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Design and Simulation of a Dynamic Voltage Restorer (DVR) for Voltage Sag Mitigation in Distribution Systems

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Abstract: The Dynamic Voltage Restorer is a custom power device employed to alleviate voltage issues at load terminals. In today's world, power quality has emerged as a significant concern. This is particularly true with the advent of advanced devices that are highly sensitive to the quality of the power supply. Power quality issues manifest as deviations in voltage, current, or frequency, leading to failures in end-user equipment. A prominent issue addressed here is power sag. To tackle this challenge, custom power devices are implemented. Among these devices is the Dynamic Voltage Restorer (DVR), recognized as the most efficient and effective modern custom power device utilized in power distribution networks. The DVR injects the necessary voltage in series with the supply voltage via an injection transformer to correct the voltage amplitude, phase, and harmonic components in the line. This paper discusses the development, simulation, and analysis of a Dynamic Voltage Restorer (DVR) using MATLAB/SIMULINK. To improve the voltage sag restoration capability of the DVR, this paper focuses on the creation of a control structure utilizing a Discrete PWM pulse generator. Furthermore, this paper explores a new control algorithm based on the abc to dq0 transformation for pulse generation. The results indicate that the developed DVR possesses a strong capability to restore voltage levels during sag conditions.
Keywords: Voltage sag, power quality improvement, dynamic voltage restorer, pulse width modulation, MATLAB/SIMULINK.

I. INTRODUCTION

In contemporary industrial equipment, the majority of devices rely on electronic components such as programmable logic controllers and electronic drives. Power electronic devices exhibit a high sensitivity to disturbances and show reduced tolerance to power quality issues, including voltage sags, swells, and harmonics. Among the various problems related to voltage dips, this is regarded as one of the most critical disturbances affecting industrial machinery. The challenge of inadequate power quality, particularly voltage sags for sensitive loads, can be effectively addressed through the use of power electronics-based Dynamic Voltage Restorers (DVR). By implementing a DVR, the power system can function without experiencing voltage sags, allowing for flexible adjustments to the distribution configuration following a fault occurrence. The DVR operates as a series conditioner utilizing a pulse width modulated (PWM) voltage source inverter (VSI), which can independently generate or absorb real or reactive power. The occurrence of voltage sags that lead to faults is particularly impactful for sensitive loads. The DVR injects specific voltages to restore and maintain sensitive loads at their nominal values. This document describes the integration of custom power devices, specifically the DVR, with a PI controller aimed at enhancing power quality within the distribution system. A novel control strategy has been devised to maximize benefits by eliminating or alleviating voltage sag/swell and power quality issues during abnormal conditions in the distribution system. To this end, the dynamic voltage restorer is proposed as a solution to enhance power quality and mitigate sag and swell issues within the system.

II. SYSTEM DISCRIPTION

The Dynamic Voltage Restorer (DVR) is a specialized custom power device designed to keep the load voltage stable within the distribution system.

DVR operates in two modes. In its normal operation mode, it remains in standby, during which the voltage injection by the DVR is zero. The primary role of the DVR is to mitigate voltage sags and swells; however, it is also capable of performing additional functions such as harmonic compensation, transient voltage reduction, and fault current limitation.

The essential components of the DVR include an injection transformer, a harmonic filter, a voltage source converter, an energy storage device, and a control and protection system [3-4]. When the control circuit identifies any voltage disturbance, it generates a reference voltage that specifies the necessary magnitude, duration, and phase, which is then injected through the injection transformer. This operational state of the DVR is referred to as the injecting mode [1]. This injection must comply with equation (1)[2]

$$\mathbf{V_L = V_S + V_{inj}} \quad \mathbf{(1)}$$

Where VS represents the source voltage, Vinj denotes the voltage injected by the DVR, and VL indicates the load voltage. Fig. 1 illustrates the fundamental configuration and functioning of the DVR, which comprises an injection transformer, a Voltage Source Converter (VSC), a harmonic filter, a storage device, and a control system.

