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Voltage Sag, Swell, and Interruption Mitigation Using a Fuzzy Logic-Based DVR with Energy Storage Integration

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ABSTRACT

Voltage sags, swells, and interruptions are the most critical power quality issues, frequently affecting sensitive loads. While most DVR systems in literature use controllers like P, PI, PID, fuzzy logic, or neural networks, this study proposes a controller-free DVR solution. The system includes a Voltage Source Inverter (VSI), LC filter, series transformer, control circuitry, and a battery bank, positioned after the distribution transformer.Supply voltages are measured and transformed into DQ0 components. If voltages are normal, no PWM is generated, and the DVR injects zero voltage. During disturbances, error signals appear in the DQ0 frame, are transformed back into three-phase signals, and used to generate switching pulses. The VSI then injects a compensating voltage via the series transformer to maintain rated load voltage.MATLAB/Simulink simulations confirm that the DVR effectively compensates for 100% balanced/unbalanced sags, swells, and both single- and three-phase interruptions.

I. OVERVIEW

Voltage sags, swells, and interruptions are major power quality issues that frequently affect sensitive loads. These disturbances arise from both the transmission and distribution sides due to motor starting, load switching, equipment faults, and grid instabilities. While utilities use FACTS devices for transmission-level issues, customers rely on custom power devices like DVRs, UPS, and DSTATCOM on the distribution side.

DVRs are highly effective in compensating voltage disturbances. Unlike traditional systems that rely on controllers such as P, PI, PID, fuzzy logic, or neural networks, the proposed DVR topology operates without any control algorithms. It uses a Voltage Source Inverter (VSI), LC filter, series transformer, and battery storage, and is installed after the distribution transformer.

The DVR continuously monitors the supply voltage, transforms it into DQ0 components, and compares it to a reference. If the voltage deviates, the resulting error signal is used to generate switching pulses, which direct the VSI to inject the compensating voltage through the series transformer. This method effectively restores the load voltage during sags, swells, and outages.

Compared to existing DVRs using complex controllers and optimization techniques (e.g., cuckoo search, neuro-fuzzy, predictive control), the proposed design simplifies operation by relying solely on DQ0 transformation and error comparison, without needing current sensing, tuning, or AI-based control. MATLAB/Simulink simulations confirm its capability to handle 100% voltage sags, swells, and both single and three-phase interruptions.

II. The proposed DVR's topology

The DVR, a key power quality device, is installed immediately after the distribution transformer to protect loads from supply voltage variations. As shown in Figure 1, the proposed DVR includes a battery bank for energy storage, supplying DC power to a Voltage Source Inverter (VSI). The VSI output is filtered through an LC filter and fed to the primary winding of a series transformer. A breaker is connected across the transformer's secondary winding.

The system continuously monitors the supply voltage and compares it to a reference. If the voltage is at its rated value, no error signal is generated, no switching pulses are sent to the VSI, and the DVR injects zero compensating voltage. At this stage, the breaker remains closed, short-circuiting the transformer's secondary, ensuring the load voltage equals the supply voltage.

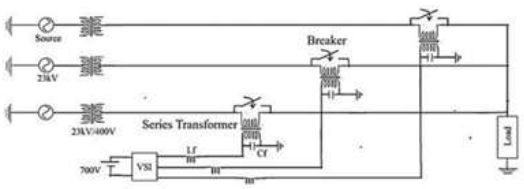

FIGURE 1.Topology of the Proposed DVR.

If a voltage sag, swell, or interruption occurs, the supply voltage deviates from its rated value, generating error signals. In response, the DVR's control circuitry activates to produce the required compensating voltage. The breaker across the series transformer is opened, allowing the compensating voltage—combined with the supply voltage—to be injected into the line via the series transformer. The system continuously monitors and tracks the supply voltage to ensure effective compensation.

