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A Review on the IEEE 9-Bus System Using STATCOM and FACTS Devices

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Abstract: Power quality issues in electrical systems are a significant concern for researchers and engineers. The increased use of power electronic circuits has improved the efficiency and performance of various equipment. However, these circuits also draw non-sinusoidal currents, which increases harmonics and reduces power quality. Furthermore, many electronic devices are sensitive to power quality problems. Advanced electronics, however, can be employed to mitigate these issues. The Distribution Static Synchronous Compensator (D-STATCOM) is a Custom Power Device (CPD) designed for this purpose. D-STATCOMs can be developed using various topologies, algorithms, and control techniques to address specific power quality issues in power systems. The design of a D-STATCOM depends on the particular power quality issue it aims to resolve. This paper provides a comprehensive review of the D-STATCOM, tracing its development from inception to its current applications.

Index Terms— FACTS, Reactive Power Compensation, D-STATCOM, CPDs.

I. INTRODUCTION

Power quality (PQ) issues significantly impact the reliability and efficiency of distribution systems. The growing use of nonlinear loads in various applications—including office and home equipment, medical devices, fluorescent lighting, renewable energy systems, high-frequency transformers, and arc furnaces—has led to increased harmonics and a decline in power quality. Additionally, unbalanced loads distort voltage waveforms in distribution systems, which affects the performance of sensitive equipment. Numerous PQ issues, such as harmonic pollution, poor power factor, noise, voltage sags, swells, impulses, unbalance, and fluctuations, can be effectively mitigated using Custom Power Devices (CPDs). CPDs represent an advanced generation of solutions for power quality issues, building on the success of Flexible AC Transmission Systems (FACTS) in enhancing power system stability, transfer capacity, and transmission line efficiency. Leveraging cutting-edge power electronics technology, CPDs are widely recognized as effective tools for addressing power quality challenges.

CPDs are classified into network reconfiguration devices and compensation devices. Network reconfiguration devices include the Static Current Limiter (SCL), Static Transformer Switch (STS), Solid State Breaker (SSB), and Uninterruptible Power Supply (UPS). Compensation devices include the Dynamic Voltage Restorer (DVR), Distribution STATCOM (D-STATCOM), and Unified Power Quality Conditioner (UPQC), which are connected to the system in series, parallel, or hybrid configurations, respectively.

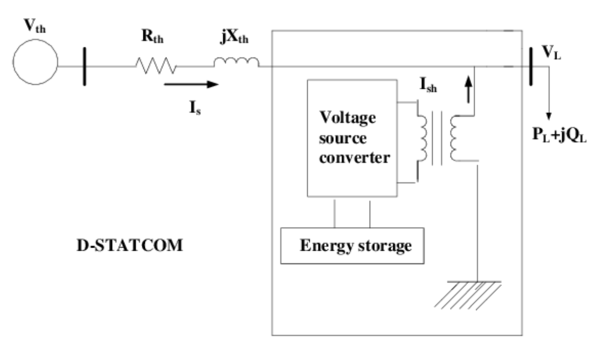

Figure 1 D-STATCOM System Configuration

The D-STATCOM is a synchronous voltage generator capable of providing both capacitive and inductive reactive power. With a very short response time—limited only by the power-electronic devices and detection time—it operates much faster than traditional voltage correction techniques like tap-changing transformers. Among CPDs, the D-STATCOM is widely used to address power quality issues such as poor power factor, poor voltage regulation, harmonics, increased neutral currents, and unbalanced currents.

The D-STATCOM operates in two control modes: current control mode, which injects the appropriate harmonic and reactive components of load current to address current-related issues; and voltage control mode, which regulates voltage to protect the load from voltage-related disturbances. The performance of a D-STATCOM is influenced by the control algorithm used to estimate reference current components, with the specific configuration determined by the power quality issue being addressed.

