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Dynamic Voltage Restorer For The Mitigation Of Voltage Disturbances: Augmenting Power Quality In Distribution Networks With Non-Linear Loads Through Comprehensive MATLAB/Simulink-Based Performance Validation

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Abstract
The increasing presence of sensitive and non-linear loads in power distribution networks has intensified the demand for high-quality, disturbance-free electrical energy. Power quality issues such as voltage sags, swells, and harmonic distortions have become a significant concern, affecting both utility providers and end-users. Among the various custom power devices developed to address these issues, the Dynamic Voltage Restorer (DVR) stands out as a reliable and efficient solution for mitigating voltage-related disturbances. This paper explores the configuration, operation, control strategy, and simulation-based performance analysis of DVR in maintaining voltage stability. The DVR's capability to inject compensating voltage under dynamic conditions is validated through MATLAB/Simulink-based simulations, highlighting its effectiveness in improving voltage profile and reducing harmonic distortion within acceptable limits.
Keywords: *Power Quality, Voltage Sag, Dynamic Voltage Restorer (DVR), Voltage Compensation, Custom Power Devices, Harmonic Mitigation, MATLAB Simulation*

1. INTRODUCTION

The quality of power supplied to industrial, commercial, and residential users plays a crucial role in the reliability and longevity of electrical and electronic systems. With the proliferation of power electronics-based devices—such as variable frequency drives (VFDs), SMPS, arc furnaces, and rectifiers—the electrical environment has become increasingly polluted with harmonics and voltage disturbances [11].

Power quality (PQ) refers to maintaining a voltage and current waveform as close to a pure sinusoidal signal as possible, within defined limits of frequency, magnitude, and continuity. Voltage sags, which are short-term reductions in RMS voltage between 10% to 90% of nominal for durations up to one minute, are particularly harmful to sensitive equipment like programmable logic controllers (PLCs), drives, and medical systems. Similarly, voltage swells, harmonics, and transients can cause equipment malfunction, overheating, increased losses, and data loss [9] [6].

To counter such disturbances, utilities and consumers are increasingly turning to custom power devices, such as:

- **D-STATCOM**: for reactive power compensation,
- **UPQC**: for both voltage and current disturbances,
- **DVR**: specifically for voltage sag/swell mitigation.

Among them, the **Dynamic Voltage Restorer (DVR)** offers a cost-effective and technically viable solution for dynamic voltage compensation at the load end.

2. Dynamic Voltage Restorer (DVR)

2.1 Overview

The DVR is a solid-state power electronics-based series compensator used in distribution networks [8]. It injects voltage in series with the supply to maintain the desired voltage at the load terminals during disturbances [6]. It is particularly effective for:

- Mitigating short-duration voltage sags,
- Correcting voltage swells,
- Compensating harmonics and phase imbalance to a limited extent.

Unlike shunt devices, DVRs deal with voltage anomalies rather than current harmonics.

2.2 Key Components of DVR

1. **Voltage Source Inverter (VSI)**

Converts the DC voltage into AC and generates the compensating voltage waveform.

2. **Energy Storage System (ESS)**

Typically a capacitor-based DC link that supplies energy during voltage dips.

3. **Injection Transformer**

Connects the DVR in series with the distribution feeder and facilitates voltage injection.

4. **Filter Circuit (LC Filter)**

Removes high-frequency switching harmonics from the inverter output.

5. **Control Unit**

Detects sags/swells and regulates the inverter output accordingly.

3. Working Principle

The basic operation of the DVR involves injecting a series voltage Vinj such that the load-side voltage Vload remains unaffected during source disturbances:

$$V_{inj}(t) = V_{load}(t) - V_{source}(t)$$

During normal conditions, the DVR remains idle. Upon detection of a disturbance (e.g., a voltage sag), the DVR quickly responds by synthesizing the missing voltage and injecting it in series to maintain the nominal load voltage.

For example, during a 20% sag in the supply voltage, the DVR compensates by injecting the 20% missing component to restore the voltage across the load to rated conditions.

