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Enhancement Of Voltage Regulation Using Optimized Dynamic Voltage Restorer

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Abstract

Voltage sags and swells can significantly disrupt sensitive equipment and operations. Dynamic Voltage Restorers (DVRs) are an effective solution for mitigating these disturbances by quickly compensating for voltage fluctuations. This paper investigates the DVR's role in voltage regulation during both sags and swells, using MATLAB/Simulink simulations. Results demonstrate that the DVR can restore voltage levels during sags and clamp voltages during swells, improving power quality and system stability. The findings highlight the DVR's potential to protect sensitive loads and enhance overall grid reliability. Future work will explore DVR integration with renewable energy sources and adaptive control strategies

Keywords: Dynamic Voltage Restorer (DVR), Voltage Sag, Voltage Swell, Power Quality, Voltage Regulation

I. Introduction

Voltage sags and other power quality disturbances are common in modern power systems, threatening the reliability of sensitive loads in industrial, commercial, and residential applications [1]. Dynamic Voltage Restorers (DVRs) are widely used to mitigate these disturbances by injecting compensating voltages during short-duration voltage sags. The increasing complexity of modern power systems, coupled with the rapid integration of renewable energy sources and advanced industrial technologies, has placed significant demands on maintaining high-quality power [2]. Among the various disturbances affecting power quality, Voltage sags are temporary reductions in voltage magnitude—are one of the most common and damaging phenomena. Voltage sags are typically caused by system faults, large motor starts, or switching events and can result in substantial economic losses, equipment damage, and reduced operational efficiency in sensitive industrial and commercial loads. These disturbances are particularly disruptive to sensitive electronic equipment, industrial processes, and automated systems, where even brief interruptions or voltage drops can lead to process shutdowns or damage to machinery [3-5]. To address the detrimental effects of voltage sags, power engineers have developed a variety of solutions aimed at compensating for these disturbances and ensuring continuous, stable voltage at the load side. One of the most effective solutions is the Dynamic Voltage Restorer (DVR), a power electronic device designed to inject compensating voltage into the system during sag events, thereby ensuring that the load voltage remains at its nominal level. The DVR is typically connected in series with the load and uses stored energy from a capacitor bank or a battery to inject the required voltage during disturbances [6]. By rapidly responding to voltage sags and compensating for them, the DVR plays a crucial role in enhancing power quality and system reliability. While DVRs have proven to be highly effective for voltage sag mitigation, their optimal performance relies heavily on sophisticated control techniques. Effective control strategies are essential for ensuring that the DVR delivers the appropriate level of voltage compensation during sag events while minimizing overshoot, steady-state error, and response time. One of the most widely used control methods for DVR systems is the Proportional-Integral (PI) controller [7-8]. The PI controller, due to its simplicity, robustness, and ability to minimize steady-state errors, has become a standard choice for regulating the operation of DVRs. The role of PI control is to maintain the load voltage by adjusting the injected voltage in response to deviations from the nominal value. This ability to precisely regulate voltage levels is particularly valuable in applications where consistent power quality is paramount. Over the past few years, significant advancements have been made in optimizing the performance of DVR systems with PI controllers [9-11]. Researchers have explored various strategies to enhance the effectiveness and efficiency of DVRs, taking into account factors such as energy storage, optimization algorithms, and hybrid control techniques. These innovations have made DVRs more adaptive, reliable, and capable of meeting the demands of modern power systems[12-15].

II. Problem Identifications

Power quality problems refer to disturbances in the electrical supply that affect equipment performance and system reliability. These issues include voltage sags (temporary drops in voltage), voltage swells (temporary increases), harmonics (distortions caused by non-linear loads), flicker (rapid voltage fluctuations), and frequency variations. Such disturbances can cause equipment malfunction, downtime, and increased maintenance costs, especially in industries with sensitive loads. Addressing power quality issues is essential to ensure reliable and efficient operation of electrical systems [16].

A. Voltage Flicker

Voltage flicker refers to the rapid and repeated variation in voltage levels, leading to noticeable changes in light intensity, especially in incandescent lamps.

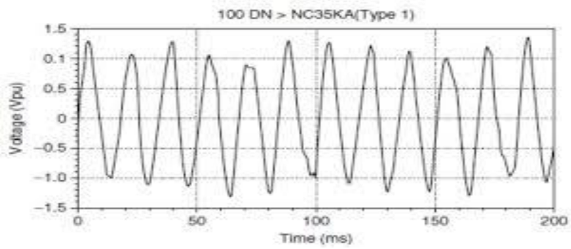

Fig. 1. Voltage flicker diagram

B. Harmonics

Harmonics are voltage or current waveforms that deviate from the fundamental frequency, resulting in distortion. They are expressed as multiples of the fundamental frequency (e.g., 3rd, 5th, 7th harmonics).

