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Power electronics-based voltage stability enhancement in smart distribution networks using solar PV and DVR under a green energy framework

Seher Kadirova[1*], *Jayant* Kulshreshtha[2], *Riaz* Kurbanali Israni[2], *Tsvetelina* Stefanova[3], *Tsvetozar* Georgiev[3], and *Amit* Lathigara[2]

[1]University of Ruse "Angel Kanchev", Department of Automatics and Electronics, 7004, Ruse, Bulgaria
[2]RK University, School of Engineering, 360020 Rajkot, Gujarat, India
[3]University of Ruse "Angel Kanchev", Department of Computer Systems and Technologies, 7004, Ruse, Bulgaria

Abstract. This paper proposes power electronics based photovoltaic (PV) array integrated three phase three wire dynamic voltage restorer (DVR) employing a novel nine switch converter for voltage regulation in low voltage distribution networks. Unlike conventional configurations that use two separate voltage source converters for PV interfacing and DVR operation, the proposed topology combines both functions into a single converter, thereby reducing switch count, converter size, and switching losses while improving overall efficiency. The DVR effectively mitigates voltage sags and maintains load side voltage within acceptable limits. The PV array acts as a DC source, supplying real power to support compensation and reducing dependence on the utility grid during sufficient solar generation. The coordinated control strategy ensures seamless power sharing and fast dynamic response under varying load and irradiance conditions. Simulation results demonstrate improved voltage profile, reduced harmonic distortion, and enhanced energy utilization. The proposed system provides an efficient and cost-effective solution for power quality improvement, grid support, and sustainable integration of renewable energy sources.

1 Introduction

This compact and efficient PV-DVR system is a promising solution for addressing voltage regulation challenges, improving power quality, and promoting sustainable energy integration into modern distribution networks. Within this scope, evaluating long-term investment viability and systemic selection frameworks between solar photovoltaic systems and alternative renewable installations represents an essential precursor for microgrid deployment [1]. A power resource with a specific arrangement that commonly defines the

* Corresponding author: skadirova@uni-ruse.bg

maximum and minimum limits for RMS (Root Mean Square) frequency and voltage, according to that most of the electrical and electronic equipment are designed to function.

The supply will be offered and within tolerance for 100% of the period, is expectancy on the user side. Power quality is good at time of generation, but some distance far from the generating point having passes through many transformers, several kilometres of transmission cables and have been mixed with the outputs of other generator [2]. Quality cannot be evaluated before delivery because electricity is not like any other product. This may not be assured by the supply and would be essentially impossible to transmit at a cost-effective price. According to the PV plant status and grid condition, the nine-switch converter can work in a number of operational modes (Figure 1). The comprehensive stabilization capacity and systemic robustness under transient line conditions remain highly contingent upon the specialized control design of the multi-terminal converter interfaces integrated into the network topology [3].

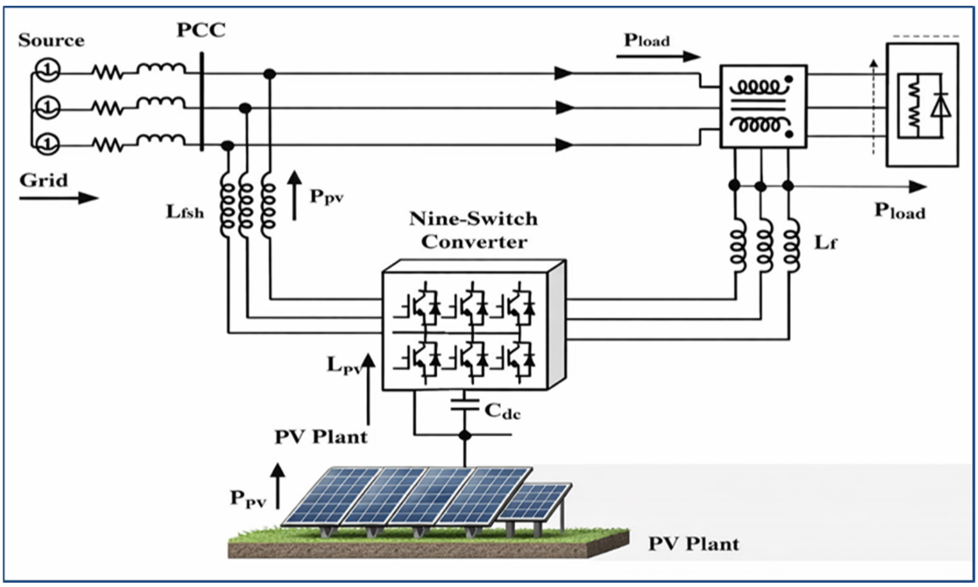

Fig. 1. Proposed PV-DVR configuration with nine switch converters.

