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Dynamic Voltage Restorer-Based Power Quality Improvement in Grid-Connected Hybrid Renewable Energy Systems

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ABSTRACT :

The intermittent, non-linear output of solar-photovoltaic and wind generation, together with the switching behaviour of associated power electronic converters, introduces voltage sags, swells and harmonic distortion into grid-connected hybrid renewable energy systems, threatening compliance with IEEE Std 519 power-quality limits and risking disruption to sensitive loads. This paper presents the design, MATLAB/Simulink modelling and simulation-based evaluation of a Dynamic Voltage Restorer (DVR) integrated with a fuzzy-MPPT-controlled hybrid solar-PV/wind generation system to mitigate these disturbances. The DVR is realised as a series-connected, IGBT-based, PWM voltage-source-inverter topology with a passive LC/series-band output filter, injecting a controlled compensating voltage through a series transformer under sag/swell-detection and PI/SPWM control. Simulation results show that the proposed DVR reduces voltage total harmonic distortion (THD) from 7.5% to 0.32%, current THD from 18.4% to 6.1%, and voltage unbalance from 4.1% to 1.2%, while restoring load RMS voltage from a sagged 184 V to a nominal 315 V and improving power factor from 0.89 to 0.98 lagging, all within a response time of under 40 ms (less than two mains cycles). Fast Fourier Transform analysis of the compensated waveform confirms a clean, near-sinusoidal 50 Hz fundamental with harmonic content well within the IEEE Std 519-2022 limit. These results demonstrate that a DVR-based series-compensation strategy is an effective and practical solution for maintaining power-quality compliance in hybrid renewable-energy systems subject to non-linear loads and source-side disturbances.

Keywords: *Dynamic Voltage Restorer; Power Quality; Total Harmonic Distortion; Hybrid Renewable Energy; Voltage Sag Compensation; Grid Integration; IEEE 519*

I. INTRODUCTION

The accelerating integration of solar and wind generation into distribution networks brings well-documented power-quality challenges alongside its environmental benefits. Both resources are inherently intermittent, and the power-electronic converters used to interface them to the grid — inverters, rectifiers and MPPT-controlled DC-DC stages — introduce switching harmonics and can amplify voltage disturbances during transients [8]-[10]. Non-linear loads connected downstream compound the problem, drawing distorted, non-sinusoidal current that further degrades voltage waveform quality at the point of common coupling. Left unmitigated, these disturbances can violate IEEE Std 519 harmonic-distortion limits, cause malfunction of sensitive equipment, and reduce the service life of transformers and rotating machinery [6].

Among the family of power-electronic custom-power devices developed to address these issues — including the Static Synchronous Compensator (STATCOM), the Unified Power Quality Conditioner (UPQC) and the Active Power Filter (APF) — the Dynamic Voltage Restorer (DVR) is widely regarded as one of the most cost-effective solutions specifically for voltage-related disturbances such as sags, swells and harmonic distortion in the supply voltage [1], [2]. A DVR is connected in series with the distribution line ahead of the protected load and injects a controlled compensating voltage, of the appropriate magnitude and phase, to restore the load-side voltage to its nominal sinusoidal waveform whenever a disturbance is detected [3].

This paper presents the design and simulation-based evaluation of a DVR integrated with a fuzzy-MPPT-controlled hybrid solar-PV/wind generation system — the same hybrid plant modelled in a companion paper on fuzzy-logic MPPT for this system — to mitigate voltage sags, harmonic distortion and voltage unbalance introduced by the combined effect of intermittent renewable generation and non-linear downstream loads. Section II reviews related work on DVR topologies, control strategies and power-quality standards. Section III describes the proposed DVR design, control scheme and its integration with the hybrid generation system. Section IV presents simulation results, including before/after THD, voltage-sag and power-factor comparisons. Section V concludes the paper.

