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Comparative Assessment of Dynamic Voltage Restorer and D-STATCOM for Voltage Sag and Swell Mitigation in a Distribution Network

Okafor Emmanuel Chigbo[1], Anionovo Ugochukwu Edebeani[2*], Charles Austeen Ibeh[3], Anazia Emmanuel Aninye[4]

[1,2,4]Department of Electrical Engineering, Nnamdi Azikiwe University Awka.

[3]Department of Forensic Sciences, Nnamdi Azikiwe University Awka.

Abstract: *Power quality disturbances, particularly voltage sag and swell, can adversely affect sensitive loads, industrial processes and the reliability of modern distribution systems. This study presents a comparative simulation-based assessment of two power-electronic mitigation devices: the Dynamic Voltage Restorer (DVR) and the Distribution Static Synchronous Compensator (D-STATCOM). A three-phase distribution network was developed in MATLAB/Simulink at 415 V and 50 Hz, with the principal disturbance represented as a severe voltage sag of 0.7 p.u. The DVR was modeled as a series-connected voltage-source converter with a 100 V dc link, 1 mH filter inductance and 1 µF filter capacitance, while the D-STATCOM was modeled as a shunt-connected converter using a 200 V dc bus and coupling interface. Performance was evaluated using load-voltage recovery, total harmonic distortion (THD), dynamic response, overshoot and ripple. The results show that the DVR restored the load voltage to 1.00 p.u., corresponding to 100% recovery, while the D-STATCOM restored it to approximately 0.96 p.u. or 96% recovery. THD decreased from 12.5% before compensation to 2.1% with the DVR and 5.8% with the D-STATCOM, representing reductions of 83.2% and 53.6%, respectively. The measured simulation response times were approximately 2 ms for the DVR and 5 ms for the D-STATCOM. The normalized aggregate technical-performance ranking gave the DVR 64.3% and the D-STATCOM 35.7%. An indicative published cost benchmark cited in the thesis gives lower equipment cost for D-STATCOM, making it attractive where reactive-power support and general voltage regulation are more important than precise deep-sag restoration. The study therefore concludes that the DVR is the stronger technical option for sensitive-load voltage restoration, while the D-STATCOM provides a lower-cost alternative for general voltage support.*

Keywords: Power quality; Voltage sag; Voltage swell; Dynamic Voltage Restorer; D-STATCOM; MATLAB/Simulink; Total Harmonic Distortion; Voltage recovery.

1. INTRODUCTION

Electric power systems are expected to supply electrical energy within acceptable voltage, frequency and waveform limits so that connected equipment can operate reliably. In practice, faults, switching operations, nonlinear loads, renewable-energy interfaces and network limitations produce deviations from ideal conditions. Power quality therefore remains an important engineering concern, particularly in networks containing sensitive electronic and automated loads [5], [7].

Among the major power-quality disturbances, voltage sag and voltage swell are especially important because they are short-duration variations in RMS voltage that can interrupt industrial processes, cause nuisance tripping and affect sensitive control equipment. Voltage sag is commonly associated with short circuits, motor starting, transformer energization and fault-clearing operations, whereas swell represents a temporary increase in RMS voltage [5]. The increasing penetration of power-electronic equipment and renewable-energy converters can introduce additional waveform disturbances and voltage variations if appropriate filtering and control are not provided [4].

Several mitigation technologies have been developed to address these problems. Passive and active filters can reduce harmonic distortion, while Flexible AC Transmission System (FACTS) and custom-power devices provide rapid voltage and reactive-power compensation. The Dynamic Voltage Restorer (DVR) is connected in series with a feeder and directly injects a compensating voltage. The Distribution Static Synchronous Compensator (D-STATCOM), in contrast, is connected in shunt and regulates the point-of-common-coupling voltage through controlled current and reactive-power exchange [11].