1.1 Mode-1: Healthy Grid Condition

This mode governs the conventional operation of the nine-switch converter when the photovoltaic system functions under Standard Test Conditions (STC) and the grid voltage operates within its nominal parameters. Under healthy grid conditions, the PV-VSI injects the active power generated by the solar PV panels into the grid, while the DVR remains in a standby mode. To generate required gate signals for all nine switches carrier-based modulation scheme is used. Switches S7-S9 are logic high or ON during Mode-1 however remaining other six switches S1-S6 execute PV-VSI operation in PWM-Pulse Width Modulation control [4, 5]. The primary winding of series injections transformer is short circuited and as a result, the active power delivered by DVR-VSI is zero because of the logical high status of S7-S9.

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1.2 Mode-2: Sag > 0.5 p.u.

This mode refers to a state when there is a three-phase fault at Point of Common Couplings. For the duration of this mode, DVR status is active and it injects required maximum compensating voltage, at a same time according to the grid safety the photovoltaic generation is stopped and all the power is supplied by DVR terminals.

1.3 Mode-3: Night time operation

This mode defines the operation of the nine-switch converter when the PV plant receives zero solar irradiance and cannot generate active power, typically during early morning, late evening, and night hours. Under these conditions, the operation of the PV-VSI is inverted. To maintain the charge of the DC-link capacitor, the converter draws a controlled amount of active power from the utility grid while the grid is operating at its rated voltage, keeping the PV plant idle [6]. In this state, the active power flow is reversed (i.e., from the grid to the DC-link). While the physical switching sequence of the converter mimics the standard stabilization routines, this mode structurally contrasts with Mode-2, as the primary energy source for the DVR shifts to grid-rectified power rather than active solar generation.

2 Parameters

The simulation model incorporates a nine-switch converter utilizing three switches per phase. Since this configuration features six output terminals, it is also formally referred to as a six-port converter (Figure 2).

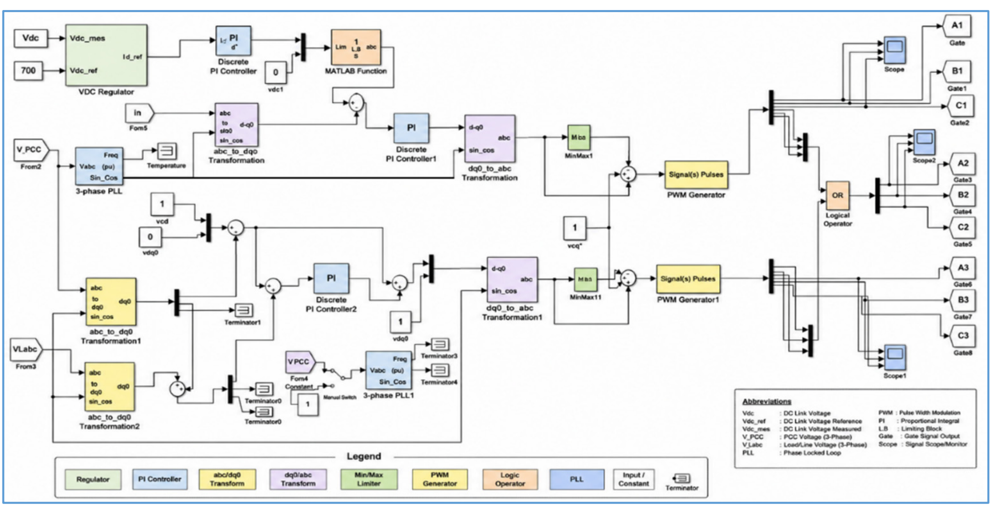

Fig. 2. Complete control system for gate pulse generation.

The system is designed with a grid voltage of 415 V (line-to-line) and operates at a base voltage of 415 V with a base power rating of 10 kW and a line frequency of 50 Hz. The DC link voltage is maintained at 700 V, supported by a DC link capacitance of 3700 μF to ensure voltage stability. A 1:1 series injection transformer is used for voltage compensation, while the load is modeled as a 10 kW RLC load. The switching devices employed are IGBTs for efficient and high-speed operation [7, 8]. Additionally, a filter network comprising a 5 mH inductor and a 50 μF capacitor is incorporated to reduce harmonics and improve power quality.

