



Comparison and analysis of different conduction modes of three phase voltage source inverter

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Abstract

A Simulink model for voltage source inverter using switching function concept is studied with the help of MATLAB/SIMULINK in this paper. The switching function concept is a powerful tool in understanding and optimizing the performance of static power converters/inverters. A three phase output can be obtained from a configuration of six IGBT. Three types of control signals can be applied to the switched: 180° conduction, 120° conduction or 150° conduction. The output voltages and current of a three phase voltage-source inverter is studied in this paper. The quality of output voltage can be improved by only changing the conduction mode which is very simple to implement. The switching operation of a three phase inverter is controlled so that output is achieved at every 60° angle in 120°, 180°, 150° conduction mode. Harmonics are created in the output of these kind of inverter. These harmonics not only reduces the life period of appliances, but also causes excessive wear in the device or appliances used in the day to day life of human being. By analyzing the output harmonic spectra of output voltages and current (line to line current and line to line voltages), their total harmonic distortion (THD) is found and compared.

Keywords: Voltage source inverter, Conduction mode, Total harmonic distortion, Line voltage, FFT analysis

1. Introduction

In the field of Power-Electronics, inverter is the class of power conversion circuits. They have input of a dc current/voltage source and have symmetric ac voltage or current as their output. It can be said that it does reverse process of what ac to dc converter does. The input to the inverter can be a dc source derived from an ac source or direct dc source. For example, in utility supplies as the primary source of input power is an ac voltage supply. This is then changed to dc by an ac-dc rectifier. A filter capacitor may be also used for this case. This dc is then converted back to ac using a dc to ac converter also known as inverter. The magnitude and frequency of the final ac output may be different from the previous ac input of the utility. A current source inverter (CSI) is the

inverter whose input is a source with constant current and variable voltage. Similarly a Voltage Source Inverter (VSI) is where the input voltage is maintained constant by using a constant voltage source. The Voltage Source Inverter circuit has direct control over output voltage whereas the current source inverter directly controls output current. Similarly, in a variable dc linked inverter the input voltage is controllable. Block diagram of VSI is shown in Figure 1.

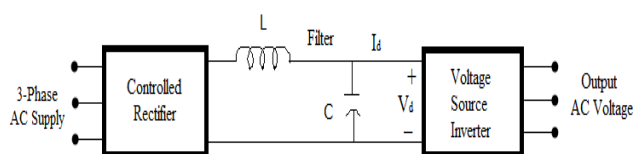


Figure 1 Block Diagram of Voltage Source Inverter (VSI)

Semiconductor devices with high power rating are used in these converters as switching devices. When closed, these devices act as short circuit due to their characteristics [1]. An Ideal switch is the one which consumes very less power when switched from one state to another. Semiconductors are those materials whose conductivity will increase or decrease based on the energy falling on to its surface. As the temperature increases, more heat energy is absorbed by the semiconductor material and hence more current is conducted by the semiconductor. Also they do not conduct at absolute zero temperature. The more there is rise in temperature, more the current rise. Some example of these kind of switches are diode, silicon controlled rectifier (SCR), metal-oxide-semiconductor field-effect transistor (MOSFET), insulated-gate bipolar transistor (IGBT), bipolar junction transistor (BJT), TRIAC etc.

Classification of semiconductor devices [2]

- Based on controllability
 1. Un-controlled
 2. Semi controlled
 3. Fully controlled
- Based on control modes
 1. Current controlled (BJT, SCR)
 2. Voltage controlled (IGBT, MOSFET)
- Based on current direction
 1. Unidirectional (SCR, MOSFET, IGBT)
 2. Bidirectional (TRIAC)

An Insulated Gate Bipolar Transistor (IGBT) is a power semiconductor device having three terminals. It is primarily used as an electronic switch. It was developed to have high efficiency and fast switching. It has many modern appliances in switching electric power. IGBT has the advantages of both MOSFETs and BJTs. An IGBT has low on state conduction

losses and high input impedance. To turn on an IGBT we need to apply a positive gate voltage. This opens the channel for n carriers. Removing the gate voltage turns off the IGBT. It has lower conductive and switching losses because of the reasons stated above. So an IGBT is faster than a BJT. The switching frequency can be upto 20 KHz and the rating for single IGBT can be upto 1200V, 400A. We have used IGBT for our simulation purpose.

2. Three Phase VSI

Many industries use three phase six-switch inverters. They are used in

- variable speed ac motor drives,
- induction heating,
- standby power supplies,
- uninterruptible power supplies

Different types of fault that commonly occur in these inverters have been investigated recently [3]. The most important of these is reducing harmonic distortion and the improvement of the output waveform. Therefore different types of inverters are presented having different structures, which can reduce harmonic and can lead to improve the output voltage too. The power circuit diagram for three phase bridge voltage source inverter is shown in Fig. 2

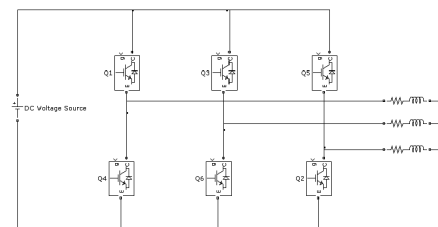


Figure 2 Three Phase Voltage Source Inverter

For high-power three phase systems, typical outputs are

- (1) 220V to 380V at 50Hz.
- (2) 120V to 208V at 60Hz.
- (3) 115V to 200V at 400Hz.

This inverter improves the output voltage and current quality. But it has the disadvantage that using this conduction mode will increase both size and weight of inveter, which will inturn causes rise in price. Thus inverters with conductive angles 120° , 180° and 150° are used for all 3 phase six- switch inverters.

2.1 180° Conduction Mode Three phase VSI

It is a very common thyristor firing technique. In this technique the duration for which in one leg of inverter only one thyristor conducts for 180° . Hence at any time 3 thyristors remain ON [2]. Suppose in first leg of inverter, if Q_1 is turned on, phase “a” of load is connected to to positive terminal (+V/2) of dc input voltage. Similarly if we turn on thyristor Q_4 phase “a” will be connected to the negative terminal (-

V/2) of the dc source. Phase “b” and “c” follows the similar sequence. There will be 6 operating pattern within the 2-cycle. There will be 60° interval for each pattern. The different intervals at which each thyristor is conducting are shown in Table 1. The bridge output frequency is specified by the rate of sequencing these patterns. If we consider a Y-balanced load in 180° conduction mode, there will be shift of 60° between gating voltage. This will get us 3 phase balance voltage at output. The load could be star or delta connected. It must be taken care that any two switches of same leg eg. Q_3 and Q_6 , Q_1 and Q_4 , or Q_5 and Q_2 should not be switched on at same time. This is to avoid short circuit across the input dc voltage supply. Similarly, two switches of same leg should not be switched off at same time as it will cause undefined ac output voltage and undefined state. If switches are turned off at same time, the output voltage will depend on polarity of line current.