A. *Injection Transformer:*

The injection transformer serves to link the DVR to the distribution network through the High Voltage winding, injecting the compensating voltage produced by the VSC upon detecting any supply voltage disturbances by the control circuit. Additionally, a primary function of the injection transformer is to restrict noise coupling and to isolate the VSC and control circuit from the overall system [5].

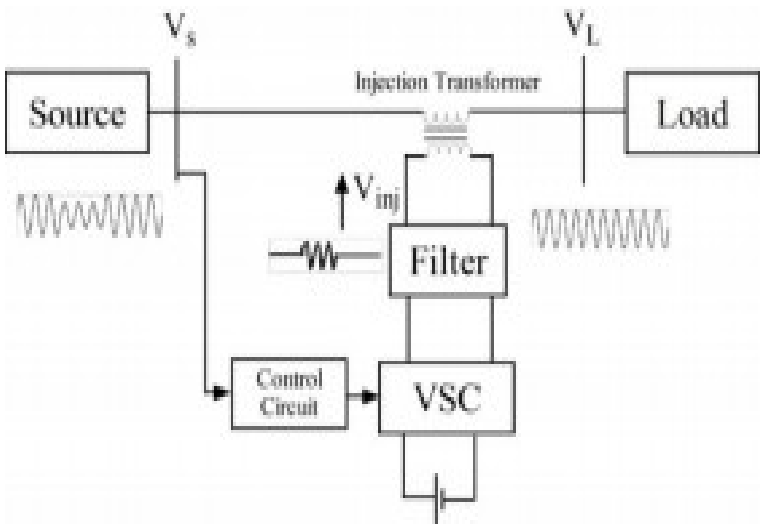

Figure1StructureofDVR.

B. *VoltageSourceConverter(VSC):*

A Voltage Source Converter (VSC) is a power electronic device that comprises a storage device and switching devices, utilized to produce a compensating sinusoidal voltage of the necessary magnitude, duration, and phase alignment with the system, instantaneously. In a Dynamic Voltage Restorer (DVR), the voltage source converter supplies the deficient voltage during instances of voltage sag [2].

C. *HarmonicFilter:*

The output generated by VSC includes a significant amount of harmonics. A harmonic filter is employed to maintain this harmonic content within permissible limits [7].

D. *StorageDevice:*

It is primarily utilized to provide the essential energy to the VSC for the generation of the compensating voltage [2], [7].

E. *ControlCircuit:*

The control circuit consistently observes the supply voltage. The role of the control system is to identify any disturbances in the supply voltage, compare these disturbances with the predetermined reference value, and subsequently produce switching pulses to the VSC, which will create the DVR output voltages necessary to counteract voltage sags or swells [2], [7].

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III. DESIGN OF DVR

The objective of the control scheme is to ensure a stable voltage magnitude at the sensitive load during conditions of voltage disturbance. The suggested control scheme relies on comparing the actual supply voltage with the desired load voltage. The error is calculated dynamically based on the difference between the desired and the measured values. Within the control scheme, both the actual voltage and the desired voltage are measured. These voltages are then transformed into dq0 using the Parks transformation [2].

V_d = 2/3*[Va*sin(wt) + Vb*sin(wt-2pi/3) + Vc*sin(wt+2pi/3)] Vq=2/3*[Va*cos(wt)+Vb*cos(wt-2pi/3)+Vc*cos(wt+2pi/3)] V0 = 1/3*[Va + Vb + Vc]

AndaccordingInverseParksTransformation Va = [Vd*(wt) + Vq*cos(wt) + Vo]

Vb = [Vd*sin(wt-2pi/3) + Vq*cos(wt-2pi/3) + Vo) Vc=[Vd*sin(wt+2pi/3)+Vq*cos(wt+2pi/3)+Vo)

Under standard and synchronous conditions, the voltage remains constant, with d-voltage at one per unit (pu) and q-voltage at zero pu; however, changes may occur under normal circumstances. The d-voltage and q-voltage, which are essential for optimal performance, are compared, resulting in the generation of d and q errors.

