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Modeling and Control of Grid-Connected PV–Battery Hybrid System Using Dynamic Voltage Restorer for Enhanced Power Quality

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Abstract

The integration of large-scale photovoltaic (PV) systems into modern power grids introduces significant challenges in maintaining power quality, including voltage sags, swells, and harmonics. To address these issues, this study presents a comprehensive modeling and control framework for a grid-connected PV–battery hybrid system equipped with a dynamic voltage restorer (DVR). The PV array is modeled using detailed mathematical equations, while the DC–DC converter incorporates advanced maximum power point tracking (MPPT) algorithms to optimize energy extraction under variable irradiance conditions. The inverter and grid interconnection are modeled to assess system stability, and the DVR is designed to compensate for voltage disturbances using a proportional-integral (PI) controller. MATLAB/Simulink simulations are performed to validate the system performance under different operating scenarios. The proposed hybrid system demonstrates improved voltage regulation, reduced power quality disturbances, and enhanced reliability of renewable energy integration into the grid. The study also lays the foundation for implementing intelligent control strategies and energy storage coordination in future smart grid applications.

Keywords: PV–battery hybrid system, maximum power point tracking (MPPT), PI controller, power quality enhancement, grid-connected photovoltaics, dynamic voltage restorer (DVR), MATLAB/Simulink modeling, renewable energy integration

INTRODUCTION

The increasing global demand for sustainable and clean energy has accelerated the integration of renewable energy sources, particularly photovoltaic (PV) systems, into the modern power grids. Solar energy, which is abundant and environmentally friendly, has emerged as a key contributor to electricity generation; however, its intermittent and variable nature presents significant challenges for grid stability and power quality. Grid-connected PV systems are susceptible to voltage sags, swells, harmonics, flicker, and other disturbances caused by rapid changes in solar irradiance, load variations, and faults in the distribution network [1–3]. These power quality issues can adversely affect sensitive loads, reduce the system efficiency, and compromise the reliability of the overall grid. To mitigate these challenges, energy storage systems, such as batteries, have been increasingly employed to store excess energy during peak generation and supply power during low-generation periods, thereby providing flexibility and enhancing system

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stability. In addition, dynamic voltage restorers (DVRs) have proven to be effective solutions for compensating voltage disturbances, injecting the required voltage into series with the grid to maintain the load-side voltage within permissible limits and protect critical equipment. The integration of PV systems with batteries and DVRs forms a hybrid system that not only addresses the intermittency and variability of solar power but also improves power quality and grid reliability [4–6]. Despite extensive research on standalone PV or DVR systems, there is a growing need to explore PV–battery–DVR hybrid configurations, where energy storage and dynamic voltage support work synergistically to enhance voltage regulation, minimize voltage fluctuations, and maintain harmonic-free operation under diverse operating conditions. Such hybrid systems are particularly relevant in modern smart grids, microgrids, and industrial applications, where maintaining an uninterrupted high-quality power supply is critical. Motivated by these challenges, this study focuses on modeling and designing a grid-connected PV–battery hybrid system integrated with a DVR, aiming to evaluate its performance under various operating scenarios, including voltage sags, swells, load changes, and partial shading conditions. The study employs detailed mathematical modeling of the PV array, battery storage dynamics, DC–DC converters with maximum power point tracking (MPPT), inverter-grid interfacing, and DVR control using a proportional-integral (PI) controller [7–10]. Furthermore, MATLAB/Simulink simulations were used to validate the capability of the system to enhance power quality, improve voltage stability, and ensure reliable energy delivery. The primary objective of this work is to develop a comprehensive modeling and simulation framework for PV–battery–DVR hybrid systems, providing insights into the optimal system design, controller performance, and effective coordination between renewable generation, energy storage, and power quality-compensating devices. Ultimately, this study aims to contribute to the advancement of sustainable and resilient grid-connected renewable energy systems capable of satisfying the increasing demand for high-quality electricity in modern power networks.

Figure 1 illustrates the block diagram of the modeling and control of a grid-connected PV–battery hybrid system using a DVR designed to enhance power quality and ensure stable energy delivery. The system comprises three major components: (1) a photovoltaic (PV) array, (2) a battery energy storage system, and (3) a utility grid. The PV array generates DC power that is regulated through a DC–DC boost converter, maintaining the desired voltage at the DC bus. Simultaneously, the battery bank, interfaced via a bidirectional DC–DC converter, supports energy management by charging during

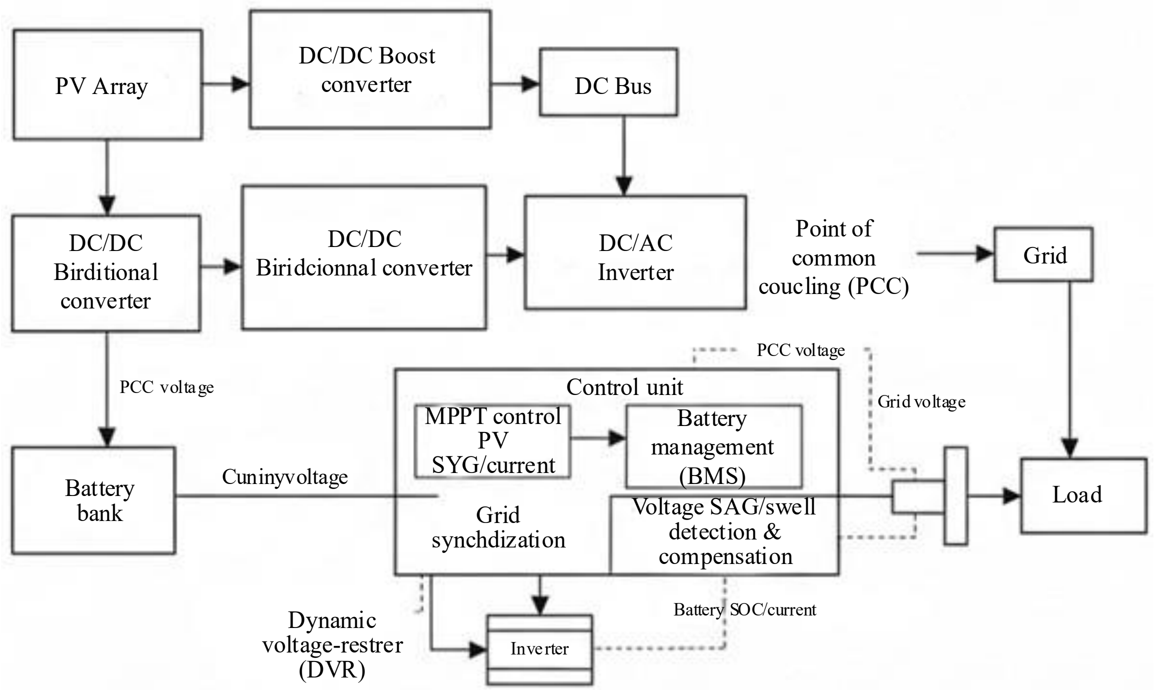

Figure 1. Block diagram of the proposed model.