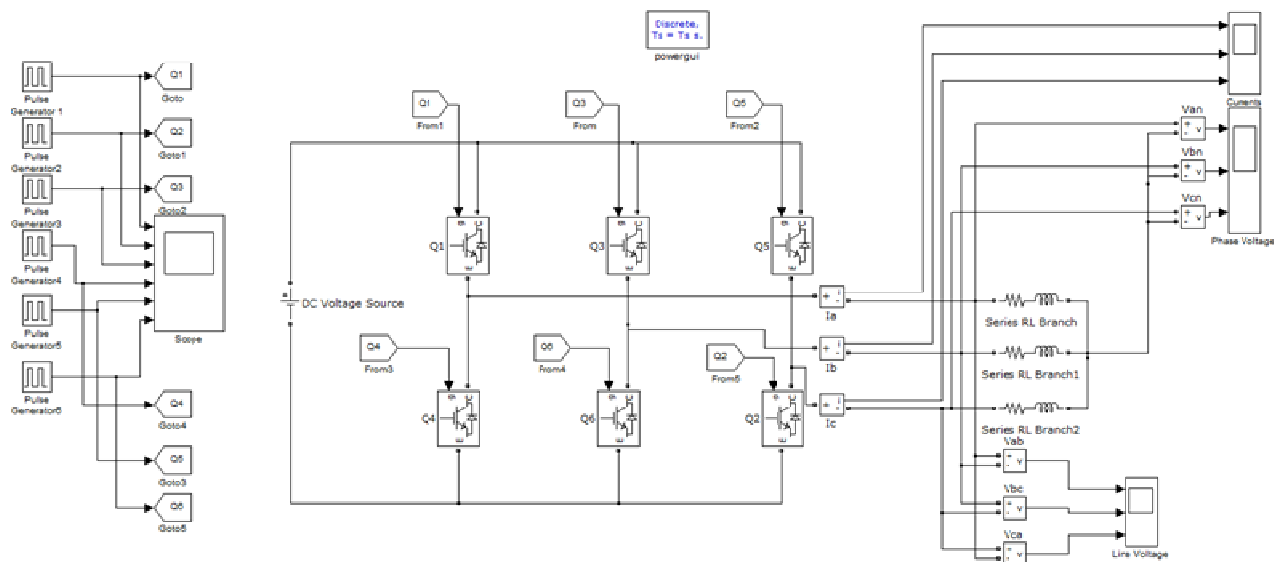


Figure 3 Simulink Model for three phase VSI

In Mode 1 the switches Q_5 , Q_6 and Q_1 are turned on for the time interval $0^\circ < \omega t < 60^\circ$. As a result of this the terminals a and c are connected to the positive terminal of input DC voltage and the terminal b is connected to the negative terminal of the DC input. Thus the voltage across each branch is $V_{an}=V_{cn}= V_{dc}/3$, $V_{bn}= -2V_{dc}/3$

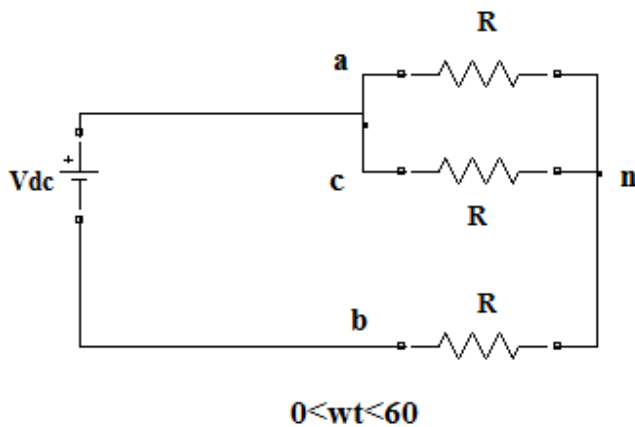


Figure 4 Mode 1 for 1800 VSI

Similarly, modes 2-6 are operated as per Table 1 below.

Table 1 Conduction Table for 1800 Three Phase VSI

| Mode | Duration (in degree) | Switches |
|------|-----------------------|-----------------|
| 1 | 0 – 60 | S 5 , S 6 , S 1 |
| 2 | 60 – 120 | S 6 , S 1 , S 2 |
| 3 | 120 – 180 | S 1 , S 2 , S 3 |
| 4 | 180 – 240 | S 2 , S 3 , S 4 |
| 5 | 240 – 300 | S 3 , S 4 , S 5 |
| 6 | 300 – 360 | S 4 , S 5 , S 6 |

Output phase voltage and line voltage for 180° three phase VSI is shown in Table 2.

Few major drawbacks of 180° conduction mode are:

- Magnitude of the m^{th} harmonic is $1/m$ times that of the fundamental.

- Two switches along the same leg (e.g. Q_1 and Q_4) may conduct simultaneously. If such condition happens, it will cause short circuit on the dc bus. This simultaneous conduction is result of absence of any time-delay between the on time of transistor Q_4 and off-time of transistor Q_1 .

Table 2 Output Phase Voltage and Line Voltage for 1800 three phase VSI

| Mode | V_{an} | V_{bn} | V_{cn} | V_{ab} | V_{bc} | V_{ca} |
|------|-----------|-----------|-----------|----------|----------|----------|
| 1 | $V_s/3$ | $-2V_s/3$ | $V_s/3$ | V_s | $-V_s$ | 0 |
| 2 | $2V_s/3$ | $-V_s/3$ | $-V_s/3$ | V_s | 0 | $-V_s$ |
| 3 | $V_s/3$ | $V_s/3$ | $-2V_s/3$ | 0 | V_s | $-V_s$ |
| 4 | $-V_s/3$ | $2V_s/3$ | $-V_s/3$ | $-V_s$ | V_s | 0 |
| 5 | $-2V_s/3$ | $V_s/3$ | $V_s/3$ | $-V_s$ | 0 | V_s |
| 6 | $-V_s/3$ | $-V_s/3$ | $2V_s/3$ | 0 | $-V_s$ | V_s |

- Very poor quality of voltage/current is obtained especially in line-to-line voltage. Thus it requires big filters to be placed in between the converter and the motor. To overcome this, switching frequency may be increased, but it will further cause increase in switching losses.

