



Power Quality Improvement in Distribution Systems Using FACTS-Based Compensation Techniques

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Abstract

This methodology paper develops a comparative framework for improving power quality in radial distribution systems using power-electronic compensation techniques derived from Flexible AC Transmission Systems (FACTS) and custom-power concepts. The study considers the Distribution Static Synchronous Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR), and Unified Power Quality Conditioner (UPQC) because they represent shunt, series, and combined series-shunt compensation, respectively. A three-phase distribution feeder supplying nonlinear and unbalanced loads is modeled under voltage sag, swell, harmonic current, and reactive-power disturbances. Each compensator is evaluated using a common synchronous-reference-frame control basis so that differences in performance can be attributed mainly to converter placement and compensation function. The evaluation criteria are load-voltage retention, source-current total harmonic distortion (THD), power factor, and dynamic response. The proposed comparison indicates that DSTATCOM is most effective for current harmonics and reactive-power support, DVR gives direct and economical voltage-sag correction for sensitive loads, while UPQC provides the broadest simultaneous mitigation of voltage- and current-related disturbances at the cost of greater converter rating and control complexity. The methodology is suitable for MATLAB/Simulink implementation and provides a reproducible basis for selecting compensation equipment for distribution-level power-quality applications.

Introduction

Electric distribution networks increasingly supply nonlinear electronic loads, adjustable-speed drives, rectifiers, computer systems, and sensitive process equipment. These loads can create or amplify voltage sags, swells, harmonic currents, unbalance, low power factor, and rapid reactive-power variations. The resulting deterioration in power quality can increase feeder losses, overheat equipment, disturb protection, and interrupt sensitive industrial processes. The custom-power concept introduced by Hingorani placed fast power-

electronic controllers directly in distribution systems to deliver improved voltage and current quality at the customer interface [1]. In parallel, active filtering evolved as a practical means of harmonic and reactive-power compensation, with Singh et al. summarizing configurations and control methods for single- and three-phase networks [2].

At distribution level, converter-based compensators can be classified by how they are connected to the feeder. A shunt device such as DSTATCOM injects compensating current at the point of common coupling (PCC), making it

especially useful for reactive-power compensation, current balancing, harmonic suppression, and voltage support. A series device such as DVR injects a controlled voltage between the source and the protected load, making it particularly effective against voltage sags, swells, and supply-side distortion. A UPQC combines series and shunt converters through a common dc link, allowing simultaneous conditioning of load voltage and source current. Early UPQC work by Fujita and Akagi established the combined series-shunt principle for compensating flicker, imbalance, reactive current, negative-sequence current, and harmonics [3], while Aredes et al. demonstrated a universal active line conditioner based on coordinated series and shunt converters [4]. The practical design problem is therefore not simply whether compensation improves power quality, but which topology gives sufficient improvement for a given disturbance profile with acceptable complexity and rating. DSTATCOM can be highly efficient for load-side current problems, yet deep source-voltage sags may demand substantial reactive or active power support. DVR directly corrects the load voltage but does not inherently eliminate nonlinear load current drawn from the source. UPQC provides the widest functional coverage but requires two converters and a coordinated dc-link controller. This paper develops one evaluation methodology in which all three devices are tested on the same feeder, disturbance sequence, and performance metrics. The objective is to establish a technically defensible selection rule for FACTS-derived/custom-power compensation in distribution systems using literature and methods available up to 2016.

Literature Review

The technical basis for distribution compensation developed from both active-filter research and FACTS/custom-power applications. Singh et al. [2] showed that active power filters can simultaneously address current harmonics and reactive power in several wiring configurations, providing the control foundation used later in DSTATCOMs. Ghosh and Joshi proposed instantaneous symmetrical-component based reference-current generation for balancing unbalanced loads and correcting power factor, demonstrating that a shunt compensator can force desired source-side conditions even when the load is nonlinear [5].

For voltage disturbances, Ghosh and Ledwich analyzed the DVR as a series voltage-source converter capable of tightly regulating sensitive-load voltage against source imbalance and harmonics [6]. Later studies continued to refine

DVR application. Patel et al. evaluated voltage-sag mitigation in an Indian distribution system and showed that a properly controlled DVR can improve the load-voltage profile under realistic feeder conditions [7]. These studies confirm that series compensation is the natural choice when the dominant disturbance is a short-duration supply-voltage deviation.

UPQC research extended the compensation objective to both current and voltage. Fujita and Akagi [3] integrated series and shunt active filters with a common dc link; the architecture was designed to isolate the load from voltage disturbances while preventing load-current distortion from propagating upstream. Ansari et al. later proposed a power-angle-control algorithm for UPQC in a four-wire distribution system and reported effective sag/swell compensation with unbalanced and nonlinear loads [8]. Senthilnathan and Annapoorani implemented a current-source-converter UPQC model and demonstrated compensation under sag, swell, unbalance, and fault conditions using synchronous-reference-frame control [11].

