Implementation of Multilevel Inverter Based Dynamic Voltage Restorer to Improve Power Quality Improvement in Distribution System

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***Abstract*—** In this paper, the implementation of a multilevel inverter-based DVR for power quality improvement in the electrical distribution systems is presented. The proposed system is designed to mitigate voltage disturbances, including voltage sags, voltage swells, and short-duration interruptions, which affects the performance and reliability of sensitive electrical loads. DVR have been widely known as effective custom power devices for voltage compensation in distribution networks [1], [4], [9]. To overcome the limitations, a multilevel inverter topology is incorporated to achieve improved output voltage quality, and to reduce THD, lower switching losses, and enhanced conversion efficiency [10]. The proposed DVR employs a PWM-based control strategy to detect voltage disturbances and inject to the required compensating voltage through the series injection transformer, thereby maintaining the load voltage within acceptable operating limits. The complete system is modelled and analysed in the MATLAB/SIMULINK environment under different voltage sag and voltage swell conditions. The proposed Multilevel inverter-based DVR provides a reliable and scalable solution for enhancing power quality in modern distribution systems and offers a suitable platform for future implementation using advanced control techniques [2], [3], [5]-[8].

Keywords- Dynamic Voltage Restorer, Multilevel Inverter, PI Controller, Power Quality Improvement, THD, PWM Generator

I. INTRODUCTION

Power quality has become a major concern in modern electrical power distribution systems due to the widespread use of sensitive electronic equipment, industrial automation, and non -linear loads. Among various disturbances of power quality, voltage sag is one of the most common and critical issues, causing equipment malfunction, process interruptions, and significant economic losses [1], [4],[8]. Therefore, maintaining a stable voltage power profile has become essential for ensuring reliable operation of distribution networks. DVR is an custom power device that compensates voltage sag and swell by injecting an appropriate voltage in series with the distribution feeder. Thereby restoring the load voltage to nominal value [1], [2]. Several researchers have proposed advanced control techniques, including Dual p-q theory, discrete-time control, optimisation algorithms, and intelligent controllers, to improve the Dynamic response and compensation capability of DVR systems [2], [3], [5], [6]. Furthermore, multilevel inverter-based DVR configurations have attracted considerable attention because of their superior output voltage quality, reduction of THD, lower switching losses, and reduced voltage stress on semiconductor devices compared with conventional inverter topologies [7], [10]. Recent studies are also focused on advanced inverter control strategies and grid-connected inverter topologies to further improve power quality and system stability [6], [8]. Motivated by these developments, this paper proposes a multilevel inverter- based DVR for a distribution system. The proposed system designed to enhance voltage sag compensation, improve power quality, reduce harmonic distortion and increase the reliability and dynamic performance of the distribution networks. Simulation results demonstrate that the proposed system provides better voltage regulation and overall performance compared with the existing DVR configuration.

II. MULTILEVEL INVERTER

The DVR utilises a multilevel inverter to inject the required compensating voltage into the distribution feeder during power quality disturbances.

The inverter consists of twelve power switches (S_1-S_{12}) arranged in three-phase legs, with each phase containing four controlled switches. The DC source is divided into two equal voltage levels by two DC-link capacitors (C_1 and C_2), creating a neutral point (N). This configuration enables the inverter to generate three output voltage levels, namely $+V_{dc/2}$, 0 and $-V_{dc/2}$, resulting in voltage waveform that closely approximates a sinusoidal output [7].