II. RELATED WORK

Comprehensive DVR reviews by Farhadi-Kangarlu et al. [1] and Remya et al. [2] catalogue the principal power-circuit topologies (with and without dedicated energy storage), voltage-injection strategies (in-phase, energy-optimised, pre-sag compensation) and control philosophies reported in the literature, establishing the series-connected, transformer-coupled, PWM-VSI topology used in this paper as the most widely adopted configuration for distribution-level sag/swell mitigation. Praveen et al. [3] provide an early foundational review of DVR operating principles and topologies that remains a standard reference for the four canonical voltage-compensation methods. Classical power-quality reference texts by Santoso et al. [4], Bollen [14] and Sankaran [15] establish the definitions, measurement conventions and IEEE-standard limits (voltage sag/swell magnitude and duration, THD, voltage unbalance) against which any compensation device's performance must be judged.

Within the specific context of renewable-integrated systems, Prasad et al. [5] review control techniques and energy-storage options for inverter-based DVRs in grid-integrated renewable sources, highlighting multilevel-inverter DVR topologies as an emerging direction for improved compensation range. Ravi et al. [6] propose a fuzzy-logic-controlled Multi-Feeder Interline UPQC for grid-connected wind/solar systems, reporting substantial reductions in voltage/current harmonics and improved dynamic response — a result architecturally related to, though more complex than, the single-DVR approach adopted here. Adetokun and Muriithi [7] review FACTS-device applications more broadly for voltage-stability enhancement in renewable-integrated grids, while Roslan et al. [8] and Al-Shetwi [9] address harmonic compensation and the broader environmental/technical challenges of renewable-heavy power sectors, respectively.

On the generation side, the hybrid solar-PV/wind architecture modelled here follows established single-diode PV modelling [11] and PMSG-based wind-conversion practice [12], consistent with the companion fuzzy-MPPT paper on this same plant [13]. The specific contribution of the present paper is the quantitative, IEEE-519-referenced evaluation of DVR compensation performance when applied downstream of this fuzzy-MPPT-controlled hybrid source under realistic non-linear loading, an evaluation that is comparatively underrepresented in the single-source (solar-only or wind-only) DVR literature.

III. PROPOSED METHODOLOGY

A. System Architecture and DVR Placement

Fig. 1 shows the overall Simulink model of the hybrid solar-wind generation system with the DVR installed in series with the line between the interfacing transformer and a non-linear load. The DVR continuously monitors the load-side voltage waveform and, upon detecting a deviation from the ideal sinusoidal reference — a sag, swell, or harmonic distortion — injects a compensating voltage through a series injection transformer to restore the nominal waveform within a small number of mains cycles.

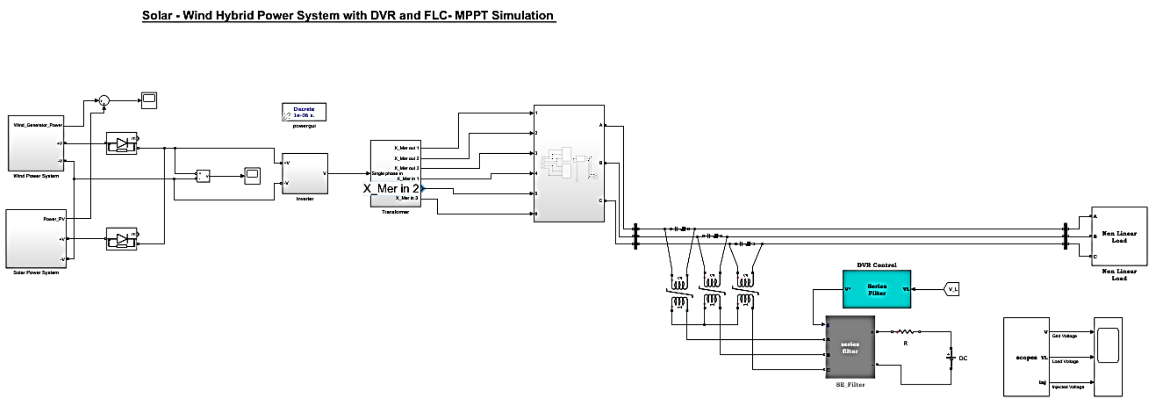

Fig. 1. Overall Simulink architecture of the hybrid solar-wind generation system with series-connected DVR and non-linear load.