The error components are transformed into abc components through the dq0 to abc transformation. A Phase Locked Loop (PLL) is employed to produce a unit sinusoidal wave that is in phase with the main voltage. These abc components are utilized to create three-phase pulses using the Pulse Width Modulation (PWM) technique. The proposed control technique block is illustrated in Fig 2.

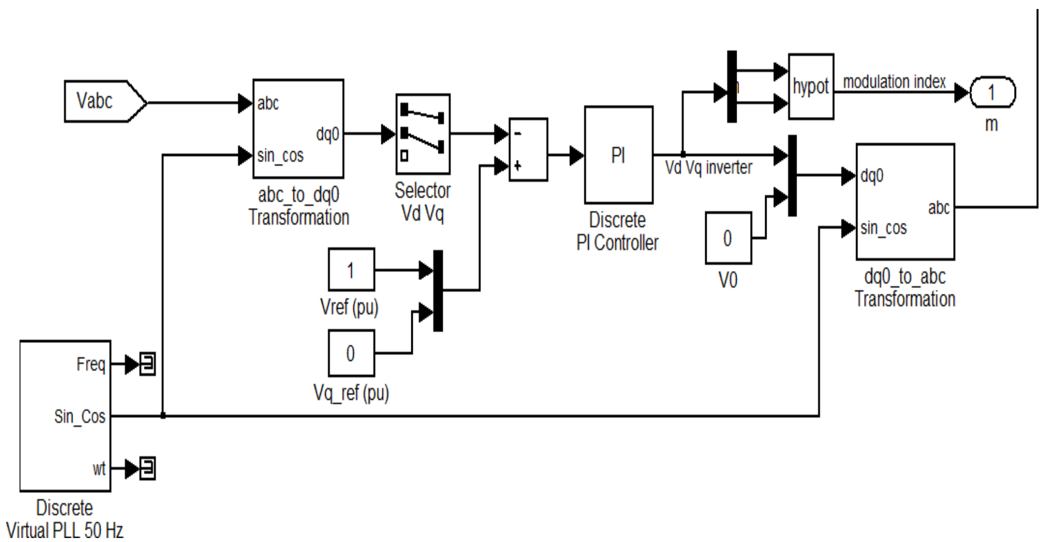

Figure2Schematicdiagramsofcontrolblock

IV. CONTROL ALGORITHM

The primary roles of a controller in a DVR include detecting voltage sag and swell events within the system; calculating the necessary corrective voltage, generating trigger pulses for the sinusoidal PWM-based DC-AC inverter, rectifying any irregularities in the series voltage injection, and ceasing the trigger pulses once the event has concluded. Additionally, the controller can be utilized to switch the DC-AC inverter into rectifier mode to recharge the capacitors in the DC energy link when voltage sags or swells are not present. The dqo transformation, also known as Park's transformation [4-5], is employed for the control of the DVR. This dqo method provides information regarding the depth of sag and phase shift, along with their respective start and end times. The quantities are represented as instantaneous space vectors. Initially, the voltage is converted from the abc reference frame to the d-q-o reference frame. For the sake of simplicity, the zero phase sequence components are disregarded. Figure 3 depicts a flow chart illustrating the feed-forward dqo transformation for the detection of voltage sags and swells. The detection process is performed across each of the three phases.

