



# Electrical Voltage Sag/Swell Mitigation Using Converter-Based Dynamic Voltage Restorer For Distribution Transformer – A Review

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**Abstract :** Power quality disturbances such as voltage sags and swells have become major concerns in modern electrical power systems due to the increasing penetration of sensitive electronic loads and automated industrial processes. Among various mitigation techniques, the Dynamic Voltage Restorer (DVR) has emerged as one of the most effective Custom Power Devices (CPDs) for compensating voltage-related disturbances in distribution systems. This review paper presents a comprehensive study of converter-based DVR topologies, including the Voltage Source Inverter (VSI)-based DVR, Z-Source Inverter (ZSI)-based DVR, and Z-Source AC-AC converter-based DVR. Their operational principles, control methodologies, advantages, limitations, and comparative performance characteristics are analyzed with reference to published literature. Special emphasis is given to the Z-Source AC-AC converter-based DVR due to its enhanced buck-boost capability and reduced dependency on energy storage elements.

**IndexTerms - Custom Power Devices, control methodologies and AC-AC converter-based DVR.**

## I. INTRODUCTION

The rapid growth of power electronic loads and automated industrial systems has significantly increased concerns regarding power quality in distribution networks. Sensitive loads such as programmable logic controllers, adjustable speed drives, and semiconductor manufacturing equipment are highly susceptible to voltage disturbances (Hingorani, 1995). Among the various power quality issues, voltage sag and voltage swell are the most frequently occurring and economically damaging disturbances (Bollen, 2000). Voltage sag is defined as a short-duration reduction in RMS voltage between 10% and 90% of nominal voltage for durations ranging from half a cycle to one minute (IEEE-2019). Voltage swell is characterized by a temporary rise in RMS voltage above 110% of nominal value (IEEE-2019). These disturbances are commonly caused by short-circuit faults, motor starting, transformer energization, and load switching operations (Ghosh et al. 2002). Custom Power Devices such as Distribution Static Compensators (DSTATCOM), Unified Power Quality Conditioners (UPQC), and Dynamic Voltage Restorers (DVR) have been developed to mitigate such disturbances (Bollen, 1996). Among these, the DVR is considered a cost-effective and efficient solution due to its fast dynamic response and simple configuration (Ghosh et al. 2002).

## II. POWER QUALITY ISSUES IN DISTRIBUTION SYSTEMS

Voltage sags account for nearly 80% of power quality problems experienced by industrial consumers (Bollen, 2000). Faults in transmission and distribution systems lead to sudden drops in voltage magnitude, affecting downstream loads. Even short-duration sags can result in contactor dropouts, drive tripping, and production interruptions (Choi et al, 2002). Voltage swells occur due to sudden load removal or single-line-to-ground faults and may cause insulation stress, overheating, and equipment malfunction (IEEE-2019). Traditional voltage regulation techniques such as on-load tap changers and capacitor banks are ineffective for mitigating short-duration disturbances due to their slow mechanical response (Boonchiam, 2006). Consequently, fast-acting power electronic devices such as DVR are preferred.

## III. DYNAMIC VOLTAGE RESTORER: OPERATING PRINCIPLE

The Dynamic Voltage Restorer is a series-connected compensating device installed between the supply and the critical load (Choi et al, 2002). Its fundamental principle is to inject a voltage in series with the supply so that the load voltage remains constant. The relationship can be expressed as:

$$V_{load} = V_{source} + V_{injected}$$

During voltage sag conditions, the DVR injects a compensating voltage in phase with the source voltage, whereas during voltage swell conditions, it injects a voltage in opposition to reduce the load voltage magnitude (Choi et al, 2002). A typical DVR system consists of an energy storage unit, a DC link, a power converter, an injection transformer, filters, and a control unit (Choi et al, 2002). The effectiveness of compensation depends largely on the converter topology and control strategy employed.

#### IV. VOLTAGE SOURCE INVERTER-BASED DVR

The VSI-based DVR is one of the earliest configurations proposed for voltage sag mitigation (Choi et al, 2002). In this topology, a DC energy storage device supplies power to a voltage source inverter, which generates an AC compensating voltage. The injected voltage is applied to the distribution line through a series transformer.