The central problem addressed in the present work is the persistence of voltage disturbances and the need to select an appropriate mitigation device according to the actual technical and economic requirement. The thesis from which this article is derived specifically investigated voltage sag and swell mitigation using DVR and D-STATCOM, mathematically modeled the disturbances, developed a sample facility distribution system in MATLAB/Simulink and evaluated the effect of the two devices on system performance. The study was simulation-based and focused on controlled disturbance conditions rather than field measurements.

The contribution of this article is a concise, quantitative comparison of the two devices under a common modeling framework. Instead of relying only on qualitative descriptions such as excellent or good, the assessment uses voltage recovery, THD reduction, response time and an aggregate normalized technical-performance ranking. The economic discussion is deliberately treated as a contextual benchmark rather than a site-specific Nigerian quotation.

2. MATERIALS AND METHODS

2.1 Simulation Environment and System Configuration

The study employed MATLAB/Simulink with the Simscape Electrical/SimPowerSystems environment. The simulation model comprised a three-phase AC source, feeder impedance, point of common coupling (PCC), load, disturbance mechanism, voltage and current measurement blocks, converter interfaces and control systems. The network was configured at 50 Hz, consistent with the Nigerian power-system frequency, and the nominal supply voltage was 415 V. The modeled facility load for the principal DVR case was 3 kW. The DVR used a 100 V dc link, 1 mH filter inductance, 1 µF filter capacitance and a 1:1 series transformer. The feeder branch included 0.1 Ω resistance and 0.5 mH inductance, with a 60 mH line inductance also specified in the simulation parameters.

Table 1: Principal simulation parameters and compensation configurations.

Parameter	DVR model	D-STATCOM model
Supply voltage	415 V	415 V
Frequency	50 Hz	50 Hz
Principal connection	Series	Shunt
Converter interface	Series transformer	Coupling reactor/interface
DC bus	100 V	200 V
Filter/interface	1 mH, 1 µF LC filter	Coupling interface
Load used in reported model	3 kW	20 kW
Main compensation variable	Injected voltage	Reactive current / power

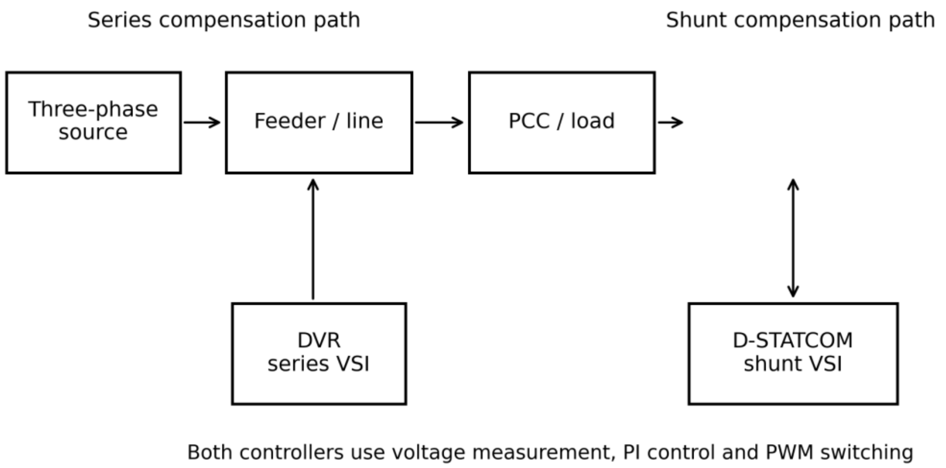

Figure 1: Simplified representation of the series DVR and shunt D-STATCOM compensation paths.