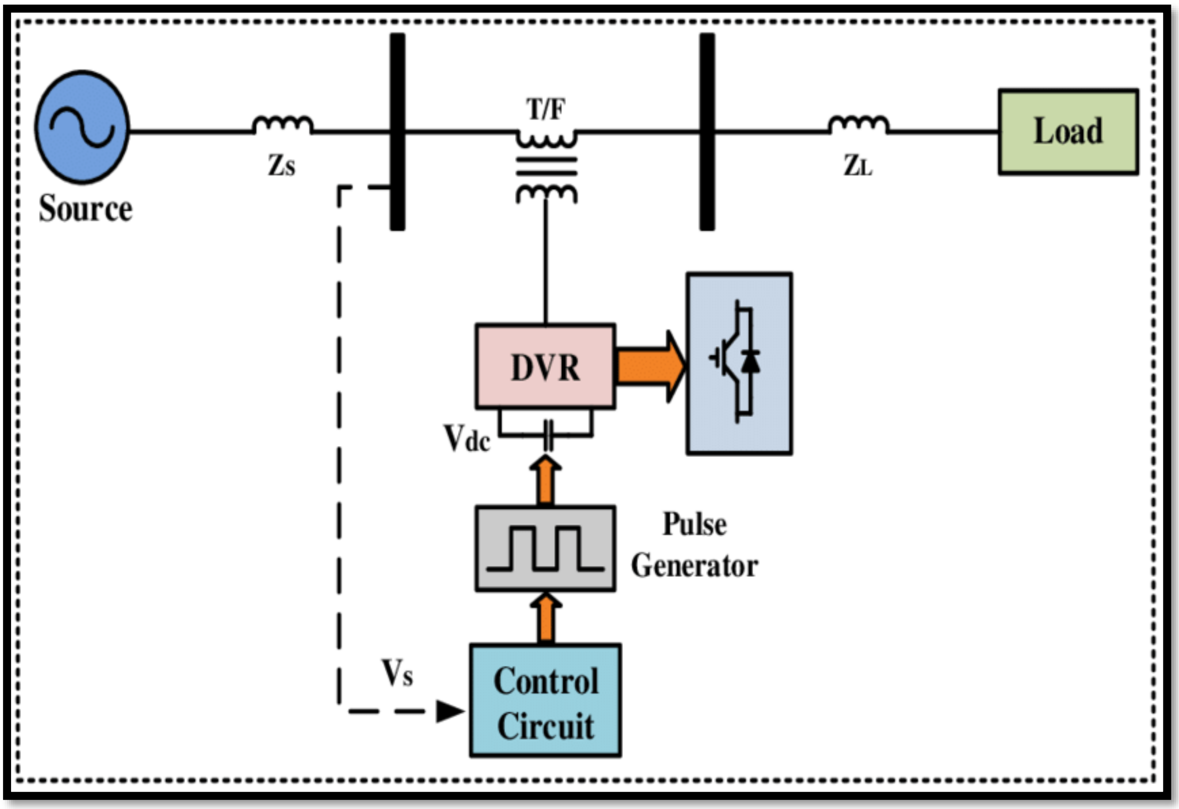

Figure 1 D-Q DVR Block diagram

4. Control Strategy

An effective control strategy is critical for DVR performance. The primary goals include fast detection, accurate voltage estimation, and low harmonic distortion in the injected voltage [2] [13].

4.1 Detection Technique

- **Phase-Locked Loop (PLL)** is employed to extract the phase information of the source voltage.
- **Root Mean Square (RMS) Estimation** determines the sag/swell magnitude.

4.2 Reference Generation

Two main techniques are widely used:

- **Synchronous Reference Frame Theory (d-q theory)**
Converts abc variables to a rotating d-q frame to extract fundamental and harmonic components.
- **Instantaneous PQ Theory (αβ theory)**
Useful for transient detection and instantaneous power flow control.

4.3 PWM-Based Inverter Control

- Pulse Width Modulation (PWM) generates precise switching pulses.
- Proportional-Integral (PI) controllers ensure minimal steady-state error between reference and actual voltage.

