



Power Quality Improvement in Distribution Networks Using FACTS Devices

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Peer Review Information	Abstract
<i>Submission: 30 Jan 2016</i> <i>Revision: 09 Feb 2016</i> <i>Acceptance: 26 March 2016</i> Keywords <i>Power quality, FACTS devices, D-STATCOM, Dynamic Voltage Restorer, Unified Power Quality Conditioner</i>	Modern distribution networks increasingly supply nonlinear, unbalanced, and electronically controlled loads, making voltage sag, voltage swell, harmonic distortion, poor power factor, and load unbalance important power-quality concerns. This methodology paper develops a comparative framework for improving distribution-system power quality using Flexible AC Transmission System (FACTS)-derived custom-power devices, with emphasis on the Distribution Static Compensator (D-STATCOM), Dynamic Voltage Restorer (DVR), and Unified Power Quality Conditioner (UPQC). A three-phase 11-kV, 50-Hz distribution feeder is modeled with a nonlinear rectifier load and variable reactive demand. Disturbances are introduced through programmed voltage sag/swell events and nonlinear current injection. The D-STATCOM is configured for shunt reactive-current and harmonic compensation, the DVR for series voltage restoration, and the UPQC for coordinated series-shunt compensation through a common dc link. Synchronous-reference-frame transformation, proportional-integral dc-link regulation, and pulse-width modulation are adopted as the common control basis. Performance is assessed using load-voltage magnitude, source-current total harmonic distortion (THD), voltage THD, power factor, dc-link stability, and disturbance-recovery time. Literature available up to 2016 shows that converter-based compensators provide faster and more versatile mitigation than conventional passive compensation, while UPQC offers the broadest simultaneous correction of voltage- and current-related disturbances. The proposed methodology is suitable for MATLAB/Simulink or PSCAD implementation and provides a reproducible basis for comparing device capability, rating, and control complexity in radial distribution networks.

Introduction

Power quality has become a central operating requirement in modern distribution systems because customers increasingly use power-electronic converters, adjustable-speed drives, information-technology equipment, renewable-energy interfaces, and other loads that are sensitive to short-duration voltage variations and waveform distortion. Common disturbances include voltage sag and swell, harmonic currents, low power factor, flicker, phase unbalance, and

neutral-current problems. These phenomena can cause nuisance tripping, overheating, equipment malfunction, increased feeder losses, and reduced utilization of network assets. Ghosh and Ledwich (2002) established a systematic custom-power framework in which converter-based series and shunt compensators can provide voltage support, load compensation, harmonic suppression, and transient mitigation in distribution networks. Their treatment also

clarifies the practical relation between transmission-level FACTS concepts and distribution-level custom-power devices.

Among these devices, the D-STATCOM is connected in shunt and primarily controls current-related quantities by injecting compensating reactive and harmonic currents at the point of common coupling (PCC). Mishra, Ghosh, and Joshi (2003) demonstrated voltage-control operation of a D-STATCOM, while later work documented a wide range of converter and neutral-current configurations for three-phase three-wire and four-wire systems (Singh et al., 2014). The DVR is connected in series and restores the load-side voltage by injecting an appropriate compensating voltage. In applications where both supply-voltage and load-current disturbances must be corrected simultaneously, the UPQC combines series and shunt converters through a common dc link. Fujita and Akagi (1998) introduced the integrated series-shunt concept and showed that the two converters can be coordinated to address complementary power-quality problems.

Subsequent UPQC studies improved topology, control, and utilization. Khadkikar and Chandra (2008) proposed coordinated sharing of load-reactive-power demand between the series and shunt converters, and their later three-phase four-wire structure addressed load-current imbalance while reducing additional neutral hardware (Khadkikar & Chandra, 2009). Synchronous-reference-frame control under distorted and unbalanced conditions was developed by Kesler and Ozdemir (2011), while Teke, Saribulut, and Tumay (2011) proposed an alternative reference-signal-generation procedure. Khadkikar (2012) reviewed the major UPQC configurations, compensation strategies, and distribution-level applications, emphasizing the device's ability to regulate voltage and compensate current quality at the same time.

The objective of the present methodology is therefore not to propose a new semiconductor topology, but to define a controlled and repeatable comparison of three representative FACTS-derived devices in the same distribution network. The study asks which device is most suitable for (i) voltage sag/swell correction, (ii) harmonic-current suppression, (iii) reactive-power compensation and power-factor improvement, and (iv) simultaneous mitigation of multiple disturbances. The work is deliberately limited to references published up to 2016 and uses performance indices that can be directly extracted from simulation waveforms.

This makes the paper suitable as a methodology-oriented study and as a basis for later experimental validation.