Figure 3 illustrates a clean and structured simulation model of a nine-switch converter integrated with a solar photovoltaic (PV) system for power conditioning applications. The PV array, supported by a Maximum Power Point Tracking (MPPT) controller, generates DC power which is regulated through a DC-link capacitor to maintain a stable voltage level. This DC power is then processed by the nine-switch converter, enabling efficient power conversion and reduced switching losses compared to conventional topologies. The system incorporates control blocks including abc–dq0 transformation, discrete PI controllers, and a phase-locked loop (PLL) to ensure synchronization with the grid and precise voltage regulation [8]. Pulse Width Modulation (PWM) techniques are used to generate appropriate switching signals for the converter. Additionally, filter components and a transformer interface are included to improve power quality and facilitate grid integration. To evaluate the dynamic performance of the proposed system under different operating regimes, two measurement blocks, designated as Scope 1 and Scope 2, are integrated into the simulation model. Scope 1 is utilized to continuously monitor the primary voltage profiles and current waveforms on the grid side, ensuring accurate tracking of supply fluctuations. Meanwhile, Scope 2 captures the instantaneous three-phase voltage variations directly across the 10 kW RLC load. This detailed multi-point monitoring enables a comprehensive analysis of the system's power quality and compensation efficiency.

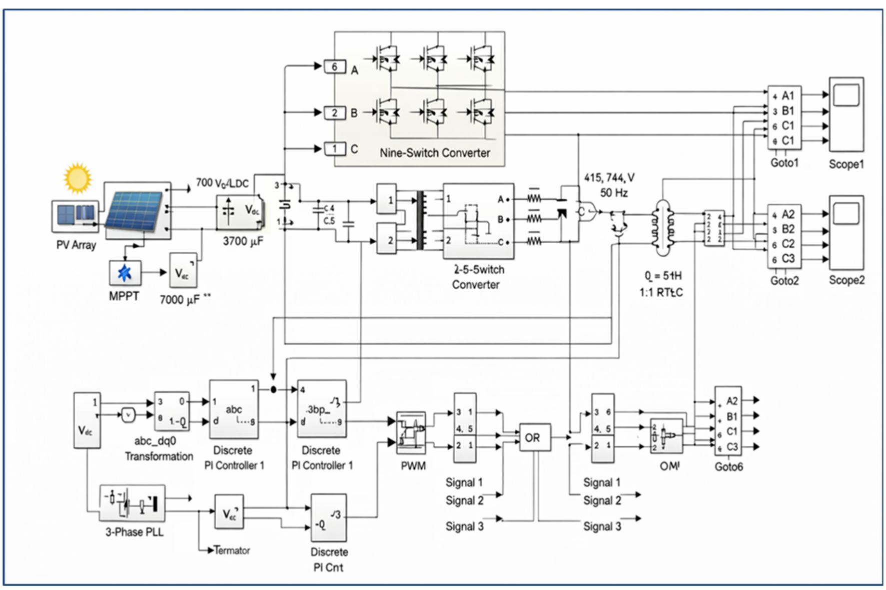

Fig. 3. Simulation of nine switch converter with Solar PV plant.

3 Analysis and discussion

The results demonstrate the effectiveness of the Dynamic Voltage Restorer (DVR) in mitigating a near to 0.2 second voltage sag at the Point of Common Coupling (PCC). During the sag period (Figure 4), the PCC voltage clearly drops below its nominal value, indicating a disturbance in the supply system. In response, the DVR injects a compensating voltage, as observed in the DVR voltage waveform, which becomes active precisely during the sag interval. This injected voltage restores the missing component of the supply voltage, ensuring continuity and stability. Consequently, the load voltage remains almost constant and sinusoidal throughout the entire duration, showing negligible distortion or reduction in magnitude [9]. This confirms that the DVR effectively isolates the load from supply-side disturbances and maintains high power quality, validating the performance of the nine-switch converter-based compensation system.

