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Mitigation of Voltage Sag Using a Transformer less DVR with a Reduced Switch Count Multilevel Inverter

Dr. Vijay Prasad

Associate Professor
Department of Electrical & Electronics Engineering,
Advait Vedanta Institute of Technology, Jaipur

ABSTRACT

In power systems, voltage sag is a critical issue affecting power quality. Dynamic Voltage Restorers (DVRs) are widely recognized as a cost-effective solution to protect sensitive loads from these disturbances. Removing the injection transformer from the system can further enhance cost efficiency, reliability, and performance. This study introduces a transformer less DVR based on a T-type multilevel inverter. The proposed DVR benefits from reduced costs, lighter weight, and a more compact design due to the absence of the injection transformer. The DVR's controller is implemented using D-q transformation techniques. Simulation results for the dynamic voltage restorer were generated using MATLAB/SIMULINK software.

Keywords: Dynamic voltage restorer, T-type Multilevel Inverter, d-q transformation.

I. INTRODUCTION

Power quality concerns are increasingly critical as sensitive loads in power systems become more prevalent. Key issues include harmonics, flicker, voltage sag, and voltage swell. Voltage sag, often caused by faults, electrical heater startups, load or supply side failures, and motor initiations, involves a temporary drop in RMS voltage from 0.1 pu to 0.9 pu over a brief period, typically ranging from 0.5 to a few cycles, as defined by the IEEE 1159-1995 standard. Distribution systems experiencing a voltage drop of 40% to 50% of the rated voltage for less than 2 seconds often lead to failures.

The rise of non-linear loads such as laser printers, adjustable speed drives (ASDs), switched mode power supplies (SMPS), and diode bridge rectifiers exacerbates power quality issues. To address voltage sag, Dynamic Voltage Restorers (DVRs) inject voltage to counteract the dip and stabilize the load voltage at the output terminals.

Recent advancements in power electronics have introduced "custom power devices" like DVRs, Unified Power Quality Conditioners (UPQCs), and Distribution Static Compensators (D-STATCOMs). Among these, the DVR is specifically designed to restore and maintain voltage levels at the load, effectively mitigating the effects of voltage sag and improving overall power quality.

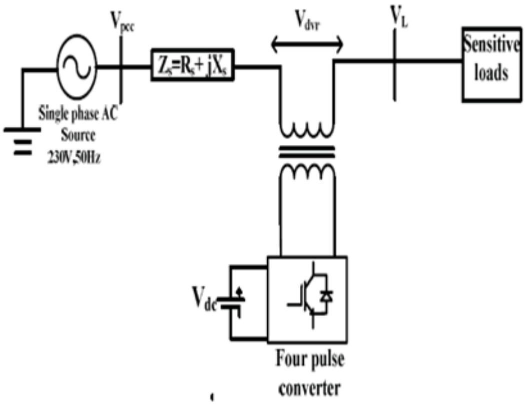

Fig:1 Basic system model of DVR

When disruptions occur in the supply voltage's quality, a Dynamic Voltage Restorer (DVR) compensates for voltage sags by injecting a compensating voltage in series with the grid voltage. This action ensures that the rated load voltage is maintained under balancing mode conditions. A typical DVR system comprises an energy storage device, an injection transformer, and an inverter.

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The primary objective of the new inverter topology design is to sustain a stable load voltage and mitigate disturbances by precisely controlling the injected voltage in terms of both magnitude and phase angle. Figure 1 illustrates a basic model of the DVR system.

II. CONVENTIONAL DVR

The voltage source inverter is the most critical component of a Dynamic Voltage Restorer (DVR), and its operation significantly impacts the DVR's performance. When selecting an inverter topology, considerations include the number of switches, DC-link voltage sources, and filter design.

Types of Power Converters:

1. **Direct Converters (AC-AC):**

Direct converters are crucial for compensating voltage sag in distribution networks. DVRs based on matrix converters do not use energy storage to counteract voltage sag or swell. They face several challenges:

- High number of power semiconductor devices (total of 18) [4].
- Complex circuit control and the need to fully conduct and block bidirectional current and voltage.
- High switching losses and stress due to voltage and current changes on the devices [5].

