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Review Paper -2

Improving Voltage Profile in Distribution Systems Under Sag and Swell Conditions Using DVR - A Review

Deeraz Roz[1], M.S. Dash[2], Devendra Sharma[3] ,Vasant Acharya[4]

dheerazroz14797@gmail.com[1],malaya_rec@rediffmail.com[2],

devendrasharma798@gmail.com[3], vasantacharyatitc@gmail.com[4]

[1]MTech Scholar, Department of Electrical and Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

[2]Professor, Department of Electrical & Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

[3]Assistant Professor, Department of Electrical & Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

[4]Assistant Professor, Department of Electrical & Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

I. Introduction

The growing penetration of highly sensitive electronic equipment and grid-tied renewable energy sources (RES) has placed unprecedented demands on power quality (PQ) in distribution systems [1]. Among the myriad PQ disturbances, voltage sags and voltage swells are the most frequently occurring and economically impactful phenomena, causing critical load interruptions and massive losses across industrial, commercial, and utility sectors [2]. These disturbances are primarily caused by symmetrical and asymmetrical short circuits on adjacent feeders [3].

The Dynamic Voltage Restorer (DVR) has emerged as the most efficient and dynamic solution to instantaneously mitigate these voltage disturbances [4], [5]. The DVR is a series-connected custom power device (CPD) that injects a controlled voltage into the line, maintaining the critical load voltage at its nominal magnitude and phase regardless of the upstream disturbance [6]. This paper provides a comprehensive review of the DVR's key operating principles, evaluates the comparative performance of its major control strategies, and highlights recent research directions aimed at enhancing its performance, reliability, and cost-effectiveness under complex sag and swell conditions.

II. DVR Operational Principles and Topology

The fundamental objective of the DVR is to inject a compensating voltage (V_DVR) such that the load voltage (V_Load) equals the desired reference voltage (V_Ref). This relationship is defined by Kirchhoff's Voltage Law (KVL):

V_Load = V_Source - (Z_line * I_Load) + V_DVR [7].

The DVR architecture comprises four main functional units [4], [8]:

Voltage Source Converter (VSC): A three-leg, six-switch inverter that synthesizes V_DVR using Pulse Width Modulation (PWM) switching.

Series Injection Transformer: Couples the VSC output voltage to the distribution line and provides galvanic isolation.

DC-Link and Energy Storage System (ESS): Typically a capacitor bank backed by a Battery Energy Storage System (BESS) or supercapacitors. The BESS supplies the necessary active power required to compensate for deep voltage sags [9].

Harmonic Filter: An LC filter positioned at the VSC output to suppress high-frequency switching harmonics and deliver a clean, sinusoidal injected voltage.

The ability of the DVR to compensate is limited by the VSC's maximum voltage injection capacity and the total energy available in the BESS [9], making the control strategy vital for energy management.

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III. Review of Compensation Control Strategies

The DVR control system must perform three crucial functions: disturbance detection, reference voltage calculation, and VSC switching pulse generation. The core distinction between DVR solutions lies in their reference generation technique, which dictates the performance and energy requirements.

A. Reference Voltage Calculation and Energy Management

Pre-Sag Compensation (PDC): This ideal method ensures the load voltage is identical in magnitude and phase angle to the pre-fault voltage [10]. It is preferred for sensitive, non-linear loads highly susceptible to phase angle jumps but demands the largest DVR rating and maximum active power from the BESS [11].

In-Phase Compensation (IPC): IPC simplifies the control by injecting a voltage that is always in phase with the source voltage. While this requires the minimum magnitude of V_DVR, it fails to correct phase angle jumps, limiting its use to loads tolerant of phase shifts [10].

Minimum Energy Injection (MEI) / Phase Advance Compensation (PAC): Recognized as a cost-effective solution, this strategy introduces a controlled phase advance to the injected voltage vector. This allows the DVR to inject the maximum possible reactive power (generated internally by the VSC) and minimize the injection of active power, thus directly reducing the required size and cost of the BESS [11], [12].

