Enhancing power quality through the utilization of Dynamic Voltage Restorers in electrical distribution systems: an overview

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Abstract:

This paper presents a comprehensive review of the dynamic voltage restorer (DVR) for enhancing power quality in electrical distribution systems. Over the last five decades, power quality issues have been on the rise. To mitigate the impact of voltage disturbances, various devices have been introduced as solutions, including the distribution static compensator (D-STATCOM), solid-state transformer (SST), uninterruptible power supply (UPS), and the dynamic voltage restorer (DVR). The DVR, known for its cost-effectiveness, stands out as a solution to address voltage disturbances such as sag/swell and harmonics. Widely applied in power distribution systems, particularly in medium and low distribution networks, the DVR plays a crucial role in voltage mitigation.

This paper focuses on reviewing the integration of DVR in systems that incorporate renewable energy resources. This emphasis is vital considering the evolving landscape of the electricity sector towards renewable energy sources. The review encompasses a detailed discussion of typical components, controllers, compensation methods, and the diverse applications of DVR. The in-depth examination of DVR technology is intended to facilitate and accelerate its development and advancement in the near future.

***Keywords**:* **Cyber-physical system, Dynamic voltage restorer, Power quality, Technological review ,Voltage compensation, Voltage sag/swell**

1.INTRODUCTION:

In the recent years, Power quality (PQ) is emerging as an issue of major concern, (globally as well as nationwide) requiring accurate monitoring, in-depth analysis and adoption of planned PQ improvement initiatives. The present scenario has changed in our country, with a large proportion of the industrial, commercial, and domestic load now turning out to be non-linear due to growing use of power electronics, automation, computers, and information technology. Widespread use of non-linear loads degenerates the quality of power in both transmission and distribution systems. All non-linear loads draw non-sinusoidal currents which cause distortion in the voltage waveform not only withinthe individual plant but also in the power supply network [3]. Harmonics propagate from one consumer to another, causing many undesirable effects on the power system. The harmonic current components do not represent useful active power due to the frequency mismatch with the source voltage [4]. A simple and effective technique for harmonic analysis is current injection model which is most commonly applied for harmonic simulation studies. This approach treats harmonic producing load as an injection current source to the system assuming steady-state condition. Consequently, all non-linearities in the system are represented as current injections of corresponding harmonic frequencies and therefore, the superposition principle can be applied. The consumption of reactive power in industrial and domestic loads also presents an important issue in the discussion of power quality problems. The reactive power consumed by non-resistive loads causes higher RMS current values in addition to extra heating of power transmission and distribution systems. The use ofbatteries of capacitors or synchronous machines for local reactive power production has been proposed for a long time. The accelerated development of power electronics and semiconductor production has encouraged the use of STATIC VAR compensators for reactive power compensation. However, these solutions look inefficient and can cause extra problems in power systems in the case of high current and voltage harmonic emissions. The fact that these systems are especially designed to Numerous scholarly articles delve into power quality improvement techniques, each focusing on distinct aspects. In reference to [5], the authors concentrate on dissecting UPS circuits, exploring various topologies, configurations, and control algorithms essential for ensuring uninterrupted electricity supply during power shortages. In a related vein, [6] offers a comprehensive examination of D-STATCOM applications in power systems. This study encompasses diverse circuit topologies, architectures, and control techniques found in the literature, emphasizing their practical implementations for power quality enhancement, particularly in harmonic filtering and power factor correction.

Moving forward, [7] conducts a systematic review of Solid State Transformers (SST) in electrical distribution systems. The analysis encompasses high-power, high-frequency transformers, AC to AC converter topologies, and high-voltage power devices. Meanwhile, [8] delves into Dynamic Voltage Restorer (DVR) implementation for power quality enhancement, providing an extensive survey on performance, control techniques, and compensation strategies. Complementing this, [9] focuses on DVR compensation methods, offering a detailed comparative analysis.

Similarly, [10] undertakes a comprehensive study on DVR, centering on power circuit topologies and control strategies. Another facet is explored in [11], which reviews various AC-AC converter-based DVRs, emphasizing the elimination of DC storage to reduce size, weight, and cost. Notably, none of these reviews addresses DVR implementation in systems with substantial renewable energy integration.

This paper fills this gap by presenting a review of Dynamic Voltage Restorers in electrical distribution systems, emphasizing their implementation alongside renewable energy resources. Given the evolving landscape of the electricity sector towards renewable sources [12], understanding the role of DVR becomes paramount in mitigating voltage stability-related disturbances. Beyond technological updates, this review delves into typical components, controllers, compensation methods, and diverse applications of DVR, specifically in systems with significant renewable energy integration.