2. **Indirect Converters (AC-DC-AC):**

Indirect converters, including both H-bridge and non-H-bridge inverter topologies, are widely used. Two-level voltage source inverters produce significant electromagnetic interference and high switching losses. Multilevel inverters (MLIs) address these issues by reducing switching losses.

Common MLI topologies include:

- **Diode-Clamped Inverters:** These inverters use (n-1) DC-link capacitors and (2n-1) switching devices to generate multiple-level sinusoidal voltage waveforms. However, they suffer from voltage imbalance in clamping diodes and DC capacitors [3].
- **Flying Capacitor Inverters:** These use energy storage capacitors instead of clamping diodes. Each phase requires (n-1) DC-link capacitors, which can be a drawback due to the need for high-capacity DC capacitors [8].
- **Cascaded H-Bridge Inverters:** These are extensively used in high-power, medium-voltage applications. They link H-bridge cells in a cascaded configuration, which results in reduced harmonic content in the output voltage. The schematic diagram of a cascaded H-bridge inverter is shown in Fig. 2.

The number of voltage levels mmm in a cascaded H-bridge converter is given by:

m=2H+1(1)m = 2H + 1 \quad (1)m=2H+1(1)

where HHH represents the number of H-bridge cells per phase. The total number of switches NswN_{sw}Nsw in a three-phase Cascaded H-Bridge (CHB) converter can be calculated using:

Nsw=6(m−1)(2)N_{sw} = 6(m-1) \quad (2)Nsw=6(m−1)(2)

The CHB converter requires a small filter to keep the Total Harmonic Distortion (THD) within acceptable limits, and it eliminates the need for a series injection transformer to connect to the medium voltage network. However, it has the disadvantage of requiring a separate DC supply and a large number of switches.

To address these issues, a new T-type multilevel inverter is proposed for the DVR system.

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III. PROPOSED T-TYPE MLI DVR

The T-type multilevel inverter is an efficient topology with a reduced switch count compared to other multilevel inverters. It consists of four unidirectional switches, which provide bi-directional conducting and blocking capabilities, and one bi-directional switch [10]. This setup allows the T-type inverter to maintain a midpoint DC source for the H-bridge configuration. As the voltage level increases, additional DC sources and bidirectional switches are required to accommodate the higher levels.

System Overview:

- **Configuration:** The T-type multilevel inverter employs a combination of four switches per phase: three unidirectional switches and one bidirectional switch. For each phase, the number of switches is expressed as (n–3), where nnn represents the number of voltage levels desired. The remaining switches are part of the H-bridge configuration.

Switching Operation: To achieve five distinct voltage levels per phase (-2V, -V, 0, V, and 2V), each phase requires a midpoint DC source. The switching actions to produce these voltage levels are as follows:

- **Voltage Levels 2V and V:** Achieved by switches S1a, S2a, S3a, and S4a, with the bidirectional switch (Bsa) used to control the levels.
- **Voltage Levels -V and -2V:** Obtained by switches S1a, S2a, S3a, and S4a, and the bidirectional switch (Bsa) controls the negative voltage levels.

Switching Process Overview: Table I summarizes the switching process for the T-type multilevel inverter, detailing how each switch configuration corresponds to the desired voltage levels for each phase.

Diagram: Figure 3 illustrates the T-type multilevel inverter system model, providing a visual representation of the switch arrangement and phase connections.

This configuration reduces the number of switches compared to other multilevel inverter topologies, making it more cost-effective and compact while still delivering multiple voltage levels for effective voltage regulation.