2.2 Mathematical Representation of the Disturbance

The balanced three-phase source was represented by sinusoidal phase voltages as shown in equation (1) to (3)

$$V_{a(t)} = V_m \sin(\omega t) \quad (1)$$
$$V_{b(t)} = V_m \sin(\omega t - 120°) \quad (2)$$
$$V_{c(t)} = V_m \sin(\omega t + 120°) \quad (3)$$

where V_m is the peak phase voltage and ω = 2πf. At 50 Hz, the angular frequency is 314.16 rad/s. Voltage sag was modeled by multiplying the normal waveform by a factor k_s less than unity during the disturbance interval as shown in equation (4):

$$V_{sag(t)} = k_s V_m \sin(\omega t + \varphi), \quad t_1 \le t \le t_2 \quad (4)$$

For the severe comparative case, the load voltage was reduced to approximately 0.7 p.u. A swell was represented by a multiplier k_{sw} greater than unity. The disturbance was applied for a defined interval so that the controller response could be evaluated separately from normal operation.

2.3 DVR Control and Compensation Principle

The DVR was implemented as a series-connected voltage-source converter. Under normal conditions, the controller detects a small voltage error and the required injection is close to zero. During a sag, the measured supply voltage falls below the reference. The error is processed by the PI controller and converted to a modulation signal, after which the PWM generator produces switching pulses for the VSI. The converter output passes through the LC filter and series transformer before being injected into the feeder. The simplified compensation relationship is shown in equation (5).

$$V_{inj} = V_{ref} - V_s \quad (5)$$

where V_{inj} is the compensating series voltage, V_{ref} is the desired load voltage and V_s is the measured supply voltage. The series connection makes the DVR particularly suitable for direct restoration of a sensitive load voltage.

2.4 D-STATCOM Control and Compensation Principle

The D-STATCOM was modeled as a shunt voltage-source converter. Its purpose was to regulate the PCC voltage through controlled current exchange. When the measured PCC voltage was below its reference, the controller commanded capacitive support; when the voltage exceeded the reference, the controller commanded inductive support. The device therefore acted as a dynamic reactive-power source or sink. Unlike the DVR, the D-STATCOM does not directly insert a compensating voltage in series with the feeder; it changes the network voltage through current and reactive-power exchange.

2.5 Performance Indicators and Ranking

Performance was evaluated using load-voltage recovery, THD, response time, overshoot and ripple. THD was used to quantify waveform distortion, while response time represented the speed with which the controller corrected the disturbance. The normalized percentage ranking in the underlying thesis treated higher voltage recovery and higher THD reduction as better, while shorter response time was better. For two values A and B, a higher-is-better share was calculated as A/(A+B) × 100. For lower-is-better quantities, inverse normalization was applied. Overshoot and ripple were qualitative in the supplied results; they were therefore converted only to ordinal analytical scores and were not presented as measured physical percentages.

2.6 Economic Assessment

The economic assessment used two levels of evidence. First, the project classified DVR as a high-cost and higher-complexity device and D-STATCOM as a medium-cost and lower-complexity alternative. Second, the thesis cited an external benchmark of approximately USD 153.30/kVAr for DVR and USD 79.55/kVAr for D-STATCOM, with a 5% annual maintenance assumption for both devices. The benchmark implies an approximately 48.1% lower installation cost for D-STATCOM in that reference case. These figures are not treated as Nigerian procurement prices because actual cost depends on rating, voltage level, transformer arrangement, converter technology, installation work and supplier.

3. RESULTS AND DISCUSSION

3.1 Voltage Restoration Performance

The uncompensated severe disturbance reduced the modeled load voltage to approximately 0.7 p.u. The DVR restored the load voltage to 1.00 p.u., corresponding to 100% voltage recovery. The D-STATCOM restored the voltage to approximately 0.96 p.u., corresponding to 96% recovery. The difference demonstrates the advantage of direct series voltage injection when the principal requirement is accurate restoration of a sensitive load voltage.

