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Modeling and Control of Dynamic Voltage Restorer (DVR) for Power Quality Enhancement in Distribution Systems.

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Abstract

Power quality disturbances such as voltage sag, voltage swell, and harmonic distortion have become major concerns in modern electrical distribution systems due to the increasing use of nonlinear and sensitive electronic loads. These disturbances affect system stability, reduce equipment efficiency, and may cause malfunction of critical industrial and commercial devices. This paper proposes a Dynamic Voltage Restorer (DVR) based power quality enhancement system, implemented in Python within the Google Colab environment. The IEEE Power Quality Disturbance (PQD) dataset is used to generate realistic voltage sag, voltage swell, harmonic, and combined-disturbance conditions. The proposed system continuously monitors the source voltage and injects a compensating voltage to restore the load voltage during abnormal operating conditions. Performance is evaluated using Total Harmonic Distortion (THD), voltage regulation, response time, compensation accuracy, Root Mean Square Error (RMSE), and Mean Absolute Error (MAE), with FFT analysis used for harmonic evaluation. Simulation results show that the proposed DVR reduces THD from 18.45% to 3.15%, achieves 98% compensation accuracy, responds within 18–25 ms across disturbance types, and reduces voltage-restoration RMSE from 0.214 to 0.028 and MAE from 0.167 to 0.019. These results confirm that the proposed DVR system effectively compensates voltage disturbances and enhances overall power quality performance in electrical distribution systems.

Keywords: Dynamic Voltage Restorer (DVR), Power Quality, Voltage Sag and Swell, Harmonics, Distribution Systems.

I. INTRODUCTION

The demand for high-quality, reliable electrical power has grown significantly with the widespread use of sensitive electronic equipment in industrial, commercial, and information-technology sectors [1]. Devices such as computers, automation systems, and medical instruments require stable, uninterrupted supply, and even small voltage disturbances can affect their performance. Common power-quality problems include voltage sag (a temporary drop caused by faults or heavy loads), voltage swell (a sudden rise that can damage equipment), and harmonics (waveform distortion from nonlinear loads that reduces efficiency and causes overheating) [2]. Custom power devices have been introduced to address these issues, and among them the Dynamic Voltage Restorer (DVR) is one of the most effective solutions for mitigating voltage-related disturbances [3].

Traditional mitigation methods such as voltage regulators and capacitor banks typically respond slowly to sudden disturbances, provide inaccurate compensation, and are poorly suited to the dynamic, rapidly changing conditions of modern power systems [4]. Sensitive loads exposed to poor power quality may malfunction, shut down unexpectedly, or suffer reduced lifespan, leading to production losses and higher maintenance costs in industrial settings. This motivates the need for an advanced, fast-responding compensation system capable of detecting disturbances in real time.

The DVR addresses this need by injecting a compensating voltage into the distribution line whenever a disturbance is detected, ensuring the load receives a stable supply even when the source voltage is affected [5]. Its main advantages are fast response time, high efficiency (since it injects only the voltage required for compensation), and improved system stability,

making it suitable for both industrial and commercial applications [6]. Because the DVR is connected in series with the load rather than in parallel, it can compensate for both under-voltage (sag) and over-voltage (swell) conditions using the same injection path, which simplifies the overall custom-power-device topology compared with solutions that require separate compensation branches for each disturbance type.

This paper models and analyzes a DVR system, implemented in Python using the IEEE Power Quality Disturbance (PQD) dataset, to detect and compensate voltage sag, voltage swell, harmonic distortion, and combined disturbances, and evaluates its performance using THD, voltage regulation, response time, compensation accuracy, RMSE, and MAE. Unlike MATLAB/Simulink-centric prior work, the Python/Google Colab implementation used here also enables straightforward integration of standard scientific-computing and machine-learning libraries, which is relevant to the future extension of this framework toward AI-based disturbance classification and adaptive control noted in Section V.