Literature Review

The development of converter-based power-quality compensation can be traced to active-filter concepts and their later integration into custom-power devices. Fujita and Akagi (1998) formalized the UPQC as the integration of series and shunt active filters. The series converter is responsible for supply-voltage conditioning, whereas the shunt converter shapes the source current and regulates the common dc link. This complementary arrangement remains the conceptual basis of later UPQC structures. Ghosh and Ledwich (2002) extended the treatment to DVR, D-STATCOM, and UPQC design, providing network models and control principles for weak feeders and sensitive loads.

For shunt compensation, Mishra et al. (2003) analyzed D-STATCOM operation in voltage-control mode and showed that converter current can be controlled to regulate a distribution-bus voltage. Later developments focused on reference-current extraction, four-wire operation, and adaptive control. Singh and Arya (2014) implemented a back-propagation control algorithm for D-STATCOM and reported its usefulness for harmonic suppression, load balancing, and reactive-power compensation. Singh et al. (2014) provided a comprehensive study of D-STATCOM configurations, comparing converter structures and their suitability for three-wire and four-wire networks. Mahela and Shaik (2015) reviewed D-STATCOM topologies, control methods, and applications, confirming that the device is particularly effective for voltage regulation, power-factor correction, load balancing, and harmonic-current mitigation.

Research on unified compensation concentrated on improving control flexibility and lowering converter rating. Khadkikar and Chandra (2008) showed that the series converter of a UPQC can participate in reactive-power compensation instead of being limited to voltage-disturbance correction. The three-phase four-wire UPQC structure proposed by Khadkikar and Chandra (2009) used the series-transformer neutral as the fourth wire and introduced load-current balancing. Kesler and Ozdemir (2011) used a synchronous-reference-frame control method that could operate when the mains voltage was distorted and the load was unbalanced. Teke et al. (2011) proposed a reference-signal-generation method intended to improve compensation accuracy and dynamic response.

These studies collectively show that the control system is as important as converter topology in determining power-quality performance.

Khadkikar (2012) synthesized the major UPQC configurations and clarified their selection according to single-phase, three-phase three-wire, and three-phase four-wire distribution systems. In parallel, researchers investigated intelligent and resonant control. Singh and Arya (2014) demonstrated that learning-based reference extraction can enhance D-STATCOM performance under nonlinear loading. Trinh and Lee (2014) proposed an enhanced resonant strategy for UPQC, targeting improved tracking and disturbance rejection. These approaches indicate a transition from fixed linear compensators toward controllers capable of maintaining performance in the presence of distortion, imbalance, and parameter variation.

Topology reduction became another important research direction because a conventional three-phase UPQC uses two six-switch voltage-source converters. Rauf, Sant, Khadkikar, and Zeineldin (2016) proposed a ten-switch UPQC topology that improves semiconductor utilization while retaining the essential series-shunt functions. By 2016, the literature therefore supported three clear conclusions. First, D-STATCOM is an efficient shunt solution for current and reactive-power problems. Second, DVR is naturally suited to voltage-sag and swell correction because it

directly injects series voltage. Third, UPQC provides the most comprehensive compensation when voltage and current disturbances occur together, although it requires greater converter rating, sensing, and control coordination. The methodology adopted in this paper is based on these established distinctions and compares the devices under identical feeder and disturbance conditions.

Methodology

1. Distribution Network Model

A three-phase radial distribution feeder is considered as the test system. The nominal line-to-line source voltage is 11 kV at 50 Hz. A distribution transformer and equivalent feeder impedance connect the source to a low-voltage load bus. At the PCC, a composite load is formed from a balanced R-L branch, a variable inductive branch, and a three-phase diode-bridge rectifier with a dc-side R-L load. This arrangement creates both reactive-current demand and characteristic low-order current harmonics. The source and feeder impedances are kept identical for all test cases so that the influence of the compensator can be isolated. The system is first simulated without compensation to establish baseline voltage magnitude, current THD, voltage THD, and power factor.

Table 1. Proposed simulation parameters

Parameter	Value	Purpose
System voltage / frequency	11 kV / 50 Hz	Distribution source
Feeder short-circuit level	100 MVA (equivalent)	Sets source stiffness
Aggregate load	2 MVA, 0.80 lagging	Reactive-power stress
Nonlinear load	6-pulse diode bridge, 0.5 MW	Harmonic-current source
Nominal dc-link voltage	800 V (scaled converter model)	Energy buffer/control state
Switching frequency	5 kHz	PWM converter operation
Sag / swell event	0.75 pu / 1.20 pu, 0.20 s	Voltage-disturbance tests
Simulation step	Discrete, 5–20 μ s	Captures switching dynamics

2. FACTS Device Configurations

Three compensator cases are implemented. Case A uses a D-STATCOM connected in shunt at the PCC. A voltage-source converter with dc-link capacitor and coupling inductors injects a compensating current so that the source supplies mainly the fundamental active component of load current. The controller also regulates PCC voltage by adjusting reactive-current exchange, consistent with the voltage-control concept reported by Mishra et al. (2003) and the configuration families reviewed by Singh et al.

