

Mitigation of Voltage Sags: A Comparative Study of D-STATCOM and DVR

Ameerussufy Mohd Noor¹, Norain Sahari^{1*}, Md Nor Ramdon Baharom¹

¹ *Department of Electrical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia*

*Corresponding Author: norains@uthm.edu.my

DOI: <https://doi.org/10.30880/peat.2025.06.01.045>

Article Info

Received: 21 January 2025

Accepted: 25 January 2025

Available online: 30 April 2025

Keywords

d-statcom, dvr, matlab, simulink, mitigation, voltage sags and fault type

Abstract

This research investigates the effectiveness of two common Flexible AC Transmission System (FACTS) devices, Dynamic Voltage Restorers (DVRs) and Distribution Static Synchronous Compensators (D-STATCOMs), in mitigating voltage sags, a significant power quality issue in electrical distribution systems. The widespread adoption of nonlinear loads and the occurrence of unsymmetrical faults in real-world power systems significantly degrade power quality, leading to disruptions in voltage and current waveforms. These disturbances, including voltage sags, swells, and harmonics, necessitate effective voltage control to maintain power quality, reliability, and availability. The research utilizes a comprehensive simulation model, developed in MATLAB/Simulink, to evaluate the effectiveness of DVRs and D-STATCOMs in mitigating voltage sags under various fault conditions. The model represents a typical power distribution system, incorporating three phase source, transformers, transmission lines, and a variety of loads. The simulation includes the introduction of different fault types, such as single line-to-ground, line-to-line, double line-to-ground, and three-phase faults. The impact of varying fault resistance on the severity of the voltage sag is also investigated. A key aspect of the research is the comparative analysis of the voltage recovery performance of DVRs and D-STATCOMs. The analysis quantifies the effectiveness of each device in restoring voltage levels to acceptable limits, measured in per unit (p.u.), and considers the voltage recovery time, the peak voltage sag depth, and the rate of voltage recovery. Statistical analysis is employed to determine the significance of any performance differences between the two devices. The research findings provide valuable insights into the optimal selection and deployment of DVR and D-STATCOM technologies for enhancing power system resilience and ensuring reliable power delivery. The results contribute to a deeper understanding of voltage sag mitigation strategies in modern power distribution systems.

1. Introduction

Nonlinear loads and unbalanced faults in power distribution systems distort voltage and current waveforms, degrading power quality. Effective voltage control is crucial to mitigate these issues and maintain reliable power delivery (Shakil et al., 2022). Methods for achieving this include the utilization of FACTS devices, reactive power injection, and tap-changing transformers. The relationship between voltage and reactive power is directly proportional: injecting reactive power increases system voltage, while absorbing reactive power decreases it (Pandey et al., 2018). These include the implementation of Flexible AC Transmission Systems (FACTS) devices such as Dynamic Voltage Restorers (DVRs) and Distribution Static Synchronous Compensators (D-STATCOM) (Tarimoradi et al., 2023).

This research compares Dynamic Voltage Restorers (DVRs) and Distribution Static Synchronous Compensators (D-STATCOMs) via simulation, analyzing their effectiveness in restoring voltage levels under various fault conditions. Findings will guide optimal selection and deployment for improved power system resilience. (Abdeelal et al., 2024) paper review nonlinear DVRs benefit from nonlinear control methods, particularly the robust Sliding Mode Control (SMC), to manage voltage fluctuations in sensitive loads. SMC, along with other techniques like adaptive neuro-fuzzy systems, enhances DVR performance, even stabilizing voltage in double-fed induction generators. Cost-effective DVR technology enhances power quality by mitigating voltage sags. (Moghassemi & Padmanaban, 2020) paper reviews a DVR designs, control methods, and applications, highlighting their lower cost and maintenance compared to UPS systems, and their ability to maintain voltage stability during disturbances. (Kilic et al., 2024) paper review a multi-objective optimization framework designed a hydrogen storage system for wind farms, improving energy storage, load tracking, and power smoothing. Various control strategies for STATCOMs in different renewable energy systems (PEM fuel cells, DFIG-based wind farms, hybrid microgrids) were explored to enhance power quality, mitigate oscillations and overvoltages, and improve overall system performance during faults. (Sulaiman et al., 2023) paper review a deep Learning-based D-STATCOM system, using a 4-leg VSC, improves power quality by compensating for unbalanced nonlinear loads. Powered by a hybrid PV-wind system, it injects current to maintain sinusoidal source currents, using a BP algorithm for reference current generation and a hysteresis controller for switching. The fourth leg handles neutral imbalances. (Bharath et al., 2015) paper review a three-phase system uses a D-STATCOM with a three-phase VSC to mitigate nonlinear load effects (simulated by a diode rectifier). AC-side inductors filter high-frequency currents. A PI controller regulates DC capacitor voltage, controlling active power flow, while a hysteresis current controller manages inverter switching. Kamarposhti et al. (2023) modeled and simulated DVR and D-STATCOM performance in a wind farm-integrated distribution system, demonstrating DVR's superior mitigation of asymmetric fault-induced power quality issues. Latha, Sharma, and Manjula (2022) provided a review of research on power quality enhancement in distributed generation systems, focusing on the application of DSTATCOM and DVR technologies. Their review encompasses diverse methods, control strategies, and assessments of effectiveness. This research provides a comprehensive comparative analysis of Dynamic Voltage Restorers (DVRs) and Distribution Static Synchronous Compensators (D-STATCOMs) for voltage sag mitigation in distribution systems. Our detailed MATLAB/Simulink model considers a wide range of fault types (single line-to-ground, line-to-line, double line-to-ground, three-phase) and quantifies performance using voltage recovery time, peak sag depth, and recovery rate, enabling a statistically significant comparison of DVR and D-STATCOM effectiveness.

This research employs a detailed MATLAB/Simulink model of a realistic three-phase power distribution system, incorporating transformers, transmission lines, and diverse load types, to evaluate the voltage sag mitigation capabilities of DVRs and D-STATCOMs. The model simulates various fault scenarios—single-line-to-ground, line-to-line, three-phase, and double-line-to-ground faults—each with a 1Ω fault resistance, investigating the impact of this resistance on voltage sag depth. A comparative analysis of DVR and D-STATCOM performance will quantify voltage recovery time, peak sag depth (p.u.), and recovery rate under these conditions, with statistical analysis determining the significance of any performance differences. This model will be use to achieve these three primary objectives. First, a MATLAB simulation model of a power distribution system will be developed, incorporating both DVR and D-STATCOM technologies for voltage sag mitigation. Second, a comparative study will be conducted to evaluate the effectiveness of DVR and D-STATCOM in mitigating voltage sags. Finally, the voltage recovery performance of both technologies will be analyzed under a variety of fault scenarios.

2. Methodology

A simulation model, constructed in MATLAB/Simulink, incorporates a DSTATCOM (shunt-connected) and a DVR (series-connected) to mitigate voltage sags resulting from various fault scenarios: Line-to-Ground (LG), Double Line-to-Ground (DLG), Three-Phase-to-Ground (TPG), and Line-to-Line (LL) faults. The simulation model comprises a three-phase source, a 100km transmission line, and a load. A baseline simulation without mitigation is also included for comparative analysis. The performance of both DVR and D-STATCOM in voltage sag mitigation is evaluated by comparing voltage recovery characteristics under each fault condition. Simulation results, presented graphically, demonstrate the effectiveness of each mitigation technique in restoring voltage levels following different fault types.