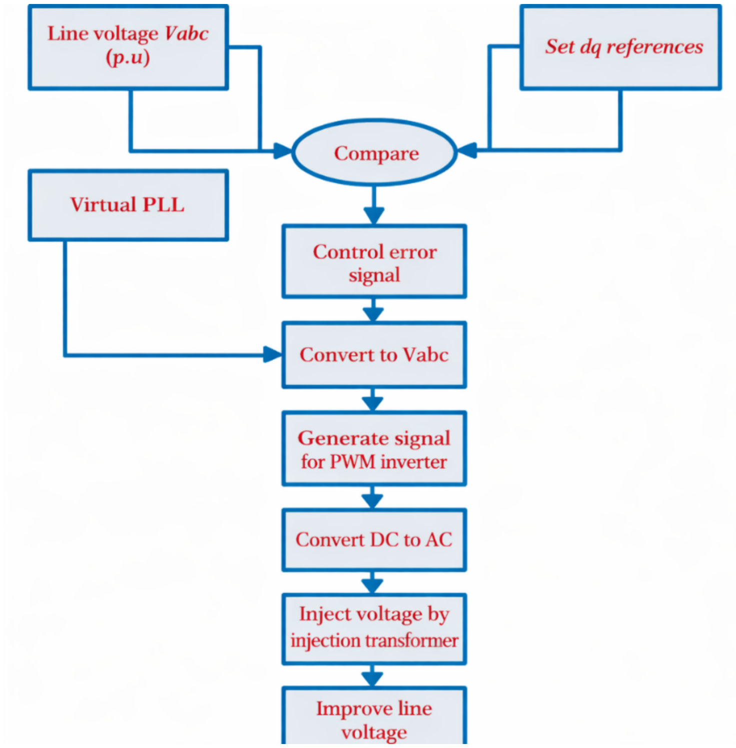

Figure3Flowchartof method

The control scheme for the proposed system relies on comparing a voltage reference with the measured terminal voltages (Va, Vb, Vc). Voltage sags are identified when the supply voltage falls below 90% of the reference value, while voltage swells are recognized when the supply voltage rises by up to 25% of the reference value. An error signal serves as a modulation signal, facilitating the generation of a commutation pattern for the power switches (IGBTs) that make up the voltage source converter. This commutation pattern is produced using the sinusoidal pulse width modulation technique (SPWM), which controls the voltages through modulation. The block diagram of the phase locked loop (PLL) is depicted in Fig 3. The PLL circuit generates a unit sinusoidal wave that is in phase with the mains voltage. Park's transformation converts the three-phase system a, b, c into the dqo stationary frame. In this transformation, phase A is aligned with the d-axis, which is orthogonal to the q-axis..

V. MATLAB MODELING AND SIMULATION

A. MATLABModelofUncompensatedSystem:

A distribution system is designed and simulated using MATLAB. The model is illustrated in Figure 5. A three-phase source of 220 kV is linked to a step-down transformer (220 kV/11 kV), and the secondary side of the transformer (11 kV) is connected to a pi section with a length of 21 km, where a three-phase load is connected via a load bus.

A fault is introduced in the distribution line, and the system is subsequently analyzed through a scope that displays the voltage magnitude in a per unit system.

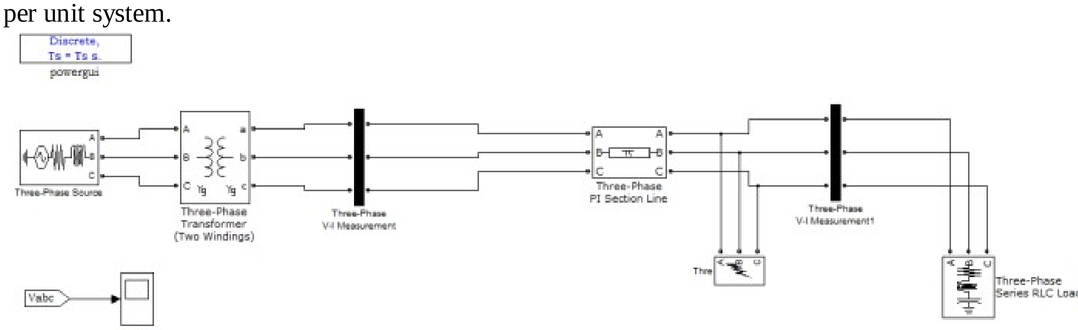

Figure4MATLAB model ofuncompensatedsystem

A. MATLABModelofDVR:
The DVR is designed and simulated utilizing MATLAB along with its Simulink and Sim Power System toolboxes. The MATLAB representation of the DVR connected system [8] is illustrated in Figure-5. The DVR comprises a PWM inverter circuit and a DC Voltage source linked at the DC Link of the VSI. The IGBT-based PWM VSI is constructed using the Universal Bridge Block from the Power Electronics subset of the Power System Block-set.