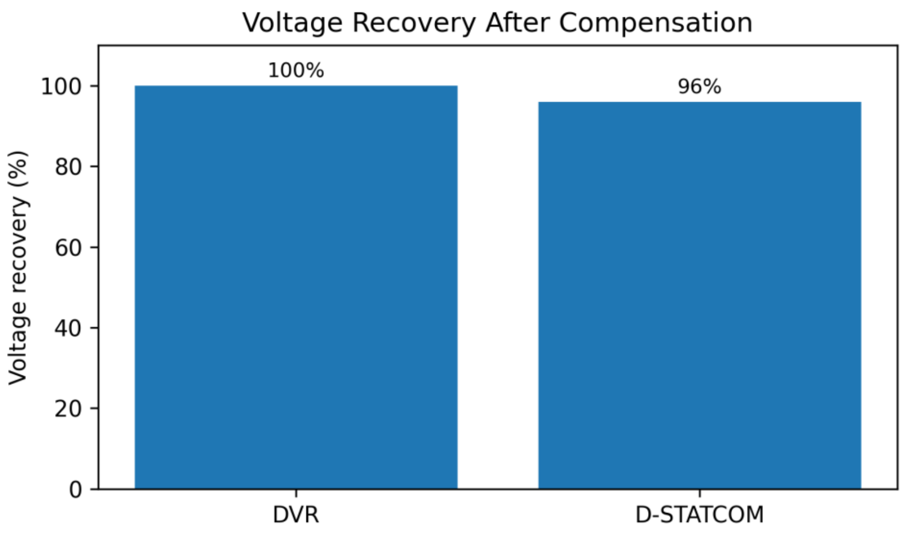

Figure 2: Voltage recovery obtained with the two compensation devices.

Table 2: Principal comparative simulation results.

Indicator	DVR	D-STATCOM
Sag depth	0.7 p.u.	0.7 p.u.
Load voltage before compensation	0.7 p.u.	0.7 p.u.
Load voltage after compensation	1.00 p.u.	0.96 p.u.
Voltage recovery	100%	96%
THD before compensation	12.5%	12.5%
THD after compensation	2.1%	5.8%
Response time	2 ms	5 ms
Overshoot	Very Low	Moderate
Ripple content	Very Low	High

3.2 Harmonic Distortion Performance

The initial THD reported for the comparative case was 12.5%. Following compensation, the DVR reduced THD to 2.1%, giving an 83.2% reduction. The D-STATCOM reduced THD to 5.8%, corresponding to a 53.6% reduction. Thus, the DVR provided the lower residual distortion and the larger reduction under the modeled conditions. The result is consistent with the different compensation mechanisms: the DVR directly controls the voltage injected into the feeder, whereas the D-STATCOM primarily supports the PCC through reactive current exchange.

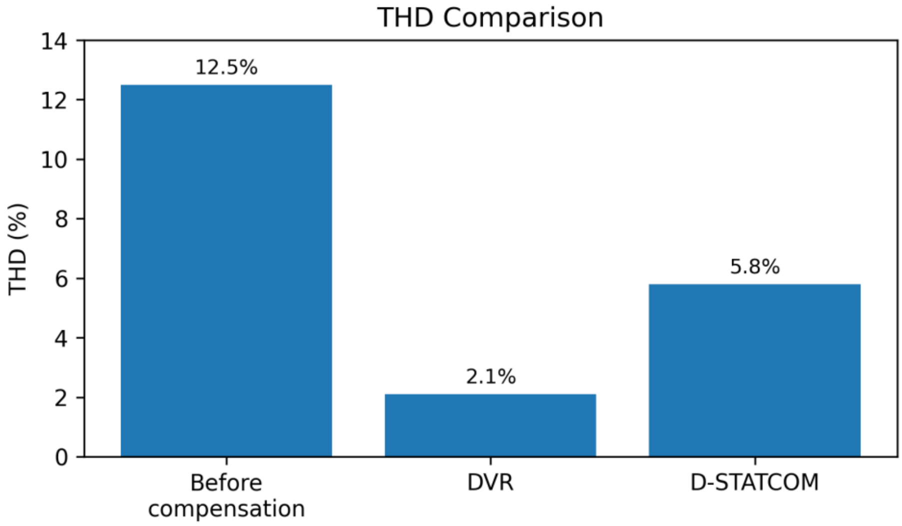

Figure 3: THD before compensation and after DVR or D-STATCOM compensation.