5. Simulation and Performance Analysis

5.1 Simulation Setup

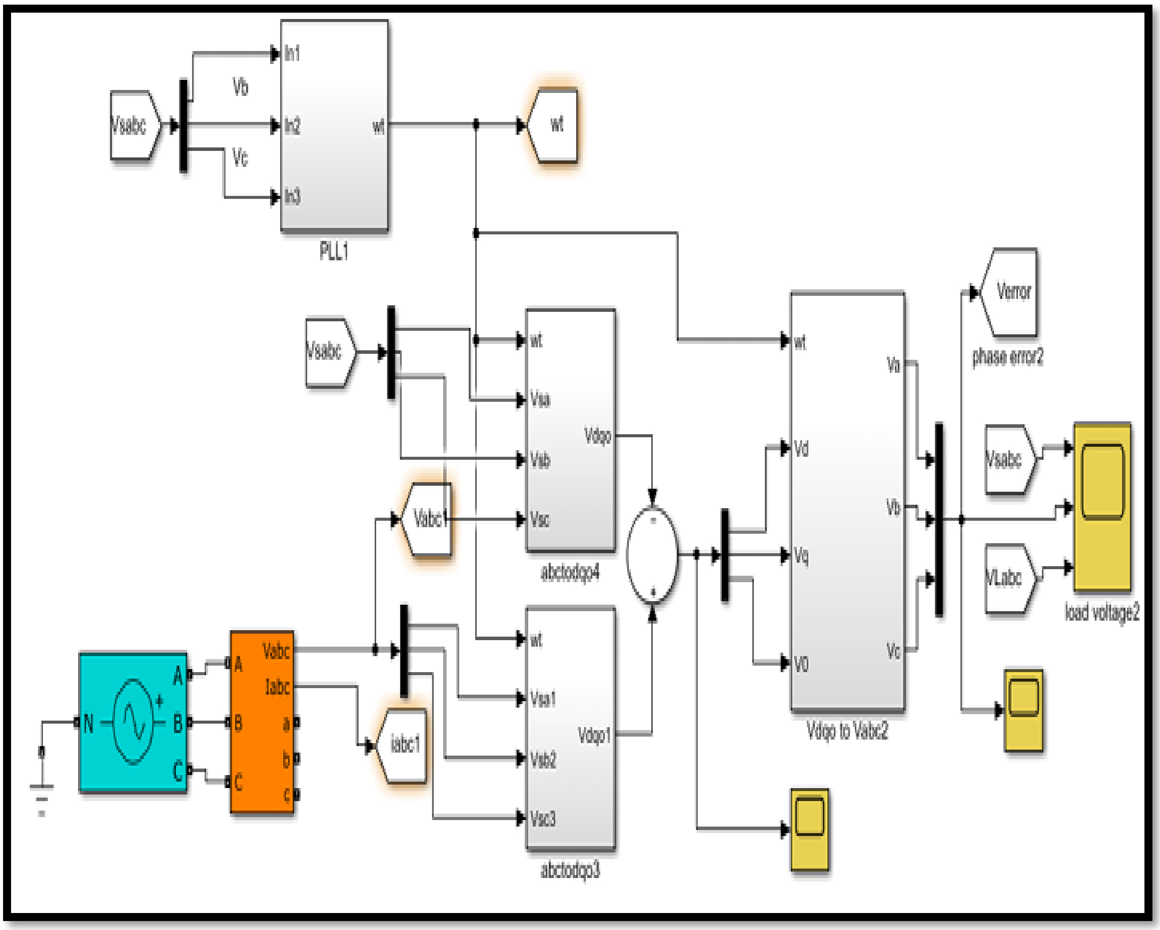

Figure 2 D-Q Theory MATLAB Setup

A MATLAB/Simulink model was created for a three-phase system comprising:

- Source: 400 V, 50 Hz
- Load: 500 Ω, 25 mH (R-L)
- DVR injected via transformer with 10 mH coupling inductance
- DC link voltage: 800 V
- Sag applied from t = 0.01s to 0.4s

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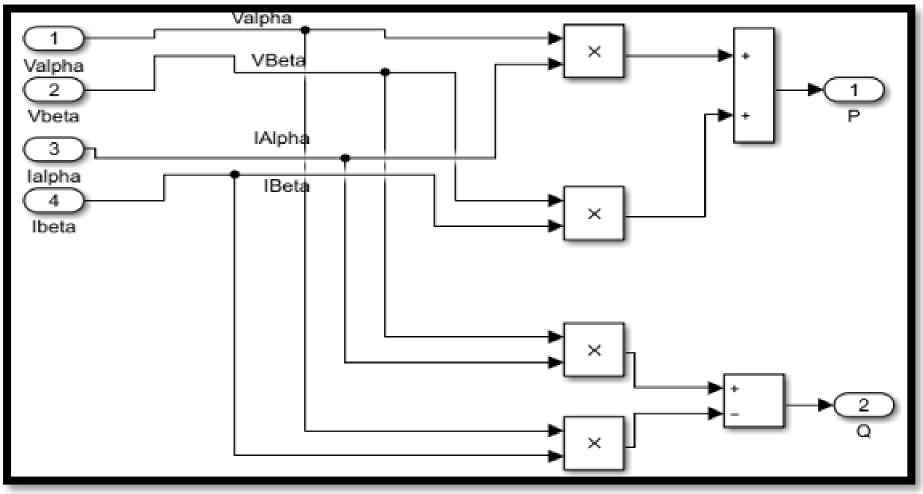

Figure 3 Alpha-beta conversion.