surplus PV generation and discharging during low-irradiance or grid disturbances. The combined DC link supplies power to a DC–AC inverter that converts DC into AC and delivers it to the grid through the point of common coupling (PCC). A central control unit coordinates the system's operation, incorporating MPPT for optimal PV output, a battery management system (BMS) for energy balance, and synchronization control for grid interfacing. The DVR, connected in series with the grid, detects voltage sags and swells and injects the compensating voltage in real time to stabilize the load-side voltage. This integrated control ensures continuous high-quality power with improved reliability and reduced harmonic distortion. Recent studies have focused on improving the power quality and system stability of grid-connected PV systems using hybrid configurations integrating batteries and DVRs. Mishra et al. (2022) analyzed the performance of a hybrid renewable generation system with a DVR and demonstrated that such systems significantly improve voltage regulation during sags and swells while enhancing the overall system reliability [1]. Shahidi et al. (2025) proposed a hybrid DVR scheme for grid-connected photovoltaic systems and reported improved harmonic mitigation and voltage-profile maintenance under variable load and irradiance conditions [2]. Molla et al. (2020) highlighted that DVR integration in grid-connected PV arrays reduces voltage fluctuations and reactive power disturbances, emphasizing the importance of real-time compensation for distributed generation systems [3]. Naruka et al. (2025) investigated a solar PV-based distribution static compensator and showed that hybrid compensation strategies can maintain the load-side voltage within permissible limits, even under severe voltage dips [4]. Ibrahim et al. (2023) optimized the DVR performance in a remote PV system and found that coordinated battery support enhanced the voltage recovery times and ensured stable energy delivery under intermittent generation scenarios [5]. Abdelkader et al. (2022) experimentally verified the effectiveness of DVRs fed by solar PV with lithium-ion battery storage, demonstrating sustained power quality improvements and reduced voltage sag duration [6]. Kaviya et al. (2025) implemented a transformerless DVR system using a marine predator algorithm for real-time optimization and reported reduced total harmonic distortion (THD) and enhanced dynamic response during transient events [7]. Mishra et al. (2022) further reinforced the benefits of integrating batteries with DVRs in hybrid systems, noting improved system resilience and efficient load-sharing during grid disturbances [8]. Mallick et al. (2025) introduced an adaptive fuzzy PI-controlled DVR for PV systems and found that intelligent control strategies outperform conventional PI controllers in mitigating voltage fluctuations and harmonics under varying operational conditions [9]. Aljafari et al. (2022) designed a hybrid PV/battery-based energy storage system for grid-connected applications, demonstrating that coordinated energy storage and voltage restoration can significantly enhance the power quality, system stability, and reliability of renewable energy integration [10]. Collectively, these studies indicate that hybrid PV–battery–DVR systems offer a robust solution for voltage regulation, THD mitigation, and stable energy delivery in modern smart grids. The integration of advanced control algorithms, such as fuzzy logic and optimization-based approaches, further enhances the performance of DVRs, particularly under dynamic operating conditions and partial shading scenarios. Moreover, experimental and simulation results consistently highlight that incorporating batteries into DVR-assisted PV systems not only provides energy buffering during intermittency but also enables fast voltage support during grid disturbances. These findings underscore the necessity of coordinated system design, optimal controller tuning, and energy storage management to achieve reliable, high-quality power in grid-connected PV systems, thereby contributing to the advancement of sustainable and resilient renewable energy infrastructure.

SYSTEM MODELING

Modeling a grid-connected PV–battery hybrid system using a DVR involves developing a detailed understanding of how each subsystem contributes to the overall stability and efficiency of the power network. The system primarily consists of four interconnected components: (1) a photovoltaic (PV) array, (2) a battery energy storage system (BESS), (3) DC–DC converter integrated with an MPPT algorithm, and (4) an inverter for grid interfacing [11]. PV array modeling forms the basis of system performance as it defines how solar energy is converted into electrical power. The output of the PV array depends heavily on the solar irradiance and temperature, which influence both the current and voltage characteristics. The current-voltage (I–V) and power-voltage (P–V) curves of a PV module demonstrate that power generation increases with higher irradiance but decreases as the temperature rises. The I–V curve is nonlinear, and its shape changes under different environmental conditions, with one unique point known as the Maximum Power Point (MPP), where the PV system operates with maximum efficiency. Temperature variations reduce the open-circuit voltage, whereas irradiance variations primarily affect the short-circuit current. The accurate modeling of these effects is crucial for achieving maximum power extraction and maintaining stability in the system [12–14]. The BESS serves as a complementary component to the PV subsystem, providing energy buffering to stabilize the output during fluctuating solar generation or grid disturbances. The BESS stores excess energy when solar power generation exceeds the load demand and releases energy when there is a shortfall. Effective battery modeling involves understanding the charge and discharge characteristics, state of charge (SOC) behavior, and response under different loading and temperature conditions. The SOC is a critical parameter that indicates the available capacity of a battery and determines its operational health [15–17]. Maintaining an optimal SOC range ensures longer battery life and prevents issues such as overcharging and deep discharging. Battery charge–discharge dynamics are influenced by the rates of energy flow, internal resistance, and environmental factors. To manage these parameters effectively, a BMS is integrated, which supervises the operation of the battery, monitors the temperature, and regulates the charge and discharge cycles. The BMS communicates with the main control unit to ensure that the battery provides reliable support to the PV system and maintains the grid balance.

The block diagram in Figure 2 illustrates the modeling and operational flow of a grid-connected PV–battery hybrid system integrated with a DVR to improve power quality. At the input stage, the PV Array Model receives solar irradiance and temperature as key parameters, generating electrical power based on it's I–V and P–V characteristics. These curves demonstrate that increased irradiance boosts the short-circuit current, whereas higher temperatures reduce the open-circuit voltage, collectively affecting the overall DC output [18–20]. The DC then processes this DC power–DC Converter Model, which operates under the supervision of an MPPT algorithm to continuously extract the maximum power under varying atmospheric conditions. The converter regulates the voltage and feeds it into the DC bus, where it interfaces with the BESS Model. The BESS manages the energy flow by storing surplus power and discharging during deficits, maintaining balance through real-time SOC monitoring [21]. The combined output is then delivered to the DC–AC Inverter Model, which synchronizes the generated AC power with the grid using phase-locked loop control. Finally, the DVR Model plays a vital role in mitigating voltage sags, swells, and transient disturbances by injecting compensating voltages, thereby ensuring consistent, high-quality power delivery to the connected grid and load.