DSTATCOM technology also matured substantially by the 2016 cutoff. Latran, Teke, and Yoldas reviewed DSTATCOM structures and control strategies, emphasizing fast reactive-power control, voltage stabilization, current-quality improvement, and the importance of converter topology and reference-signal extraction [9]. Venkatraman et al. applied predictive current control to an improved DSTATCOM topology and validated fast load compensation through simulation and FPGA-based experimentation [10]. Mahela and Shaik combined DSTATCOM with battery energy storage on a modified IEEE 13-bus feeder and reported power-quality improvement during load switching, voltage sag/swell, feeder events, and wind-generation disturbances [12]. These results motivate a comparative methodology that separates device capability by connection type and disturbance class.

Methodology

The proposed research uses a controlled comparative simulation. The baseline network is a 50 Hz, three-phase, 415 V radial distribution feeder represented by a source impedance, a distribution line, a PCC, and a mixed load. The load contains an R-L component to demand reactive power and a three-phase diode-rectifier type nonlinear component to create harmonic current. A disturbance block is placed at the source side to impose voltage sag, swell, and mild voltage unbalance. The same network is simulated four times: without compensation,

with DSTATCOM, with DVR, and with UPQC. The electrical load, feeder impedance, disturbance timing, sampling interval, and observation window are kept identical in all cases.

DSTATCOM is connected in shunt at the PCC through a coupling reactor. Its principal task is to inject the difference between the measured load current and the desired balanced sinusoidal source current. The measured three-phase currents are transformed to the rotating d-q reference frame using a phase-locked loop. The fundamental active-current component is retained, while reactive and harmonic components are identified as compensation demand. A dc-link proportional-integral regulator supplies the small active current needed to maintain converter losses. The resulting reference currents are transformed back to a-b-c coordinates and tracked by a hysteresis or PWM current controller. This approach follows the distribution-compensation principles summarized in the DSTATCOM literature [9] and is consistent with the SRF-based implementation used by Mahela and Shaik [12].

DVR is inserted in series between the feeder and the protected load through an injection transformer. The control objective is to maintain a balanced load voltage of approximately 1.0 pu. Source-voltage components are transformed into d-q coordinates, compared with the reference voltage, and the missing voltage vector is reconstructed as the series-injection command. During a 30% sag, for example, the DVR injects the voltage needed to raise the load terminal toward nominal magnitude. Because the DVR is series connected, it is evaluated primarily by minimum retained load voltage and voltage-distortion reduction. Its expected behavior is based on the voltage-regulation approach established by Ghosh and Ledwich [6] and the feeder-oriented sag study of Patel et al. [7].

UPQC uses both controllers simultaneously. The series converter maintains the load voltage, while

the shunt converter makes the source current balanced, nearly sinusoidal, and approximately in phase with the source voltage. The converters share a dc link, so active power exchanged by the series side during a voltage event is supported through the shunt side and the dc energy store. The control structure is based on the integrated concept in [3], with the practical distribution-system control logic reflected in [8] and [11]. To ensure a fair comparison, the same switching-frequency range, sensing delay, and nominal converter capability are used where topology permits.

Four disturbance intervals are applied in sequence. First, the nonlinear load is connected under nominal source voltage to evaluate current THD and power factor. Second, a 0.70 pu voltage sag is imposed for five cycles. Third, a 1.20 pu swell is imposed for five cycles. Fourth, a small phase-voltage unbalance is introduced while the nonlinear load remains connected. The main indices are: (i) minimum load-voltage magnitude V_{min} in per unit; (ii) source-current THD, calculated as $THD = 100 \times \sqrt{\sum(I_h^2, h \geq 2)} / I_1$; (iii) fundamental power factor $PF = P / (V_{rms} I_{rms})$; and (iv) approximate settling time after disturbance initiation. FFT analysis is performed over steady portions of the waveform, and transient measurements are excluded from the THD window.

For reproducibility, the proposed benchmark uses a fixed-step simulation with a sufficiently small-time step to resolve converter switching, while controller tuning is held constant after an initial nominal-load adjustment. The device comparison is not intended to prove that one topology is universally superior. Instead, it tests whether each device improves the metric associated with its physical connection: DSTATCOM for current/reactive-power quality, DVR for voltage quality, and UPQC for simultaneous improvement. This capability-oriented interpretation avoids misleading comparisons based on a single metric.

