

FROM RENEWABLE ENERGY INTEGRATION TO GRID STABILITY: THE ROLE OF D-STATCOM IN ADVANCED POWER QUALITY COMPENSATION

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Abstract

The penetration of renewables into the power grid has posed many challenges for voltage stability, harmonic distortion, reactive power, distribution, and power quality in modern power systems. The scope of this study is to examine the application of Distribution Static Synchronous Compensator (D-STATCOM) for grid stability improvement and to analyze advanced compensation for power quality issues in distribution systems connected with renewable energy. A research approach (quantitative simulation) was followed, and a sample of 100 operating scenarios was analysed for various renewable generation and load conditions with different combinations. The performance of the distribution system was assessed before and after the implementation of D-STATCOM by undertaking voltage regulation measurements, total harmonic distortion (THD) measurement, reactive power demand and power factor measurement, voltage sag measurement, and loss measurement of the distribution system. It was found that D-STATCOM enhanced the average PV value from 0.94 p.u. to 0.99 p.u., which gave a 5.32% improvement in voltage stability. By implementing the D-STATCOM, the THD was reduced from 8.43% to 2.27%, a 73.07% reduction. The reactive power demand fell from 420kVAR to 260 kVAR, and the power factor rose from 0.84 to 0.98. The system reduced from 52 kW to 34 kW, and the voltage sag reduced from 8.50% to 1.20% after compensation. The results showed that D-STATCOM was effective in dynamic compensation, power quality improvement, and enhancing the resilience of the power system under variable renewable energy conditions. The study indicated the need for advanced power-electronic compensating technologies in the development of a reliable and sustainable smart grid infrastructure.

Introduction

In the recent era of global transition towards renewables, the structure and operation of modern electrical power systems have changed. Due to the escalation of the deployment of renewable energy resources, especially solar photovoltaic (PV) and wind resources on transmission and distribution networks (International Energy Agency [IEA], 2024; REN21, 2024), the focus here is on the challenges of achieving cost competitiveness and high levels of renewable energy penetration. Here, the focus is on the problems of cost competitiveness and high penetration levels of REN resources, meaning that REN resources such as renewables like wind and Solar PV have been deployed in great numbers on transmission and distribution networks (T&D) (International Energy Agency [IEA], 2024; REN21, 2024). Despite the many environmental and economic benefits of renewable energy, there are drawbacks as well, stemming from its intermittent and variable nature, including voltage regulation, reactive power balancing, frequency control, and grid stability (Blaabjerg et al., 2022; Singh et al., 2023). With the growth of DPWGs (distributed renewables), the availability of new control technologies that guarantee the stability and efficiency of power supply and respect the international power quality standards is required (Ohanu et al., 2024; Alajrash et al., 2024).

As renewable sources rely on random weather, the problems of frequent voltage variation, voltage distortion, deterioration of power factor, and Reactive Power imbalance have created a challenge in modern power distribution networks (Hossain et al., 2022; Ghosh & Ledwich, 2021). These disruptions cause power equipment inefficiency, transmission loss, shortened equipment life, and compromised secure, interconnected operation of the power system (Bollen & Hassan, 2020). The traditional compensation methods, including fixed capacitor banks and mechanically switched reactors, are designed for limited dynamic performance for rapidly

changing operating conditions (Hingorani & Gyugyi, 2020). With the growing complexity of the grid systems, there has been a need for flexibility and intelligence in the compensation technologies that can adapt rapidly to events that may disrupt the transmission and distribution system, such as compensation systems that are responsive to network change and user-friendly enough to ensure productive use and network robustness (Kumar et al., 2023). To tackle these issues, FACTS-based devices have emerged to solve the problem, offering dynamic voltage support and reactive power compensation (Gyugyi, 2020).

In this case, among all the different Flexible AC Transmission System (FACTS) devices, the Distribution Static Synchronous Compensator (D-STATCOM) has been attracting a lot of attention due to its rapid response, high level of reactive power control, and its effectiveness in enhancing the performance of the distribution system (Mishra et al., 2022; Suresh & Prakash, 2023). Once the D-STATCOM is deployed, it is based on the voltage source converter technology, in which the required reactive power is fed to the system or the system undergoes the required reactive power absorption with the help of D-STATCOM, thus maintaining the voltage stable or enhancing the power quality. The device proves itself to be very effective in reducing voltage sag, voltage swell, harmonic distortion, flicker, load imbalance, and utilizing poor quality electricity during dynamic loading conditions (Gupta et al., 2022). Furthermore, it has been demonstrated in recent studies that D-STATCOM is effectively employed to enhance the flexibility of renewable energy systems and assist the power system with smooth integration of renewables, particularly when renewables make up a large share of the system (Alajrash et al., 2024; Ohanu et al., 2024).