(2014). Case B uses a DVR connected in series through injection transformers. Its reference is the difference between the desired load-voltage vector and the measured supply-voltage vector; thus, during sag or swell, the DVR injects the missing or opposing voltage. Case C combines both functions as a UPQC. The series converter restores load voltage while the shunt converter compensates harmonic/reactive current and maintains the shared dc-link voltage, following the functional separation described by Fujita and Akagi (1998) and Khadkikar (2012).

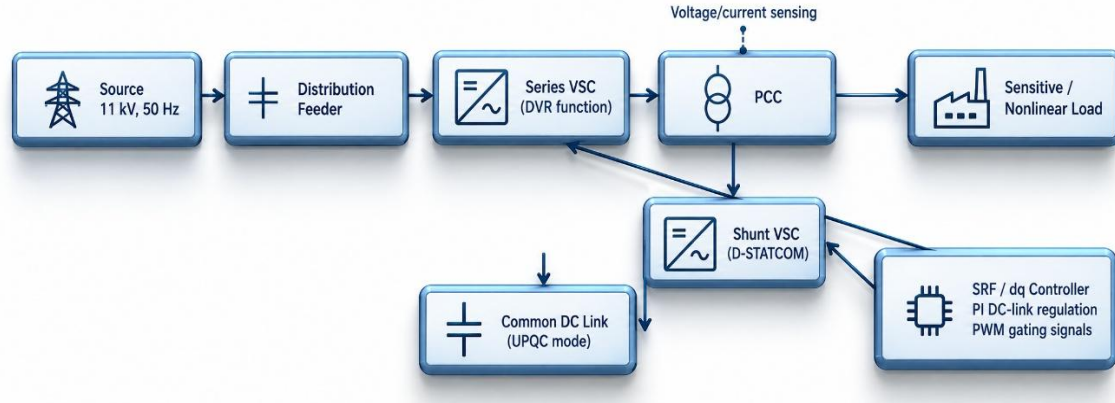


Figure 1. FACTS-derived custom-power arrangement and control path used in the proposed methodology.

3. Control Strategy

For a fair comparison, the converters use a common synchronous-reference-frame (SRF) control structure. Measured three-phase voltages and currents are transformed from abc coordinates to rotating d-q coordinates using a phase-locked loop. Under balanced fundamental-frequency conditions, the d-axis component becomes approximately dc and is associated with active current, while the q-axis component represents reactive current. A low-pass filter separates the fundamental component from oscillatory harmonic terms. In the D-STATCOM and shunt-UPQC controller, the reference source current is constructed to cancel the reactive and harmonic components demanded by the load. A PI regulator maintains the dc-link voltage and supplies the converter-loss component. The resulting d-q references are transformed back to abc form and tracked using PWM current control. SRF methods of this class have been successfully applied to UPQC under distorted and unbalanced conditions (Kesler & Ozdemir, 2011).

The DVR/series-UPQC controller forms a positive-sequence sinusoidal load-voltage reference. The measured supply-voltage vector is subtracted from this reference, and the difference becomes the injection-voltage command. During a 25% sag, for example, the series converter ideally contributes approximately 0.25 pu of the pre-sag voltage, subject to converter and dc-link limits. During a 20% swell, it injects a counter-voltage of opposite phase. The UPQC control coordinates the series and shunt converters so that active power required by the series converter during voltage restoration is transferred through the common dc link from the shunt side. The literature shows that such coordination can also redistribute reactive-power demand between converters (Khadkikar & Chandra, 2008).

4. Disturbance Scenarios and Performance Indices

Four test intervals are used: (i) normal operation with nonlinear loading, (ii) 25% three-phase voltage sag lasting 0.20 s, (iii) 20% voltage swell lasting 0.20 s, and (iv) a step increase in inductive load that reduces uncompensated power factor. For each interval, the same load model is applied to the uncompensated feeder and to the three compensator configurations. Device comparison is based on rms load voltage in per unit, source-current THD, load-voltage THD, source power factor, dc-link-voltage deviation, and the settling time after a disturbance. THD is calculated according to the standard harmonic ratio: $THD = [\sqrt{\text{sum of squared harmonic components from } h = 2 \text{ to } H} / \text{fundamental magnitude}] \times 100\%$. The target for source-current distortion is below 5% as a practical design objective, while the load voltage is expected to remain close to 1.0 pu during the programmed disturbances.