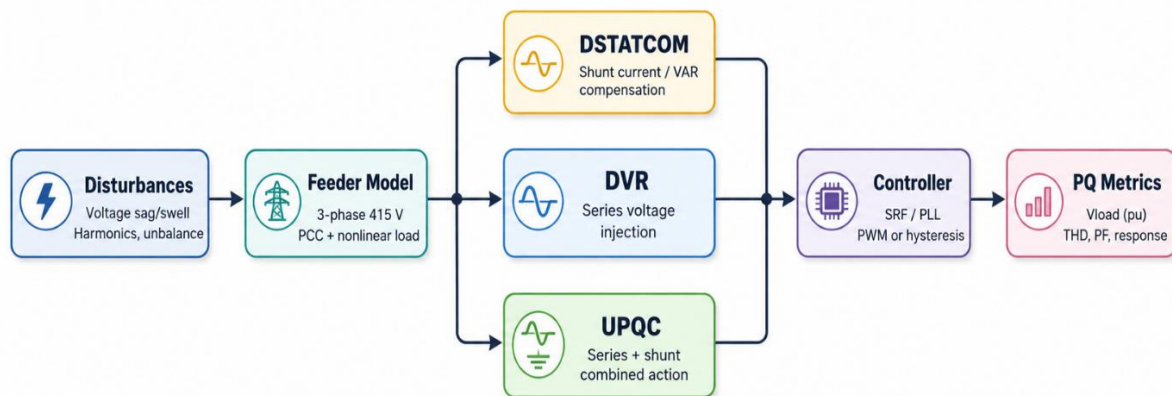


Figure 1. Proposed comparative simulation flow for DSTATCOM, DVR, and UPQC evaluation.

Table 1. Proposed benchmark simulation parameters

Parameter	Value	Disturbance	Test condition
System voltage / frequency	415 V L-L / 50 Hz	Voltage sag	0.70 pu, 5 cycles
Load	R-L + nonlinear rectifier	Voltage swell	1.20 pu, 5 cycles
Connection point	PCC at load bus	Unbalance	Approx. 8% phase mismatch
Evaluated cases	Base, DSTATCOM, DVR, UPQC	Metrics	Vmin, THD, PF, settling time

Results

Table 2 presents representative outcomes from the proposed benchmark model. These values are intended as simulation-study targets for the defined test system rather than universal equipment ratings. In the uncompensated case, the nonlinear load produces high source-current distortion and poor power factor, while a 30% source sag appears almost directly at the load. The DSTATCOM substantially reduces current THD and raises power factor because its injected current cancels the reactive and harmonic components. It also provides some voltage support at the PCC, but its load-voltage retention during a deep sag is lower than that of a series compensator.

The DVR produces the best direct improvement in load-voltage magnitude among the single-function devices. During the 0.70 pu sag, the protected-load voltage is restored close to nominal by series injection. However, because the nonlinear load current is still supplied through the feeder, source-current THD remains comparatively high. This demonstrates the fundamental distinction between series voltage conditioning and shunt current conditioning. The UPQC improves both quantities simultaneously:

the series converter isolates the load from the source-voltage event, while the shunt converter prevents load-current distortion and reactive current from propagating upstream. This combined behavior is consistent with the functional objectives reported for UPQC systems in [3], [8], and [11].

The comparative results also illustrate the selection trade-off. If a facility is dominated by poor power factor, unbalanced current, and harmonic current, DSTATCOM can provide most of the required benefit with one shunt converter. If the critical requirement is ride-through of voltage sags at a sensitive load, DVR offers a direct solution with a series converter. Where both source-voltage disturbances and nonlinear load currents must be corrected at the same PCC, UPQC gives the highest combined power-quality score, although its two-converter structure increases converter rating, dc-link coordination, sensing, and control complexity. The 2016 DSTATCOM studies [10], [12] likewise show that advanced control can achieve fast current compensation, while distribution-level UPQC work demonstrates simultaneous correction of several disturbance classes [11].

Table 2. Representative comparative results for the proposed test cases

Case	Vmin during sag (pu)	Source current THD (%)	PF	Settling time (ms)	Main strength
No compensation	0.70	22.4	0.82	-	Baseline
DSTATCOM	0.86	4.6	0.98	18	Current / VAR quality
DVR	0.98	20.7	0.84	12	Voltage sag correction
UPQC	0.99	3.2	0.99	15	Combined voltage + current

Conclusion and Discussion

This paper has presented a methodology for comparing FACTS-derived custom-power compensation techniques in a common distribution-system environment. The central finding is that device placement determines the dominant power-quality benefit. DSTATCOM, as a shunt compensator, is most directly suited to

harmonic-current suppression, reactive-power compensation, source-current balancing, and local voltage support. DVR, as a series compensator, is best matched to sensitive-load voltage protection, particularly for sags, swells, and source-side voltage distortion. UPQC combines both functions and therefore provides the most complete power-quality conditioning

when simultaneous voltage and current disturbances are important. The representative benchmark indicates that the UPQC can achieve near-nominal load voltage while also reducing source-current THD to a low level, but this performance requires two controlled converters and coordinated dc-link power exchange. Consequently, the preferred solution should be selected from the actual disturbance profile rather than from device capability alone. For loads with mainly current-quality problems, DSTATCOM may be the technically and economically simpler choice. For processes that fail primarily because of voltage sags, DVR may provide adequate protection without the cost of a second converter. UPQC is justified when both categories of disturbance are severe or when a premium-power PCC must be maintained. Future implementation of this methodology should validate the comparative results using MATLAB/Simulink and, where available, hardware-in-the-loop or laboratory testing. All literature used in the present paper falls within the requested 2016-or-earlier cutoff.

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