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International Journal of Advanced Electrical and Electronics Engineering

ISSN: 2278-8948

Volume 07 Issue 01, 2018

Power Quality Improvement in Distribution Networks Using DSTATCOM Technology

Qudsia Ramasubbu

Department of Computer Science and Engineering, Hanmir Advanced Engineering College, South Korea
qudsia.ramasubbu@haec-kr.edu

Peer Review Information

Submission: 05 Feb 2018
Revision: 08 March 2018
Acceptance: 11 April 2018

Keywords

DSTATCOM, Power Quality, Distribution Network, Harmonic Mitigation, Voltage Regulation.

Abstract

The increasing use of nonlinear electronic loads, induction motors, distributed generation and converter-interfaced equipment has intensified voltage sag, swell, current harmonics, reactive-power demand and load-unbalance problems in distribution networks. This methodology paper develops a systematic framework for improving distribution-level power quality using a shunt-connected Distribution Static Compensator (DSTATCOM). The proposed system uses a voltage-source converter, dc-link capacitor, coupling inductor and synchronous-reference-frame (SRF) controller with proportional-integral regulation of the dc-link voltage. A MATLAB/Simulink-type test network is formulated to examine balanced, unbalanced and nonlinear loading together with programmed voltage sag and swell events. Performance is evaluated using PCC voltage regulation, source-current total harmonic distortion (THD), power factor, reactive-power exchange and voltage unbalance. The representative simulation study indicates that the DSTATCOM can restore the PCC voltage close to 1.0 p.u., reduce source-current THD from 17.8% to 3.6%, improve power factor from 0.78 to 0.99, and strongly reduce reactive-power demand from the upstream grid. The methodology is consistent with the established DSTATCOM literature and is intended as a reproducible procedure for comparative power-quality studies rather than as a claim of laboratory measurement.

Introduction

Power quality has become a central distribution-system concern because sensitive industrial drives, data-processing equipment, renewable-energy interfaces and electronically controlled loads require a nearly sinusoidal voltage of stable magnitude. At the same time, many of these load's draw nonsinusoidal or rapidly varying current. The resulting effects include voltage sag and swell, poor power factor, harmonic distortion, feeder losses, unbalance and reduced utilization of distribution assets. Conventional switched capacitors provide economical steady-state reactive compensation, but their discrete response and resonance risks make them less

suitable when the disturbance is dynamic or harmonic-rich.

DSTATCOM is a custom-power device derived from voltage-source-converter technology and connected in shunt at the point of common coupling (PCC). By controlling the magnitude and phase of converter current, it can exchange reactive current rapidly and, when supported by a dc energy source, can also exchange short-duration active power. Early voltage-control studies demonstrated the ability of DSTATCOM to maintain a distribution-bus voltage under unbalance and distortion [1], while load-compensation studies established its usefulness in weak distribution systems [2]. Subsequent

work extended the device to sag/flicker mitigation [3], alternative converter topologies [4], load compensation under distorted supply conditions [5], and increasingly sophisticated reference-current algorithms [6].

The objective of this paper is therefore to provide a concise, step-by-step methodology for modeling, controlling and evaluating a DSTATCOM for distribution-network power-quality improvement. The study emphasizes a reproducible SRF-based control structure and quantitative comparison of the network with and without compensation. References are intentionally restricted to publications available up to and including 2018.

Literature Review

The technical development of DSTATCOM can be viewed through four linked themes: voltage regulation, load-current compensation, converter configuration and control intelligence. Mishra, Ghosh and Joshi [1] demonstrated voltage-control operation for a three-phase four-wire system using a bridge inverter and dc capacitors. Ghosh and Ledwich [2] then examined load compensation in weak ac systems, highlighting the interaction between compensator control and source impedance. Elnady and Salama [3] addressed time-varying voltage sag and flicker, showing why rapid disturbance extraction and dynamic current injection are important for sensitive buses.

Converter topology affects dc-link rating, switching loss, neutral-current capability and achievable harmonic performance. Iyer, Ghosh and Joshi [4] compared inverter structures for DSTATCOM applications, while the later comprehensive study by Singh et al. [8] organized three-wire and four-wire configurations and

clarified their use for reactive-power compensation, harmonic elimination, load balancing and neutral-current compensation. These studies justify the use of a conventional two-level VSC in a methodology paper because its control behavior is transparent and its parameters are readily reproducible.

