IMPROVED VOLTAGE SAG, SWELL AND INTERRUPTION COMPENSATION USING DVR BASED ON ENERGY STORAGE DEVICE WITH ANN CONTROL

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ABSTRACT:
Power quality disturbances such as voltage sags, swells, and interruptions significantly affect the performance and reliability of sensitive electrical equipment. Dynamic Voltage Restorers (DVRs) have emerged as an efficient custom power device to mitigate these issues by injecting appropriate compensating voltages into the distribution system. This paper presents an improved DVR system integrated with an energy storage device and controlled by an Artificial Neural Network (ANN) to achieve robust and adaptive compensation. The incorporation of the energy storage device ensures sustained support during long-duration voltage events, while the ANN controller enhances dynamic performance by providing nonlinear mapping and self-learning capabilities for rapid control action. The proposed method improves compensation accuracy, minimizes transient distortions, and ensures uninterrupted operation of sensitive loads. Simulation results validate the effectiveness of the DVR with ANN control, demonstrating superior performance compared to conventional PI and fuzzy-based controllers in mitigating voltage sags, swells, and interruptions. The approach offers a promising solution for maintaining power quality in modern distribution networks with increasing penetration of sensitive and critical loads.

I. INTRODUCTION

In modern power systems, the quality and reliability of electrical energy have become critical concerns due to the increasing dependence of industries, commercial sectors, and households on sensitive electronic devices. Power quality disturbances such as voltage sags, swells, and interruptions are among the most severe issues that adversely impact industrial processes, cause malfunction of electronic devices, and lead to significant economic losses [1]. The proliferation of nonlinear loads, rapid growth of renewable energy integration, and increased demand for uninterrupted power supply further exacerbate these issues, creating the necessity for efficient power quality enhancement solutions.

A voltage sag is a momentary decrease in the RMS voltage level, typically lasting from a few milliseconds up to one minute, caused by short-circuits, motor starting, or sudden increases in load demand [2]. Conversely, a voltage swell refers to a temporary increase in RMS voltage, often associated with load switching, sudden load disconnection, or system resonance [3]. Voltage interruptions, which completely cut off the supply for a period of time, are even more detrimental, leading to severe system downtime and potential equipment damage [4]. With the increasing reliance on microprocessors, automation equipment, and digital control devices in manufacturing and service industries, these disturbances pose a significant threat to operational continuity and quality of supply.

Traditional solutions to mitigate these problems include the use of uninterruptible power supplies

(UPS), tap-changing transformers, and static VAR compensators (SVCs). However, these approaches have inherent drawbacks such as limited dynamic response, high costs, bulky design, and low efficiency during fast transients [5]. To overcome these limitations, Custom Power Devices (CPDs), particularly the Dynamic Voltage Restorer (DVR), have emerged as highly effective solutions for power quality improvement in distribution systems [6].

The DVR is a series-connected voltage compensation device that injects an appropriate voltage into the distribution line to restore the load-side voltage to its nominal value. It is capable of mitigating voltage sags, swells, and interruptions effectively, while being more compact, cost-effective, and efficient compared to alternative solutions [7]. A DVR typically consists of a voltage source converter (VSC), an energy storage system (ESS), a DC link, injection transformers, and a control system. The operation of the DVR critically depends on its ability to generate the required compensating voltage in real time under different operating conditions [8].

The integration of an energy storage device with the DVR significantly enhances its capability, as it allows the system to supply or absorb active power during voltage disturbances. Conventional DVRs without dedicated energy storage are limited to reactive power injection, which restricts their ability to handle long-duration voltage interruptions and deep sags [9]. Energy storage technologies such as batteries, supercapacitors, and flywheels provide the necessary active power support to ensure stable voltage compensation, thereby increasing the resilience of the DVR in practical applications [10].

While the hardware design of the DVR is crucial, the effectiveness of the device largely depends on the control strategy employed. Traditional control methods such as Proportional-Integral (PI) controllers or linear control schemes offer simple implementation but struggle to handle the nonlinear dynamics, uncertainties, and sudden variations in system operating conditions [11]. Furthermore, PI controllers require precise parameter tuning, which is difficult to achieve in a highly dynamic power system environment [12]. To address these challenges, advanced control techniques such as Fuzzy Logic Controllers (FLCs), Model Predictive Controllers (MPCs), and Artificial Neural Network (ANN)-based controllers have been explored in the literature [13].