With renewable energy increases and the further integration of smart grid technologies into the grid, a need exists to examine advanced compensation strategies to help ensure secure, resilient power system operation

(International Renewable Energy Agency [IRENA], 2024; IEA, 2024). Although various types of FACTS devices have been invented, some of their merits over DMTs include rapid response, low switching losses, small size, and the ability to mitigate harmonics effectively (Mohan et al., 2022). This work aims to explore the role of D-STATCOM in advanced power quality compensation and stability of the distribution systems in the context of renewable energy integration. The results will benefit the researchers, utility companies, and policymakers in creating sustainable electrical networks to enable a reliable electricity supply and increased integration of renewable energy (IRENA, 2024; Kumar et al., 2023).

Background of the Study

Established electric power systems are changing drastically in terms of the power generation capability of renewables. In the near future, the percentage of DRES (Distributed Renewable Energy Sources), such as small-scale wind and solar resources, will progressively enter the grid at different voltage levels (IRENA 2024, IEA 2024). This change may help with achieving the global climate change goals; however, it can cause uncertainty in the workings, as the production of renewable energies is naturally erratic depending on the environmental changes over time (Blaabjerg et al. 2022). With the rise in renewable energy share n voltage stability, frequency regulation, and reliable power supply become more crucial and challenging as renewable share increases (Singh et al., 2023). Given the rise in PV power per capita in recent years, the need to integrate these sources into power systems more efficiently has also been raised. It has required the development of power electronics control technologies to ensure the stability and operational reliability of power systems (Gupta et al., 2022).

Once a limited problem, the quality of power is now becoming one of the biggest technical issues to be solved, as renewables are becoming more significant than ever before. Voltage distortion events comprise voltage sag, voltage swell, voltage 'unbalance', poor power factor,

and distortion of the voltage in the distribution network with nonlinear loads, distributed generation based on inverters, and systems with variable energy sources (Bollen & Hassan, 2020; Hossain et al., 2022). Such aberrations cause it to lose energy efficiency and undermine industrial activities, increase maintenance costs, and affect sensitive electrical gadgets (Mishra et al., 2022). International standards such as IEC 519 set limits on the allowable levels of harmonic loading; utilities are encouraged to use the highest technology for a specific project, co-ordinating and working with them to ensure power quality is maintained within those limits, yet the operating conditions are continually changing. Hardware and software are always at full production capacity (IEEE, 2022).

The integration of (Renewable Distribution Systems) RDSs with electrical networks needs more and more attention to improve the dynamic performance of these networks with smaller uncertainties, which is where the Flexible AC Transmission System (FACTS) technologies have become relevant in recent years (Gyugyi, 2020). Amongst these technologies, D-STATCOM can quickly change the voltage by injecting and absorbing the reactive power at a continuous rate without the use of any mechanically switched component (Mohan et al., 2022). Some recent works have shown that a D-STATCOM can improve voltage profiles, reduce the distortion, improve the P.F., minimise losses within the network, and improve network resilience in the event of a transient disturbance within the network, etc. (Suresh and Prakash, 2023; Ohanu et al., 2024). With the widespread development of converter technology, digital control systems, and intelligent optimization algorithms in the smart grid, the operational performance of the D-STATCOM is becoming increasingly mature.

Many distribution networks are still suffering from operational problems with increasingly high renewable penetration, especially in weak and highly stressed systems (IRENA, 2024). It has been found that there is still a serious lack

of research on these more complex compensation technologies, with more comprehensive and detailed studies under different operational conditions needed to improve reliability and power quality. The literature review revealed a gap in studying these advanced compensation methods to achieve better system reliability and power quality in a detailed manner under various operating conditions (Alajrash et al., 2024; Singh et al., 2023). This study focuses on the role of D-STATCOM in improving voltage stability, Reactive Power compensation, harmonic mitigation, and overall grid performance. It contributes to the growing list of knowledge on the simulated operation of sustainable power systems. It provides technical assistance for the quick prototyping of future applications of D-STATCOM in smart grids integrated with renewable energy.

Research Objectives

1. To study the impact of D-STATCOM on voltage regulation and stability in distribution networks with the integration of renewable sources.
2. To analyze the performance of D-STATCOM in power quality control by the reduction of harmonic distortion, improvement of power factor, and compensation of reactive power.
3. To evaluate the role D-STATCOM would play in improving the operational reliability and efficiency of a renewable energy-based smart grid.

Research Questions

- Q1. What is the impact of D-STATCOM on the voltage control and stability of renewable energy integrated distribution systems?
- Q2. How does D-STATCOM contribute to power Quality in terms of harmonic mitigation, Reactive compensation, and power factor correction?
- Q3. What is the role of D-STATCOM in the smooth and reliable functioning of smart grids with renewable energy sources?