2.2 120° Conduction Mode Three Phase VSI

In 120° conduction scheme each device conducts for 120° . At any instant of time, two switches will conduct simultaneously. At every 60° interval any one switch will turn off and other will be turned on and start conducting [2]. But the advantage of this mode is that there is 60° interval between turning on and off of switch in the same leg. This eliminates the possibility of short circuit. But as compared to 180° conduction mode, in 120° mode rms output value and switch utilization factor of switches is less.

It is preferable for a star connected load because it provides a six step waveform across any phase. As each device conducts for 120° , only two devices are in conduction state at any instant. During the period 0° to 60° , Q1 to Q6 are conducting. Load terminals A and B are connected to positive terminal and negative terminal of the source respectively. Load terminal C is in floating state.

Line Voltages:

$$V_{ab} = V$$

$$V_{bc} = -V/2$$

$$V_{ca} = -V/2$$

In mode 1 the switches Q₆ and Q₁ are turned on for the time interval $0^\circ < \omega t < 60^\circ$. As a result of this the terminal a is connected to the positive terminal of input DC voltage and the terminal b is connected to the negative terminal of the DC input. Thus the voltage across each branch is $V_{an}=V_{dc}/2$, $V_{bn}=-V_{dc}/2$, $V_{cn}=0$

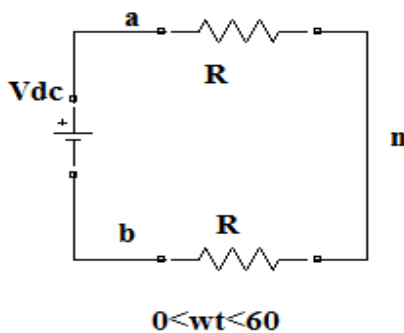


Figure 5 Mode 1 for 1200 VSI

Similarly modes 2-6 are operated according to Table 3. Output phase voltage and line voltage for 120° three phase VSI is shown in Table 4

Advantages of 120° three phase VSI are:

- Short circuit conduction of 180° mode is overcome in 120° mode inverter. In this inverter there is a 60° interval between turning off of S₁

and turning ON of S₄. During this 60° interval, S₁ can be commutated safely.

Table 3 Conduction Table for 1200 Three Phase VSI

| Mode | Duration (in degree) | Switches |
|------|-----------------------|-----------|
| 1 | 0 – 60 | S 6 , S 1 |
| 2 | 60 – 120 | S 1 , S 2 |
| 3 | 120 – 180 | S 2 , S 3 |
| 4 | 180 – 240 | S 3 , S 4 |
| 5 | 240 – 300 | S 4 , S 5 |
| 6 | 300 – 360 | S 5 , S 6 |

Table 4 Output Phase Voltage and Line Voltage of 1200 three Phase VSI

| Mode | V an | V bn | V cn | V ab | V bc | V ca |
|------|----------|----------|----------|----------|----------|----------|
| 1 | $V s/2$ | $-V s/2$ | 0 | $V s$ | $-V s/2$ | $-V s/2$ |
| 2 | $V s/2$ | 0 | $-V s/2$ | $V s/2$ | $V s/2$ | $-V s$ |
| 3 | 0 | $V s/2$ | $-V s/2$ | $-V s/2$ | $V s$ | $-V s/2$ |
| 4 | $-V s/2$ | $V s/2$ | 0 | $-V s$ | $V s/2$ | $V s/2$ |
| 5 | $-V s/2$ | 0 | $V s/2$ | $-V s/2$ | $-V s/2$ | $V s$ |
| 6 | 0 | $-V s/2$ | $V s/2$ | $V s/2$ | $-V s$ | $V s/2$ |

In general this angular interval of 180° exists between turning off of one device and turning on of the complementary device in the same leg. This 60° period provide sufficient time for the outgoing switch to regain forward blocking capability.

- When compared to 180° mode, switch utilization factor and rms output value are less in 120° conduction mode.

2.3 150° Conduction Mode three phase VSI

In 150° conduction mode of three phase VSI conduction period for each switch is 150° [4-5]. The output phase voltage becomes 7 level, 12 step waveform, while 180° and 120° conduction modes have only 4 level and 3 levels

respectively. The 12 switching patterns with 30° duration are formed in this mode. 2 transistors conduct in one interval and 3 in next one and so on. The factors on which total harmonic distortion of the output voltage depends are conductive angle and power factor. Only conduction mode can be decided by designer, while power factor of load completely depends on load. So conduction mode must be selected such that output voltage must have high RMS value and low THD.

In mode 1 the switches Q1, Q2 and Q3 are turned on for the time interval $0^\circ < \omega t < 30^\circ$. Hence, terminal c is connected to the -ve terminal of the DC input while the terminals a and b are connected to the +ve terminal of input DC voltage. Thus the voltage across each branch is

$$V_{an}=V_{bn}=V_{dc}/3, V_{cn}=-2V_{dc}/3$$

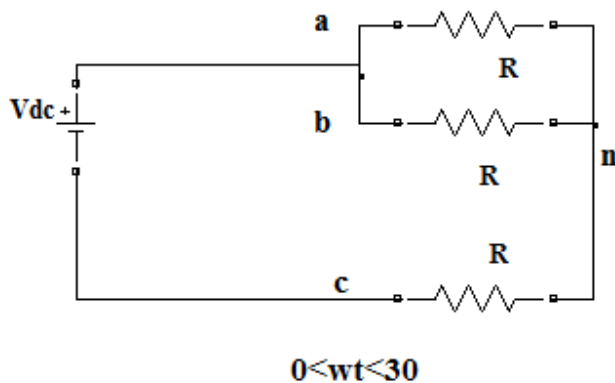


Figure 6 Mode 1 for 1500 VSI

Similarly mode 2-6 are operated according to conditions given in Table 5 and Output phase voltage and line voltage for 1500 three phase VSI is shown in Table 6

. The advantage of 1500 conduction mode three phases VSI are as follows:

- A 30° gap time period is placed in between 2 series switches of same leg. It will be enough to avoid short circuit on input DC supply.

