

Comparative analysis of THD for square-wave inverter at different conduction modes

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ABSTRACT

This paper proposes conduction schemes for the most common six-switch voltage sources inverter. Also, a comparative study of the output THD for different conduction modes of switches for a three-phase square wave inverter is done, as the harmonic content of any electrical system is important to analyze its performance. The harmonic distortion of the load voltage and load current is taken as the main constraint to evaluate the performance of the three-phase inverter. So, control strategies for various loads are executed for different modulation schemes of inverter switches using MATLAB/Simulink software. Obtained results show that 150° conduction gives the least THD for output current, and 170° conduction gives the least THD for output voltage for three-phase inverters. Also, harmonic contents are reduced using a passive LC filter at the output of the inverter.

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1. INTRODUCTION

In the present era, power electronics play a huge role in industrial and research applications. These applications involve conversion and control of output voltage and frequency [1]. As a result, power electronic devices are used to convert electric power and establish a connection between them. Three-phase inverters are widely used in many applications, including variable frequency drives. They produce variable output (voltage and current) using the appropriate control modes [2]–[10].

A square-wave inverter is a voltage source inverter (VSI) in which the output ac voltage waveform is similar to a square wave as analyzed for different applications, including photovoltaic applications [11]–[15]. Traditionally, a three-phase inverter employs a 120° or 180° conduction period for each switch (power MOSFETs, IGBTs, GTOs, and so on). It has been observed that when the conduction period of switches increases, the magnitude of output voltage increases for any type of load like resistive load, resistive plus inductive load, and motor load, but the harmonic contents of voltage and current are more than the specified limit. The advantage of increased output magnitude helps only if the harmonics contents are less because power electronic switches are non-linear devices that generate a significant amount of harmonics [1], [4].

Total harmonic distortion (THD) is one of the important parameters for describing the characteristics of any electrical circuit because it has a severe effect on the same. Power electronic switches generate harmonics that have a significant and negative impact on circuit output. So, the least THD is desired for a circuit's reliable operation. In previous works of literature, the analysis has been done for different types of low-power inverters to analyze the harmonic content and to find the novel conduction modes with lower

THD [16]–[20]. Performance analysis for a three-phase square-wave inverter has been carried out for different conduction modes to suggest a better conduction mode for applications like induction motor drives, photovoltaic systems, and household applications [21]–[26].

This paper uses MATLAB-Simulink software to analyze and compare output voltage THD and current THD for various loads at different conduction angles of the inverter. Also, harmonic contents are reduced using a passive LC filter at the output of the inverter. The paper is organized in the following sections: proposed method is introduced in section 2. Section 3 presents the analysis of a three-phase square wave inverter at different conduction modes. Results obtained from the simulation have discussed in section 4. Finally, section 5 concludes the findings.

2. PROPOSED APPROACH

The power circuit diagram of a six-switch three-phase inverter with R-L load for the proposed approach is shown in Figure 1. This approach proposes a different conduction period for switches between 120° and 180° to compare the harmonic contents at the output for a three-phase six-switch VSI for R-L load. Here the THD of output voltage and current is studied using the proposed scheme because THD is a good index to quantify the level of harmonics in voltage and current. A comparison of the R-L load with the dynamic load has been performed to find a better conduction mode for the lower level of harmonics in the output [22]–[25].

A comparative study of THD of output using different modulation schemes for three-phase VSI is being presented to get better results than the traditional modulation scheme. The main aim of this approach is to find the conduction period of switches that will give fewer harmonic contents at the output. Keeping constant load as an induction motor at the output of three-phase VSI is being studied for the same conduction periods of switches (120° conduction, 180° conduction, and in between these two) as shown in Figure 2(a) that is modelled in MATLAB-Simulink software [21], [25].

Analysis and comparison have been made for three-phase VSI as shown in Figure 1 and Figure 2(a) with R-L load and induction motor load having different ratings (4 kW, 400 V, 1430 rpm, and 7.5 kW, 400 V, 1440 rpm) to assure the performance and result. Further, this paper has analyzed a passive filter with an LC element to reduce the harmonic contents from voltage and current. The value of L and C has been calculated to minimize harmonics at selected frequencies to be eliminated. Figure 2(b) shows the circuit connection with the passive filter.