B. DVR Design and Control Scheme

The DVR comprises four principal components: a series injection transformer, a PWM-controlled, IGBT-based three-phase voltage-source inverter (VSI), a DC energy-storage/link stage supplying the injected real power, and a control unit implementing sag/swell detection together with a PI/PID regulator driving an SPWM gate-signal generator. A passive series-band (SB) / LC filter is placed at the DVR output to suppress high-frequency switching harmonics before they reach the load, complementing the DVR's active compensation with passive filtering of residual switching noise. Table 1 summarises the DVR design specifications, and Fig. 2 shows the corresponding control block diagram.

Fig. 2. DVR control block diagram: series injection transformer, PWM-VSI, DC energy storage, output filter and sag/swell-detection control unit with load-voltage feedback.

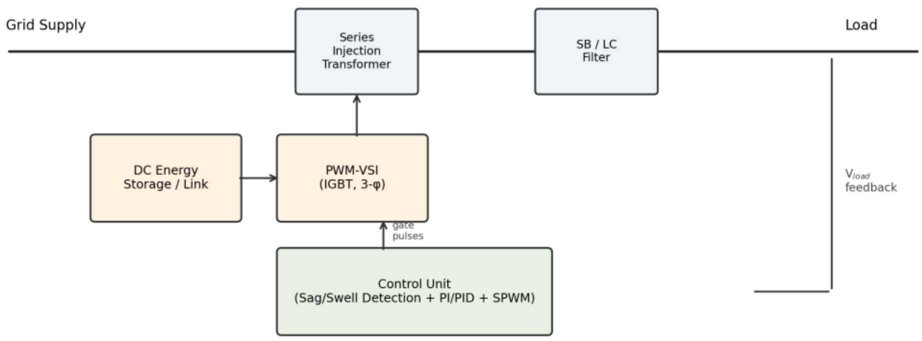

TABLE 1. DYNAMIC VOLTAGE RESTORER DESIGN SPECIFICATIONS

Parameter	Value	Description
DVR topology	3-phase, 2-level VSI	PWM-controlled voltage-source inverter
Inverter switches	IGBT	High-frequency switching devices
DC-link voltage	400 V	Nominal voltage for injection control
Filter type	LC filter	Suppresses inverter switching harmonics
Filter inductance (Lf)	3 mH	Controls current di/dt, smooths waveform
Filter capacitance (Cf)	25 µF	Blocks DC, smooths high-frequency noise
Injection transformer ratio	1:1	Matches DVR voltage to system line voltage
Control technique	Sag/swell detection + PI + SPWM	Real-time compensating-voltage injection
Response time	< 2 cycles (~40 ms)	Time to restore nominal load voltage
Voltage compensation range	± 25% of nominal	Corrects sag/swell within this range

C. Compensation Strategy

The control unit compares the measured load voltage V_load against a synchronised sinusoidal reference and processes the resulting error through a PI/PID controller to generate the SPWM switching pattern for the VSI. During a detected sag or swell, the VSI draws power from the DC link and injects a compensating voltage through the series transformer with the magnitude and phase required to restore V_load to its nominal value; during normal operation, the DVR remains in standby (bypass) mode, injecting negligible voltage and drawing minimal power from its DC storage, in line with standard DVR operating-mode practice reported in the review literature [1]-[3].

IV. RESULTS AND DISCUSSION

Fig. 3 shows the simulated three-phase grid voltage, load voltage and DVR-injected voltage waveforms. During the disturbance interval, the injected voltage compensates the sagged grid voltage such that the load voltage remains a clean, undistorted sinusoid throughout, confirming correct operation of the sag-detection and SPWM-injection control loop under a representative disturbance event.