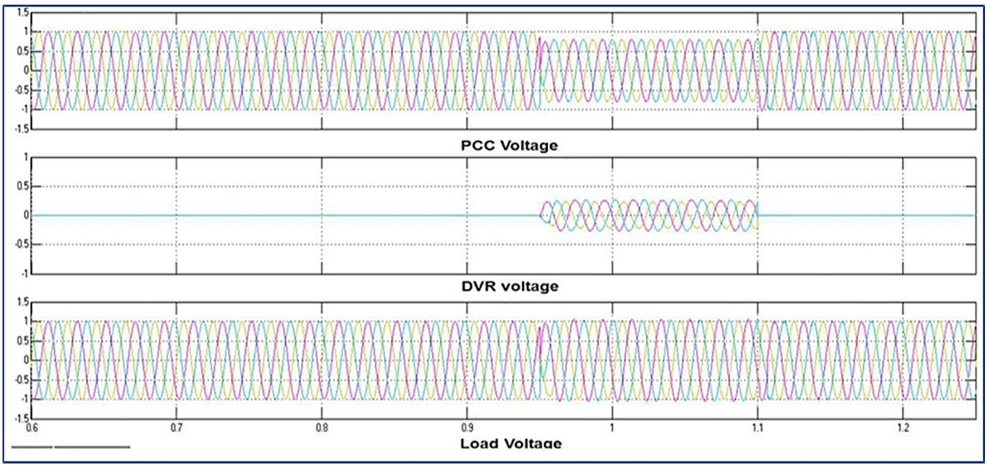

Fig. 4. Waveform for ≈ 0.2s sag removes.

Figure 5 illustrates the power generated by the solar plant along with the DVR power contribution. The DVR is connected at the PCC. It injects the required voltage during disturbances to maintain system stability [10]. This operation enables effective control of both active and reactive power in the grid. As a result, power quality is improved and the load receives a stable supply [10].

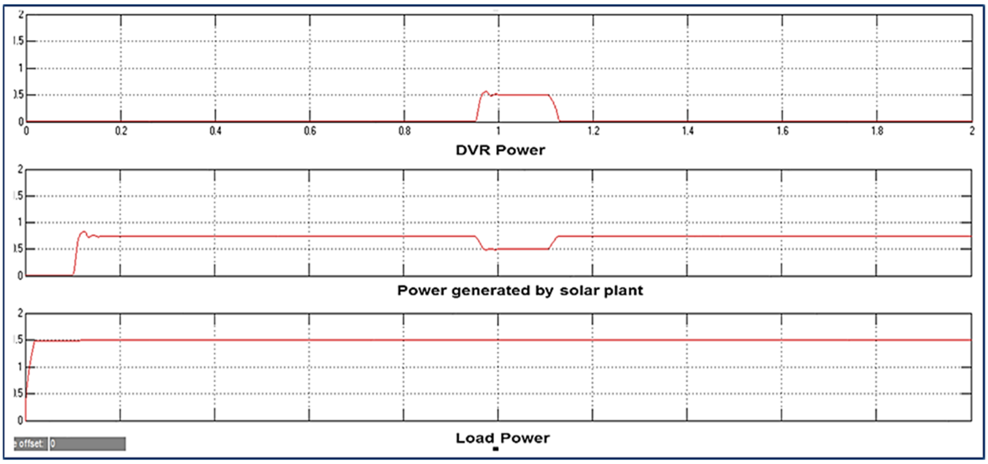

Fig. 5. Equivalent change in solar power due to DVR operation.

Figure 6 shows the combination of PCC voltage and DVR injected voltage supplying the load. The DVR compensates the voltage during disturbance conditions at the PCC. Both voltages merge to maintain a continuous and stable load voltage. The waveform clearly demonstrates the removal of the 0.2 s voltage sag.

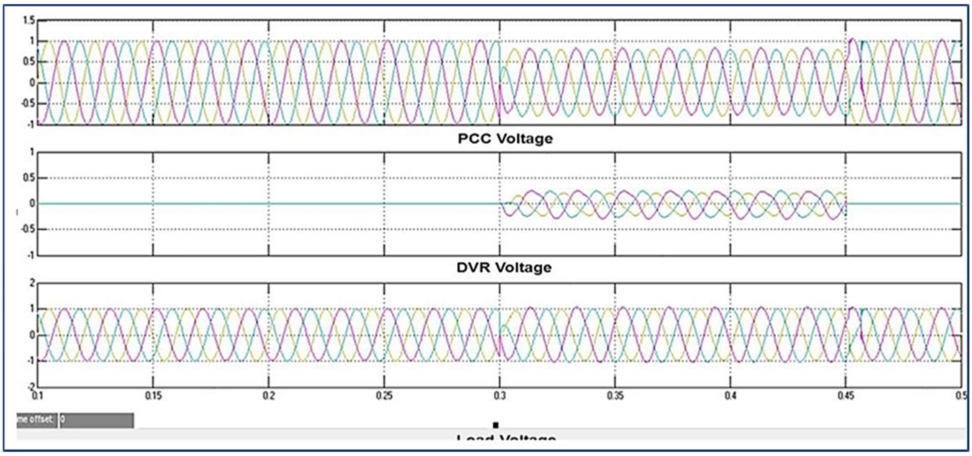

Fig. 6. Waveform for ≈ 0.2s sag removes (At different duration).