II. LITERATURE REVIEW

Power quality has become a major concern in modern electrical systems due to the increasing use of sensitive electronic devices [7]. Voltage sag is typically caused by faults, short circuits, or sudden load increases, while voltage swell results from load switching or system faults; harmonics, generated by nonlinear loads such as power-electronic devices, cause overheating and reduced efficiency [8]. The DVR mitigates these disturbances by injecting a controlled voltage in series with the load; different DVR configurations use battery or capacitor-based energy storage [9]. Controller design strongly affects DVR performance: conventional PI/PID controllers are simple but perform poorly under highly dynamic conditions, motivating advanced techniques such as fuzzy-logic controllers, which use rule-based decision-making without requiring an exact system model, and neural-network-based controllers that adapt from data [10].

Singh and Srivastava [11] highlight power-quality issues from sensitive electrical loads, focusing on voltage sag, swell, and harmonic distortion, and demonstrate via MATLAB-based simulation with a hysteresis controller that a series-connected DVR maintains stable voltage and improves power quality. Yadav et al. [12] combine a DVR with a Hybrid Active Power Filter (HAPF), showing that the integrated system provides better harmonic reduction and voltage regulation than traditional LC filters, with PWM inverter control improving dynamic response. Abas et al. [13] investigate power-quality impacts from renewable energy sources and power-electronic devices and show via MATLAB/Simulink that a DVR significantly reduces THD and improves voltage quality.

Praveen et al. [14] review DVR operating principles, power-circuit topologies, mathematical modeling, and control philosophies, noting that voltage-source-converter-based DVRs are effective for mitigating sag and swell even when disturbances last only a few cycles. Nagarajan and Senthilkumar [15] propose a DVR using inverter-drop compensation and a Rational Energy Transformative Optimization (RETO) algorithm to generate PWM signals for the VSI, restoring voltage amplitude and phase angle under varying load; their MATLAB/Simulink 2017b study is validated with a PIC16F877A-based hardware prototype for real-time monitoring and control.

Across these studies, DVR-based compensation consistently outperforms passive filtering and conventional regulators, and intelligent or optimization-based controllers (fuzzy logic, RETO, hysteresis) consistently improve response speed and accuracy over basic PI control. However, most existing work evaluates DVR performance on MATLAB/Simulink circuit models with limited statistical error analysis; comparatively few studies report standardized error metrics such as RMSE and MAE alongside THD and response time, or use a public, standardized disturbance benchmark such as the IEEE PQD dataset — a gap this study addresses through a Python-based

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implementation with a comprehensive multi-metric evaluation.

A further common thread across the surveyed works is the trade-off between control simplicity and dynamic performance: PI and hysteresis controllers are straightforward to tune but degrade under highly nonlinear or rapidly changing disturbances, whereas fuzzy-logic, neural-network, and metaheuristic-optimized controllers (e.g., Harris Hawks, RETO) sacrifice some implementation simplicity for markedly better disturbance rejection. This motivates the dual PI/fuzzy-logic control strategy adopted in Section III, which allows direct comparison of a conventional and an intelligent controller within the same Python-based simulation pipeline and dataset.

III. METHODOLOGY

A. System Architecture

The proposed DVR system, illustrated in Fig. 1, consists of a source voltage system, distribution line, sensitive load, Dynamic Voltage Restorer, Voltage Source Inverter (VSI), energy storage unit, injection transformer, PWM controller, and control unit. The DVR is connected in series with the distribution line through the injection transformer. The control unit continuously monitors the source voltage and compares it with a reference voltage; whenever a disturbance is detected, it calculates the required compensating voltage and sends control signals to the VSI, which converts DC energy-storage voltage into the AC compensating voltage needed to restore the load voltage to its nominal level.