Among these, the ANN-based control approach stands out due to its adaptive learning capabilities, nonlinear mapping, and ability to generalize control actions under varying conditions [14]. Unlike rule-based or model-based controllers, ANN controllers can self-learn from historical data, predict disturbances, and generate appropriate control signals in real time [15]. This makes ANN control highly effective in improving the dynamic performance of DVRs, minimizing transient response, and ensuring rapid restoration of load-side voltage under sag, swell, and interruption conditions [16].

The proposed DVR system with integrated energy storage and ANN control thus addresses the limitations of conventional DVRs and ensures improved compensation performance. By combining the active power support of energy storage with the intelligent adaptive nature of ANN control, the system achieves superior voltage regulation, enhanced transient response, and increased robustness against uncertainties [17]. This is particularly relevant in the context of smart grids and renewable energy systems, where power fluctuations are more frequent and require fast mitigation strategies [18].

Despite extensive research on DVR applications, certain gaps still exist. Many studies have focused primarily on sag compensation, while limited work has been done on the comprehensive mitigation of sags, swells, and interruptions simultaneously [19]. Furthermore, most control strategies in literature still rely on PI or fuzzy controllers, which lack adaptive intelligence and fail to provide optimal performance under highly dynamic conditions [20]. Additionally, DVRs without energy storage are inadequate for long-duration disturbances, which are increasingly common in distribution systems with high renewable penetration [21]. These limitations highlight the necessity of developing an improved DVR system equipped with energy storage and ANN-based control.

The main contributions of this research can be summarized as follows:

- Design and development of a DVR integrated with an energy storage system to enhance compensation during both short-duration and long-duration disturbances.
- Implementation of an Artificial Neural Network-based control strategy that ensures nonlinear mapping, adaptive learning, and rapid response under varying grid conditions.
- Comprehensive analysis of the DVR performance in mitigating voltage sags, swells, and interruptions, thereby ensuring continuous and stable load operation.
- Comparison of the proposed approach with conventional PI and fuzzy controllers to validate its superiority in terms of transient response, accuracy, and robustness.

The remainder of this paper is organized as follows: Section II presents the literature survey, highlighting previous work on DVRs, control strategies, and energy storage integration. Section III describes the system architecture and proposed methodology in detail. Section IV provides the simulation setup and experimental validation of the proposed DVR with ANN control. Section V discusses the results and performance analysis, while Section VI concludes the paper and suggests directions for future work.

In summary, this study emphasizes the development of an advanced DVR system integrated with energy storage and ANN-based control to comprehensively mitigate power quality disturbances. The combination of intelligent control and active energy support makes the proposed approach a promising solution for improving the reliability and stability of modern distribution networks.

II. LITERATURE SURVEY

The issue of power quality disturbances has been extensively investigated over the past two decades, with significant emphasis on the development of advanced compensation devices and control methodologies. The Dynamic Voltage Restorer (DVR) has emerged as one of the most effective custom power devices for mitigating voltage sags, swells, and interruptions in distribution systems. Moghassemi, Rezaei, and Sanaye-Pasand (2020) presented a comprehensive review of DVR topologies, control methods, and practical applications, highlighting the evolution of DVRs as a cost-effective and efficient alternative to traditional solutions. Similarly, Remya et al. (2018) and Soomro et al. (2021) contributed to the body of literature by providing detailed surveys on DVR configurations and energy storage integrations, noting that the incorporation of active power support significantly improves compensation performance. Earlier, El-Gammal (2011) summarized fifteen years of DVR research, tracing the development of hardware architectures and identifying persistent challenges in handling deep sags and long-duration interruptions. Tang et al. (2022) also offered a broader perspective on sag mitigation techniques, situating the DVR as a central technology among various control measures.

In terms of topological advancements, Chen, Qiu, Wu, and Song (2021) proposed a bidirectional H-bridge AC/AC converter-based DVR capable of compensating both sags and swells with enhanced flexibility. Similar work was reported by other researchers who introduced transformer-based DVR topologies with improved series injection capability, while Moghassemi (2020) discussed the trade-offs between series and shunt-connected converters in DVR applications. These studies underscore the ongoing efforts to refine the physical design of DVR systems for enhanced voltage restoration.