Table I. Switching operation of T-type inverter

Switches in Conduction	Voltage level
B_{sa} and S_{4a}	V
S_{1a} and S_{4a}	2V
(S1and S2) or(S3 and S4)	0
B_{sa} and S_{2a}	-V
S_{3a} and S_{2a}	-2V

Benefits of the T-Type Multilevel Inverter

The T-type multilevel inverter offers several significant advantages over conventional inverter topologies:

- **High Power Capability:** The T-type design supports high power applications due to its robust topology.
- **Reduced Switching Losses:** The reduced number of switches leads to lower switching losses.
- **Compact Design:** Compared to traditional topologies, the T-type inverter is lighter and more compact, making it easier to integrate into various systems.
- **High Efficiency and Rapid Response:** Its efficient design allows for quick response times and high overall efficiency.
- **Reduced Switching Redundancy:** The T-type inverter minimizes unnecessary switching, improving performance and reliability.
- **Minimal Disturbances:** It produces smaller disturbances in the sinusoidal input and output currents, enhancing the quality of power delivery.
- **Lower Switch Count:** The T-type configuration reduces the number of switches by 37.5% compared to other topologies [10].
- **Fewer Diodes Required:** It reduces the diode count by 60% compared to diode-clamped multilevel inverters [19].
- **Fewer Switching Devices:** Fewer switching devices are required, and isolated DC supplies are not needed.

DVR Controller

Dynamic Voltage Restorers (DVRs) use different control approaches to manage voltage sag and maintain power quality. Two primary control methods are:

1. **Open-Loop Control:**
   - **Speed:** Open-loop controllers respond more quickly, making them suitable for applications requiring rapid voltage correction.
   - **Limitations:** They might not be as effective in minimizing steady-state errors as closed-loop controllers.
2. **Closed-Loop Control:**
   - **Accuracy:** Closed-loop controllers are more effective in reducing steady-state error but have a slower response time for voltage sag correction.

d-q Rotating Frame Control

The d-q rotating frame control is an effective method for DVR systems:

- **Transient Response:** It helps reduce overvoltage and decrease voltage drop across filters, ensuring appropriate transient responses.
- **Phase-Locked Loop (PLL):** By using a PLL, the DVR is phase-locked to the supply voltage, which reduces steady-state error in the fundamental component.
- **Harmonic Reduction:** PLLs also help in reducing harmonics and managing unsymmetrical component output voltages, even with sudden supply voltage changes.

Reduced Carrier PWM Technique

The reduced carrier PWM (Pulse Width Modulation) technique simplifies the modulation process for the T-type multilevel inverter:

- **Modulation Signal:** Only a single modulation signal is required for controlling the inverter.
- **Carrier Signals:** To achieve "n" levels in phase voltages, (n-1)/2 carrier signals are used.
- **Operation:**
   - If the unipolar modulation signal is less than the peak of carrier1, the phase voltages are 0-V.
   - If the modulation signal exceeds carrier1, the phase voltages switch to V-2V.
   - The polarity of the voltage bands is determined by the modulation signal, resulting in the phase values of -2V, -V, 0, V, and 2V.