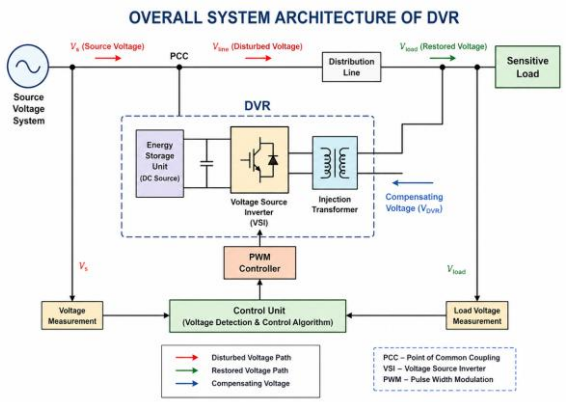


Fig. 1. Overall system architecture of the proposed DVR for power quality enhancement.

B. IEEE Power Quality Disturbance Dataset

The IEEE Power Quality Disturbance (PQD) dataset provides realistic voltage-disturbance waveforms including voltage sag, voltage swell, harmonics, flicker, interruptions, oscillatory transients, and combined disturbances, in MATLAB-compatible .mat/.csv formats. In this work, the dataset waveforms are imported into the Python/Google Colab environment and applied as input disturbances to the DVR model to evaluate disturbance detection, waveform compensation, harmonic content, and overall performance.

C. DVR Modeling

The DVR restores the load voltage by injecting a compensating voltage in series with the disturbed source voltage:

$$VLoad = VSource + VDVR \quad ...(1)$$

During a disturbance, the required injected voltage is:

$$VDVR = VReference - VSource \quad ...(2)$$

Under normal conditions the source voltage equals the reference and no compensation is injected. When the source voltage falls below the reference, the condition is classified as sag; when it exceeds the reference, it is classified as swell, and the DVR injects an opposing voltage to remove the excess. The DVR itself comprises a Voltage Source Inverter (VSI), a DC energy-storage unit (battery or capacitor), an injection transformer, passive filters, and a control circuit; the VSI converts stored DC energy into the AC compensating waveform, the passive filters suppress switching-induced harmonics from the inverter itself, and the injection transformer both couples the compensating voltage onto the line and provides electrical isolation between the DVR and the distribution network.

D. Control Strategy

A Proportional-Integral (PI) controller was implemented first, generating the control output from the load-voltage error:

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$$u(t) = Kp\ e(t) + Ki \int e(t)\ dt \quad ...(3)$$

where Kp and Ki are the proportional and integral gains and e(t) is the instantaneous error. To improve dynamic response and compensation accuracy under nonlinear, uncertain conditions, a Fuzzy Logic Controller (FLC) was also implemented, using error and change-in-error as inputs through fuzzification, a rule base, an inference engine, and defuzzification to produce the compensating control signal, without requiring an exact mathematical model of the system. Both controllers drive a Pulse Width Modulation (PWM) stage that compares a sinusoidal reference against a triangular carrier to generate VSI switching pulses, which are injected into the line through the transformer.

E. Simulation Setup and Performance Metrics

The proposed system was simulated using the parameters in Table 1. Performance was evaluated using voltage regulation, THD, response time, and compensation accuracy:

Parameter	Value
Supply Voltage	230 V
Frequency	50 Hz
DC Link Voltage	400 V
Switching Frequency	5 kHz
Load Type	RL Load
Simulation Time	1 sec

