Performance Investigation of Transformerless DVR Based on T-type Multilevel Inverter With Reduced Switch Count

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Abstract: Voltage sag is typically the most severe power quality problem in power systems. Dynamic voltage restorers (DVR) are recognized to be a cost-effective solution for protection of sensitive loads from the power quality problems. Continuation of cost reduction, reliability and efficiency can be achieved by eliminating the injection transformer. This paper explains transformerless DVR based on a T-type multilevel inverter. The proposed DVR will not have an injection transformer which leads to less cost, less weight, and small size. The controller of the DVR is implemented by d-q transformation. The simulation results of dynamic voltage restorer are generated by MATLAB/SIMULINK software.

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

I. Introduction

Day to day there is an increase in the intensity of sensitive loads in power systems, so the power quality issues play a vital role in the present days. There are extreme power quality problems mentioned as voltage swell, voltage sag, harmonics, flicker etc. Voltage sag generally origin from the faults on load or supply side, maloperation, electrical motor startup, electrical heaters turning on, etc. So the DVR is mitigating the voltage sag through injecting the voltage. Power quality problems are affected due to the appearance of various non-linear loads such as diode bridge rectifiers, adjustable speed drives (ASD), switched mode power supplies (SMPS), laser printers etc.[1].As stated on IEEE 1159-1995 standard[2] voltage sag is the reduction in RMS voltage from 0.1pu to 0.9pu for a short time period of 0.5 cycles to few cycles. Generally, faults occurred in distribution systems having a reduction from 40% to 50% of the rated voltage until less than 2secs. Due to the above mentioned power quality problems on sensitive loads, minimization their effects are necessary. Furthermore, new power electronic devices are introduced and named as custom power devices. These devices are distribution static compensator (D-STATCOM), unified power quality conditioner (UPQC), dynamic voltage restorer (DVR). DVR is the perfect solution for restoring the load voltage at output terminals. When, the quality of source voltage is disturbed. DVR compensate the voltage sag with an appropriate injection of voltage in series with grid voltage, in order to maintain the rated load voltage with balance mode condition. Generally, DVR consists of inverter, injection transformer and energy storage device. The design of new inverter topology is to inject the voltage with proper control of the magnitude and phase angle, to maintain the constant load voltage and avoid disturbances at load voltage. The basic system model of DVR is shown in Fig.1

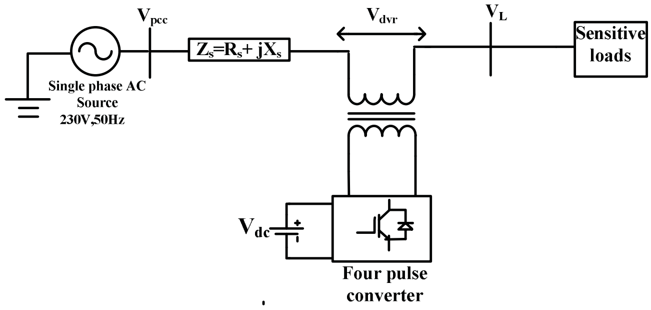

Fig.1 Basic system model of DVR

II. CONVENTIONAL DVR

The voltage source inverter is the most important device of the DVR. The DVR performance is effected by operation of inverter functioning. The number of switches, dc-link voltage sources, and filter design are to be considered while choosing the inverter topology.[3]
Power converters are classified into two categories.

a) Direct converters(AC-AC)
b) Indirect converters(AC-DC-AC)

a) Direct converters (AC-AC)

The direct converters play a vital role to compensate the voltage sag in distribution systems. Matrix converters based DVR do not have energy storage device to compensate the voltage sag or voltage swell. The main disadvantages are excessive of power semiconductor devices(18 in total) [4], fully conducting bidirectional current, bidirectional blocking voltage and controlling the circuit is complex, high switching losses, conflict resolution, high stresses of changing voltage and changing current on devices [5]

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b) Indirect converters(AC-DC-AC)