A D-STATCOM is built on either a voltage source converter (VSC) or a current source converter (CSC) and functions as a reactive power source within power systems. It regulates the voltage at the point of common coupling (PCC) by injecting or absorbing reactive power as needed. Key components of a D-STATCOM include a voltage converter, DC energy storage unit, injection transformer, and control unit. The AC voltage output of the D-STATCOM (Vc) is adjusted to achieve the desired voltage level. When the system voltage (Vs) at the PCC is higher than the target voltage, the D-STATCOM absorbs reactive power; conversely, if the system voltage is lower, it injects reactive power to boost the voltage. When the system voltage matches the desired level, the D-STATCOM neither injects nor absorbs reactive power.

II. RELATED WORK

The concept of Custom Power Devices (CPDs) was first introduced by Hingorani in 1995. Since then, extensive research has focused on the study of D-STATCOM, expanding its applications, and developing control strategies to enhance its performance in mitigating various power quality problems. This literature review traces the evolution of D-STATCOM research, highlighting key studies and identifying research gaps over time.

In 1996, S. Ramsay et al. explored the application of D-STATCOM for voltage regulation on voltage-limited, long feeders. Their findings demonstrated that D-STATCOM could serve more load and cover greater distances on voltage-limited feeders than conventional methods. The device's fast response significantly improved voltage regulation, enhancing power quality for customers served by long feeders or sensitive loads.

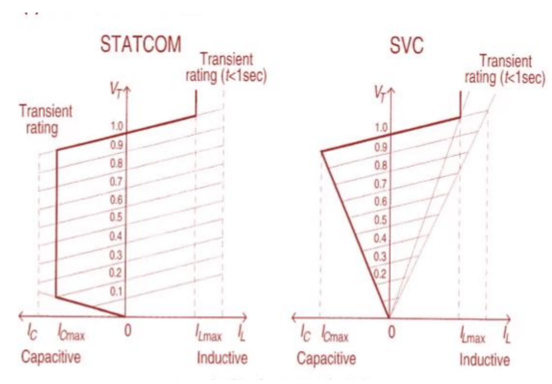

Figure 2 STATCOM and SVC VI Characteristics

In 1999, G. Moon proposed a voltage and current control technique for D-STATCOM using space vector PWM and a predictive scheme. Comparisons with other current control techniques showed that the proposed method produced less harmonic distortion and faster transient responses, making it superior for power factor correction.

In 2000, G.F. Reed et al. tested a 5 MVA, 4.16 kV D-STATCOM at a steel recycling facility to mitigate voltage flicker caused by a 4000 HP shredder motor. The results indicated that fast reactive power compensation improved voltage regulation and power factor control, effectively reducing voltage flicker and other disturbances.

In 2001, M. Haque compared the steady-state performance of D-STATCOM and the Dynamic Voltage Restorer (DVR) under various voltage drops, system failures, and load levels. The simulations showed that D-STATCOM could correct more severe voltage drops than DVR, underscoring its effectiveness.

In 2004, S. Bashi et al. developed a 12-pulse D-STATCOM prototype to mitigate voltage sag in an unbalanced distribution system. Using a PI controller to manage reactive power flow, their simulations confirmed that D-STATCOM significantly improved power quality.

In 2006, J. Wang et al. introduced a new control method for D-STATCOM based on source current detection under imbalanced conditions. Their proposed scheme, simpler and requiring lower computational power than traditional decoupled control, demonstrated excellent performance in such conditions.

In 2008, Z. Xi et al. integrated an Ultra-capacitor (UCAP) with a D-STATCOM system, finding that UCAP effectively regulated voltage during system faults, maintaining stable D-STATCOM voltages and preventing over currents and tripping.

In 2010, N. Ismail et al. improved power factor, reduced voltage sag, and minimized harmonic distortion using D-STATCOM with LCL Passive Filters. Simulations showed substantial power quality improvements, with THD reduced to within IEEE standards and power factor nearly one.

In 2013, S. Mohamed et al. studied E-STATCOM, a STATCOM integrated with a Battery Energy Storage System (BES). Using a PI controller, simulations of various disturbances showed improved transient and dynamic stability, reduced active power oscillation, and THD maintained within IEEE standards.

