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Performance Analysis of PWM based Voltage Source Inverter

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***Abstract*— In industrial markets, voltage source inverters have proven to be more efficient, has greater reliability and higher dynamic response. Pulse Width Modulation (PWM) techniques are increasingly applied in industrial applications for variable speed drives. The PWM technique results in reduced Total Harmonic Reduction (THD) improving the spectral quality of the output. This paper investigates on unipolar and bipolar PWM method for a single-phase voltage source inverter. The paper also discusses on the performance of the unipolar PWM inverter. Simulation studies of the above techniques and circuit configuration are carried out in PSIM. The parameters such as Weighted Total Harmonic Distortion(WTHD), Distortion factor(DF), Harmonic Spread Factor(HSF) and switching losses are computed. A prototype of the single-phase PWM inverter is developed and the results are verified for normal and Voltage/frequency(V/f) method at various switching frequencies.**

***Index Terms*— DF, HSF, switching losses, WTHD.**

I. Introduction

Voltage Source Inverters are used to transfer real power from a DC power source to an AC load. Usually, the DC source voltage is nearly constant and the amplitude of AC output voltage is controlled by adapting a suitable control strategy. Areas where VSI's are used include adjustable speed drives for AC motors, Electronic frequency changer circuits etc. VSI's are also becoming widely adopted for other applications such as grid connection for renewable energy sources, where a variable voltage DC power source supplies power to an AC system with a nearly constant voltage. There are three main types of VSI's namely Single Phase Half Bridge Inverter, single phase full bridge inverter and three phase voltage source inverter.

The harmonics generated by the nonlinear loads can have detrimental effects on the power systems. These harmonics cause the current to increase to higher values beyond the permissible limits, which in turn leads to temperature rise in conductors. They also increase the losses, thereby reducing the efficiency of the power converter. In order to minimize the Total Harmonic Distortion, unipolar and bipolar modulation are discussed [1]. In this paper, the proposed modulation techniques are studied, simulated and applied to a single-phase voltage source inverter. This paper also presents the analysis of the single phase inverter on its various performance parameters.

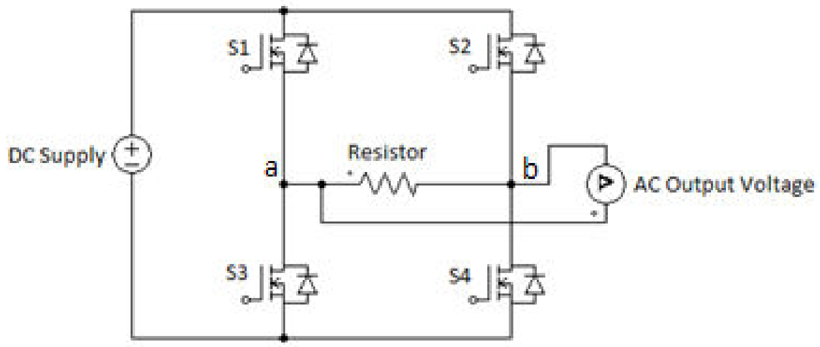

Fig. 1. Full Bridge Inverter.

II. FULL BRIDGE INVERTER

The full bridge inverter consists of four switches, two in each leg as shown in Fig 1. The basic operation of the inverter is as follows: When S1 and S2 are turned on simultaneously, the input voltage V_{dc} appears across the load and current flows from the point a to b. And when the switches S3 and S4 are turned on simultaneously the voltage across the load is reversed and the current through the load flows from b to a [2].

III. MODULATION STRATEGIES FOR VOLTAGE SOURCE INVERTERS

The main objective behind adopting control strategies is to generate good quality controllable AC voltage and to minimize the harmonic distortion, switching losses and the filtering requirements. Various modulation techniques for VSI are reported in the literature. The modulation strategy discussed in this paper is Pulse Width Modulation (PWM). The reasons for adopting this technique are allowing flexible control over the AC power, reduced power loss, easy generation of gating signals [3]. Pulse width modulation is the process of modifying the width of the pulses proportional to the control voltage. Greater the control voltage, wider the resulting pulses become. By modulating the relative time intervals corresponding to conduction and non-conduction periods, it is possible to spread the voltage during the period in such a way that the conduction time of the switching device becomes practically proportional to the instantaneous value of the fundamental.