This study used a three-stage methodology to compare D-STATCOM and DVR voltage sag mitigation. First, a realistic power system model was created and subjected to various fault simulations to establish a baseline. Second, a D-STATCOM, then a DVR, was integrated into this model, and the simulations were repeated, recording voltage sag depth, recovery time under each fault type. Finally, a comparative analysis, including statistical analysis, determined the relative effectiveness of each mitigation strategy against the baseline, considering factors like fault type. # This ensured a robust comparison of D-STATCOM and DVR performance in mitigating voltage sags.

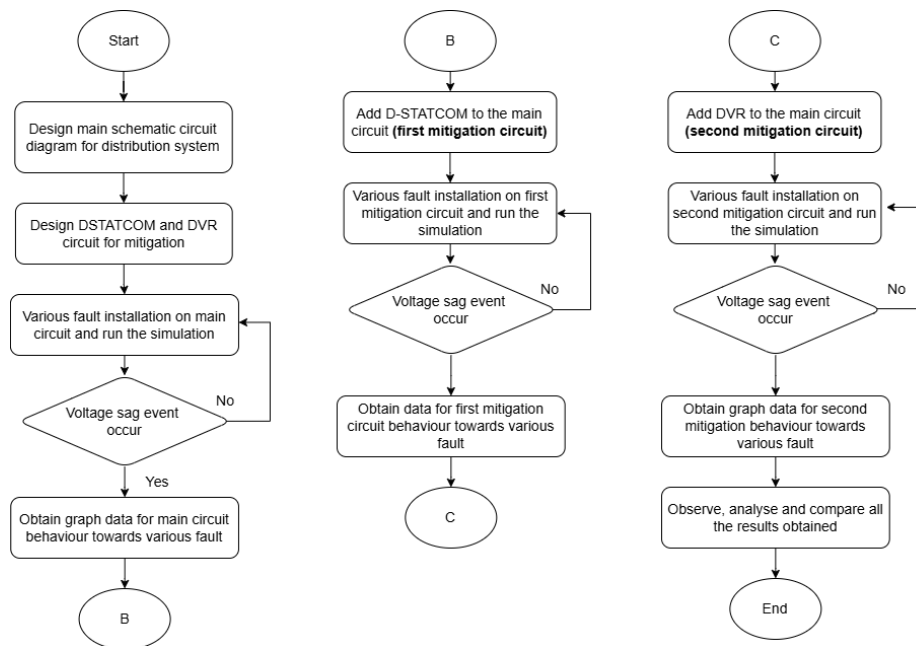


Fig. 1: System design flowchart

2.1 Circuit Integration

This Simulink simulation utilizes a three-phase power source model with parameters of 33 kV voltage, 50 Hz frequency, and a three-phase short-circuit capacity of 100 MVA. This source is connected to a 100 km transmission line, representing the power distribution network. A dynamic load, characterized by 10 MW active power and 1000 VAR of combined inductive and capacitive reactive power, is connected at the end of the transmission line. This configuration allows for the simulation of voltage sags and power quality issues under various fault conditions, providing a realistic representation of a power distribution system. Figure 3.4 is present in baseline circuit with fault.

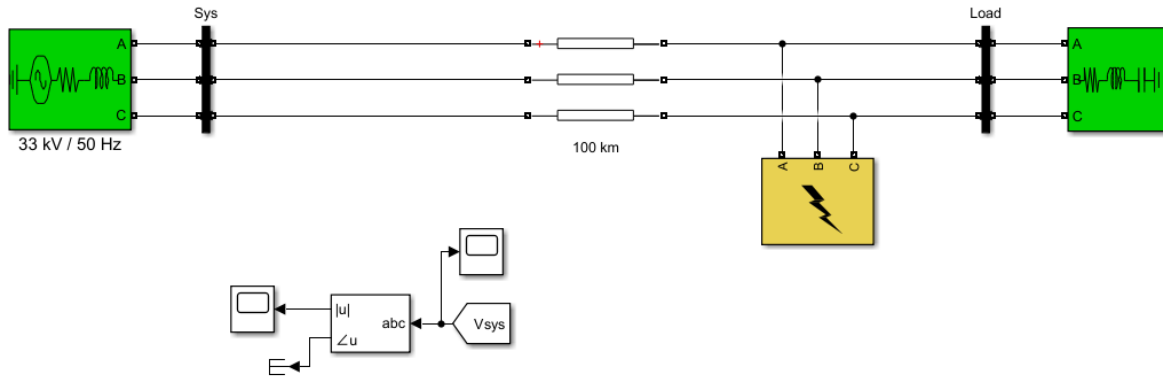


Fig. 2: Baseline circuit diagram

The D-STATCOM uses a sinusoidal Pulse Width Modulation (PWM) phase-shift control strategy to maintain stable load voltage, relying solely on RMS voltage measurements. A PI controller adjusts the phase angle based on the voltage error, generating switching signals for the VSC thyristors to regulate reactive power injection. This simple, responsive method effectively controls the D-STATCOM (Saraf et al., 2014).