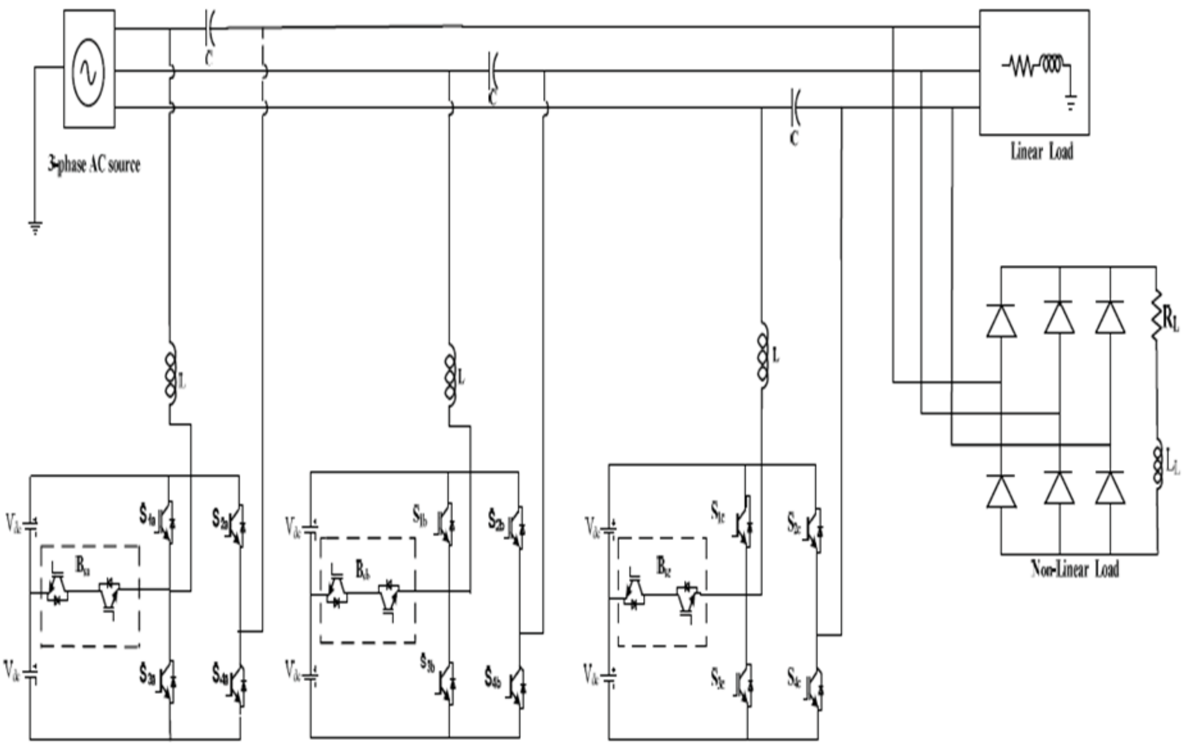

Fig.3 Proposed T-type Multilevel inverter-based DVR

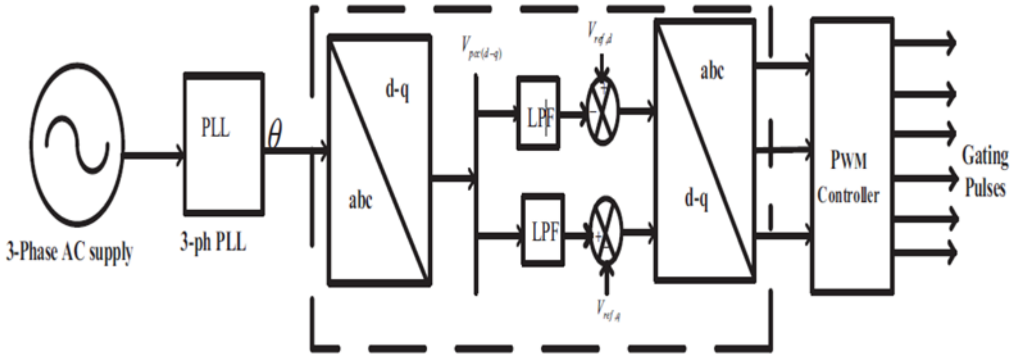

Fig.4 DVR controller with dq rotating frame

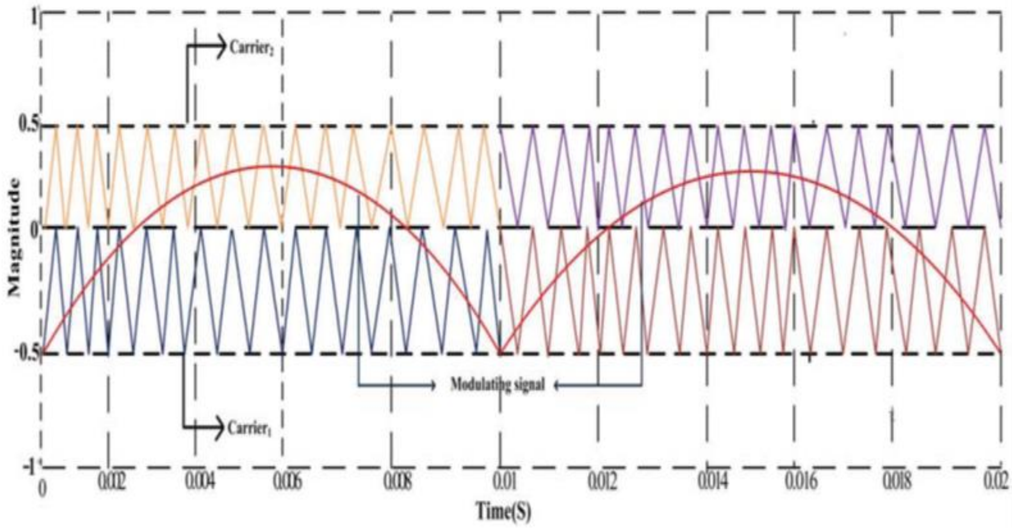

Fig.5 Reduced carrier PWM technique

IV. SIMULATION RESULTS

Simulation and Results of the Transformer less DVR with T-Type Multilevel Inverter
Switching Pulses and PWM Technique

- **Switching Pulses:**

○ **Decreased Carrier PWM Technique:** The switching pulses produced by the reduced carrier PWM technique for the T-type multilevel inverter are illustrated in Figure 6. The switching patterns for the S1 and S2 switches are visible from the start, with their complementary counterparts, S3 and S4, operating in opposition. The bidirectional switch (denoted by B) receives switching pulses that control its operation. Specifically, the bidirectional switch is activated for positive and negative "V" voltages by the corresponding pulses from switches Bs and S4, and Bs and S2.

- **Operational Details:**

○ **Switching Pattern Analysis:** The distinct switching pattern becomes evident at 0.2 seconds. During this interval, the bidirectional switch manages the voltage transitions effectively, providing necessary voltage levels while minimizing harmonic distortion and switching losses.

Simulation Results

- **Simulation Setup:**

○ **Parameters:** The simulation parameters for the T-type multilevel inverter-based DVR are detailed in Table III. The inverter operates at a switching frequency of 2 kHz, with an LC filter used to eliminate higher-order harmonic components.

- **Voltage Sag Compensation:**

○ **Grid Voltage Response:** Figure 7 shows the DVR's response to a 40% voltage sag. Initially, from 0 to 0.2 seconds, the injecting voltage remains zero as the grid voltage is normal. At 0.2 seconds, when the grid voltage experiences a sag, the DVR starts injecting voltage to counteract the sag. Between 0.2 and 0.5 seconds, the DVR successfully compensates for the 40% sag in source voltage. During this period, the DVR maintains the load voltage at its nominal value by injecting the appropriate compensatory voltage.

- **Effectiveness of the LC Filter:**
  - **Voltage Enhancement:** The LC filter significantly improves the T-type multilevel inverter's performance by filtering out high-frequency components and enhancing the quality of the injected voltage. The filter ensures that the output voltage is smooth and meets the required specifications for effective compensation.