The given below waveforms (Figure 7) illustrate the performance of a DVR in maintaining power quality under disturbed conditions. From the plots, it can be observed that the PCC voltage experiences a significant sag during specific time intervals, indicating the presence of a disturbance in the supply system. During normal operation, the DVR remains inactive; however, as soon as the sag occurs, it injects a compensating voltage in series with the supply [11].

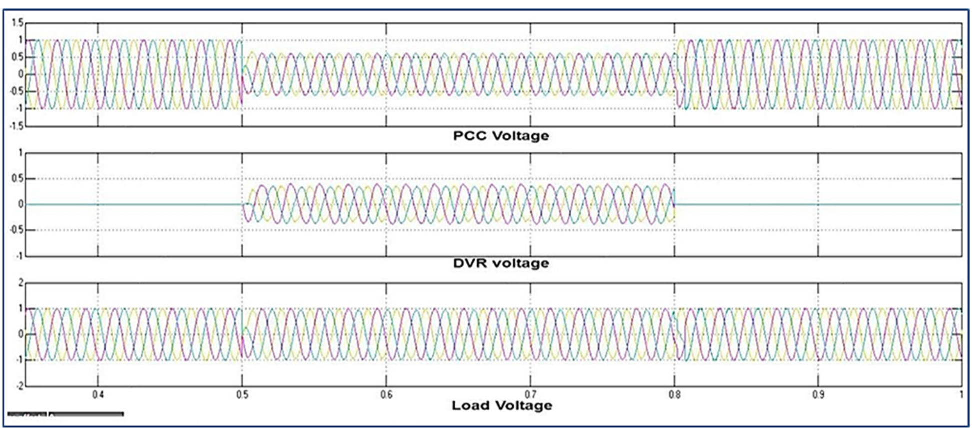

Fig. 7. Waveform for 0.3s sag removes (At different duration and depth).

This injected voltage is properly synchronized in magnitude and phase, which helps in restoring the load voltage to its nominal value. Despite the variations in the PCC voltage, the load voltage waveform remains nearly constant and sinusoidal, demonstrating the effectiveness of the DVR in mitigating voltage disturbances.

To evaluate the system's resilience under critical grid disturbances, a severe 0.3-second voltage sag was introduced into the simulation profile. Quantitative analysis of the simulation data reveals that during this transient period, the coordinated control loop of the nine-switch converter immediately detected the supply drop at the PCC. The DVR responded within less than half a cycle, injecting the precise missing active power component into the lines. Consequently, the load voltage profile remained fully stabilized at its nominal 1.0 p.u. value throughout the entire 0.3 s sag duration, confirming the robustness and fast dynamic execution of the proposed single-stage topology even under worst-case degradation scenarios.

The DVR effectively regulates the load voltage to the desired magnitude and phase, although its performance is influenced by the energy storage capacity available in the DC link [12, 13]. In this scenario, a deeper voltage sag occurs at the PCC, and the DVR responds by injecting a higher magnitude compensating voltage to restore the voltage profile. The injected voltage dynamically adjusts in accordance with the disturbance, demonstrating the fast response capability of the DVR control system. As a result, the load voltage remains stable, balanced, and nearly unaffected despite significant variations in the supply voltage. Furthermore, the integration of the photovoltaic (PV) system with the DVR enhances the overall system performance by providing additional energy support during compensation. This coordinated operation ensures efficient utilization of renewable energy while maintaining power quality [14]. The results clearly indicate that the PV-supported DVR system achieves reliable and rapid voltage sag compensation, minimizes disturbances at the load end, and maintains continuous operation of sensitive equipment. Overall, the system demonstrates healthy grid operation with improved voltage stability, reduced power quality issues, and enhanced resilience against severe voltage disturbances.

4 Conclusion

The study demonstrates that the integration of a photovoltaic (PV) supported Dynamic Voltage Restorer (DVR) effectively mitigates voltage sag and enhances overall power quality in the system. Simulation results confirm that the DVR successfully compensates both magnitude reduction and phase angle deviation (δ) occurring during voltage sag conditions at the Point of Common Coupling (PCC). For a demonstrated 0.2 s sag scenario and a quantitatively evaluated severe 0.3 s sag duration, the DVR injects the required compensation voltage with a fast dynamic response, maintaining the load voltage close to its nominal value with minimal distortion. The results also indicate that the DVR restores phase alignment, thereby preventing phase angle elevation issues commonly observed in fixed-speed wind and grid-connected systems. The inclusion of the PV source supports the DC link, improving energy availability during compensation. Overall, the system achieves stable operation, reduced voltage fluctuations, and improved reliability, confirming the effectiveness of the PV-DVR configuration for sensitive load protection.

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