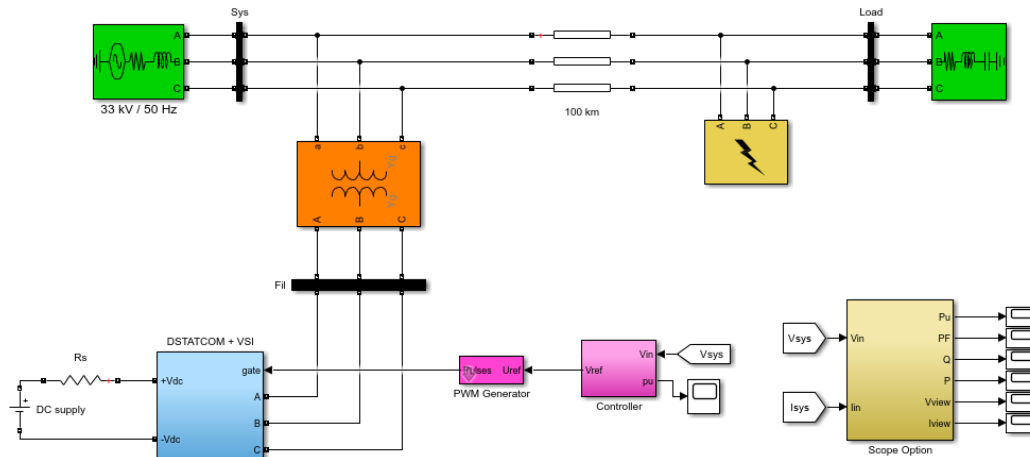


Fig. 3: D-STATCOM circuit diagram

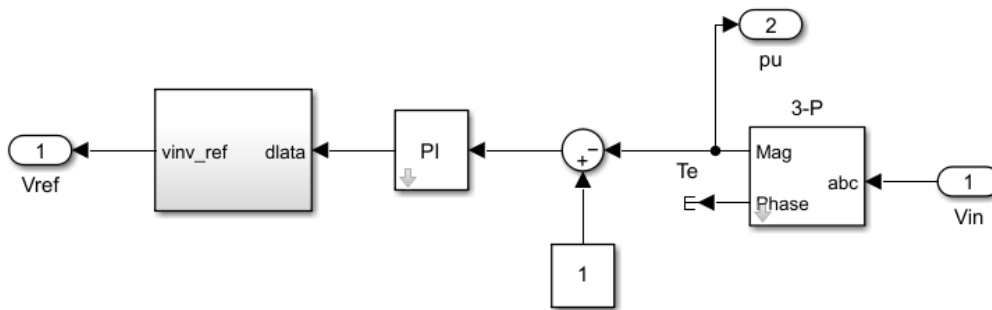


Fig. 4: D-STATCOM control circuit

Dynamic Voltage Restorers (DVRs) mitigate voltage sags by injecting or absorbing real or reactive power. Reactive power injection, generated internally, corrects sags within a limited depth, maintaining a 90-degree phase shift with the load current. Beyond this limit, in-phase real power injection, requiring external energy storage, becomes necessary. Effective DVR control necessitates managing these limitations, including inverter and transformer capabilities and energy storage sizing (Vishwakarma et al., 2015).

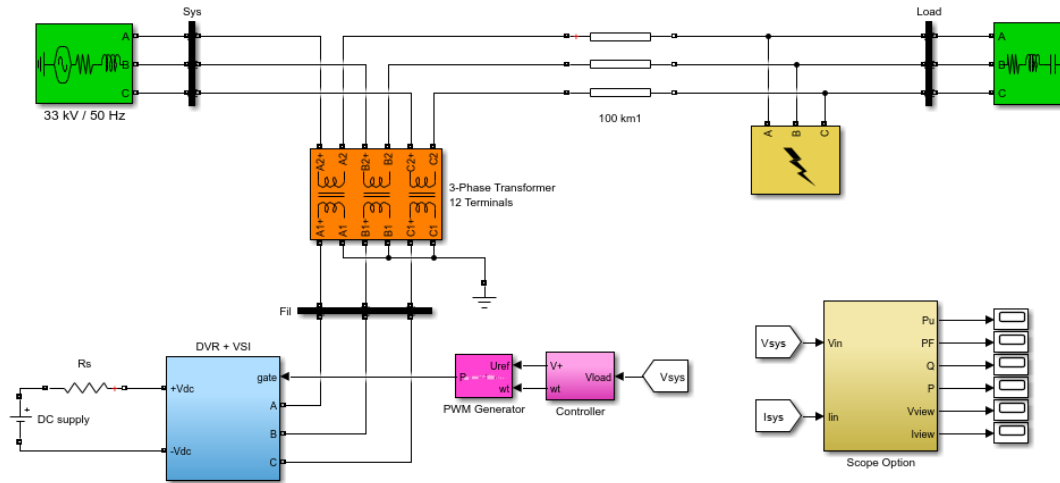


Fig. 5: DVR control circuit

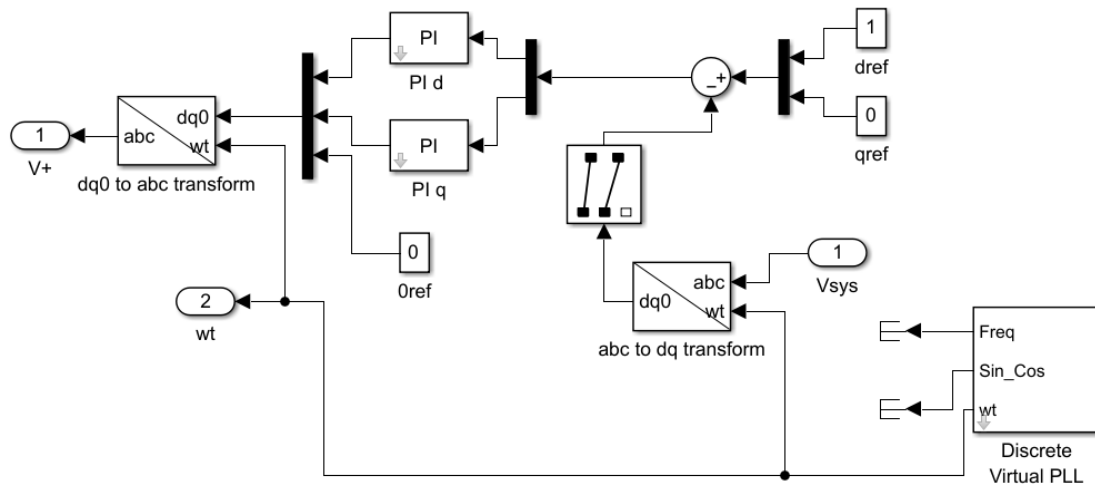


Fig. 6: DVR control circuit

3. Result and discussion

This section presents the results obtained from the MATLAB/Simulink simulations conducted to evaluate the effectiveness of D-STATCOM and DVR in mitigating voltage sags within a power distribution system. The simulations modeled a three-phase system subjected to various fault scenarios (Line-to-Ground (LG), Double Line-to-Ground (DLG), Three-Phase-to-Ground (TPG), and Line-to-Line (LL) faults), incorporating shunt-connected D-STATCOM circuit and series-connected DVR circuit configurations. A baseline simulation without mitigation was also performed to provide a benchmark for comparison.

3.1 Baseline circuit

In analyzing voltage sags within electrical systems, the severity of disruptions is notably influenced by the type of fault occurring. Among the various fault types, the three-phase-to-ground (TPG) fault is recognized as the most critical, resulting in the most significant voltage sag. This level of disruption aligns with theoretical expectations, as a TPG fault creates a substantial impedance mismatch across the three-phase system, leading to considerable instability in voltage levels. The magnitude of the voltage sag during a TPG fault can severely affect the performance and reliability of the electrical system, resulting in potential operational challenges and increased risk of equipment damage. In contrast, the single-phase-to-ground (SPG) fault is characterized by the least severe sag among the fault types examined. This phenomenon highlights the protective benefits of the system's grounding configuration, which effectively mitigates the impact of a single-phase fault. The grounding mechanisms in place allow for better voltage stability during SPG events, ensuring that the system can maintain a

more balanced voltage profile despite the fault. The double-phase-to-ground (DPG) and line-to-line (LL) faults present intermediate sag depths, existing between the extremes of the SPG and TPG faults.

The voltage sags caused by these fault types indicate that while they do disrupt the system, the extent of their impact is less severe than that of a TPG fault. Interestingly, the relatively similar sag depths observed for the SPG and DPG faults suggest that introducing a second faulted phase does not proportionally escalate the overall voltage disturbance within the system. This implies that the inherent design and grounding mechanisms of the electrical network can absorb certain fault conditions without a linear increase in voltage disturbance, showcasing the resilience of the system under specific fault scenarios. Overall, understanding the dynamics of these faults and their effects on voltage stability is crucial for designing robust electrical systems capable of withstanding various fault conditions while minimizing disruptions to service and equipment.