In Sinusoidal Pulse Width Modulation (SPWM), two signals are compared: a reference signal, usually a sine wave and a high frequency carrier wave, which is mostly triangular [4]. Gating pattern is produced by comparing the two signals and the width of each pulse is varied in proportion to the amplitude of the sine wave and this is referred as amplitude modulation index m_a. The inverter output frequency depends on the frequency of reference signal and the modulation index and RMS value of the output voltage is controlled by the peak value of reference waveform. There are two types of switching for SPWM namely, bipolar and unipolar switching [5].

A. Bipolar Modulation

The sampling of SPWM bipolar switching is that the reference sinusoidal waveform having magnitude V_{ref} is compared with triangular carrier signal having amplitude $V_{carrier}$. The upper and the lower switches in the same inverter leg work in a complimentary manner which means the gating signals are generated for only one of the switches in each leg and the compliment of the same is given to the other switch belonging to the same leg. The output voltage will swing between $+V_{dc}$ and $-V_{dc}$.

The schematic for the simulation of bipolar modulation is shown in Fig 2. The pulse pattern for the various switches under this modulation for the full bridge inverter is shown in Fig 3.

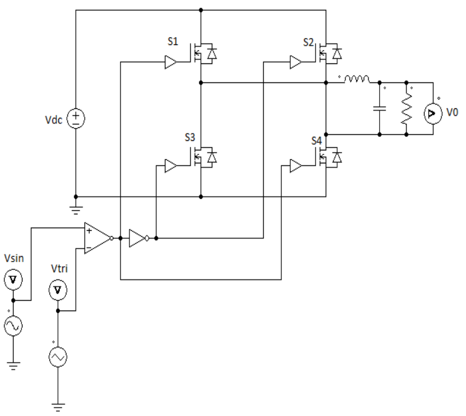

Fig. 2. Schematic for bipolar modulation.

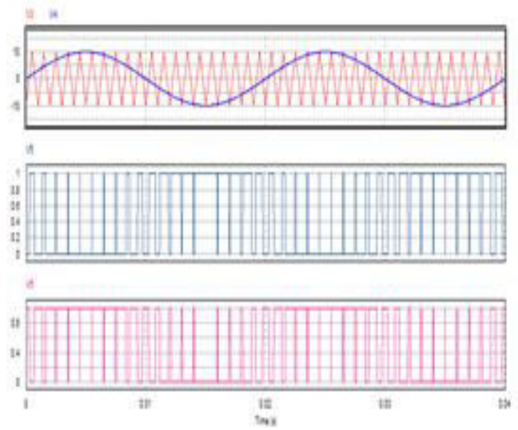

Fig. 3. Carrier, Reference and Gating -pattern for bipolar modulation.

B. Unipolar modulation

The unipolar modulation normally requires two sinusoidal modulating waves V_{ref1} and V_{ref2} which are of same magnitude and frequency but 180 degree out of phase [6].

The two modulating wave are compared through a common triangular carrier wave $V_{carrier}$ generating two gating signals V_{g1} and V_{g3} for the upper two switches S_1 and S_3. It can be observed that the upper two devices do not switch simultaneously, which is well-known from the bipolar PWM. The inverter output voltage switches either between zero and $+V_{dc}$ during positive half cycle or between zero and $-V_{dc}$. during negative half cycle. This is referred as unipolar modulation. The schematic for simulation of unipolar modulation is shown in Fig 4. The Carrier wave, Reference wave and gating pattern for a full bridge inverter under this scheme is shown in Fig 5. The reference wave comprises two sinusoidal waves phase shifted by 180 ° from each other. The carrier wave is a high frequency triangular waveform. The gating pattern for S1 and S3 are shown. The gating pattern for S2 is the complement of S1 and that of S4 is the complement of S3.