- It provides output phase voltage having 7 levels waveform, which is far much better as compared to only 3 and 4 levels in 120° and 180° modes respectively.
- This mode reduces the total harmonic distortion and distortion factor of output voltage waveforms to much better extent.
- Lower Order Harmonics are eliminated to a greater extent in this mode.

Table 5 Conduction Table for 1500 Three Phase VSI

| Mode | Duration (in degree) | Switches |
|------|----------------------|-----------------|
| 1 | 0 – 30 | S 1 , S 2 , S 3 |
| 2 | 30 – 60 | S 2 , S 3 |
| 3 | 60 – 90 | S 2 , S 3 , S 4 |
| 4 | 90 – 120 | S 3 , S 4 |
| 5 | 120 – 150 | S 3 , S 4 , S 5 |
| 6 | 150 – 180 | S 4 , S 5 |
| 7 | 180 – 210 | S 4 , S 5 , S 6 |
| 8 | 210 – 240 | S 5 , S 6 |
| 9 | 240 – 270 | S 5 , S 6 , S 1 |
| 10 | 270 – 300 | S 6 , S 1 |
| 11 | 300 – 330 | S 6 , S 1 , S 2 |
| 12 | 330 – 360 | S 1 , S 2 |

Table 6: Output Phase Voltage and Line Voltage for 1500 Three Phase VSI

| Mode | V an | V bn | V cn | V ab | V bc | V ca |
|------|-----------|-----------|-----------|----------|----------|----------|
| 1 | $V_s/3$ | $V_s/3$ | $-2V_s/3$ | 0 | V_s | $-V_s$ |
| 2 | 0 | $V_s/2$ | $-V_s/2$ | $-V_s/2$ | V_s | $-V_s/2$ |
| 3 | $-V_s/3$ | $2V_s/3$ | $-V_s/3$ | $-V_s$ | V_s | 0 |
| 4 | $-V_s/2$ | $V_s/2$ | 0 | $-V_s$ | $V_s/2$ | $V_s/2$ |
| 5 | $-2V_s/3$ | $V_s/3$ | $V_s/3$ | $-V_s$ | 0 | V_s |
| 6 | $-V_s/2$ | 0 | $V_s/2$ | $-V_s/2$ | $-V_s/2$ | V_s |
| 7 | $-V_s/3$ | $-V_s/3$ | $2V_s/3$ | 0 | $-V_s$ | V_s |
| 8 | 0 | $-V_s/2$ | $V_s/2$ | $V_s/2$ | $-V_s$ | $V_s/2$ |
| 9 | $V_s/3$ | $-2V_s/3$ | $V_s/3$ | V_s | $-V_s$ | 0 |
| 10 | $V_s/2$ | $-V_s/2$ | 0 | V_s | $-V_s/2$ | $-V_s/2$ |
| 11 | $2V_s/3$ | $-V_s/3$ | $-V_s/3$ | V_s | 0 | $-V_s$ |
| 12 | $V_s/2$ | 0 | $-V_s/2$ | $V_s/2$ | $V_s/2$ | $-V_s$ |

3. Simulation Results

The stepped wave output voltage of an inverter when operated in various conducting modes consists of fundamental components and several harmonic components [6-7]. The purpose of analyzing the output of an inverter is to determine the harmonics in the output voltage waveform. Total Harmonic Distortion (THD) is the general harmonic index that is

$$V_{an180} = \sum_{n=6k \pm 1} \frac{2V_s}{n\pi} \sin n\omega t \quad (6.2)$$

where, $k=0,1,2,\dots$

$$V_{an120} = \sum_{n=1,3,5,\dots} \frac{2V_s}{n\pi} \cos \frac{n\pi}{6} \sin n\left(\omega t + \frac{\pi}{6}\right) \quad (6.3)$$

$$v_{an_{-150^\circ}} = \sum_{n=1,3,5,\dots} \frac{V_d}{6n\pi} \left[4 + \cos \frac{n\pi}{6} + \cos \frac{n\pi}{3} - \cos \frac{2n\pi}{3} - 2 \cos \frac{5n\pi}{6} - \cos \frac{7n\pi}{6} - \cos \frac{4n\pi}{3} + \cos \frac{5n\pi}{3} + 2 \cos \frac{11n\pi}{6} \right] \cdot \sin n\left(\omega t + \frac{\pi}{6}\right) \quad (6.4)$$

FFT analysis of line current with wave forms are shown below:

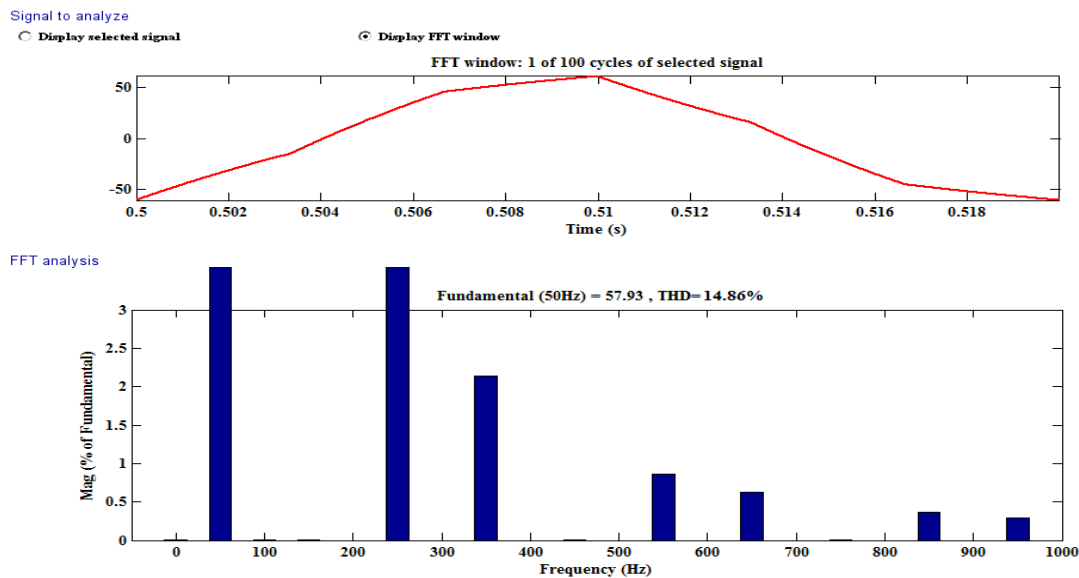


Figure 7 (a) FFT analysis of 1800 three phase VSI

used. THD is a measure of harmonic content in the output voltage waveform [8]. THD is defined as the Root Mean Square (RMS) of the harmonics expressed as the percentage of the fundamental component. THD is also known as Harmonic Factor (HF). Greater the value of THD, greater the harmonic content and greater is the distortion of the output voltage.