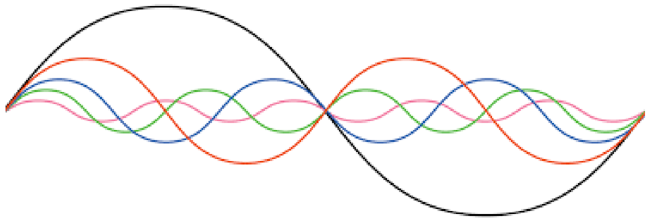

Fig. 2. Harmonics diagram

C. Transients

Transients are short-lived voltage or current spikes that occur in the power supply, often lasting only a few microseconds to milliseconds.

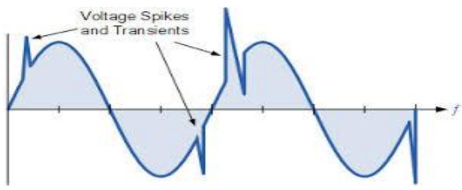

Fig. 3. Transients diagram

D. Frequency Variations

Frequency variations occur when the supply frequency deviates from its nominal value (typically 50 or 60 Hz).

Fig. 4. Frequency Variation Diagram

E. Voltage Sag

Voltage sag (also known as a voltage dip) is a short-term reduction in voltage level, typically lasting from a few milliseconds to several seconds. It occurs when the voltage falls below a specified threshold, usually around 10% to 90% of the nominal voltage. Voltage sags are commonly caused by short circuits, equipment faults, or sudden large load changes in the power system. These sags can lead to operational issues in sensitive equipment, including malfunctioning, data corruption, or even complete shutdowns of industrial machinery, computers, and control systems. Voltage sags are one of the most frequent power quality disturbances and can cause significant economic losses in industries that rely on continuous and stable power. Mitigating voltage sags is critical for protecting sensitive loads and ensuring system reliability.

$$\text{Voltage Sag (\%)} = \frac{\text{Vnominal} - \text{Vsag}}{\text{Vnominal}} \times 100 \qquad (1)$$

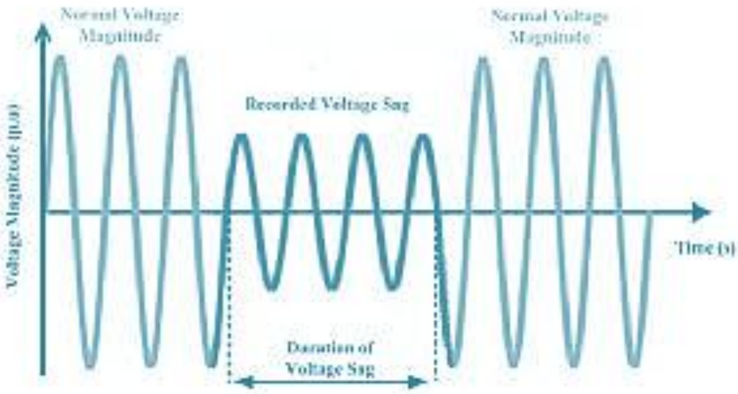

Fig. 5. Voltage Sag

F. Voltage Swell

Voltage swell is a brief increase in the voltage level, typically lasting from a few milliseconds to a few seconds. It occurs when the voltage rises above the nominal value, often by 10% or more. Voltage swells can be caused by events such as the sudden removal of large loads or faults in the power system [17-19]. These swells can damage sensitive equipment, cause overheating, and lead to malfunction or failure of electrical devices. Mitigating voltage swells is crucial for maintaining the stability and protection of electrical systems and ensuring reliable operation of sensitive machinery

$$\text{Voltage swell (\%)} = \frac{\text{Vnominal} - \text{Vswell}}{\text{Vnominal}} \times 100 \qquad (2)$$

III. Dynamic Voltage Restorer

Dynamic Voltage Restorer (DVR) is a device used to mitigate voltage sags and swells in power systems, ensuring stable voltage supply to sensitive equipment [20]. It consists of three main components: a Voltage Source Converter (VSC), an energy storage system (such as batteries or super capacitors), and a control system. The DVR detects voltage disturbances and injects the necessary compensating voltage to restore or regulate the load voltage. The DVR operates by quickly compensating for voltage sags and absorbing excess voltage during swells, providing fast protection to critical loads. It is widely used in industrial, commercial, and data centre applications to improve power quality, prevent equipment damage, and minimize downtime. DVRs offer a cost-effective solution for voltage regulation, with rapid response times and enhanced system reliability [21-23].

