Fuzzy Logic-Based DVR Using Energy Storage Devices for Compensation of Voltage Sag, Swell, and Interruptions.

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ABSTRACT Although there are many power quality problems, voltage sag, interruption, and swell are thought to be the most significant since they happen frequently and negatively impact sensitive loads. Despite the fact that there are numerous DVR topologies described in the literature, all of them use fuzzy or neural network controllers, P or PI, PID, or some combination of these to address power quality concerns. However, this study demonstrates that Dynamic Voltage Restorer (DVR) can be used to reduce voltage sag, swell, and outages without the need for controllers such as P, PI, PID, fuzzy, or neural networks. The Voltage Source Inverter (VSI), control circuitry to produce switching pulses, an LC filter, a series transformer, and a battery bank for energy storage make up the suggested DVR. To safeguard the load against variations in supply voltage, the suggested DVR is attached just after the distribution transformer. To produce error signals, the three-phase supply voltages are always measured, transformed into Direct-Quadrature-Zero (DQ0) quantities, and then compared to the reference value. The error signal is zero when the supply voltage is at its rated value. Therefore, the control circuitry won't produce PWM, and the VSI won't produce any compensatory voltage. In this scenario, a breaker will also be used to short circuit the series transformer's secondary winding. Thus, the DVR injects zero voltage into the line. As a result, the supply and load voltages are equal and kept at their rated values. The three phase voltages are not at their rated value and are also out of balance whenever there is a supply side sag, swell, or interruption. Error signals will therefore be produced in the DQ0 frame. Using the inverse DQ0 transformation, these error signals in the DQ0 frame are once more transformed into three-phase voltages. Switching pulses are produced for the VSI using these three-phase error signals. To keep the load voltage at its rated value, the series transformer injects the generated compensating voltage along with the supply voltage. The results of simulations conducted using MATLAB Simulink software confirm that the suggested DVR is capable of mitigating 100% balanced and unbalanced voltage sag, 100% balanced and unbalanced voltage swell, single phase outage, and three outages.

I. OVERVIEW

Disturbances in both the transmission and distribution sides result in a reduction and degradation of power quality. (Adaptable AC Transmission Mechanism) FACTS gadgets
are used to address power quality issues at the transmission side [1], [2]. On the distribution side, custom power devices are used to offset power quality issues such as harmonic distortions, swells, interruptions, and voltage sags. The type of utility determines the impact of a power quality problem. For a particular utility class, some difficulties might be a major concern, but they might not be seen as a significant problem for a different class. Therefore, it is practically very challenging to rank the aforementioned difficulties in order of severity [3], [4]. Unpredictable distribution and transmission system problems typically result in voltage sag, interruption, and swell. Large motor starting, heavy load switching, transformer energization, and equipment failures are additional causes of voltage sags. Seventy to eighty percent of these defects will self-clear in a few milliseconds, as [5, 6], and 7 demonstrate. "A rms reduction in the AC voltage from 90% to 10% of nominal supply, at the power frequency, for durations from a half-cycle to a few seconds" is how IEEE Standard 1100-1992, found in the IEEE Emerald Book, defines voltage sag. "A short duration increase in rms supply with an increase in voltage ranging from 110% to 180% of nominal supply" is the definition of voltage swell. noted that abruptly removing high loads or switching large capacitors are the