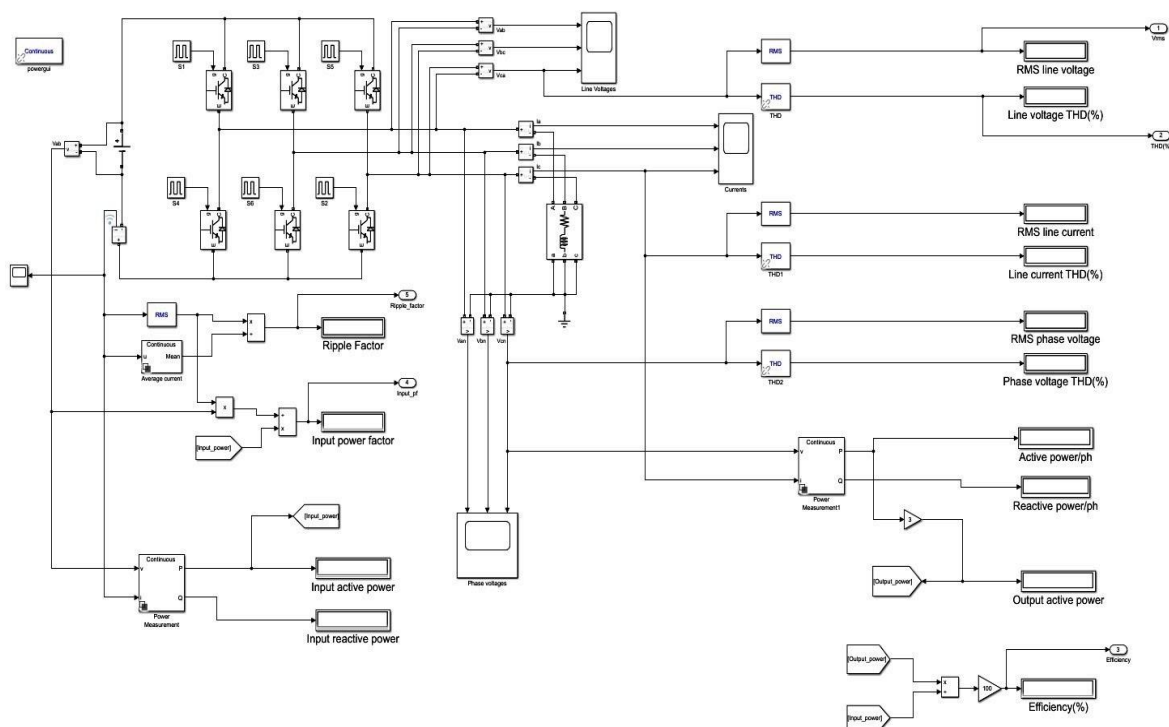


Figure 1. Detailed MATLAB/Simulink model of three-phase six-switch VSI with R-L load

