Design and Analysis of A Three Phase Differential Boost Inverter

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Design and Analysis of A Three Phase Differential Boost Inverter

By

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Declaration

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

…………………………..

(Nushrat Sharita)

Dedication

To my beloved parents, husband, only brother and daughter.

The thesis entitled “Design and Analysis of A Three Phase Differential Boost Inverter.” Submitted by Nushrat sharita, Roll No. 040506105F, Session April 2005 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING on March 2011.

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Abstract

In this thesis a three phase differential boost inverter is designed . ORCAD Capture 9.1 simulations are used to perform the analysis of the inverter. The output voltage of traditional single or three phase inverter is sinusoidal at any particular frequency. But the output voltage of three phase inverter is non-sinusoidal at variable frequency. Different control technique/strategy such as linear control technique, sliding mode control technique etc has been developed where output voltage is controlled by both voltage and current feedback. To make output voltage of the designed inverter sinusoidal at different variable frequency a control circuit has been designed where only voltage feedback technique is used. The three phase differential boost inverter is designed where a reduced number of feedback from the power circuit to the control circuit is used.

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CHAPTER 1

Introduction

1.1. Introduction

A DC-DC converter is a device that accepts a DC input voltage and produces a DC output voltage. Typically the output produced is at different voltage level than the input. In addition, DC-DC converters are used to provide noise isolation, power bus regulation, etc [1-2].

DC-DC power converters are employed in a variety of application, including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunication equipment, as well as DC motor drives.

The input to a DC-DC converter is an unregulated dc voltage. The converter produces regulated output voltage, having a magnitude (and possibly polarity) that differs from the input. This is achieved using switched- mode, or chopper circuits, whose elements dissipate negligible power. Pulse-With Modulation (PWM) allows control and regulation of the output voltage.

1.2. Literature Review

1.2.1. Modeling of the Boost Inverter

The DC and small-signal performance of a boost converter can be determined by substituting the circuit by PWM switch model [3-7] and analyzing the resulting linear circuit [8, 9]. The accuracy of the model depends on switching period, power device non-linearity, command dead times etc.

The boost inverter is modeled in [10] using PWM switch model [3]. Controller design analysis is not done [10] and behavior of output voltage under load and source variations is not reported. Here a converter is modeled using the models of the current-bidirectional switch based PWM converter [5]. The main step is to replace converter phase legs with voltage and current sources. The waveforms of voltage and current sources are identical to the switch waveforms of the converter. Then the converter waveforms are averaged over one switching period to remove switching harmonics. Any nonlinear element in the phase leg‟s average model is perturbed and linearized leading to small-signal ac model [11].

1.2.2. Techniques for Controlling Boost Inverter

Several control techniques have been proposed to control the individual boost converter of the boost inverter [12, 13-19].

Controlled based on Energy shaping theory [14] is limited to known resistive load only. The theory is a complex one. Later the controller is modified [15] to drive known resistive and inductive load. For different load the control parameters need to be readjusted, which makes it less worthy.

Controller based on passivity theory [16] involves current mode control. Only resistive load operation is reported.

An adaptive control [17] is designed for the boost inverter in order to cope with unknown resistive load. This involves very complex non-linear control theory.

A double-loop regulation scheme [18] is a very robust controller including compensations in order to cope with the boost variable operation point condition. The circuit is highly complex. At least four current sensors are necessary in order to implement this control strategy. It involves complex implementation of the circuit and high cost.

H^{∞} control [19] can be used to control individual DC-DC boost converter. In H^{∞} control strategy, the controls can be formulated to directly include the reduction of the output impedance as much as possible. It would thus appear that the H^{∞} control could overcome some difficulties encountered with conventional control approach. But it has current mode controller which includes both voltage and current-feedback loops. The inductor current is being measured and fed to so-called inner-loop controller. The later helps to stabilize the system. But it includes additional circuit components and adds complexity to the control system. A simplified controller with only voltage mode control is described [20].

The Sliding mode controller [12, 13] involves complex theory, variable switching frequency and also involves current mode control in addition to voltage mode. At least two current sensors are necessary in order to implement this control strategy. This implies high cost and rather complex implementation. The effect of supply voltage variation on output voltage is not reported.

A simplified sliding mode controller can be a good option to control the DC-AC boost inverter. Reduced number of feedback variable to one by modifying the scheme referenced in [12,20] will be used for generating the switching signals of the six switches of the three phase inverter.

1.3. Objectives

The main objective of the present research work is to extend the proposed single phase DC-AC scheme of references [12, 14, 20, 21] to make a three phase inverter. The aim of this work is to design a three phase inverter which will generate an output voltage lower than the DC input one. Also, the control strategy is designed to reduce the number of feedback from the power circuit to the control circuit. Appropriate power circuit will be proposed and implemented (by simulation) to meet this objective. Topological modification of the original DC-DC converter is done to achieve this objective.

Modifications of power circuit will be done by providing voltage lift circuit in each leg of the DC-DC converter to provide path for four quadrant operation as necessary in the inverters.

Modification of the scheme will be made to reduce the feedback variable to one. Three legs of the DC-DC converters of the three phase inverter will be controlled using voltage mode control PWM technique by comparing a saw tooth ramp carrier with a reference sine wave and standard feedback technique from the load voltage.

Reduction of the feedback will be the result of use of voltage lift circuit, which makes output voltage input current insensitive.

1.4. Organization of the Thesis

Chapter 1 includes background of single and three phase boost inverter with different control technology for single or three phase inverter and objective of the thesis.
Chapter 2 describes introduction of power converter modeling, simplified modeling and operation of single phase boost inverter. Proposed three phase power circuit and a control technology have been designed. Manual and automatic control technology is designed to control the output of the proposed inverter.
Chapter 3 includes simulation results and analysis of the proposed three phase differential boost inverter. And their simulation results are also presented.
Chapter 4 concludes the thesis with some recommendations for future research.

CHAPTER 2

Proposed Three Phase Boost Inverter with Differential Mode Control

2.1. The Conventional VSI

Voltage source inverters, as the name indicate, receive DC voltage at one side and invert it to other side. The conventional single phase voltage source inverter (VSI) in Figure.2.1 uses the topology which has the characteristic that the average output voltage is always lower than the input DC voltage. Thus if an output voltage higher than the input one is needed, a boost DC-DC converter must be used between the source and the inverter, shown in Figure. 2. 2. [10, 12, 22-28]

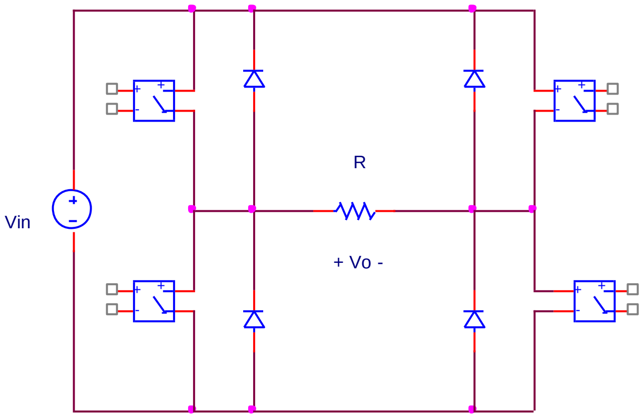


Figure 2.1: The conventional voltage source inverter or buck inverter

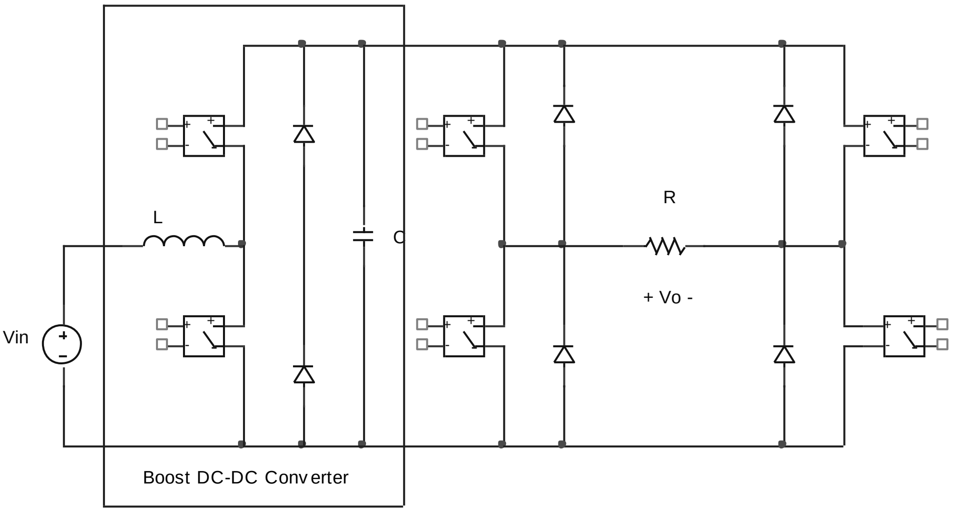


Figure 2.2: Circuit used to generate an AC voltage larger than DC input voltage

2.2. Analysis of the Converter Waveforms

Under steady-state conditions, the voltage and the current waveforms of a DC-DC converter can be found by using of two basic circuit analysis principles. The principle of inductor volt-second balance states that the average value, or DC component, of voltage applied across an ideal inductor winding must be zero. This principle also applies to each winding of a transformer or other multiple winding magnetic devices. The principle of capacitor amp-second or charge balance states that the average current that flows through an ideal capacitor must be zero. Hence, to determine the voltage and current of DC-DC converters operating in periodic steady state, one averages the inductor current and capacitor voltage waveforms over one switching period, and equates the results to zero. The inductor current and capacitor voltage contains dc components, plus switching ripple at the switching frequency and its harmonics. In most well designed converters, the switching ripple is small in magnitude compared to the DC components. For inductor currents, a typical value of switching ripple at maximum load is 10% to 28% of the dc component of current. For an output capacitor voltage, the switching ripple is typically reduced to be much less than 1% of the DC output voltage. In both cases, the ripple magnitude is small compared with the dc component, and can be ignored.

Some of the popular DC-DC converter topologies are:

1. Buck Converter/ Step down converter.
2. Boost Converter/ Step up converter.
3. Buck-Boost Converter/ Step up-down converter
4. Cuk Converter

2.2.1. Buck Converter

The buck converter, also known as the step down converter, is a switching converter that has the five basic components, namely a power semiconductor switch, a diode, an inductor, a capacitor and a PWM controller. This converter produces an output voltage lower than the source. Here,

$$\frac{V_o}{V_{in}} = \frac{t_{on}}{T}$$

and defining "duty ratio" as

$$D=\frac{t_{on}}{T}$$

The voltage relationship becomes $V_o=DV_{in}$. Since the circuit is lossless and the input and output powers must on the average $V_o*I_o=V_{in}*I_{in}$. Thus the average input and output current must satisfy $I_{in}=DI_o$ These relations are based on the assumption that the inductor current does not reach zero (continuous conduction mode).

2.2.2. Boost Converter

The boost converter, also known as the step-up converter, is another switching converter that has the same components as the buck converter, but this converter produces an output voltage greater than the source. The ideal boost converter has the five basic components, namely a power semiconductor switch, a diode, an inductor, a capacitor and a PWM controller. The placement of the inductor, the switch and the diode in the boost converter is different from that of the buck converter. Here

$$\frac{V_o}{V_{in}} = \frac{T}{t_{off}} = \frac{1}{(1-D)}$$

Since the duty ratio "D" is between 0 and 1 the output voltage must always be higher than the input voltage in magnitude.

2.2.3. Buck-Boost Converter

Here the output voltage may be higher or lower than the source depending upon the value of D. The circuit components are same. Here,

$$\frac{V_o}{V_{in}} = \frac{-D}{(1-D)}$$

Since the duty ratio "D" is between 0 and 1 the output voltage can vary between lower or higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.

2.2.4. Cuk Converter

The buck, boost and buck-boost converters all transferred energy between input and output using the inductor, analysis is based on voltage balance across the inductor. The Cuk converter uses capacitive energy transfer and analysis is based on current balance of the capacitor. Here,

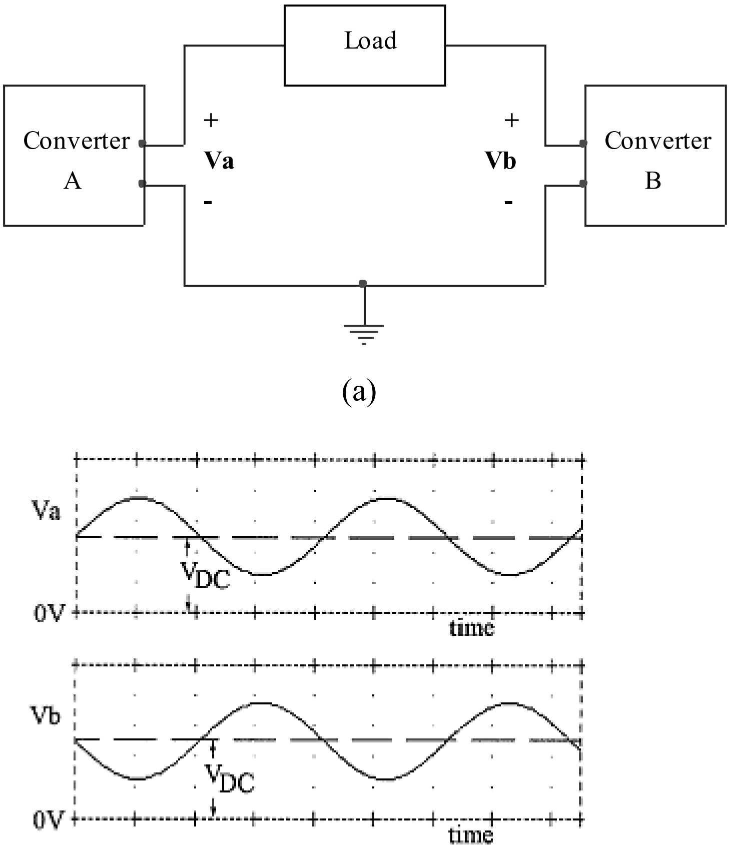
$$\frac{V_o}{V_{in}} = -\frac{D}{(1-D)}$$

Thus the voltage ratio is the same as the buck-boost converter.

2.3. Boost Inverter Circuit

The boost inverter achieves dc–ac conversion [10, 12] as indicated in Figure. 2. 3. (a) by connecting the load differentially across two DC-DC converters and modulating the dc–dc converter output voltages sinusoidally.

The blocks A and B represent dc–dc converters. These converters produce a dc-biased sine wave output, so that each source only produces a unipolar voltage. The modulation of each converter is 180° out of phase with the other, which maximizes the voltage excursion across the load. The load is connected differentially across the converters. Thus, whereas a dc bias appears at each end of the load, with respect to ground, the differential dc voltage across the load is zero. The generating bipolar voltage at output is solved by a push–pull arrangement. Thus, the DC-DC converters need to be current bidirectional.



(a)

(b)

Figure 2.3: A basic approach to achieve DC-AC conversion, with boost characteristics

The current bidirectional boost dc–dc converter is shown in Fig.2.4. A circuit implementation of the boost DC-AC converter is shown in Fig.2.5.

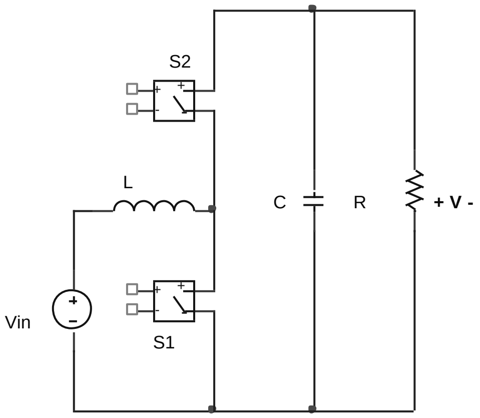


Figure 2.4: The current bi-directional boost converter

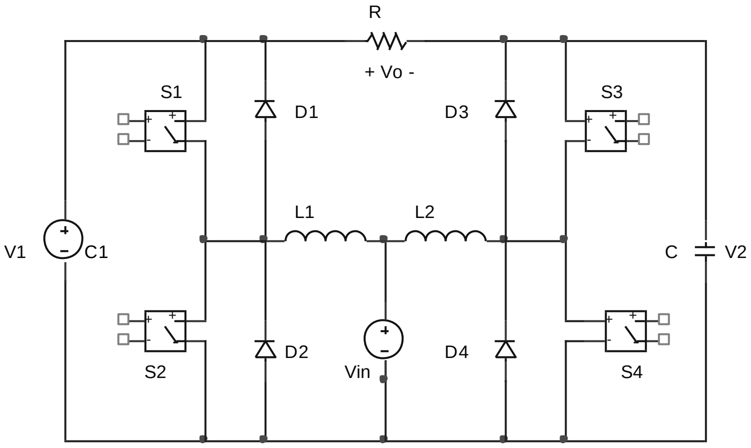


Figure 2.5: DC-AC boost converter

2.4. Circuit Operation of One Leg for the Boost Inverter

For a dc–dc boost converter, by using the averaging concept, we obtain the voltage relationship for the continuous conduction mode given by the operation of the inverter, which can be explained by considering one converter A only as shown in Figure 2.6. There are two modes of operation: mode 1 and mode 2.

