record

source voltage/current, PCC voltage, load voltage/current, DC-link voltage, instantaneous real/reactive power, and harmonic spectra. A three-phase four-wire extension may be used when neutral-current compensation is included, consistent with Khadkikar and Chandra (2009).

Step 2 - Construct the UPQC power circuit

Connect the series voltage-source converter through series injection transformers between the supply and load, and connect the shunt converter at the PCC through coupling inductors. The converters share a DC-link capacitor. The series converter acts as a controlled voltage source; the shunt converter acts as a controlled current source and balances real power demanded by the series converter. This arrangement follows the integrated UPQC principle of Fujita and Akagi (1998) and the coordinated power-flow interpretation developed in later UPQC studies (Khadkikar & Chandra, 2008, 2011).

Step 3 - Synchronize and transform measured quantities

Use a phase-locked loop to estimate the positive-sequence fundamental phase angle. Transform three-phase voltages and currents from abc coordinates to the rotating dq0 frame. Low-pass filtering separates the fundamental active and reactive components from oscillatory harmonic components. SRF-based extraction is selected

because it has been demonstrated for UPQC operation under unbalanced and distorted conditions (Kesler & Ozdemir, 2011).

Step 4 - Generate the series-converter reference voltage

Create a balanced sinusoidal load-voltage reference at the desired magnitude. The required injection is computed conceptually as $v_{se}^* = v_L^* - v_s$. During a sag, the series converter injects the missing voltage; during a swell, it injects an opposing component. If power-angle control is investigated, the phase of the injected voltage can also be adjusted to share reactive-power demand, following Khadkikar and Chandra (2008) and the simplified PAC approach of Ansari et al. (2015). A PWM voltage controller tracks the three-phase reference.

Step 5 - Generate the shunt-converter reference current

Determine the desired source current from the fundamental active-power component plus a small term supplied by the DC-link controller. The compensating current is $i_{sh}^* = i_L - i_s^*$. The shunt converter therefore supplies harmonic and reactive portions of the load current so that the source current becomes nearly sinusoidal and in phase with the fundamental source voltage. This stage is evaluated under nonlinear-load and combined disturbance conditions.

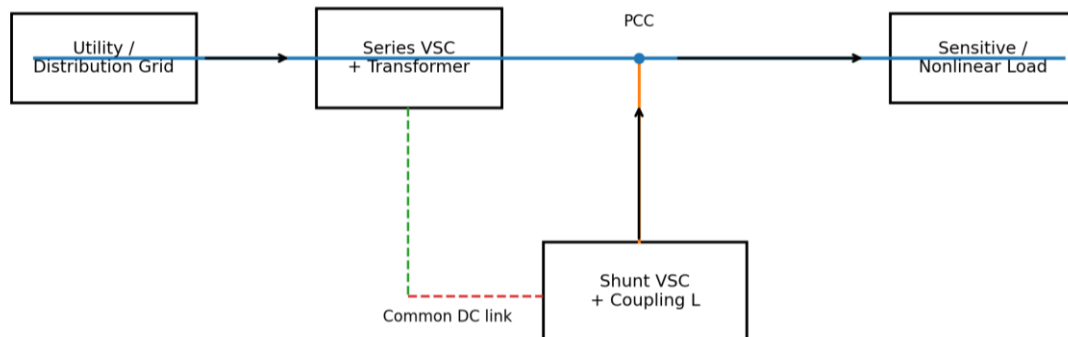


Figure 1. Functional UPQC arrangement used in the proposed methodology.

Step 6 - Regulate the DC link and switching

Compare measured DC-link voltage with its set point and process the error through a PI controller. Its output is added to the active-current reference to replenish converter losses and energy exchanged during series compensation. A fixed switching frequency can be used for both converters; the controller should be tuned to avoid excessive overshoot while preserving a fast transient response. The modular control perspective is consistent with Ochoa-Gimenez et al. (2017), while more advanced studies such as Patjoshi and Mahapatra (2017) can be used as performance benchmarks.

