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Review Paper 1

A Review Paper on Improving Voltage Profile in Distribution Systems Under Fault Conditions Using a DVR

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I. Introduction to Power Quality and the DVR Challenge

The reliability of electrical power systems is increasingly challenged by power quality (PQ) disturbances, primarily **voltage sags** (dips) and **voltage swells** [1]. These events, often rooted in upstream transmission or distribution faults (e.g., Single-Line-to-Ground, Double-Line-to-Ground faults) or the abrupt switching of large loads/capacitors, cause significant economic losses, particularly in industries relying on sensitive electronic equipment [2]. The integration of distributed generation (DG) and renewable energy sources (RES) further exacerbates the problem by introducing high-frequency variations and asymmetrical disturbances [3].

Among the various custom power devices (CPDs), the **Dynamic Voltage Restorer (DVR)** has emerged as the most effective solution for mitigating short-duration voltage disturbances in distribution networks [4]. The DVR is a series-connected, power electronic-based device that injects a controlled voltage vector into the distribution line to instantaneously restore the critical load voltage to its nominal magnitude and phase angle [5].

This paper reviews the fundamental operation principles, key components, prominent control strategies, and recent advancements in DVR technology aimed at enhancing voltage profile stability, particularly under complex and unbalanced fault conditions.

II. DVR Topology and Operating Principles

A typical DVR system is composed of four main components [6], as shown in its schematic representation:

1. **Series Injection Transformer:** Couples the compensation voltage from the DVR to the main distribution line.
2. **Voltage Source Converter (VSC):** A three-phase inverter (usually insulated-gate bipolar transistor, or IGBT-based) that synthesizes the necessary injection voltage through Pulse Width Modulation (PWM).
3. **DC-Link and Energy Storage System (ESS):** The DC-link capacitor is backed by an ESS, such as a battery bank (BESS) or super capacitors, which supplies the **active power** required during compensation [7].
4. **Harmonic Filter (LC Filter):** Filters out the high-frequency switching ripple generated by the VSC before injection.

III. Review of Control Strategies

The performance and reliability of the DVR are critically dependent on the control strategy used to calculate the required VSC gate signals. Control strategies can be broadly classified based on their reference generation method and their modulation technique.

A. Reference Voltage Generation Techniques

Generating the reference voltage involves two sub-tasks: disturbance detection and calculation of the required compensation vector (magnitude and phase angle).

1. **Pre-Sag Compensation (PDC):** This ideal strategy restores the load voltage magnitude and phase angle exactly to its pre-fault value [9]. While theoretically perfect for sensitive non-linear loads, it often requires the largest DVR rating and maximum active power injection, stressing the ESS [10].
2. **In-Phase Compensation (IPC):** The injected voltage is maintained in phase with the source voltage or the post-sag voltage. This minimizes the required voltage magnitude, thereby limiting the DC-link voltage requirement, but it **does not compensate for phase angle jumps** [9], making it unsuitable for loads sensitive to phase variations.
3. **Minimum Energy Injection (MEI) / Phase Advanced Compensation (PAC):** A more cost-effective approach that deliberately introduces a controlled phase advance to the load voltage to minimize the active power component of the injected voltage [11], [12]. This directly reduces the size and cost of the BESS, leading to a highly sought-after cost-effective design.
4. **Synchronous Reference Frame (SRF) Theory:** This widely adopted method transforms the three-phase AC voltages into DC quantities using a Phase-Locked Loop (PLL) for synchronization [13], [14]. This simplifies control by separating the positive and negative sequence components, allowing for effective compensation under unbalanced and distorted conditions. However, the PLL can be slow and sensitive to high harmonic content or rapid phase shifts, affecting transient response [15].
5. **Unit In-Phase Voltage Template (UTT) Method:** A simpler, time-domain approach that avoids complex transformations. The UTT method generates a pure, sinusoidal reference template by instantaneously extracting the fundamental frequency component from the distorted source and scaling it to the desired nominal voltage [16]. This method is favored for its simplicity and fast reference tracking capabilities, particularly when paired with high-speed switching controllers.