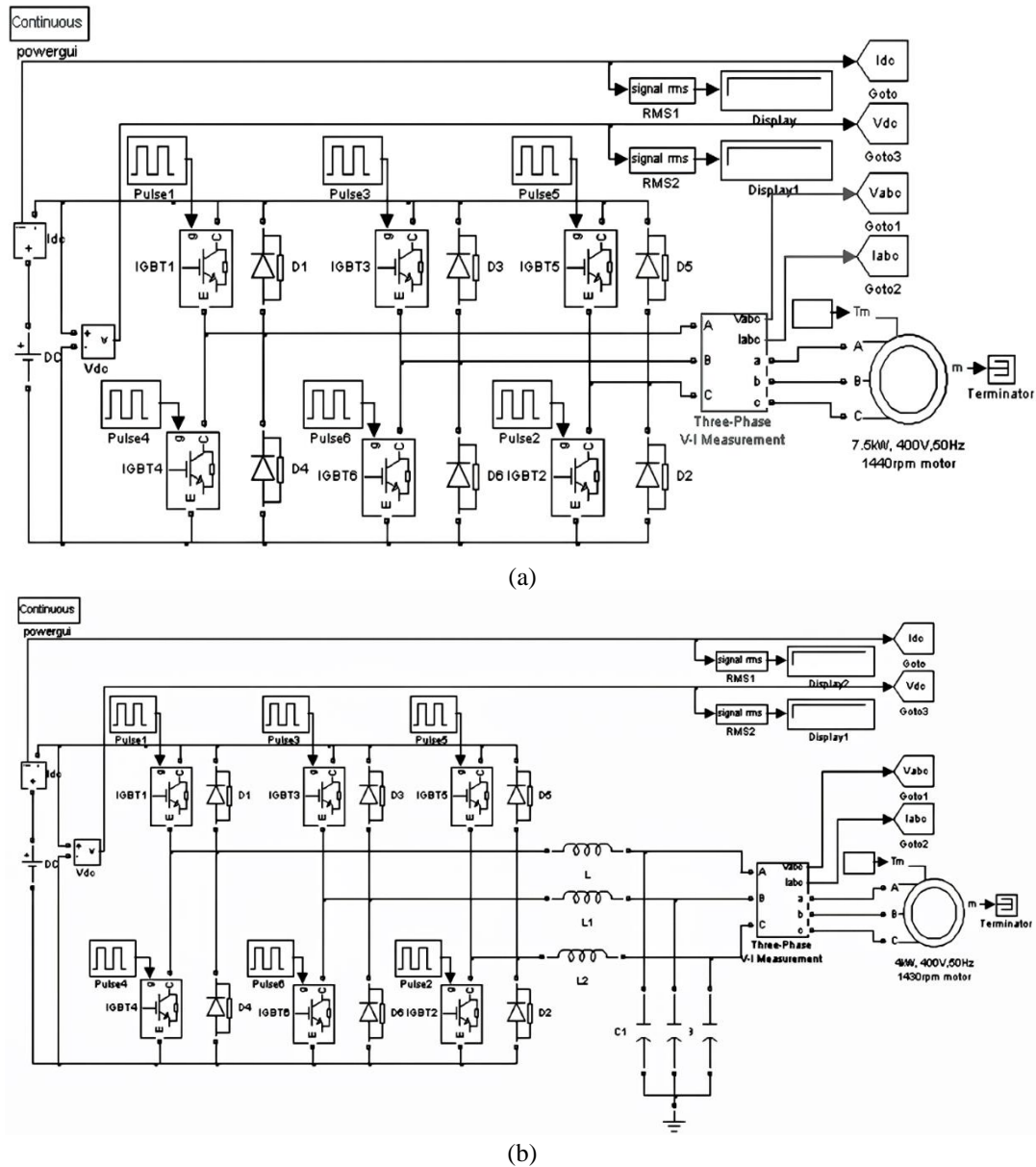


Figure 2. MATLAB model of three-phase six-switch VSI (a) motor load and (b) motor load with filter

3. ANALYSIS OF SQUARE-WAVE INVERTER

In previous literature, the output voltage and output current analysis has been done for 120° and 180° conduction of three-phase VSI. This paper presents THD analysis for both output current and output voltage for different conduction modes between 120° and 180° to obtain minimum THD for three-phase VSI having the same load. The conduction period of switches for different conduction modes is shown in Table 1. The line and phase voltage waveform corresponding to the conduction periods are shown in Figures 3 to 9.

For 120° conduction, from the output waveforms shown in Figures 3(a) and 3(b); the rms value of the phase voltage is $V_{ph} = 0.408 V_{in}$ and the rms value of the line voltage is $V_L = 0.707 V_{in}$. For 130° conduction, from the output waveforms shown in Figures 4(a) and 4(b); the rms value of the phase voltage is $V_{ph} = 0.419 V_{in}$ and the rms value of the line voltage is $V_L = 0.726 V_{in}$. For 140° conduction, from the output waveforms shown in Figures 5(a) and 5(b); the rms value of the phase voltage is $V_{ph} = 0.430 V_{in}$ and the rms value of the line voltage is $V_L = 0.745 V_{in}$. For 150° conduction, from the output waveforms shown in Figures 6(a) and 6(b); the rms value of the phase voltage is $V_{ph} = 0.408 V_{in}$ and the rms value of the line voltage is $V_L = 0.764 V_{in}$. For 160° conduction, from the output waveforms shown

in Figures 7(a) and 7(b); the rms value of the phase voltage is $V_{ph} = 0.451 V_{in}$ and the rms value of the line voltage is $V_L = 0.782 V_{in}$. For 170° conduction, from the output waveforms shown in Figures 8(a) and 8(b); the rms value of the phase voltage is $V_{ph} = 0.462 V_{in}$ and the rms value of the line voltage is $V_L = 0.799 V_{in}$. For 180° conduction, from the output waveforms shown in Figures 9(a) and 9(b); the rms value of the phase voltage is $V_{ph} = 0.471 V_{in}$ and the rms value of the line voltage is $V_L = 0.817 V_{in}$.

Table 1. Conduction periods of switches for different conduction modes of VSI

Conduction period switches	For 120°	For 130°	For 140°	For 150°	For 160°	For 170°	For 180°
S1	$0^\circ-120^\circ$	$0^\circ-130^\circ$	$0^\circ-140^\circ$	$0^\circ-150^\circ$	$0^\circ-160^\circ$	$0^\circ-170^\circ$	$0^\circ-180^\circ$
S2	$60^\circ-180^\circ$	$60^\circ-190^\circ$	$60^\circ-200^\circ$	$60^\circ-210^\circ$	$60^\circ-220^\circ$	$60^\circ-230^\circ$	$60^\circ-240^\circ$
S3	$120^\circ-240^\circ$	$120^\circ-250^\circ$	$120^\circ-260^\circ$	$120^\circ-270^\circ$	$120^\circ-280^\circ$	$120^\circ-290^\circ$	$120^\circ-300^\circ$
S4	$180^\circ-300^\circ$	$180^\circ-310^\circ$	$180^\circ-320^\circ$	$180^\circ-330^\circ$	$180^\circ-340^\circ$	$180^\circ-350^\circ$	$180^\circ-360^\circ$
S5	$240^\circ-360^\circ$	$0^\circ-10^\circ$, $240^\circ-360^\circ$	$0^\circ-20^\circ$, $240^\circ-360^\circ$	$0^\circ-30^\circ$, $240^\circ-360^\circ$	$0^\circ-40^\circ$, $240^\circ-360^\circ$	$0^\circ-50^\circ$, $240^\circ-360^\circ$	$0^\circ-60^\circ$, $240^\circ-360^\circ$
S6	$0^\circ-60^\circ$, $300^\circ-360^\circ$	$0^\circ-70^\circ$, $300^\circ-360^\circ$	$0^\circ-80^\circ$, $300^\circ-360^\circ$	$0^\circ-90^\circ$, $300^\circ-360^\circ$	$0^\circ-100^\circ$, $300^\circ-360^\circ$	$0^\circ-110^\circ$, $300^\circ-360^\circ$	$0^\circ-120^\circ$, $300^\circ-360^\circ$