Indirect converters generally considered with H-bridge and without H-bridge inverter topologies. Two level voltage source inverters having high voltage semiconductor switches during turning on and turning off leading to large $dv/_{dt}$ and causes electromagnetic interference. Multilevel inverters (MLI) overcome this problem by having lower $dv/_{dt}$ per switching. Some of the popular topologies implemented among multilevel inverter topologies are [6 -7]

a) Diode-clamped
b) Flying capacitor
c) Cascaded

a) Diode-clamped MLI

The diode-clamped multilevel inverter consists of (n-1)*(n-2) clamped diodes, (n-1) dc-link capacitors, (2n-1) switching devices to produce sinusoidal voltage waveforms with multiple levels. Disadvantages of diode-clamped multilevel inverters are voltage unbalance in their dc capacitors and clamping diodes [3].

b) Flying capacitor MLI

Operating principle of diode clamped and flying capacitor multilevel inverter topologies are similar, but flying capacitor multilevel inverter is having energy storage capacitors replacing the clamping diodes. N-level flying capacitor multilevel inverters used storage capacitors and (n-1) dc link capacitors are required per phase. The disadvantage of flying capacitor multilevel inverter is needs large dc capacitors [8].

c) Cascaded H-bridge MLI

Cascaded H-bridge multilevel inverter is one of the most popular converter topologies used in high-power medium voltage applications [9].The H-bridge cells connected in cascaded mode. Therefore harmonic content in the output voltage is less. The schematic diagram of cascaded H-bridge inverter is depicted in Fig.2

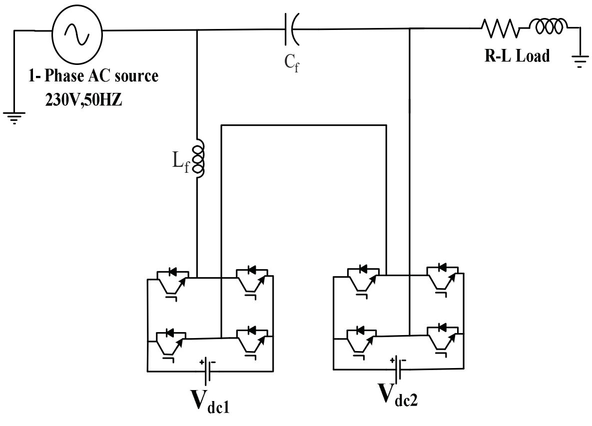


Fig.2 Basic system model of CHB DVR

N-levels of voltages in a cascaded H-bridge converter can be calculated from (1).

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

Where 'H' is a number of H-bridge cells of per phase. The voltage level 'm' is always an odd number of voltage levels. Cascaded H-bridge multilevel inverter dissimilar with other multilevel inverter topologies such as diode-clamped multilevel inverters or flying capacitor multilevel inverters. The total number of switches (IGBTS) for three phase CHB converter can be calculated from (2)

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

Where N_{sw} is the number of switches for CHB multilevel inverter, the CHB converter requires a small filter to keep the THD in minimum range, a reduction in size of the output filter leads to fewer losses. However, the converter does not require a series injection transformer to connect the medium voltage network. The main drawback of CHB converter is the excessive switches and isolated dc supplies are required. In order to overcome the above drawbacks, a new T-type multilevel inverter is proposed for the DVR system.

III. PROPOSED T-TYPE MLI DVR

T-type is one of the reduced switch count multilevel inverter topologies. It consists of one bi-directional and four unidirectional switches which are having bi-directional blocking, bi-directional conducting and unidirectional-blocking and bi-directional conducting [10]. Midpoint dc source is given to H-bridge through the bidirectional switch. As the voltage level increases the requirement of dc sources and bidirectional switches are increased but the H-bridge remains unchanged. The system model of T-type multilevel inverter shown in Fig.3.The T-type multilevel inverter consists of combinations of unidirectional and bi-directional switches, for each phase (n-3) + 4 switches required. Here (n-3) denotes the additional unidirectional switch, four denotes the number of switches in H-bridge

Switching operation of a T-type inverter:

To get five levels per phase the voltage levels -2V,-V, 0, V and 2V are needed and midpoint dc source is required per phase. For switches S_{1a}-S_{4a} and B_{sa}–S_{4a} obtains 2V, V voltage levels respectively. Similarly, switches B_{sa} –S_{2a} and S_{3a}-S_{2a} obtain -V, -2V voltage levels respectively in phase 'a'. The switching operation of the T-type multilevel inverter summarizes in Table I.