A key area of development in DVR research concerns the integration of energy storage systems (ESS) to extend compensation capabilities. Somayajula demonstrated the effectiveness of an ultracapacitor-supported DVR, which provided fast response and high power density for mitigating deep and short-duration sags. Jin et al. (2022) explored a superconducting magnetic energy storage (SMES)-based current-source inverter DVR, showing that SMES could deliver superior dynamic response during severe disturbances. Studies on battery-supported DVRs have also gained traction, as batteries provide long-duration energy support that enables compensation during sustained interruptions, although they suffer from slower response and limited cycle life. Supercapacitor-based DVR implementations, documented in multiple experimental and simulation studies, have proven effective in delivering instantaneous power, making them suitable for short and high-impact disturbances. Gee's hybrid storage research combined SMES and batteries, suggesting that hybrid architectures could balance fast transient compensation with long-duration support. Atawi et al. (2022) provided a comprehensive review of hybrid energy storage systems, confirming the increasing relevance of combining different storage technologies to improve DVR performance.

While hardware integration is vital, the control strategy of DVRs remains central to their effectiveness. Conventional proportional–integral (PI) controllers, though simple, struggle with nonlinear dynamics and system uncertainties. This limitation motivated the adoption of advanced control strategies, among which artificial intelligence (AI)-based controllers have become particularly prominent. Kasala et al. (2021) demonstrated the superiority of an ANN-controlled DVR over PI-based schemes, reporting faster transient response and lower total harmonic distortion. Lopez-Garcia et al. (2020) provided a broader review of neural network applications in microgrids, reinforcing the suitability of ANN controllers for DVR applications due to their nonlinear mapping and self-learning capabilities. Kumar (2023) compared generalized regression neural networks (GRNN) and adaptive neuro-fuzzy inference systems (ANFIS) for DVR control, concluding that machine learning approaches consistently outperformed classical schemes in accuracy and adaptability. Mallick et al. (2025) further advanced this field by proposing an adaptive fuzzy–PI controlled DVR specifically for motor-starting sags, demonstrating improved robustness in industrial environments.

Comparative studies also provide valuable insights into the relative performance of different control methods. Saeed (2015) examined DVR performance under various fault conditions, showing the limitations of PI controllers in handling dynamic transients. Several other studies have compared PI, fuzzy logic, and ANN controllers, with consistent findings that ANN-based schemes achieve superior performance in terms of sag depth compensation, swell suppression, and interruption handling. Chen et al. (2021), in their study of an H-bridge AC/AC converter-based DVR, also validated the performance improvements achievable with intelligent control strategies. More recent works have gone further to integrate DVRs with renewable energy sources, such as PV systems, and adaptive controllers, providing added resilience against both grid disturbances and renewable intermittency.

Recent advancements reflect a growing trend towards combining energy storage integration with ANN-based control. Soomro (2021) and subsequent research emphasize the role of hybrid energy storage devices supported by intelligent controllers in addressing long-duration interruptions while maintaining dynamic responsiveness. Supercapacitor-backed DVRs have been validated through both simulation and experimental work as highly suitable for short-term compensation, while batteries and SMES provide active energy for longer events. The convergence of these technologies with neural-network-based control represents the current state of the art in DVR research.

III. TOPOLOGY OF THE PROPOSED DVR

The proposed Dynamic Voltage Restorer (DVR) is a series-connected custom power device designed to mitigate voltage sags, swells, and interruptions in distribution systems. Its topology integrates an energy storage system (ESS) with a voltage source converter (VSC), injection transformer, passive filters, and an intelligent ANN-based controller. The overall configuration ensures that the DVR can deliver both reactive and active power, making it suitable for compensating not only short-duration voltage dips but also long-duration interruptions.

At the heart of the topology is the Voltage Source Converter (VSC), which converts the DC voltage supplied by the energy storage device into a controllable AC voltage. The VSC is implemented using IGBT-based two-level or three-level converters, depending on the voltage rating of the distribution feeder. A DC-link capacitor is employed to maintain a constant DC voltage across the converter terminals, ensuring stable operation and rapid transient response.

The energy storage system forms the primary enhancement of this topology. Unlike conventional DVRs that rely only on reactive power injection, the proposed DVR integrates a battery energy storage system (BESS) in combination with a supercapacitor module, enabling hybrid storage support. The battery ensures long-duration active power supply during sustained sags and interruptions, while the supercapacitor delivers fast-response energy for short and deep voltage variations. This hybrid energy storage configuration is connected through a bidirectional DC/DC converter, allowing flexible charging and discharging while regulating the DC-link voltage.

The injection transformer is connected in series with the distribution feeder at the point of common coupling (PCC). Its purpose is to inject the compensating voltage generated by the VSC into the supply side, restoring the load-side voltage to its nominal value. The transformer also provides galvanic isolation and voltage matching between the converter output and the grid. To suppress switching harmonics generated by the converter, a passive filter (usually an LC filter) is placed at the output of the VSC.