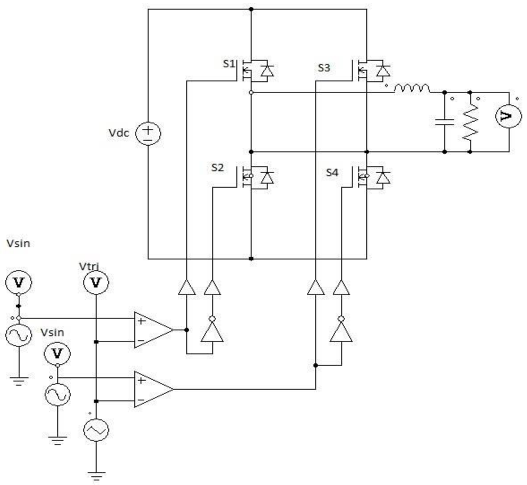

Fig. 4. Schematic for Unipolar Modulation.

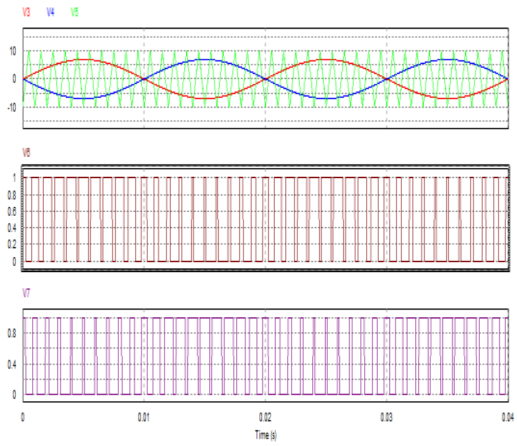

Fig. 5. Carrier, Reference and Gating pattern for unipolar modulation.

IV. Experimental Results

The gating pattern of the switching devices and the output waveform has been obtained from the developed prototype of the single phase PWM inverter. The results have been verified experimentally.

The experimental setup is given by Fig. 6. The output voltage observed in DSO for R load is shown in Fig. 7.

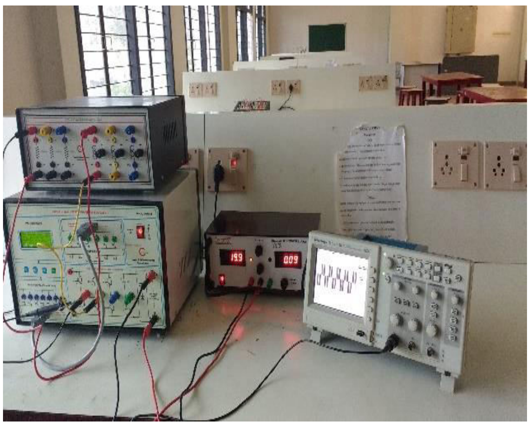

Fig. 6. Waveform in DSO.

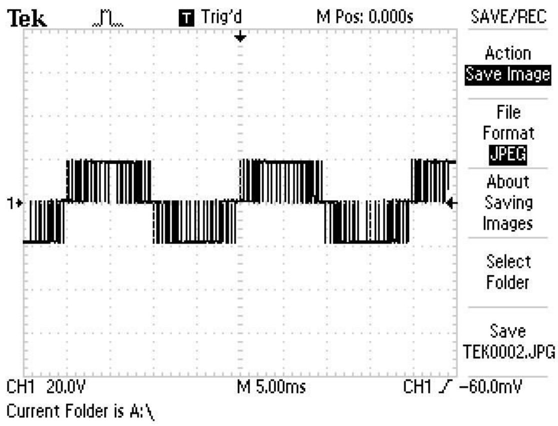

Fig. 7. Output voltage waveform of R-Load.