5.2 Performance Metrics

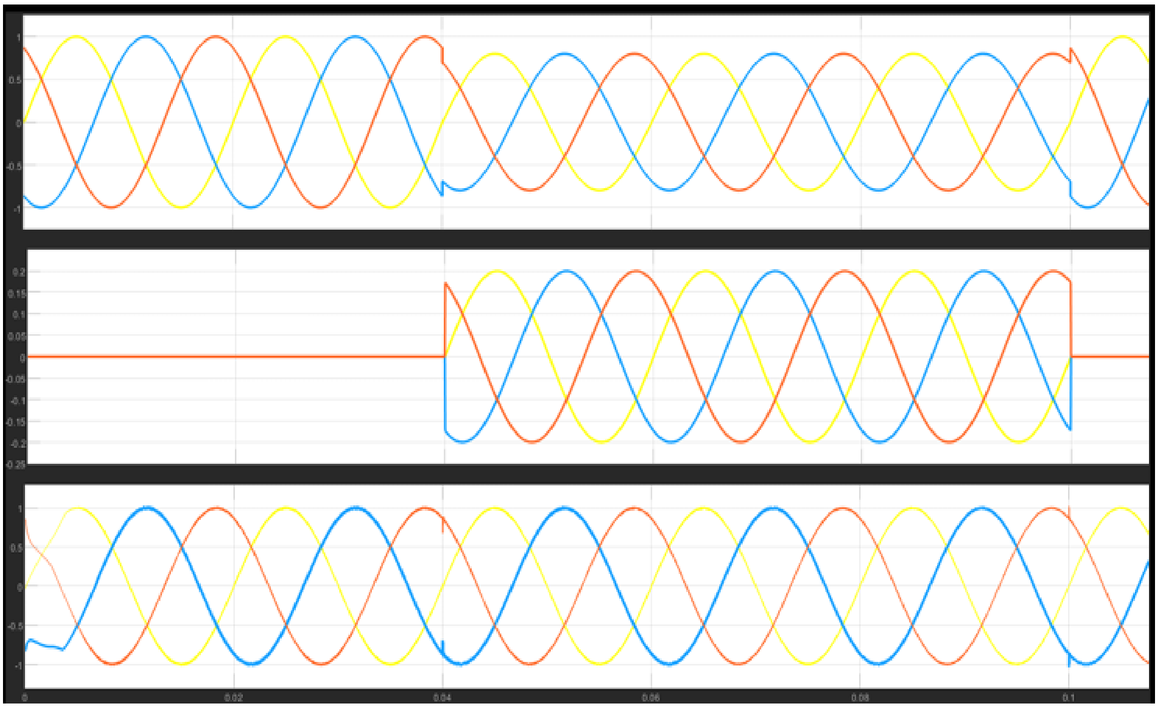

Figure 4 Compensation in voltage sag

- **Voltage Sag Compensation**: DVR restored load voltage from 320 V to 400 V within 10 ms.
- **Harmonic Mitigation**: THD reduced from 11.85% to 3.70%, meeting IEEE 519 standards.

5.3 Results Summary

Parameter	Without DVR	With DVR
Load Voltage (min)	320 V	400 V
Total Harmonic Distortion	11.85 %	3.70 %
Response Time	—	< 10 ms

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6. Applications and Benefits

- **Industrial Automation**: Protects PLCs, CNCs, and VFDs from voltage dips.
- **Healthcare Systems**: Maintains stable supply for diagnostic and life-support equipment.
- **Commercial Buildings**: Prevents lighting and HVAC disruptions during grid disturbances.

Advantages

- Fast dynamic response
- Cost-effective for voltage-specific problems
- Modular and scalable

• No active power drawn in steady-state

7. CONCLUSION

This paper investigates the application and performance of the Dynamic Voltage Restorer in mitigating power quality problems in distribution systems. Through its fast control response and efficient voltage injection, the DVR successfully mitigates voltage sags and improves power quality for sensitive loads. The simulation results validate the DVR's effectiveness in reducing THD and maintaining voltage stability, thereby enhancing the reliability and performance of the power system.

8. Future Scope

Future studies can explore DVR integration with renewable energy sources such as solar PV and wind, enabling hybrid functionalities like grid support. Additionally, the application of artificial intelligence (AI) for adaptive DVR control under uncertain grid conditions is a promising area for further research.

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