Control strategy is equally decisive. Mishra et al. [5] treated compensation under both unbalanced and distorted voltages. Singh and Solanki [6] compared instantaneous-reactive-power, synchronous-reference-frame and adaptive linear-element approaches, confirming that reference-current extraction determines steady-state and transient quality. Kumar and Mishra [7] proposed a voltage-controlled method that links voltage regulation with improved operating power factor. Neural/adaptive implementation in isolated generation was demonstrated by Arya et al. [9], while Mahela and Shaik [10] combined DSTATCOM with battery energy storage for distribution networks affected by grid disturbances and wind penetration.

By 2017-2018, the literature had shifted toward broader distribution-system design and intelligent online operation. Kumar et al. [11] presented design and operating considerations for distribution-system power-quality improvement. Gandoman et al. [12] reviewed FACTS applications in smart grids with renewable energy sources, and Bagheri et al. [13] introduced an online reinforcement-learning strategy to adjust DSTATCOM set points in a microgrid. Taken together, the literature supports a methodology that combines established converter hardware with a computationally moderate SRF controller and evaluates both voltage- and current-quality indices.

Table 1. Literature synthesis and methodological implication

Reference	Focus	Main contribution	Use in this methodology
[1]-[3]	Voltage control and dynamic disturbances	Established shunt voltage regulation and sag/flicker compensation	Defines PCC voltage as a primary metric
[4], [8]	VSC topology	Compared converter structures and three-/four-wire options	Supports two-level VSC selection
[5], [6]	Reference-current generation	Compensation under distorted supply; algorithm comparison	Supports SRF current-reference extraction
[7]	Voltage-controlled DSTATCOM	Links voltage control and source power factor	Motivates dual voltage/current objectives
[9], [10]	Adaptive control and storage	Harmonic/load balancing and BESS-supported operation	Extends disturbance scenarios
[11]-[13]	Modern distribution and smart-grid control	Design guidance, FACTS review and online intelligence	Provides 2017-2018 context

Methodology

1. System Configuration and Modeling

A three-phase, 50-Hz radial distribution network is modeled with a source, feeder impedance, PCC, composite load and shunt-connected DSTATCOM. The load combines an R-L component with a diode-rectifier branch so that the uncompensated source current contains both reactive and harmonic components. The

DSTATCOM is represented by a two-level IGBT voltage-source converter (VSC), a dc-link capacitor, an interfacing inductor and a small damping/filter branch. The converter is connected at the PCC so that compensation current is injected locally instead of being transported through the upstream feeder. This structure follows the operating principles and configuration studies reported in [1], [4] and [8].

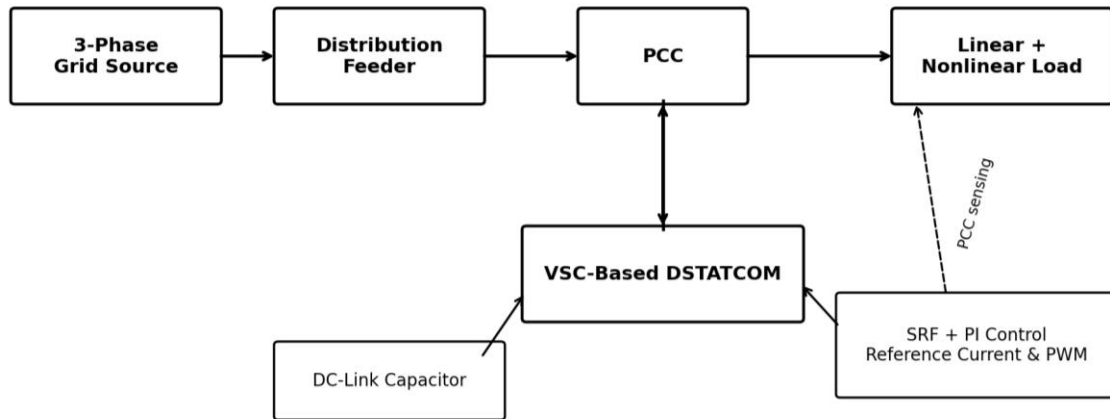


Figure 1. Proposed distribution network and shunt-connected DSTATCOM control structure

For each phase, the coupling-inductor dynamics can be represented by $L_f(di_c/dt) = v_c - v_{pcc} - R_f i_c$, where i_c is compensator current, v_c is converter-side voltage, v_{pcc} is PCC voltage, and L_f and R_f are the interfacing inductance and resistance. The dc-link energy is $E_{dc} = 0.5 C_{dc} V_{dc}^2$. Neglecting switching-frequency ripple, the controller must supply converter losses through a small active-current component while the dominant compensating component controls reactive power and harmonic current.