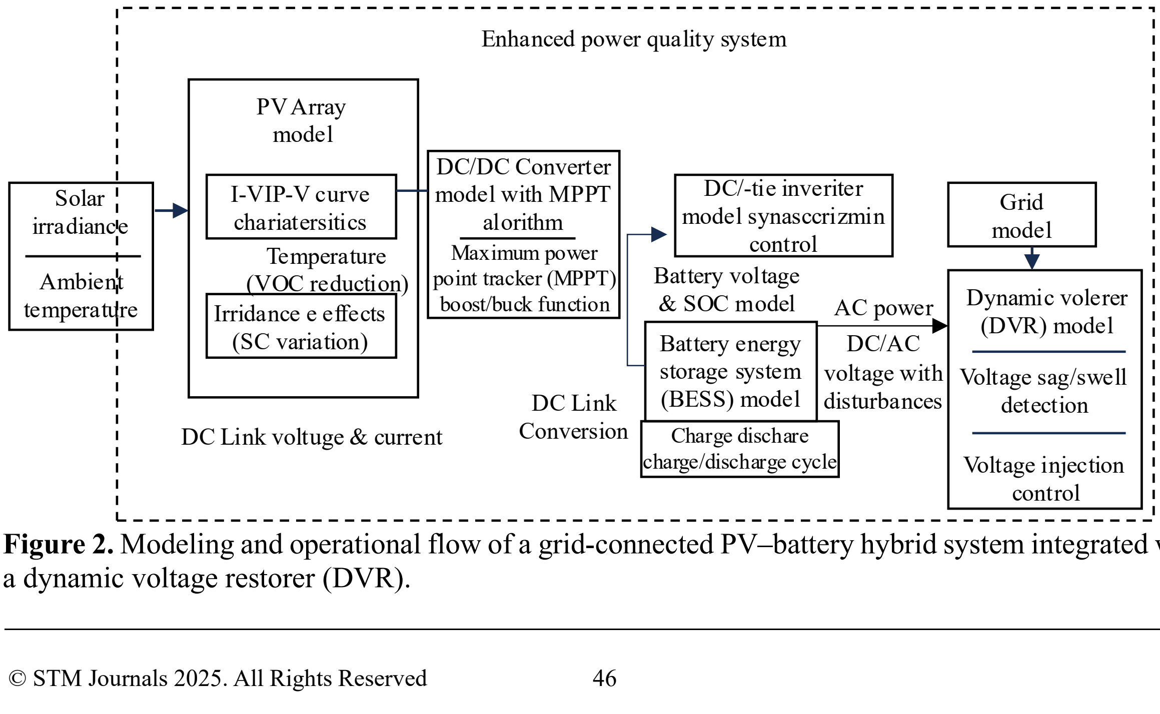

Figure 2. Modeling and operational flow of a grid-connected PV–battery hybrid system integrated with a dynamic voltage restorer (DVR).

The DC–DC converter acts as an interface between the PV array and the DC bus, regulating the voltage and ensuring that the PV array operates at its maximum efficiency point. The boost converter is the most commonly used topology in this context, as it can step up the PV voltage to the required DC link level. The operation of the converter is controlled by the MPPT algorithm, which continuously adjusts the converter's duty cycle to extract the maximum possible power from the PV array under varying irradiance and temperature conditions [22]. Classical MPPT techniques, such as perturb and observe (P&O) and incremental conductance (IncCond), are widely adopted because of their simplicity and effectiveness in steady-state conditions. However, these methods can experience oscillations around the MPP and a slow convergence under rapidly changing conditions. To overcome these drawbacks, advanced MPPT algorithms based on intelligent optimization methods, such as fuzzy logic control (FLC), particle swarm optimization (PSO), artificial neural networks (ANN), and seed optimization algorithm (SOA), have been proposed. These advanced controllers offer a faster tracking speed, reduced steady-state error, and improved adaptability to partial shading and transient environmental variations, thereby enhancing the overall energy efficiency of the hybrid system. The inverter and grid interface stage play a vital role in converting the regulated DC output into AC power that can be supplied to the utility grid or local loads [23–25]. A voltage source inverter (VSI) is typically used for this purpose, employing control strategies such as sinusoidal pulse width modulation (SPWM) or space vector pulse width modulation (SVPWM) to generate smooth and synchronized AC waveforms. The inverter ensures that the output voltage and current remain in phase with the grid voltage, maintains a unity power factor, and minimizes power losses. Grid synchronization is achieved using a phase-locked loop (PLL) mechanism that continuously monitors the grid voltage and adjusts the inverter output to ensure seamless integration [26–28]. The inverter also provides reactive power compensation, harmonic reduction, and voltage regulation. In the hybrid PV–battery–DVR configuration, the inverter works in coordination with the DVR to enhance the overall power quality. The DVR detects voltage sags, swells, and other disturbances in the grid, and compensates by injecting a corrective voltage, thereby maintaining a stable load-side voltage. This dynamic interaction ensures a continuous, disturbance-free power supply for sensitive loads and improves the reliability of grid connections.

In essence, the integrated modeling of the PV array, BESS, DC–DC converter with MPPT, and inverter with grid interfacing forms a comprehensive and robust structure for the PV–battery–DVR hybrid system. The PV array provides a renewable energy source, the BESS ensures energy continuity, the DC–DC converter with MPPT maximizes efficiency, and the inverter maintains grid compatibility and power quality. Together, these components work under an intelligent control framework that optimizes the energy flow, stabilizes the voltage, and mitigates disturbances, leading to enhanced system performance and sustainability. Such detailed system modeling is essential for developing smart, resilient, and efficient renewable energy systems that can support the increasing demand for reliable and clean power in modern grid environments.

Dynamic Voltage Restorer Design and Control

The dynamic voltage restorer is a custom power device designed to protect sensitive loads in grid-connected renewable systems from voltage disturbances such as sags, swells, and transient fluctuations. The DVR operates as a series-connected voltage compensator that injects an appropriate voltage into the grid through a series injection transformer, ensuring that the load voltage remains within acceptable limits, even when supply side anomalies occur. Structurally, the DVR system consists of several key components: a VSI, a DC energy storage unit, a filter circuit, and a series injection transformer. The VSI converts the DC voltage from the storage unit or DC bus (connected to the PV–battery hybrid system) into an AC voltage of controlled magnitude and phase [29]. This AC voltage was injected in series with the grid via the injection transformer to restore the desired load voltage. The transformer provides galvanic isolation and voltage matching between the inverter and distribution system, making it a vital interface in the DVR configuration. The performance of the DVR is characterized by its voltage compensation capability, which is determined by its maximum injection voltage limit, which depends on the inverter's DC link capacity and the transformer's turn ratio. Under typical conditions, the DVR compensates for voltage sags of up to 50% of the nominal voltage without overloading the inverter while maintaining power factor correction and harmonic suppression. The filter circuit, usually a combination of inductors and capacitors, smooths out the inverter output and prevents switching harmonics from propagating into the grid [30, 31]. The control unit continuously monitors the supply voltage at the PCC. When a disturbance is detected, the controller calculates the required compensating voltage and commands the inverter to inject it within milliseconds. Depending on the system configuration, the DVR can operate in one of three compensation modes: (1) pre-sag compensation, (2) in-phase compensation, or (3) energy-optimized compensation, each with a unique trade-off between energy consumption and voltage restoration accuracy. To ensure accurate voltage regulation, the control strategy of the DVR plays a decisive role in maintaining stable operation and quick transient response. The most adopted approach is the PI controller, which regulates the injected voltage by minimizing the error between the reference and measured load voltages [32]. The simplicity and robustness of the PI controller make it a preferred choice for real-time grid-compensation applications. Controller tuning involves determining the optimal proportional gain (Kp) and integral gain (Ki) to balance the trade-off between transient response and steady-state accuracy. Classical tuning methods, such as Ziegler–Nichols, Cohen–Coon, and trial-and-error techniques, are often employed to achieve the desired dynamic performance. However, in renewable-based systems with nonlinear and time-varying characteristics, the fixed parameters of the PI controller may not be sufficient to maintain optimal compensation under all conditions [33–36]. Therefore, advanced control strategies have been explored to enhance DVR performance, such as FLC, Neural Network-based control, and optimization-driven approaches using algorithms such as PSO, genetic algorithm (GA), and seagull optimization algorithm (SOA). Fuzzy logic controllers provide adaptive gain adjustment and decision-making capabilities based on linguistic rules, eliminating the need for precise mathematical modeling and improving robustness under uncertain grid conditions. Similarly, optimization-based controllers dynamically tune the PI parameters to achieve minimal THD, faster transient recovery, and improved compensation accuracy. The integration of these intelligent control approaches ensures stable operation of the DVR, even under sudden load changes or varying solar irradiance.