primary causes of voltage swells [8, 9, 10]. Since the different problems come from both the utility and the customer sides, both sides must offer solutions. The customers install, run, and maintain the bespoke power devices at their locations, while the utility controls the FACTS equipment. As a result, line conditioners were created to control, condition, isolate, purify, and distribute incoming power while maintaining sufficient power quality standards. Computers, microcontrollers, microprocessors, digital signal processors, and field programmable gate arrays are examples of embedded systems used in almost every industry and automation system. Variations in supply voltage have a significant impact on these embedded electronics [11], [12]. These embedded devices will shut down and cause data, time, labor, and financial losses if the supply voltage changes. For instance, if there is a supply voltage fluctuation in the paper manufacturing sector, the motor's speed will alter or abruptly cease. The paper will either alter thickness as a result of this or eventually tear. As a result, the entire bundle of the document is rejected, stopping the process and requiring a system restart. Time, money, and human resources are all lost as a result of all of these [13], [14]. Therefore, maintaining the system's power quality is essential to preventing process
disruptions in the automated and precision sectors, which use a lot of embedded equipment that are highly susceptible to power supply interruptions. DVR is a new and efficient tool to enhance power quality, even if there are other CUPS devices, such as UPS and DSTACOM, available to increase power quality on the distribution side [15], [16], and [17]. The battery holds the energy after the uninterruptible power supply converts the AC to DC. After being transformed into AC, this stored DC is sent to the utilities. By using a twofold conversion procedure, it reduces the majority of power quality issues [18]. An energy storage device is not required for mitigation when using a solid state transfer switch. The malfunctioning feeder is disconnected when there is a power quality issue. and attaches to a nutritious feeder [19]. Since UPS must run constantly whether or not there is a power quality issue, DVR is more economical and efficient than UPS. As a shunt controller, Dstatcom requires a transformer with a high power rating that can tolerate high shunt injection currents in order to reduce voltage sag, swell, or interruption [20], [21]. DynamicVoltageRestorers (DVR) are a new type of active controller designed to maintain a clean, regulated voltage at important loads by compensating for power quality problems during the full time they occur. Power quality problems, such as voltage sag, swell, and interruption, were recognized in this article and are addressed with the DVR. The literature review presents a variety of DVR topologies. Direct converter-based DVRs are described in [6] and [7], where the AC supply side provides the power needed for correction, and AC/AC direct converters are utilized to create compensating voltage to reduce voltage sag and swell. Because there is no voltage available at the supply side during an outage, single phase or three phase outages cannot be compensated for in these topologies. Furthermore, depending on the supply-side voltage availability, these topologies can only accommodate for 50% of voltage sag. Energy storage device-based DVRs store DC power using either battery banks or capacitor banks, and they synthesize the power using a voltage source inverter (VSI). compensating voltage from the battery banks' DC power reserves. These topologies can completely eliminate voltage sag, swell, and outages because the compensating voltage is generated from the DC power stored in the battery banks. To address power quality issues, [22] uses a DVR based on an energy storage device and the Cuckoo search algorithm. In order to improve DVR capacity, the Zero Active Power Tracking Technique is introduced in [23]. Together with the synchronous reference frame approach, an a hysteresis voltage control loop is used in [24]. In [25], the Harris Hawks Optimization Algorithm is used to improve the DVR control system. In [26], a discrete time control technique is used in DVR for quick transient voltage sag compensation. In [27], power quality is improved through the use of an adaptive neuro-fuzzy control method based on soft computing. In [28], A unique recurrent compensation petri fuzzy neural network controller is utilized to enhance the transient responses of the DC-link voltage and the three-phase load voltage under the conditions of rapid grid voltage distortion. [29] presents a predictive space vector transformation with proportional resonant controller for DVR-based power quality improvement. In [30], an enhanced instantaneous reactive power theory-based DVR control system for adjusting for excessive sag and swell is introduced. and the compensatory voltage is produced by sensing the supply side voltages as well as the line current. However, with the suggested control method, the only way to generate a compensatory voltage is to sense the supply side voltage.

Additionally, all of the DVR topologies listed above have specific control loops or algorithms. or sophisticated controllers for voltage sag and swell compensations, such as P, PI, or PID controllers. However, no algorithm, PI controller, current measurement, artificial intelligence, neuro, or fuzzy technique is used for compensating in the suggested topology. The suggested topology just involves calculating the supply side voltage and converting it into DQ0 values. The error signals are produced by comparing the resulting DQ0 amounts with the reference values. The error signal is used to create the switching pulses, which synthesize the compensatory voltage.