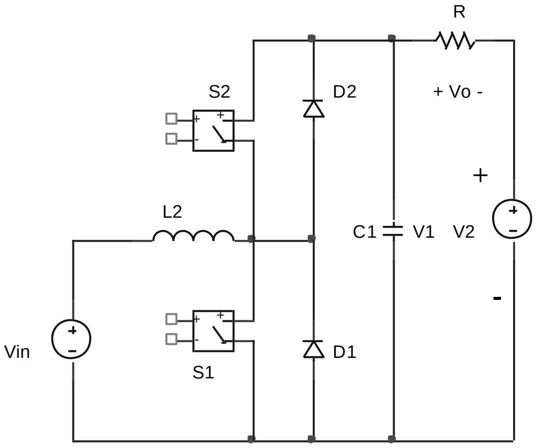
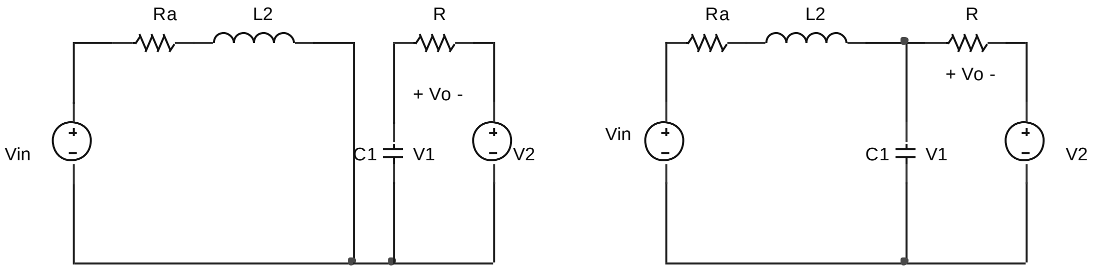


Figure 2. 6: Equivalent circuit of one leg for the boost inverter

Mode 1: When the switch S_1 is closed and S_2 is open as shown in Figure 2.7(a), current I_{L2} rises quite linearly, diode D_1 is reverse polarized, capacitor C1 supplies energy to the output stage, and voltage V_1 decreases.

Mode 2: When switch S_1 is open and S_2 is closed as shown in Figure 2.7(b), current I_{L2} flows through capacitor and the output stage. The current I_{L2} decreases while capacitor C_1 is recharged.



(a) Mode 1: S_1 is closed and S_2 is open (b) Mode 2: S_1 is open and S_2 is closed

Figure 2. 7: Circuit mode of Operation

The average output of converter A, which operates under the boost mode, can be found from

At mode 1: $V_{La} = V_{in}$

At mode 2: $V_{La} = V_{in} - V_0$

From the above two equations,

⇨ $V_{La}T_{ON} + V_{L2}T_{OFF}=0$

⇨ $V_{in}T_{ON} + (V_{in}-V_0)\ T_{OFF}=0$

⇨ $V_{in}T_{ON} + V_{in}T_{OFF}= V_oT_{OFF}$

⇨ $V_{in}T = V_o(T-T_{On})$

⇨ $\frac{V_o}{V_{in}} = \frac{T}{T-T_{ON}}$

⇨ $\frac{V_o}{V_{in}} = \frac{D}{1-D}$

So, $\frac{V_1}{V_{in}} = \frac{1}{1-D}$ .... (1)

The average output of converter B, assuming which operates 180° out of phase, can be found

$$\frac{V_2}{V_{in}} = \frac{1}{D} \quad \text{..................} \ (2)$$

Therefore, the average output voltage is given by

$$V_O = V_1-V_2 = \frac{V_{in}}{1-D} - \frac{V_{in}}{D} \text{..................}(3)$$

This gives the dc gain of the boost inverter as

$$G_{dc}= \frac{V_O}{V_{in}} = \frac{2D-1}{D(1-D)} \text{..................} \ (4)$$

Where D is the duty cycle.

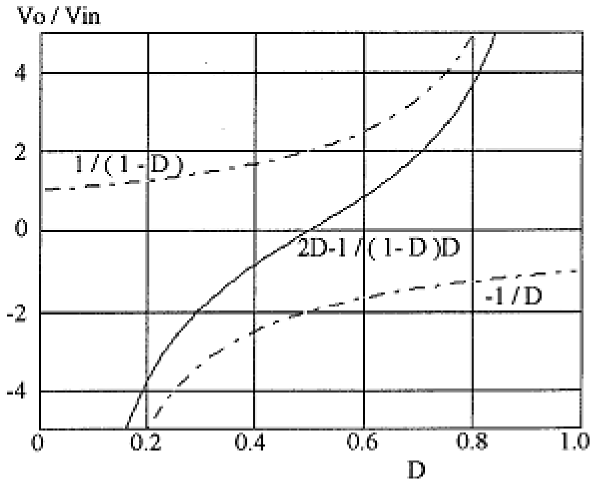


Figure 2. 8: DC gain characteristic

The gain characteristic of the boost inverter is shown in figure 2.8. It is noted that V_0 becomes zero at D=0.5. If the duty cycle D is varied around the quiescent point of 50% duty cycle, there is an ac voltage across the load. Because the output voltage in equation (3) is twice the sinusoidal component of converter A, the peak output voltage equals to

$$V_{0(pk)} = 2V_m = 2V_1 - 2V_{dc} \ldots\ldots\ldots\ldots(5)$$

Because the boost converter cannot produce an output voltage lower than the input voltage, the dc component must satisfy the condition

$$V_{dc} \geq (V_m + V_{in})$$

Which implies there are many possible values of V_{dc}. However, the equal term produces the least stress on the devices. From the equation (5), we get

$$V_{0(pk)} = \frac{2V_{in}}{1-D} - 2(\frac{V_{0\,(pk)}}{2} + V_{in})$$

Which gives the ac voltage gain is

$$G_{ac} = \frac{V_{O\,(pk)}}{V_{in}} = \frac{D}{(1-D)} \ldots\ldots\ldots\ldots(6)$$

Thus, $V_{o(pk)}$ becomes V_{in} at D=0.5.

The output current is given by

$$I_0 = \frac{V_O}{R} = \frac{V_{in}(2D-1)}{RD(1-D)} \qquad \text{............(7)}$$

From equation (4) it is shown that if duty cycle (D) >0.5, the output voltage is less than input voltage ($V_{in} > V_o$) and when duty cycle (D) < 0.5, the output voltage is greater than input voltage ($V_{in} < V_o$).

In the proposed three phase boost DC-AC converter circuit implementation has been designed so that the duty cycle (D) > 0.5. So output voltage is less than input voltage.

2.5. Proposed Single Phase Boost Differential Inverter Circuit

2.5.1. Power Circuit Design

Single phase boost DC-AC converter [10, 12] cannot be implemented for three phase differential boost inverter, moreover circuit implementation has been designed so that the output voltage is less than the input one. So the boost DC-AC converter [10, 12] shown in figure 2.5 has been modified. In figure 2.9. single phase boost DC-AC converter has been proposed. Voltage deep circuit has been used in the power circuit where voltage charges through capacitor C_3 or C_4 and discharges through capacitor C_1 or C_2. If three single phase boost inverters can be combined three phase output voltage will produce and If we separate a single phase from the three phase circuit it will produce single phase output voltage.

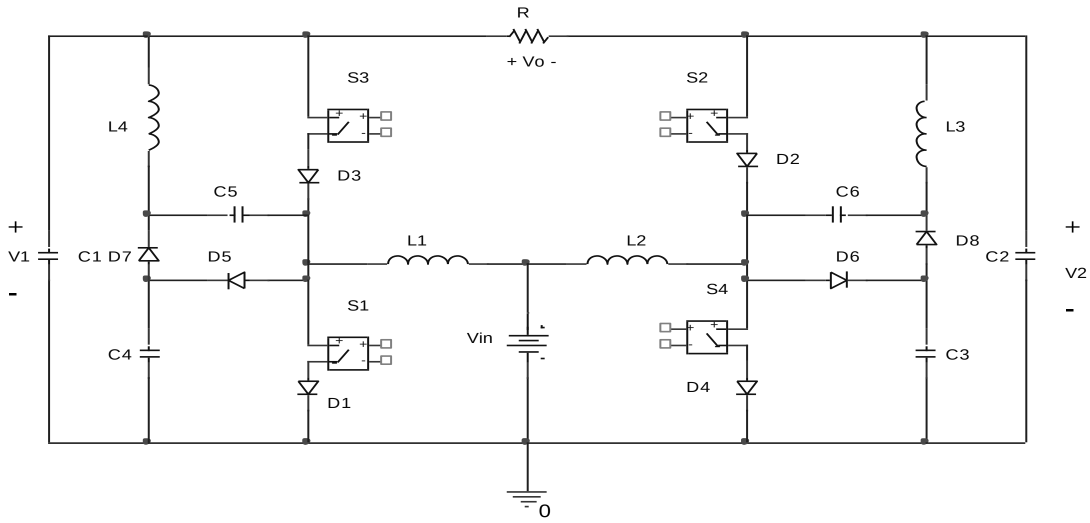


Figure 2. 9: Single phase differential boost inverter

In figure 2.9 DC voltage is given to the input (V_{in}) and single phase AC voltage is found across the load (R).

2.5.2. Gate Drive Circuit for Single Phase Boost Differential Inverter Circuit

To operate the switches (S_1, S_2, S_3 and S_4) shown in figure 2.9 switching circuit or gate drive circiut is needed. In the switching circuit a triangular carrer signal and sinusoidal modulating signal produce gating signal by Pulse Width Modulation (PWM). The switching circuit or gate drive circiut for the switches S_1, S_4 is shown in figure 2.10. The modulating signal for the switches S_2, S_3 has 120^0 degree phase difference.

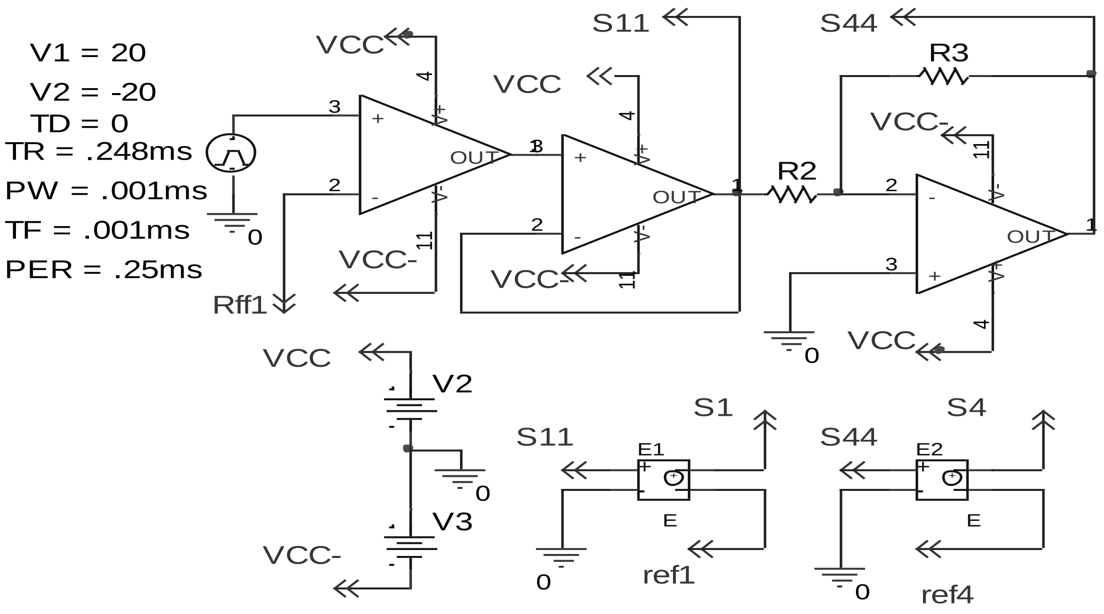


Figure 2. 10: Switching circuit for the switches S_1, S_3

Modulating signal (R_{ff1}) and career triangular signal generate the signals for the gate drive circuit (switches S_1, S_3) by Pulse Width Modulation (PWM) . Modulating signal (R_{ff1}) and career triangular signal are shown in figure 2.11.

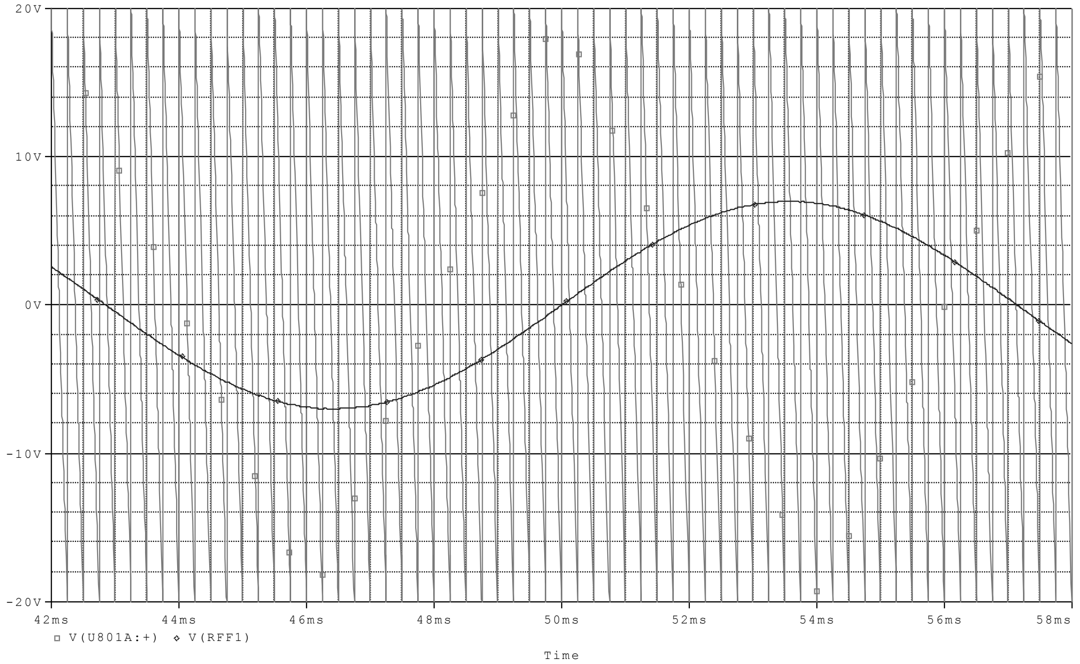


Figure 2. 11: Modulating and Carrier signal

The duty ratio for the inverter,

$$D = \frac{t_{on}}{T} = 0.99$$

Modulating signal and career signal generate the modulated signals which is given to the gate of one MOSFET. This modulated signal is inverted to drive another MOSFET of one leg of the single phase inverter. Thus each pulse generator circuit creates digital signals for every MOSFET. The modulated and inverse modulated signals are shown in figure 2.12

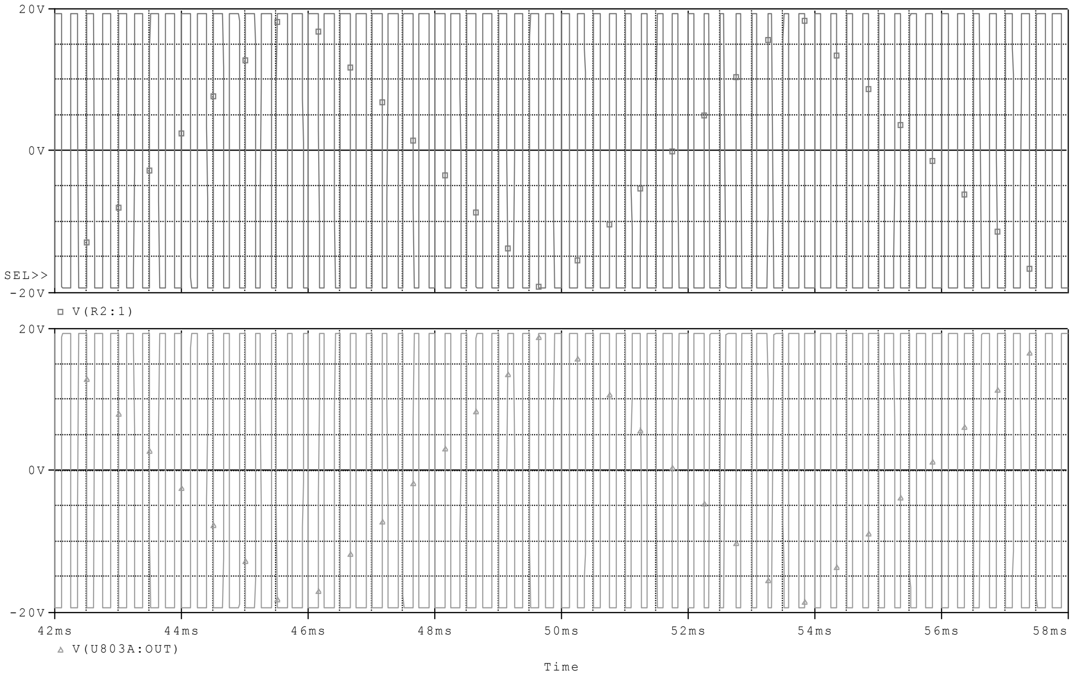


Figure 2. 12: Modulated and inverse modulated signal

Output voltage of the single phase differential boost inverter across load for different modulating frequency is shown in figure 2.13 (a) and (b).