III. ALGORITHM OF CONTROL

The control circuit continuously monitors the grid's supply voltage and detects deviations by comparing it to a preset reference. Positioned just before the distribution transformer, the DVR and control system work together to synthesize PWM pulses for the Voltage Source Inverter (VSI) as needed.Using Clarke and Park transformations, the three-phase voltages (Vsa, Vsb, Vsc) are converted into DQ0 components (Vsd, Vsq, Vs0). Under rated conditions, these transform to Vsd = 1 p.u., Vsq = 0, and Vs0 = 0. These values are compared to reference values (Vsd = 1, Vsq = 0, Vs0 = 0). If matched, no error signal is generated, the VSI produces no compensating voltage, and the breaker remains closed, shorting the transformer's secondary side. This ensures that the load voltage equals the rated supply voltage.

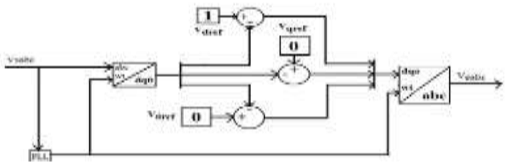

FIGURE 2. Control Circuit Block Diagram

During a voltage sag, swell, or interruption, the supply voltages become unbalanced and deviate from their rated values. As a result, Vsd ≠ 1, and Vs0, Vsq ≠ 0, generating error voltages (Ve0, Ved, Veq) in the DQ0 frame. These are transformed back into three-phase error signals (Vea, Veb, Vec) and compared with carrier signals to generate PWM pulses for the VSI.A phase-locked loop (PLL) tracks the phase of the supply voltages to ensure synchronization. The DVR then injects the appropriate compensating voltage via the series transformer to restore the load voltage to its rated condition.To validate the proposed DVR system, a 23 kV grid supply is stepped down to 400 V using a 6.25 kVA, 23 kV/400 V distribution transformer. A 5 kVA RL load with a 0.8 lagging power factor is connected. The DVR is placed after the transformer, powered by a 700 V battery bank.A Voltage Source Inverter (VSI) with six IGBT switches and anti-parallel diodes is used. An LC filter (2 mH, 15 μF) is connected at the VSI output, followed by a 6.25 kVA series transformer (1:1 ratio) to inject the compensating voltage.Simulation results confirm the DVR's ability to mitigate voltage sags, swells, and outages. Performance is presented in per-unit values:**Figure 3**: 50% mitigation of single-phase sag in phase "a."**Figures 4 & 5**: 20% and 50% mitigation of balanced voltage sags.**Figure 6**: Unbalanced sag mitigation — 20% in phase "a," 50% in "b," and 25% in "c."The results demonstrate the DVR's effectiveness and reliability under various fault conditions.