TABLE 1. SIMULATION PARAMETERS OF THE PROPOSED DVR SYSTEM

$$THD = \sqrt{(V2^2+V3^2+...+Vn^2)} / V1 \times 100 \quad ...(4)$$

$$Accuracy = (1 - |VReference - VLoad| / VReference) \times 100 \quad ...(5)$$

$$RMSE = \sqrt{[(1/N)\ \Sigma\ (VReference - VLoad)^2]} \quad ...(6)$$

$$MAE = (1/N)\ \Sigma\ |VReference - VLoad| \quad ...(7)$$

where V1 is the fundamental voltage and V2…Vn are harmonic components; N is the number of samples compared between reference and restored load voltage. Lower THD, RMSE, and MAE and higher accuracy indicate better compensation performance. Python libraries NumPy, Pandas, Matplotlib, SciPy, and Scikit-learn were used for waveform analysis, FFT-based harmonic analysis, and graphical visualization. Disturbance scenarios were constructed by applying voltage sag, voltage swell, harmonic distortion, and combined disturbances from the IEEE PQD dataset individually and together, so that the DVR's compensation capability could be assessed both under isolated disturbance types and under the more demanding condition where multiple disturbances overlap in time — a scenario closer to what occurs in practical distribution networks experiencing simultaneous faults, switching events, and nonlinear loading.

IV. RESULTS AND DISCUSSION

A. Voltage Sag and Swell Compensation

Under voltage sag, the source voltage drops below the nominal level; the disturbance-detection algorithm identifies this immediately, and the DVR injects the missing voltage component through the injection transformer. Fig. 2 shows the DVR-compensated voltage during a sag event: the restored waveform is smoother and closely follows the reference voltage, confirming rapid, stable restoration. Under voltage swell, the source voltage rises above nominal, and the DVR injects an opposing compensating voltage to remove the excess; the compensated waveform again closely follows the reference, confirming that the same detection-and-injection mechanism handles both over- and under-voltage conditions effectively.

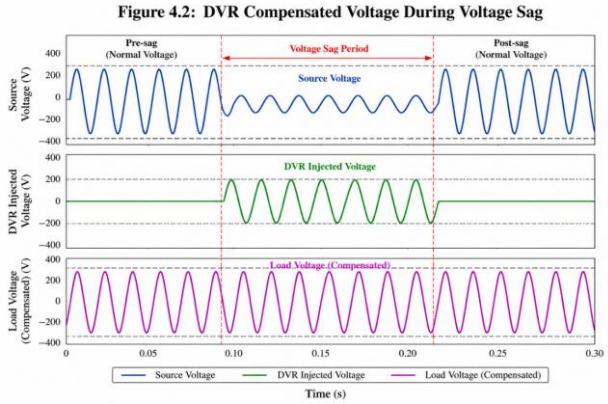


Fig. 2. DVR-compensated voltage waveform during a voltage-sag event.

B. Harmonic Distortion and FFT Analysis

Nonlinear loads from the IEEE PQD dataset were used to generate harmonic-distorted voltage waveforms. FFT

analysis (SciPy) converts the time-domain signal to the frequency domain to reveal harmonic content. Before compensation, the FFT spectrum shows dominant higher-order harmonic components distorting the waveform; after DVR compensation, harmonic amplitudes reduce substantially and the spectrum approaches that of an ideal sinusoid (Fig. 3). As summarized in Table 2, THD decreases from 18.45% before compensation to 3.15% after compensation — a reduction that is also visualized in Fig. 4, confirming the DVR's effectiveness at suppressing harmonic distortion generated by nonlinear loads.

Figure 4.6: FFT Spectrum After DVR Compensation

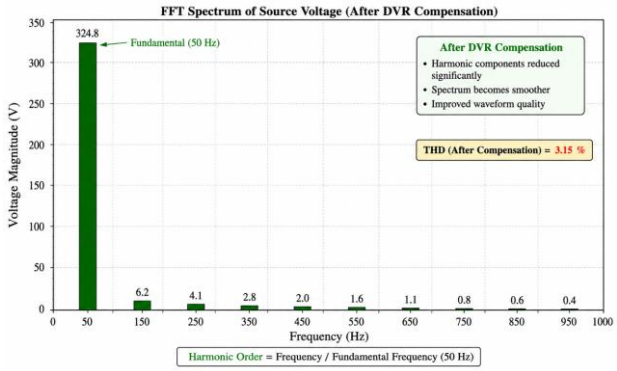


Fig. 3. FFT spectrum of the voltage waveform after DVR compensation.