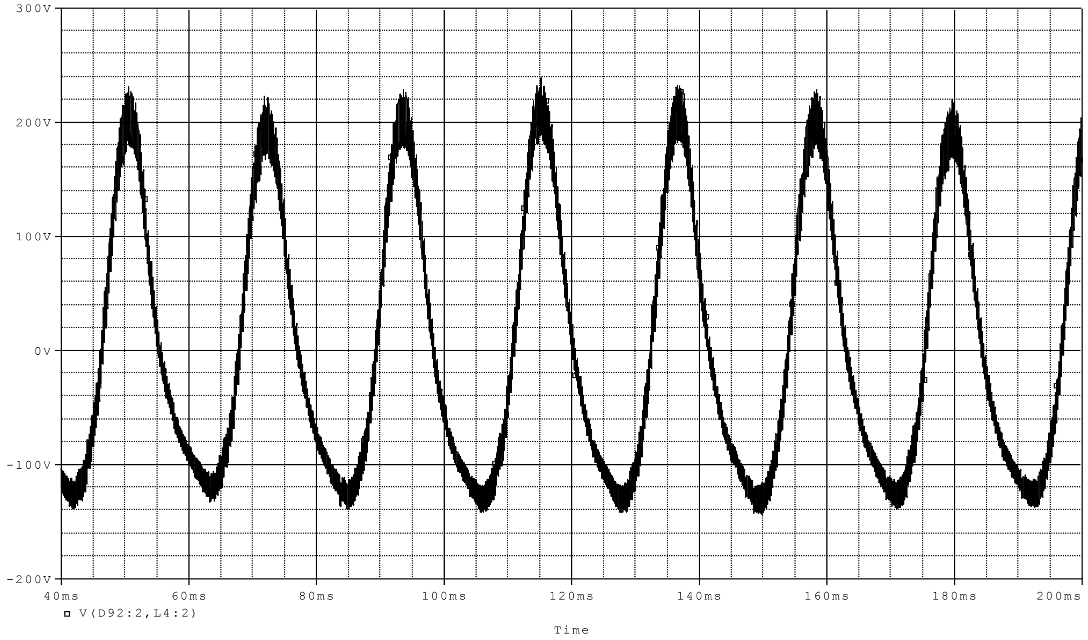


Fig 2. 13 (a) Output voltage for modulating frequency 46.5 Hz and 7 v

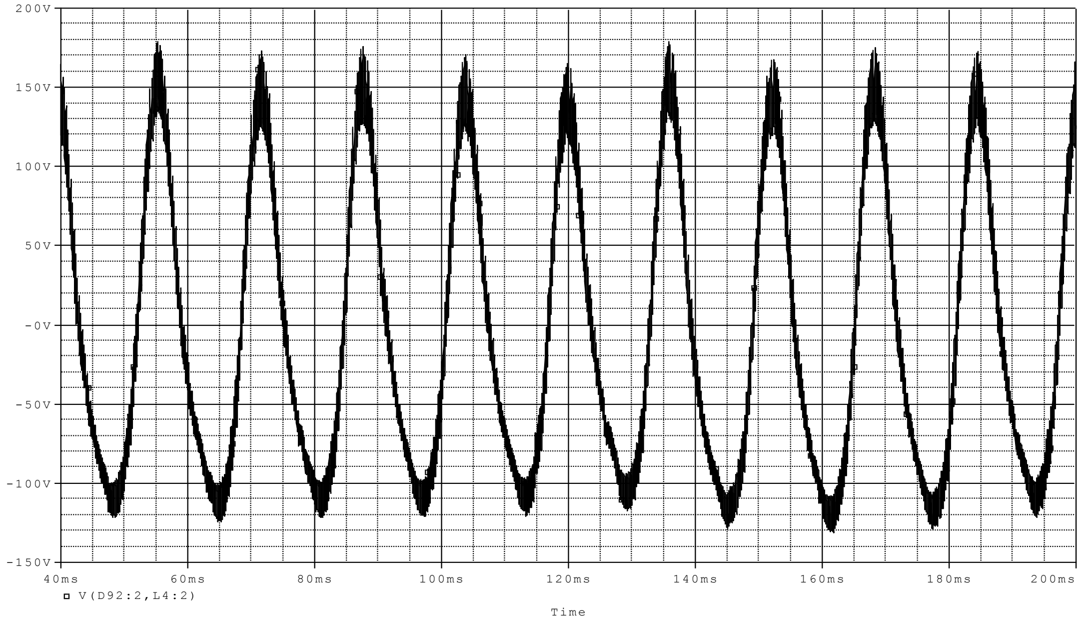


Fig 2. 13 (b) Output voltage for modulating frequency 62 Hz and 8.6 volt

Figure 2. 13: Output voltage of the single phase boost inverter

It is observed from the figure 2.13 that the output voltage of the single phase boost inverter is sinusoidal.

2.6. The three phase boost inverter

In three phase boost inverter the DC electric power is converted to AC. This is virtually implemented with one that is shown at the Figure 2.14. In [29] a 3 leg inverter for 3-phase conversion is shown which is composed of 6 MOSFETs and control unit. The control unit generates control pulses to drive the MOSFETs. The pulse generator gives a digital signal to the MOSFETs. When the signal from the pulse generator is not zero then it reacts as a switch and opens. This consists of the basic operation in order to convert the DC to AC, with the technique of the Pulse Width Modulation (PWM). For the time interval the MOSFETs are open, A pulse is produced at power circuit. The RMS time integral gives the output values. The on-off is determined by a control unit which is analyzed below. The modulation factor m_a can be used as a parameter for the dynamic control of the system. By changing m_a the output voltage is controlled. The losses will be analogue to the change over the m_a. A useful reference for cascaded multilevel converters which discuses the control circuit of new topology is shown in [30].

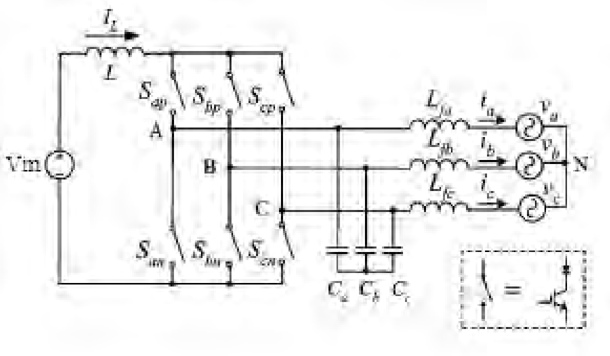


Figure 2. 14: Power stage of the differential mode boost type inverter

Fig.2.14. shows the power stage of the three-phase boost-type grid connected inverter, where V_{in} is a dc voltage source, v_a, v_b, and v_c are three-phase ac voltages, and L_{fa}, L_{fb}, L_{fc} and C_a, C_b, C_c form an output filter. Each switch of the bridge is realized by a MOSFET in series with a diode as shown in the dashed line box.

According to the zero-crossing points of grid voltages, each line cycle can be divided into six regions as shown in Fig.2.15.

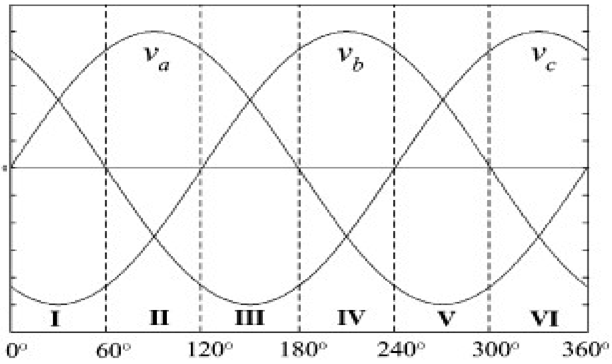


Figure 2. 15: Six regions in a line cycle

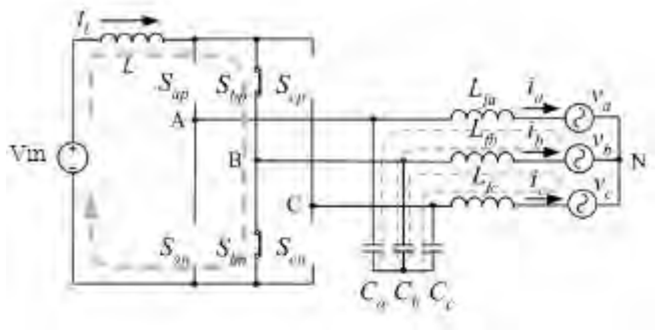


Fig 2. 16 (a)

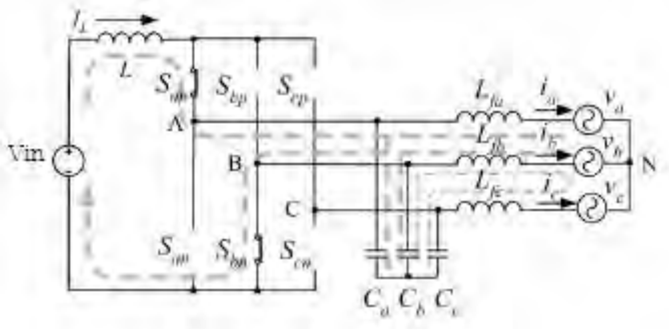


Fig 2. 16 (b)

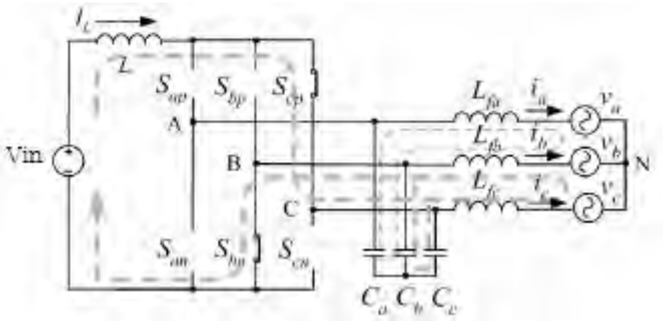


Fig 2. 16 (c)

Figure 2. 16: Three stages for different switching patterns in Region I. (a) Stage I. (a) Stage II. (c) Stage III

Region I, S_{an} and S_{cn} are kept off and S_{bn} is on for the entire region, while switches S_{ap}, S_{bp}, and S_{cp} are operated at the switching frequency. There are three stages with different

switching strategies in Region I:

1) In Stage I [Fig. 2. 16 (a)], S_{bp} is turned on and S_{ap} , S_{cp} are off. The inductor current I_L increases, and output currents are supplied by C_a, C_b, C_c.

2) In Stage II [Fig. 2. 16 (b)], S_{ap} is turned on and S_{bp}, S_{cp} are off. The inductor current I_L discharges through C_a, C_b and the grid v_a, v_b. Current i_c is supplied by C_c, C_b.

3) In Stage III [Fig. 2. 16 (c)], S_{cp} is turned on and S_{ap}, S_{bp} are off. I_L decreases through C_c, C_b and v_c, v_b. i_a is supplied by C_a, $C_{b..}$

2.7. Proposed Three Phase Boost Inverter Circuit

In the proposed three phase differential boost inverter power stage and switching strategy generates the output voltage which is less than the input voltage. In figure 2.17 the proposed three phase boost inverter has been shown where three single phase boost inverters have been combined to produce three phase output voltage. Here differential concept has been implemented to create the output voltage. Magnitude of the output voltage of the proposed three phase boost inverter is almost constant for different modulating frequency. Three phase AC can be achieved by introducing three DC-AC boost converters along with modulated switching wave produced from reference sine wave with difference 120° phase shift. The proposed three phase boost inverter is designed with only voltage feedback from the power circuit to the control circuit which simplifies the control strategy.

2.7.1. Power Circuit for Three Phase Boost Inverter Circuit

In Figure 2.17 power circuit has been developed for three phase boost type inverter. Modification of power circuit from that of proposed in single phase application has been made for each leg to provide path for four quadrant operation. To drive 6 MOSFET‟s three gate drive circuit have been designed like single phase single phase boost differential inverter. Modulated signals found in each phase are 180° out of phase with one another and modulated signals for each phase have 120° phase difference as the modulating signals (V_{sina}, V_{sinb} and V_{sinc}) have 120° phase difference. A control circuit has also been designed to control output voltage for different modulating voltage and frequency. Output voltages for different modulating voltage and frequency have been shown in figure 3.1(a-k).

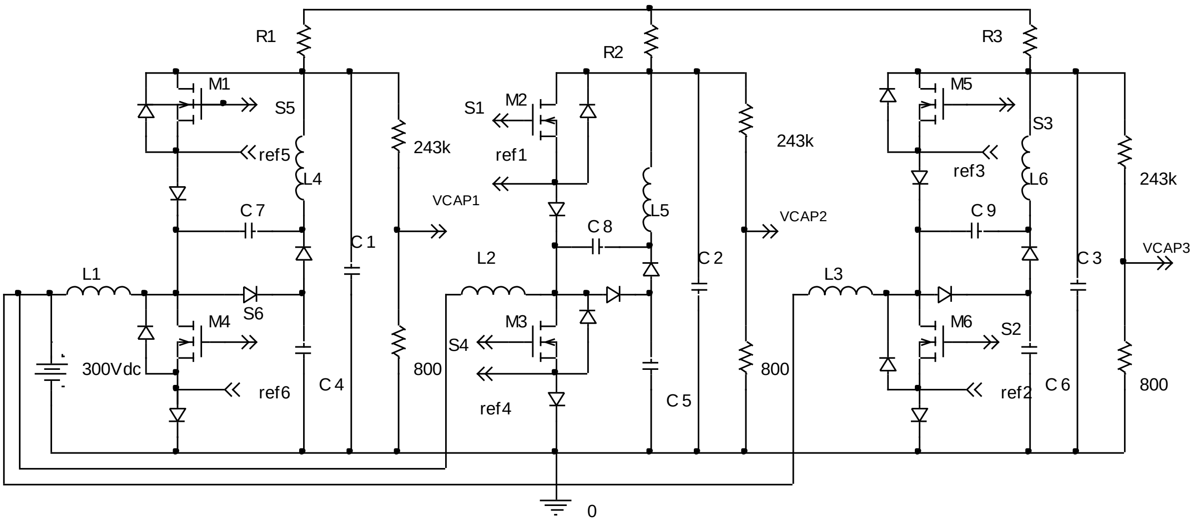


Figure 2. 17: Proposed three phase differential boost inverter circuit

In figure 2.17 power circuit for three phase differential boost inverter is designed where only voltage feedback from the power circuit is given to the control circuit.

2.7.2. Manual Control Circuit for Three Phase Boost Inverter

Three modulating signals with 120° phase difference are given from a control circuit shown in figure 2.18. The magnitude and frequency of the modulating signal is controlled manually. Magnitude and frequency of the modulating signals can be changed from V_{sina}, V_{sinb} and V_{sinc} in figure 2.18.