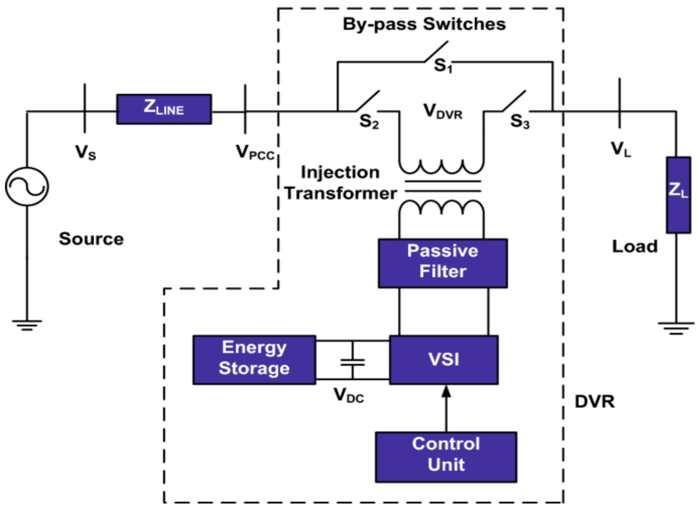

Fig 6 Block diagram of DVR

IV. Modelling Of DVR

The **VSC** is typically a **power electronic inverter** that converts **DC (direct current)** from the energy storage element (such as a battery or capacitor) into **AC (alternating current)** at the required voltage and frequency to match the load voltage. It is the heart of the DVR, enabling the device to inject compensating voltage into the system to correct voltage sags or other power quality issues [24-25].

Voltage rating of the VSC

$$Vc = \sqrt{Vs^2 - VL^2} \qquad (3)$$

Current rating of the VSC

$$Ic = \sqrt{3}VsIs \qquad (4)$$

KVA rating of the VSC

$$S = \frac{3VcIs}{1000} \qquad (5)$$

Injection transformer rating

$$KVA = \frac{3VcIs}{1000} \qquad (6)$$

DC Capacitor voltage of the VSC

$$Vdc > 2\sqrt{2}Vsc \qquad (7)$$

DC Bus capacitance of the VSC

$$\left(\frac{1}{2}\right) \mathrm{Cd}(\mathrm{Vdc}^2 - \mathrm{Vdc1}^2) = 3\mathrm{VcIs}\Delta\mathrm{t} \quad (8)$$

Inductor of the VSC

$$L = n * \left(\frac{\sqrt{3}}{2}\right) m * \frac{Vdc}{6af\Delta Is} \quad (9)$$

Ripple filter

$$fr = \frac{1}{2} * (2 * \pi * Rr * Cr) \quad (10)$$

A. *Modelling Of PI Controller*

A PI controller (Proportional-Integral) is a type of feedback controller used to maintain a system's output at a desired setpoint by adjusting the input. It combines two actions:

1. Proportional (P): Adjusts the control input based on the current error

e(t)=r(t)−y(t) (11)

2. Integral (I): Addresses the accumulation of past errors to eliminate steady-state error by summing over time. The integral gain Ki determines how aggressively past errors are corrected.

The controller's transfer function in continuous time is:

C(s)=Kp + KisC(s) (12)

Table. 1 Design Parameters

Parameter	Values
Power Supply voltage Frequency	3-Phase, 400V, 50Hz ,
Step down Transformer	11KV /400V, r1= r2= 0.0003 pu , L1=L2= 0.001pu,
Linear load Active power	1.5KW,
Reactive power	100VAR
DC voltage	200V
DC Injection Transformer & Ratio	1.5kva, 1:10, r1= r2= 0.00001 pu, x1=x2= 0.0003 pu
PI controller	KPd=40, kId=154 ; KPq=25, kIq=260 ;

LC filter	L=6mH C=20μF
DVR switching frequency	Fs = 2250 (Hz)

V.Simulation And Result

The simulation diagram of a Dynamic Voltage Restorer (DVR) with a PI controller consists of several key components. The system includes an AC supply feeding both the load and DVR, where the load experiences voltage sags and swells. The DVR, modeled as a three-phase voltage source inverter (VSI) with a DC link, compensates for voltage fluctuations by injecting or absorbing voltage. The PI controller monitors the load voltage, compares it to a reference voltage, and adjusts the DVR output based on the error signal to maintain stable voltage at the load