B. Modulation and Control Loop Techniques

The technique used to generate the VSC gate signals directly determines the transient response speed and output waveform quality.

Synchronous Reference Frame (SRF) Control: This conventional technique transforms the three-phase voltages into DC components (the d-q frame) for easier regulation using PI controllers [13]. SRF-based control excels at decoupling positive and negative sequence components, making it popular for handling unbalanced faults [14]. However, its performance suffers during severe phase jumps or high harmonic content, as the accompanying Phase-Locked Loop (PLL) can introduce detection delay [15].

Unit In-Phase Voltage Template (UTT) Control: This method focuses on directly generating a clean, three-phase sinusoidal reference signal by instantaneously extracting the fundamental frequency and scaling it to the nominal magnitude [16]. This approach simplifies the architecture by bypassing the complex coordinate transformations required by SRF, making it suitable for low-cost, high-speed applications where simplicity is paramount [17].

Hysteresis Voltage Control: As a high-speed, non-linear switching technique, Hysteresis control uses a defined error band to directly command the VSC switches, forcing the output voltage to track the reference instantaneously [16], [18]. Its inherent advantage is its rapid response time (often less than half a cycle), making it highly effective at suppressing transients and achieving low Total Harmonic Distortion (THD) by operating as an inherent active filter [19]. Hysteresis is often preferred over conventional PWM for its superior dynamic performance during fault clearing and initiation [20].

IV. Performance under Complex and Unbalanced Conditions

Modern distribution faults rarely result in clean, balanced sags. The DVR must demonstrate robustness against combined disturbances [21].

A. Unbalanced Sag and Swell Compensation

Asymmetrical faults (e.g., Single-Line-to-Ground or Double-Line-to-Ground) are the most common disturbances and typically cause a severe voltage sag in the faulted phase(s) alongside a consequential voltage swell in the healthy phases [3]. Effective compensation requires the DVR to inject a voltage vector that addresses both simultaneously. Techniques like the UTT, when coupled with an instantaneous controller like Hysteresis, monitor and correct the voltage error on a phase-by-phase basis [16]. This allows the DVR to automatically inject a high voltage to compensate the sag while injecting a smaller, opposing voltage to mitigate the swell, thereby maintaining a balanced voltage at the load terminals [22].

B. Harmonic and Transient Mitigation

The VSC must generate a compensating voltage that is not only correct in magnitude and phase but also clean and harmonic-free. The instantaneous control afforded by techniques like Hysteresis and advanced non-linear controllers (e.g., Sliding Mode Control) has been shown to achieve load voltage THD well below the 5% threshold set by standards [19], [23]. Furthermore, these fast-acting controllers are critical for damping the sharp voltage transients that occur when a fault is detected or cleared, ensuring smooth transitions for sensitive loads [24].

V. Conclusion and Future Directions

The Dynamic Voltage Restorer remains the gold standard among CPDs for mitigating voltage sags and swells. Recent research has focused heavily on shifting from complex, sequence-decoupled SRF control to simpler, faster non-linear methods. The synergistic combination of techniques like the UTT for rapid reference generation and Hysteresis control for instantaneous VSC switching has emerged as a particularly effective approach, demonstrating superior transient response (compensation in milliseconds) and robust performance under unbalanced, harmonic-rich conditions [17].

Future research efforts will concentrate on:

Cost and Efficiency Optimization: Implementing MEI/PAC strategies to reduce BESS sizing and integrating advanced optimization algorithms (e.g., Bee Optimization Algorithm) to fine-tune control parameters for minimal energy draw [25].

Hardware Validation and High-Voltage Application: Confirming the simulated performance of simplified control schemes on physical prototypes and addressing the engineering challenges related to insulation and component selection in high-voltage distribution environments [26].

Integration with Smart Grid Assets: Developing advanced control strategies for DVRs integrated with photovoltaic (PV) systems and battery storage to provide dual functionality: voltage support during faults and grid support (e.g., Volt/VAR control) during normal operation [27].

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