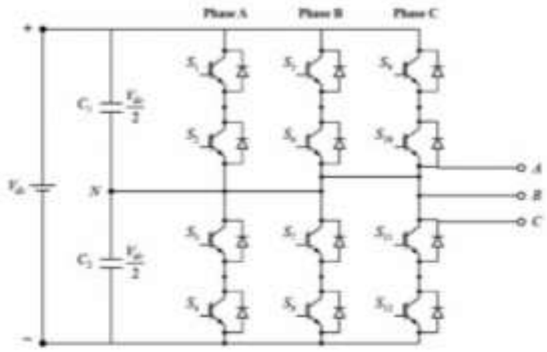

Figure 1 : Multilevel Inverter

The Multilevel inverter offers some advantages, including reduced THD, lower switching losses, decreased voltage stress across the semiconductor devices, and improved output voltage quality [8]. The multilevel switching technique also minimizes electro mangnetic interference and reduces the size of the output filter, thereby improving overall efficiency and reliability of the DVR system. In this work, the inverter is controlled through a PWM-based gating strategy to generate the switching pulses required for voltage injection. During conditions of voltage sag or swell, the inverter injects an appropriate compensating voltage through the series injection transformer, ensuring that the sensitive load receives a balanced and regulated voltage. Owing to its superior harmonic performance and voltage regulation capability[2], [7].

III. Operation of DVR

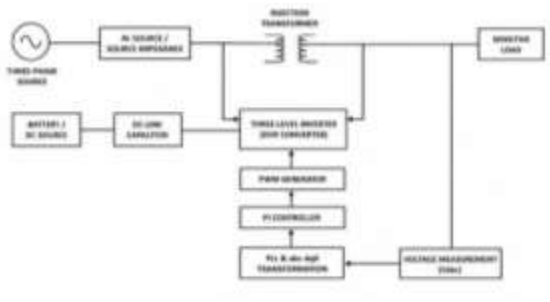

Figure 2: Block Diagram

The DVR is a custom power device that is connected in series with the distribution feeder to compensate voltage disturbances and maintain a constant voltage across sensitive loads. It is widely employed to mitigate voltage sags, swells, short-duration interruptions, and other power quality issues that may affect the reliable operation of industrial and commercial equipment [1], [2], [4].

The proposed DVR consists of a three-level inverter, DC-link capacitor, battery energy source, series injection transformer, voltage measurement unit, Phase Locked Loop (PLL), abc-dq0 transformation, PI controller and

PWM generator [2], [5].

Under normal operating conditions, the supply voltage remains balanced and close to its rated value. During this period, the DVR operates in standby mode, and the three-level inverter does not inject any compensating voltage into the feeder. The sensitive load receives power directly from the utility source through the injection transformer with negligible losses. The battery and DC-link capacitor maintain the required DC voltage so that the DVR can respond immediately whenever a voltage sag, swell or other disturbances appear in the supply; the voltage measurements block continuously monitors the three-phase load voltages(V_{abc}) and detects the deviation from the reference voltage. The measured voltages are synchronised with the utility supply using a Phase-Locked Loop(PLL), which extracts the fundamental positive-sequence components and provides accurate phase information even under distorted or unbalanced operating conditions [3], [5]. The transformed voltages are compared with their reference values to generate an error signal. This error is processed by the PI controller, which produces the required reference compensating voltage. The proportional component ensures a rapid response to sudden voltage changes, whereas the integral component eliminates steady-state error and improves voltage regulation [5], [6]. The controller output is then converted back into three-phase reference signals through the reverse dq0-abc transformation. These reference signals are supplied to the PWM generator, which produces high-frequency switching pulses for the three-level VSI. In this work, a three-level neutral-point-clamped(NPC) inverter is employed because it provides lower harmonic distortion, reduced switching stress, improved output waveform quality and higher voltage handling capability [7].

The inverter utilises the energy stored in the DC-link capacitor and battery source to generate the required compensating voltage. This voltage is injected into the distribution feeder through the series injection transformer with the appropriate magnitude and phase angle, thereby restoring the load voltage to its rated value despite disturbance in the supply voltage [2], [4]. As a result, the DVR effectively maintains a balanced and regulated load voltage while minimising voltage fluctuations and harmonic distortion. The coordinated operation of voltage sensing, synchronization, reference frame transformation, PI control, PWM switching, energy storage, and the three- level inverter enable fast dynamic response, improved compensation capability and enhanced power quality. Consequently, the DVR ensures reliable operation of sensitive loads, improves system stability, and enhances the performance of the distribution network under both balanced and distributed operating conditions [1], [2], [5], [8].