2. THE DYNAMIC VOLTAGE RESTORER

This section explores the typical configuration of the DVR applied in practical scenarios. Functioning as a specialized power device, the DVR plays a crucial role in compensating for voltage fluctuations, such as sagging, swelling, and harmonics within the distribution network [13]. Its significance is particularly evident in sustaining the smooth operation of sensitive loads [14]. At its core, the DVR is designed to identify voltage disturbances within the system and promptly inject the necessary voltage to restore the system back to its normal operating levels. This injection process aims to stabilize the voltage input, ensuring high-quality voltage for connected appliances [15].

3. THE DVR POWER CIRCUIT

Comprising four fundamental elements, the DVR power circuit includes a voltage injection transformer, Voltage Source Inverter (VSI), low-pass filters, and a mechanism for storing DC energy [16], as illustrated in

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Figure 1. The characteristics of each DVR component are detailed in Table 1.

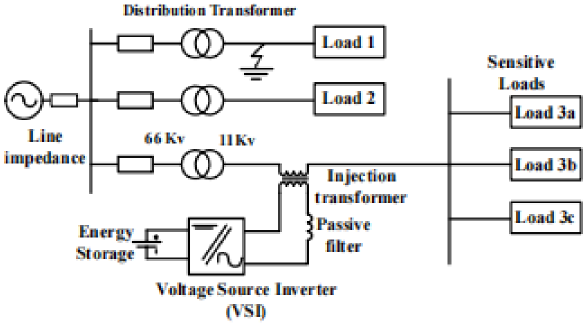

Figure 1. The typical power circuit of a DVR

Table 1. The descriptions of DVR's components

Component	Discussion
Energy storage	• To supply the required energy to compensate the voltage in the system (e.g., supercapacitors, batteries with superconducting magnetic energy storage, lead-acid, and flywheel. • Lead-acid batteries are the most popular types of energy storage considered for DVR due to it is highly responsive during the charging and discharging process [17].
VSI	• To convert the DC supply from the energy storage to the AC supply of the distribution network. • The inverted voltage needs to be balanced, pure sinusoidal; synchronized with the system voltage.
Filter circuit	• To filter out any harmonics generated by the VSI in order to maintain the quality of the compensated voltage [16]. • The VSI filter may be located either on the grid [18] or the converter side [19].
Bypass switch	• To prevent high current from passing through the DVR circuit in the event of a fault in the system. • Upon detecting an excessive current flow, the switch bypasses the current from the DVR circuit to protect it from the overcurrent.
Voltage injection transformer	• To increase the compensation voltage derived from the output of the VSI to meet the voltage level in the distribution network. • It also functions as isolation between the DVR and the distribution network.

4. DVR COMPENSATION METHODS

In controlling a Dynamic Voltage Restorer (DVR) for voltage injection, the phase angle and magnitude emerge as critical factors. Achieving the necessary voltage supply involves employing three distinct compensation methods. The fundamental control approaches encompass in-phase, pre-sag, and minimal energy compensation techniques [20].

4.1. Compensation via Pre-Sag

Illustrated in Figure 2, the pre-sag compensation technique is a pivotal method applied in DVR applications. This strategy addresses sagging voltage discrepancies by restoring both the magnitude and phase of the voltage before the onset of the sag [21]. In the depicted figure, the system's voltage before the disturbance is denoted as $Vpre{-}sag$. Subsequent to the voltage disturbance, the voltage and phase angle decrease to $Vsag$ and θsag, respectively. To counteract this sag, the method injects voltage magnitude $VDVR$ and phase angle θDVR into the system, compensating for the decrement in $Vsag$ and θsag during the disturbance, respectively.

This pre-sag compensation technique necessitates a relatively higher magnitude of voltage injection compared to other methods, leading to a relatively high active power requirement during voltage sag occurrences. Typically, this approach finds application in appliances sensitive to phase angle shifts, such as thyristor-type converters.

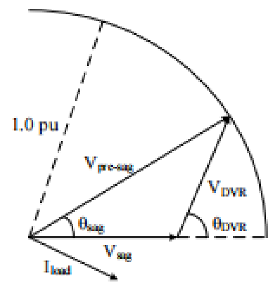

Figure 2. The pre-sag compensation technique

4.2. Compensation via In-phase

The in-phase voltage compensation method of a Dynamic Voltage Restorer (DVR) is depicted in Figure 3. In this particular approach, the DVR injects the voltage magnitude $VDVR$ without compensating for the phase angle (θDVR), as observed in the previous compensation method. This method specifically addresses the reduction in voltage magnitude without incorporating phase angle compensation. As a result, it proves suitable for linear loads that do not necessitate any phase angle adjustments [19]. When the voltage supply experiences a decrease due to a disturbance, this approach supplements the load with the missing voltage magnitude $VDVR$.