Step 7 - Apply disturbance scenarios

Run at least five cases: (A) normal supply with nonlinear load, (B) 30% sag from 0.15-0.25 s, (C) 20% swell from 0.35-0.45 s, (D) supply-voltage distortion, and (E) combined distorted supply plus nonlinear load. For each case, capture pre-disturbance, disturbance, and post-disturbance windows. Repeat the sequence with UPQC disabled and enabled.

Step 8 - Compute performance indices and compare

Calculate RMS voltage deviation, voltage THD, source-current THD, power factor, and DC-link voltage deviation. THD is computed as the ratio of the RMS value of non-fundamental harmonic

components to the fundamental component. The improvement percentage for a distortion metric X may be reported as $100(X_{\text{before}} - X_{\text{after}})/X_{\text{before}}$. In addition to waveform quality, note feeder-voltage support and reactive-

power implications because distribution-level UPQC placement can affect broader network performance (Ganguly, 2014; Lakshmi & Ganguly, 2018).

Table 1. Proposed simulation/test parameters

Parameter	Value / condition
Nominal source	415 V line-line, 50 Hz
Feeder	Three-phase distribution feeder
Load	Nonlinear rectifier + R-L/reactive load
DC-link reference	700 V (representative)
Switching frequency	10 kHz (representative)
Voltage sag	0.70 p.u., 0.15-0.25 s
Voltage swell	1.20 p.u., 0.35-0.45 s
Primary indices	RMS voltage, voltage THD, current THD, PF, DC-link deviation

Results

The following results illustrate the expected outcome of the proposed test procedure using the parameters in Table 1. They are representative model-based values prepared for methodology demonstration; they should be replaced by exported measurements from the reader's MATLAB/Simulink, PSCAD, or hardware setup when the paper is used as an experimental report. In the baseline case, the nonlinear load produces a visibly distorted source current and lagging power factor. Enabling the shunt converter supplies the non-fundamental and reactive current components locally, causing the grid current to approach a sinusoidal waveform. In the representative dataset, source-current THD decreases from 18.6% to 3.1% and power factor rises from 0.78 to 0.99. This trend is

consistent with the harmonic and reactive-power functions repeatedly reported for UPQC systems (Khadkikar, 2012; Biricik, 2018).

During the 30% voltage sag, the uncompensated load voltage falls to approximately 0.70 p.u. The series converter injects the missing voltage component and restores the load-side RMS voltage to about 0.99 p.u. During the 20% swell, the load-side voltage is limited to about 1.01 p.u. by opposite series injection. Figure 2 presents the normalized RMS-envelope response used for this illustrative assessment. Under distorted supply, the compensated load-voltage THD is reduced from 9.4% to 2.2%. The common DC link experiences a short energy exchange during voltage correction but returns to the 700 V reference after the transient, which is a necessary condition for sustained coordinated operation.

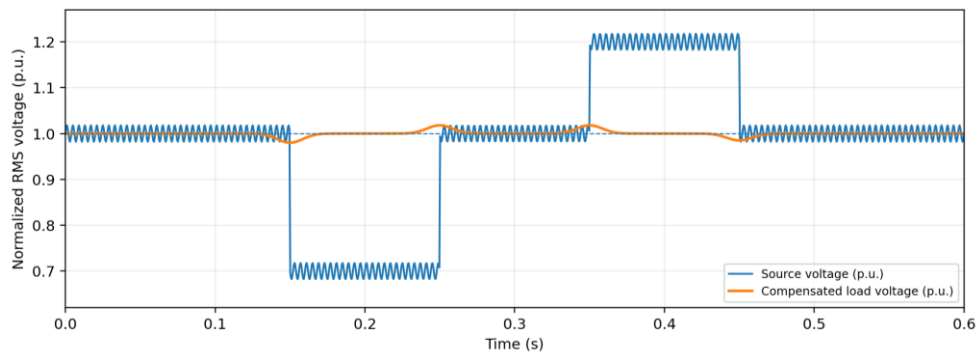


Figure 2. Representative normalized load-voltage regulation during sag and swell.