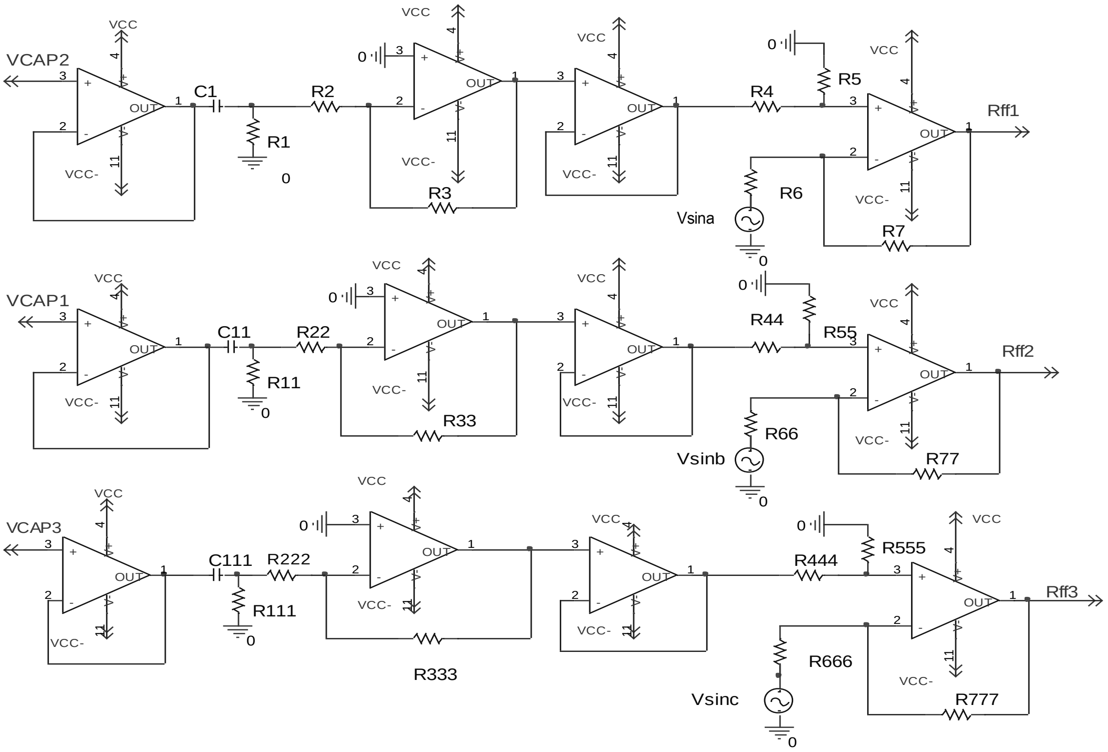


Figure 2.18: Manual Control Circuit

The output voltage of the proposed three phase inverter can be controlled by the modulating signal V_{sina}, V_{sinb} and V_{sinc} . The output voltage for different modulating signals are shown in figure 3.2(a-k).

It is observed from figure 3.2(a-k) that output voltage of the proposed three phase boost inverter is constant and sinusoidal if it is controlled manually.

2.7.3. Automatic Control Circuit for Three Phase Boost Inverter

The output voltage of the proposed three phase boost inverter can be varied by controlling the amplitude and frequency of the modulating signal manually as described in the previous section. An automatic three phase voltage control oscillator has been designed in figure 2.19 to simplify the control strategy. It will automatically control the modulating signal and as well as output voltage . Amplitude and frequency of the modulating signal can be controlled only by controlling the control voltage V_c.

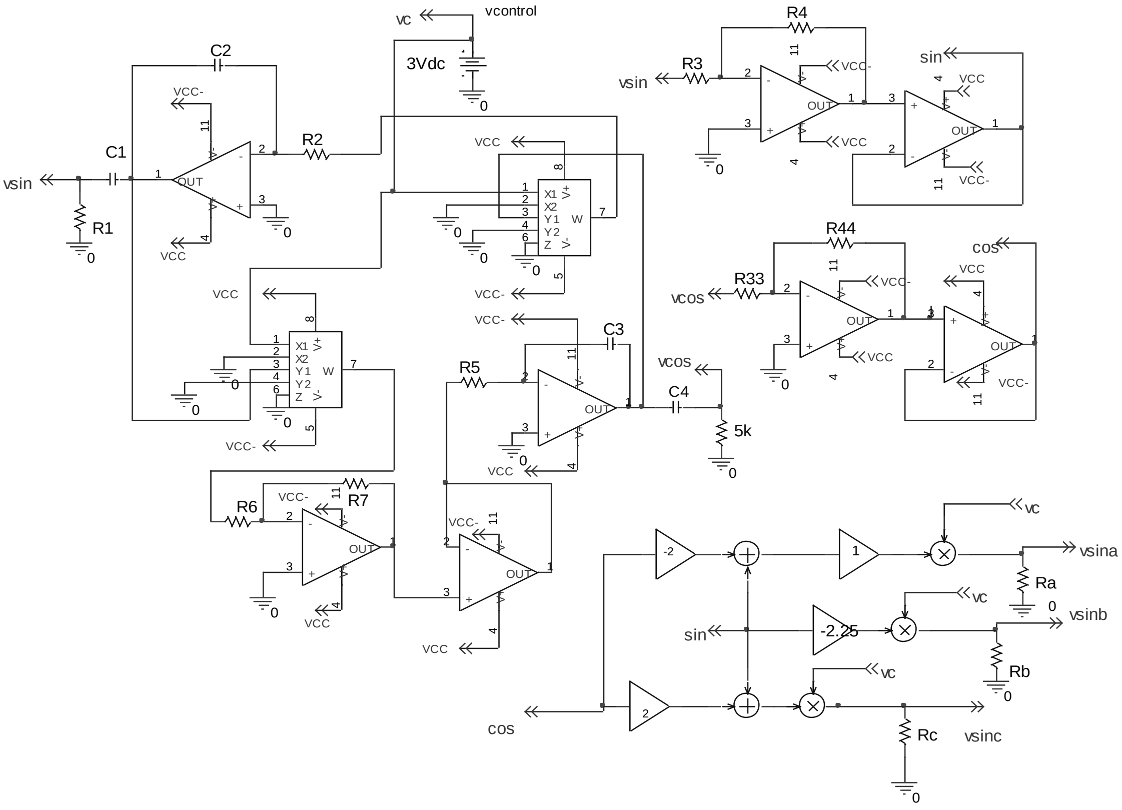


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Figure 2.19: Automatic three phase voltage control oscillator

Amplitude and frequency of the modulating signal (V_{sina}, V_{sinb} and V_{sinc}) generated from the automatic control circuit vary with respect to the control voltage V_c . Three phase voltage control oscillator in the automatic control circuit generates three modulating signals Vsina, Vsinb and Vsinc . Our aim is to make the modulating signals (V_{sina}, V_{sinb} and V_{sinc}) as sinusoidal and constant as the reference signals in the manual control circuit.

2.7.4. Modulating Signal Generates from Automatic Control Oscillator

Different modulating signals for various control voltage (V_c) are shown in figure 2.20 (a-l).