The pattern generated by comparing the carrier wave with the sine wave which triggers the switch S1 is shown in Fig.8. Similarly, comparing the 180 degree phase shifted modulating wave and the carrier wave generates the gating pattern for the power switch S3, which is shown in Fig.9.

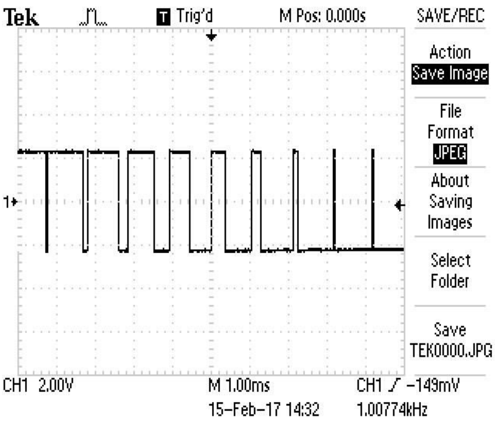

Fig. 8. Gating pattern of Switch S1

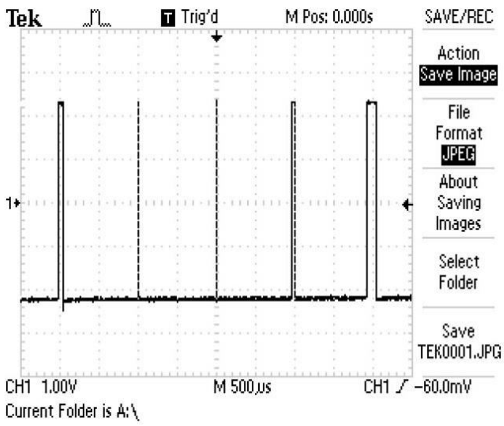

Fig. 9. Gating pattern of Switch S3.

The output voltage of single phase PWM inverter for various switching frequencies was measured for normal and V/f method and the results are plotted below

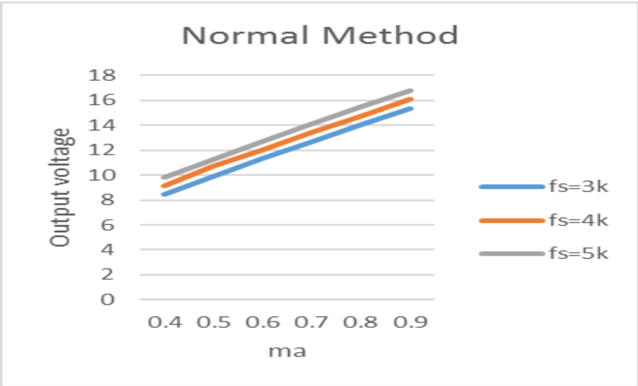

Fig. 10. Graph of output voltage vs m_a

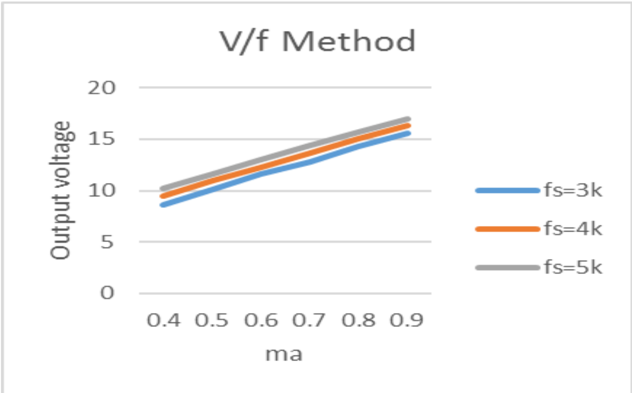

Fig. 11. Graph of output voltage vs in normal mode m_a in V/f mode

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V. Performance Analysis

The quality of the inverter output is normally evaluated in terms of the performance parameters discussed below [7].