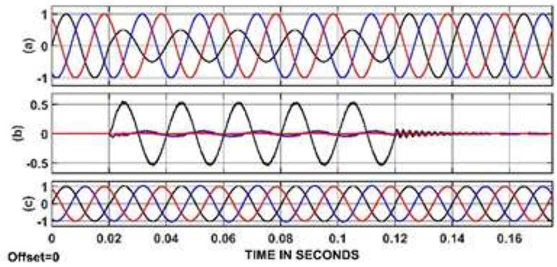

FIGURE 3. Single phase voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

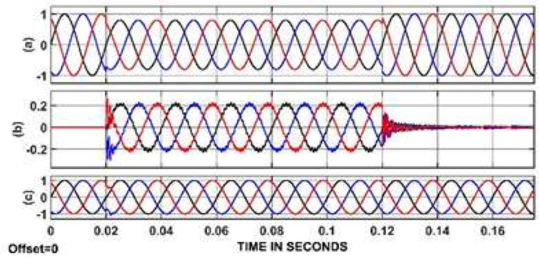

FIGURE 4. Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

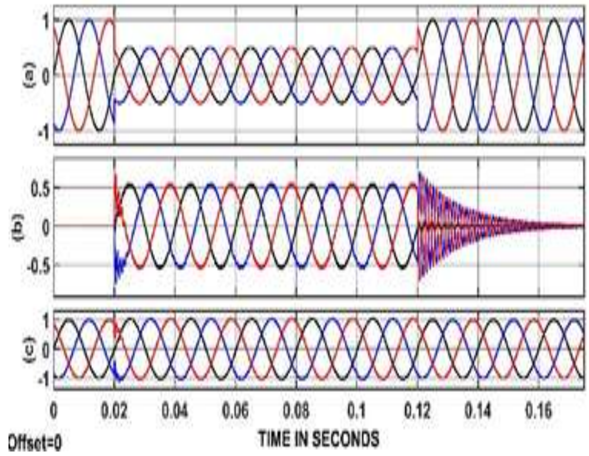

FIGURE 5. Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit

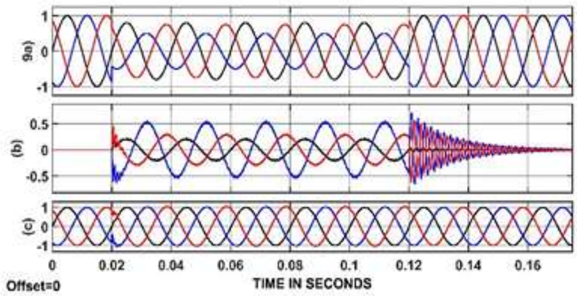

FIGURE 6. Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

Figure 7: Shows mitigation of a single-phase outage in phase “c” with simultaneous unbalanced sags—20% in phase “a” and 50% in phase “b.”Figure 8: Demonstrates DVR performance during a full three-phase outage.
Figures 9 & 10: Highlight correction of 100% balanced voltage swell and 100% single-phase swell in phase “a,” respectively.Figure 11: Displays mitigation of an unbalanced swell—100% in phase “a,” 75% in “b,” and 50% in “c.”These results confirm the DVR's robust compensation capabilities across a wide range of voltage disturbances

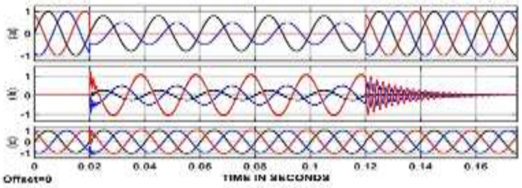

FIGURE 7. Single phase outage and Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

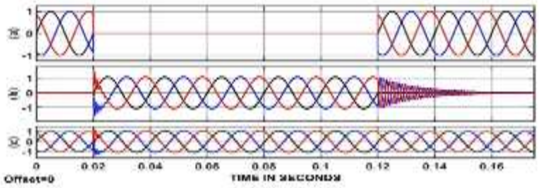

FIGURE 8. Three phase outage mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