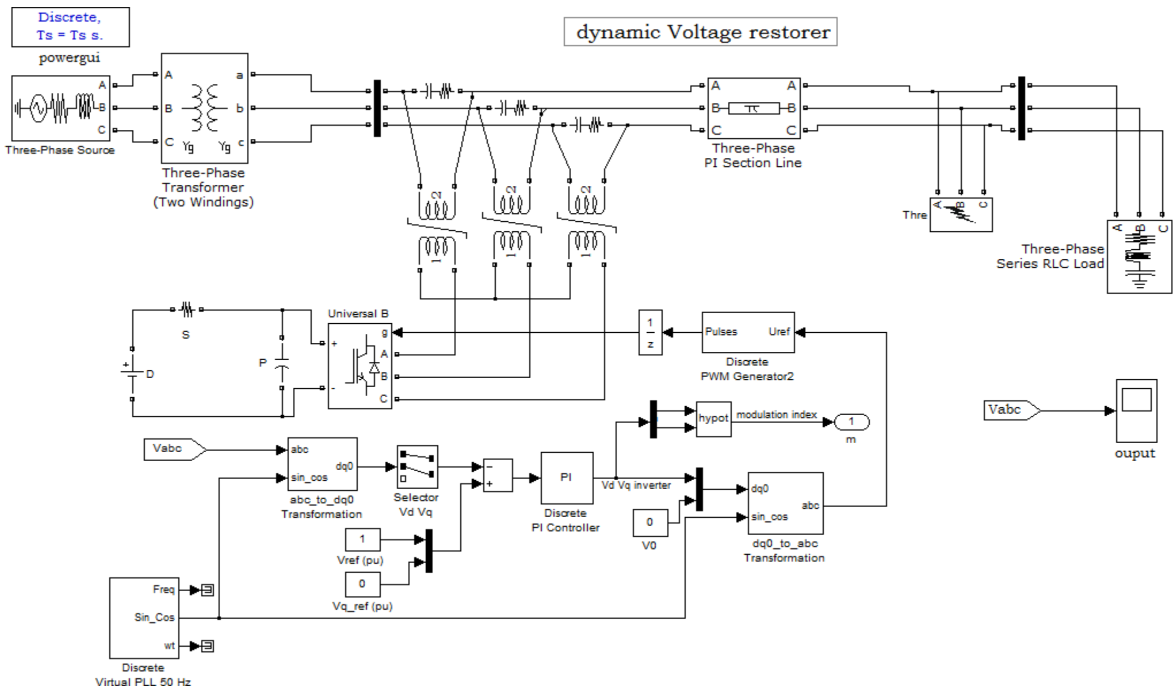

Figure5MATLABmodel ofDVRconnectedsystem

VI. RESULT AND DISCUSSION

A. SimulationResultofUncompensatedSystemduringfault:
In the simulation of an uncompensated system, when a three-phase short-circuit fault occurs at point A, during a duration of 200 ms, the voltage sag at the load point is nearly 80% in relation to the reference voltage.