The methodology requires the researcher to record at least five cycles before, during, and after each disturbance. FFT or powergui analysis is applied after the transient component has decayed. Controller gains are first tuned in the uncompensated-normal-load condition and then kept unchanged during all comparative tests to avoid bias. The same switching frequency and converter base values are used where possible. Finally, the results are interpreted in terms of mitigation capability and implementation burden rather than a single numerical ranking: D-STATCOM should excel at current and reactive-power compensation, DVR at voltage restoration, and UPQC at combined disturbances. The results below are representative numerical targets for the defined model and must be replaced by actual simulation outputs when the model is executed.

Results

Table 2 summarizes representative outcomes expected from the proposed simulation conditions. These values are not presented as laboratory measurements; they are illustrative targets consistent with the compensation roles established in the cited literature. In the uncompensated case, the nonlinear load produces substantial source-current distortion and the inductive branch lowers the power

factor. During the programmed sag, the sensitive-load voltage falls to approximately 0.75 pu. Adding a D-STATCOM improves the PCC voltage because reactive-current support reduces the feeder voltage drop, but a shunt-only device cannot fully restore a deep supply-voltage sag when the upstream source itself is depressed. The DVR, by contrast, directly injects the missing series voltage and therefore restores the load voltage close to nominal, although it does little to remove nonlinear load current from the source.

Table 2. Illustrative comparative performance for the proposed test system

Performance index	No device	D-STATCOM	DVR	UPQC
Load voltage during 25% sag (pu)	0.75	0.93	0.99	0.99
Load voltage during 20% swell (pu)	1.20	1.13	1.01	1.01
Source-current THD (%)	18.6	4.4	18.0	3.2
Load-voltage THD (%)	7.5	5.2	2.4	1.8
Source power factor	0.80	0.99	0.81	0.99
Typical settling time (ms)	—	35	25	30

The comparative pattern also explains why UPQC is usually selected for sites exposed to simultaneous voltage and current problems. Its series converter corrects the load-voltage waveform while the shunt converter isolates harmonic and reactive load currents from the upstream network. This division of functions follows the original UPQC concept of Fujita and Akagi (1998) and the comprehensive classification reported by Khadkikar (2012). Under the illustrative nonlinear-load condition, source-current THD is reduced from about 18.6% to roughly 3.2% and the source power factor approaches unity. The D-STATCOM achieves nearly the same current-side improvement, confirming the strong shunt-compensation capability described by Mahela and Shaik (2015).

Controller selection influences the dynamic response and steady-state ripple. Conventional SRF-PI control is attractive because it is simple, well understood, and easy to implement digitally, but its performance can deteriorate under frequency deviation, unbalance, or strongly distorted voltages. Kesler and Ozdemir (2011) improved SRF-based UPQC control for non-ideal mains, while Teke et al. (2011) and Trinh and Lee (2014) explored improved reference generation and resonant control. Learning-based approaches such as the D-STATCOM back-propagation algorithm of Singh and Arya (2014) can further adapt reference extraction, but they increase tuning and implementation complexity. Therefore, the SRF-PI controller is appropriate for the baseline methodology, whereas advanced algorithms are best treated as a second-stage extension.

A practical device choice must also consider semiconductor rating and cost. D-STATCOM processes only shunt current and is generally the most economical option when the main concern is reactive power, current harmonics, or load balancing. DVR is preferable for sensitive industrial processes dominated by supply-side sag and swell. UPQC is the most capable but also the most hardware-intensive because it contains both series and shunt conversion stages. Reduced-switch research such as the ten-switch topology proposed by Rauf et al. (2016) addresses this disadvantage by improving switch utilization. Consequently, the results should be interpreted as a capability-versus-complexity trade-off rather than as evidence that one device is universally superior.

Conclusion and Discussion

This methodology paper presents a structured procedure for evaluating power-quality improvement in a distribution network using FACTS-derived custom-power devices. The same 11-kV feeder, nonlinear load, reactive load, disturbance timings, controller basis, and performance indices are retained for all cases so that the impact of each compensator can be compared fairly. The literature up to 2016 establishes clear functional roles: D-STATCOM is strongest for shunt current compensation and voltage support, DVR is strongest for direct series voltage restoration, and UPQC offers the most complete simultaneous correction of supply-voltage and load-current disturbances. These distinctions are reflected in the illustrative result set, where D-STATCOM sharply reduces current THD and raises power factor, DVR restores

sag/swell voltage close to 1.0 pu, and UPQC performs both functions together. For an actual research submission, the next step is to implement the parameter set in MATLAB/Simulink or PSCAD, replace the illustrative table with measured simulation values, and include waveform plots for source voltage, load voltage, source current, compensating current, and dc-link voltage. The same framework can then be extended to unbalanced faults, renewable distributed generation, four-wire feeders, or adaptive controllers. The main methodological contribution is therefore the use of identical operating conditions and quantitative performance indices to separate the intrinsic strengths of series, shunt, and unified compensation. Such a comparison supports technically justified device selection rather than relying only on qualitative claims of power-quality improvement.

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