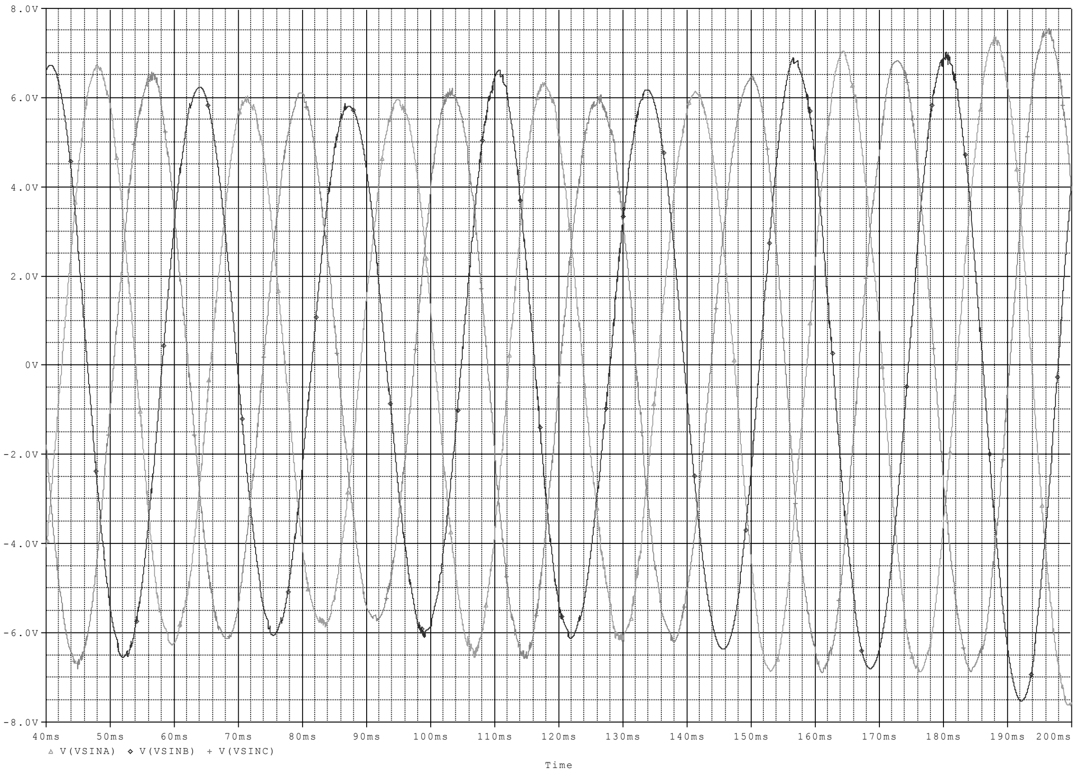

Fig 2.20 (a) Modulating signals for control voltage (V_c=) 2.7 volt

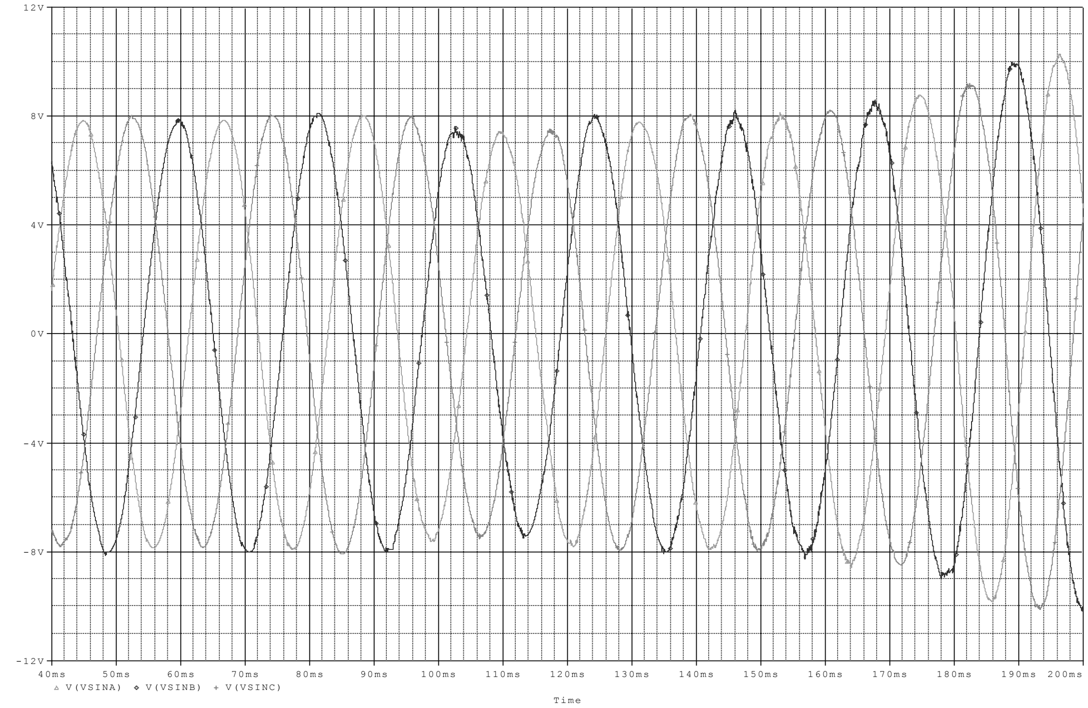

Fig 2.20 (b) Modulating signals for control voltage (V_c=) 2.9 volt

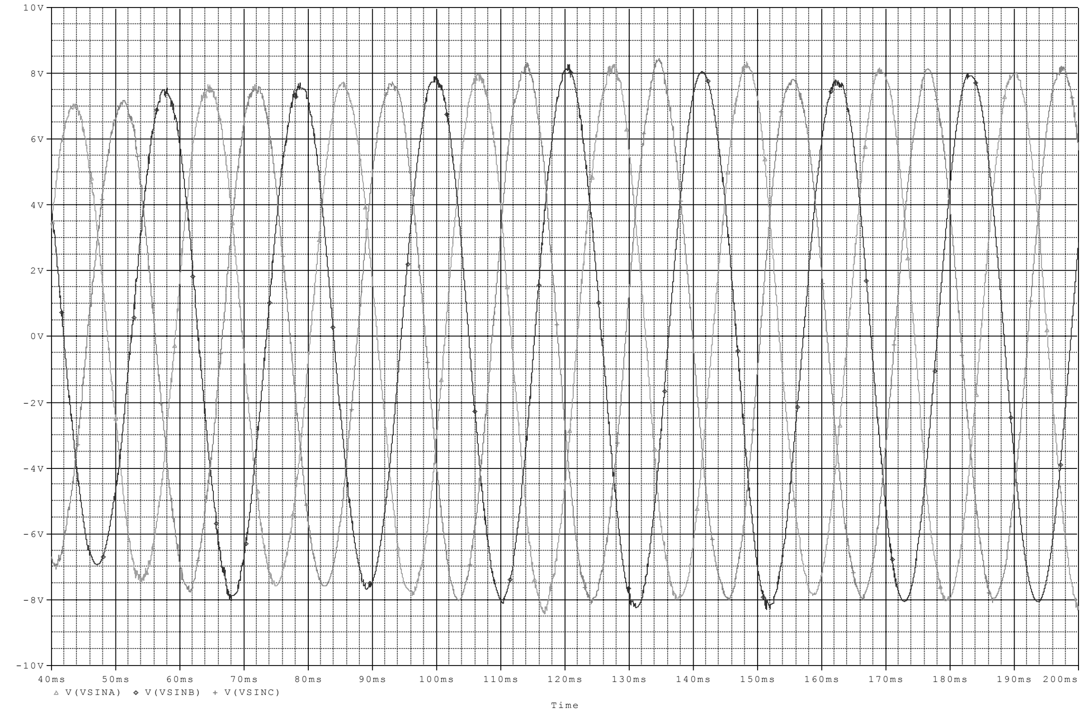

Fig 2.20 (c) Modulating signals for control voltage (V_c=) 3volt

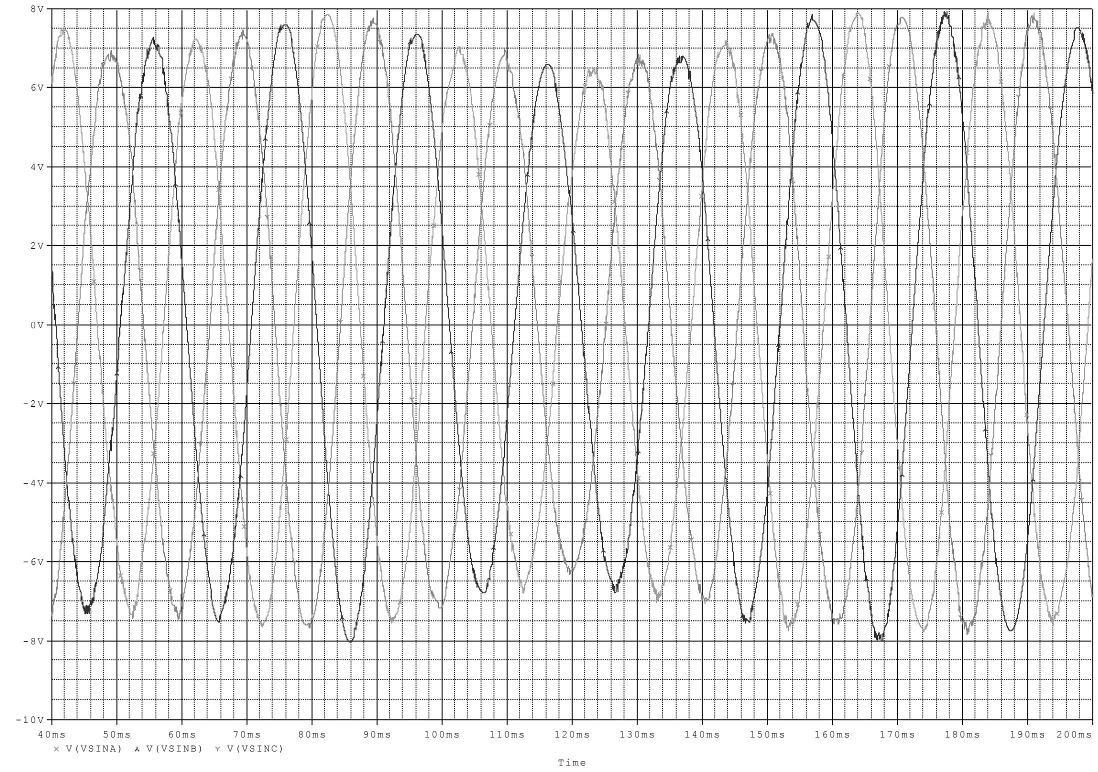

Fig 2.20 (d) Modulating signals for control voltage (V_c=) 3.1volt

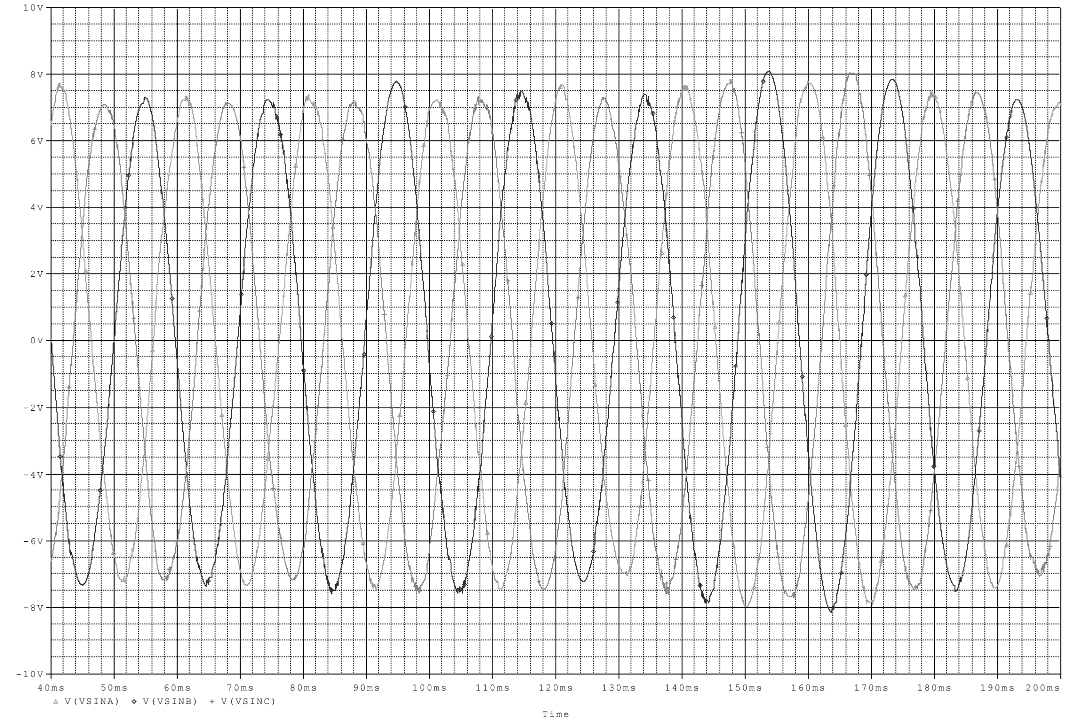

Fig 2.20 (e) Modulating signals for control voltage (V_c=) 3.2 volt

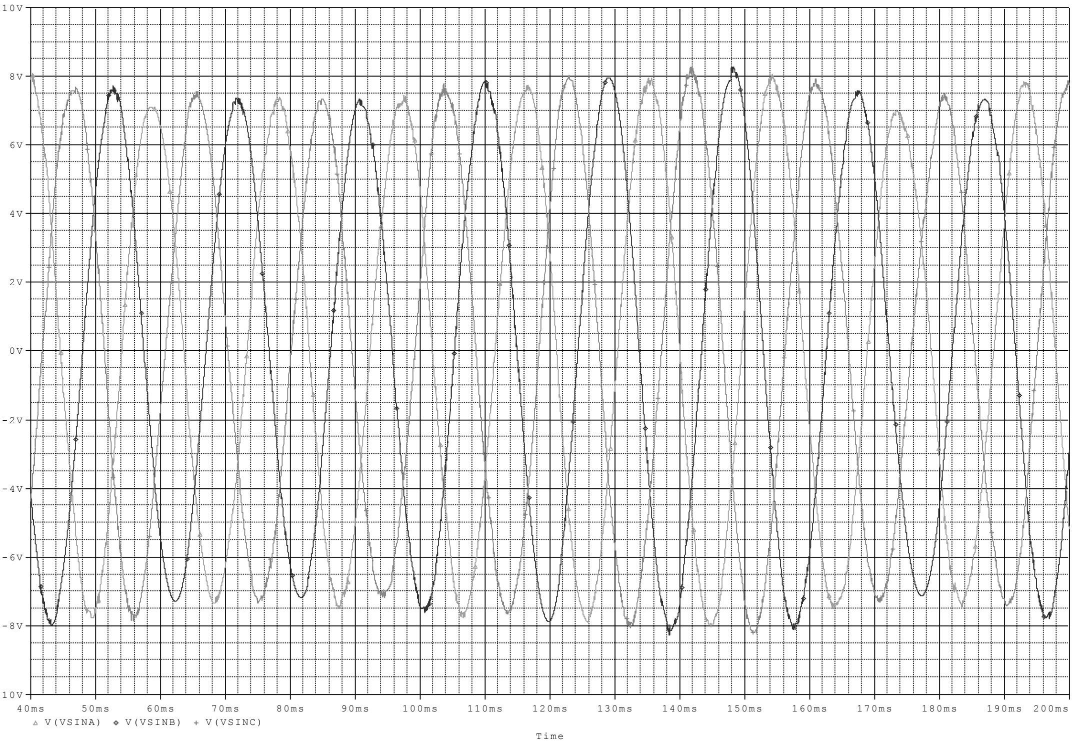

Fig 2.20 (f) Modulating signals for control voltage (V_c=) 3.3 volt

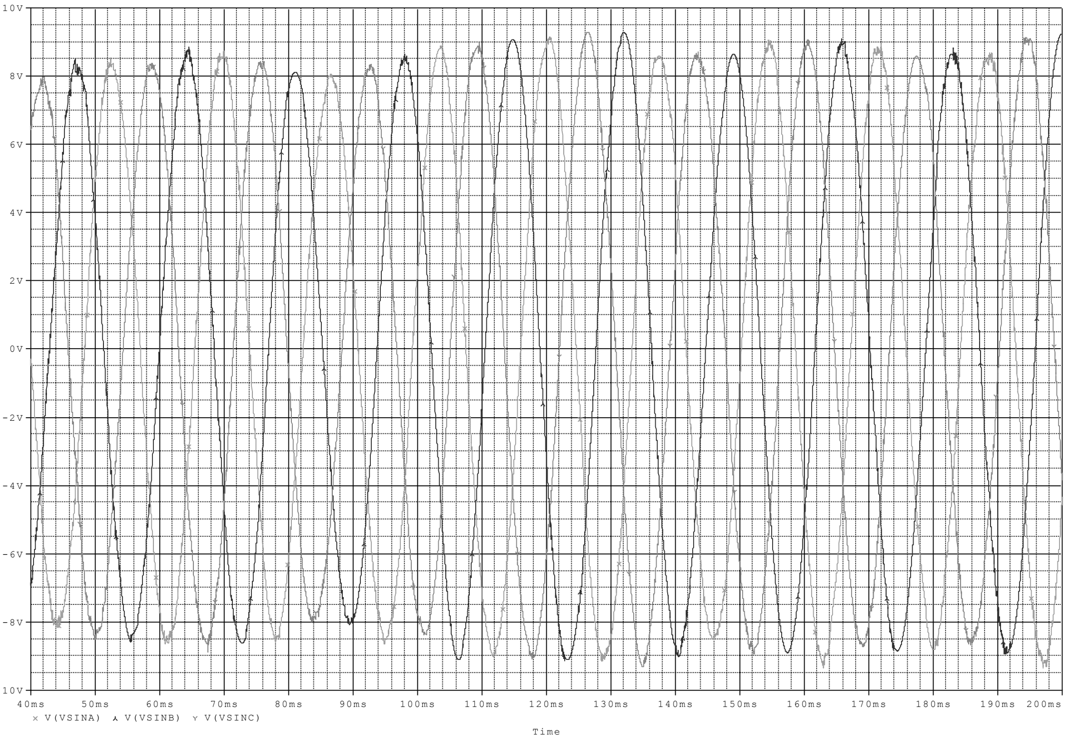

Fig 2.20 (g) Modulating signals for control voltage (V_c=) 3.4volt

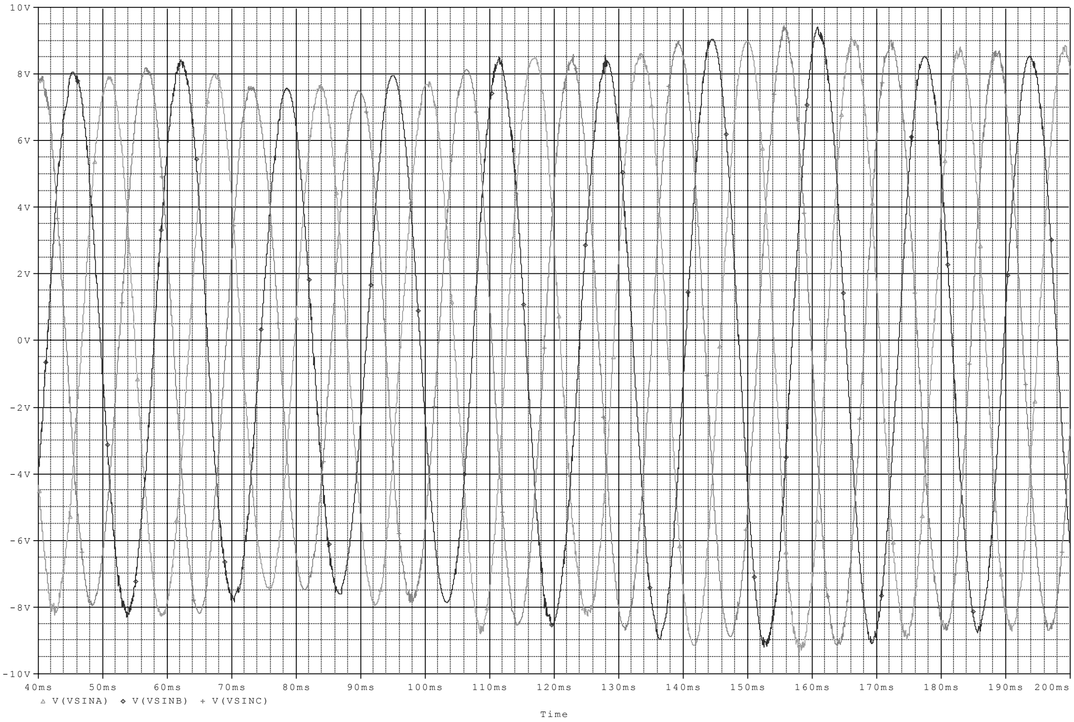

Fig 2.20 (h) Modulating signals for control voltage (V_c=) 3.7volt

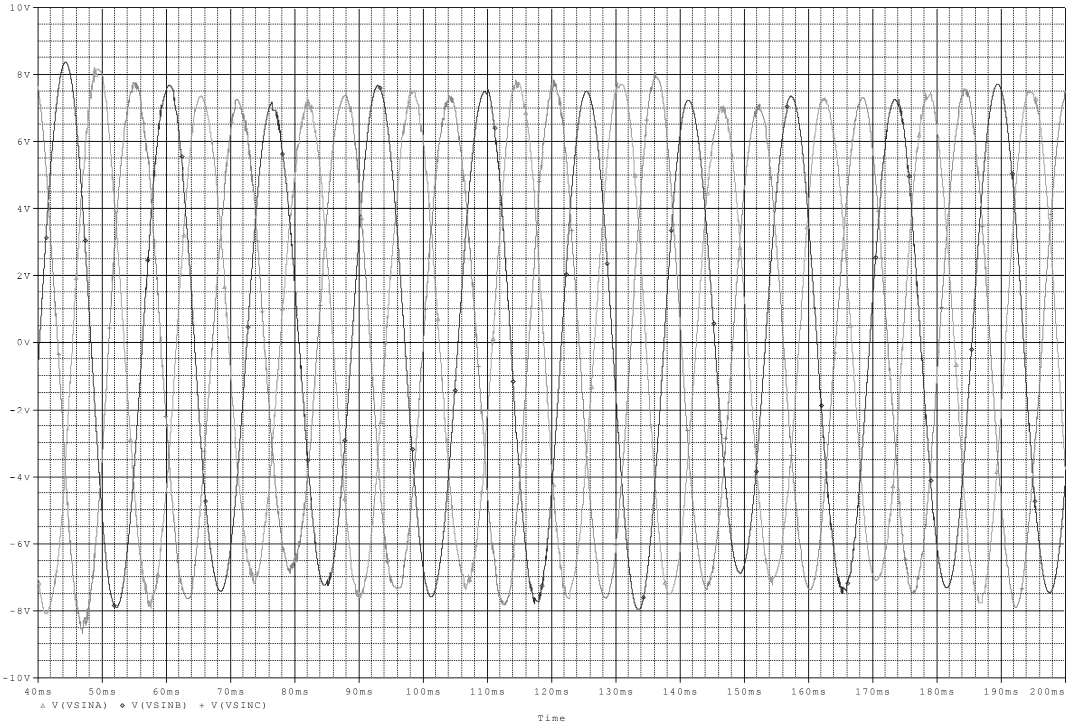

Fig 2.20 (i) Modulating signals for control voltage (V_c=) 3.8volt

Fig 2.20 (j) Modulating signals for control voltage (V_c=) 3.9volt

Fig 2.20 (k) Modulating signals for control voltage (V_c=) 4.2volt

Fig 2.20 (l) Modulating signals for control voltage (V_c=) 4.5volt

Figure 2.20: Modulating signals in automatic control circuit

It is found from the figure 2.20 that amplitude of the modulating signals produced from automatic control circuit is not constant. Frequency of the modulating signal vary by changing control voltage V_c . This modulating signal is given to the switching circuit for Pulse Width Modulation (PWM).

2.7.5. Output Voltage of Automatic Control Three Phase Boost Inverter

The modulated signal produces the gating signal (S_1- S_6) for the MOSFETs (M_1- M_6). The MOSFETs are turned on by the gating signal. The output voltage of the inverter is controlled by PWM technique. Output voltage of the three phase boost inverter produce for the modulating signal at different control voltage (V_C) is shown in figure 2.21(a-l).