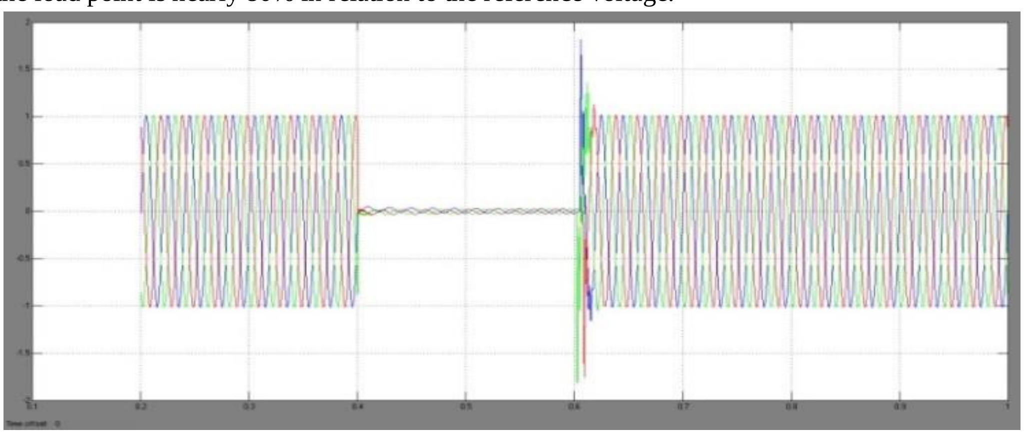

Figure:6Source VoltagewaveformduringFaultwithUncompensatedsystem

B. SimulationResultlofDVRduringFault:
Now, simulate the system utilizing a DVR at point A, where a three-phase short-circuit fault has been introduced. The voltage sag at the load point now approaches nearly 90% in relation to the reference voltage. By employing the tools available in MATLAB, the DVR is configured to operate solely for the duration of the fault.

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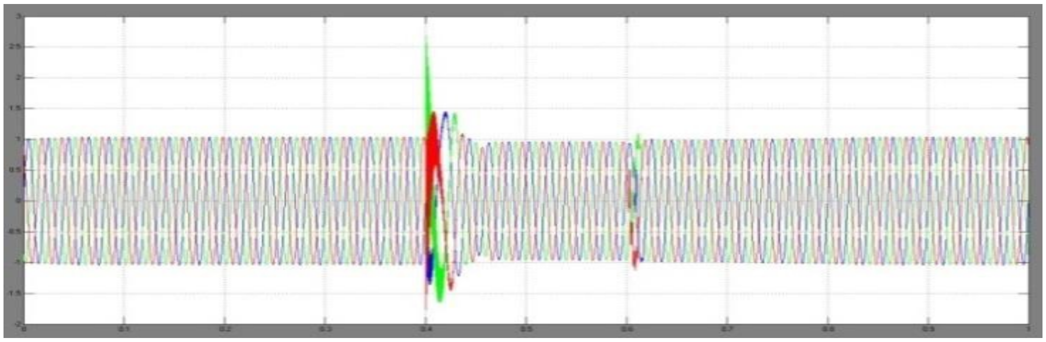

Figure:7SourceVoltagewaveformbeforeFault mitigationwithoutDVR

VoltageImprovement:

The voltage on the load side (expressed in per unit) during a fault condition of the DVR is displayed in this table. This table indicates that the DVR provides effective compensation..

VoltageMagnitude(p.u.)	DVR
Beforecompensation	0.2p.u.
Aftercompensation	0.9p.u.
improvedvoltage	0.7p.u.

THDAnalysis:

Total harmonic distortion serves as a crucial factor in enhancing power quality. The calculation of THD is based on the harmonics present in a power line. This table was generated using the results from MATLAB FFT Analysis. Under fault conditions, the THD of the load side voltage is illustrated in this table. From the data presented, it is evident that the DVR system outperforms the DSTATCOM, as the harmonics generated in the distribution line are effectively eliminated by the DVR system, resulting in a load voltage that is nearly sinusoidal.

THD	DVR
BeforeCompensation	5.92
AfterComensation	3.49

TableIITHDanalysisofuncompensatedsystem:

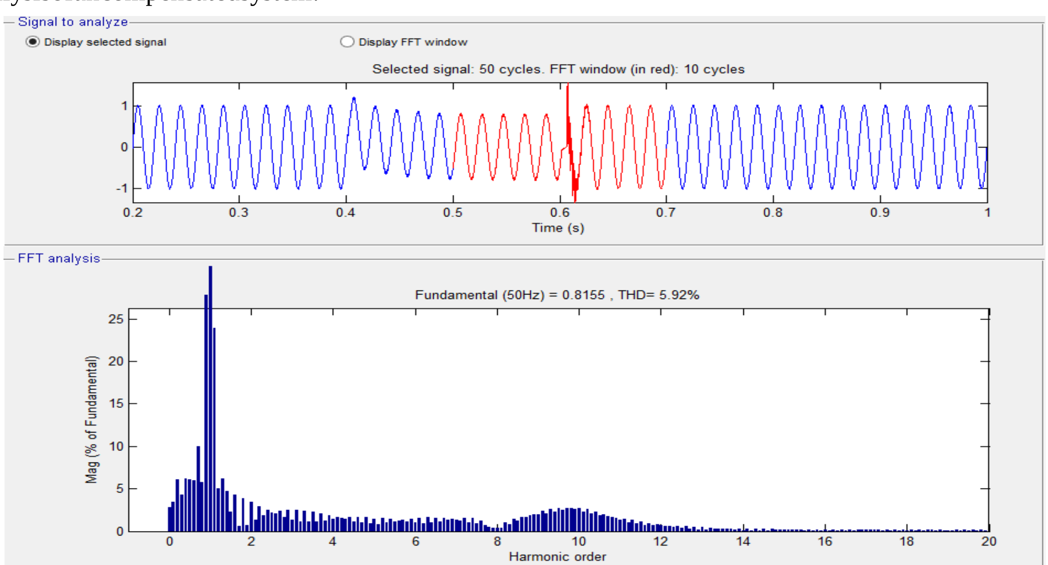

Figure9THDanalysisofuncompensatedsystem

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THDanalysisof DVR:

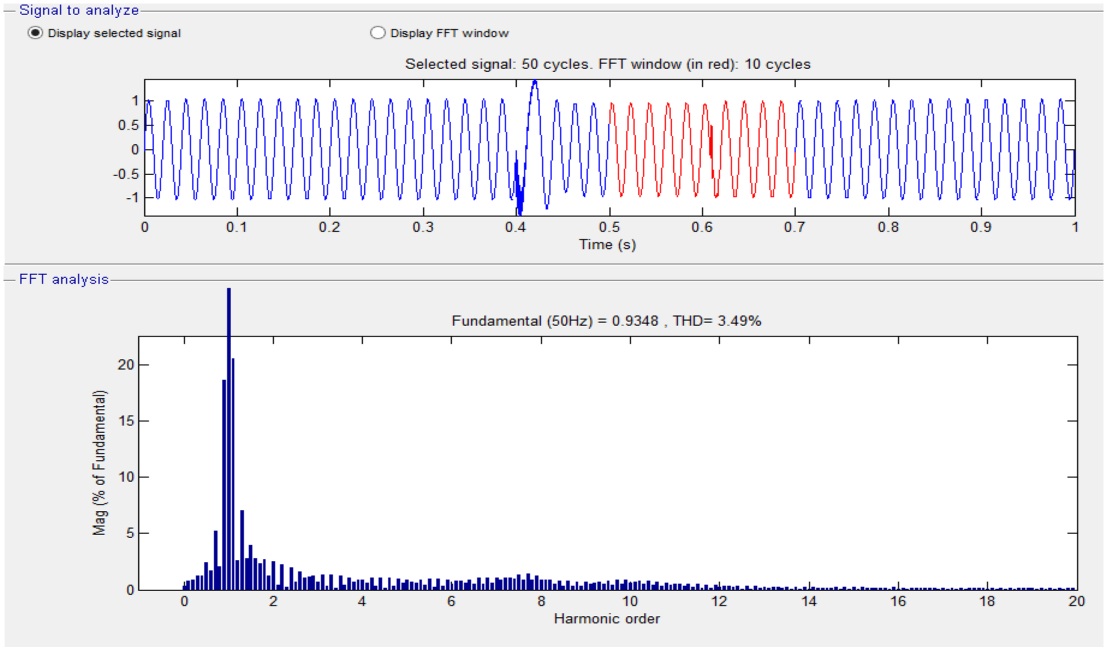

Figure10THDanalysisofDVR

VII. CONCLUSION

This paper has discussed power quality issues, including voltage dips, swells, and interruptions, along with mitigation techniques for the custom power electronic device known as DVR. The design and applications of DVR for addressing voltage sags and interruptions are thoroughly presented, along with comprehensive results.

A novel PWM-based control scheme has been developed to manage the electronic valves in the VSI utilized in the DVR. Unlike the fundamental frequency switching schemes currently available in MATLAB/SIMULINK, this PWM control scheme relies solely on voltage measurements. This feature renders it particularly suitable for low-voltage custom power applications. The simulations conducted demonstrated that the DVR offers effective voltage regulation capabilities. The results of the simulations indicate a high level of accuracy in the findings.