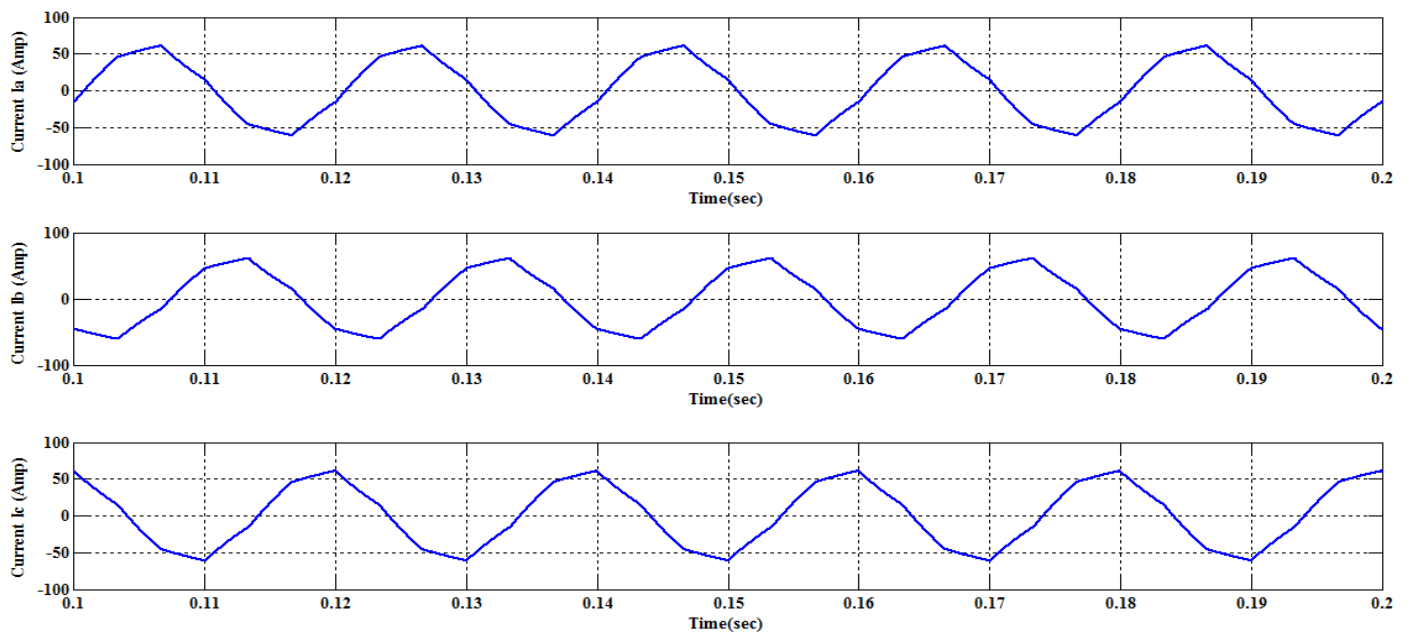


Figure 7 (b) Output Line Current of 1800 Three Phase VSI

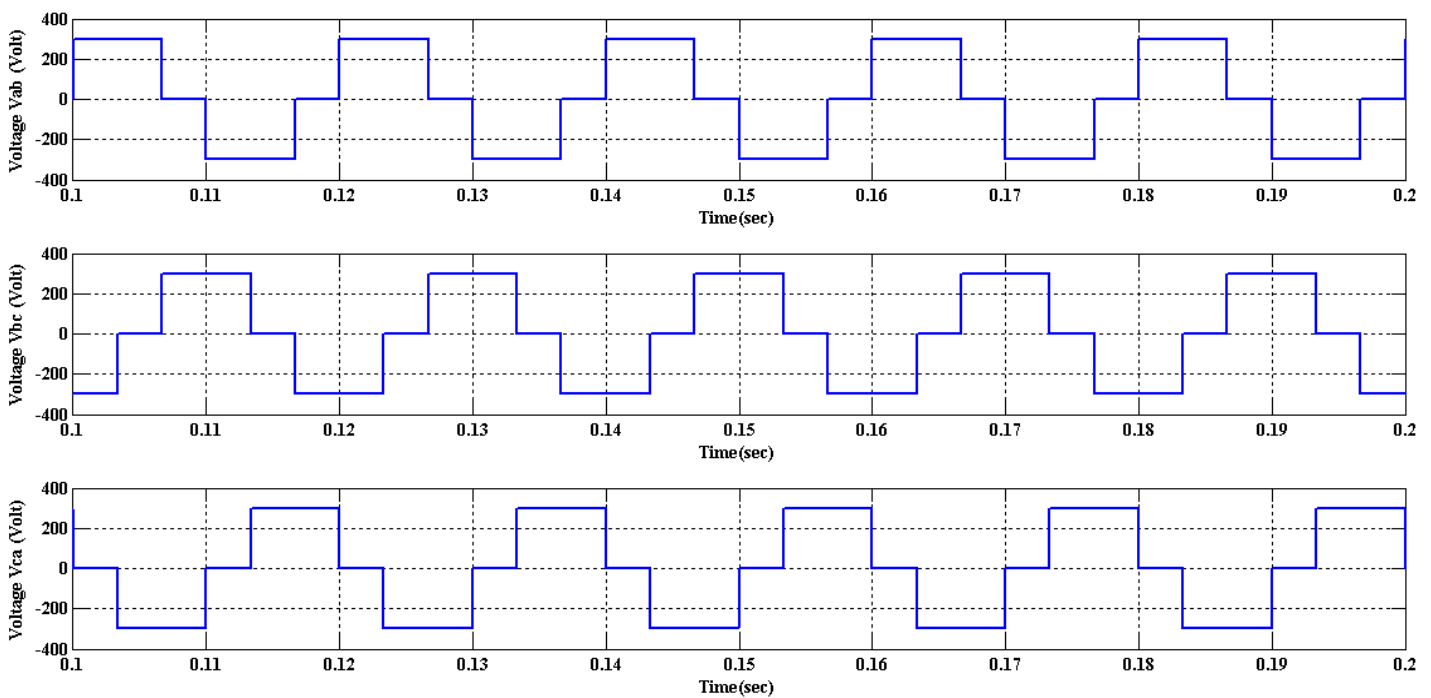