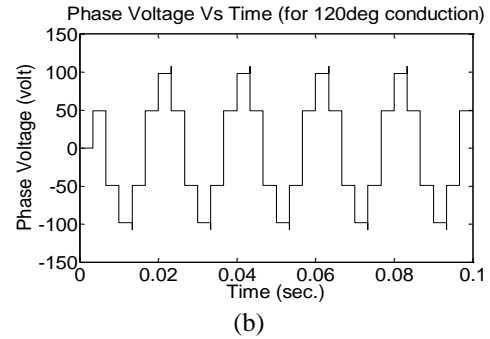
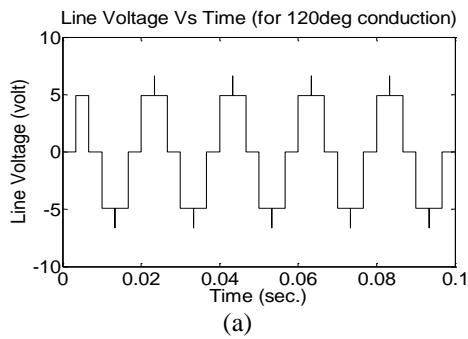


Figure 3. For 120° conduction (a) output line voltage and (b) output phase voltage

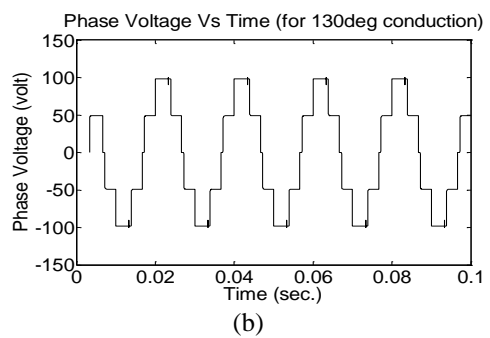
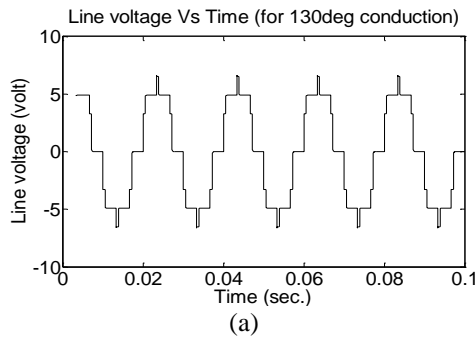


Figure 4. For 130° conduction (a) output line voltage and (b) output phase voltage

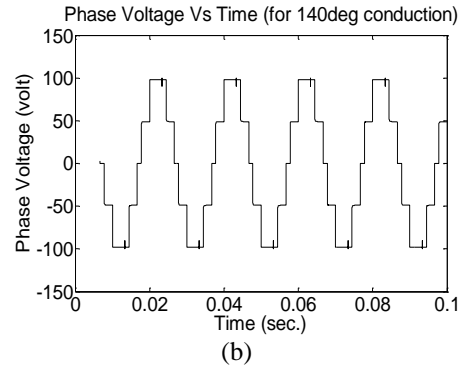
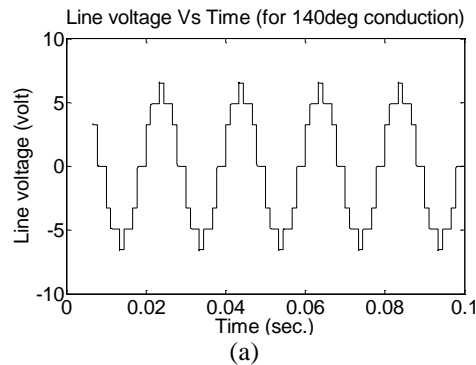


Figure 5. For 140° conduction (a) output line voltage and (b) output phase voltage