Table 1: Result of baseline circuit

Type of Fault	Voltage Sag Without DVR and D-STATCOM (p.u)
SPG	0.8966
DPG	0.8183
TPG	0.7280
LL	0.8424

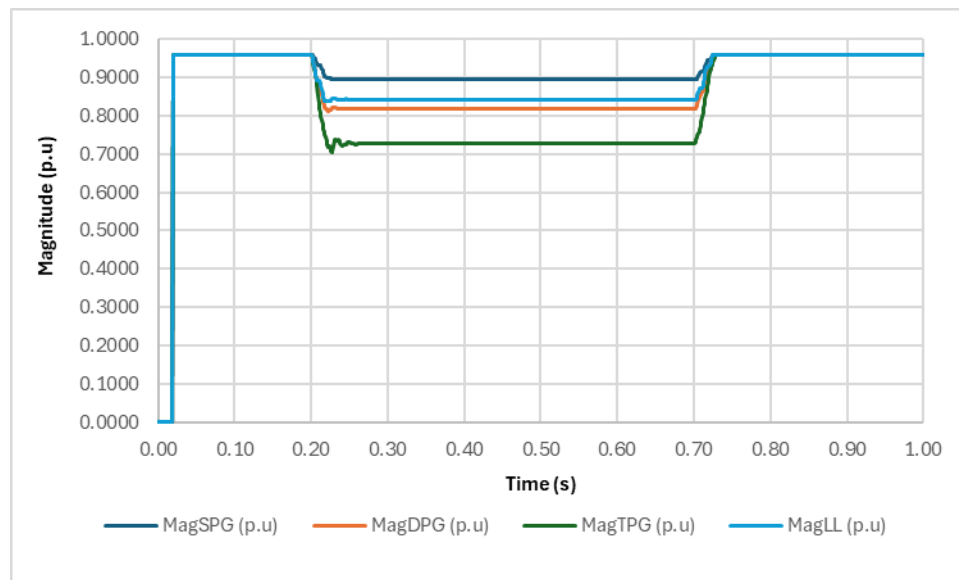


Fig. 7: Magnitude fault vs time graph

3.2 DVR circuit

The graph clearly illustrates that the DVR significantly mitigates the depth and duration of voltage sags across all fault types. The TPG fault, being the most severe, experiences the most drastic voltage drop without the DVR, falling to approximately 0.7280 p.u. However, it also demonstrates the highest recovery percentage at 26% with the DVR, highlighting its effectiveness in addressing severe voltage disturbances. Conversely, the SPG fault shows the least severe sag, with a minimum voltage of approximately 0.8966 p.u. and the lowest recovery of 9.2%. This indicates that while the DVR plays a role in recovery, the inherent characteristics of the fault type limit the extent of improvement. The DPG fault exhibits a moderate recovery of 17% with a minimum voltage around 0.8183 p.u., while the LL fault, despite showing a similar recovery percentage of 14.6%, has a slightly higher minimum voltage of approximately 0.8424 p.u. This comparison suggests that while the DVR is effective in reducing voltage sags,

the specific impedance characteristics and current distribution associated with each fault type also play a critical role in determining the overall effectiveness of voltage recovery. In conclusion, the analysis underscores the DVR's ability to enhance voltage stability and mitigate disturbances across varying fault conditions, showcasing its importance in modern electrical systems for maintaining reliable power quality. This visualization and comparative analysis effectively demonstrate how different fault types interact with the DVR's capabilities, guiding further enhancements in power system reliability.

Table 2: Result of DVR circuit

Type of Fault	Voltage Sag Without DVR (p.u.)	Voltage Sag With DVR (p.u.)	Percentage Voltage Recovery (%)
SPG	0.8966	0.9886	9.2
DPG	0.8183	0.9883	17.0
TPG	0.7280	0.9880	26.0
LL	0.8424	0.9885	14.6