A. Harmonic Spread Factor

An important parameter to indicate the generation of noise in the motor is the harmonic spread factor. It can be calculated for evaluating the quality of voltage spectrum of inverters.

$$HSF = \sqrt{\frac{\sum_{j=2}^{N}(H_j - H_i)^2}{N}} \quad (1)$$

Where,

H_n - Value of n^{th} harmonic
H_0 -Average value of all N harmonics

B. Distortion Factor

When Distortion factor indicates the amount of harmonic distortion that remains in a particular waveform even after being subjected to second order attenuation.

$$DF = \frac{1}{V_1}\left[\sum_{n=2,3,..}^{\infty}\left(\frac{V_n}{n^2}\right)^2\right]^{\frac{1}{2}} \quad (2)$$

Where,

V_n – Voltage component of n^{th} harmonic.

C. Weighted Total Harmonic Distortion

This index gives a better measure of the harmonic pollution in the output voltage using the order of each harmonic component as its weight factor [8].

$$WTHD = \frac{\sqrt{\sum_{n=2}^{\infty}\left(\frac{V_n}{n}\right)^2}}{V_1} \quad (3)$$

Where,

V_n – Voltage component of n^{th} harmonic
V_1 – Voltage of the fundamental component

D. Switching Losses

The efficiency of voltage source inverters depends mainly on power losses that occur in semi-conductor elements. The switching losses are a function of the supply voltage, load current, operating frequency and on the dynamic parameters of the switching elements.

The formula for switching loss for one switch is given as:

$$P_{sw} = \frac{1}{2} \times V \times I \times (T_{on} + T_{off}) \times f_{sw} \quad (4)$$

Where,

V – Voltage across the switch
I – Current through the switch
T_{on} – Turn on time
T_{off} – Turn off time
f_{sw} – Switching frequency

VI. SIMULATION RESULTS

The simulation parameters considered for simulating the inverter are tabulate below.

The values of the parameters chosen for the simulation of the above mentioned control strategies are listed in Table .1.

TABLE I: SIMULATION PARAMETERS

Parameter	Value
Input DC voltage	50 V
Reference Frequency	50 Hz
Switching Frequency	1050 Hz
Load Resistor	10Ω
Load Inductor	1mH
Filter Capacitor	150µF
Filter Inductor	50mH

A. *Bipolar Modulation*

1) R Load with and without Filter: Fig 12. Shows the output voltage waveform of full bridge inverter with bipolar switching. In this case, a resistive load is connected to the inverter. From the above waveform, it can be observed that the output voltage varies from -V_{dc} (50, in this case) to +V_{dc} and the obtained output is in the form of pulses which indicates the harmonics present. Filtered output voltage waveform of full bridge inverter with bipolar switching is shown in Fig 13. A resistive load is connected to the inverter. A low pass filter consisting of inductor and capacitor is connected to the inverter which reduces the ripple content of the full bridge inverter.

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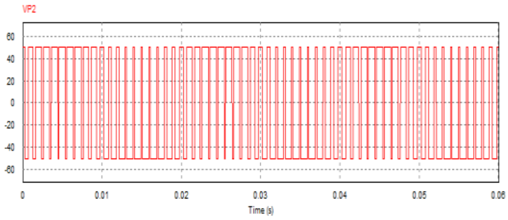


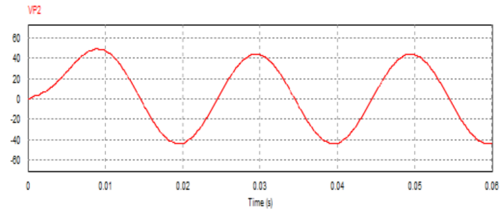
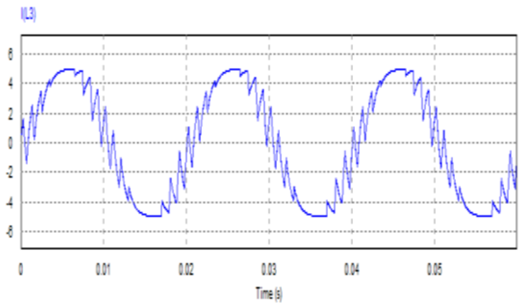