Figure 3 illustrates a DVR with advanced control integrated into a grid-connected PV–battery hybrid system designed to safeguard sensitive loads against voltage disturbances. The system begins with the grid AC supply, which delivers power to the sensitive load through a series injection transformer located at the point of injection coupling (PPC). The DVR injects a compensating voltage in series whenever a sag, swell, or transient is detected, thereby ensuring a stable load voltage. The DVR configuration includes a VSI supplied by a DC Energy Source derived from the PV array and BESS via DC–DC converters and a DC link capacitor, which stabilizes the DC voltage. Reactive power converters manage bidirectional power flow, enabling smooth energy exchange between the PV–battery system and the DVR. At the heart of the system lies the DVR control unit, which continuously senses the PCC voltage, detects anomalies, and computes the required compensating voltage using selected compensation modes, such as pre-sag, in-phase, or energy-optimized operation. A classical PI controller ensures voltage regulation, while advanced intelligent algorithms such as PSO, GA, or the seagull optimization algorithm (SOA), combined with a fuzzy signal generator, enable adaptive and optimal control under dynamic grid conditions. The PWM signal generator translates these control decisions into gating signals for the VSI to ensure a precise voltage injection. Additionally, energy coordination and BESS management maintain DC link stability and ensure that the DVR has sufficient energy support during transient or extended compensation periods, effectively demonstrating the strong integration between the DVR and PV–battery hybrid system for superior power quality and grid resilience. In the integration of the DVR with the PV–Battery hybrid system, coordination between the BESS and the DVR is critical during voltage disturbances. The DVR requires a stable DC link voltage to inject a compensating voltage into the grid; hence, the battery acts as an auxiliary energy source, supplying or absorbing power based on the system's demands. During a voltage sag event, the DVR draws energy from the battery to inject the compensating voltage, thereby ensuring an uninterrupted supply to sensitive loads. Conversely, during normal operation or when excess PV power is available, the battery is recharged through the DC bus to maintain energy balance within the system. This energy coordination mechanism enhances the system's resilience by allowing the DVR to operate effectively, even during prolonged disturbances or partial PV generation. The control unit synchronizes the actions of the MPPT algorithm, inverter, and DVR to simultaneously optimize energy flow, voltage stability, and power quality. Furthermore, the integrated system enhances the reactive power support and harmonic compensation, contributing to overall grid stability and reliability. Advanced configurations also enable bidirectional power flow between the grid and storage system, allowing grid support functions such as voltage regulation, load balancing, and peak shaving. By combining the fast dynamic response of the DVR with the energy flexibility of the battery storage system, the PV–battery–DVR hybrid architecture achieves superior performance in mitigating grid disturbances, minimizing voltage imbalance, and maintaining high-quality, uninterrupted power delivery. Thus, the DVR not only safeguards sensitive loads from power quality issues but also plays an essential role in enabling the sustainable and resilient integration of renewable energy into modern smart grids.

MATLAB/Simulink Simulation and Results

The MATLAB/Simulink simulation and results section presents the modeling, analysis, and validation of the proposed grid-connected PV–battery hybrid system integrated with a DVR for power quality enhancement. The simulation framework was developed in MATLAB/Simulink, incorporating detailed subsystem models for the PV array, battery storage, DC–DC converters, inverter, DVR, and control units. System parameters, such as irradiance, temperature, grid voltage, and load characteristics, were configured to represent realistic operating conditions.

Figure 4 illustrates the comprehensive Simulink model of a grid-connected PV–battery hybrid system integrated with a DVR designed to improve voltage stability and power quality enhancement. The model is systematically divided into interconnected subsystems that collectively simulate real-time

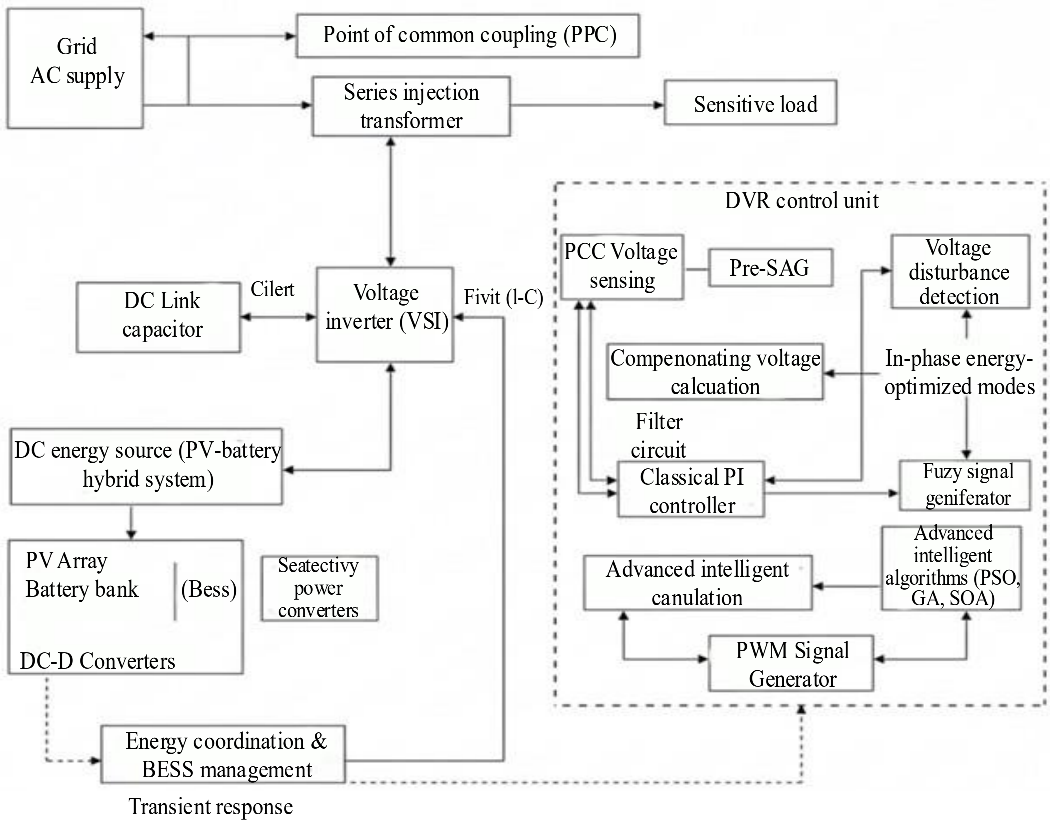

Figure 3. Dynamic voltage restorer (DVR) with advanced control integrated into a grid-connected PV–battery hybrid system.