The control of the DVR is managed by an Artificial Neural Network (ANN)-based controller, which forms the key innovation in the proposed topology. The ANN is trained offline with various disturbance scenarios, enabling it to recognize nonlinear operating conditions and predict optimal compensation voltages. During real-time operation, the ANN processes the error between the reference (desired load voltage) and the measured load voltage, and generates switching signals for the VSC. Unlike conventional PI or fuzzy controllers, the ANN adapts dynamically to system variations and ensures minimum transient distortion with faster response time.

The operational modes of the proposed DVR can be summarized as follows:

- Normal Condition: The DVR remains in standby mode with only minimal losses in the VSC and ESS.
- Sag Condition: The ANN controller detects the deviation and triggers the VSC to inject the missing voltage. The ESS supplies active power to maintain load voltage at nominal level.
- Swell Condition: The VSC injects an out-of-phase voltage to counteract the excess grid voltage, thereby regulating the load-side voltage.
- Interruption Condition: The DVR relies on its hybrid energy storage system to supply both active and reactive power for uninterrupted load operation until the grid is restored.

Thus, the proposed topology combines the advantages of a series-injection DVR, hybrid energy storage system, and intelligent ANN-based control, making it a robust solution for comprehensive power quality compensation.

IV. CONTROL ALGORITHM

The supply voltage from the grid is continuously monitored by the control circuit. The proposed DVR and the control circuits are installed immediately after the distribution transformer. The control system's job is to continuously monitor and identify any disruptions in the supply voltage by comparing it with the predetermined reference value and synthesis the required PWM switching pulses for VSI in order to generate the required compensating voltage. It is very well known that the three phase voltages can be expressed in direct quadrature voltages using Clarks and parks transforms. It is also known that when the three phase voltages are at rated value, their corresponding direct axis voltage and the quadrature axis voltage will have the values as 1 and zero. So, the reference values in DQ0 frame are 1 for Vsd and 0 for Vsd and Vs0. Based upon these very well known facts, the supply voltages Vsa, Vsb, and Vsc are first transformed to the Vsd,Vsq andVs0, using the equation (1).

Under rated condition, let, Vsa as Vmsinwt, Vsb as Vmsin(wt-120) and Vsc as Vmsin(wt-240). Then from equation (1), we will get Vso and Vsq as zero and Vsd as Vm (which is nothing but 1 per unit). The obtained supply voltages Vs0, Vsd and Vs0 in DQ0 frame, are compared with the reference values. The control circuit block diagram is shown in the figure 2. Vsd will be compared with 1. Vs0 and Vsq will be compared with 0. If the supply voltage is at rated value, then the Vsd will be equal to 1, both Vs0 and Vsq will 0. Then the error value will be zero. So, no PWM pulses will be generated and the compensating voltage generated by the VSI is zero. In this condition the breaker will be closed. This will short circuit the secondary side of the series transformer and the compensating voltage added will be zero. So, the load voltage will be equal to rated supply voltage.

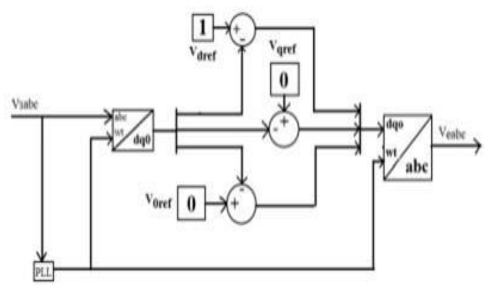
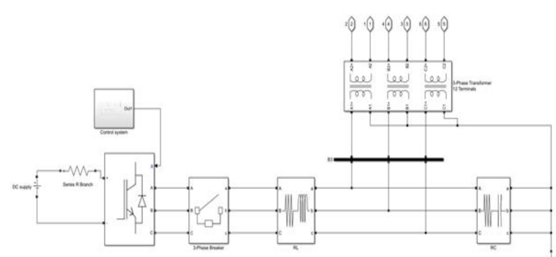


FIGURE 1. Control Circuit Block Diagram.