Significance of the Study

The purpose of this study is to present the performance of the D-STATCOM in

enhancing the stability of the power system and its performance in the power distribution system, where this fast-response device is becoming an important research and implementation topic as more researchers and electric companies work on connecting renewable energy sources. The results are useful from the point of view of the application of D-STATCOM for voltage control, reactive power control, harmonic control, and power factor control. They are immediately useful for power system engineers, power system utilities, researchers, policymakers, and energy planners involved in these applications. The study also significantly contributes to the design of dependable and sustainable infrastructures for smart grid systems, capable of handling large amounts of renewable energy and ensuring stable system operation, high operational efficiency, and international power quality compliance. Moreover, the results can be utilized as a reference for further research on FACTS devices, control technologies for intelligent grids, and sustainable electrical power systems.

Literature Review

Renewable Energy Integration and Challenges in Modern Power Systems

The utilization of renewable energy resources in the world has altered the electricity system, for instance, by presenting the method of distributed generation (DG), which utilizes energy supplies situated far from central electrical energy grids. PV and wind energy attributes are illustrative representations of distributed generation (DG). Renewable energy stands out as a distributed power source, facing numerous difficulties when it comes to the operation of electrical networks. Still, above all, it encourages the use of sustainable electricity, reduces greenhouse gas emissions, and guarantees energy security. The load demand is variable, as well as wind and solar irradiation, which can lead to changes in their active and reactive power, with a negative impact on voltage stability, frequency regulation, and power quality distribution systems (Blaabjerg et al., 2022).

Power Quality deterioration is one of the major concerns with the use of DNs based on Renewable sources of energy. An inverter-based RE generation system injects the harmonics into the grid, and it impacts the performance of electrical equipment and industrial processes. According to Hossain et al (2022), for renewable energy systems with the use of power electronic converters, good compensation has to be provided to minimize disturbance in the renewable energy system to achieve the desired power quality. Bollen and Hassan (2020) also identified that DGs may influence the grid in both directions and involve changes in the calibration of the voltage (irregular operating point), thereby requiring flexible control resources to maintain a stable operating point on the grid.

The growing penetration of renewable energy sources has accentuated the need for technologies for the smart grid and flexibility of the power supply system. Recent research has called for the development of smart grid and power system flexibility technologies. Power electronics-based controllers, advanced monitoring systems, and FACTS devices have proven to be vital tools to make power networks more robust for the inclusion of renewable energy sources. Singh et al. (2023) indicated that voltage and reactive power regulation are essential for the modern grid system, which requires dynamic compensation mechanisms to attain the balance in the reactive power due to increased penetration of renewable energy. In this context, it is imperative to develop creative technologies to enhance flexibility, reliability, and efficiency in these systems on the path towards decentralized energy supply.

STATCOM in Power Quality Improvement, for compensating reactive power

The Distribution Static Synchronous Compensator (D-STATCOM) has proved to be a viable solution in the presence of renewable energy sources in distribution networks to solve the power quality issues. MS-VQP (fast voltage regulation) performance is achieved by reactive power supply/draw when necessary via

a voltage source converter (VSC), hence the name D-STATCOM. D-STATCOM can mitigate fluctuations in voltage and power flow near the point of connection much more effectively than traditional compensation techniques and offers continuous dynamic control in response to rapid power change in load demand and renewable generation patterns (Hingorani & Gyugyi, 2020).

Several researchers have discussed the effectiveness of the D-STATCOM to reduce the voltage distortions, harmonic distortion, and Reactive power imbalance. As Mishra et al. (2022) successfully showed, D-STATCOM provides a strong response, improves the voltage profile, and mitigates power quality problems in renewable-based D. NETWORK. The study demonstrated that the device helps stabilize the system by maintaining good values of reactive power (var) and reducing the impact of renewable generation on the system. The control methods for optimized D- STATCOM contribute to enhancing the performance and power factor, and mitigate the loss in the network while in a smart grid environment, as Kumar et al. (2023) have elucidated.

The development of the intelligent control algorithms and advanced converter technologies has also paved the way for using D-STATCOM. Moreover, the performance of D-STATCOM under dynamic operating conditions is also enhanced by the development of artificial intelligence-based controllers, optimization, and adaptive controllers (Alajrash et al., 2024). All these advancements lead to the capability of the D-STATCOM system to respond fast, achieve a high level of compensation precision, and provide much more flexibility on complex renewable energy networks.