Figure 7 (c) Output Line Voltage of 1800 Three Phase VSI

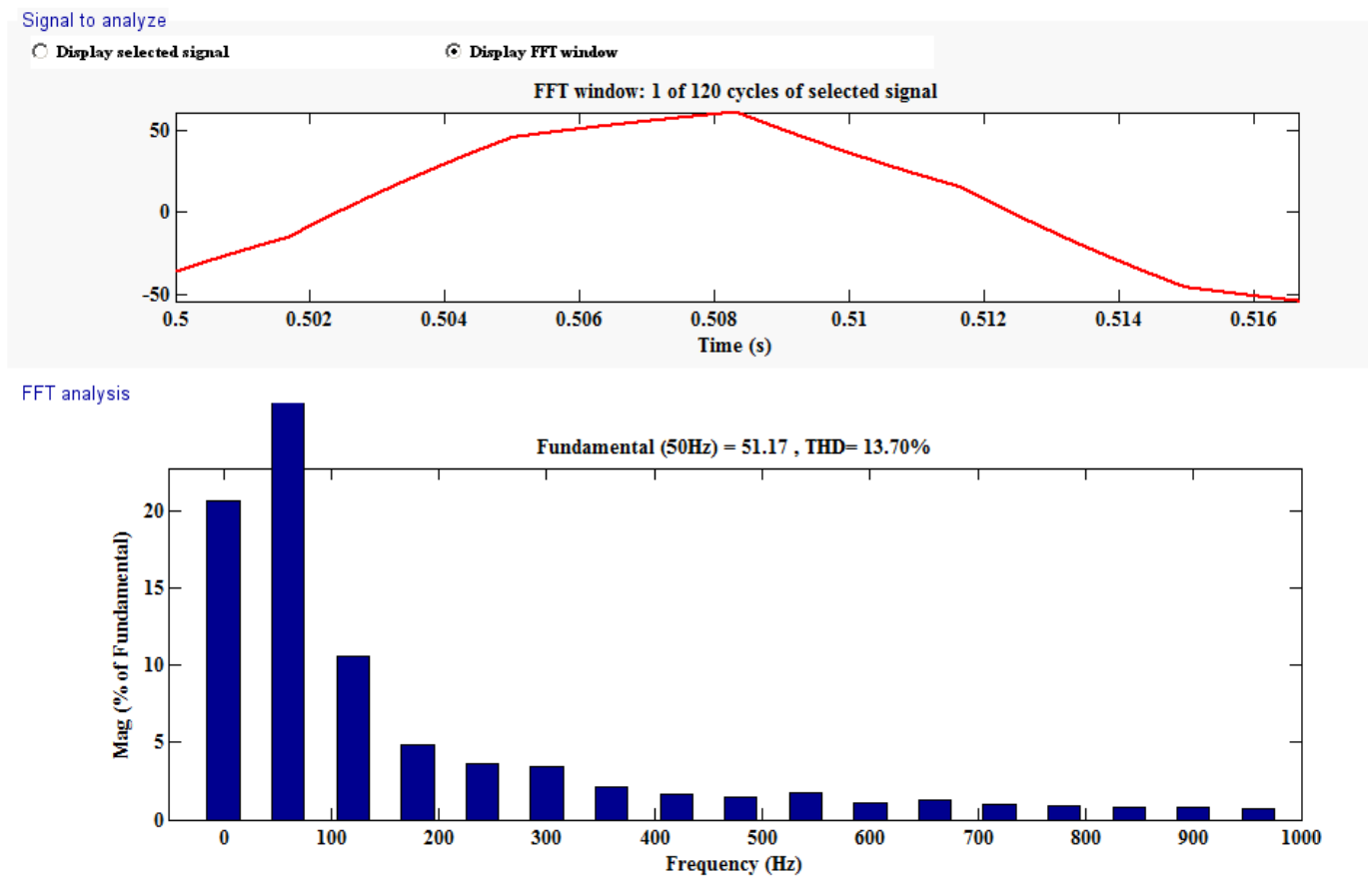


Figure 8 (a) FFT analysis of 1500 three phase VSI

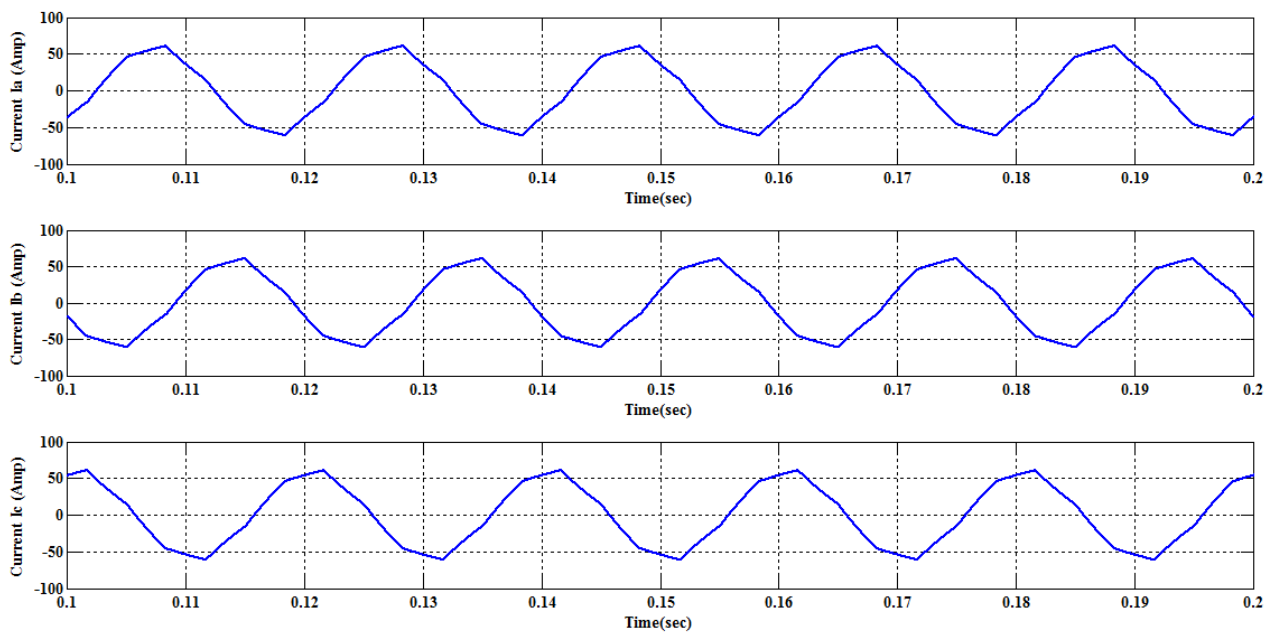