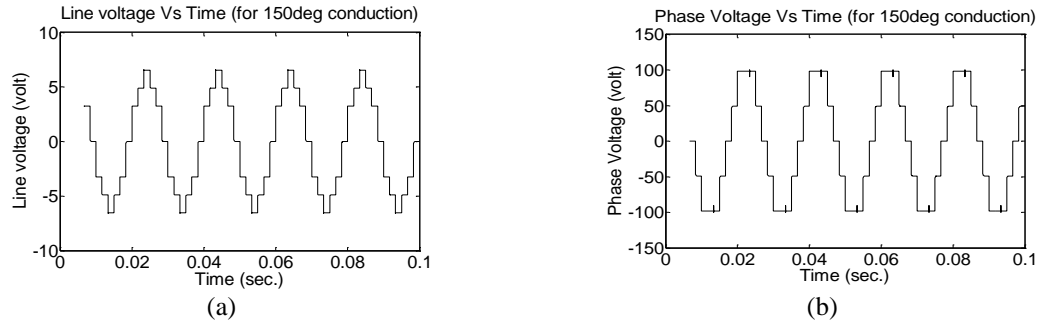


Figure 6. For 150° conduction (a) output line voltage and (b) output phase voltage

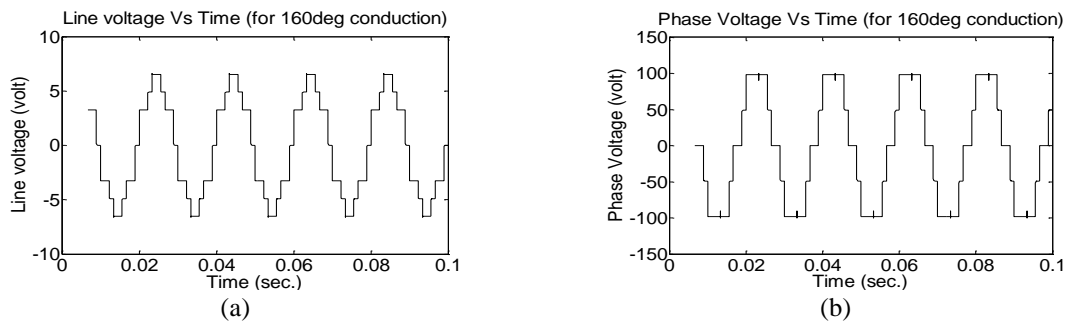


Figure 7. For 160° conduction (a) output line voltage and (b) output phase voltage

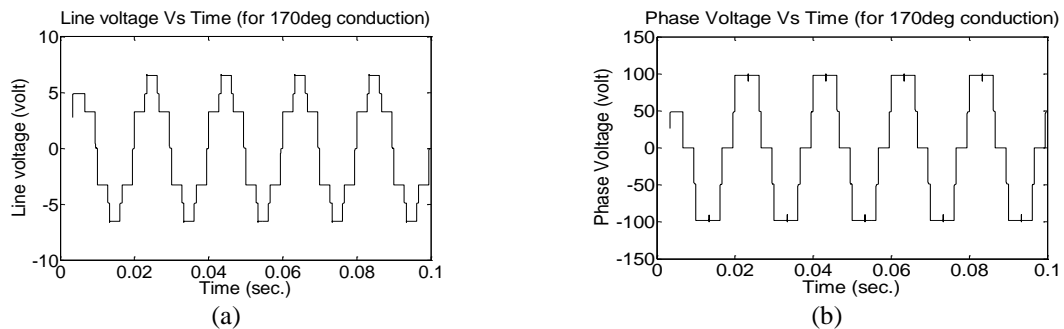


Figure 8. For 170° conduction (a) output line voltage and (b) output phase voltage

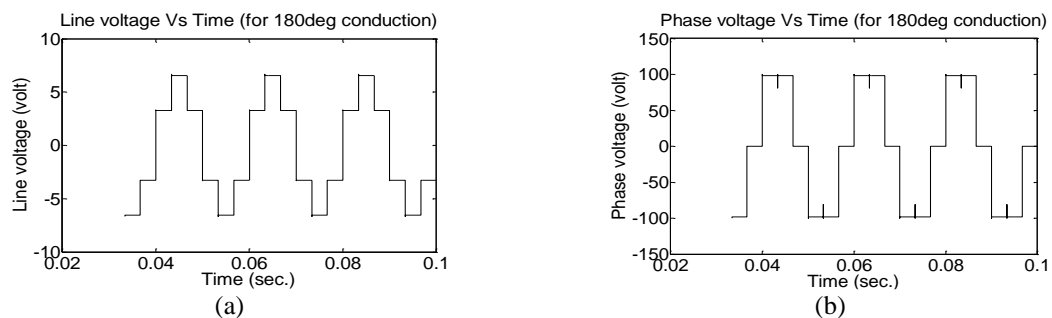


Figure 9. For 180° conduction (a) output line voltage and (b) output phase voltage

4. RESULTS AND DISCUSSION

This section provides the simulated results of the proposed scheme. Observed results are tabulated and plotted in Table 2 and Figures 10 to 16, respectively. Figure 10(a) shows the variation of output voltage for different conduction modes that it is increasing with the increase in the conduction period of switches for

VSI. It is true for the output current of VSI, as shown in Figure 10(b). The result for THD of output voltage for an inverter with R-L load is shown in Figure 11(a). It shows that minimum THD is obtained for 150° conduction compared to other R-L load conduction schemes. The same is observed for THD of the inverter's output current with R-L load, as shown in Figure 11(b). It is observed that THDs are reduced for 150° conduction, which is a basic requirement of any network.