IV.PI CONTROLLER

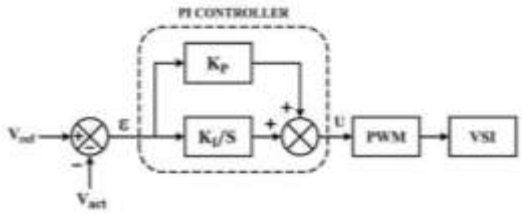

Figure 3: PI Controller

The PI controller is one of the control techniques in DVR applications because of its simple implementation, high reliability, and excellent steady-state performance [2], [5], [6]. As shown in fig 3, the PI controller receives error signal, it is generated by comparing the reference voltage (V_{ref}) with the measured load voltage (V_{act}). This error is continuously processed to produce the controller signal required for generating the compensating voltage. [5], [6]

The output of the PI Controller is supplied to the PWM generator, which produces the appropriate Gate pulses for the three-level VSI. The inverter then injects the required compensating voltage through the series injection transformer to restore the load voltage to its rated magnitude during voltage sag or swell conditions [2], [7]. Proper tuning of the K_P and K_i ensures fast transient response, improved voltage regulation, minimum overshoot, and reduced settling time. Consequently, the PI controller significantly enhances the dynamic performance of the DVR and maintains high power quality under varying operating conditions [5].