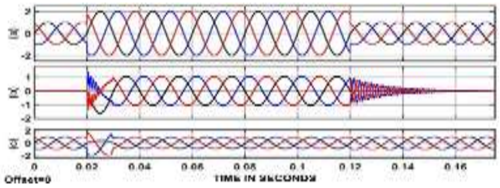

FIGURE 9. Balanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

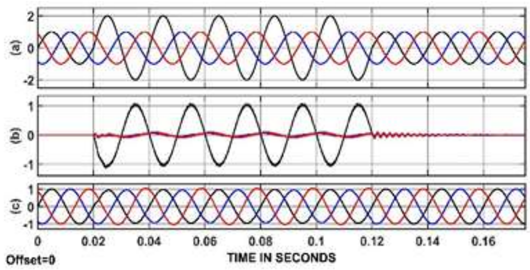

FIGURE 10. Single phase voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

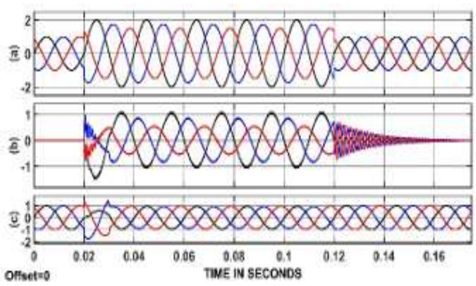

FIGURE 11. Unbalanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

V. COMPARISON OF PERFORMANCE

The proposed DVR architecture presents a simplified yet highly effective solution compared to existing topologies. Unlike conventional designs that rely on complex algorithms such as the Cuckoo Search Algorithm, Zero Active Power Tracking, or intelligent controllers like Neuro-Fuzzy systems and PID controllers, the proposed method eliminates the need for any such control strategies. Instead, it solely relies on the measurement of supply-side voltage, which is transformed into DQ0 values and compared with predefined reference values to generate error signals. These error signals are then converted back into three-phase quantities using the inverse DQ0 transform, and switching pulses are directly derived to synthesize the required compensating voltage. This straightforward approach removes the need for DC link capacitors, current sensing, or multiple switching elements around the series transformer, as seen in previous works. A single breaker across the series transformer efficiently shorts the secondary winding when the voltage is at the rated level, reducing complexity. The proposed DVR successfully mitigates 100% voltage sag, swell, and both single-phase and three-phase outages using a 1:1 series transformer ratio, a 6.25 kVA rating suitable for a 5 kVA load, and only six inverter switches—making it a practical, robust, and easily implementable solution.

VI.Fuzzy Controller-Based DVR Performance and Simulation Results

The control circuit in the proposed DVR system continuously monitors the grid’s supply voltage to detect any disturbances such as voltage sags, swells, or interruptions. Positioned immediately before the distribution transformer, the DVR and its control circuitry operate by transforming the measured three-phase voltages into DQ0 components using Clarke and Park transforms. These transformed values—Vsd, Vsq, and Vs0—are then compared with their respective reference values (Vsd = 1, Vsq = 0, Vs0 = 0) under ideal, rated voltage conditions. When these values match, the resulting error signals (Ved, Veq, and Ve0) are zero, leading to no generation of PWM pulses by the Voltage Source Inverter (VSI). In this state, the breaker across the series transformer remains closed, ensuring that no compensating voltage is injected, and the load receives the rated supply voltage directly. However, during any voltage anomaly, the DQ0 components deviate from their references, generating non-zero error signals. These errors are transformed back into the three-phase domain and compared with carrier signals to generate the necessary PWM pulses for the VSI. A phase-locked loop (PLL) maintains synchronization with the grid, enabling accurate and phase-aligned injection of the compensating voltage. To enhance adaptability and responsiveness, fuzzy logic is integrated into the control strategy. Unlike fixed threshold-based systems, the fuzzy logic controller uses linguistic rules and membership functions to interpret both the magnitude and rate of change of the voltage errors. This results in smoother, more intelligent control decisions, improving dynamic response, voltage regulation, and reducing stress on the system components. Thus, the fuzzy-enhanced DVR ensures that the load voltage remains consistently stable and close to its rated value, even under complex, non-linear, or unpredictable grid conditions.