VSI-based DVR systems provide fast response and relatively simple control implementation (Choi et al, 2002). However, the voltage boosting capability is limited by the DC link voltage, and additional DC-DC converters may be required for higher compensation levels (Peng, 2003). Furthermore, large energy storage systems increase system cost and maintenance requirements (Nielsen et al., 2005).

Despite these limitations, VSI-based DVR remains widely implemented due to its maturity and proven reliability in industrial applications (Choi et al, 2002).

#### V. Z-SOURCE INVERTER-BASED DVR

The Z-Source Inverter (ZSI) was introduced as an alternative to conventional VSI to overcome voltage boosting limitations (Peng, 2003). The ZSI incorporates an impedance network composed of inductors and capacitors arranged in a unique X-shaped configuration between the DC source and inverter bridge.

Unlike traditional VSI, the ZSI allows shoot-through states without damaging switching devices, thereby enabling inherent buck-boost capability (Peng, 2003). This feature eliminates the need for an additional DC-DC converter and increases voltage gain. ZSI-based DVR systems therefore provide improved compensation range and reduced energy storage requirements compared to VSI-based DVR (Peng, 2004). However, the inclusion of additional passive components increases system complexity, and careful design of the impedance network is necessary to ensure stability (Shen et al 2006).

#### VI. Z-SOURCE AC-AC CONVERTER-BASED DVR

Recent developments in power electronics have led to the introduction of Z-Source AC-AC converter-based DVR systems (Shen et al 2006). In this configuration, direct AC-AC power conversion is achieved without an intermediate DC link stage. The Z-source impedance network enables both buck and boost operation, allowing output voltage magnitude to be either greater or smaller than the input voltage. This topology offers several advantages, including reduced dependency on energy storage systems, improved harmonic performance, enhanced reliability, and bidirectional power flow capability (Shen et al 2006). Since energy is drawn directly from the grid during compensation, the overall system cost and maintenance requirements are reduced.

Simulation studies reported in literature indicate that Z-source AC-AC converter-based DVR provides faster voltage restoration and improved stability under deep sag conditions compared to VSI and ZSI-based DVR configurations (Peng, 2004).

#### VII. CONTROL STRATEGIES FOR DVR

The performance of DVR systems depends significantly on the adopted control strategy. Voltage detection methods typically employ synchronous reference frame (SRF) theory for accurate magnitude and phase extraction (Rodriguez et al., 2007). Pulse Width Modulation techniques such as Sinusoidal PWM and Space Vector PWM are widely used for generating switching signals (Holmes et al., 2003). Closed-loop control systems incorporating Proportional-Integral controllers enhance dynamic performance and steady-state accuracy. Advanced control strategies, including adaptive control and artificial intelligence-based approaches, are being explored to further improve compensation efficiency (Singh et al., 1999).

#### VIII. COMPARATIVE ANALYSIS

Comparative studies indicate that VSI-based DVR systems are simpler but require higher energy storage capacity (Nielsen et al. 2005). ZSI-based DVR systems improve voltage gain and reduce storage requirements but increase control complexity (Peng, 2003). The Z-source AC-AC converter-based DVR demonstrates superior performance in terms of voltage boosting capability, reduced harmonic distortion, improved reliability, and lower storage dependency (Peng, 2004).

MATLAB/Simulink simulation results presented in various studies confirm that all three topologies effectively mitigate sag and swell disturbances, but the Z-source AC-AC converter-based DVR achieves better dynamic response and waveform quality (Peng, 2004).

#### IX. APPLICATIONS IN DISTRIBUTION TRANSFORMERS

DVR systems are commonly installed at the secondary side of distribution transformers to protect sensitive loads from upstream disturbances (Ghosh et al., 2002). They improve transformer utilization, prevent nuisance tripping, and enhance overall system reliability. With increasing integration of renewable energy sources and distributed generation, DVR systems play a crucial role in maintaining voltage stability in modern distribution networks (Bollen et al. 1996)

#### X. CONCLUSION

Voltage sag and swell disturbances remain dominant power quality issues in distribution systems. The Dynamic Voltage Restorer has proven to be an effective solution for maintaining constant load voltage. This review examined VSI-based, ZSI-based, and Z-source AC-AC converter-based DVR topologies. Among these, the Z-source AC-AC converter-based DVR offers enhanced voltage regulation range, reduced energy storage requirement, improved harmonic performance, and superior reliability. Future research should focus on intelligent control strategies, cost optimization, and integration with smart grid technologies.

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