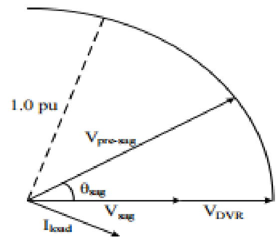

Figure 3. Compensation technique via in-phase

4.3. Minimum Energy Compensation

The minimal energy compensation method of a Dynamic Voltage Restorer (DVR) is visually represented in Figure 4, showcasing the injection of the required voltage magnitude $VDVR$ with a phase angle of 90∘ to the load [16]. Following a voltage disturbance in the system, the system voltage Vpre−sag$\angle\theta pre{-}sag$ drops to $Vsag\angle 0°$. Subsequently, upon detecting the voltage disturbance, the DVR injects the necessary $VDVR\angle 90°$ to elevate the voltage to $Vcomp$. While this method does not require active power injection into the system, the injected voltage may demand a higher-rated transformer and inverter to effectively compensate for the voltage disturbance. As depicted in the figure, $VDVR$ in Figure 4 is relatively higher compared to the VDVR required for the pre-sag and in-phase compensation methods, as shown in Figures 2 and 3, respectively.

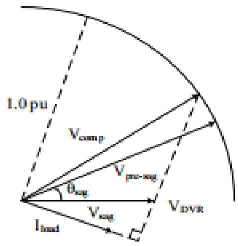

Figure 4. Minimum energy compensation

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5. TYPES OF DVR CONTROL STRATEGIES

The effectiveness of a Dynamic Voltage Restorer (DVR) hinges significantly on its strategies for controlling both active and reactive power to address power quality issues within the system [22]. As previously discussed in Section 2, the control strategies of the DVR primarily revolve around the Voltage Source Inverter (VSI) [23, 24]. Therefore, this section delves into the control strategies specifically pertaining to the VSI, which can be broadly categorized into linear and non-linear control, considering the nature and sensitivity of the load in the system.

5.1. Conventional Control

The conventional control methodology encompasses three distinct categories: feedforward, feedback, and hybrid. Feedforward control stands out as the most commonly employed method in DVR applications. This approach mitigates power quality issues by calculating the difference between the pre-sag and real-time voltages in the system through an open-loop system [25]. Although it may lack the precision of other control methods, its popularity stems from its simplicity, cost-effectiveness, and swift response. Consequently, it is preferred for mitigating less sensitive and critical loads compared to more advanced methods.

In contrast, the feedback method adopts a closed-loop control strategy, comparing the load voltage with the reference voltage [26]. This method surpasses the feedforward approach in terms of accuracy in power quality mitigation. However, it introduces complexity and a time delay in delivering the required control response. On a different note, the hybrid control method integrates both feedforward and feedback strategies, aiming to leverage the advantages of both [27]. While offering enhanced accuracy in power quality compensation, this composite control method comes at the expense of controller simplicity and cost.

5.2. Artificial Intelligence-based Control

In practical power systems, the inherent non-linear behavior poses limitations on the effectiveness of linear control strategies, especially within a certain operating range. Typically, conventional controllers are designed to cater to the application of DVR within this limited range. However, the performance of linear control becomes inadequate for the dynamic operating conditions encountered in higher-level distribution networks. Consequently, non-linear control methods, utilizing artificial neural networks (ANN), fuzzy logic, and space vector pulse width modulation (SVPWM), have emerged in the literature.

Artificial Neural Networks (ANN) have gained prominence as a versatile tool in various engineering applications due to their capability to emulate human decision-making processes and model complex systems. Several studies have utilized ANN for nonlinear control in DVR applications, showcasing its ability to represent intricate correlations between input and output without requiring explicit knowledge of complex mathematical functions representing the system [21]. The efficacy of ANN depends on factors such as the quantity of training data and the neural network's structure.

In contrast to ANN, the fuzzy logic controller has demonstrated its effectiveness in practical applications by replacing conventional controllers. The fuzzy logic controller facilitates a definite decision-making process based on imprecise or ambiguous data. Research presented in [28] illustrates the fuzzy logic controller's effectiveness in reducing the transient overshoot of the Voltage Source Inverter (VSI). Additionally, in [29], Space Vector Pulse Width Modulation (SVPWM) is employed to eliminate the negative sequence component's impact on the load voltage in DVR applications. The study shows that this technique successfully mitigates power quality issues even in unbalanced systems.