The voltage error is given by

$$e(t) = V_{ref}(t) - V_{act}(t)$$

The PI controller output is

$$u_{(t)} = \mathrm{K}_p\, e(t) + \mathrm{K}_i \int_0^t e(\tau)\, d\tau$$

The transfer function of the PI controller is

$$G_{PI}(s) = \mathrm{K}_p + \frac{\mathrm{K}_i}{s}$$

V.RESULTS AND CONCLUSION

Case 1: a. Simulation model of with DVR

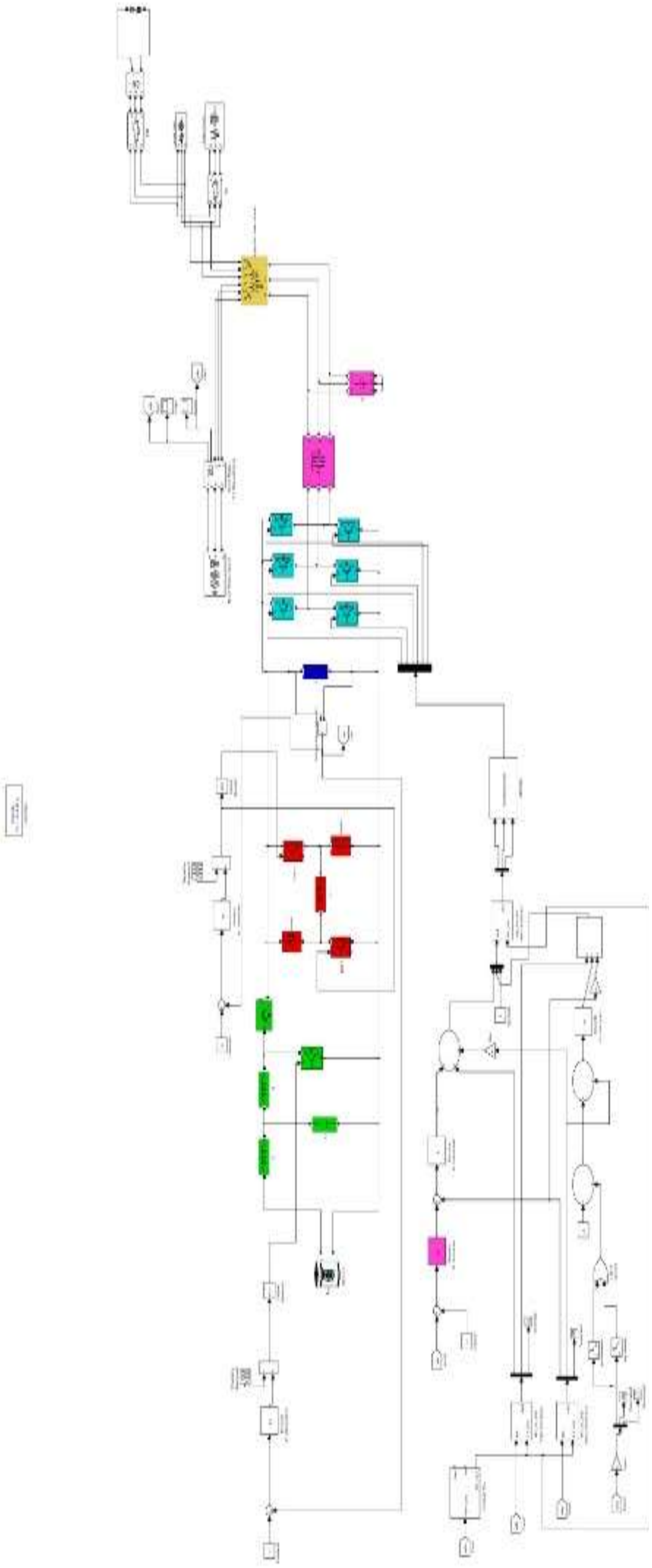

Figure 4: Simulink model with DVR

The above figure presents the Simulink model of DVR used to investigate its performance in mitigating voltage disturbances in a three-phase distribution system. The developed simulation model is designed to evaluate the DVR to verify its voltage compensation capability.

B. Results:

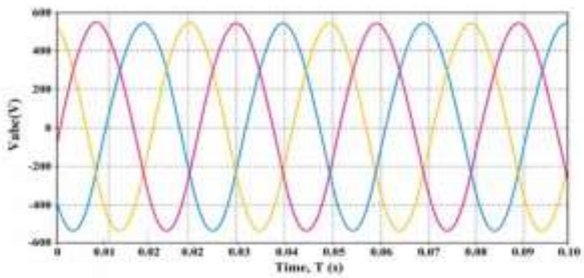

Figure 5: Voltage(V) vs Time(s)

The above graph fig 5 illustrates the 3 phase voltage sinusoidal waveforms with an electrical phase displacement of 120^0 between each phase. The simulation is carried out over a time interval of 0-0.1 S corresponding to 5 complete cycles of a 50 Hz three-phase power system. The peak voltage of each phase is ±540V, which corresponds to a line-to-line RMS voltage of approximately 440V.

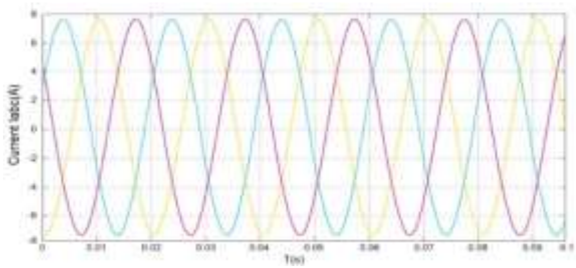

Figure 6: Current(I) vs Time(s)

This figure -6 represents the three-phase load current (Iabc) of the DVR system Over a simulation period of 0–0.1 s. It is evident that the three currents are sinusoidal in nature and are displaced by 120° from each other, indicating balanced three-phase operation. The peak current reaches ±8 A, while the frequency remains constant, confirming the stable performance of the distribution system.

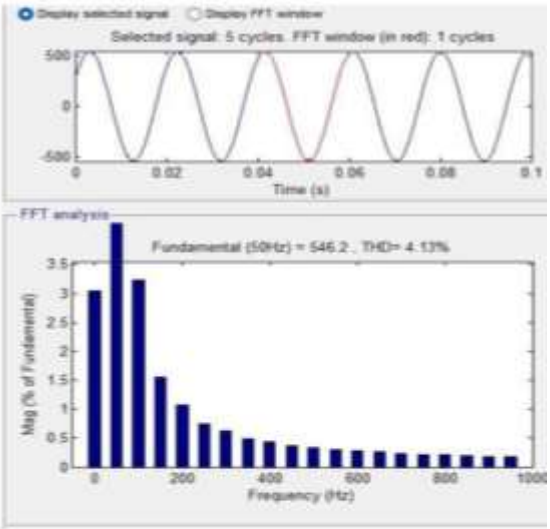

Figure 7: THD of with DVR

The waveform shows a nearly sinusoidal profile with a fundamental frequency of 50 Hz, indicating stable operation of the distribution system. The peak amplitude of the fundamental component is approximately 546.2 V, demonstrating that the DVR is capable of maintaining the desired voltage magnitude under operating conditions.