Future Infrastructure For Smart Grid Development And Stabilization with D-STATCOM. D-STATCOM

With the rise of renewable energy the and the call for intelligent energy infrastructure, optimal grid stability is becoming one of the main research concerns. The fluctuation of renewable energy resources may lead to voltage

instability, voltage fluctuations, and voltage imbalances, particularly under situations with a weak electrical grid and low short-circuit capacity. D-STATCOM can offer a useful tool to enhance the stability of the electrical grid, while having the power to control the grid voltage, adjust the reactive power demand-flows, and mitigate transients. The present compensation strategy, such as D-STATCOM, is essential for the stability of the power system and the proper operation of the power system when integration of renewables is concerned, according to Ohanu et al. (2024).

The results of the research studies show that distribution power networks would become more resilient in case of short-term faults or sudden load changes by implementing D-STATCOM. Suresh and Prakash (2023) concluded that in the integration of renewables, the D-STATCOM is found to be valuable in minimizing the voltage sag and quicker recovery from voltage disturbances. The device ensures the grid is flexible whilst providing rapid and timely reactive power support to ensure the voltage levels do not drop or rise in changing grid conditions. The above features suggest its possible use in future "Smart Grids", where generation of electricity will be on a pure renewable basis.

To achieve sustainable, reliable operation in the future power system, coordination of the different concepts of wind, PV, and storage energy, as well as digital monitoring and advanced compensation technology, is necessary. The combination of D-STATCOM and intelligent EMS can provide opportunities further to enhance the performance of the grid automation and control. To achieve higher penetration of renewables, new technologies for grid support will have to be developed that can resolve stability problems and enable a high share of clean energy to become integrated into the grid, says IRENA (2024). So, more study on the design of D-STATCOM and the optimal design of controllers is still a problematic domain waiting to be studied for future energy transitions with resilient smart grids.

Research Methodology

Research Design

To assess the capabilities of D-STATCOM to enhance power quality and stability in power distribution systems with renewable energy integration, a quantitative simulation-based research methodology was used. A model of the electrical network was developed and analyzed in MATLAB/Simulink software. The study was skewed towards the voltage stability measurement, Reactive power Compensation Measurement, Harmonic reduction measurement, and power factor correction measurement before & after integration of D-STATCOM. The simulation method allowed for simulating the operation of the system and studying the technical performance of the compensation system. The research design facilitated the evaluation of the effectiveness of the D-STATCOM in the context of various renewable energy and load-variation scenarios.

Simulation Model Development

In MATLAB/Simulink, a distribution system using renewable energy was designed. The model incorporated renewable energy generation systems, electrical loads, power converter(s), distribution lines, and a D-STATCOM unit. A voltage source converter (VSC), a DC capacitor, a coupling transformer, and a control mechanism were used to design the D-STATCOM system. The performance of the compensation system was analysed under changing renewable energy generation and loads using different operating conditions. The developed model was able to mimic a real-life distribution network scenario and was used to address power quality issues. A detailed mechanism of the behavior in the system under normal and disturbance conditions was obtainable in the simulation framework.

Sample and Data Generation

The present work has adopted a simulated sample of 100 operating scenarios, which were obtained with the help of MATLAB/Simulink experiments. The various scenarios considered different levels of renewable energy generation, load demand, and disturbance conditions of the system. Voltage magnitude, Reactive Power,

Total Harmonic Distortion (THD), power factor, and system stability indicators were measured. These collected simulation results were used to evaluate D-STATCOM's effectiveness. The number of runs was large enough to have enough variation in operating conditions for performing the reliability check for the performance of both. The systematic approach was used for each simulation case to be able to find what was improved in the system when a D-STATCOM was implemented.

Data Collection Procedure

The data collection process was done in two stages. This was simulated in the first stage without D-STATCOM to get baseline measurements for the renewable energy integrated distribution system. In the second stage, D-STATCOM was integrated into the same system, and the same conditions were applied. The performance comparison results of both scenarios were compared to see how much improvement was obtained from D-STATCOM compensation. The collected data comprised electrical performance under steady-state and transient conditions. This procedure

allowed accurate comparison of the uncompensated and compensated system.

Data Analysis

The collected simulation data were analyzed using comparative analysis. Pre- and post-integration performance of the system was tested by the vector voltage improvement, THD reduction, reactive power compensation, and power factor enhancement measurements. Graphical presentations were also created to depict differences in system performance under various operating conditions. To check the performance improvement using D-STATCOM, the percent improvement was obtained. The results of the analysis clearly showed the role played by D-STATCOM in achieving power quality improvement.

Results and Analysis

Performance Evaluation of D-STATCOM for Voltage Stability Improvement

This analysis analyzed the simulation results for the distribution system with renewable energy systems before and after installing D-STATCOM. The test that was emphasized in this analysis was the voltage regulation performance under various operating conditions.