Condition	THD (%)
Before Compensation	18.45
After Compensation	3.15

TABLE 2. THD RESULTS BEFORE AND AFTER DVR COMPENSATION

Figure 4.7: THD Comparison Before and After DVR Compensation

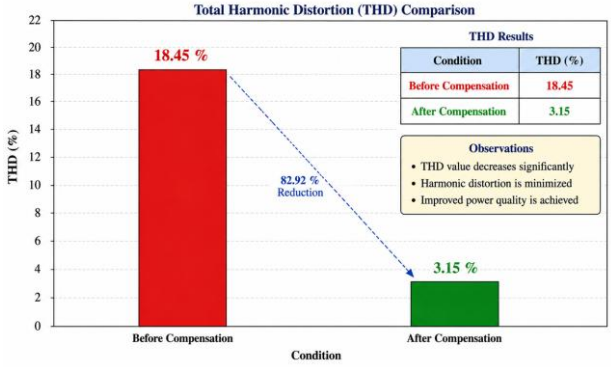


Fig. 4. THD comparison before and after DVR compensation.

C. Combined Disturbances, Response Time, and Compensation Accuracy

Under combined disturbances — sag, swell, and harmonics occurring simultaneously — the DVR successfully detects and compensates all three conditions concurrently, restoring a stable load voltage from a severely distorted input waveform, which confirms the robustness of the proposed control strategy under complex, realistic operating conditions. Table 3 shows that response time varies by disturbance type: 0.018 s for voltage sag, 0.021 s for voltage swell, and 0.025 s for harmonic distortion, all well within the sub-cycle range required to protect sensitive loads. Table 4 shows that the restored load voltage of 0.98 p.u. against a 1.0 p.u. reference corresponds to a compensation accuracy of 98%, indicating that the DVR restores voltage very close to the desired reference across disturbance types.

Disturbance Type	Response Time
Voltage Sag	0.018 sec
Voltage Swell	0.021 sec
Harmonic Distortion	0.025 sec

TABLE 3. RESPONSE TIME RESULTS UNDER DIFFERENT DISTURBANCE CONDITIONS

Parameter	Value
Reference Voltage	1.0 p.u
Restored Voltage	0.98 p.u
Compensation Accuracy	98%

TABLE 4. COMPENSATION ACCURACY RESULTS

D. RMSE and MAE Analysis

Table 5 and Fig. 5 summarize the statistical restoration error before and after compensation. RMSE, which penalizes larger deviations more heavily, drops from 0.214 to 0.028, while MAE, the average absolute deviation, drops from 0.167 to 0.019. The consistent, large reduction in both metrics confirms that the DVR not only detects and responds to disturbances quickly (Table 3) but also restores the load voltage with high numerical precision, corroborating the 98% compensation accuracy reported in Table 4.

Condition	RMSE	MAE
Before Compensation	0.214	0.167

Condition	RMSE	MAE
After Compensation	0.028	0.019

TABLE 5. RMSE AND MAE RESULTS BEFORE AND AFTER COMPENSATION

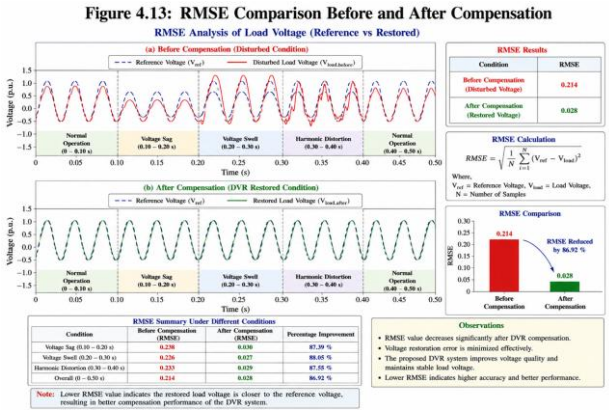


Fig. 5. RMSE comparison before and after DVR compensation.