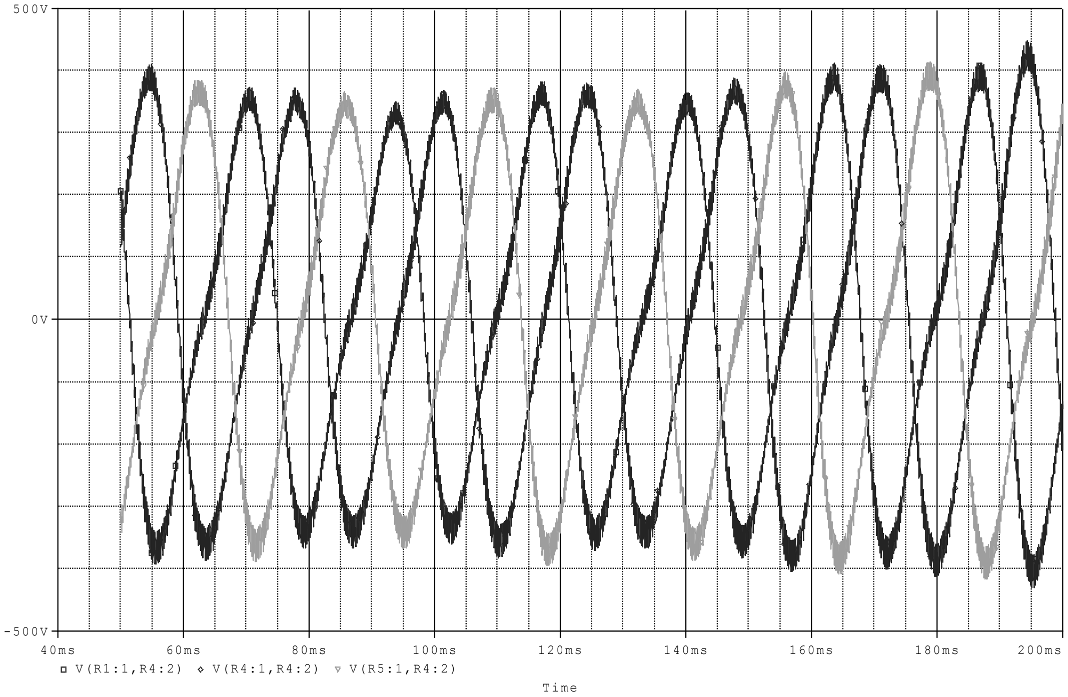

Fig 2.21 (a) Output voltage for control voltage (V_c=) 2.7 volt

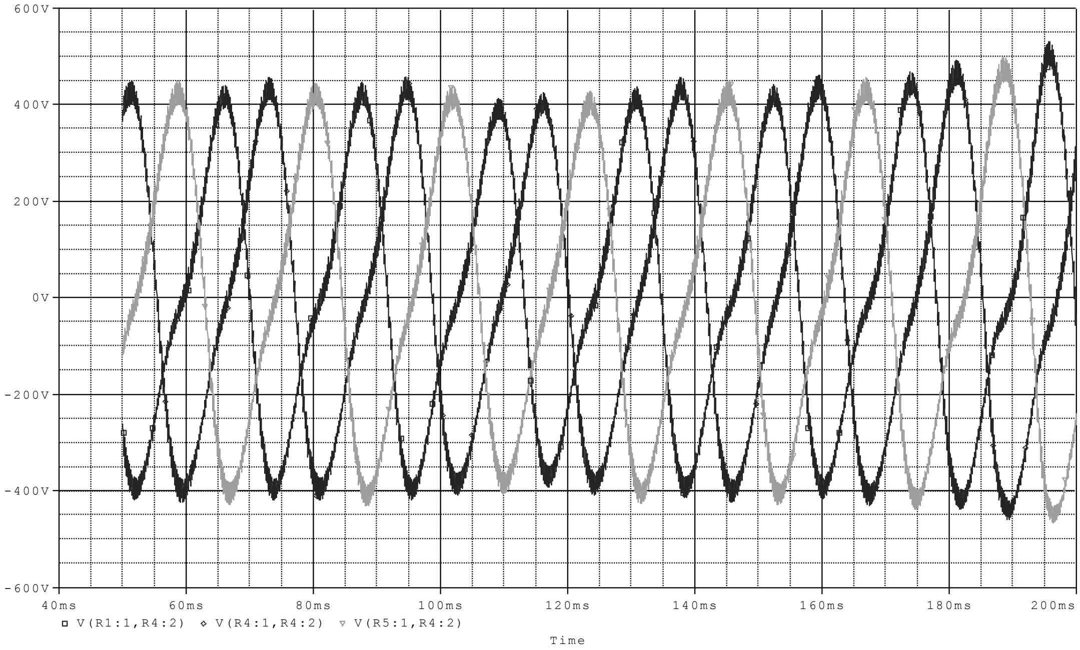

Fig 2.21 (b) Output voltage for control voltage (V_c=) 2.9 volt

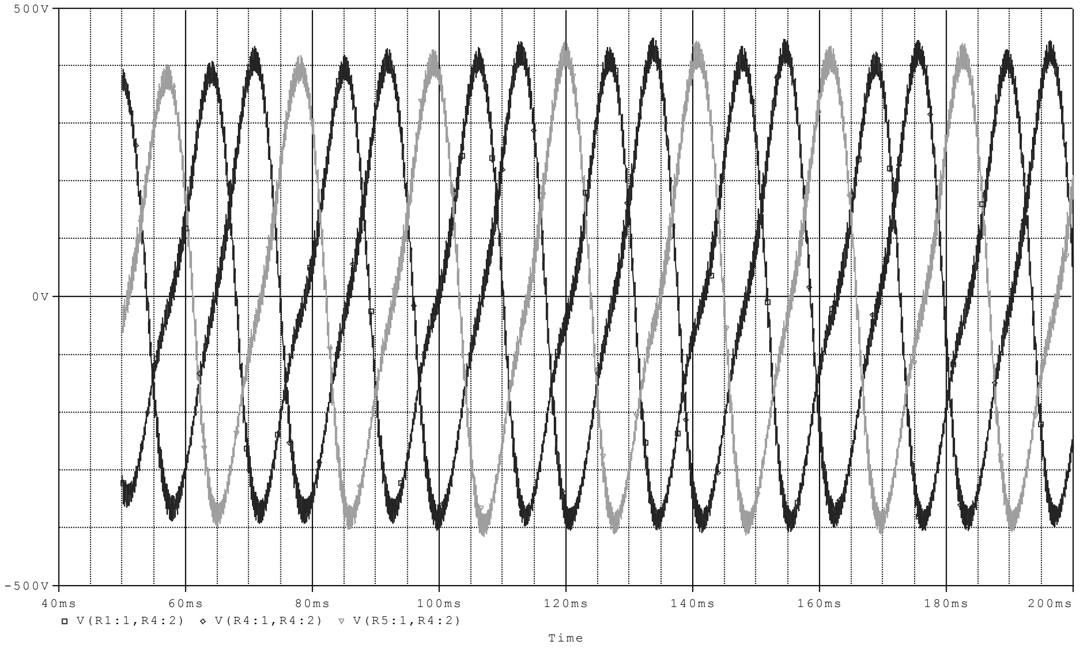

Fig 2.21 (c) Output voltage for control voltage (V_c=) 3 volt

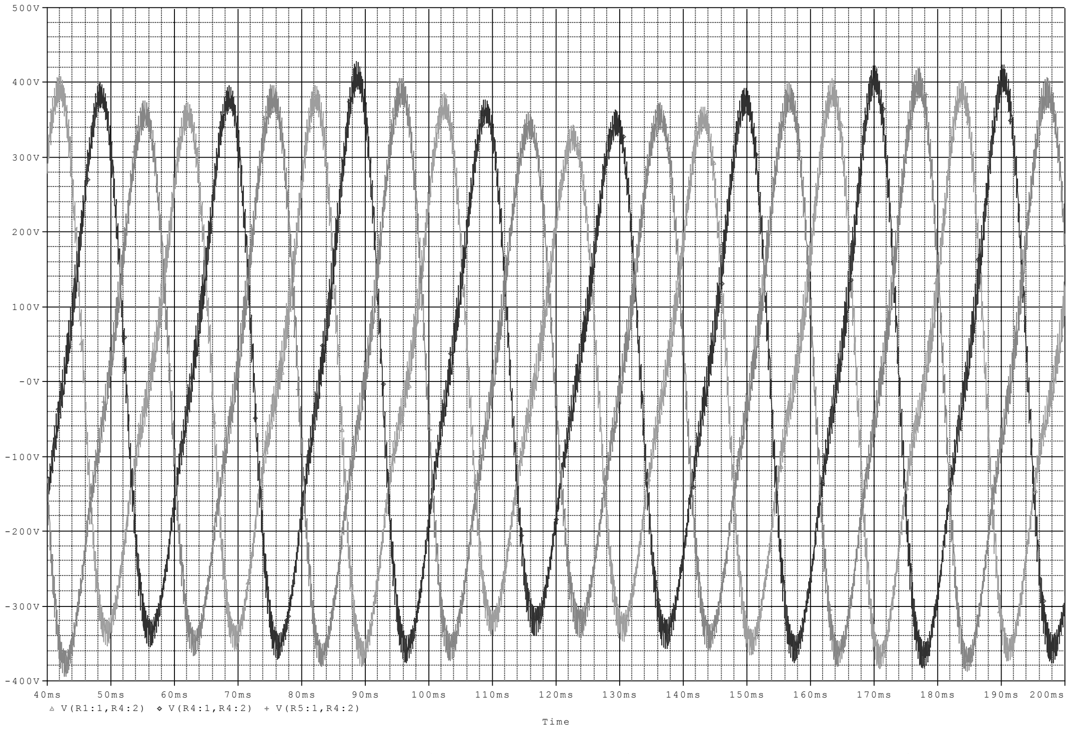

Fig 2.21 (d) Output voltage for control voltage (V_c=) 3.1 volt

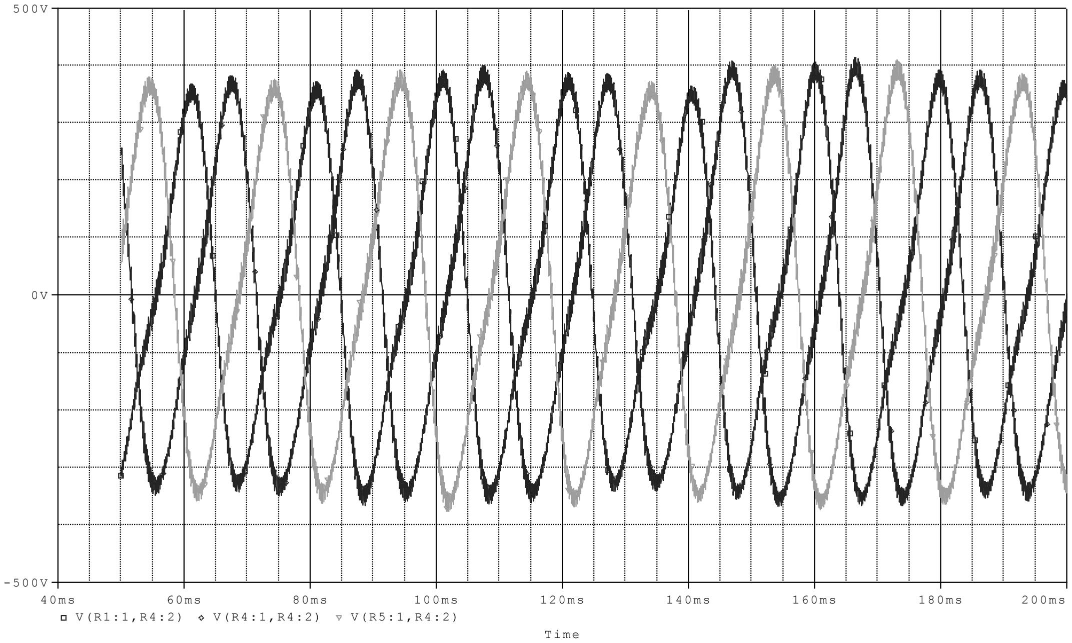

Fig 2.21 (e) Output voltage for control voltage (V_c=) 3.2 volt

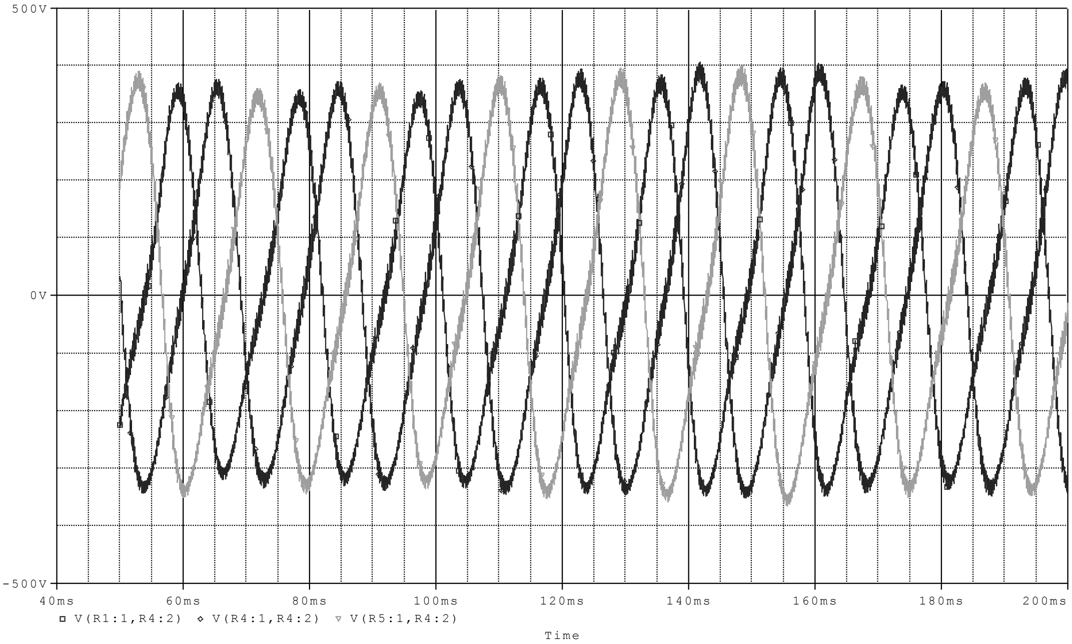

Fig 2.21 (f) Output voltage for control voltage (V_c=) 3.3 volt

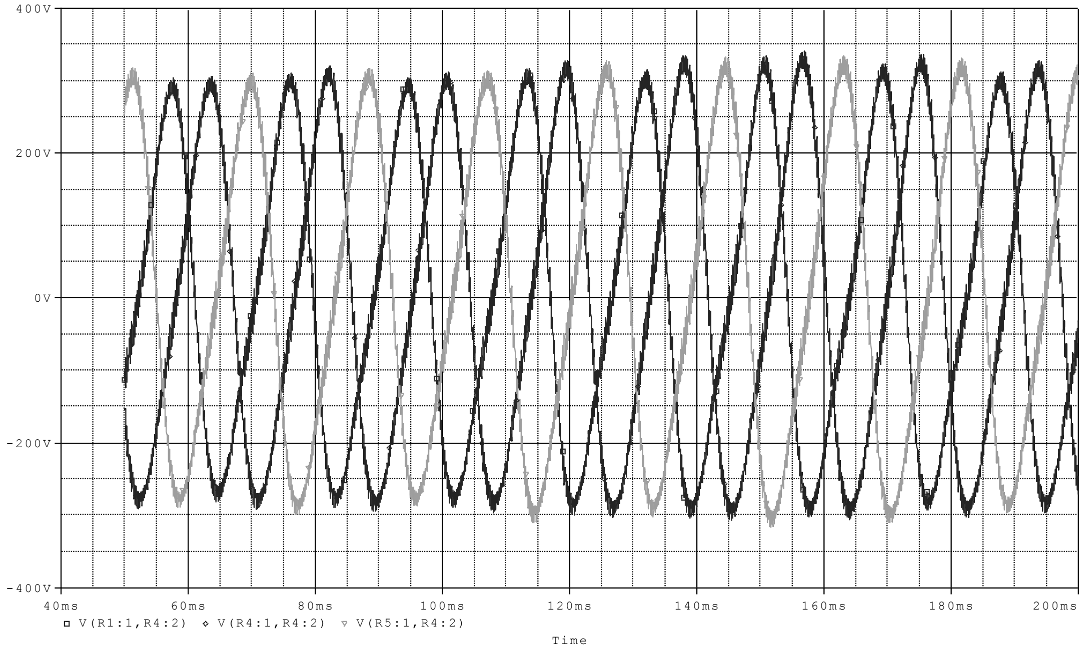

Fig 2.21 (g) Output voltage for control voltage (V_c=) 3.4 volt

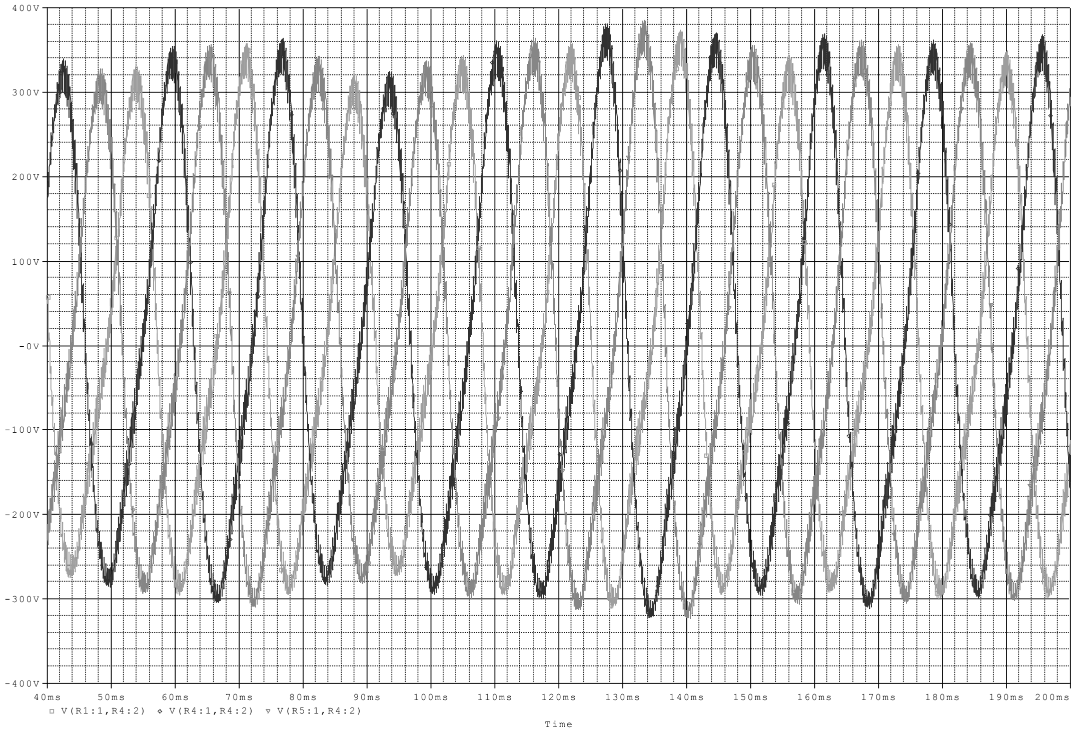

Fig 2.21 (h) Output voltage for control voltage (V_c=) 3.7 volt

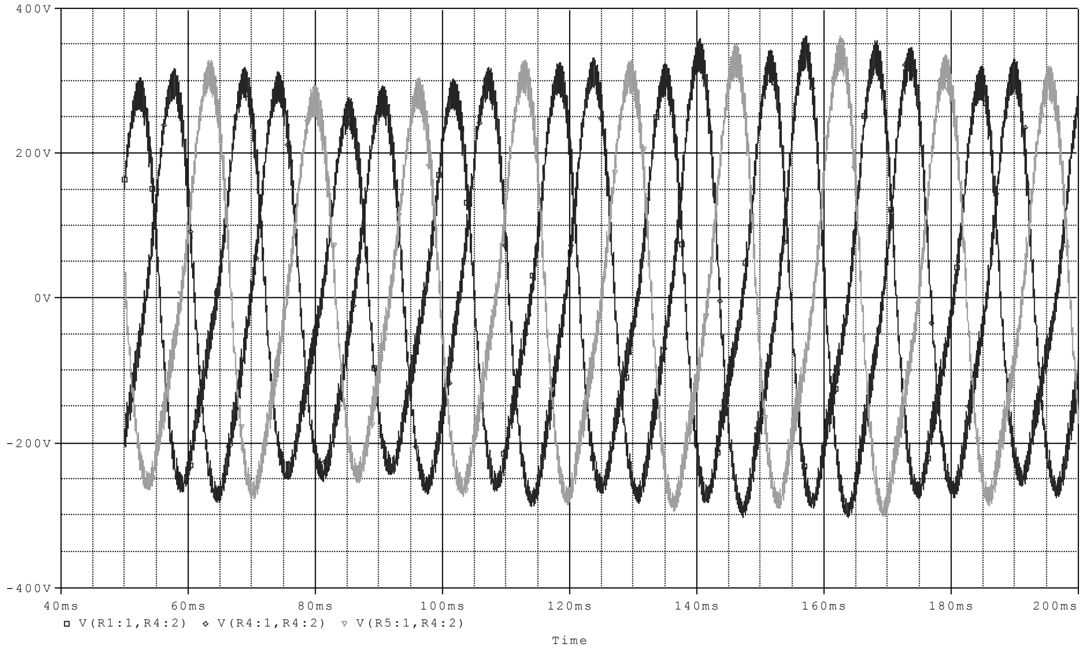

Fig 2.21 (i) Output voltage for control voltage (V_c=) 3.8 volt

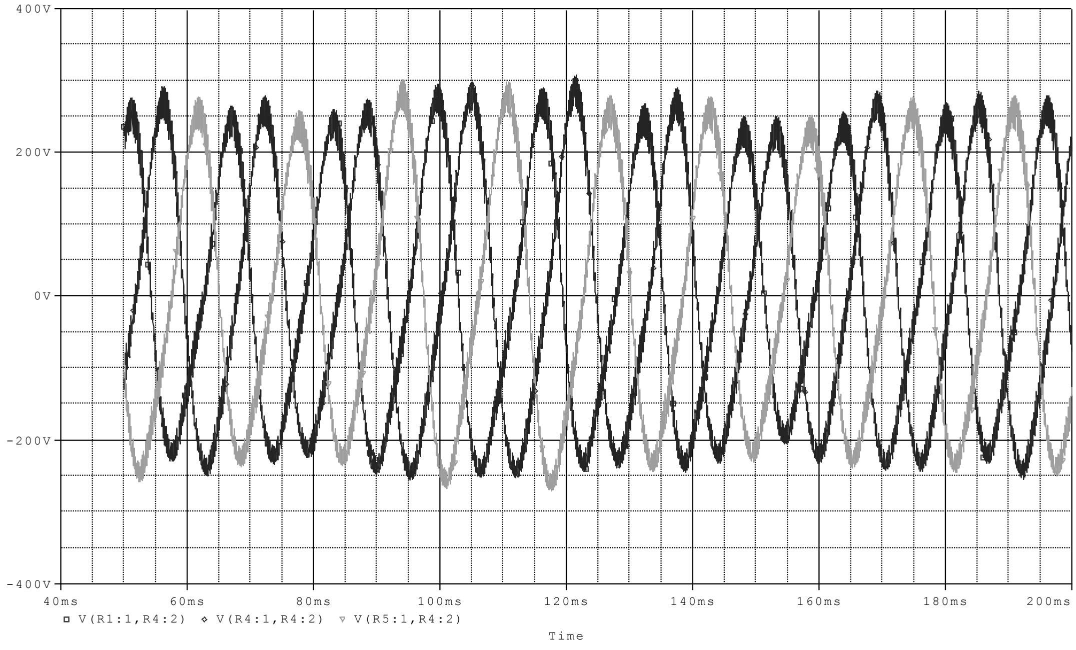

Fig 2.21 (j) Output voltage for control voltage (V_c=) 3.9 volt

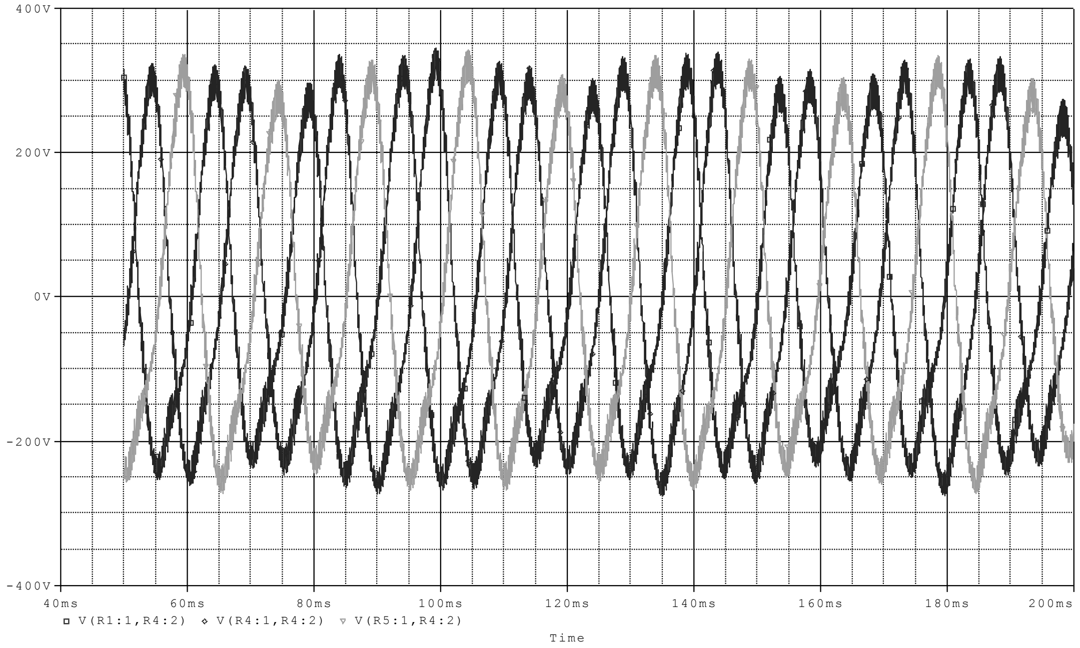

Fig 2.21 (k) Output voltage for control voltage (V_c=) 4.2 volt

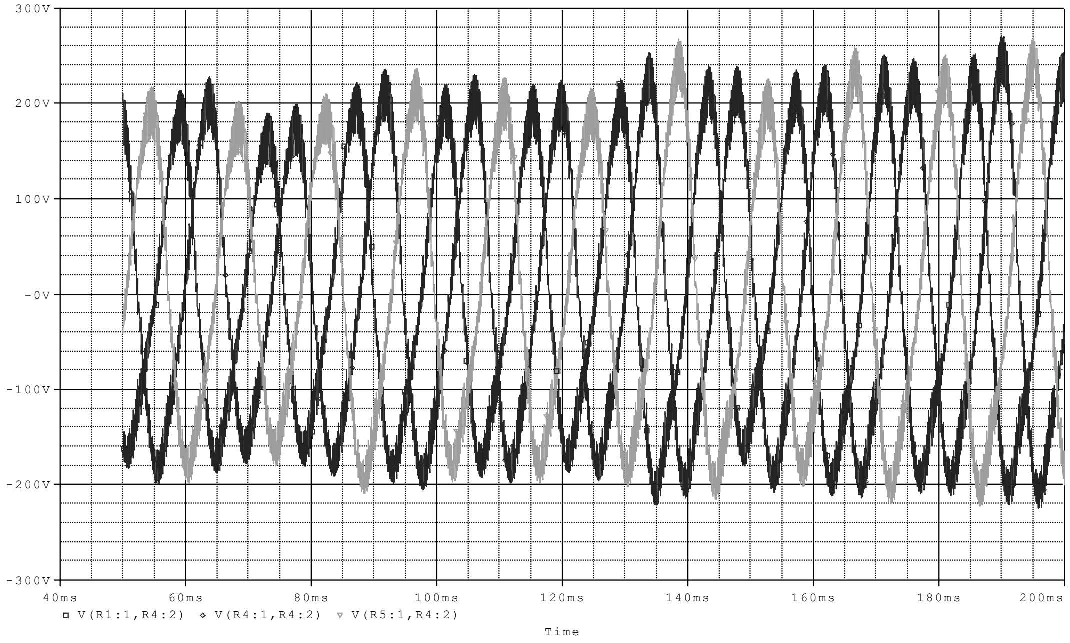

Fig 2.21 (l) Output voltage for control voltage (V_c=) 4.5volt

Figure 2.21: Output voltage for automatic control three phase boost inverter