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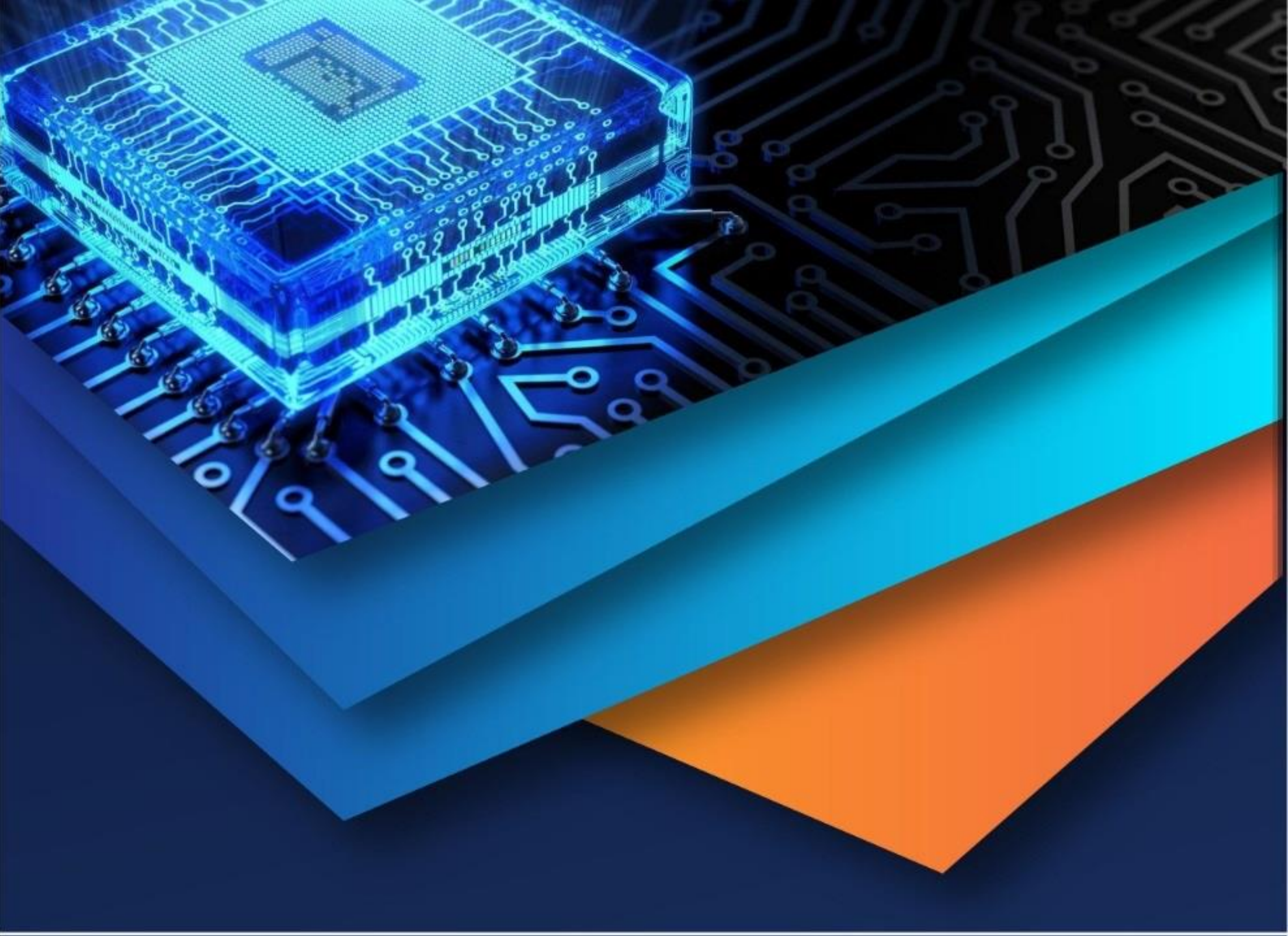

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