6. ADVANCEMENT OF DVR

6.1. Conventional Sources

6.1.1. Using Interline Dynamic Voltage Restorer

Despite the proven efficacy of DVR in mitigating voltage disturbances, the cost associated with replacing the energy storage system can be undesirable in certain situations. To address this challenge, the concept of an interline DVR is introduced in [30-32]. Figure 5 illustrates the typical configuration of an interline DVR, where two closely located DVRs share the same energy storage system to provide voltage compensation to two distinct distribution lines. The effectiveness of interline DVR has sparked further investigation by power system researchers and engineers. Optimization studies, as reported in [33], and the development of fast control schemes, outlined in [34], contribute to the ongoing exploration of its application.

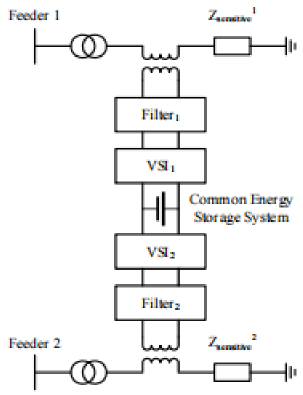

Figure 5. The typical configuration of an interline DVR

6.1.2. Development based on SOGI-PLL

In [35], a control algorithm for generating reference voltage and current in DVR applications is presented. This method relies on the second-order generalized integrator (SOGI) applied to each phase in the distribution line. The DVR is integrated with the D-STATCOM approach, serving as both shunt and series active compensators to address harmonics, sag, and swell in the system voltage and current, respectively. The SOGI-based algorithm effectively generates the required reference voltage and current from distorted signals. Addressing issues with the conventional DVR under unbalanced voltage sag conditions, researchers in [36] employ a dual SOGI (DSOGI) algorithm. This approach extracts symmetrical components and eliminates double-frequency interference from the measured signal, showcasing promising performance in mitigating various power quality issues.

Additionally, second-order - SOGI (SO-SOGI) is introduced in [37] to achieve rapid power quality compensation, both with and without phase jumps during harmonic conditions.

6.1.3. Other Controllers

Ongoing development in DVR technology is reflected in various advanced controllers proposed to address diverse power quality issues. In [38], a positive and negative sequence extractor (PNSE) is suggested to overcome challenges with the conventional SRF-PLL, filtering out negative sequence voltage and harmonics

in the power system. Researchers propose a soft-switching single-phase three-arm DVR in [39] to reduce switching during voltage compensation, enhancing the reliability of the DVR power circuit. An innovative Moving Average Filter (MAF)-based DVR, outlined in [33], aims to extract the positive sequence fundamental component from distorted supply voltage, addressing performance issues in generating an accurate reference instantaneous injected voltage. In [40], a self-tuning filter (STF) combined with the PQ control method is reported to enhance DVR performance, significantly reducing the required number of filters in the DVR design.

6.2. Renewable Energy Integration

As the incorporation of renewable energy sources becomes increasingly integral in power system studies, DVR development is not exempt from this trend. In [41], a feedforward vector control algorithm is utilized to generate firing angles for the Voltage Source Inverter (VSI) in DVR applications, showcasing its effectiveness on actual wind farm measured data during voltage sag and swell events. [42] introduces a PV-based DVR to enhance power quality post-disturbance, where PV serves a dual role by supplying power to the load and the DC-link of the DVR. A switching controller based on wavelet transform is proposed in [42] to detect power quality events and transform the PV system into a DVR. Furthermore, [43] combines feedforward and feedback control of the DVR to mitigate voltage sag during unbalanced fault conditions, demonstrating its crucial role in improving fault ride-through (FRT) capability in doubly-fed induction generator (DFIG) based wind turbines, compensating for voltage variations under both balanced and unbalanced conditions.

7. CONCLUSION

In conclusion, this review provides a comprehensive examination of Dynamic Voltage Restorer (DVR) implementation in power systems. The typical power circuit structure is elucidated, offering a detailed review of each DVR component. Various compensation methods, including pre-sag, in-phase, and minimum energy compensation, are presented and discussed. The diverse landscape of control strategies is explored, encompassing both conventional and artificial intelligence-based approaches.

The paper also delves into the current advancements in DVR technology, considering both conventional and renewable energy sources. The integration of renewable energy sources into DVR systems is specifically highlighted, emphasizing the dual role they play and the challenges posed to power quality.

Based on the discussion, it is recommended to focus on further development of DVR control circuits, particularly in addressing unbalanced voltage disturbances. Despite existing research efforts, there is substantial room for improvement in terms of controller performance and response time. Additionally, the integration of renewable energy sources into DVR systems warrants attention, with a need for comprehensive research addressing the multifaceted functions of renewable energy systems and the associated power quality issues in conventional power networks. Urgent attention from researchers is required to navigate the complexities of this evolving field.

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