3.3 Dynamic Response

The simulated response time was approximately 2 ms for the DVR and 5 ms for the D-STATCOM. The faster DVR response is important for sensitive loads because a short disturbance can still interrupt automated processes or electronic equipment. The result also supports the use of fast series compensation where precise voltage restoration is the dominant requirement.

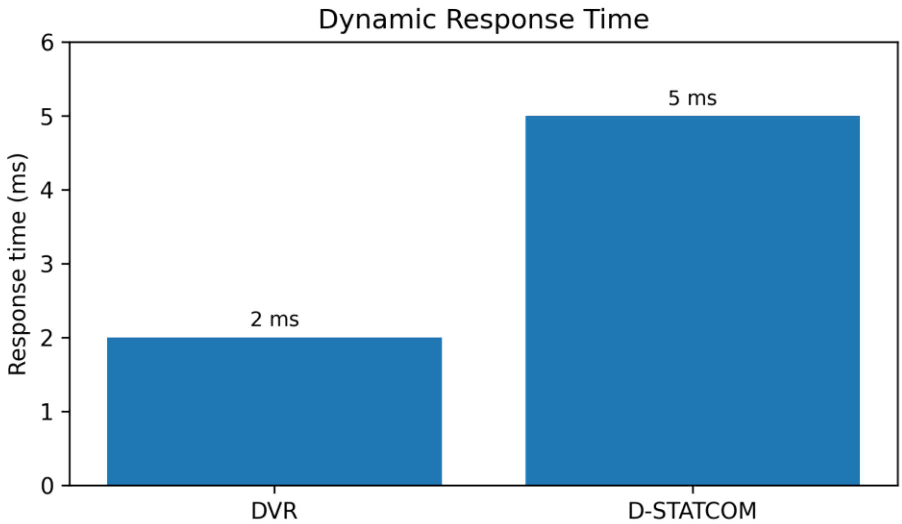

Figure 4: Reported dynamic response times of the two devices.

3.4 Aggregate Technical Ranking

The normalized ranking combined six indicators: load-voltage performance, voltage recovery, THD reduction, THD after compensation, response speed, and qualitative overshoot/ripple scores. The resulting aggregate technical-performance share was approximately 64.3% for the DVR and 35.7% for the D-STATCOM. The ranking is an analytical normalization of the reported indicators and should not be interpreted as a physical percentage of device efficiency or market share.

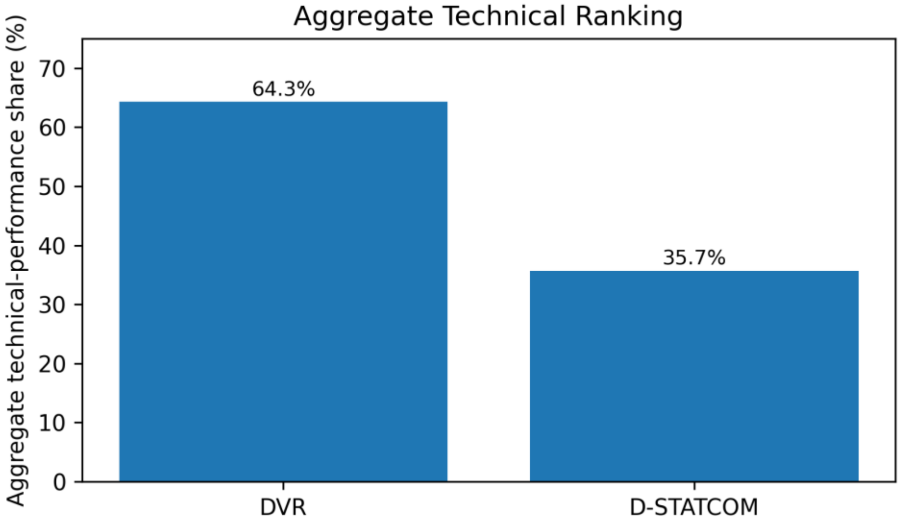

Figure 5: Aggregate normalized technical-performance ranking.