II. The proposed DVR's topology

Since the DVR is a unique power device, it is positioned right after the distribution transformer to safeguard the loads from variations in the supply voltage. Figure 1 depicts the topology of the suggested DVR. A battery bank serves as an energy storage component of the suggested DVR. To provide DC power to the VSI, the battery is linked to it. Through LC filters, the primary winding of the series transformer receives the VSI's output voltage. The series transformer's secondary winding has a breaker connected across it. Continuous measurements of the supply voltage are made and compared to the rated reference value. There won't be any error signals when the supply voltage is at its rated level. For the VSI, no switching pulses will be produced. Therefore, the DVR's compensating voltage will be 0. The breaker will be in a closed state at this point. The series transformer's secondary winding will experience a short circuit. The load voltage will be at its rated value and equal to the supply voltage.

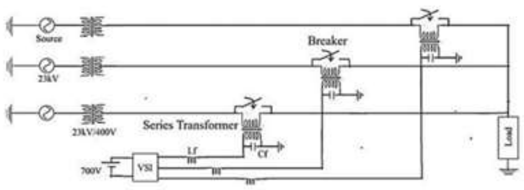

FIGURE 1. Topology of the Proposed DVR.

The supply voltage will never be equal to the rated value if there is a voltage sag, swell, or interruption. Error signals will therefore be produced. The DVR will use the control circuitry to generate the necessary compensatory voltage. We'll open the breaker across the series transformer. To reduce voltage sag, swell, and interruption, the compensating voltage will be added to the line via the series transformer together with the supply voltage. The supply voltage is tracked and measured continually.

III. ALGORITHM OF CONTROL

The control circuit continuously monitors the grid's supply voltage. The distribution transformer is put just after the suggested DVR and control circuits. The function of the control system is to continuously observe and detect any variations in the supply voltage.
by synthesizing the necessary PWM switching pulses for VSI and comparing it to the preset reference value in order to produce the necessary compensating voltage. It is commonly known that the Clarks and Parks transforms can be used to convert the three phase voltages into direct quadrature voltages. It is also known that the corresponding direct axis voltage and the quadrature axis voltage will have values of 1 and 0 when the three phase voltages are at their rated value. Accordingly, Vsd and Vs0 have reference values of 0 and 1, respectively, in the DQ0 frame. The supply voltages Vsa, Vsb, and Vsc are first converted to the Vsd, Vsq, and Vs0 using equation (1) based on these well-known facts. Let Vsa be Vmsinwt, Vsb be Vmsin(wt-120), and Vsc be Vmsin(wt-240) under rated conditions. We shall then obtain Vso and Vsq as zero and Vsd as Vm (which is just one per unit) from equation (1). The reference values and the derived supply voltages Vs0, Vsd, and Vs0 in the DQ0 frame are contrasted. Figure 2 displays the control circuit block diagram. Vsd and 1 will be contrasted. We'll compare Vs0 and Vsq to 0. The Vsd, Vs0, and Vsq will all be equal to 1 if the supply voltage is at its rated level. After that, there will be no error value. Thus, the compensating voltage produced by the VSI is zero, and no PWM pulses will be produced. The breaker will be closed in these circumstances. This will cause the series transformer's secondary side to short circuit, adding zero compensatory voltage. As a result, the rated supply voltage and the load voltage will match.

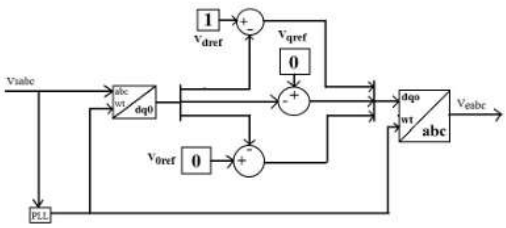

FIGURE 2. Control Circuit Block Diagram

The supply voltages are out of balance and below their rated value if there is a voltage sag, swell, or interruption. Therefore, neither Vs0 nor Vsq will equal 0, nor will Vsd equal 1. When compared to the reference DQ0 values, an error voltage will be produced. Ve0, Ved, and Veq are the error DQ0 voltages. In the DQ0 frame, the error voltages Ve0, Ved, and Veq will once more transform into three phases. PWM switching pulses are produced for the VSI after comparing the Vea, Veb, and Vec error signals with the carrier signals. In order to produce the compensating voltage in accordance with the three distinct phases of the supply voltage, a phase-locked loop circuit is utilized to track the phase of the supply voltages. To keep the load voltage at rated condition at all times, the compensating voltage produced by the DVR is injected into the line along with the supply voltage via the series transformer.