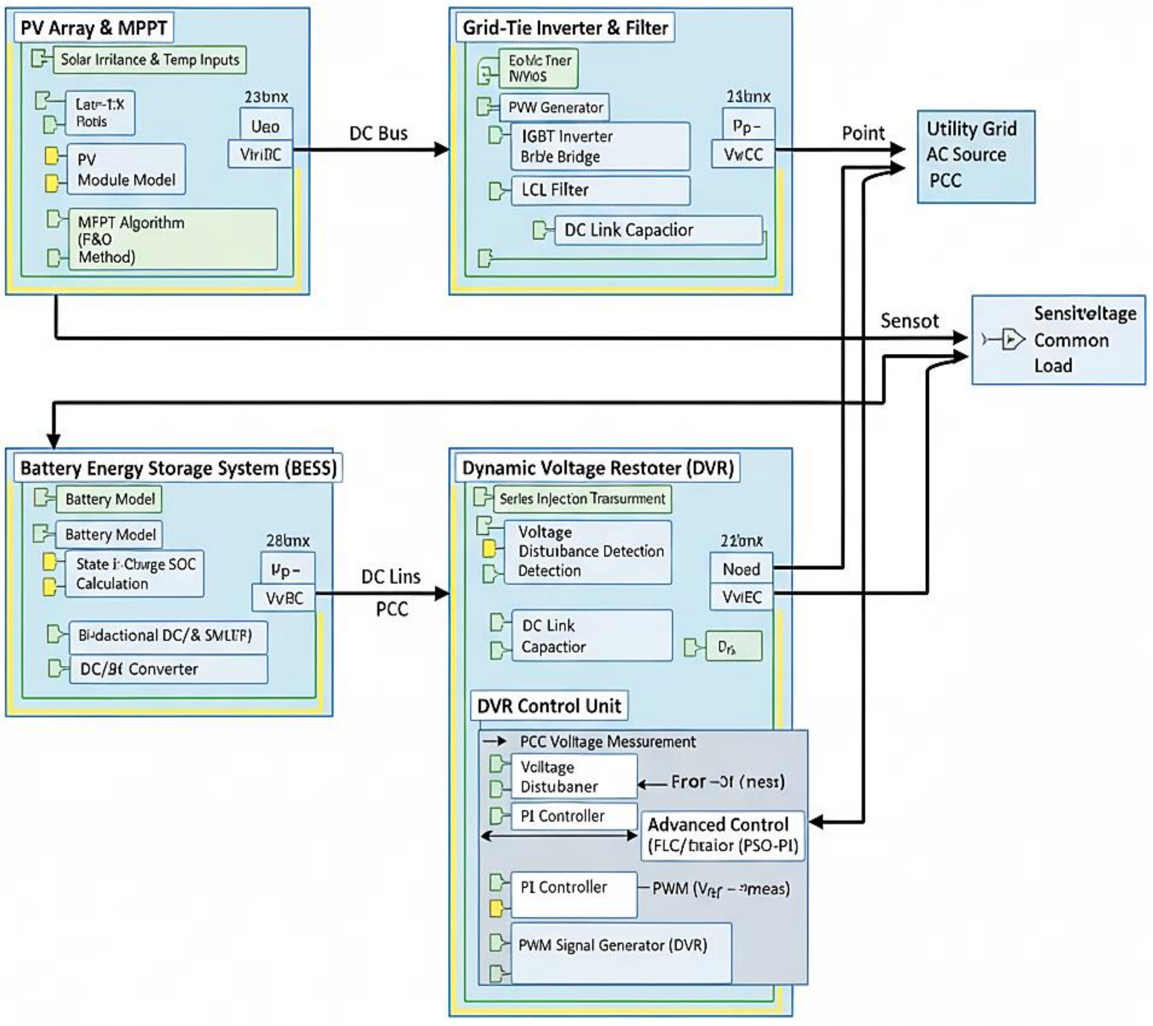

Figure 4. MATLAB Model of the proposed technique.

grids and renewable interactions. The PV Array and MPPT subsystem capture inputs of solar irradiance and temperature, modeling the photovoltaic characteristics while implementing an MPPT algorithm, typically the P&O method, to ensure maximum energy extraction from the solar array. This power is supplied to the DC bus, which acts as a central energy conduit. The BESS is modeled with precise SOC estimation and is interfaced via a bidirectional DC/DC converter, enabling efficient charging during excess PV generation and discharging during low-generation or voltage-disturbance conditions. Both the PV and battery units are connected at the DC link PCC, which is stabilized by a DC link capacitor that maintains voltage consistency. The grid-tie inverter and LCL filter subsystem convert DC power into synchronized AC power suitable for grid injections, ensuring minimal harmonic distortion and a smooth power exchange with the Utility Grid AC Source PCC. The DVR segment includes a series injection transformer connected in series between the grid and the sensitive load, enabling compensation during voltage sags, swells, or transients. A dedicated VSI within the DVR, powered through a DC link, generates a compensating voltage. The DVR control unit operates as the central intelligence of the system, continuously monitoring the PCC voltage, detecting anomalies, and processing control signals through a PI controller or advanced intelligent control algorithms such as fuzzy logic or PSO-based PI tuning. These controllers drive the PWM signal generator, which controls the inverter-gating signals to inject the precise voltage required for real-time disturbance compensation. This integration of the PV–battery hybrid system with the DVR ensures continuous and clean power delivery to sensitive loads, maintains grid voltage stability, reduces harmonic distortion, and achieves superior dynamic performance under varying solar, load, and grid conditions.