The harmonic spectrum obtained from the FFT analysis. The spectrum indicates that the dominant component is the 50 Hz fundamental frequency, while the remaining frequency components correspond to higher-order harmonics with significantly lower magnitudes. The FFT analysis reports a THD of 4.13%.

Case 2: A. Simulation model of Multi-level inverter

The below figure illustrates the complete MATLAB/Simulink model of the proposed multilevel inverter based DVR for power quality enhancement in a three-phase distribution network. The proposed model consists of a three-phase AC source, transmission line, sensitive load, fault generation block, voltage and current measurement units, control system, Battery unit, SMES unit, DC-link capacitor, multilevel inverter, pulse generation circuit, and a series injection transformer.

The multilevel inverter converts the stored DC energy into a high-quality AC voltage with significantly reduced harmonic distortion and injects the compensating voltage into the distribution feeder through the series transformer, thereby restoring the load voltage to its rated value. The proposed system also incorporates voltage, current, active power, reactive power, and harmonic measurement blocks to evaluate the overall system performance under different fault conditions.

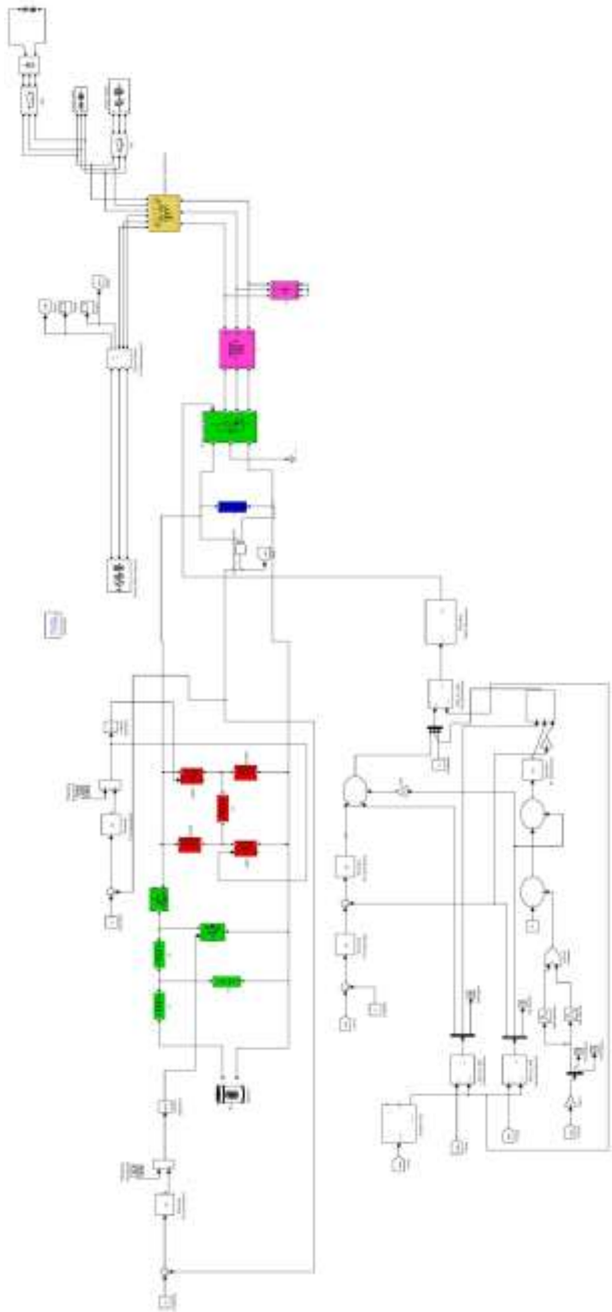

Figure 8: Simulink model of multi-level inverter

B. Result:

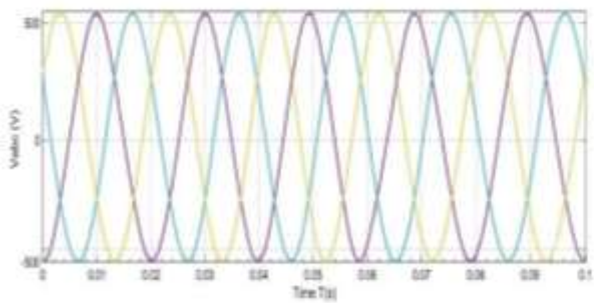

Figure 9: Voltage(V) vs Time

The simulation results are presented over a time interval of 0–0.1 s, during which the proposed system operates under steady-state conditions while maintaining the desired load voltage. The peak voltage of each phase is ±550 V, and the waveform amplitude remains constant throughout the simulation period.