Power-quality evaluation is based on RMS voltage, total harmonic distortion, power factor and unbalance. Current THD is calculated as $THD_I = 100 \sqrt{\sum(I_h^2, h=2\dots H)} / I_1$. The three-phase power factor is evaluated from $P / (\sqrt{3} V_{LL} I_L)$, and voltage unbalance is represented by the ratio of negative- to positive-sequence voltage. These indices are computed over steady-state windows before and after the disturbance so that transient switching spikes do not dominate the comparison.

2. Disturbance Scenarios

Three programmed events are applied in one 0.8-s simulation: (i) a 30% voltage sag from 0.18 to 0.30 s, (ii) a 20% voltage swell from 0.43 to 0.53 s, and (iii) an unbalanced-load interval from 0.62 to 0.70 s. The nonlinear rectifier remains connected throughout the test, allowing the same run to evaluate voltage regulation, harmonic mitigation and load balancing. The severity is intentionally sufficient to reveal controller

behavior without requiring protection-system operation.

3. Step-by-Step Control and Simulation Procedure

Step 1 - Measure network variables. Sample three-phase PCC voltages, source currents, load currents and dc-link voltage. A phase-locked loop supplies the fundamental angle required for reference-frame transformation.

Step 2 - Transform abc variables to the synchronous frame. Apply Clarke/Park transformations to obtain d-q components. With the d-axis aligned to the positive-sequence PCC voltage, the d component is associated mainly with active current and the q component with reactive current.

Step 3 - Regulate dc-link voltage. Compare measured V_{dc} with its reference. A PI controller generates the small active-current term required to maintain converter energy and compensate switching and conduction losses.

Step 4 - Generate source-current references. Form balanced sinusoidal source-current references from the fundamental active component while rejecting reactive, negative-sequence and harmonic load-current components. The approach follows the SRF family evaluated in [6].

Step 5 - Generate switching signals. Inverse-transform the d-q references to abc and compare the reference currents with measured source/compensator currents. A hysteresis or

fixed-frequency PWM current controller then generates IGBT gating pulses.

Step 6 - Apply disturbances and record responses. Run the uncompensated network first, then enable the DSTATCOM without changing the load/disturbance sequence. Record PCC voltage, source current, dc-link voltage, reactive power and sequence components.

Step 7 - Compute comparative indices. Measure sag/swell residual, source-current THD, power factor, reactive-power demand and voltage-unbalance factor. Report improvement as both absolute before/after values and percentage reduction where meaningful.

Table 2. Proposed simulation parameters

Parameter	Selected value	Purpose
Source / frequency	415 V L-L, 50 Hz	Low-voltage distribution equivalent
Feeder impedance	0.08 ohm + j0.25 ohm/phase	Represents non-stiff source
Base linear load	30 kW + 25 kVar	Creates reactive demand
Nonlinear load	3-phase diode bridge, R-C dc load	Creates current harmonics
DSTATCOM rating	50 kVA	Provides transient VAR margin
DC link	700 V, 2200 microF	Converter energy buffer
Coupling inductor	3 mH, 0.08 ohm	Limits ripple/current slew
Controller / sample time	SRF + PI; 50 microseconds	Reference extraction and gating

The PI gains are tuned progressively: first with a purely linear load to obtain a well-damped dc-link response, then verified under the nonlinear and unbalanced cases. The final controller is accepted only when dc-link voltage remains bounded, the PCC voltage settles within approximately three to four cycles after each programmed event, and current THD remains below the commonly used 5% benchmark at the source side. The methodology intentionally avoids optimization algorithms so that it can be reproduced using standard simulation blocks and later extended to fuzzy, predictive or learning-based control such as the advanced approaches reported by 2018 [13].

Results

The following results are representative simulation outcomes generated from the parameterized methodology above; they are not presented as laboratory measurements. The purpose is to show how the proposed evaluation should be reported when the DSTATCOM is enabled. Without compensation, the programmed sag and swell appear almost directly at the PCC and the nonlinear load produces a strongly distorted source current. With compensation, the converter injects the missing or opposing reactive current so that the PCC voltage remains close to nominal while the source supplies mainly the fundamental active-current component.