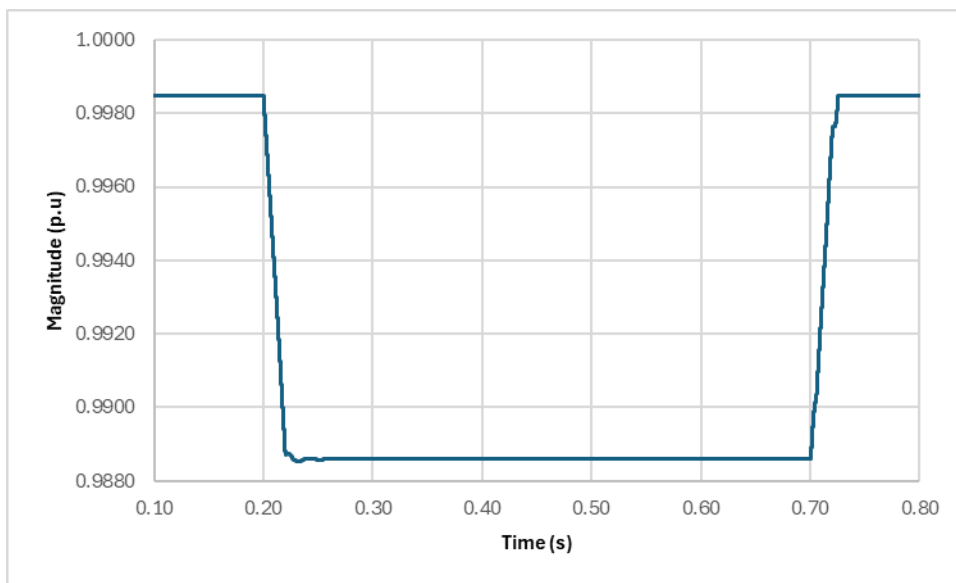


Fig. 8: DVR magnitude fault SPG vs time graph

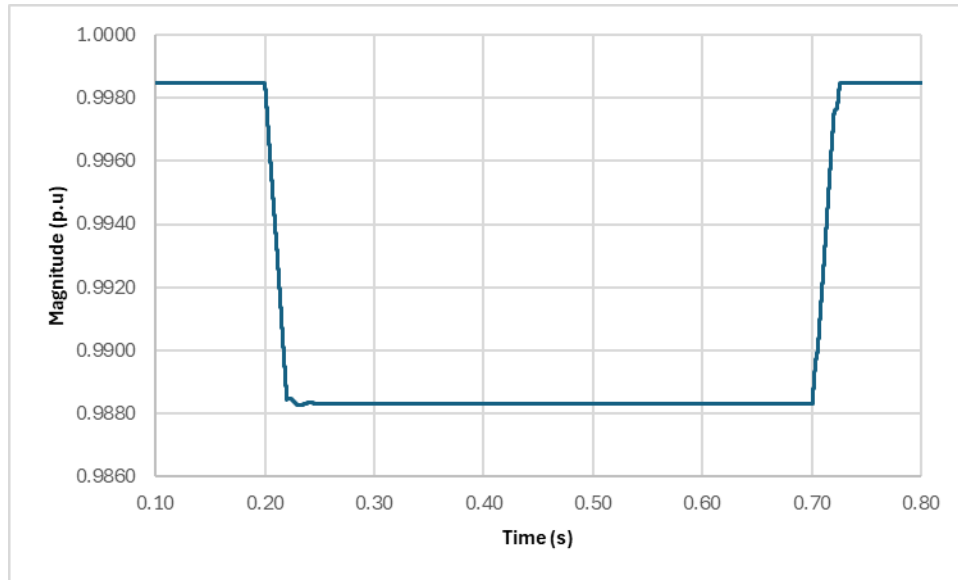


Fig. 9: DVR magnitude fault DPG vs time graph

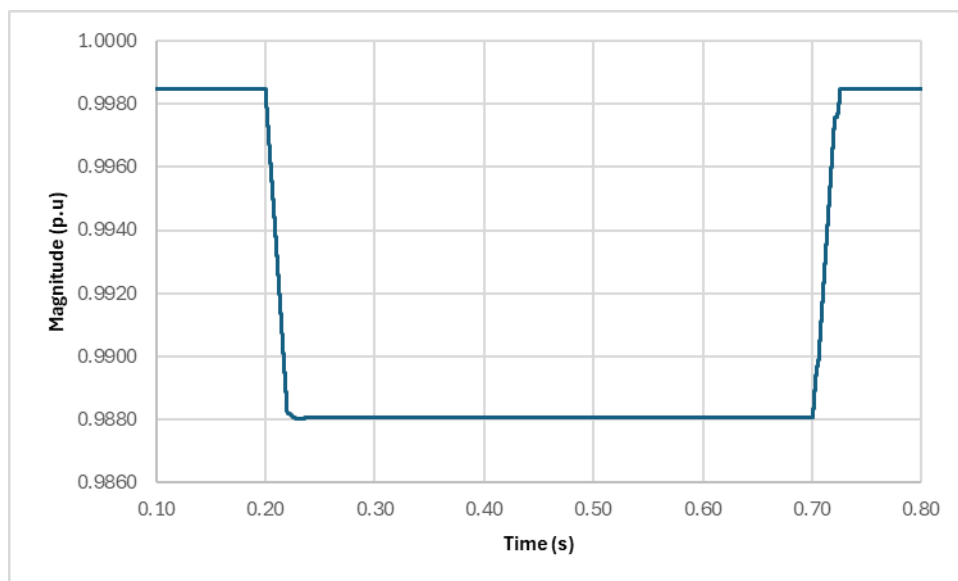


Fig. 10: DVR magnitude fault TPG vs time graph

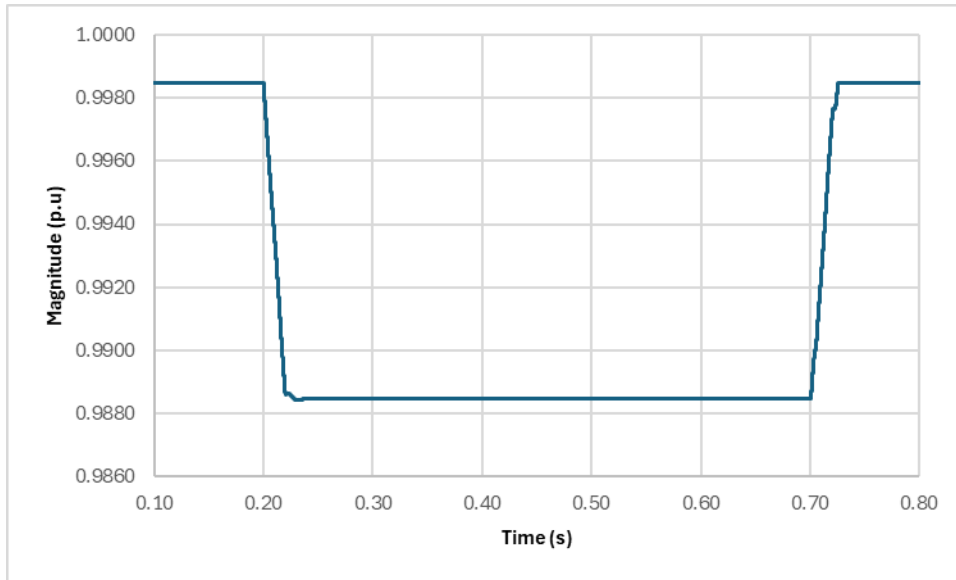


Fig. 11: DVR magnitude fault LL vs time graph

3.3 D-STATCOM circuit

The provided data and graph illustrates the effectiveness of a D-STATCOM (Distribution Static Synchronous Compensator) in mitigating voltage sags under various fault conditions: single-phase-to-ground (SPG), double-phase-to-ground (DPG), three-phase-to-ground (TPG), and line-to-line (LL). The table quantifies the voltage sag in per-unit (p.u.) both with and without the D-STATCOM, and calculates the percentage voltage recovery achieved by the D-STATCOM for each fault type. Analysis reveals a clear trend: the D-STATCOM significantly improves voltage recovery across all fault types. However, the degree of improvement varies considerably depending on the fault's nature. The three-phase-to-ground (TPG) fault, representing the most severe disturbance, experiences the most dramatic voltage drop without the D-STATCOM (to 0.7280 p.u.). The D-STATCOM, however, provides the highest percentage recovery (23.6%), effectively mitigating the significant voltage dip. This highlights the D-STATCOM's crucial role in maintaining system stability during catastrophic events. Conversely, the single-phase-to-ground (SPG) fault, generally the least severe, shows the lowest percentage recovery (9.1%). While the D-STATCOM still offers some improvement, the inherent nature of the SPG fault limits the extent of voltage restoration. This suggests that the D-STATCOM's impact is most pronounced in scenarios with more extensive system imbalances. The double-phase-to-ground (DPG) fault demonstrates a moderate recovery (15.9%), indicating a substantial but not complete restoration of voltage. Similarly, the line-to-line (LL) fault shows a recovery of 13.7%, falling between the SPG and DPG in terms of improvement. The relatively similar recovery percentages between DPG and LL faults suggest that the addition of a second faulted phase does not proportionally increase the challenge for the D-STATCOM. However, the lower recovery in the LL fault compared to the DPG fault hints at the complex interplay between fault type and the D-STATCOM's compensation capabilities.

Table 3: Result of D-STATCOM circuit

Type of Fault	Voltage Sag Without D-STATCOM (p.u.)	Voltage Sag With D-STATCOM (p.u.)	Percentage Voltage Recovery (%)
SPG	0.8966	0.9880	9.1
DPG	0.8183	0.9768	15.9
TPG	0.7280	0.9636	23.6
LL	0.8424	0.9796	13.7