IV. RESULTS OF SIMULATION

23 kV is selected as the grid supply voltage in order to validate the suggested algorithm. With a 6.25 kVA distribution transformer of 23 kV/400 V, this supply voltage is reduced.
A 5 kVA RL load with a 0.8 power factor lag is selected.

The distribution transformer is connected first, followed by the DVR. The battery bank has a voltage of 700 volts. Six IGBT switches with anti-parallel diodes are used in the construction of a voltage source inverter. At the VSI's output, a 2 milli Hendry and 15 micro farad LC filter is attached. A 6.25 kVA series transformer with a 1:1 turn ratio is used to add the output voltage that has been filtered to the supply voltage. Voltage sag, swell, single phase outages, and three phase failures can all be effectively mitigated by the suggested DVR. The results of the simulation are shown in perunitvalue below. The effectiveness and dependability of the suggested DVR are readily understood since the results are self-explanatory and are given in terms of a unit value. Figure 3 illustrates the 50% reduction in single-phase voltage sag in phase "a." Figures 4 and 5 illustrate 20% and 50% mitigation of balanced voltage sag, respectively. Figure 6 illustrates the mitigation of unbalanced voltage sag of 20% in phase "a," 50% in phase "b," and 25% in phase "c."

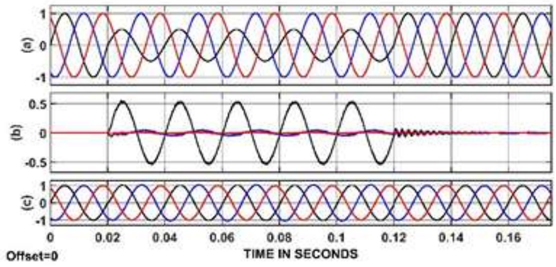

FIGURE 3. Single phase voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

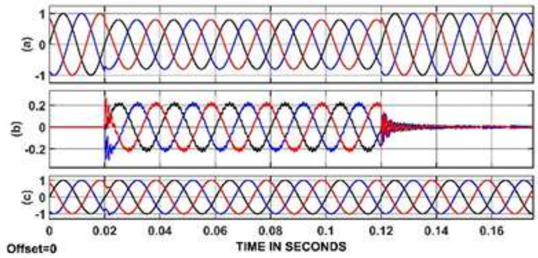

FIGURE 4. Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

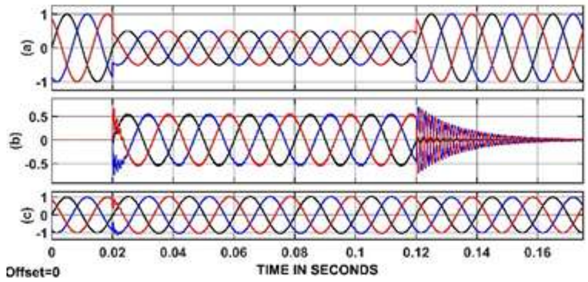

FIGURE 5. Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit

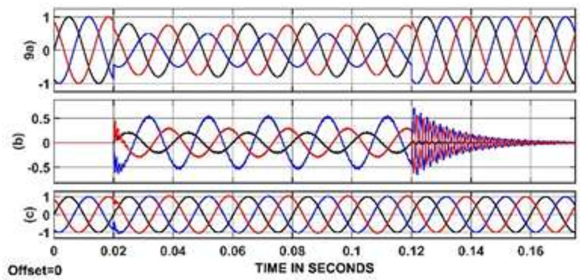

FIGURE 6. Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

Figure 7 illustrates the mitigation of a single-phase outage in phase "c" with an unbalanced voltage sag of 20% in phase "a" and 50% in phase "b." Figure 8 depicts three-phase outage mitigation. Figures 9 and 10 demonstrate the proposed DVR's capacity to correct for a 100% balanced voltage well and a 100% single-phase swell in phase "a," respectively. Figure 11 illustrates an imbalanced voltage swell of 100% in phase "a," 75% in phase "b," and 50% in phase "c."