In 2014, F. Shahnia et al. analyzed the effectiveness of DVR and D-STATCOM in improving voltage unbalance in feeders with rooftop PVs. Their Monte Carlo stochastic analysis indicated that D-STATCOM provided better results than DVR, reducing voltage imbalance to within standard limits.

In 2015, A. Gupta and A. Kumar applied a variational technique to optimize the size and location of D-STATCOM in radial distribution systems. Their MATLAB-based research demonstrated significant loss reduction and voltage profile improvement, with the optimized D-STATCOM size being lower than those in previous studies.

In 2017, A. Majed et al. employed Differential Evolution to realize Harmonic Elimination PWM (HE-PWM) for direct D-STATCOM control. Their analysis, compared with phase-shifted PWM, showed that HE-PWM required a smaller coupling inductor and successfully eliminated low-order harmonics, providing a rapid dynamic response.

In 2018, W. Rohouma et al. proposed using inductors as energy storage in a D-STATCOM system with a Matrix Converter and model predictive control technique. Their simulations demonstrated that this approach offered effective reactive power compensation and greater reliability than traditional capacitor-based systems.

In 2019, I. Mehouachi et al. designed a high-powered D-STATCOM using an isolated-dual converter topology. Practical experiments showed stable DC vector voltages and balanced currents between VSCs, eliminating the need to oversize converters' power ratings.

In 2020, S. Duarte et al. developed a time-domain strategy to estimate voltage imbalance caused by consumer load variations, enabling a D-STATCOM-based 3-phase-4-wire system to compensate effectively under various scenarios.

In 2020, E. Kantar and E. Tedeschi designed a D-STATCOM with a 4-wire inductor-capacitor-inductor (LCL) filter for neutral current compensation, load balancing, reactive power compensation, and harmonic elimination. Their design effectively addressed resonance issues while maintaining voltage and THD levels below 3% for nonlinear and unbalanced loads.

In 2021, M. Ullah and A. Hanif proposed a control scheme using a second-order super twisting algorithm with sliding mode control for the D-STATCOM converter. Simulations demonstrated effective mitigation of voltage sags and swells, with THD maintained below 5%.

In 2022, B. Khan optimized the placement and sizing of D-STATCOM in radial distribution systems using the improved bacterial foraging search algorithm (IBFA), resulting in significant power loss reduction, voltage profile improvement, and enhanced stability.

In 2022, A. Abdelsalam introduced a modified D-STATCOM design with a proposed current controller for microgrid applications, effectively managing balanced and unbalanced loads and improving power factor, voltage stability at the PCC, and reducing harmonic currents during islanding incidents.

In 2022, A. Özer developed a novel control algorithm for D-STATCOM to regulate voltage in self-excited induction generator (SEIG)-based wind energy systems. The enhanced phase-locked loop based on a current synchronous detection (CSD) algorithm effectively filtered SEIG voltage from harmonics, DC offset, and frequency deviations, outperforming existing methods under varied load conditions.

Table 1: Comparison of Various FACTS Devices

Feature	STATCOM	SVC	TCSC	UPFC
Type	Shunt compensator	Shunt compensator	Series compensator	Combined compensator
Reactive Power Control	Fast and precise	Slower than STATCOM	Moderate	Fast and versatile
Harmonic Generation	Low	High	Moderate	Moderate
Cost	High	Moderate	High	Very high
Stability Improvement	Good	Moderate	Excellent	Excellent
Applications	Voltage regulation, power quality improvement	Voltage stability	Power flow control	Comprehensive control of voltage, power flow, and stability

This table provides an overview of different FACTS devices like STATCOM, SVC, TCSC, and UPFC, comparing them based on type, reactive power control, harmonic generation, cost, stability improvement, and applications. It highlights STATCOM's strengths and limitations compared to other devices. This helps justify the choice of STATCOM for the IEEE 9-Bus System.