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
($S_1$and S_2) or(S_3 and S_4)	0
B_{sa} and S_{2a}	-V
S_{3a} and S_{2a}	-2V

B_{sa} =Bi-directional Switch

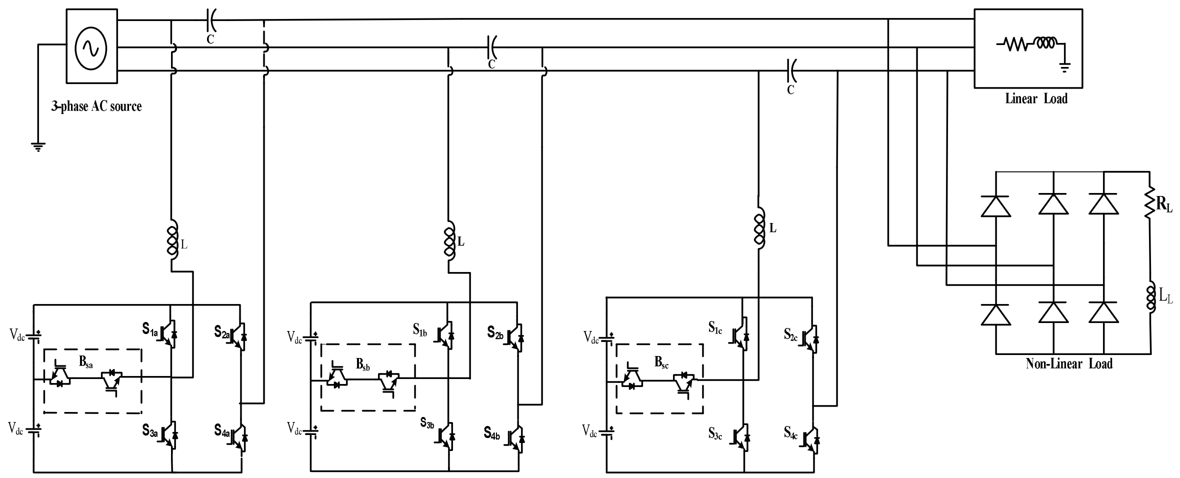


Fig.3 Proposed T-type Multilevel inverter based DVR

Table II. Comparison of different types of inverter Topologies

Sl. No	Types of inverter Topologies	Advantages	Disadvantages
1	Half-bridge inverter[11]	Less cost and less switch count	The output voltage is high harmonic content
2	Full-bridge Inverter[12]	Independent single phase connection available	High harmonic content
3	Three-phase Inverter[13]	Less cost and simple control	Presence of differential and common mode EMI
4	Three phases four wire Inverter[14]	Less DC-link ripples, unbalanced compensation capability	High switching frequency, two extra switches
5	Multilevel inverter[15], [16]	Stress on devices is less and less switching frequency	Increase in number of switching devices, control the circuit is complex after 5 level
6	Cascaded multilevel inverter[17],[18]	High voltage and medium power applications	Increase in number of switching devices, requires isolated dc supplies and complex control structure
7	T-type Multilevel Inverter	reduced number of switching devices, isolated dc supplies are not required	Requires high power rating switches

Some advantages of T-type multilevel inverter

- High power capability,
- Less switching losses
- Switching redundancy is reduced,
- Less weight and less size compared to conventional Topology,
- High efficiency and fast response,
- Input and output currents are sinusoidal with small disturbances.
- The T-type topology configuration is a reduction with 37.5% switch count compared with other topologies[10],
- The T-type reduces the number of diodes by 60% when compared with diode-clamped multilevel inverter[19],

T-type multilevel inverter requires a reduced number of switching devices and isolated dc supplies are not required. Comparison of commonly inverter topologies is summarized in Table II.

IV. DVR CONTROLLER

Generally, two controller methods applied to DVRs include open loop and closed loop controllers [20]. Open loop control is faster than closed-loop control for the required injecting voltage. The closed-loop control methods are better in reducing the steady-state error but are not fast in the correcting the voltage sag. The d-q controller method is one of the best open loop (feed-forward) control method.