A stable DC-link voltage by supplying or absorbing energy according to the system requirement, enabling rapid compensation during voltage disturbances. Consequently, the injected compensating voltage effectively restores the load voltage to its nominal value while maintaining waveform continuity. The obtained voltage waveforms verify that the proposed DVR successfully maintains balanced three-phase load voltages with excellent waveform quality and stable amplitude, thereby ensuring reliable operation of sensitive loads and significantly enhancing the power quality of the distribution network under various operating conditions.

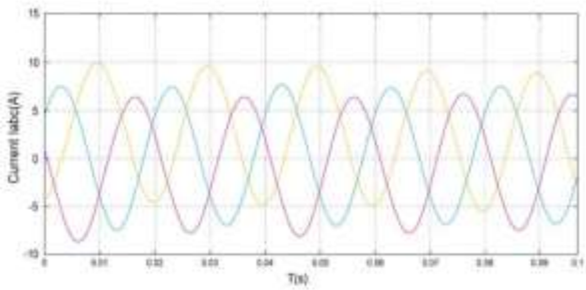

Figure 10: Current(I) vs Time(s)

The three-phase currents corresponding to phases A, B, and C exhibit balanced sinusoidal waveforms with a uniform 120° phase displacement, confirming the correct operation of the three-phase distribution system. The simulation results are recorded over a time interval of 0–0.1 s, demonstrating the current response of the proposed system during steady-state operation. The current amplitude remains nearly constant at approximately ±10A throughout the simulation period, indicating stable load.

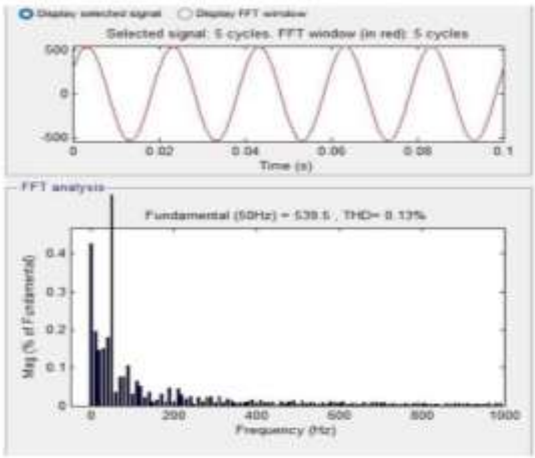

Figure 11: THD of Multi level Inverter

The above waveform of THD with multilevel inverter in which it maintains a constant amplitude of ±550 V with a fundamental frequency of 50 Hz, indicating the proposed DVR effectively preserves the rated load voltage under steady-state operating conditions. The calculated THD is only 0.13%, which is substantially lower than the maximum limit of 5%.

VI. CONCLUSION

The proposed multilevel inverter-based Dynamic Voltage Restorer (DVR)demonstrates effective mitigation of voltage disturbances and significant enhancement of power quality. Simulation results confirm stable three-phase voltage and current waveforms with balanced operation and rapid dynamic response. The FFT analysis yields a low THD of 0.13%. These results validate the proposed system's capability to provide reliable voltage compensation, superior harmonic suppression, and improved performance for sensitive loads in modern distribution networks.

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