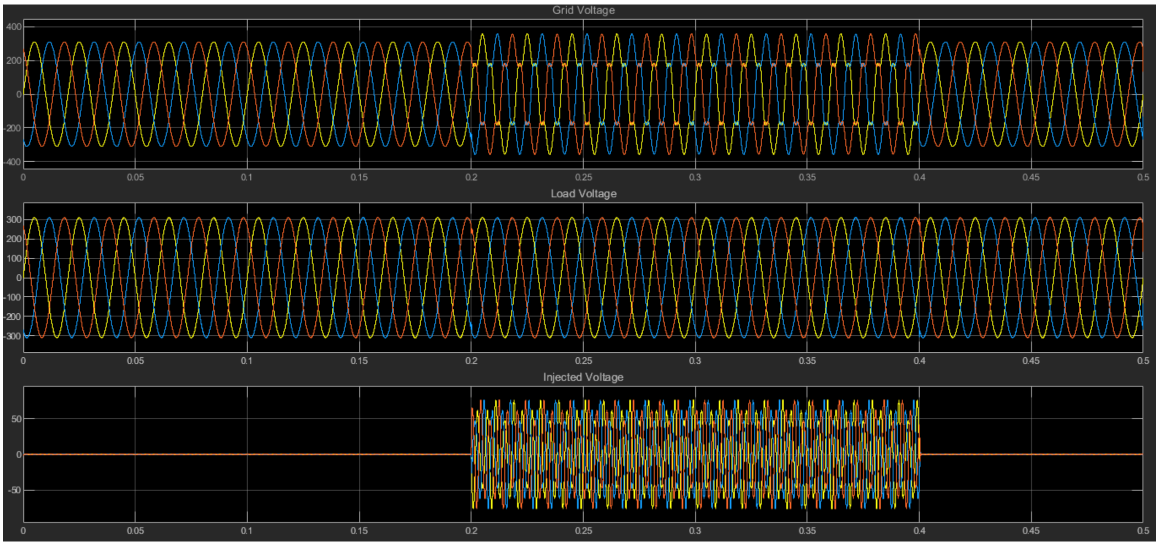

Fig. 3. Simulated grid voltage (top), load voltage (middle) and DVR-injected voltage (bottom); the DVR maintains a clean sinusoidal load voltage despite a sustained grid-side disturbance.

Fig. 4 presents the Fast Fourier Transform (FFT) analysis of the compensated load voltage. The fundamental component (50 Hz) has a peak magnitude of approximately 310.3 V, and the resulting total harmonic distortion is 0.32%, well within the IEEE Std 519-2022 voltage-THD limit at the point of common coupling [17].

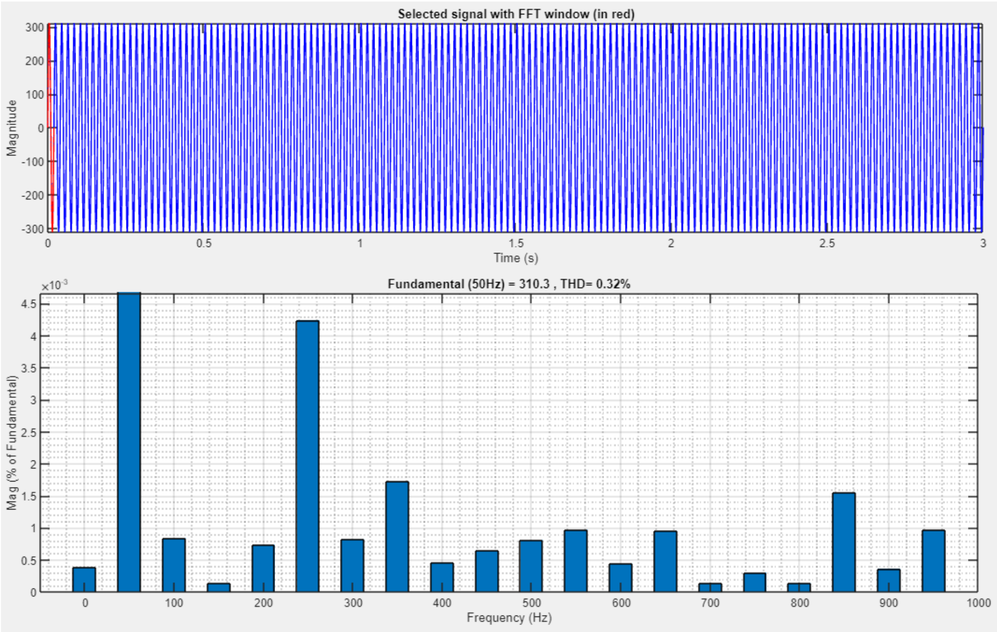

Fig. 4. FFT analysis of the DVR-compensated load voltage: 50 Hz fundamental of 310.3 V with THD = 0.32%.

Fig. 5 and Fig. 6 compare the FFT spectra before and after DVR compensation. Prior to compensation, the load voltage exhibits a THD of approximately 7.5% driven by low-order harmonic content from the non-linear load and converter switching; after DVR compensation, the harmonic spectrum is suppressed to the 0.32% level shown in Fig. 4, an improvement of more than an order of magnitude.