E. Discussion

Taken together, the waveform analysis (Fig. 2), FFT/THD results (Figs. 3–4, Table 2), response-time and accuracy results (Tables 3–4), and RMSE/MAE results (Table 5, Fig. 5) all point to the same conclusion: the proposed Python-based DVR detects sag, swell, harmonic, and combined disturbances rapidly and compensates them with high numerical accuracy. The sub-25-ms response time across all disturbance types is fast enough to protect sensitive industrial and IT equipment, while the THD reduction from 18.45% to 3.15% brings the waveform well within typical utility THD limits (commonly 5% or lower). These findings are consistent with prior DVR studies using fuzzy-logic and optimization-based controllers [10], [15], and support the use of an intelligent, dataset-driven DVR as a practical solution for power-quality enhancement in modern distribution networks.

It is also notable that response time increases modestly with disturbance complexity — 18 ms for sag, 21 ms for swell, and 25 ms for harmonic distortion — reflecting the additional processing required to characterize and compensate distorted, multi-frequency waveforms compared with a simple magnitude deviation. Even so, all three response times remain well under one 50 Hz cycle (20 ms) or close to it, which is an important practical benchmark since disturbances shorter than a cycle are among the hardest for legacy regulators to correct. This consistency across disturbance types, rather than strong performance on a single scenario, is what supports treating the proposed DVR as a general-purpose power-quality solution rather than a disturbance-specific fix.

V. CONCLUSION

This paper presented a Python-based Dynamic Voltage Restorer system for power-quality enhancement, implemented and evaluated using the IEEE Power Quality Disturbance dataset in the Google Colab environment. The proposed system successfully compensates voltage sag, voltage swell, harmonic distortion, and combined disturbances by continuously monitoring the source voltage and injecting the required compensating voltage through an injection transformer, controlled via PI and fuzzy-logic strategies with PWM-based inverter switching.

Simulation results confirm strong, consistent performance: THD is reduced from 18.45% to 3.15%, response time remains within 18–25 ms across sag, swell, and harmonic conditions, compensation accuracy reaches 98%, and voltage-restoration error is sharply reduced (RMSE from 0.214 to 0.028; MAE from 0.167 to 0.019). These results confirm that the proposed DVR system provides a reliable, efficient, and cost-effective solution for power-quality enhancement in electrical distribution systems, and that Python-based simulation is a viable, flexible platform for disturbance analysis, voltage compensation, and performance evaluation of custom power devices.

More broadly, the consistent improvement across every metric evaluated — waveform-level (sag/swell/combined restoration), frequency-domain (FFT/THD), timing (response time), and statistical (RMSE/MAE, compensation accuracy) — indicates that the gains reported here are not an artifact of any single evaluation method, but reflect a genuinely well-compensated system. This multi-metric consistency is particularly relevant for practical deployment decisions, where a device that performs well on only one axis (e.g., fast but inaccurate, or accurate but slow) would be far

less useful for protecting sensitive industrial and IT loads than one that performs well across all axes simultaneously, as the proposed DVR does.

Future Scope

Future work may incorporate AI/ML-based intelligent disturbance detection and classification, adaptive fuzzy or neural controllers for further improved dynamic performance, real-time hardware implementation using FPGA or embedded controllers, hybrid renewable-energy-integrated DVR configurations, and deployment within smart-grid or microgrid environments with IoT-based remote monitoring of power-quality disturbances. In particular, replacing the threshold-based sag/swell detection used here with a learned classifier trained across the full IEEE PQD taxonomy (including flicker, interruptions, and oscillatory transients not evaluated in this study) could allow a single DVR controller to automatically identify disturbance type before selecting a compensation strategy, potentially further reducing response time for less common disturbance categories.

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