V. COMPARISON OF PERFORMANCE

Cuckoo search algorithm-based DVR control, which was introduced in [22], uses two DC link capacitors to keep the DC link voltage steady. The cuckoo search method is used to keep the DC voltage steady. However, in the suggested

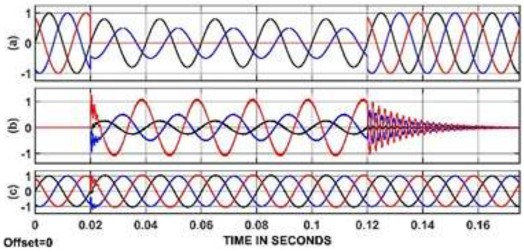

FIGURE 7. Single phase outage and Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

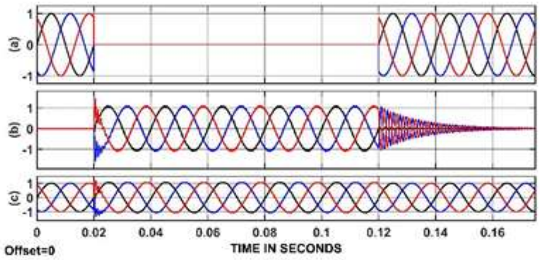

FIGURE 8. Three phase outage mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

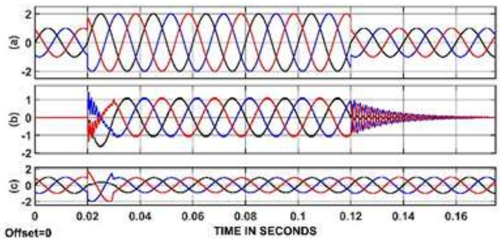

FIGURE 9. Balanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

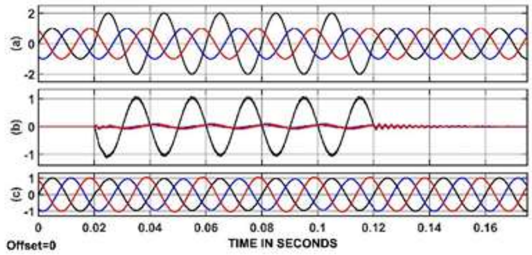

FIGURE 10. Single phase voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

topology, the DC link voltage is kept constant without the need of any algorithms, but no DC link capacitors are employed.

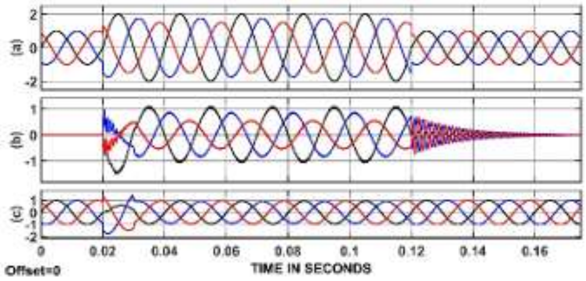

FIGURE 11. Unbalanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

The DVR based on the Zero Active Power Tracking Technique is introduced in [23] and uses 12 switches to construct a voltage source inverter. However, just six switches were employed for the VSI in the suggested architecture. Both the soft computing adaptive Neuro-Fuzz controllers-based DVR introduced in [27] and the synchronous reference frame-based DVR in [24] used three switches surrounding the series transformer in addition to a DC link capacitor to maintain the DC link voltage constant. When the supply voltage is at its rated level, a single breaker across the series transformer will short circuit. When a voltage fluctuation occurs, two switches on either side of the transformer connect these transformers along the line. In the suggested architecture, when the supply voltage is at rated condition, the secondary side of the transformer is shorted by a single breaker. It is sufficient to open the breaker when there are variations in the supply voltage since the series transformer is permanently linked in the line. When the supply voltage is at rated condition, the Harris

Hawks Optimization Algorithm-based DVR suggested in [25] does not employ a breaker across the series transformer to set the compensation voltage to zero. Additionally, a DC link capacitor is used across the battery in this architecture, and the series transformer turns ratio is 3:1. However, the suggested architecture eliminated 100% sag, swell, and outages by using a series transformer with a 1:1 turn ratio in place of a DC link capacitor. For quick transient voltage sag compensation in DVR, a discrete temporal control technique is used in [26]. This topology has using a 20kVA rated a series transformer with a 5kVA load. This rating is extremely high. However, a 6.25 kVA series transformer was employed for a 5 kVA load in the suggested topology.