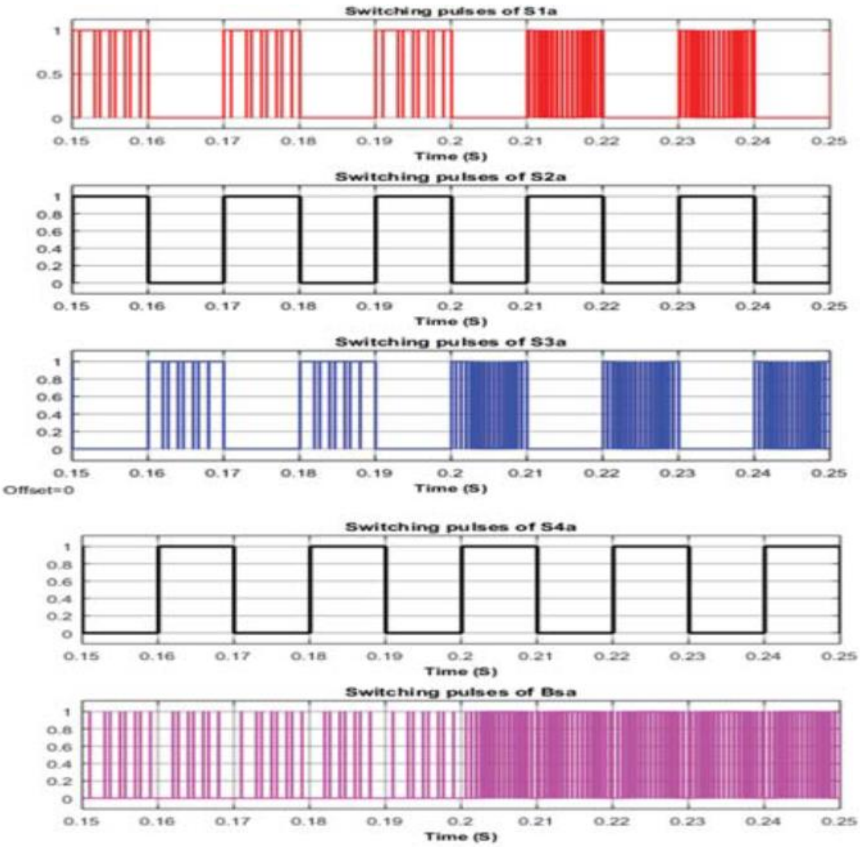

Fig.6 Switching pulses of reduced carrier PWM technique

Table II. T-type Inverter parameters for simulation studies

Parameter	***Values***
Source voltage (*rms* $V_{Line-to-Line}$)	1kV
Resistance/phase	0.005ohm
Inductance/phase	0.1mH
Filter Resistance (f_R)	1.5ohm
Filter Inductance (f_L)	1.5mH
Filter Capacitance (f_C)	1100µF
Switching Frequency	2KHz

The subject matter of the secondary case study is total harmonic distortion (THD). Compared to the CHB inverter architecture, the T-type multilevel inverter topology has less overall harmonic distortion of the load voltage and load current.

VI. THD ANALYSIS

Here, we have performed an FFT analysis of the load voltage and load current for the CHB five level inverter topology and the suggested design at a frequency of 50 Hz and a beginning time of 0.3. There is a maximum of ten cycles. The load voltage harmonic spectrum waveforms for the proposed DVR are displayed in Figures 8 and 9. The THD analysis values are shown in Table III.

Table III. THD Analysis of both Topologies

Type of Inverter	THD%	
	Load Voltage	Load Current
T-type multilevel inverter	2.77%	3.28%
CHB five level inverter	4.83%	3.76%