Control using dq rotating frame:

The dq rotating frame provides appropriate transient response and reduces the overvoltage and reducing the voltage drop across the filter. Then the steady-state error of the fundamental component is reduced when the DVR is synchronized with the supply voltage through the phase locked loop. Phase locked loop is used to minimize the harmonics, unsymmetrical component output voltages even during sudden changes in the supply voltage. As shown in Fig.4. Actually supply voltage is transferred from abc to d-q rotating frame. Dq transformation is used to detecting the voltage disturbance and generate the reference voltage for the DVR, the difference in the measured voltage $V_{pcc(d-q)}$ and the reference voltage $V_{ref(d-q)}$ are used to determine the referenced DVR injected voltage.

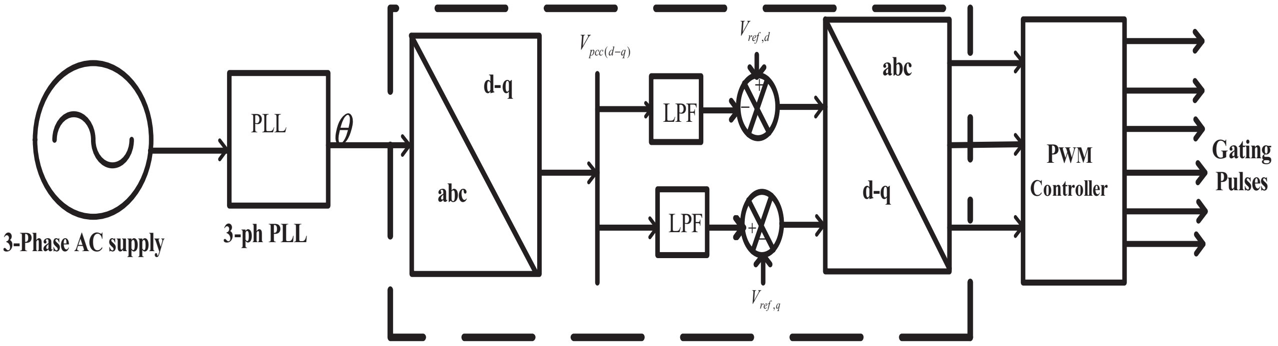


Fig.4 DVR controller with dq rotating frame

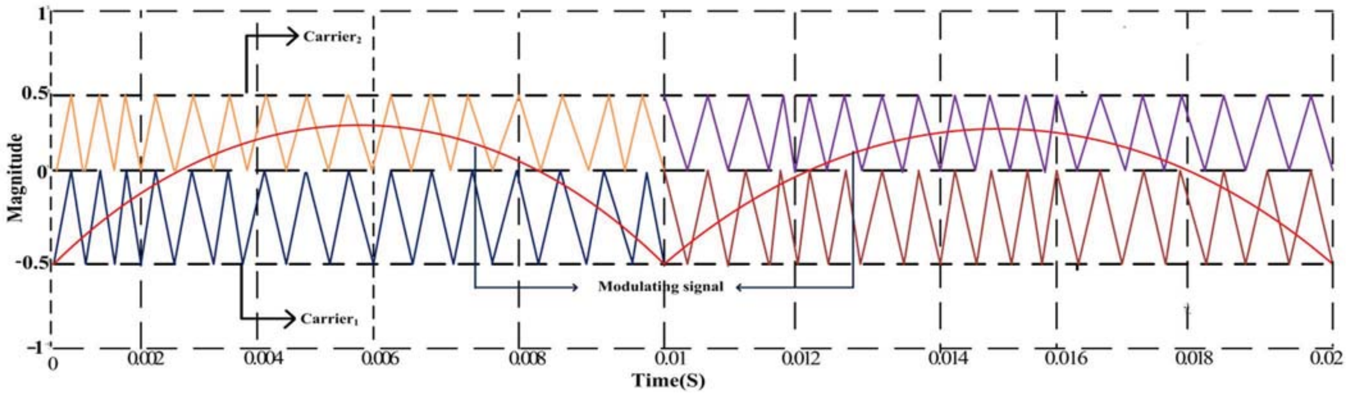


Fig.5 Reduced carrier PWM technique

Reduced carrier PWM Technique:

Reduced carrier modulation technique involves a single modulation signal and (n-1)/2 carrier signals are required to obtain 'n' levels in phase voltages. Modulation signal and a carrier signal arrangement for T-type multilevel inverter topology is show in Fig.5. If unipolar modulation signal is less than the $carrier_1$ peak, then in phase voltages 0-V is obtained. During V-2V voltages unipolar modulation signal is greater than the $carrier_1$. The polarity of the voltage bands is decided by the unipolar modulation signal such that -2V,-V, 0, V, 2V voltage levels obtained in phase voltages

V. SIMULATION RESULTS

Fig.6 shows switching pulses generated by reduced carrier PWM technique method for T-type multilevel inverter. At 0.2s sag is created then the difference in the switching pattern can be observed. Switching pulses of S_1 and S_2 are gives to the $S_1$and S_2 switches and switching pulses of S_3 and S_4 are operating with the complementary manner of $S_1$and S_2 switches respectively. Switching pulses of B_{sa} gives to the bidirectional switch. The bidirectional switch conducting for positive 'V' voltage and '-V' voltage with Bs and S_4, Bs and S_2 switches respectively.

T-type multilevel inverter based DVR and its control technique are verified by MATLAB/SIMULINK software. The parameters of simulation systems are as shown in Table III. The switching frequency of the T-type multilevel inverter is 2kHz and it requires low pass filter to reduce higher order components, with these values of DVR will compensate the 40% voltage sag. In Fig.7 shows, until 0.2s the grid voltage is normal position and therefore the injecting voltage is zero. From 0.2s to 0.5s 40% voltage sag is reduced in source voltage. During this time interval, the DVR compensate the necessary voltage and injecting to source voltage to maintain the desired load voltage to the nominal value. The LC filter is used to improve the output of T-type multilevel inverter voltage. The secondary case study is about total harmonic distortion (THD). The total harmonic distortion of the load voltage and load current of T-type multilevel inverter topology is better than the CHB invertertopology.

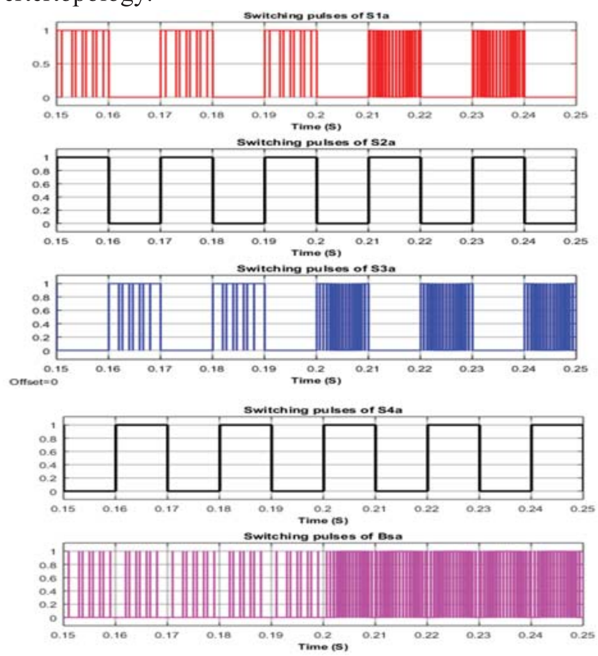


Fig.6 Switching pulses of reduced carrier PWM technique.