Fig. 12. Output voltage of R load without filter Fig. 13. Output voltage of R load with filter

2) RL Load with and without Filter: The simulation result of the RL load connected full bridge inverter with bipolar switching is shown in Fig 14. The full bridge inverter has been simulated without any filter in this case. The waveform depicts the output current of the RL load. It is almost sinusoidal in shape consisting of ripples. The ripples in the output current can be eliminated by including a low pass LC filter at the output. The filtered output current waveform with RL load is shown in Fig 15. It can be inferred from the waveform that, with filter at its output, the full bridge inverter produces a sinusoidal output reducing the ripple and harmonics to a greater extent.



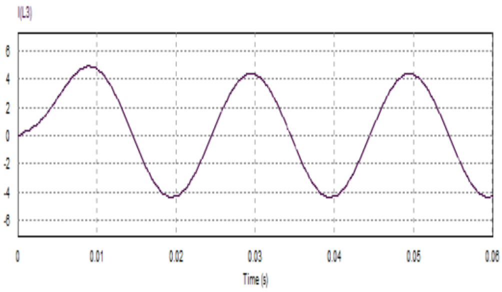
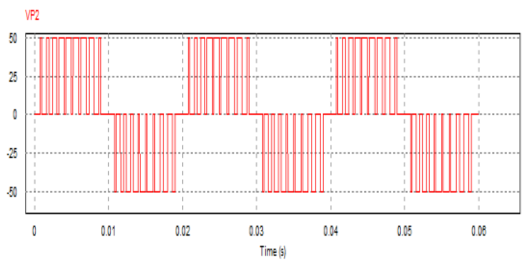


Fig. 14. Output current of RL load without filter Fig. 15. Output current of RL load with filter.

B. *Unipolar Modulation*

1) R Load with and without Filter: The full bridge inverter with unipolar modulation has been simulated with R load and its output voltage waveform is shown in Fig 16. From the above waveform, it can be observed that the voltage switches from $-V_{dc}$ to zero and from zero to $+V_{dc}$. The output voltage waveform is in the form of pulses. The filtered output of the unipolar full bridge inverter with R load is shown in Fig 17. The low pass filter connected at the output produces a sinusoidal waveform decreasing the harmonics which existed when no filter was incorporated.



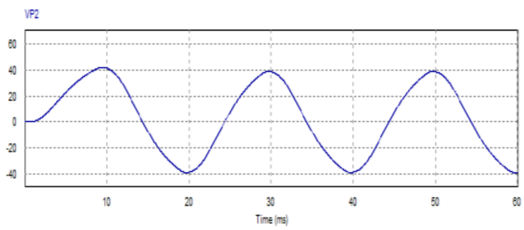


Fig. 16. Output Voltage of R Load without filter. Fig. 17. Output Voltage of R load with filter.

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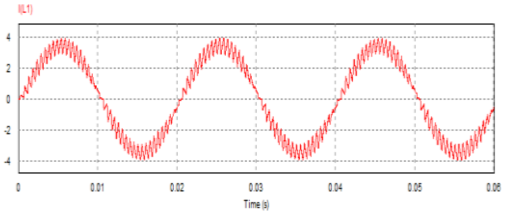
2) RL Load with and without Filter: The full bridge inverter with unipolar switching and RL load has been simulated. The Fig 18 shows the output current waveform from this scheme. The current waveform of RL load connected inverter is nearly sinusoidal with harmonics at its peak. The harmonics can be reduced by incorporating a filter at its output. The filtered output current waveform of the RL load connected unipolar inverter is shown in Fig 19. With the LC filter at the output of the inverter, the ripples are reduced and the output is purely sinusoidal.