It is found from the above figure 2.21(a-l) that output voltage of the automatic control three phase boost inverter for different control voltage is non-sinusoidal and not constant as the modulating signal produced from the automatic control circuit is not constant the output voltage is distorted and not constant.

2.7.6. Modification of the Automatic Control Circuit

The output voltage obtained from the designed automatic control three phase differential boost inverter is not constant and it is non-sinusoidal also. For this reason the automatic control circuit has been modified to generate constant and sinusoidal modulating signals. In figure 2.22 modification of the automatic control circuit has been done.

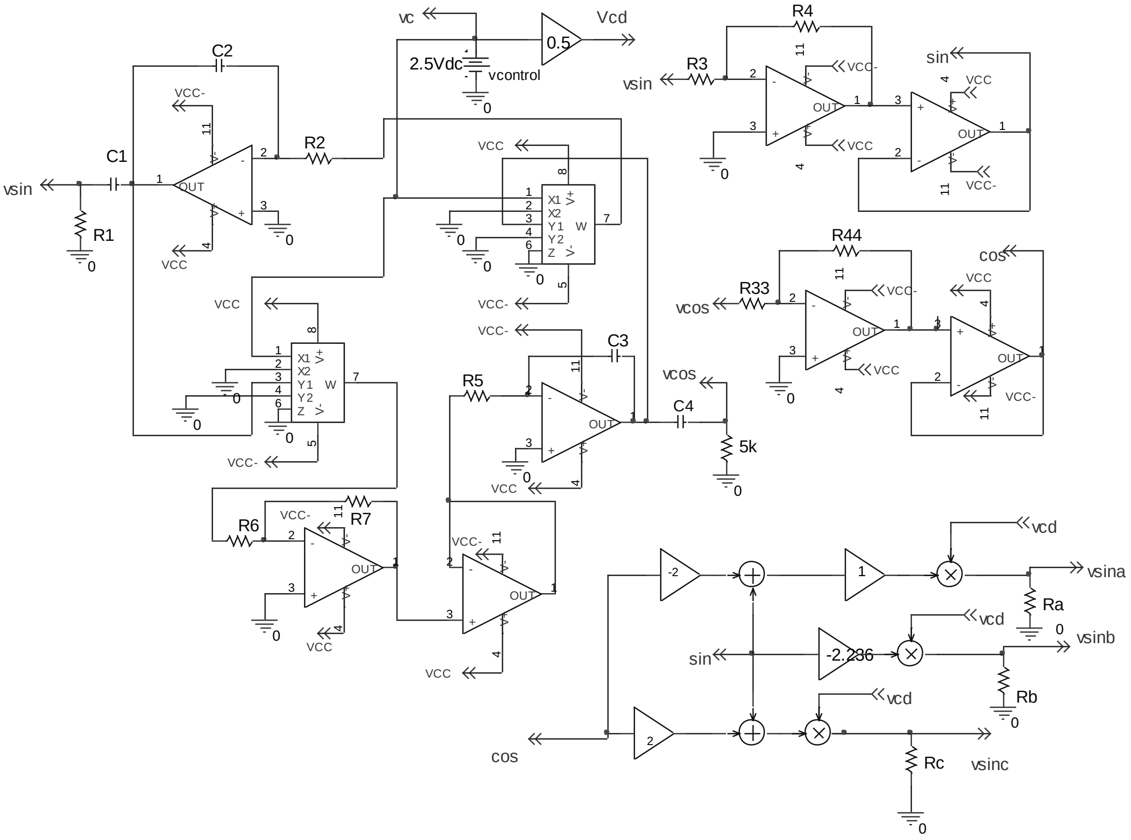

Figure 2.22: Modified automatic control circuit for three phase boost inverter

In the modification of the automatic control circuit multiplication factor or gain is inserted. The output voltage of manual control three phase boost inverter is recorded in table 3.1 for different modulating signal. Automatic control three phase voltage control oscillator has been modified to make same modulating frequency and voltage recorded in table 3.1. Than the output voltage for the automatic control three phase inverter has been recorded in table 3.2.

Different modulating signals V_{sina}, V_{sinb} and V_{sinc} for different control voltage (V_c) of the three phase modified voltage control oscillator in the automatic control circuit are shown in figure 2.23(a-j).