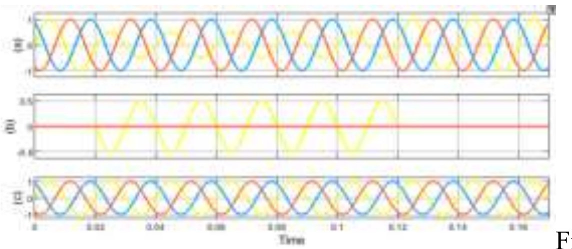

Figure 12: Single phase voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

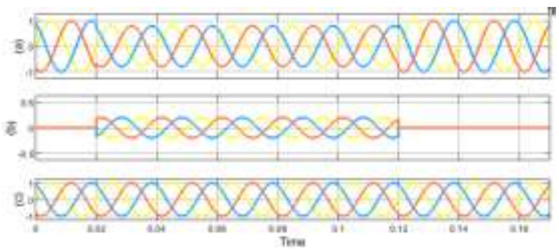

FIGURE 13. Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

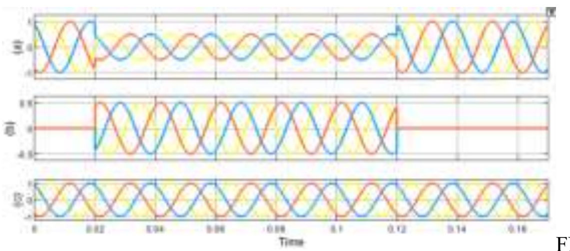

FIGURE 14. Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit

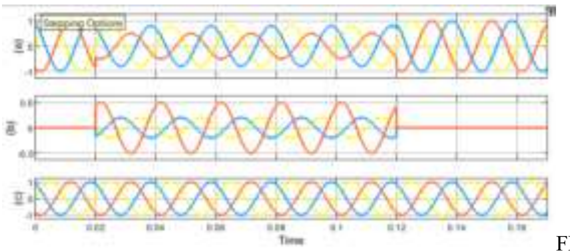

FIGURE 15. Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

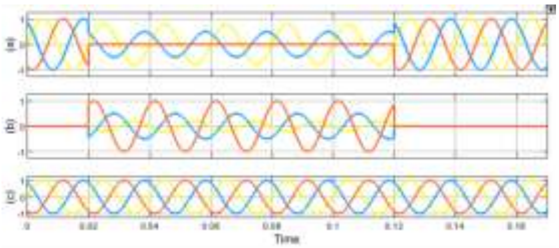

FIGURE 16. Single phase outage and Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

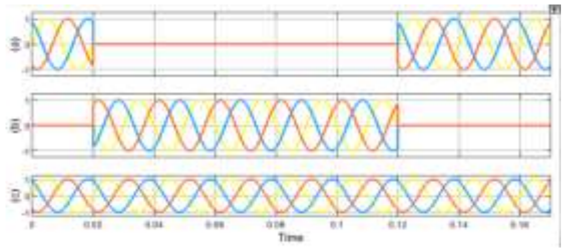

FIGURE 17. Three phase outage mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

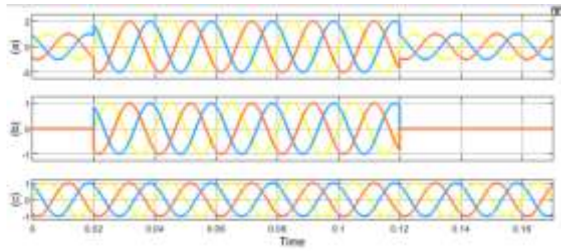

FIGURE 18. Balanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

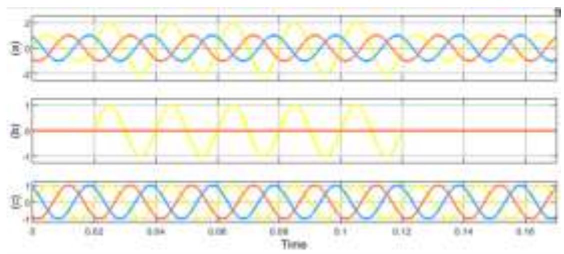

FIGURE 19. Single phase voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

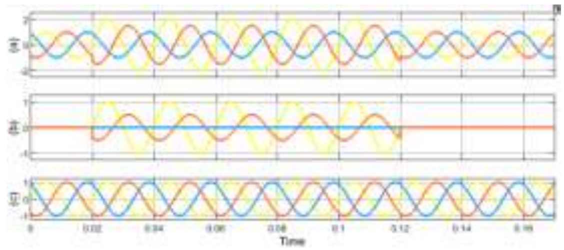

FIGURE 20. Unbalanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

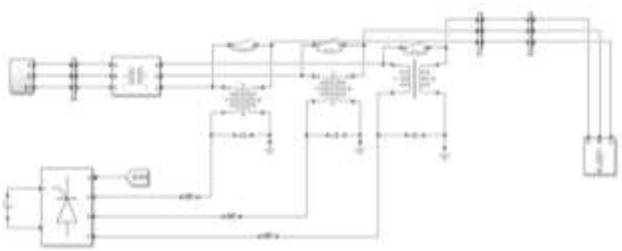

FIGURE 21. Simulation of Fuzzy Logic-Based Dynamic Voltage Restorer (DVR) for Voltage Sag Compensation