In [28], a novel recurrent compensation micro fuzzy neural network controller is utilized to enhance the transient responses of the DC-link voltage and the three-phase load voltage under the conditions of rapid grid voltage distortion. In this presentation, the secondary side of the transformer is shorted out when the supply voltage is at rated condition without the usage of a breaker across the series transformer. Implementing the control algorithm is really difficult. However, the suggested topology is straightforward, robust, and simple to put into practice. [29] presents a predictive space vector transformation with proportional resonant controller for DVR-based power quality improvement. A DC link has been employed in this topology. No breaker is utilized across the series transformer, and a capacitor is employed to maintain the DC connection voltage. Both line current and supply side voltages are detected in order to generate the compensatory voltage in [30], which presents an improved instantaneous reactive power theory-based control of DVR for compensating excessive sag and swell. This architecture uses a DC link capacitor in place of a braker across the series transformer. However, the suggested control method does not require a DC link capacitor; instead, compensatory voltage is produced just by measuring the supply side voltage. Regarding the mitigation of single-phase and three-phase outages, none of the aforementioned topologies demonstrated any outcomes. This paper demonstrates how to use the suggested DVR to mitigate single-phase and three-phase outages. For compensation, all of the DVR topologies listed above use methods like the Cuckoo Search Algorithm, unique control loops, or intelligent controllers like neuro or fuzzy, or at the very least P, PI, or PID controllers. However, no algorithm, P, PI, PID controller, current measurement, artificial intelligence, neuro, or fuzzy technique is used for compensating in the suggested architecture. The supply side voltage is simply measured and expressed in DQ values using the suggested topology. The error signals are produced by comparing the resulting DQ amounts with the reference values. Using the inverse DQ0 transform, the error signal acquired in the DQ0 frame is once more expressed in three phase quantities. Without the use of controllers or algorithms, the switching pulses are produced from the erroneous signal in order to synthesize the compensating voltage and mitigate 100% voltage sag, swell, and outages.

VI. Fuzzy Controller-Based DVR Performance and Simulation Results

The control circuit continuously monitors the grid's supply voltage to detect any disturbances such as voltage sags, swells, or interruptions. The distribution transformer is placed immediately after the proposed DVR and its control circuit. When the supply voltage is stable and at its rated value, the control system compares the actual supply voltages, converted into DQ0 components using Clarke and Park transforms, with their reference values—Vsd as 1, and Vsq and Vs0 as 0. Under these ideal conditions, the resulting error voltages in the DQ0 frame (Ve0, Ved, and Veq) are zero, leading to no PWM pulses being generated by the VSI. Consequently, the breaker remains closed, the series transformer injects no compensating voltage, and the load receives the rated supply voltage. However, in the case of voltage abnormalities, the DQ0 components deviate from their references, producing non-zero error signals which are then transformed back into the three-phase domain. These errors are compared with carrier signals to generate the appropriate PWM pulses for the VSI. A phase-locked loop ensures synchronization with the grid's phase, allowing the DVR to inject the compensating voltage effectively. To enhance this control mechanism, fuzzy logic is incorporated. Instead of relying on fixed threshold comparisons, fuzzy logic uses linguistic rules to interpret the voltage errors and their rate of change, generating smooth and adaptive control actions. This allows the DVR to respond intelligently to various fault conditions and grid disturbances, providing faster dynamic response, improved voltage regulation, and reduced stress on system components. As a result, the fuzzy-enhanced control system ensures that the load voltage remains

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stable and close to its rated value, even under non-linear or unpredictable grid scenarios