Table 2: IEEE 9-Bus System: Bus Parameters

Bus Number	Bus Type	Voltage (pu)	Angle (degrees)	Load (MW)	Generation (MW)
1	Slack Bus	1.04	0	0	72.3
2	Load Bus	1.02	-4.98	163	0
3	Generation Bus	1.01	-12.72	0	85.0

This table lists the parameters of each bus in the IEEE 9-Bus System, including voltage, angle, load, and generation at each bus. It establishes the initial conditions and power distribution across the network, providing a foundation for the system's analysis and STATCOM’s impact on each bus.

Table 3: Performance of STATCOM with Different Control Strategies

Control Strategy	Voltage Stability	Power Factor Improvement	Reactive Power Support	Response Time
PI Control	Moderate	Good	Limited	Moderate
Fuzzy Logic Control	Good	Excellent	High	Fast
Neural Network-Based Control	Excellent	Excellent	Very High	Very Fast
Sliding Mode Control	Very Good	Very Good	Moderate	Fast

This table compares various control strategies for STATCOM, such as PI control, fuzzy logic, neural networks, and sliding mode control, based on voltage stability, power factor improvement, reactive power support, and response time. It demonstrates how different control techniques can enhance STATCOM’s effectiveness in power quality improvement.

Table 4: Key Performance Indicators for STATCOM and Synchronous Condenser in Power Quality Improvement

Performance Indicator	STATCOM	Synchronous Condenser
Voltage Regulation (%)	95	90
Response Time (ms)	20	50
Losses (%)	0.2	1.5
Operational Flexibility	High	Moderate
Cost Efficiency	Moderate	Low
Maintenance Requirements	Low	High

This table compares STATCOM and synchronous condensers on metrics such as voltage regulation, response time, losses, operational flexibility, cost efficiency, and maintenance needs. It highlights STATCOM's advantages, showing its suitability for power quality enhancement in modern power systems.

Table 5: IEEE 9-Bus System: Simulation Results with STATCOM

Scenario	Voltage (pu) without STATCOM	Voltage (pu) with STATCOM	Reactive Power Compensation (MVAr)	Stability Margin
Base Case	0.98	1.00	10	Stable
High Load	0.92	0.99	15	Stable
Contingency (Line Outage)	0.85	0.96	18	Stable
Fault Condition	0.80	0.94	20	Stable

This table presents simulation results showing voltage levels, reactive power compensation, and stability margin with and without STATCOM under different scenarios, such as high load and fault conditions. It provides quantitative evidence of STATCOM's impact on voltage stability and system resilience in the IEEE 9-Bus System.

Table 6: Harmonic Content Reduction with STATCOM in IEEE 9-Bus System

Harmonic Order	Without STATCOM (THD%)	With STATCOM (THD%)	Reduction (%)
3rd	3.5	1.2	65.7
5th	2.8	1.0	64.3
7th	2.2	0.8	63.6
9th	1.9	0.6	68.4

This table shows the reduction in Total Harmonic Distortion (THD) at different harmonic orders with STATCOM. By illustrating how STATCOM minimizes harmonic content, the table emphasizes STATCOM's role in improving power quality by reducing distortions in the system.

III. CONCLUSION

Custom Power Devices (CPDs) are crucial for mitigating power quality issues in modern electrical systems. Among these devices, the Distribution Static Synchronous Compensator (D-STATCOM) stands out for its effectiveness in addressing challenges such as voltage sags and swells, poor power factor, harmonic currents, neutral currents, unbalanced voltages, and load imbalances. D-STATCOM systems integrate various components in flexible configurations to target specific power quality requirements, with designs tailored to address distinct issues. This paper reviews multiple D-STATCOM designs from recent research, categorizing them by converter topology, control algorithm, and switching technique. The analysis concludes that a 3-phase-4-wire multi-level voltage source converter, optimized with artificial intelligence-based control and selective harmonic elimination PWM techniques, represents the optimal design approach for D-STATCOM.

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