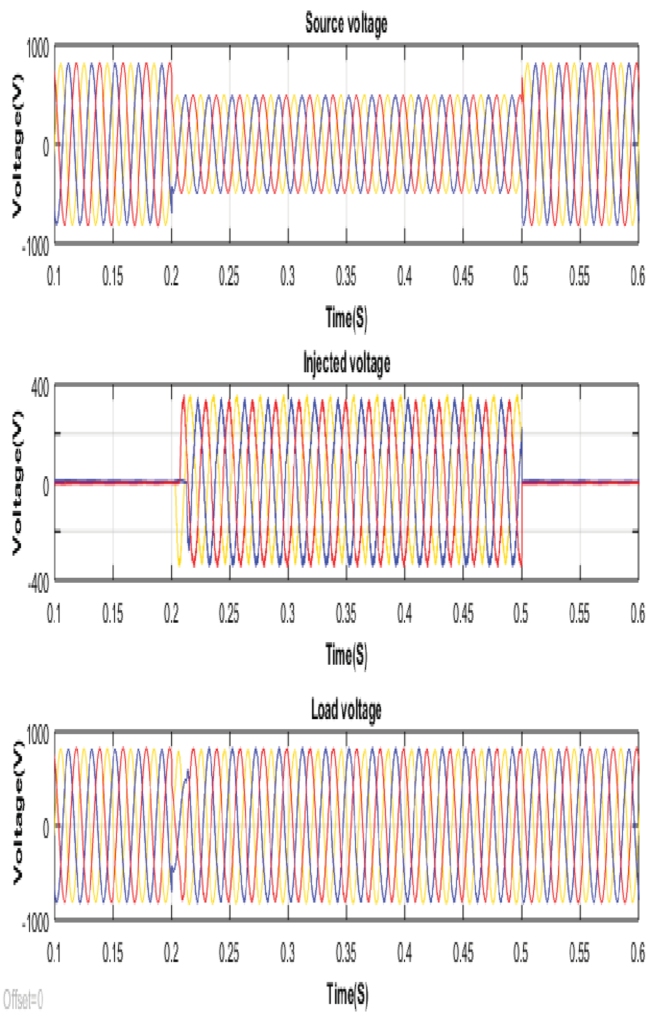


Fig.7 Simulation results of the proposed DVR a) Source voltage b) injected voltage c) Load voltage

Table III. T-type Inverter parameters for simulation studies

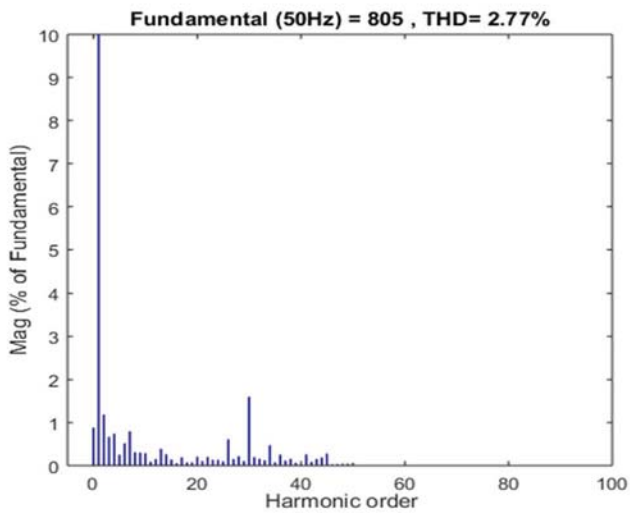
Parameter	***Values***
Source voltage (V_{rms} Line-to- Line)	1kV
Resistance/phase	0.005ohm
Inductance/phase	0.1mH
Filter Resistance(R_f)	1.5ohm
Filter Inductance(L_f)	1.5mH
Filter Capacitance(C_f)	1100µF
Switching Frequency	2KHz

VI. THD ANALYSIS

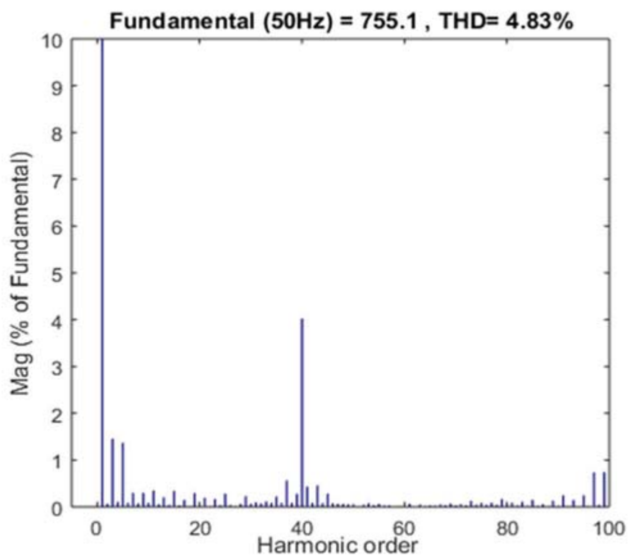
Here we have taken FFT analysis of load voltage and load current for the proposed topology and CHB five level inverter topology at 50Hz frequency along with 0.3 starting time. The maximum number of cycles is 10. Fig.8 and Fig.9 show the harmonic spectrum waveform of the load voltage and load current for the proposed DVR and CHB five level inverter based DVR. The THD analysis of both topology values are shown in Table IV.