In the proposed fuzzy logic-based DVR system, the distribution transformer is placed before the DVR unit, which incorporates a 700V battery bank as its energy storage source. A Voltage Source Inverter (VSI), constructed using six IGBT switches with anti-parallel diodes, is employed to synthesize the compensating voltage. The inverter output is smoothed using an LC filter composed of a 2 mH inductor and a 15 µF capacitor to ensure high-quality voltage waveforms. A 6.25 kVA series transformer with a 1:1 turns ratio is used to inject the filtered compensating voltage directly into the supply line. The fuzzy controller processes real-time voltage error signals, calculated using DQ0 transformations, and generates accurate PWM pulses for the VSI based on a predefined set of fuzzy inference rules. This adaptive control strategy enables the DVR to perform dynamic voltage regulation and effectively reject disturbances without relying on conventional P, PI, or PID controllers.The simulation results, expressed in per-unit (p.u.) values, validate the system's performance and robustness across various fault conditions. Figure 12 demonstrates the DVR's mitigation of a 50% single-phase voltage sag in phase "a," clearly showing the source voltage, compensating voltage, and restored load voltage. Figures 13 and 14 illustrate balanced sag mitigation of 20% and 50%, respectively. Figure 15 showcases the DVR's effectiveness in addressing an unbalanced voltage sag of 20% in phase "a," 50% in phase "b," and 25% in phase "c." In Figure 16, the DVR compensates for a severe disturbance involving a complete single-phase outage in phase "c" alongside unbalanced sags in phases "a" and "b." Figure 17 highlights successful mitigation of a three-phase outage. The DVR's ability to counteract voltage swells is presented in Figures 18 and 19, where it handles a 100% balanced swell and a 100% single-phase swell in phase "a," respectively. Figure 20 illustrates the system's response to a complex unbalanced swell scenario—100% in phase "a," 75% in phase "b," and 50% in phase "c." These results confirm the fuzzy controller's superior adaptability, fast dynamic response, and precision in maintaining stable load voltage under a wide range of voltage disturbance scenarios.

VII. FINAL COMMENT

The simulation results unequivocally validate the effectiveness of the proposed DVR system, which incorporates energy storage through battery banks and leverages DQ0 transformation theory along with fuzzy logic control. The system successfully mitigates 100% of common voltage disturbances, including single-phase and three-phase outages, balanced and unbalanced voltage swells, as well as balanced voltage sags. Designed with a voltage source inverter (VSI) utilizing only six IGBT switches for three-phase operation, the architecture is both hardware-efficient and cost-effective, ensuring ease of implementation and reliability.

Unlike conventional DVR designs that depend heavily on fixed-parameter controllers such as P, PI, or PID, or require complex intelligent control strategies like neural networks or adaptive algorithms, the proposed DVR adopts fuzzy logic for real-time, intelligent decision-making. By analyzing the magnitude and rate of change of voltage error signals derived from DQ0 transformations, the fuzzy controller adaptively generates smooth PWM signals without the need for extensive tuning or mathematical complexity. This allows the DVR to dynamically synthesize accurate compensating voltages in response to grid disturbances.Overall, the simulation confirms that the fuzzy logic-enhanced DVR delivers a robust and responsive solution for power quality improvement. It ensures stable load voltage, mitigates a wide range of voltage abnormalities, and maintains uninterrupted power supply under diverse and unpredictable grid conditions—demonstrating superior adaptability, accuracy, and control performance.

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