Figure 8 (b) Output Line Current of 1500 Three Phase VSI

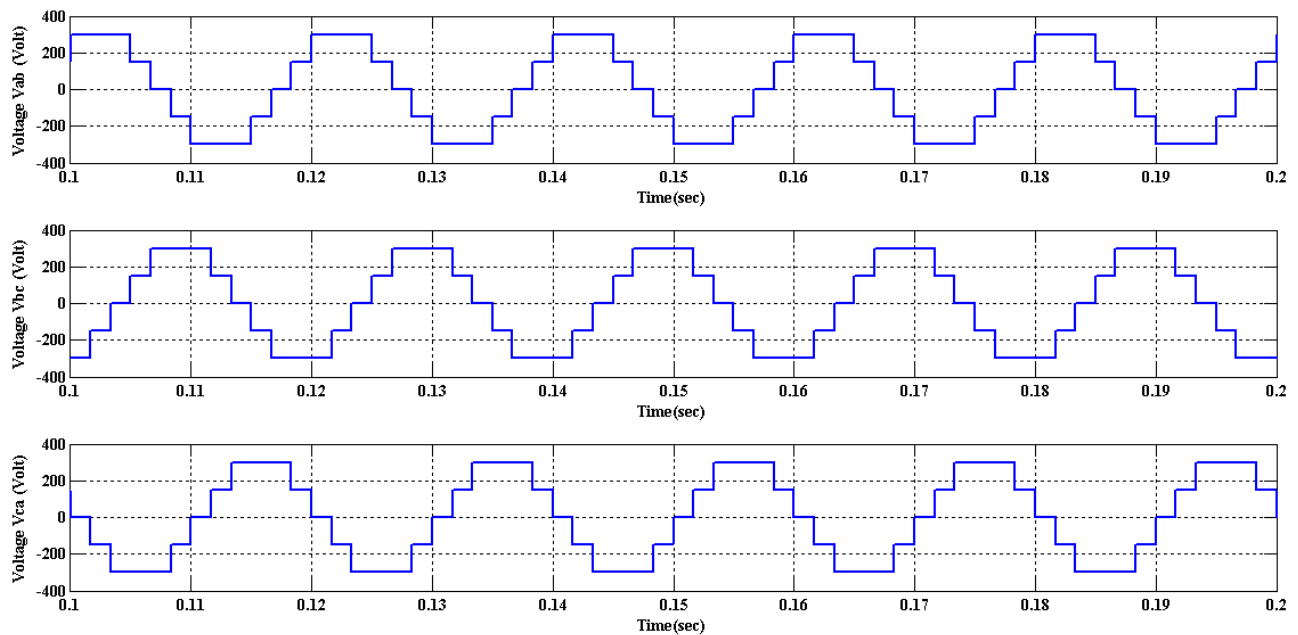
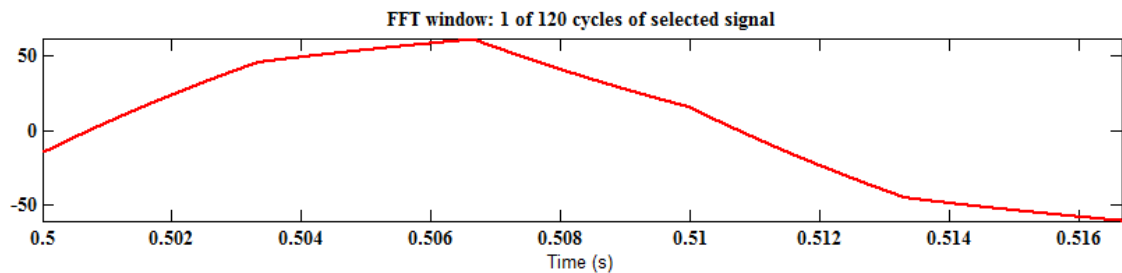