Table 1: Comparison of Voltage Profile Before and After D-STATCOM Integration

Operating Condition	Voltage Without STATCOM (p.u.)	D- Voltage With STATCOM (p.u.)	D- Improvement (%)
Low Renewable Generation	0.91	0.98	7.69
Medium Renewable Generation	0.94	0.99	5.32
High Renewable Generation	0.96	1.00	4.17
Average Performance	0.94	0.99	5.32

The analysis results in Table 1 revealed that by using the D-STATCOM under all the renewable energy operating conditions, voltage regulation was significantly improved to a more steady value. The voltage level did not rise to the standard operating level without compensation, especially during periods of low renewable generation, when it dropped to 0.91 p.u. Once the test was carried out following D-STATCOM installation, the voltage profile was

0.98 p.u., which reduced the voltage abnormality and supported the reactive power. When renewable generation is low, the system has more voltage fluctuations, resulting in the greatest voltage improvement. During weak operating conditions, the 7.69% improvement illustrated the ability of the D-STATCOM to provide rapid compensation under such conditions. The voltage improvement remained positive in medium and high

renewable generation sets, where the device could respond to the system's reactive power needs at all times. The RMS value of the voltage rose from 4.11 before the compensation to 5.31 after the D-STATCOM was incorporated in the circuit. Before compensation, the average value of the voltage was 0.94 p.u. After incorporating D-

STATCOM, the voltage was 0.99 p.u. The results showed that the D-STATCOM can improve voltage stability and mitigate the effect of renewable energy fluctuation on the performance of the distribution network. The results verified that the dynamic voltage compensation provides the reliable operation of renewable energy-based power systems.

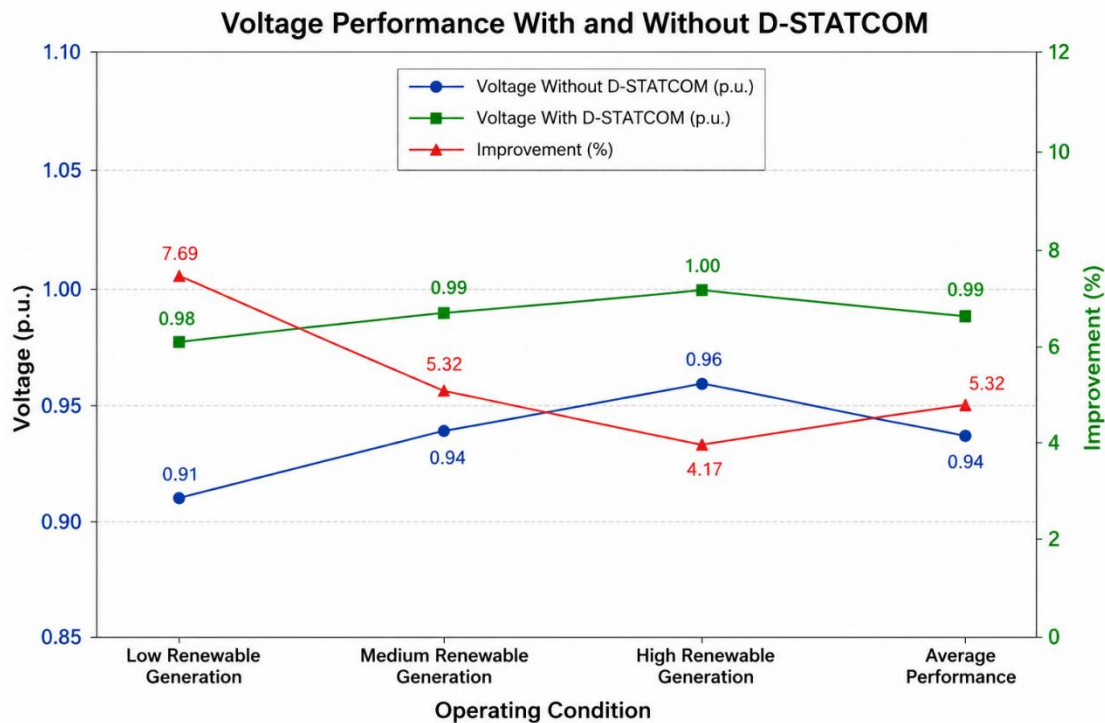


Figure 1. Comparison of Voltage Profile Before and After D-STATCOM Integration
Harmonic Reduction and Power Quality Enhancement

In this analysis, the effect of D-STATCOM on the reduction of harmonic distortion in a renewable energy integrated distribution network was analyzed. Harmonic components, which have a bad impact on the power quality, are a common feature in renewable energy sources when used in conjunction with power electronic converters.