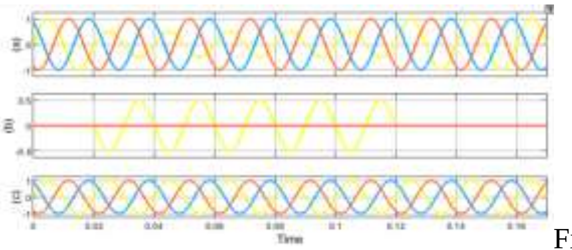

Figure 12: Single phase voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

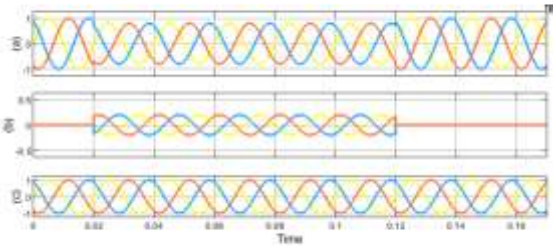

FIGURE 13. Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

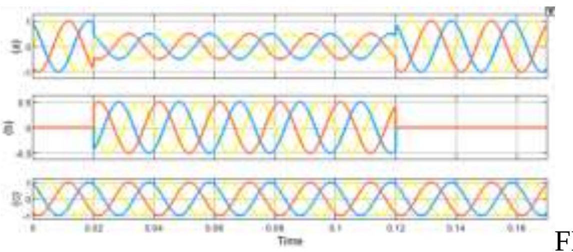

FIGURE 14. Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit

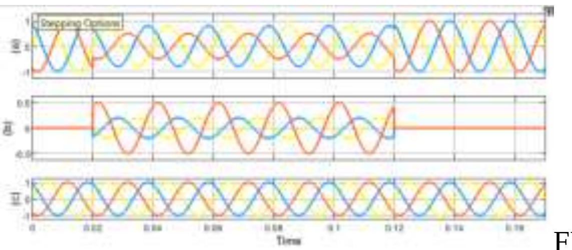

FIGURE 15. Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

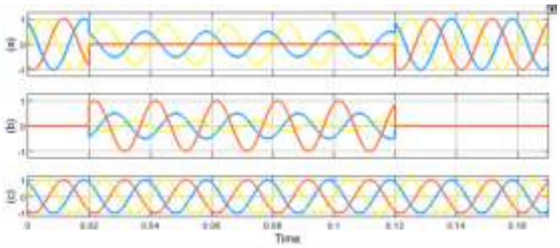

FIGURE 16. Single phase outage and Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

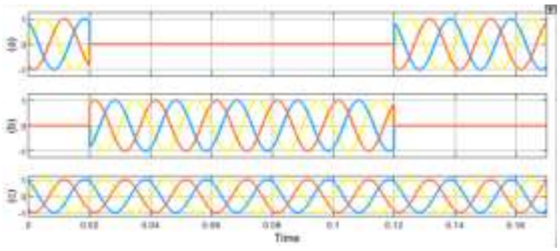

FIGURE 17. Three phase outage mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