Figure 8 (c) Output Line Voltage of 1500 Three Phase VSI

Signal to analyze

☐ Display selected signal

☒ Display FFT window



FFT analysis

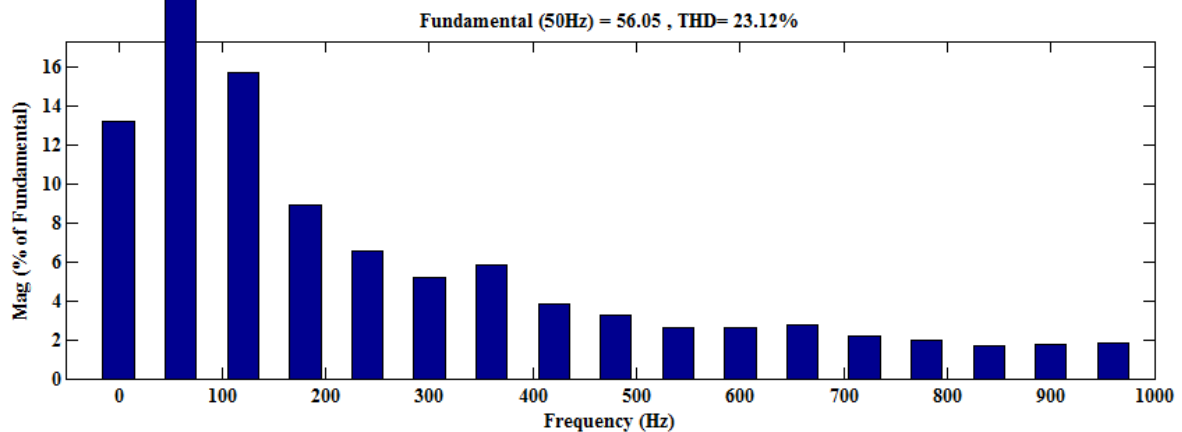


Figure 9 (a) FFT analysis of 1200 three phase VSI

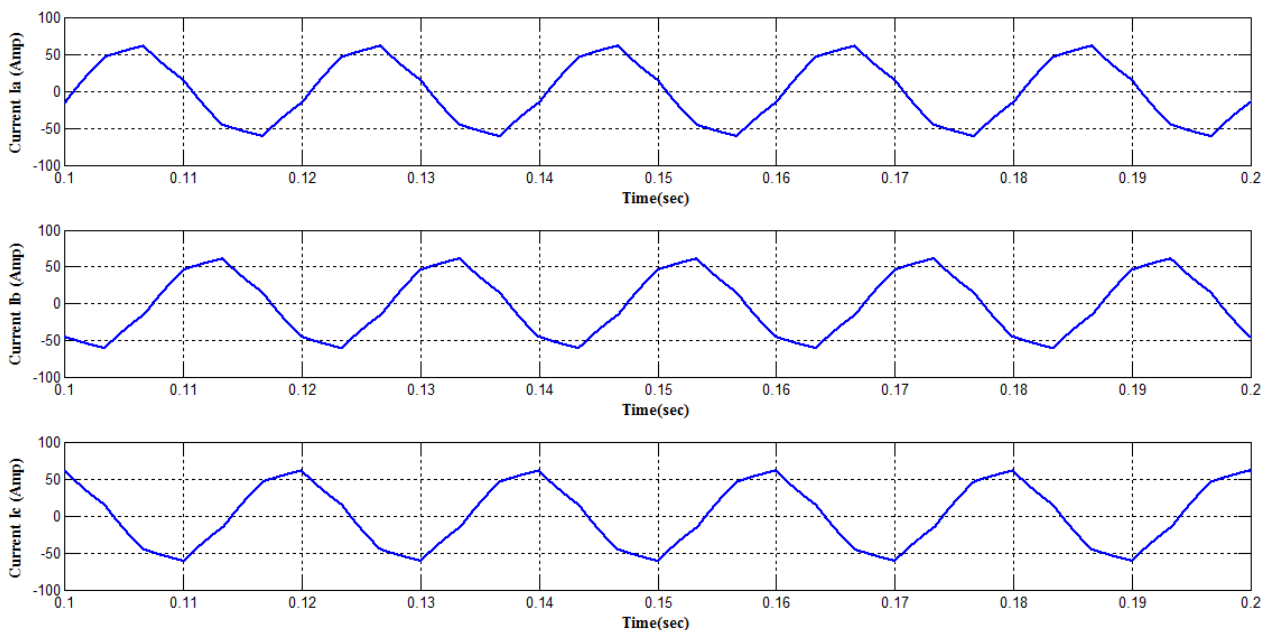


Figure 9 (b) Output Line Current of 1200 Three Phase VSI

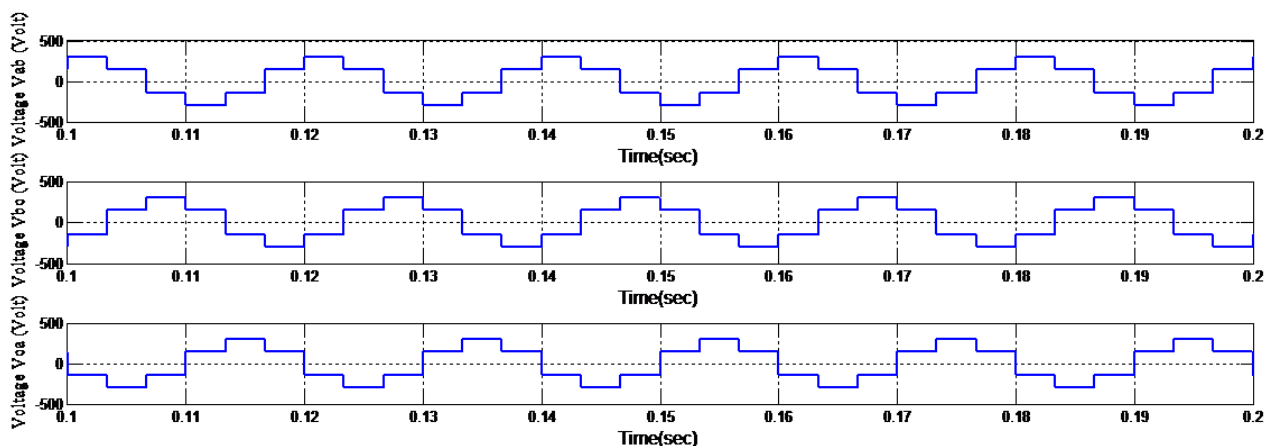


Figure 9 (c) Output Line Voltage of 1200 Three Phase VSI

On the basis of FFT analysis following observation is obtained:

Table 7 Comparison of THD in different modes

| Mode | Magnitude of fundamental (%) | THD (%) |
|-------------|------------------------------|---------|
| 180° | 57.93 | 14.86 |
| 120° | 56.05 | 14.12 |
| 150° | 51.17 | 13.70 |

Conclusion

In this article, simulink model for 3 phase Volatage Source Inverter (VSI) has been developed and tested in MATLAB/SIMULINK environment for different conduction modes. The method used to analyse the harmonic spectra of different output current is by comparing and plotting simulation results. THD (Total Harmonic Distortion) are also compared

to get a clear result. It is known that output with minimum THD will have minimum losses hence more efficient. The input is DC voltage source and output are 3 phase sinusoidal voltage in dc-to-ac inverter which are analysed in this paper. The frequency of output is lower than the switching frequency. Calculation of performance parameters i.e., THD for output voltages and THD for output current has been done using M-file coding. Using MATLAB

Simulation models, it was found that for RL of resistance equals to 1Ω and inductance equals to 5mH, THD is maximum in 1800 conduction mode and minimum in 1500 conduction mode.

Conflict of interest

The authors declare no conflict of interest.

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