B. VSC Switching Control (Modulation Techniques)

Once the reference injection voltage is calculated, a controller must generate the optimal PWM pulses for the VSC switches.

1. **PI/PID Control with SPWM:** Conventional Proportional-Integral (PI) controllers are widely used with Sinusoidal PWM (SPWM) generators to track the error between the reference and measured voltage [17]. While simple to tune for steady-state performance, fixed-gain PI controllers often yield slow transient response and struggle to suppress instantaneous voltage ripple and harmonics when system parameters fluctuate [18]. Recent work has attempted to improve performance using adaptive PI controllers or hybrid PI-Fuzzy Logic Control (FLC) schemes [19].
2. **Hysteresis Voltage Control:** This method is characterized by a very fast, non-linear control loop that uses the instantaneous error signal to directly control the VSC switches [16], [20]. By forcing the measured voltage to stay within a small defined **hysteresis band** around the reference, it achieves superior instantaneous tracking and inherent harmonic elimination. Its main drawback is the variable switching frequency, which must be carefully managed [20].
3. **Sliding Mode Control (SMC):** An advanced, non-linear technique known for its robustness against system parameter variations and external disturbances [21]. SMC offers a fast response and high tracking accuracy, often achieving a faster compensation time than PI controllers [22]. However, the technique suffers from a high-frequency switching effect known as "chattering," which newer algorithms like Real-Twisting Sliding Mode Control (RTSMC) attempt to mitigate [22].

IV. DVR Performance Under Fault Conditions

The most critical test for any DVR control strategy is its performance under unbalanced fault conditions, which combine sag and swell in different phases.

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A. Unbalanced Sag and Swell Mitigation

Unbalanced faults (SLG, DLG) produce **negative sequence components** that must be rapidly mitigated to ensure the load receives a balanced voltage. SRF control is often used to decouple and regulate these components independently [14]. However, simpler methods like the **UTT method** coupled with **Hysteresis Control** have proven highly effective because they instantaneously monitor and correct the voltage error on a phase-by-phase basis, automatically counteracting sag in one phase and swell in another without explicit positive/negative sequence decomposition [16]. Studies show that the DVR is effective in **simultaneously compensating for voltage sag and swell** in multi-phase systems [23].

B. Harmonic and Transient Compensation

The ability of the DVR to eliminate transients (spikes upon fault initiation/clearing) and harmonics is crucial for protecting sensitive loads. The use of instantaneous control methods, particularly **Hysteresis Control**, forces the VSC to generate a voltage that cancels out the high-frequency content present in the grid voltage [20]. This makes the DVR not only a sag/swell compensator but also an effective **Active Power Filter (APF)** component, capable of maintaining the load voltage THD well below the IEEE standards [24].

C. Sequential and Complex Events

Recent research focuses on testing the DVR under sequential and dynamic fault events to ensure system stability. Compensation strategies must demonstrate non-stop operation without losing synchronization or degrading performance during consecutive fault occurrences [25]. Furthermore, combining the DVR with other CPDs, such as current-limiting capabilities (e.g., FCL-DVR hybrid) or integrating it with distributed energy resources (PV-DVR), is an active area of research to address multiple PQ issues simultaneously [26], [27].

V. Conclusion

The DVR remains the most effective and dynamic custom power solution for mitigating voltage sags and swells in distribution networks. Research has evolved from optimizing simple in-phase injection to developing sophisticated, non-linear control algorithms capable of handling highly distorted, unbalanced grid conditions. The development of simpler, yet robust, techniques like the **UTT combined with Hysteresis Control** demonstrates a clear path toward achieving the critical goals of **high compensation speed (less than half a cycle)**, **low cost** (due to simpler hardware requirements), and **high reliability** (through superior transient and harmonic mitigation) under all fault conditions [16], [20]. Future work will continue to focus on hardware validation, cost-effective ESS optimization, and integrated solutions for comprehensive PQ management.

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