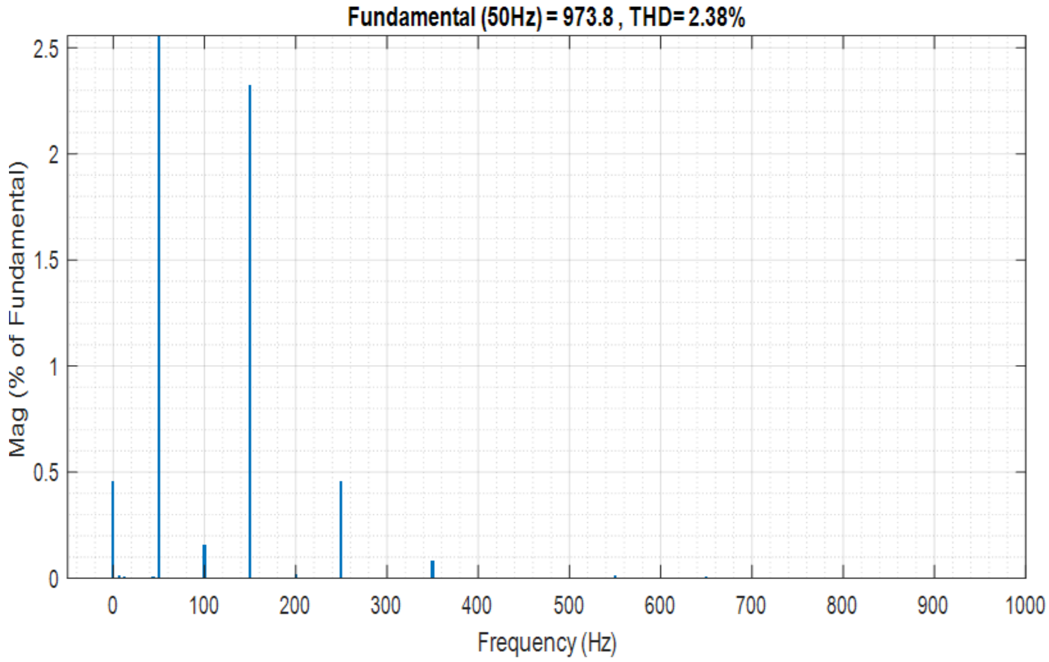

Fig:7 Harmonic analysis of output volage without DVR

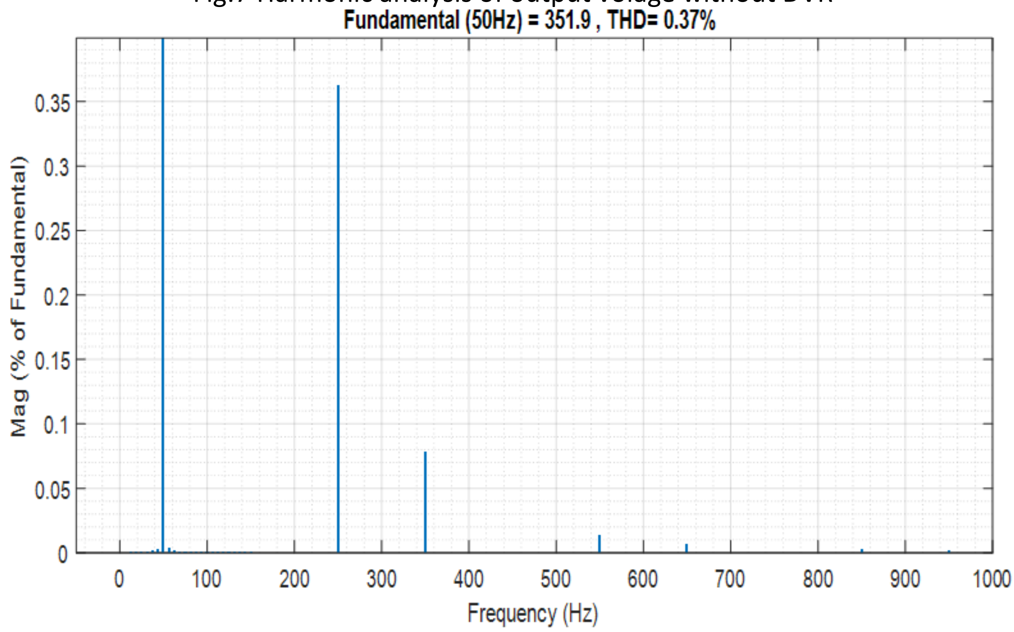

Fig:8 Harmonic analysis of output volage with DVR

V. CONCLUSION

This research proposes a transformer less DVR based on T-type multilevel inverter. The suggested DVR has fewer switches, is more efficient, and has a lower THD than the other topologies. The rotating reference frame of d-q governs the suggested DVR. A detailed explanation of the DVR model, switching method, and control approaches is provided. The suggested DVR regulates the load voltage to maintain the target load voltage by compensating for sag circumstances, and MATLAB/SIMULINK software is used to validate the results. Additionally, a hardware prototype will be used to verify the suggested DVR concept.

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