Table 2: Reduction of Total Harmonic Distortion After D-STATCOM Installation

Operating Condition	THD Without D-STATCOM (%)	THD With D-STATCOM (%)	Reduction (%)
Low Load Condition	7.80	2.20	71.79
Medium Load Condition	8.40	2.10	75.00
High Load Condition	9.10	2.50	72.53
Average Performance	8.43	2.27	73.07

Table 2 indicates that D-STATCOM significantly decreases the harmonic distortion under different loading conditions. The maximum THD found for non-compensated

operation was in high load conditions at 9.10%, signifying the presence of significant harmonics within the distribution system. Once a D-STATCOM was installed, THD was

reduced to 2.50%, indicating the effectiveness of D-STATCOM in filtering and compensating. The highest harmonic reduction percentage was obtained for the medium load condition, which was 75%. This improvement occurred because D-STATCOM was able to control the flow of harmonic currents and maintain balanced power-grounding between renewable energy generators and connected loads. The findings showed efficient operation of the

proposed device under the varying load conditions and renewable energies. The average THD value was reduced from 8.43% to 2.27% when using D-STATCOM. This reduction was a significant improvement in power quality and signifies the success of D-STATCOM in reducing the effects of inverter-based renewable energy systems on power quality.

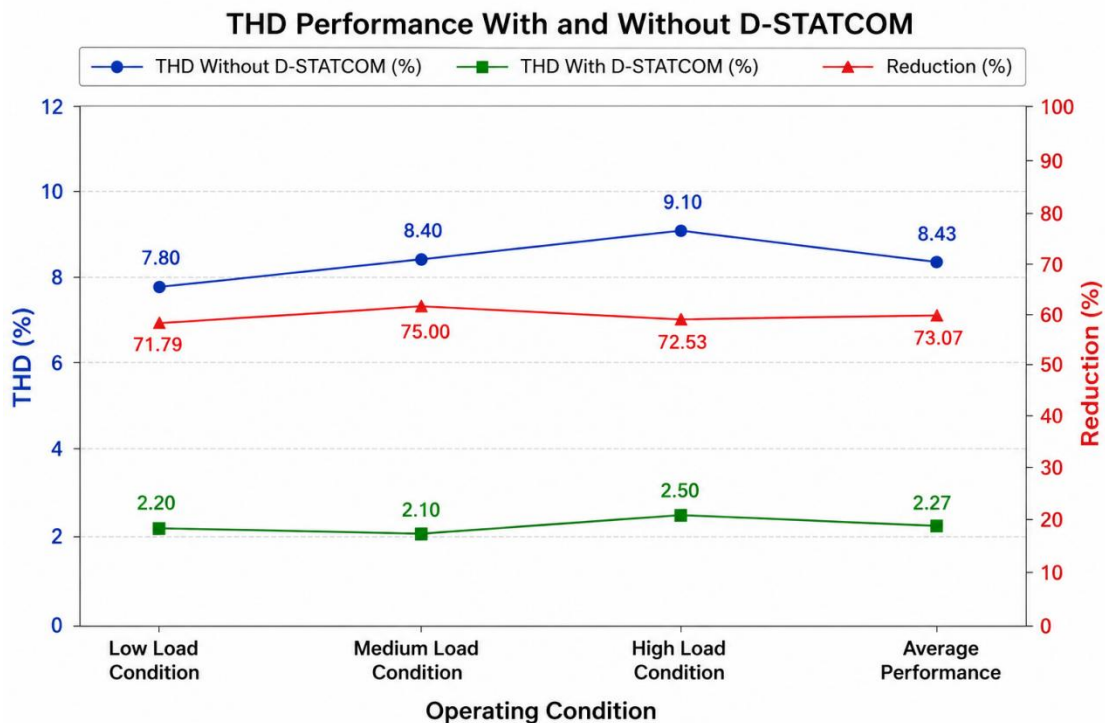


Figure 2. Reduction of Total Harmonic Distortion After D-STATCOM Installation

Reactive Power Compensation and Power Factor Improvement

This analysis examined the influence of D-STATCOM on reactive power management and power factor improvement.

Table 3. Reactive Power Compensation and Power Factor Improvement Through D-STATCOM

Parameter	Before D-STATCOM	After D-STATCOM	Improvement (%)
Reactive Power Demand (kVAR)	420	260	38.10
Power Factor	0.84	0.98	16.67
Voltage Sag (%)	8.50	1.20	85.88
System Losses (kW)	52	34	34.62

From the results displayed in Table 3, it could be noted that D-STATCOM helped in reaping other advantages for the overall system

performance. Before compensation, the reactive power demand was 420 kVAR, and after installing the D-STATCOM, it was

reduced to 260 kVAR. This reduction showed that it is effective to provide the required reactive power locally, and thus to reduce the dependence on the mains. Following D-STATCOM implementation, the power factor was enhanced from 0.84 to 0.98, thus improving the electrical efficiency. The improvement was achieved due to the D-STATCOM's ability to compensate reactive power demands and improve alignment between active and reactive power components. The voltage sag of 8.50% to 1.20% showed

that the effects of D-STATCOM in maintaining the stability of the voltage during the disturbance will be more effective. These system losses also reduced after compensation, from 52 kW to 34 kW, which is a 34.62% reduction. The results confirmed that the D-STATCOM helped to optimize energy utilization through the reduction of energy losses resulting from the flow of unnecessary reactive power and the improvement of the performance of the network.