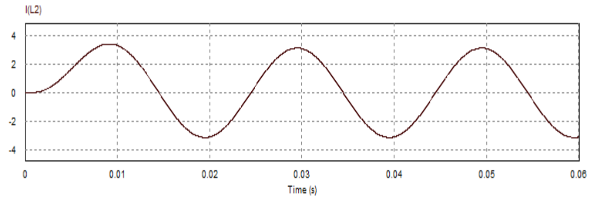


Fig. 18. Output Current of RL Load without filter. Fig. 19. Output current of RL Load with filter.

VII. Tabulation

A. Bipolar Modulation

The values of voltage THD for different modulation index for R load with and without filter (expressed as percentage) are tabulated below:

TABLE II: Voltage THD for R Load

Modulation Index	Voltage THD Without Filter (%)	Voltage THD With Filter (%)
0.4	34.302	1.557
0.5	26.458	1.18
0.6	21.262	0.927
0.7	17.677	0.741
0.8	14.671	0.601
0.9	12.067	0.497
1.0	10.033	0.421

The values of current THD for different modulation index for RL load with and without filter (expressed as percentage) are tabulated below:

TABLE III: Current THD for RL Load

Modulation Index	Current THD With Filter (%)
0.4	1.39
0.5	1.057
0.6	0.828
0.7	0.662
0.8	0.539
0.9	0.446
1.0	0.38

From the Table 2 and Table 3, it can be inferred that as the modulation index increases, the THD decreases. It is evident that too much harmonics exist at the output for a fundamental frequency of 50Hz. The voltage and current THD for R and RL loads respectively ranges between 34% and 10% as the modulation index is varied from 0.4 to 1.0. Such high values of THD can be reduced by connecting a low pass LC filter at its output. With filter the voltage THD for R Load has been considerable reduced from a value of 34% to 1.5% and from 34% to 1.39% in case of current THD for RL Loads.

B. Unipolar Modulation

The values of THD for different modulation index (expressed as percentage),with and without filter are plotted below:

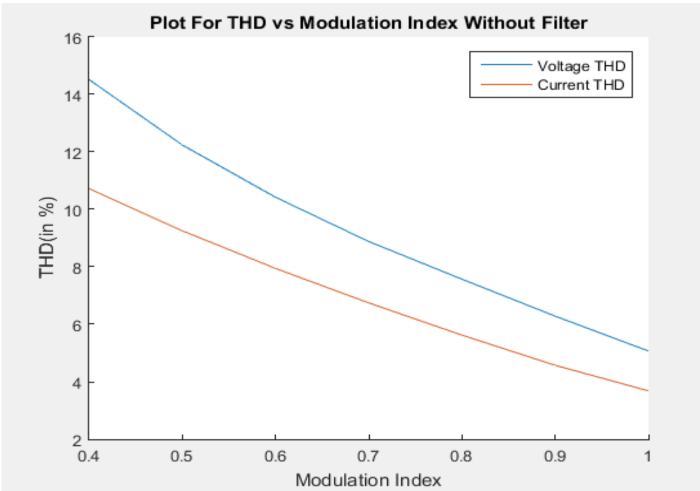


Fig. 20. Graph of THD Vs modulation index

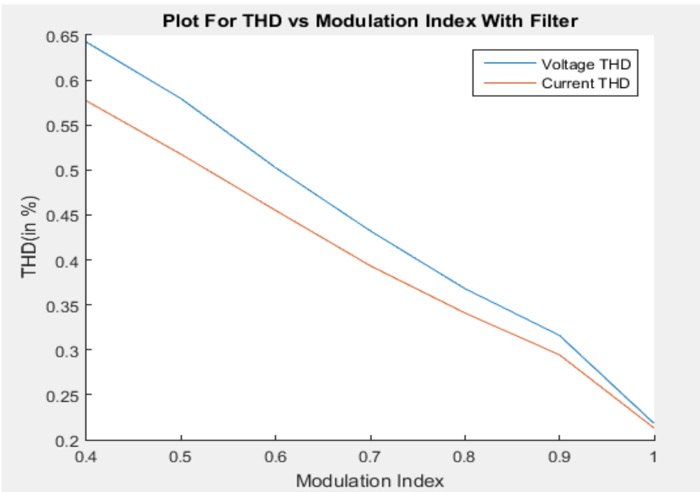


Fig. 21. Graph of THD Vs modulation index without filter
with filter.