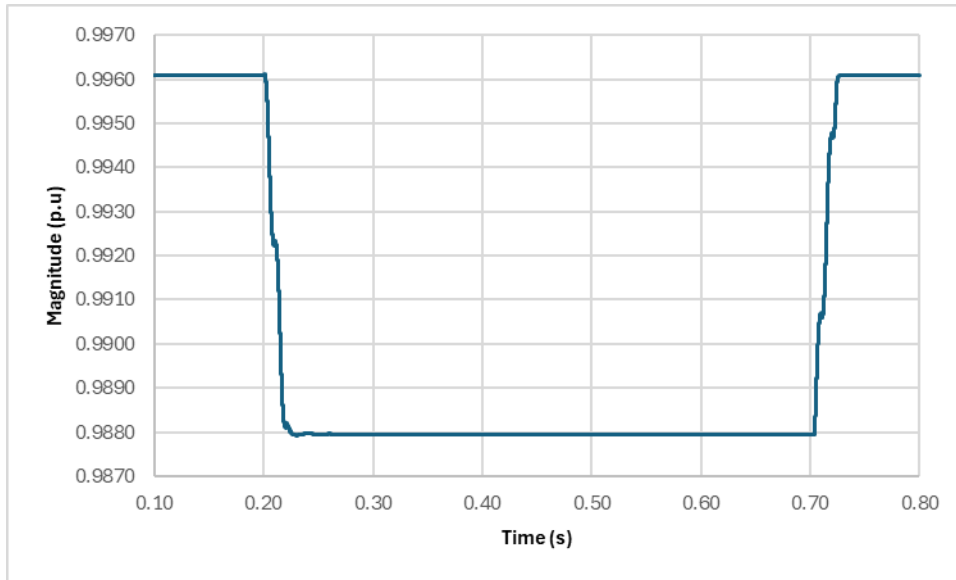


Fig. 12: D-STATCOM magnitude fault SPGvs time graph

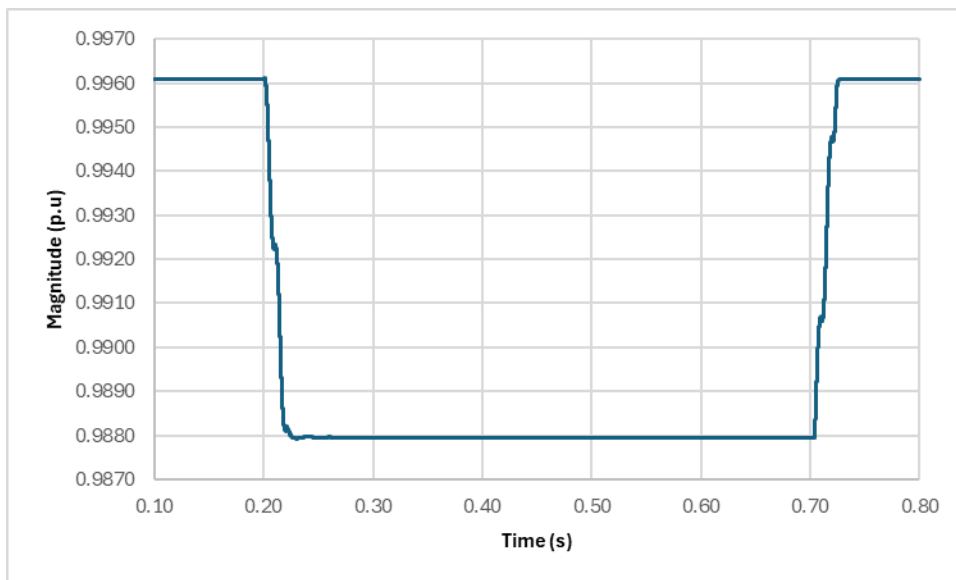


Fig. 13: D-STATCOM magnitude fault DPG vs time graph

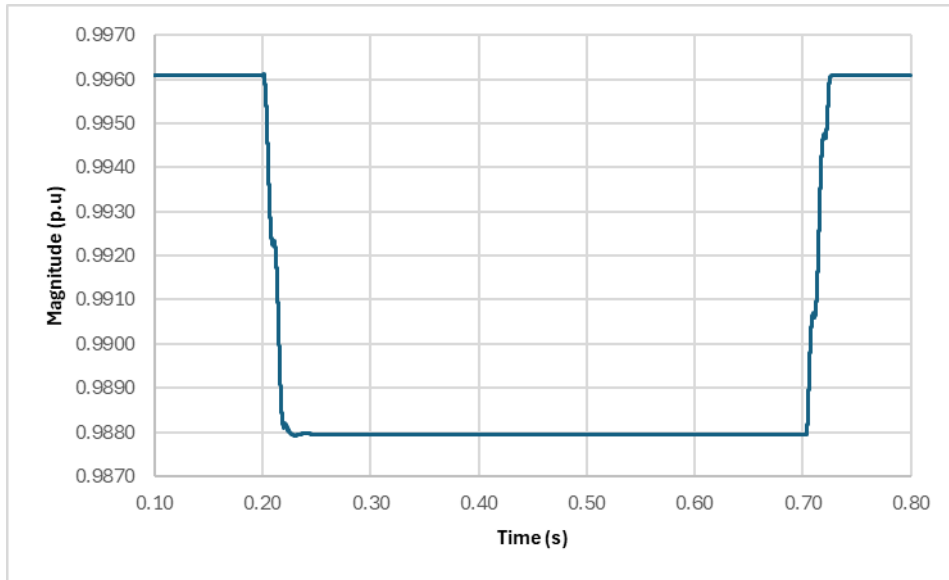


Fig. 14: D-STATCOM magnitude fault tpg vs time graph

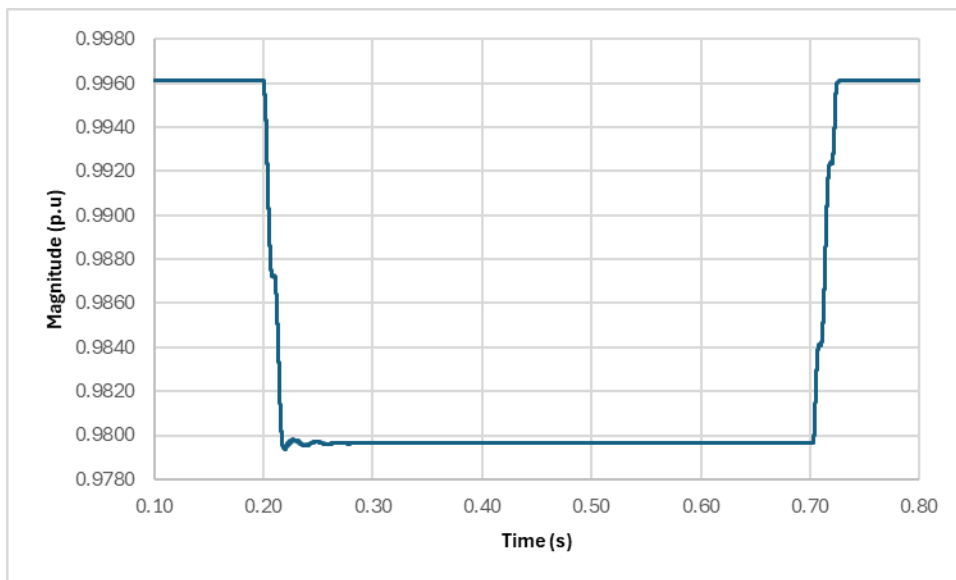


Fig. 15: D-STATCOM magnitude fault LL vs time graph

3.4 Comparison circuit

The provided data and graph present a comparison of voltage sag mitigation using a DVR (Dynamic Voltage Restorer) and a D-STATCOM (Distribution Static Synchronous Compensator). The data focuses on the percentage voltage difference between the voltage sag with the DVR and the voltage sag with the D-STATCOM for four different fault types: single-phase-to-ground (SPG), double-phase-to-ground (DPG), three-phase-to-ground (TPG), and line-to-line (LL). The percentage voltage difference represents the improvement achieved by the D-STATCOM over the DVR in reducing voltage sag. Analysis of the data reveals that the D-STATCOM consistently outperforms the DVR in mitigating voltage sags across all fault types. The percentage voltage difference is positive in all cases, indicating that the D-STATCOM results in a higher voltage level compared to the DVR under the same fault conditions. However, the degree of improvement varies. The most significant improvement is observed for the three-phase-to-ground (TPG) fault, with a voltage difference of 2.44%. This suggests that the D-STATCOM is particularly effective in handling severe fault conditions, where the voltage sag is more pronounced. The higher improvement in TPG could be attributed to the D-STATCOM's superior ability to compensate for the larger voltage