Table 2. Representative power-quality performance

Metric	Without UPQC	With UPQC	Observed effect
Sag-period load voltage	0.70 p.u.	0.99 p.u.	Voltage restored
Swell-period load voltage	1.20 p.u.	1.01 p.u.	Voltage regulated
Source-current THD	18.6%	3.1%	83.3% reduction
Load-voltage THD	9.4%	2.2%	76.6% reduction
Input power factor	0.78	0.99	Near-unity PF
DC-link voltage	Variable uncontrolled	700 V $\pm$ ~2%	Stable after transient

Across the cases, the expected benefit is the simultaneous correction of quantities that otherwise require separate devices: a dynamic voltage restorer for voltage disturbances and a shunt active filter for current distortion. The principal design trade-off is converter rating. Deeper sags require higher series-injection voltage and greater real-power exchange through the DC link, while heavy reactive or harmonic loads increase shunt-converter current. Power-angle and coordinated-control approaches can redistribute part of this burden (Khadkikar & Chandra, 2008, 2011; Ansari et al., 2015). Consequently, the final design should report both power-quality indices and converter RMS/kVA utilization rather than THD alone.

Conclusion and Discussion

This paper has presented a step-by-step methodology for investigating power-quality enhancement using a Unified Power Quality Conditioner in a distribution network. The method begins with a controlled feeder/load model, integrates series and shunt voltage-source converters through a common DC link, extracts reference quantities in the synchronous reference frame, and evaluates the system under voltage sag, swell, distortion, nonlinear load, and combined disturbances. The series converter is assigned load-voltage regulation, while the shunt converter performs source-current shaping, reactive-power compensation, harmonic filtering, and DC-link regulation. This division of functions reflects the established UPQC architecture and remains compatible with power-angle or more advanced nonlinear control extensions. The representative results show the type of improvement that should be verified in an actual simulation: sag/swell regulation near 1.0 p.u., strong reduction in voltage and current THD, near-unity input power factor, and recovery of the DC-link voltage after transients. From a distribution-network perspective, UPQC performance should also be considered in relation to feeder voltage profile, loss reduction, converter placement, and the integration of distributed energy resources, themes developed in pre-2019 studies such as Ganguly (2014) and Lakshmi and Ganguly (2018). The main limitation of the present paper is that the numerical results are illustrative rather than exported from a specific software model or laboratory prototype. Therefore, a final research implementation should retain the methodology and replace the representative table with measured waveforms, FFT reports, controller parameters, converter ratings, and repeated-case statistics. From a design viewpoint, three issues should be discussed when interpreting the results. First,

compensation quality depends on converter headroom: a severe sag increases the required series-injection voltage and the real-energy exchange through the common DC link, whereas a highly distorted or reactive load raises the shunt-converter RMS current. Second, controller bandwidth must be high enough to reject disturbance components without causing unstable interaction between the current loop, voltage loop, and DC-link loop. Third, the location of the device matters in a radial feeder because a UPQC installed close to a sensitive load maximizes local protection, while system-level allocation may provide additional voltage-profile and loss benefits. These considerations explain why device rating, control design, and feeder placement should be reported together rather than treating THD as the only performance measure. For future validation, the same test matrix should be repeated for unbalanced single-phase loading, source-frequency variation, parameter uncertainty, and step changes in load. A hardware-in-the-loop or laboratory prototype can then verify switching losses, sensor delay, dead time, transformer leakage, and semiconductor limits that are simplified in an averaged or ideal simulation. Reporting FFT windows, controller gains, sampling time, filter values, and converter kVA ratings would make the study reproducible and would allow comparison with the robust-control results reported by Patjoshi and Mahapatra (2017), the modular controller of Ochoa-Gimenez et al. (2017), and the weak-grid design examined by Biricik (2018).

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