With unipolar modulated full bridge inverter, the maximum of voltage THD for R load is 14% as seen from Fig 20 and the maximum current THD for RL load is nearly 10%. These high values need to be mitigated for better performance of the inverters. A LC filter is connected at its output which reduces the ripple and harmonic content. Having including the filter, the voltage THD has considerably reduced from a maximum of 14% to 0.64% and the current THD dropping to 0.5% from its 10% as shown in Fig 21.

The voltage THD and current THD for a modulation index of 0.8 under the bipolar and unipolar modulations have been tabulated in Table 4.

TABLE IV: THD VALUES FOR MODULATION INDEX OF 0.8

Parameters	Bipolar	Unipolar
Voltage THD	0.601	0.3681
Current THD	0.539	0.3410

From the above tabulation, it is clear that among the two topologies considered for the analysis, unipolar modulation produces a lesser value of THD. Therefore, it follows that the unipolar modulation has lesser harmonic distortion compared to the bipolar modulation. The parameters discussed above where calculated by simulating the full bridge inverter for different modulation index and the results obtained are tabulated below.

TABLE V: CALCULATED VALUES OF DIFFERENT PARAMETERS

m_a	HSF	DF	WTHD
0.4	0.0406	0.0008	0.0037
0.5	0.0702	0.0007	0.0038
0.6	0.0485	0.0002	0.0018
0.7	0.0427	0.0011	0.0035
0.8	0.042	0.0007	0.0025
0.9	0.046	0.0009	0.0028
1.0	0.026	0.0002	0.0010

The graph of switching losses for various frequencies are plotted below.

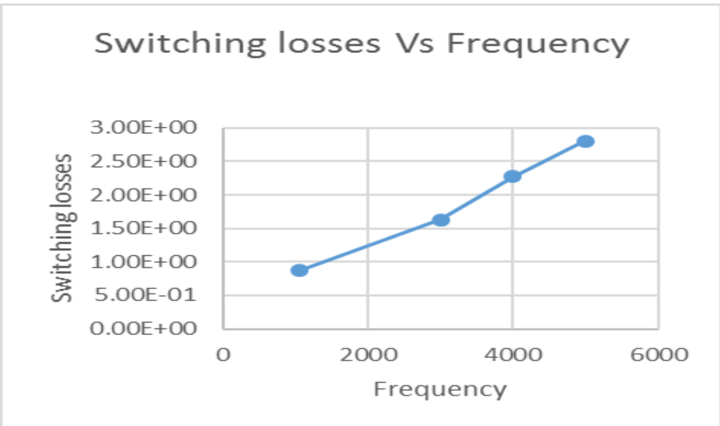


Fig. 22. Graph of switching losses vs frequency.

Thus, it can be inferred that as the switching frequency increases, the switching losses increases proportionately.

VIII. Conclusion

The various switching techniques in full bridge inverter has been simulated using PSIM software. From the results of simulation, it has been found that the Unipolar Modulation has lesser total harmonic distortion and better power quality. With unipolar technique, reduced voltage THD of about 0.368% is obtained compared to bipolar. The various performance parameters of the VSI such as distortion factor, harmonic spread factor, weighted total harmonic distortion and switching losses have been analysed. The output voltage of the single phase inverter operating in normal mode and v/f mode was studied. The analysis carried out in the paper can be extended by using induction motor as a load for the PWM inverter. Torque pulsations due to the distortions in the inverter output can be reduced, which is one of the major considerations in the design of electric vehicle.

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