dips associated with this fault type. The line-to-line (LL) fault shows the least improvement (0.89%), indicating that the difference in performance between the DVR and D-STATCOM is less pronounced under this fault condition. This might be due to the relatively smaller voltage sag experienced during LL faults compared to other fault types. The double-phase-to-ground (DPG) fault shows a moderate improvement (1.15%), falling between the TPG and LL faults. The single-phase-to-ground (SPG) fault also shows a marginal improvement (0.06%), suggesting that even under less severe conditions, the DVR offers a slight advantage over the D-STATCOM. In conclusion, the data strongly suggests that the DVR is a more effective device for mitigating voltage sags compared to the D-STATCOM, particularly under severe fault conditions. The consistent improvement across all fault types, although varying in magnitude, highlights the DVR superior capabilities.

Table 4: Comparison D-STATCOM and DVR circuit

Type of Fault	Voltage Sag With DVR (p.u.)	Voltage Sag With D-STATCOM (p.u.)	Percentage Voltage Difference (%)
SPG	0.9886	0.9880	0.06
DPG	0.9883	0.9768	1.15
TPG	0.9880	0.9636	2.44
LL	0.9885	0.9796	0.89

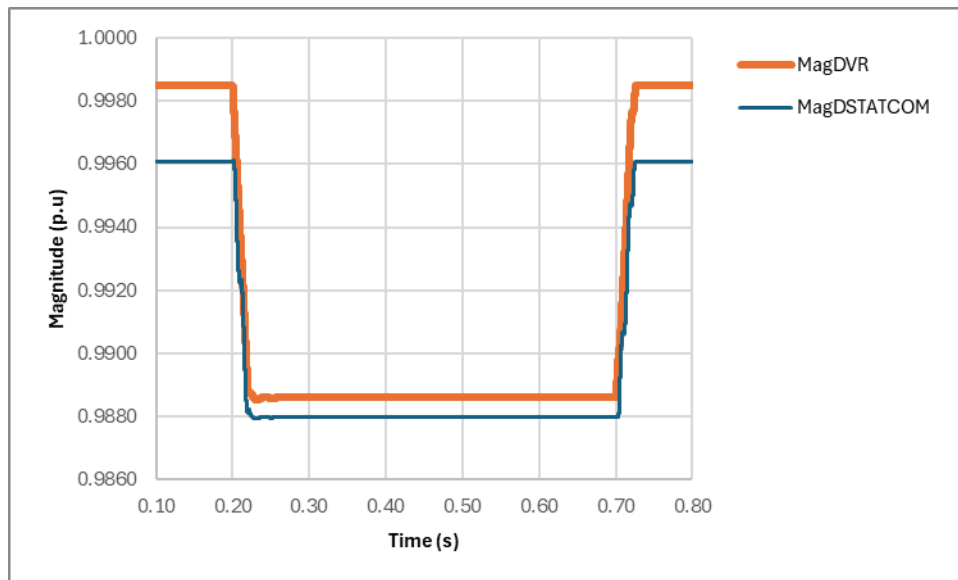


Fig. 16: D-STATCOM and DVR magnitude comparison SPG vs time graph

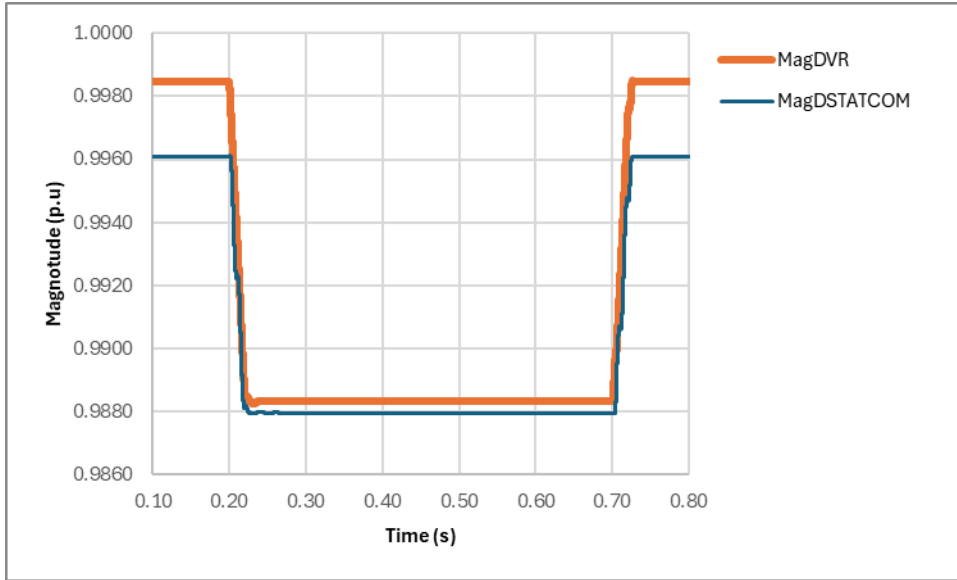


Fig. 17: D-STATCOM and DVR magnitude comparison DPG vs time graph

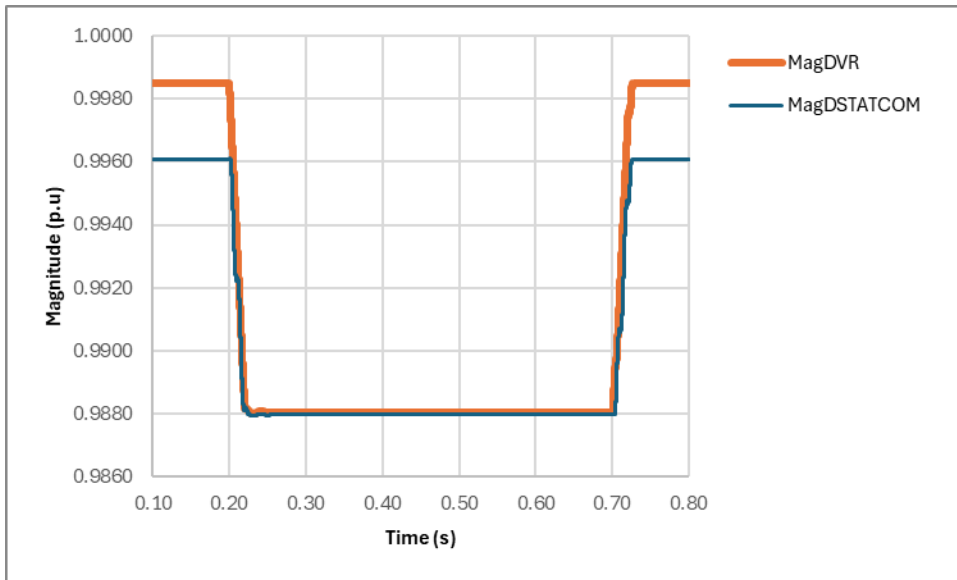


Fig. 18: D-STATCOM and DVR magnitude comparison TPG vs time graph

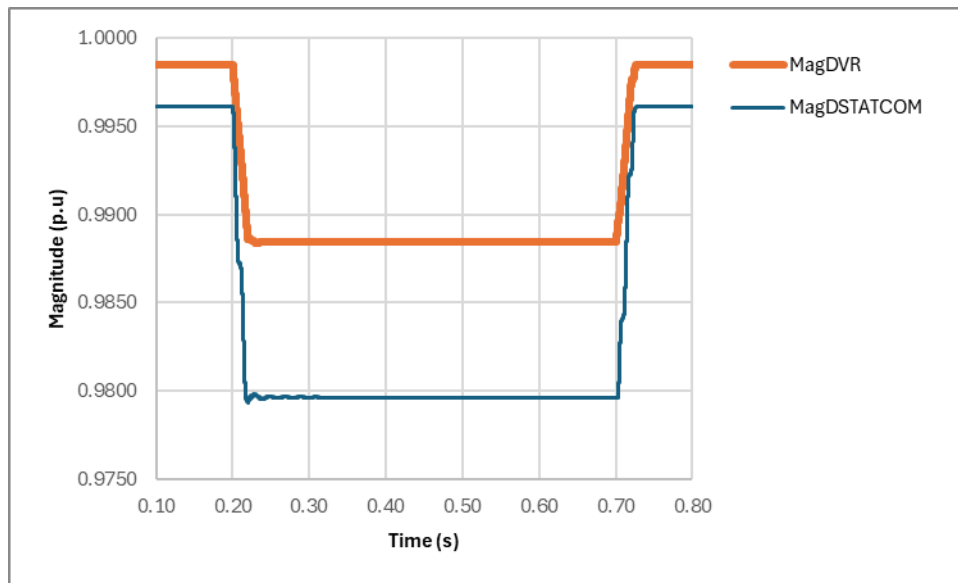


Fig. 19: D-STATCOM and DVR magnitude comparison LL vs time graph

4. Conclusion

This research successfully achieved its objectives of developing and validating a MATLAB model of a power distribution system incorporating DVR and D-STATCOM for voltage sag mitigation, comparatively analyzing their performance under voltage sags, and analyzing voltage recovery under diverse fault scenarios. The validated MATLAB model, incorporating real-world data where available, enabled comprehensive simulation of various fault types, locations, and severities, providing a robust platform for analysis. Comparative analysis revealed distinct strengths for each FACTS device. The DVR demonstrated superior performance in mitigating deep voltage sags, particularly during severe or prolonged faults, due to its direct voltage injection capability. This characteristic allows for rapid voltage restoration, minimizing the impact on sensitive loads during critical events. Conversely, the D-STATCOM proved more effective in maintaining voltage stability under fluctuating loads and harmonic distortions by dynamically adjusting reactive power. This highlights its suitability for applications requiring consistent voltage regulation and power quality enhancement. The research extended beyond simple metrics like recovery time, considering broader aspects such as flicker mitigation and overall system stability for a more holistic performance assessment. Simulations across a wide range of fault scenarios consistently demonstrated the effectiveness of both DVR and D-STATCOM in accelerating voltage recovery and minimizing the impact on sensitive loads. Furthermore, analysis of transient responses during fault events identified potential areas for future optimization of control strategies, suggesting avenues for further research and improvement. The comprehensive nature of