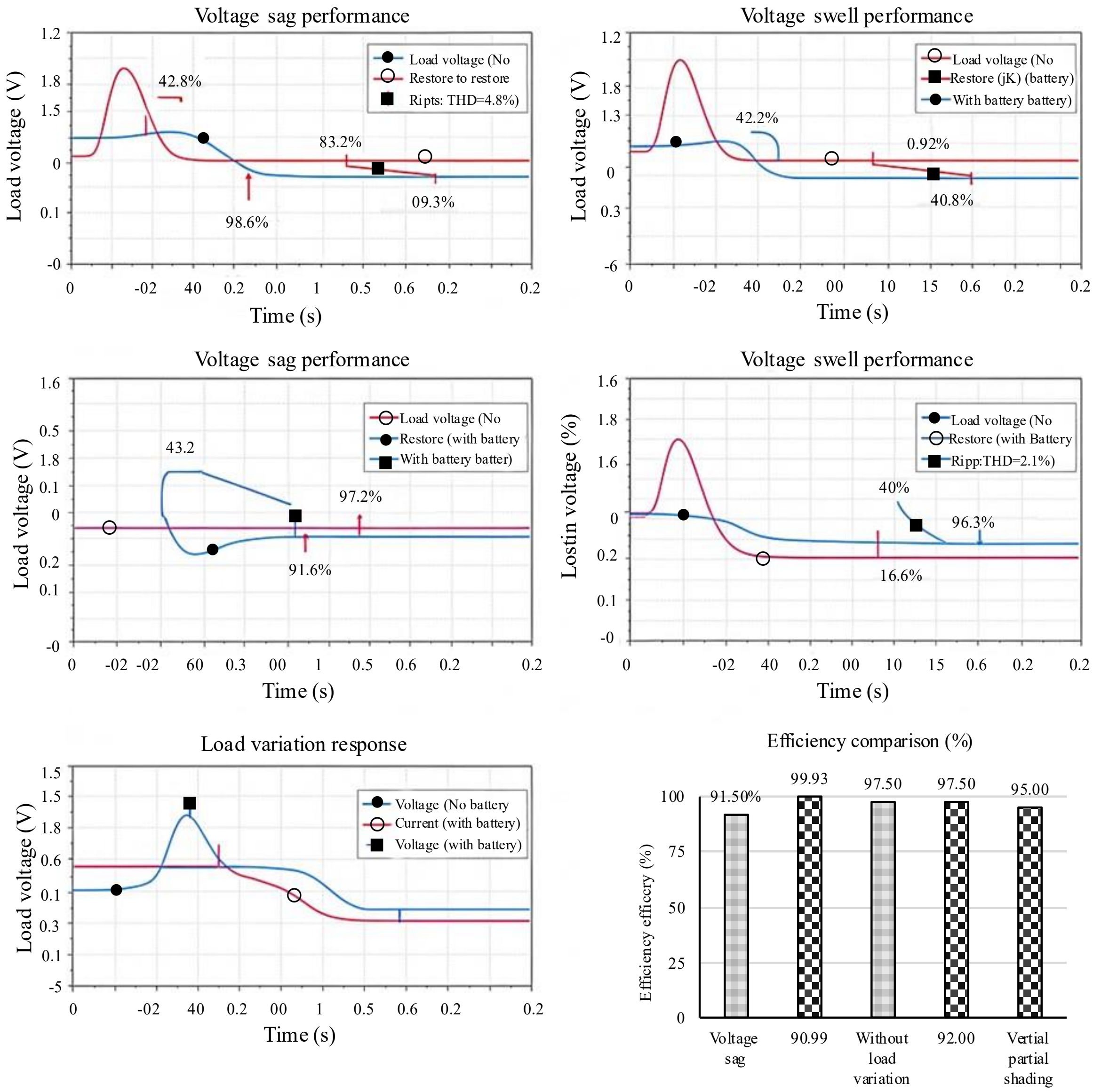

Figure 5. Simulink results of the proposed technique.

Figure 5 provides a comprehensive graphical representation of the performance of a grid-connected PV–battery hybrid system equipped with a DVR under various power quality disturbances, aligning with the numerical results presented in Table 1. Figure 5 shows multiple plots, each illustrating specific aspects of the system response, enabling a clear comparison between operations with and without battery support. The "voltage sag performance" graphs depict the system's response to a 20% voltage sag. In the top-left plot, representing the scenario without a battery, the red voltage trace shows a significant drop from the nominal value and slower recovery, indicating a longer restoration time and lower voltage regulation. Conversely, the bottom-left plot with battery support shows a blue trace where the voltage quickly recovers to its nominal value, demonstrating enhanced regulation and a reduction in restoration time from 85 ms to 42 ms. This illustrates the battery's critical role in providing immediate compensation during sag events. The voltage well performance graphs, located on the top-right and bottom-right sides, capture the system's ability to handle overvoltage conditions. Without a battery, the top-right plot exhibited a pronounced swell with slower mitigation, highlighting the vulnerability to overvoltage. With the battery integrated, the bottom-right plot shows a rapid and smooth return to nominal voltage, effectively reducing THD from 4.3% to 2.0% and improving voltage regulation from 92.5% to 99.1%, confirming superior swell suppression. The "load variation response" plot illustrates the system's transient behavior under a 30% load change. The blue line representing the battery integration maintains a stable voltage and current profile, whereas the red line without a battery shows larger deviations and slower recovery. This emphasizes the battery's role in maintaining power quality during fluctuating demand. Finally, the "efficiency comparison (%)" bar chart consolidates the system performance under all tested conditions, showing that battery integration consistently enhances efficiency, with improvements of up to 7–8% across sags, swells, load variations, and partial shading scenarios. Overall, Figure 5 clearly demonstrates that combining a DVR with battery storage significantly strengthens voltage stability, reduces THD, accelerates transient recovery, and boosts the overall system efficiency, highlighting the effectiveness of the hybrid system in enhancing power quality and operational reliability.

Table 1 presents the performance analysis of a grid-connected PV–battery hybrid system integrated with a DVR under different power quality disturbances and operating conditions. The scenarios included voltage sags, voltage swells, load variations, and partial shading, each tested with and without battery support, to evaluate the robustness and effectiveness of the system. For voltage sags (Cases 1 and 2), the system without a battery exhibited a 20% sag, requiring 85 ms for voltage restoration, achieving 93.2% voltage regulation with 4.8% THD and 91.5% efficiency. Introducing a battery (Case 2) significantly improved the performance, halving the restoration time to 42 ms, enhancing the voltage regulation to 98.6%, reducing the THD to 2.1%, and increasing the system efficiency to 96.8%. Similarly, during voltage swell events (Cases 3 and 4), battery integration reduced the restoration time from 78 ms to 40 ms, improved the voltage regulation from 92.5% to 99.1%, lowered the THD from 4.3% to 2.0%, and increased the efficiency from 90.9% to 96.3%. For load variations (Cases 5 and 6) and partial shading (Cases 7 and 8), the presence of a battery consistently enhanced the system performance by reducing restoration times, improving voltage regulation, minimizing THD, and boosting overall efficiency. Overall, Table 1 clearly demonstrates that incorporating a battery into a DVR-supported PV system substantially improves power quality and operational reliability, making it more resilient against voltage disturbances, load changes, and partial shading conditions.

Figure 6 presents a detailed Simulink-based performance analysis of the PV–battery hybrid system integrated with a DVR, highlighting improvements in power quality and system control under various operating conditions. The "THD comparison" graph demonstrates a clear reduction in THD during a

Table 1. Findings of the proposed research.