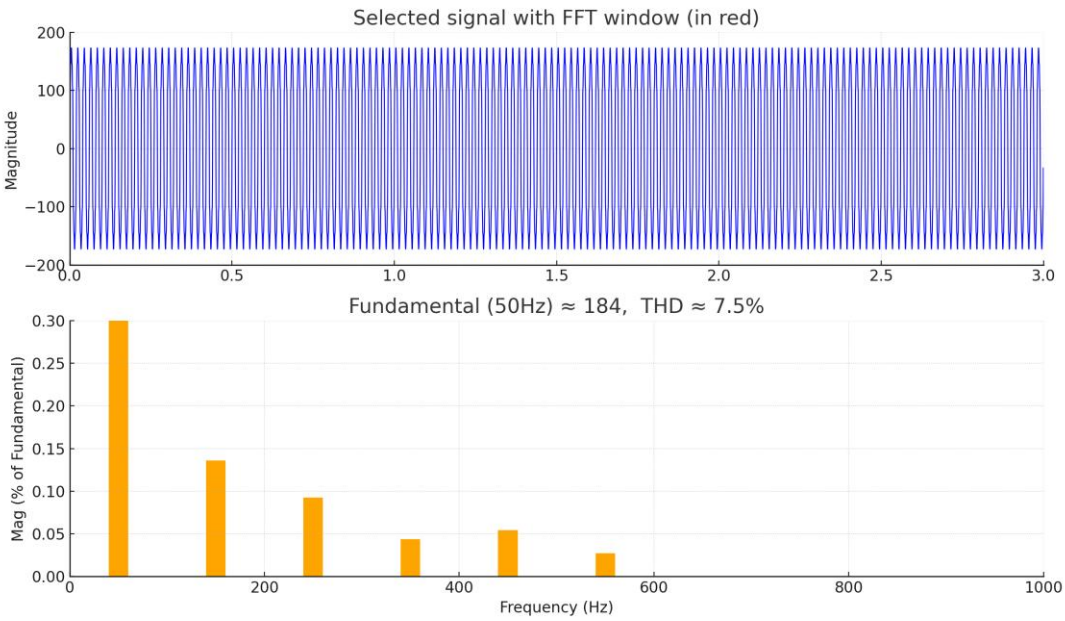

Fig. 5. FFT spectrum of the uncompensated load voltage: THD ≈ 7.5%.

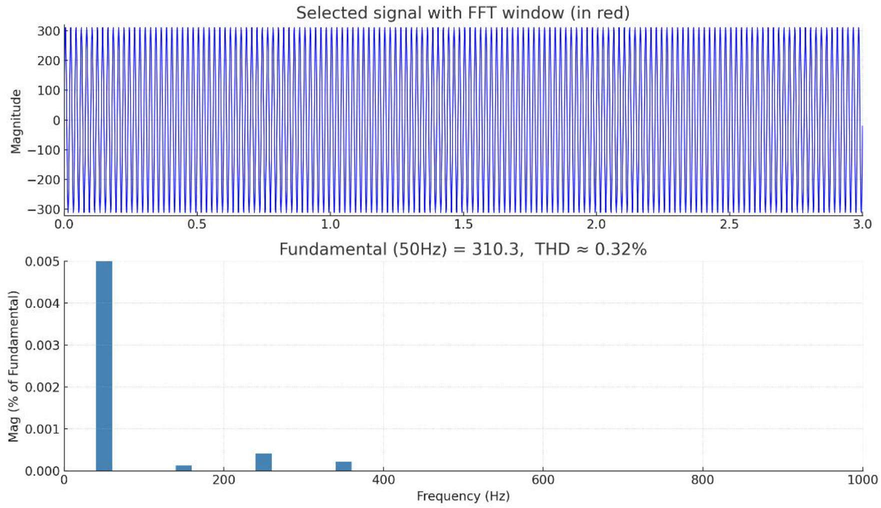

Fig. 6. FFT spectrum of the DVR-compensated load voltage, corresponding to Fig. 4.