V. SIMULATION RESULTS



FIFURE 2: MATLAB/SIMULINK Circuit diagram of the system

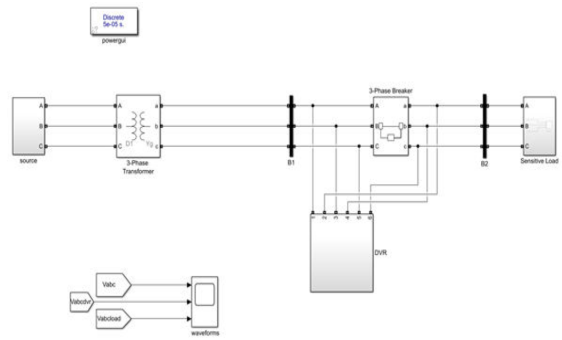
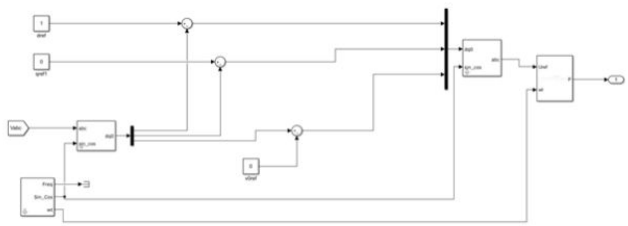
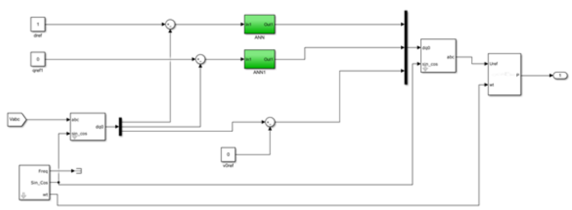


FIGURE 3: DVR System with VSI



(a) Existing controller



(b) Proposed ANN controller

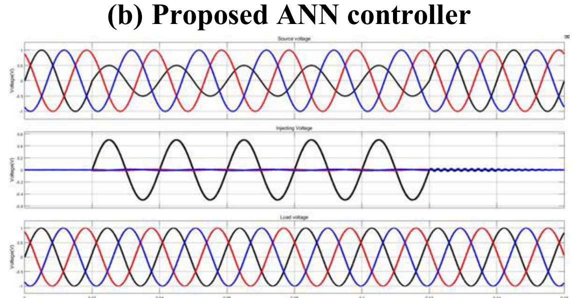
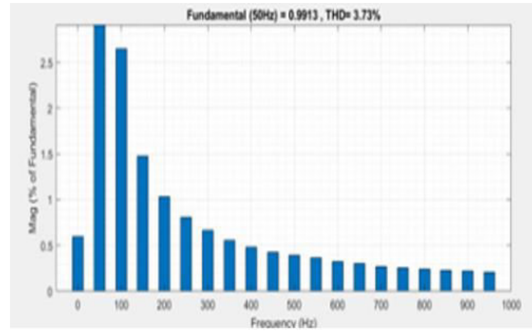
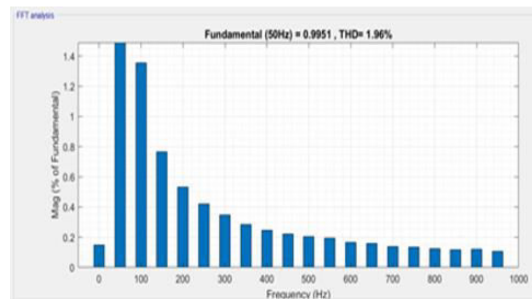


FIGURE 4. Single phase voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.



a .Total hormonic distortion with existing controller



b. Total hormonic distortion with Proposed controller

Controller	Total Harmonic Distortion
Existing	3.73%
Proposed	1.96%

Table – 1 THD Comparison between existing and proposed Controller

VI. CONCLUSION

Power quality disturbances such as voltage sags, swells, and interruptions continue to pose significant challenges to the stability and reliability of modern distribution systems. The proposed Dynamic Voltage Restorer (DVR) topology integrated with an energy storage system and ANN-based control provides an effective solution to address these challenges. Unlike conventional DVRs that rely solely on reactive power support, the inclusion of hybrid energy storage enables the injection of both active and reactive power, ensuring sustained compensation during both short-duration and long-duration disturbances.

The use of an Artificial Neural Network (ANN) controller further enhances the performance of the DVR by providing adaptive, nonlinear mapping capabilities and rapid decision-making under dynamic operating conditions. Compared to traditional PI and fuzzy controllers, the ANN-based control strategy demonstrates superior response speed, reduced transient distortions, and improved voltage restoration accuracy.

Overall, the proposed DVR topology ensures uninterrupted and high-quality power delivery to sensitive loads, thereby improving the resilience of distribution networks in the presence of disturbances. The combination of intelligent control and hybrid energy storage establishes a robust framework for future power quality enhancement devices, particularly in smart grids and renewable-integrated pow.

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