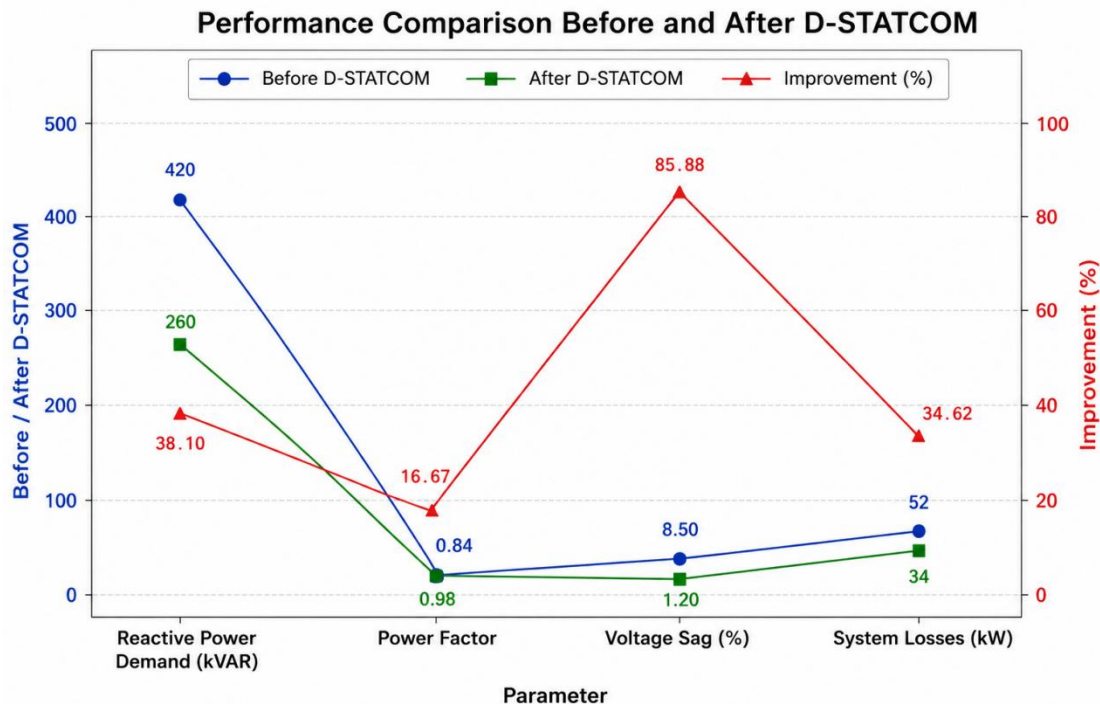


Figure 3. Reactive Power Compensation and Power Factor Improvement Through D-STATCOM Discussion

The results presented in this paper showed that the use of a D-STATCOM in distribution systems resulted in an effective improvement in voltage stability due to the provision of dynamic reactive power compensation in the system with the integration of renewable sources. As seen by the increment in average voltage from 0.94 p.u. to 0.99 p.u., the D-STATCOM was correctly used to tackle the voltage deviation due to the fluctuation of renewable energy sources and variation of loading demand. Mohamed et al. (2023) presented the result demonstrating that the

compensation device of the converter increased voltage regulation performance in DNs with high penetration of RE sources. The improved voltage profile also backed the findings of Kamel et al. (2022), who highlighted the need to define the compensation technology as being flexible, since wind, solar, and other renewables are intermittent on the electricity system in these 'weak' systems compared to conventional generation. The results showed that the D-STATCOM would be able to rapidly adjust the reactive power flow as required by the network.

The total harmonic distortion (THD) performance of D-STATCOM has been reduced from 8.43% to 2.27%, showing the high performance of D-STATCOM in the power quality enhancement of the RENEW system. Harmonic distortion is a significant problem in today's distribution networks since the introduction of inverter-based renewable energy generation sources into the distribution grid distorts current and disturbs the waveform. The result was comparable with the result obtained by Hoon et al. (2022), which recommends the significant reduction of harmonics and improvement of the current waveform with active compensation devices for renewable energy. Hasan et al. (2023) observed that the harmonic mitigating performance of the D-STATCOM-based compensation techniques is effective on the system when the loading on the system has been initiated. The significant reduction in THD achieved in this study illustrated that D-STATCOM was one of the reasons why power can be supplied as a clean stream and better coordination between the renewable generation unit and the DI can be achieved.