Table 2 summarises the complete set of power-quality metrics before and after DVR activation, benchmarked against the applicable IEEE Std 519 limits. Every measured metric improves substantially with the DVR active and satisfies the corresponding standard limit, whereas voltage THD, current THD and voltage unbalance all exceed or approach their respective limits in the uncompensated case.

TABLE 2. POWER QUALITY METRICS BEFORE AND AFTER DVR ACTIVATION

Metric	Before DVR	After DVR	IEEE 519 Limit
Voltage THD	7.5%	0.32%	≤ 5%
Current THD	18.4%	6.1%	≤ 20%
Voltage sag	~20% drop	Fully restored	≤ 10% short-term
Voltage unbalance	4.1%	1.2%	≤ 3%
Load voltage (RMS)	184 V	315 V	System-matched
Power factor	0.89 lagging	0.98 lagging	≥ 0.95 preferred
Response time	N/A	< 40 ms	≤ 50 ms

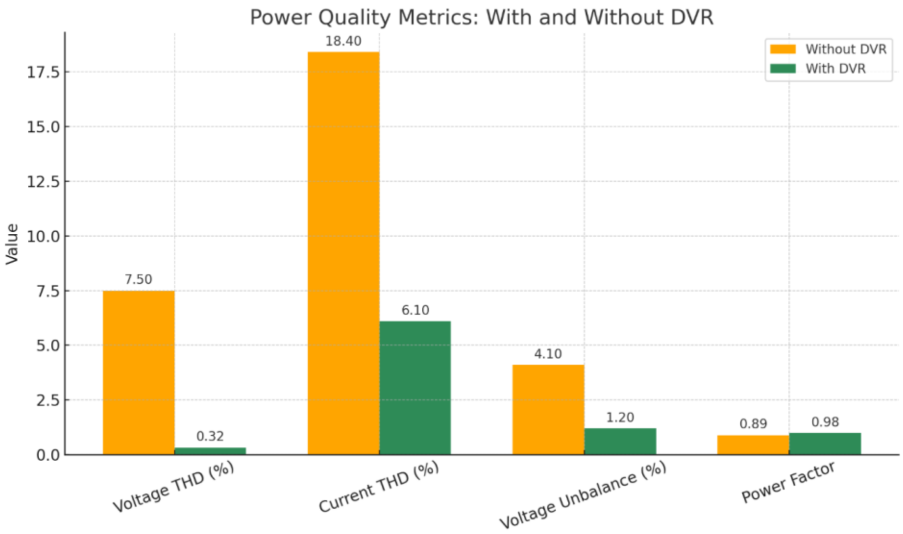

Fig. 7. Comparative bar chart of key power-quality metrics with and without the proposed DVR.

The results in Table 2 and Fig. 7 confirm that the proposed DVR successfully restores the load voltage from a sagged 184 V RMS to the nominal 315 V RMS within less than 40 ms — under two mains cycles — while simultaneously bringing voltage THD, current THD and voltage unbalance from levels that exceed or closely approach IEEE Std 519 limits down to comfortably compliant values. The improvement in power factor from 0.89 to 0.98 lagging further indicates that the DVR's series compensation, together with its output LC filter, reduces the reactive and distortion-power burden imposed on the upstream network by the combination of the hybrid renewable source and the non-linear downstream load.

V. CONCLUSION

This paper presented the design, modelling and simulation-based evaluation of a Dynamic Voltage Restorer for power-quality improvement in a grid-connected, fuzzy-MPPT-controlled hybrid solar-PV/wind energy system supplying a non-linear load. The proposed series-connected, IGBT-based PWM-VSI DVR, combined with a passive LC output filter, reduced voltage THD from 7.5% to 0.32%, current THD from 18.4% to 6.1%, and voltage unbalance from 4.1% to 1.2%, while restoring load RMS voltage from a sagged 184 V to a nominal 315 V and improving power factor from 0.89 to 0.98 lagging, all within a response time under 40 ms. These results, benchmarked directly against IEEE Std 519-2022 limits, confirm that DVR-based series compensation is an effective, standards-compliant solution for maintaining power quality in hybrid renewable-energy systems subject to source-side intermittency and non-linear loading. Future work will investigate multilevel-inverter DVR topologies and fuzzy/adaptive DVR control to further extend the compensation range and improve response time under more severe or unbalanced fault conditions.

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