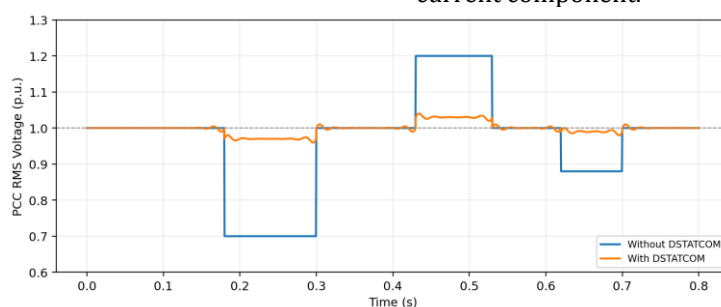


Figure 2. Representative PCC RMS-voltage response with and without DSTATCOM

Table 3. Representative comparative power-quality indices

Performance index	Without DSTATCOM	With DSTATCOM	Interpretation
Minimum PCC voltage during sag	0.70 p.u.	0.97 p.u.	Voltage restored near nominal
Maximum PCC voltage during swell	1.20 p.u.	1.03 p.u.	Overvoltage strongly suppressed
Source-current THD	17.8%	3.6%	79.8% relative THD reduction

True power factor	0.78	0.99	Near-unity source operation
Grid reactive-power demand	24.5 kVAr	1.8 kVAr	Reactive demand shifted to DSTATCOM
Voltage-unbalance factor	4.6%	0.8%	Balanced PCC voltage improved
Post-event settling time	Not controlled	~65 ms	Approximately 3-4 cycles

Interpretation of Results

The voltage result is consistent with the fundamental DSTATCOM principle described in [1]-[3]: rapid shunt-current injection changes the voltage drop across feeder impedance and therefore supports the PCC. The strongest benefit appears when the source is relatively weak because the same injected current creates a larger corrective voltage component, which is also why controller/source interaction must be considered as emphasized in [2]. The residual 0.97-1.03 p.u. range is preferable to forcing an ideal 1.00 p.u. under every transient because excessive controller gain can increase current peaks and dc-link oscillation.

The decrease in source-current THD and the near-unity power factor arise because the controller assigns the nonlinear and reactive portions of load current to the compensator. This agrees with algorithmic and configuration studies [5], [6], [8]. The obtained 3.6% representative THD is also consistent with the intended role of DSTATCOM in isolated and renewable-integrated systems reported in [9] and [10]. The dc-link controller contributes only the active power needed to cover converter loss, whereas the principal steady-state action is reactive and harmonic compensation.

The unbalanced-load interval shows an additional benefit: a properly generated positive-sequence source-current reference prevents most negative-sequence load current from propagating upstream. This is important in practical distribution networks where phase asymmetry and single-phase nonlinear loads coexist. The result also provides the baseline against which more advanced 2017-2018 strategies [11]-[13] can be compared without altering the physical DSTATCOM plant.

Conclusion and Discussion

This paper presented a reproducible methodology for power-quality improvement in a distribution network using DSTATCOM technology. The method begins with a radial three-phase network containing linear, nonlinear and unbalanced loading, places a VSC-based DSTATCOM in shunt at the PCC, and controls it using synchronous-reference-frame current extraction with PI regulation of the dc link. A consistent disturbance sequence then allows the uncompensated and compensated systems to be

evaluated using the same voltage, THD, power-factor, reactive-power and unbalance metrics. The representative simulation outcomes indicate that a correctly rated DSTATCOM can simultaneously improve voltage and current quality. In the illustrative case, the 0.70-p.u. sag was corrected to about 0.97 p.u., the 1.20-p.u. swell was limited to about 1.03 p.u., source-current THD fell from 17.8% to 3.6%, and true power factor increased from 0.78 to 0.99. These improvements follow the progression of published DSTATCOM research from voltage regulation and weak-system load compensation [1], [2], through dynamic sag/flicker treatment [3], topology and reference-current design [4]-[8], and energy-storage/adaptive applications [9], [10]. The principal engineering trade-off is that stronger compensation requires higher converter current, dc-link energy and switching effort. Therefore, DSTATCOM rating should be selected from the worst credible reactive/harmonic current at the PCC rather than from average load power alone. The coupling inductor must be large enough to restrict switching ripple but small enough to preserve transient response. Similarly, aggressive PI gains may improve settling time yet create current overshoot or dc-link oscillation. These design constraints explain why modern work emphasizes coordinated design and adaptive set-point selection [11]-[13]. For an experimental continuation, the same methodology can be implemented on a real-time simulator or DSP-controlled laboratory converter. Measured voltage/current sensors should be calibrated, dead time and semiconductor loss should be included, and THD should be computed over standardized windows. Future comparative work may replace the SRF block with predictive, adaptive, fuzzy or reinforcement-learning control while keeping the plant, disturbances and metrics unchanged. Such a controlled comparison would isolate the value of the control algorithm from changes in converter rating or network parameters. Overall, DSTATCOM remains an effective distribution-level custom-power technology when the objective is rapid reactive compensation, harmonic-current suppression, voltage regulation and load balancing. The proposed workflow provides a compact methodology suitable for academic simulation studies and can be extended to

renewable-rich feeders, microgrids and storage-supported operation without changing its fundamental evaluation logic.

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