3.5 Economic and Practical Interpretation

The technical and economic results do not identify the same device as universally preferable. The DVR has the stronger performance where the objective is accurate, rapid restoration of a sensitive load voltage. Its series transformer, converter, dc link and filtering arrangement, however, increase system complexity and capital requirements. The D-STATCOM provides shunt reactive-power support and general voltage regulation with lower implementation complexity. The cited benchmark in the thesis indicates substantially lower equipment cost for D-STATCOM, but this should be treated only as contextual evidence rather than a project quotation.

From an application perspective, a critical industrial facility containing PLCs, adjustable-speed drives, control systems or other sensitive loads can justify the additional DVR cost if voltage-sag consequences are severe. Conversely, a distribution network whose dominant requirement is voltage support, reactive-power management and moderate disturbance correction may obtain greater value from a D-STATCOM. This application-specific interpretation is more appropriate than selecting a device solely on the basis of one performance indicator.

3.6 Discussion of Findings

The findings agree with the established operating principles of custom-power devices. A DVR is intrinsically suited to voltage restoration because its compensation path is in series with the feeder. The controller can therefore synthesize the missing voltage component and place it directly between the source and load. A D-STATCOM operates through a shunt converter and influences the PCC voltage by controlling current and reactive-power exchange. Its effectiveness consequently depends more strongly on the network impedance and available reactive-power capability. The simulation results show this distinction clearly: both devices improved the disturbance, but the DVR produced the closer voltage recovery, lower THD and faster response.

The study should nevertheless be interpreted within its methodological limits. The results were generated from a MATLAB/Simulink model under controlled conditions, not from field measurements. The D-STATCOM and DVR models also used different converter/interface parameter sets because the underlying project models were developed with different ratings. Therefore, the numerical comparison demonstrates performance under the specified modeled conditions rather than establishing universal superiority for every possible hardware configuration. Experimental or hardware-in-the-loop validation would strengthen the practical applicability of the findings.

4. CONCLUSION

This study presented a comparative assessment of DVR and D-STATCOM for voltage sag and swell mitigation in a modeled distribution network. The investigation used MATLAB/Simulink to represent a 415 V, 50 Hz three-phase system and evaluated the devices using voltage recovery, THD, response time and normalized technical-performance indicators. The results showed that the DVR restored the load voltage from a severe 0.7 p.u. sag to 1.00 p.u., while the D-STATCOM restored it to approximately 0.96 p.u. The DVR reduced THD from 12.5% to 2.1%, whereas the D-STATCOM reduced it to 5.8%. Their response times were approximately 2 ms and 5 ms, respectively.

The aggregate normalized technical-performance ranking favored the DVR at 64.3%, compared with 35.7% for the D-STATCOM. The DVR was therefore the preferred technical solution for precise and rapid voltage restoration in the investigated case. The D-STATCOM, however, remained attractive for general voltage support and reactive-power compensation because of its lower implementation complexity and the lower equipment-cost benchmark reported in the underlying study. The appropriate selection is consequently application-dependent.

Future work should validate the simulation results using real-time simulation or hardware-in-the-loop platforms and investigate coordinated operation of DVR, D-STATCOM, energy storage and intelligent controllers under combined disturbances such as sag, swell, harmonic distortion, flicker and unbalanced loading. Site-specific procurement and lifecycle-cost studies are also required before either device is selected for practical deployment.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During preparation of this article, AI-assisted drafting and formatting tools may have been used to organize and condense material from the supplied thesis. The technical content, numerical results and interpretations were grounded in the supplied thesis, and the authors remain responsible for verification of the final manuscript before submission.

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