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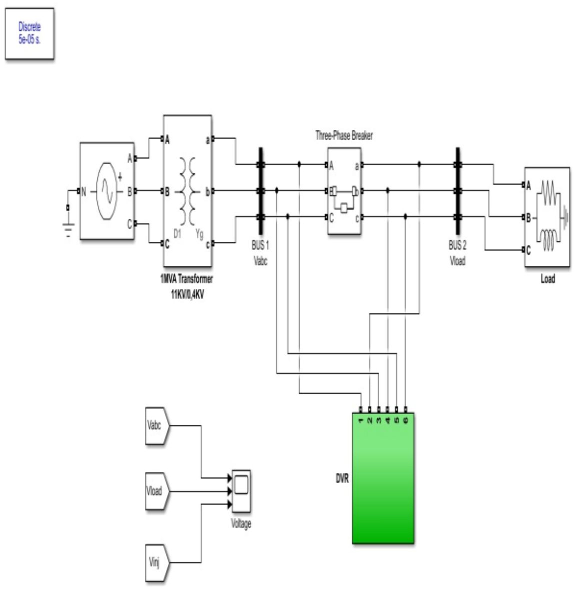

Fig. 7 Simulink model

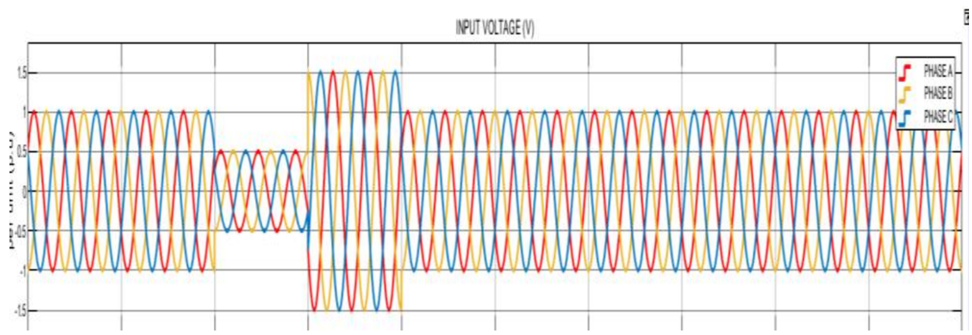

Fig. 8 Input/source voltage

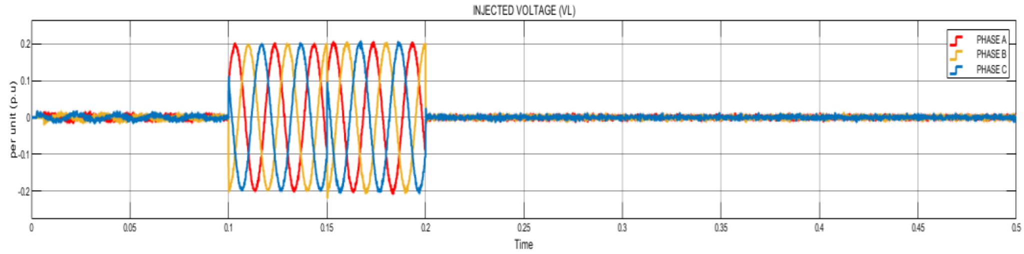

Fig. 9 Injected voltage

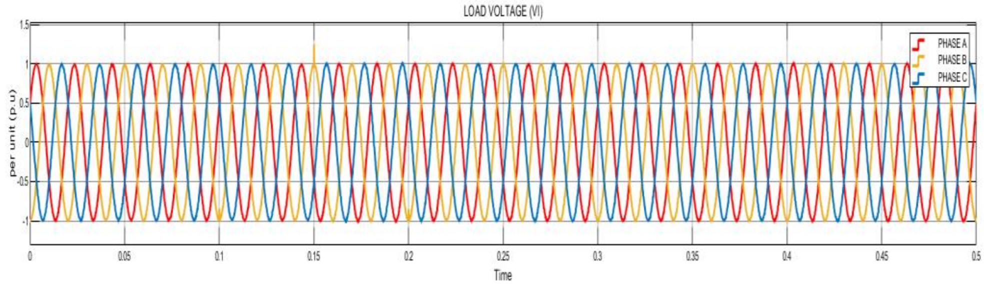

Fig. 10 Output Voltage

In a DVR system with a PI controller, the output waveforms reflect the system's ability to maintain stable voltage during disturbances. Under normal conditions, the output matches the reference voltage. During voltage sags (50% of nominal voltage), the DVR injects voltage to restore stability, causing the output to rise. During voltage swells (150% of nominal voltage), the DVR injects the negative voltage to limit the increase, causing the output to decline The PI controller adjusts the DVR output based on the error signal, which spikes during these events, ensuring continuous voltage regulation.

VI. Conclusion

The proposed dynamic voltage sag and swell compensation technique enhances voltage regulation by quickly detecting and mitigating voltage disturbances. Key benefits include improved stability, faster response times, better power quality, and increased energy efficiency. This solution reduces downtime, minimizes equipment damage and is scalable for various applications. The approach is effective in stabilizing voltage, ensuring reliable power supply, and can be integrated into existing systems with minimal modification. Future work may focus on further optimization, energy storage integration, and renewable energy integration for enhanced resilience.

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