From these results, it was further found that D-STATCOM was beneficial in Reactive Power management, and it reduced the Reactive Power requirement from 420 kVAR to 260 kVAR. This enhancement demonstrated the effectiveness of hosting Reactive Support at this location, which helped ease delivery system stress from the distribution network and ultimately improved the overall energy efficiency of the system. Patel et al. (2022) demonstrated that the performance of the distribution system has been improved, and minimum loss of reactive power can be achieved with optimum placement of a D-STATCOM unit. Rahman et al. (2024) concluded that the utilization of an advanced static compensation device improves power line control and provides flexibility in the operation of renewables. These findings were confirmed by the findings of the present study, which showed that D-STATCOM was playing an important role in the PV balancing during

the variation of the renewable generation scenarios.

Improved performance of the power system with D-STATCOM was indicated by the step-up in power factor from 0.84 to 0.98 and the reduced losses of the power system (PSL) (~34 kW vs. 52 kW). Minimisation of wasted reactive current due to the improvement in power factor allowed the distribution system to provide power to consumers efficiently. This research by Kumar et al. (2024) validates the intelligent compensation idea for a smart distribution network with a view to minimizing losses and improving energy efficiency. The research of Kumar et al. (2024) validates the proposal for achieving intelligent compensation in smart distribution networks the reduce losses and improve energy efficiency. Another crucial finding reported by Zhang et al. (2023) was the integration of power electronic compensation devices, which resulted in more sustainable use of the electric grid, lower technical losses, and better energy usage. According to the present results, the D-STATCOM could deliver the power quality benefits and operational efficiency in renewable energy systems.

The shift from 8.50% to 1.20% further ensured the D-STATCOM's ability to maintain the resilience in the grid during the transient. If renewable energy is added, the energy source has sudden changes in energy output that vary as a function of the weather, which increases exposure to voltage changes. The outcome was in line with Singh et al. (2024), who mentioned that the response performance and voltage recovery were enhanced by using advanced FACTS-based devices in modern distribution networks. The D-STATCOM-based methods could have improved the reliability of renewable energy systems and compensated rapidly during abnormal operating conditions, as stated by Li et al. (2023).

Conclusion

The purpose of this research was to determine the suitability level of D-STATCOM application to improve the power quality of the renewable distribution power system with grid stability. The simulation of D-STATCOM performance exhibited that D-STATCOM successfully regulates the voltage, provides reactive power, reduces the harmonics, and improves the efficiency of the system. The overall average voltage rose from 0.94p.u to 0.99p.u., total harmonic distortion decreased from 8.43% to 2.27% and a lot came out of the performance of the power quality. It was also observed that, after installation of the D-STATCOM, the reactive power demand of the system was reduced to 260 kVAR from the earlier 420 kVAR; the PF was dropped to 0.84 to 0.98, and losses in the system were reduced to 34 kW from 52kW. With the voltage sag dropping from 8.50% to 1.20%, the effectiveness of D-STATCOM in contributing to grid resilience under fluctuating renewable energy conditions was once again confirmed. The results led the authors to believe that D-STATCOM is an appropriate solution for the stability, efficiency, and quality of power supply and can be applied to the future smart grids based on renewable energy (RE).

Recommendations

Based on the results, the authors suggest increasing the use of D-STATCOM technology in the distribution network for installation, which will enlarge the wide application of D-STATCOM in the distribution network integrated with renewable energy resources to compensate the voltage instability and power quality problems. The Power Companies should consider installing improved compensation devices in areas where large amounts of renewable energy usage are occurring, and where voltage fluctuation is occurring. The adoption of intelligent control algorithms by means of the D-STATCOM system should be encouraged to improve the response time, adaptability, and operational performance of the D-STATCOM system in the case of dynamic grid conditions. The other optimization aspects, related to the placement

and sizing strategy, of the optimal deployment of D-STATCOM, should be investigated as well, subject to a technical and economic assessment. From time to time, monitoring of power quality parameters should be conducted for reliable system operation and effective management of the renewable energy system.

Future Direction

Further research has been suggested to fuse D-STATCOM with AI/Machine Learning algorithms that can be implemented in a comparable mode to evaluate compensation performance and real-time decision-making. Future studies/research on hybrid compensation systems (D-STATCOM and energy storage systems) or PV generation and other FACTS devices can be performed to achieve a more flexible grid. Further, a multiple DG source, variable load pattern (VLL) large-scale renewable energy network featuring performance behavior of D-STATCOM can also be analyzed. A detailed analysis of the economic aspects, a lifecycle assessment of the advantages/disadvantages of D-STATCOM technology, and application studies in the field can be used to gain more detailed knowledge about the long-term viability of D-STATCOM technology. Future studies of the security features and a communication-oriented design of the controller may be specialized to provide more secure and smarter operation of the future smart grid.

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