Table IV. 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%

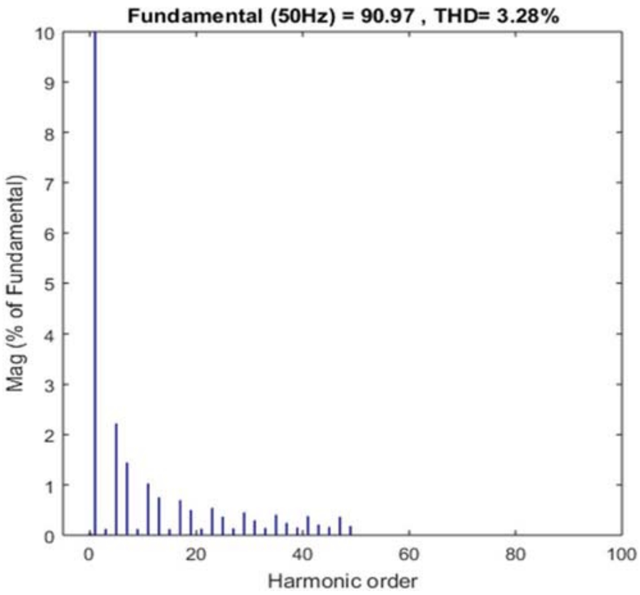


(a)

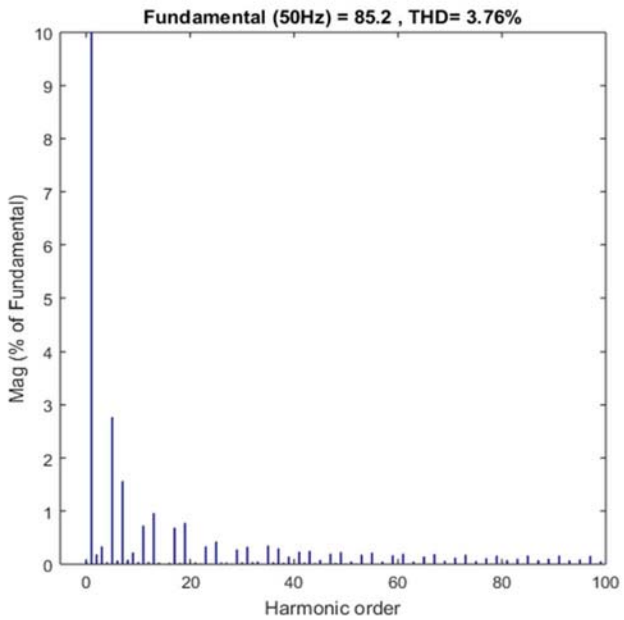


(b)

Fig:8. a) Harmonic spectrum waveform of the load voltage for proposed DVR b) Harmonic spectrum waveform of the load voltage for CHB five level inverter based DVR



(a)



(b)

Fig:9. a) Harmonic spectrum waveform of the load current for proposed DVR b) Harmonic spectrum waveform of the load current for CHB five level inverter based DVR.

VII. CONCLUSION

Transformerless DVR based on T-type multilevel inverter is proposed in this paper. Proposed DVR has less number of switches, high efficiency and THD is better than the other topologies. The proposed DVR is controlled by d-q rotating reference frame. The DVR model, switching strategy and control techniques are explained in detail. Compensation of the load voltage under sag conditions is done for the regulation of the load voltage to maintain the desired load voltage by proposed DVR and validated through MATLAB/SIMULINK Software. Furthermore, the proposed DVR model will be verified with hardware prototype.

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