Table 2. Comparison of voltage THD and current THD for three-phase VSI with different loads

Loads→	R-L load		Motor load (4 kW, 400 V, 1430 rpm)		Motor load (7.5 kW, 400 V, 1440 rpm)		R-L load with filter	
Conduction modes	% V _{THD}	% I _{THD}	% V _{THD}	% I _{THD}	% V _{THD}	% I _{THD}	% V _{THD}	% I _{THD}
120	31.74	32.44	48.61	25.86	50.18	25.4	1.9595	0.7181
130	25.05	24.81	44.57	22.29	45.39	22.2	1.9744	0.7168
140	23.89	19.21	40.47	18.21	40.96	17.71	1.9599	0.7181
150	16.25	15.89	31.92	15.17	31.93	13.67	1.9599	0.7181
160	16.75	16.51	29.83	18.35	30.01	16.92	1.9596	0.7181
170	27.64	19.86	29.39	18.22	29.38	18.33	1.9745	0.7181
180	30.05	29.66	31.88	20.42	31.86	20.54	1.9596	0.7181

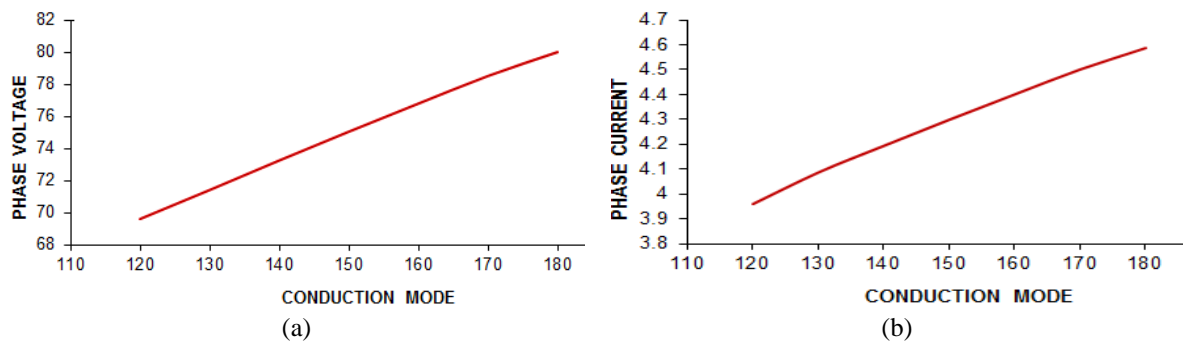


Figure 10. Variation with different conduction modes (a) output phase voltage and (b) output current

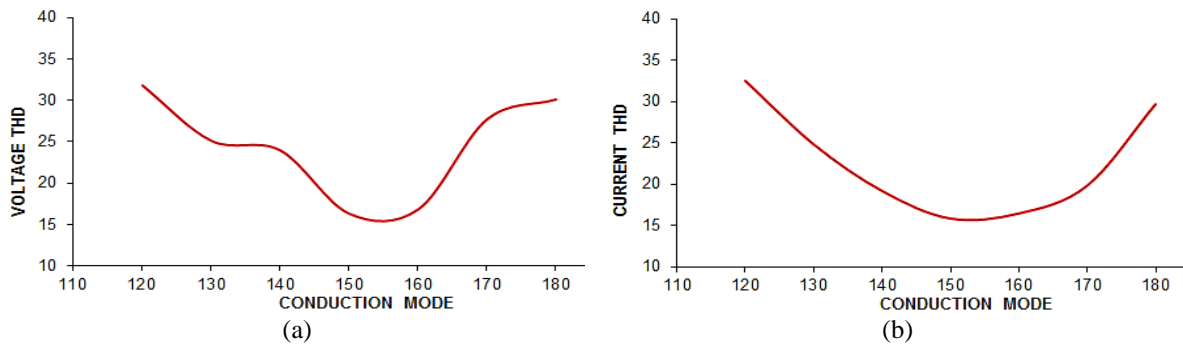


Figure 11. THD versus conduction angle for R-L load (a) voltage THD and (b) current THD

Figures 12(a) and 12(b) show the variation of THD in output voltage and output current of inverter with induction motor load (4 kW, 400 V, 1430 rpm), respectively. Similar results have been found for a three-phase inverter with induction motor load (7.5 kW, 400 V, 1440 rpm), as shown in Figures 13(a) and 13(b). The simulation result for two types of motor load validates the results for harmonic distortion for a similar conduction scheme for the inverter. The comparative effects of voltage THD and Current THD for a three-phase square-wave inverter having different loads without filter and with filter are tabulated in Table 2. Figures 14(a) and 14(b) show the variation of THD of output voltage and THD of the output current of an inverter having R-L load with a passive filter that THD is reduced within the specified threshold.