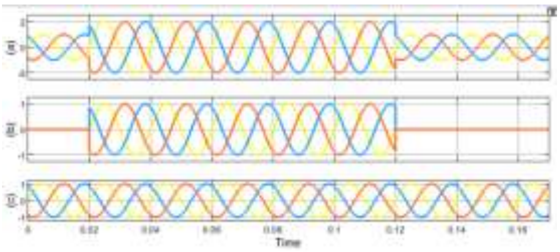

FIGURE 18. Balanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

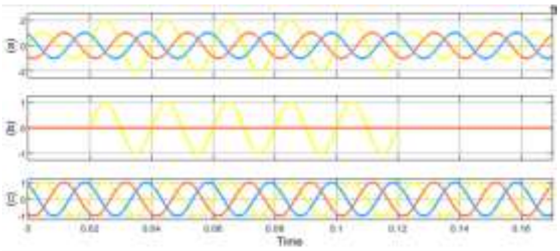

FIGURE 19. Single phase voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

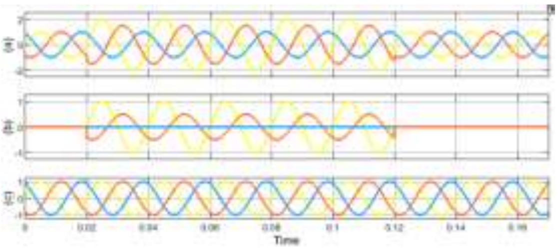

FIGURE 20. Unbalanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

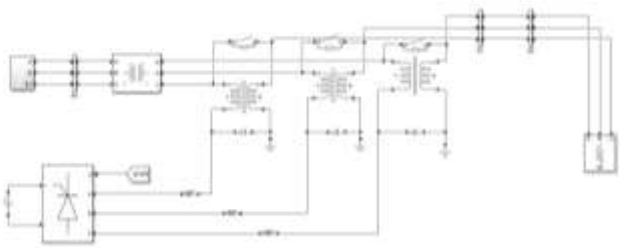

FIGURE 21. Simulation of Fuzzy Logic-Based Dynamic Voltage Restorer (DVR) for Voltage Sag Compensation

In the proposed fuzzy logic-based DVR system, the distribution transformer is connected first, followed by the DVR unit. The DVR utilizes a 700V battery bank as the energy storage source. A voltage source inverter (VSI) built with six IGBT switches, each having anti-parallel diodes, is used to synthesize the compensating voltage. At the output of the VSI, an LC filter consisting of a 2 mH inductor and a 15 µF capacitor ensures smooth waveform generation. A 6.25 kVA series transformer with a 1:1 turns ratio injects the filtered compensating voltage directly into the supply line. The fuzzy controller processes real-time voltage error signals—calculated using DQ0 transformations—and, based on a predefined fuzzy rule base, generates precise PWM pulses for the VSI. This intelligent control enables dynamic voltage regulation and disturbance rejection without requiring conventional controllers. The simulation results, presented in per-unit (p.u.) values, demonstrate the system's effectiveness and reliability.

Figure 12 illustrates mitigation of a 50% single-phase voltage sag in phase "a," showing source voltage, DVR compensating voltage, and load voltage in p.u. Figures 13 and 14 display balanced voltage sag mitigation of 20% and 50%, respectively. Figure 15 shows the DVR's response to an unbalanced sag condition—20% in phase "a," 50% in phase "b," and 25% in phase "c." Figure 16 captures the mitigation of a more severe fault—complete single-phase outage in phase "c" with an accompanying unbalanced sag of 20% in phase "a" and 50% in phase "b." In Figure 17, the DVR successfully mitigates a complete three-phase outage. Figures 18 and 19 present the DVR's ability to compensate for a 100% balanced voltage swell and a 100% single-phase swell in phase "a," respectively. Finally, Figure 20 shows how the fuzzy-controlled DVR handles a complex unbalanced swell scenario: 100% in phase "a," 75% in phase "b," and 50% in phase "c." These results confirm the fuzzy logic controller's robustness, fast dynamic response, and accuracy in compensating for diverse voltage disturbances, ensuring stable voltage delivery to the load at all times.

VII. FINAL COMMENT

The simulation results clearly demonstrate that the proposed DVR system, enhanced with energy storage devices such as battery banks and supported by DQ0 theory and fuzzy logic control, is capable of mitigating 100% of common voltage disturbances, including single-phase outages, three-phase outages, balanced voltage swells, unbalanced voltage swells, and balanced voltage sags. The system utilizes a voltage source inverter (VSI) with only six IGBT switches for the three-phase setup, making the hardware implementation simple, robust, and cost-effective. While various DVR topologies in existing literature rely heavily on conventional controllers like P, PI, or PID, as well as advanced techniques like fuzzy logic controllers, neural networks, or adaptive algorithms, the integration of fuzzy logic in this design allows for intelligent, real-time decision-making based on the magnitude and rate of change of the voltage error signals. Unlike rigid control approaches, fuzzy logic provides smooth, adaptive PWM generation by evaluating the error components derived from DQ0 transformation. This enables the system to produce precise compensating voltages without the need for complex mathematical modeling or tuning. The simulation confirms that the fuzzy logic-enhanced DVR system effectively addresses voltage sags, swells, and outages with high accuracy and reliability, maintaining the load voltage at rated conditions and ensuring uninterrupted power delivery under all tested fault scenarios.

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