this research, encompassing detailed modeling, rigorous simulation, and in-depth comparative analysis, provides a strong foundation for informed decision-making regarding the selection and implementation of FACTS devices in power distribution systems. The findings offer valuable insights into the specific strengths of DVR and D-STATCOM technologies, enabling engineers and system operators to choose the most appropriate technology based on the specific needs and characteristics of their power system. The robust methodology employed ensures the reliability and generalizability of the results, contributing significantly to the advancement of power system design and operation.

References

- [1] Abdelaal, A. K., Shaheen, A. M., El-Fergany, A. A., & Alqahtani, M. H. (2024). Sliding mode control based dynamic voltage restorer for voltage sag compensation. *Results in Engineering*, 24, 102936. <https://doi.org/10.1016/j.rineng.2024.102936>
- [2] Bharath, Y. K., & Purushothama, G. K. (2015). Power quality enhancement using ANN-based optimal placement of D-STATCOM in a radial distribution system. In *International Conference on Intelligent and Autonomous Systems (ICIAS-2015)* (pp. 150-153). Hassan, India. <https://www.researchgate.net/publication/311713623>
- [3] Kamarposhti, M. A., Colak, I., Thounthong, P., & Eguchi, K. (2023). Modeling and simulation of DVR and D-STATCOM in presence of wind energy system. *Computers, Materials & Continua*, 74(2), 4547–4570. <https://doi.org/10.32604/cmc.2023.034082>
- [4] Kilic, H., Asker, M. E., & Haydaroglu, C. (2024). Enhancing power system reliability: Hydrogen fuel cell-integrated D-STATCOM for voltage sag mitigation. *International Journal of Hydrogen Energy*, 75, 557-566. <https://doi.org/10.1016/j.ijhydene.2024.03.313>
- [5] Latha, K. S., Sharma, P. M., & Manjula, M. (2022). Review on power quality improvements in DG using DSTATCOM and DVR. *Anveshana's International Journal of Research in Engineering and Applied Sciences*, 7(9), 79–89.
- [6] Moghassemi, A., & Padmanaban, S. (2020). Dynamic voltage restorer (DVR): A comprehensive review of topologies, power converters, control methods, and modified configurations. *Energies*, 13(16), 4152. <https://doi.org/10.3390/en13164152>
- [7] Pandey, S., Singh, S. P., & Yadav, R. S. (2018). Performance comparison of DVR and D-STATCOM for power quality improvement using non-linear loads. *International Journal of Advance Research in Science and Engineering*, 7(Special Issue 01), 395–402.
- [8] Sulaiman, S., & Rahman, M. A. (2023). Harmonic mitigation in power systems using STATCOM for improved power quality. *Energy Reports*, 9, 456-467. <https://doi.org/10.1016/j.egy.2023.04.012>
- [9] Tarimoradi, H., Mahmoodi, S., & Rezaei, N. (2023). Network leveling based on voltage-sag mitigation using dynamic voltage restorers. *Electric Power Systems Research*, 220, 109348. <https://doi.org/10.1016/j.epsr.2023.109348>
- [10] Vishwakarma, J., & Sharma, A. K. (2015). Simulation and comparison of DVR and DSTATCOM used for voltage sag mitigation at distribution side. *International Journal of Recent Research in Electrical and Electronics Engineering (IJRREEE)*, 2(2), 197–205. www.paperpublications.org
- [11] Whakil Ahamed Shakil, Midhat Rahman, Md Samiur Rahman. (2022). Fault Analysis on Three Phase Transmission Lines and its Detection. *ResearchGate*. Retrieved from <https://www.researchgate.net/publication/360005102>