Motor speed is near the rated value for rated input to the motor for 150° conduction mode and is rated for 180° conduction mode, as shown in Figure 15(a). In Figure 15(b), the variation of the motor power factor concerning conduction modes shows that the motor power factor is better than the 150° mode of conduction. The output rotor current is found to be minimum at 150° conduction for the motor load, as shown in Figure 16(a). Efficiency is seen better in the case of 160° conduction mode relative to other conduction modes, as shown in Figure 16(b).

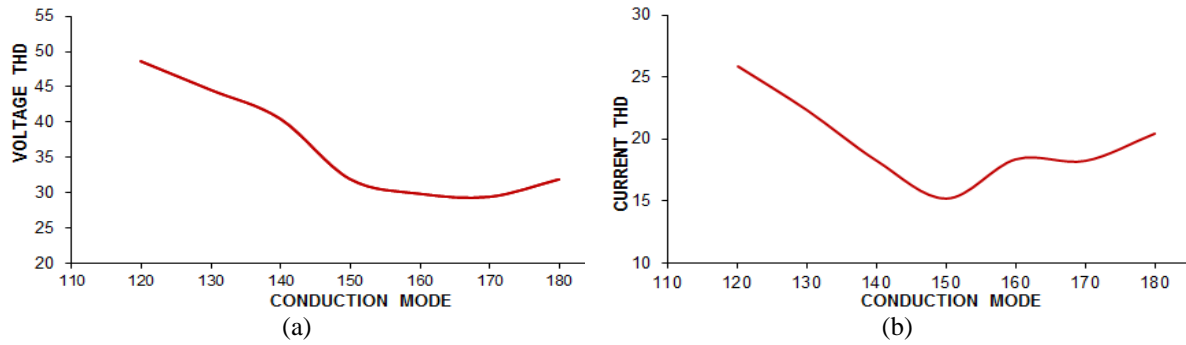


Figure 12. THD versus conduction angle for motor load (4 kW) (a) voltage THD and (b) current THD

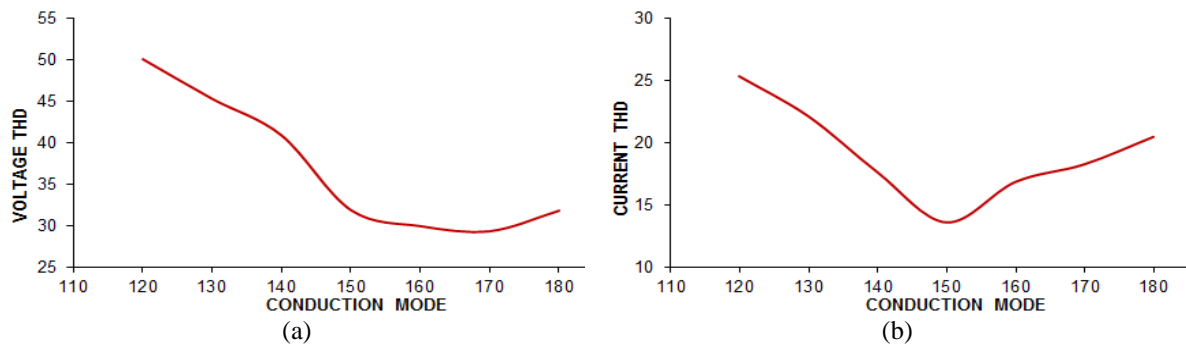


Figure 13. THD versus conduction angle for motor load (7.5 kW) (a) voltage THD and (b) current THD

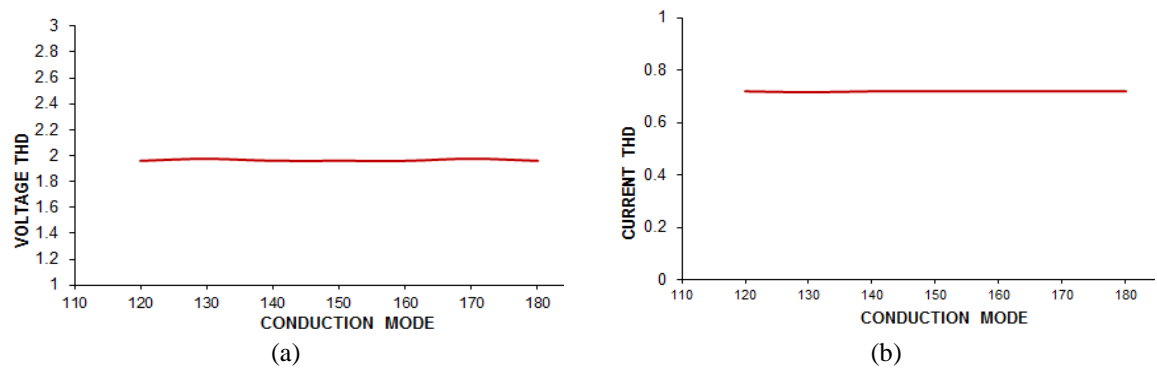


Figure 14. THD versus conduction angle for R-L load with filter (a) voltage THD and (b) current THD