Test scenario	Battery status	Voltage sag/swell (%)	Restoration time (ms)	Voltage regulation (%)	THD (%)	System efficiency (%)
Case 1: Voltage sag (20%)	Without battery	20	85	93.2	4.8	91.5
Case 2: Voltage sag (20%)	With battery	20	42	98.6	2.1	96.8
Case 3: Voltage swell (15%)	Without battery	15	78	92.5	4.3	90.9
Case 4: Voltage swell (15%)	With battery	15	40	99.1	2.0	96.3
Case 5: Load variation (30%)	Without battery	—	95	91.8	5.0	89.7
Case 6: Load variation (30%)	With battery	—	48	97.5	2.3	95.2
Case 7: Partial shading (25% PV loss)	Without battery	—	110	90.6	5.2	88.5
Case 8: Partial shading (25% PV loss)	With battery	—	52	98.2	2.4	94.6

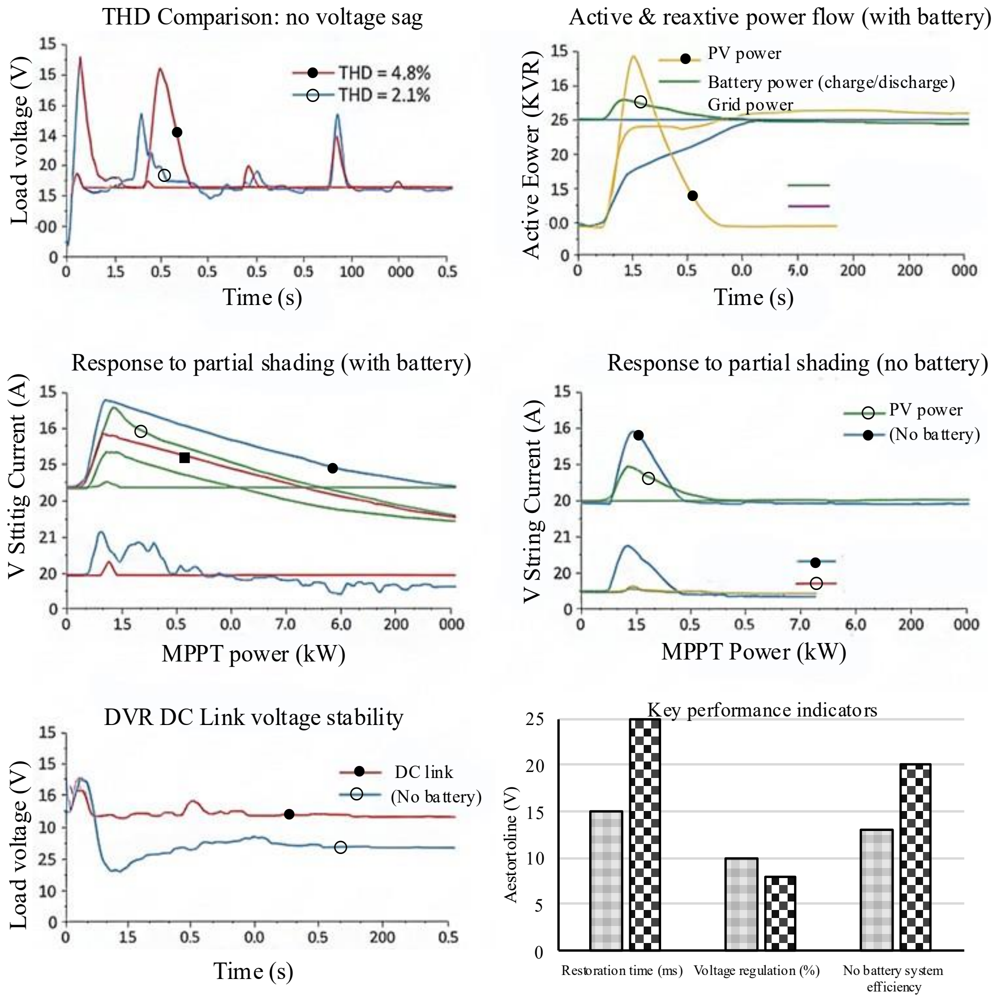

Figure 6. Response under partial shading.

voltage sag event, decreasing from 4.8% without battery support to 2.1% with the battery. This indicates a significant improvement in the waveform quality, reflecting smoother voltage profiles and reduced harmonic-related stress on the connected loads. The "active & reactive power flow (with battery)" plot illustrates coordinated power management within the hybrid system. It shows the dynamic interaction among PV generation, battery charge/discharge, and grid power to maintain the supply-demand balance, ensuring stable load support while optimizing energy usage from both the PV array and battery storage. This coordinated control helps mitigate voltage fluctuations and enhances the overall grid integration. The "response to partial shading" graphs compare PV string current and MPPT power output with and without battery support. Under partial shading conditions, the battery stabilizes the PV output, preventing large fluctuations and improving the reliability of energy delivery while enabling the MPPT algorithm to maintain efficient operation despite irradiance variations. The "DVR DC link voltage stability" plot highlights the battery's role in maintaining a stable DC link voltage for the DVR, which is essential for effective voltage compensation during disturbances. A stable DC link ensures that the DVR can inject or absorb power rapidly, thereby minimizing voltage sags or swells.

Figure 7 shows an advanced Simulink-based performance analysis of the three-phase PV–battery hybrid system integrated with a DVR, emphasizing its dynamic response and power quality enhancement during grid disturbances. The "DVR injected voltage & grid sag" plot clearly visualizes the DVR's compensatory action. The grid voltage (blue trace) experiences a sag, whereas the DVR injects a precisely phased and amplified voltage (red trace) to restore the load voltage. This confirms the ability of the DVR to actively counteract voltage sags in real time. The "ideal load voltage" plots