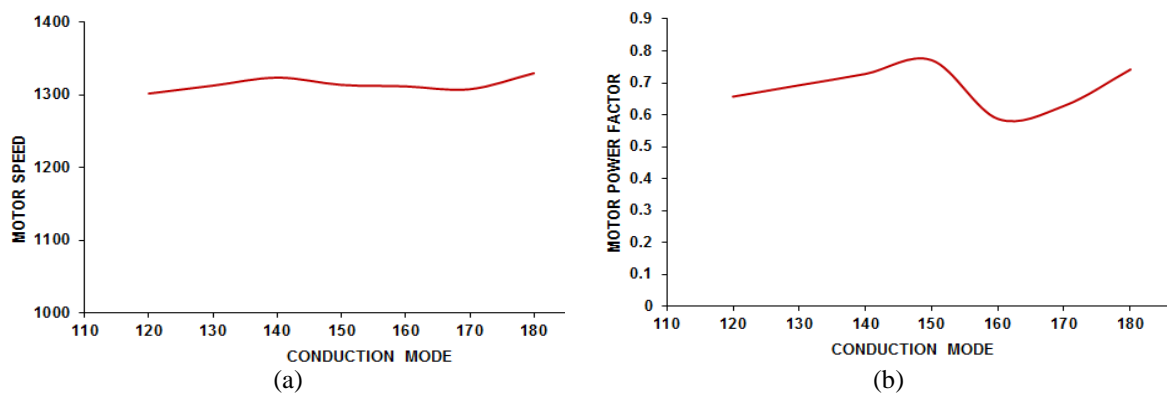


Figure 15. For motor load (a) speed Vs conduction angle and (b) P.F. Vs conduction angle

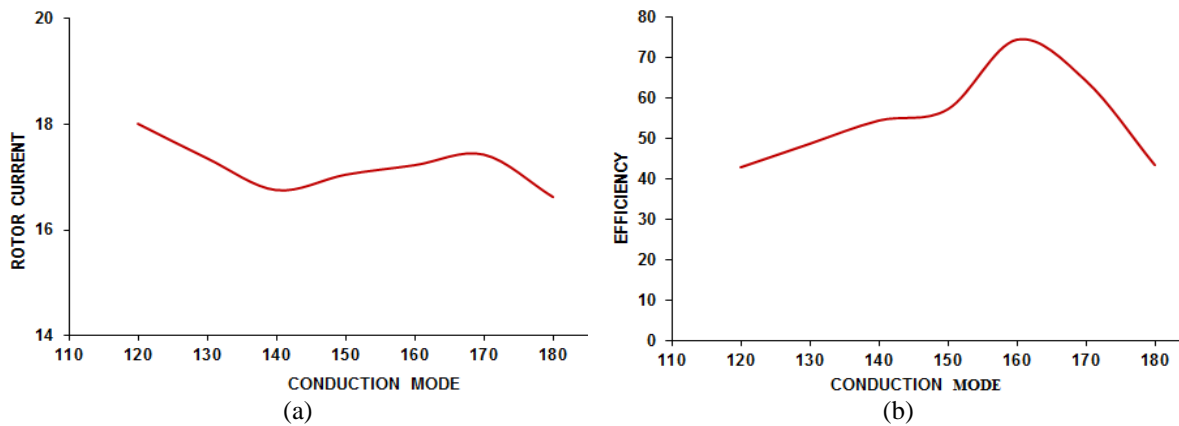


Figure 16. For motor load (a) rotor current Vs conduction angle and (b) efficiency Vs conduction angle

5. CONCLUSION

The paper concludes for square-wave VSI with R-L load, THD of output current, and the output voltage is least for 150° conduction. However, for both types of induction motor load, the least THD of the output voltage is found for 170° conduction, and the least THD of output current is found for 150° conduction without any additional structural changes or complexity, or costs in the circuit. The total harmonic content is found to be reduced using these conduction modes. It is also explored that harmonic contents are reduced to a particular threshold after applying the passive filter. Because of this performance and efficiency of the square-wave inverter have been improved. Hence, after analysis and simulation, it can be suggested that 150° conduction is the best angle of conduction of switches for a three-phase inverter for the motor load. Since harmonic distortion plays an important role in the efficient operation of power circuits, this work may be extended to study better power quality in inverters with reduced voltage and current harmonics.




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