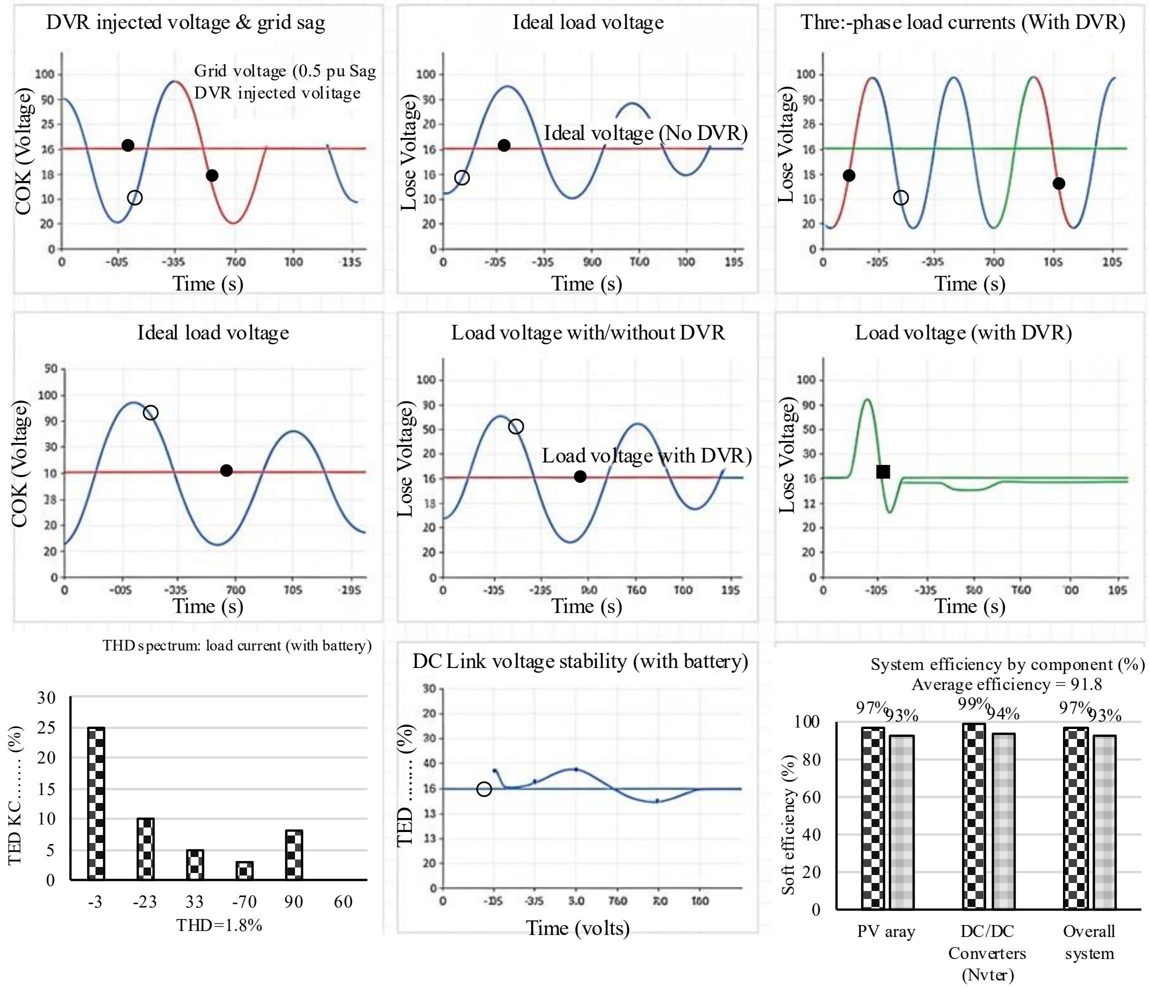

Figure 7. DVR response to load demand.

(top-, middle-, and bottom-left) establish a reference sinusoidal waveform under undisturbed conditions. Comparing these with the "load voltage with/without DVR" and "load voltage (with DVR)" plots shows that, with the DVR active, the load voltage closely tracks the ideal waveform even during sags, illustrating effective voltage restoration and disturbance mitigation. The "three-phase load currents (with DVR)" graph demonstrates that the load currents remain balanced and sinusoidal, indicating high-quality power delivery [37]. In the "THD spectrum, load current (with battery)", the quantification of this shows a low total harmonic distortion of 1.8%, reflecting a significant reduction in harmonics and cleaner current supplied to the load. The "DC link voltage stability (with battery)" plot highlights the battery's role in maintaining a stable DC link for the DVR inverter, which is critical for uninterrupted compensatory action and reliable voltage injection. Finally, the "system efficiency by component (%)" chart provides a component-level efficiency breakdown, including the PV array, DC/DC converters, inverter, and overall system. This illustrates the effectiveness of energy conversion throughout the system, emphasizing that battery integration and DVR operation collectively enhance efficiency, stabilize voltages, and improve the overall power quality. Overall, Figure 7 confirms that the hybrid PV–battery system with DVR ensures balanced three-phase operation, rapid disturbance mitigation, low harmonic distortion, and high system efficiency [38].

The simulation environment allows for dynamic interaction between PV generation, energy storage, and DVR compensation under varying grid and load scenarios. In the scenario analysis, different test cases were simulated, including voltage sag and swell events, sudden load variations, and partial shading conditions on the PV array, to assess the robustness of the system. The DVR operates to inject a compensating voltage in real time, ensuring uninterrupted and regulated power to sensitive loads. Performance evaluation focuses on key indicators such as voltage regulation accuracy, THD, system stability, and overall efficiency. The results demonstrate that the integrated PV–battery–DVR system maintains voltage at the desired level, even during severe disturbances, with THD well below the IEEE-519 standards, confirming improved power quality. The system also exhibited a fast transient response and stable voltage restoration, thereby proving the effectiveness of the proposed control strategies. In comparative analysis, simulations were performed using both conventional PI controllers and advanced intelligent control algorithms such as PSO and fuzzy logic-based PI tuning. The results reveal that while the classical PI controller provides satisfactory steady-state performance, intelligent controllers deliver a superior dynamic response, reduced overshoot, and faster recovery during disturbances. Additionally, the behavior of the system is compared with and without battery integration, demonstrating that the inclusion of the BESS significantly enhances the voltage support capability and system resilience during prolonged grid faults or rapid irradiance fluctuations. Overall, the MATLAB/Simulink-based results validate the feasibility and efficiency of the proposed PV–battery–DVR hybrid configuration as a robust solution for maintaining voltage stability, minimizing harmonics, and improving power quality in modern grid-connected renewable energy systems.

CONCLUSION

This study presents the modeling and control of a grid-connected PV–battery hybrid system integrated with a DVR for enhanced power quality. Performance analysis under voltage sags, voltage swells, load variations, and partial shading conditions demonstrated that incorporating a battery alongside the DVR significantly improved the system behavior. The key findings include faster voltage restoration, improved voltage regulation, reduced THD, and increased overall system efficiency. The results confirm that the PV–battery–DVR hybrid system can provide reliable grid support while mitigating common power quality disturbances, ensuring the stable and efficient operation of renewable energy sources. The primary contribution of this work lies in the detailed modeling and simulation of the hybrid PV–battery–DVR system, highlighting its ability to enhance power quality and maintain grid stability under various dynamic conditions. A comparative analysis between scenarios with and without battery integration provides clear evidence of the battery's role in transient mitigation, voltage stabilization, and efficiency improvement. Furthermore, this study emphasizes the practical relevance of integrating energy storage with voltage compensation devices for smart grid applications. However, this study has certain limitations. The analysis is primarily based on simulations using MATLAB/Simulink, without experimental validation through hardware-in-loop (HIL) testing. The models assume ideal operating conditions for the PV array and battery, without accounting for aging effects, partial failures, or grid contingencies. In addition, the control strategy relies on conventional PI-based DVR control, which may have limitations under highly nonlinear or rapidly changing disturbances. Future research should focus on developing intelligent control strategies, such as fuzzy logic, neural networks, or hybrid optimization-based approaches, to further enhance system adaptability and resilience. Real-time HIL experiments are recommended to validate the practical performance and reliability of hybrid systems. Moreover, extending the framework to renewable energy microgrids and multi-source integration can explore coordinated control strategies, demand response, and resilience under diverse operating scenarios, supporting the development of smarter and more sustainable power systems.

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