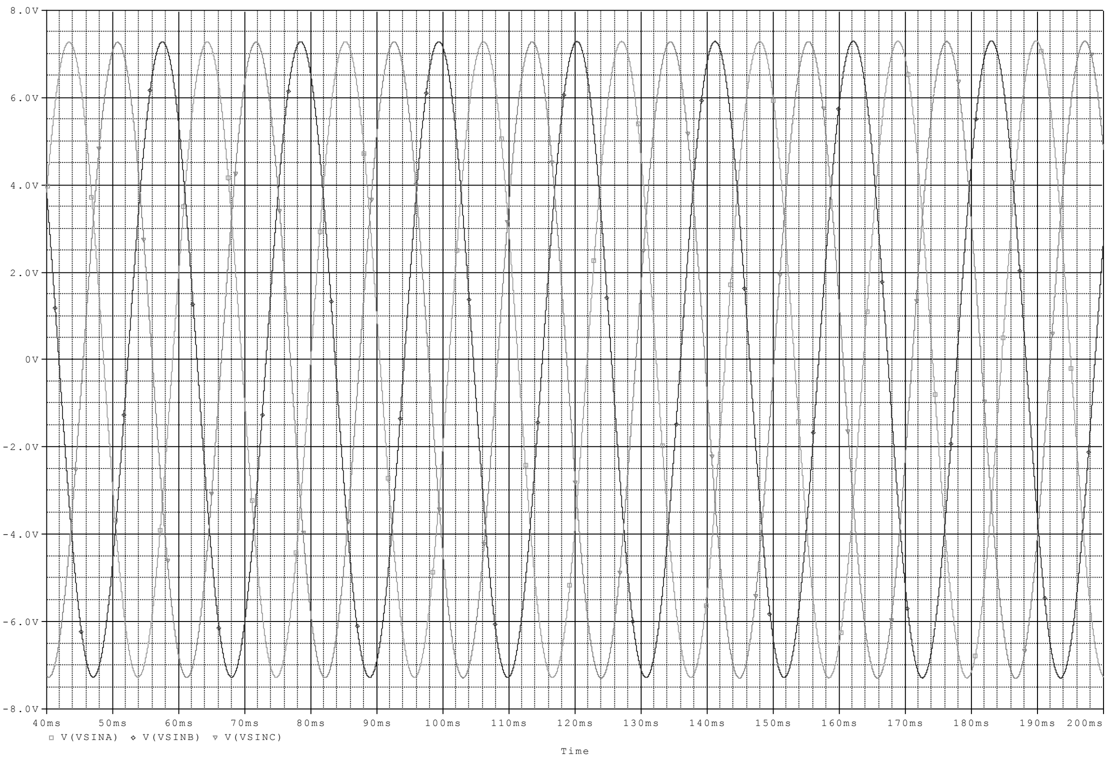

Fig 2.23 (a) Modulating signals for control voltage (V_c=) 3 volt

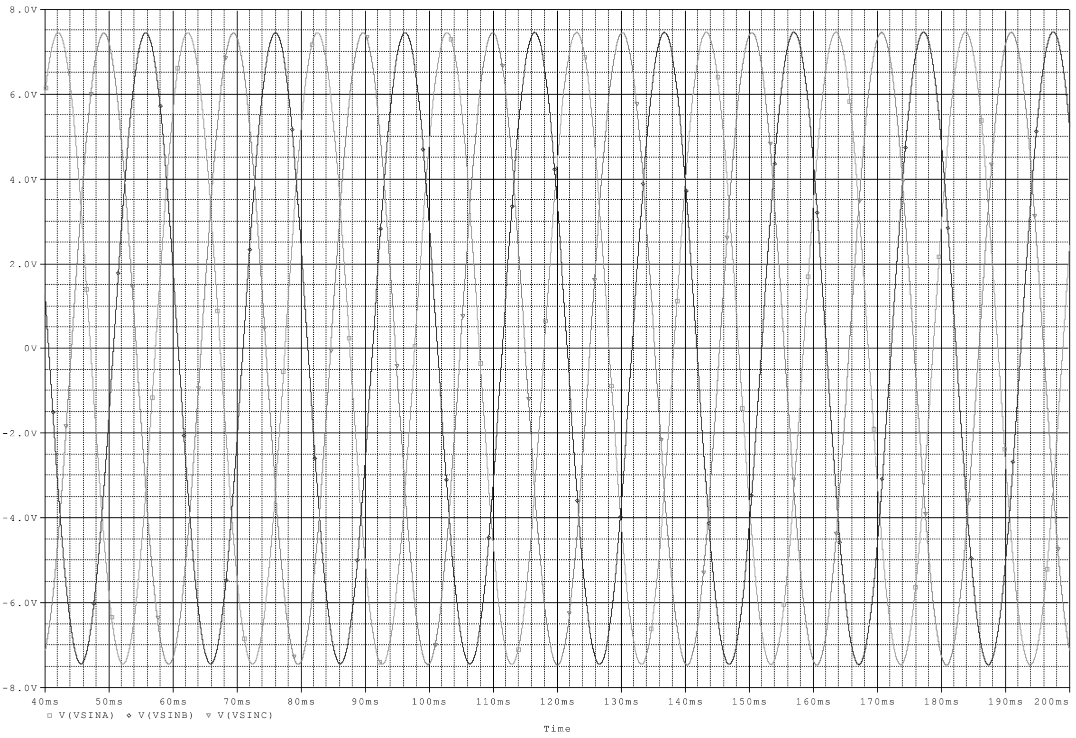

Fig 2.23 (b) Modulating signals for control voltage (V_c=) 3.1 volt

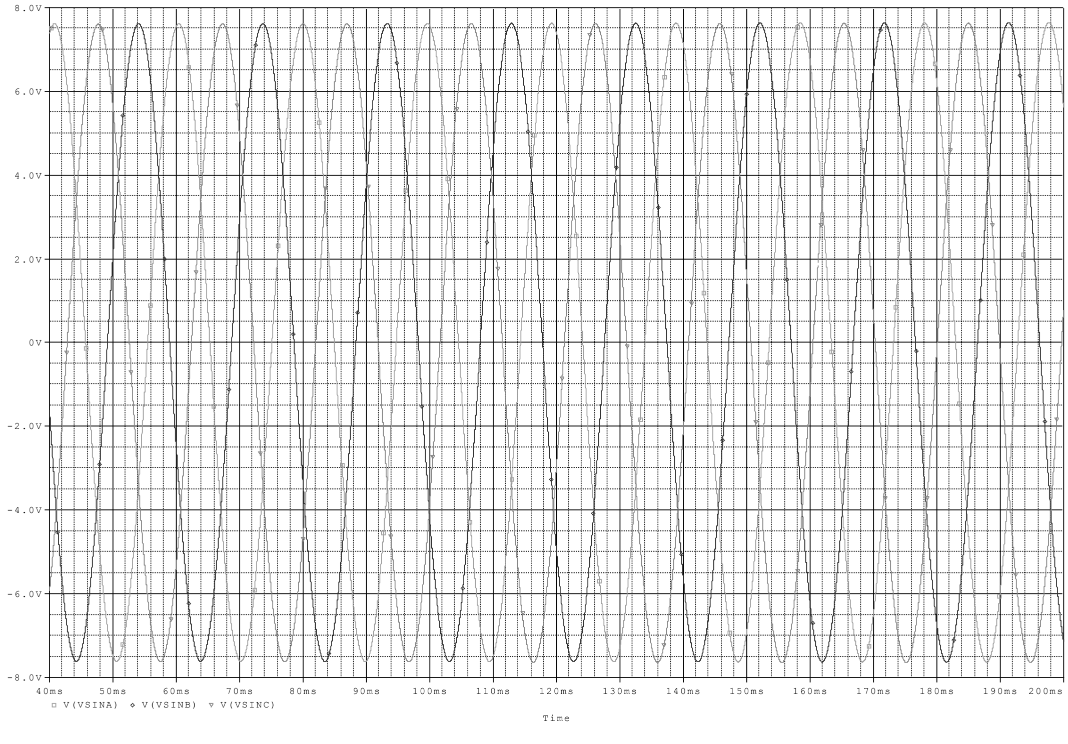

Fig 2.23 (c) Modulating signals for control voltage (V_c=) 3.2 volt

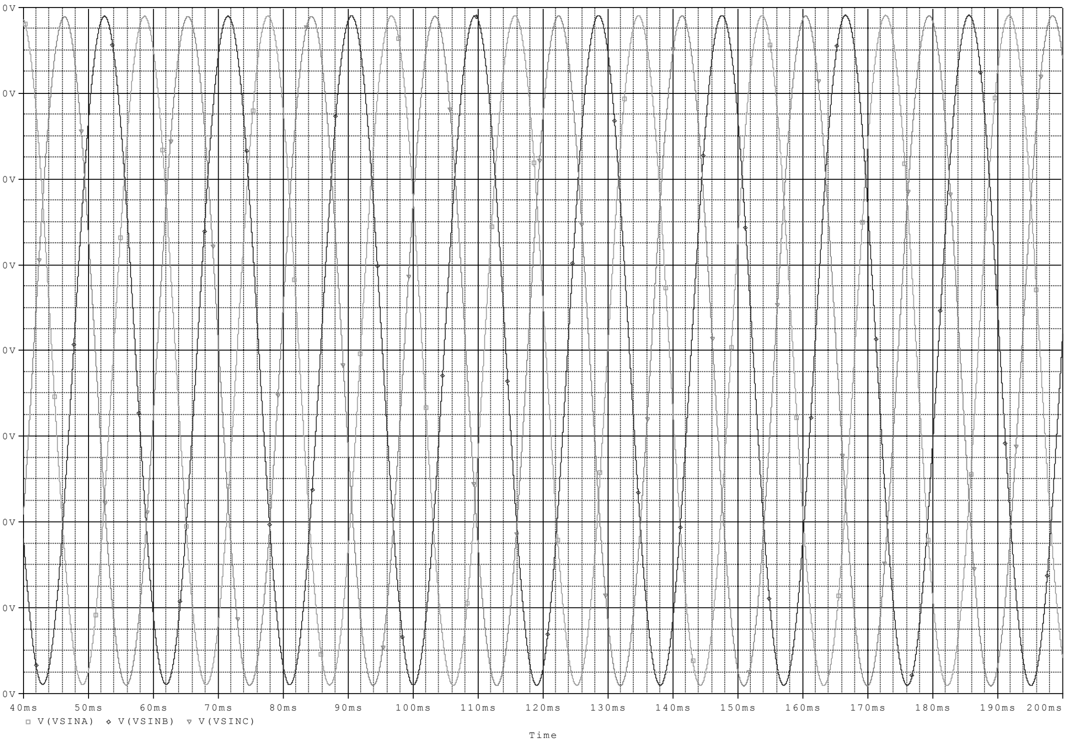

Fig 2.23 (d) Modulating signals for control voltage (V_c=) 3.3 volt

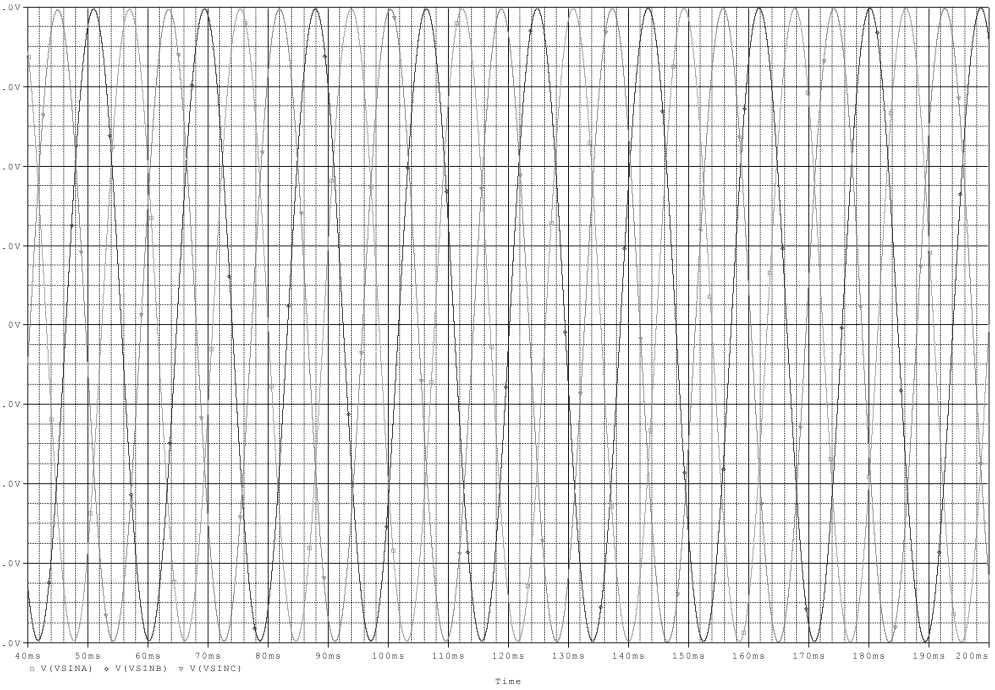

Fig 2.23 (e) Modulating signals for control voltage (V_c=) 3.4 volt

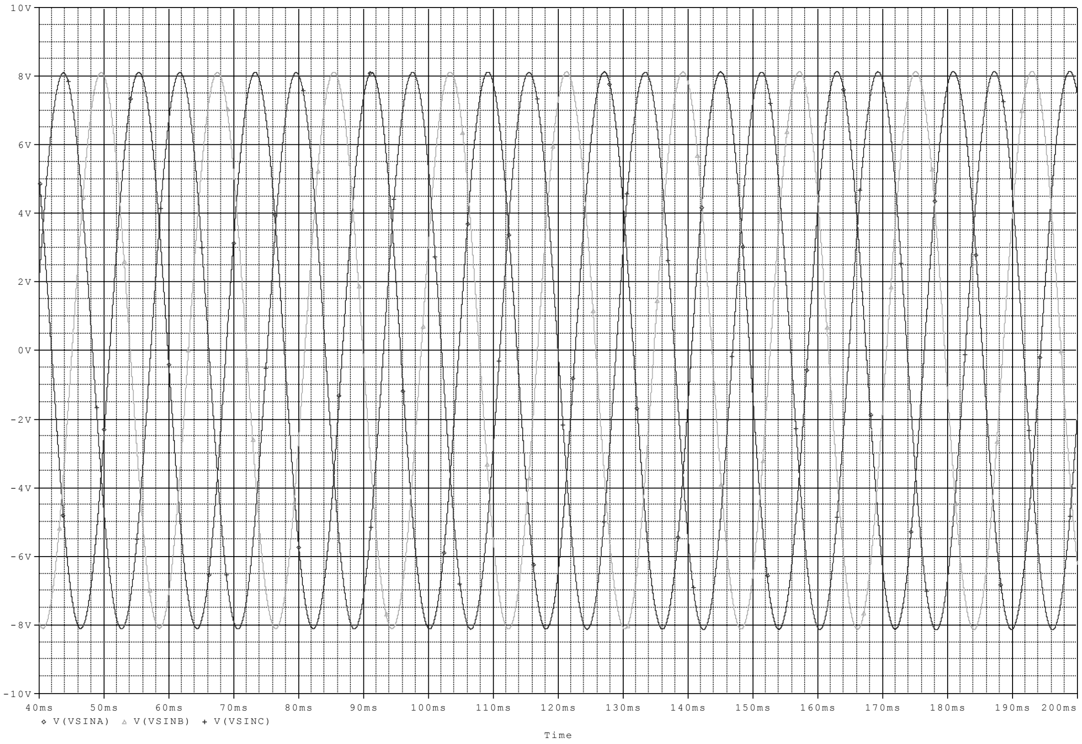

Fig 2.23 (f) Modulating signals for control voltage (V_c=) 3.5 volt

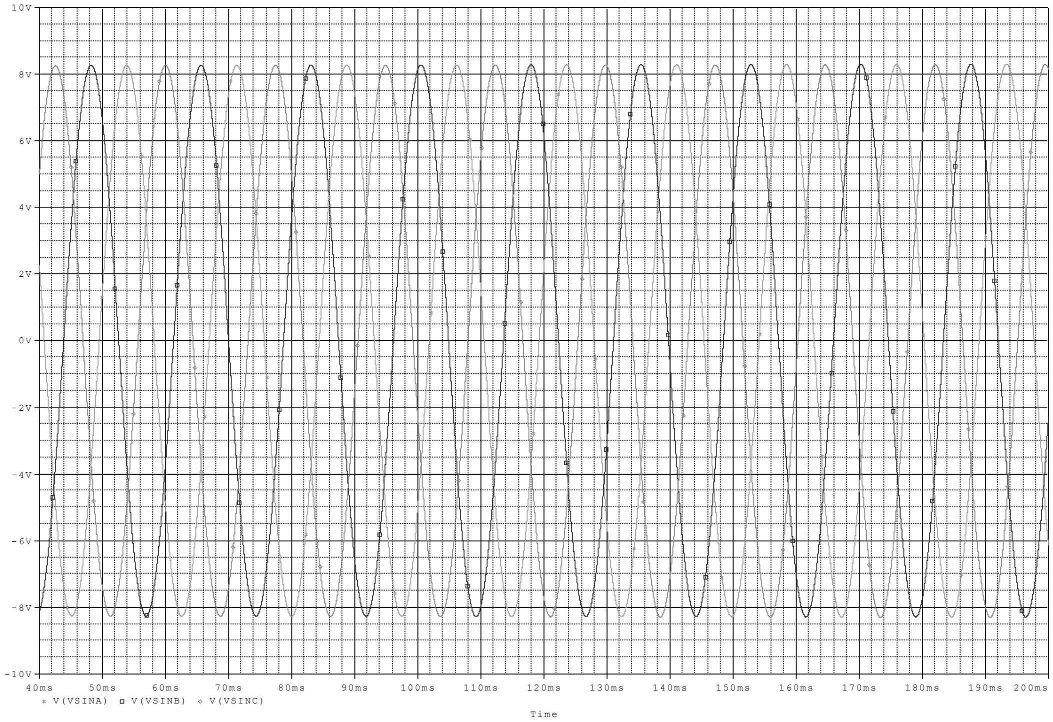

Fig 2.23 (g) Modulating signals for control voltage (V_c=) 3.6 volt

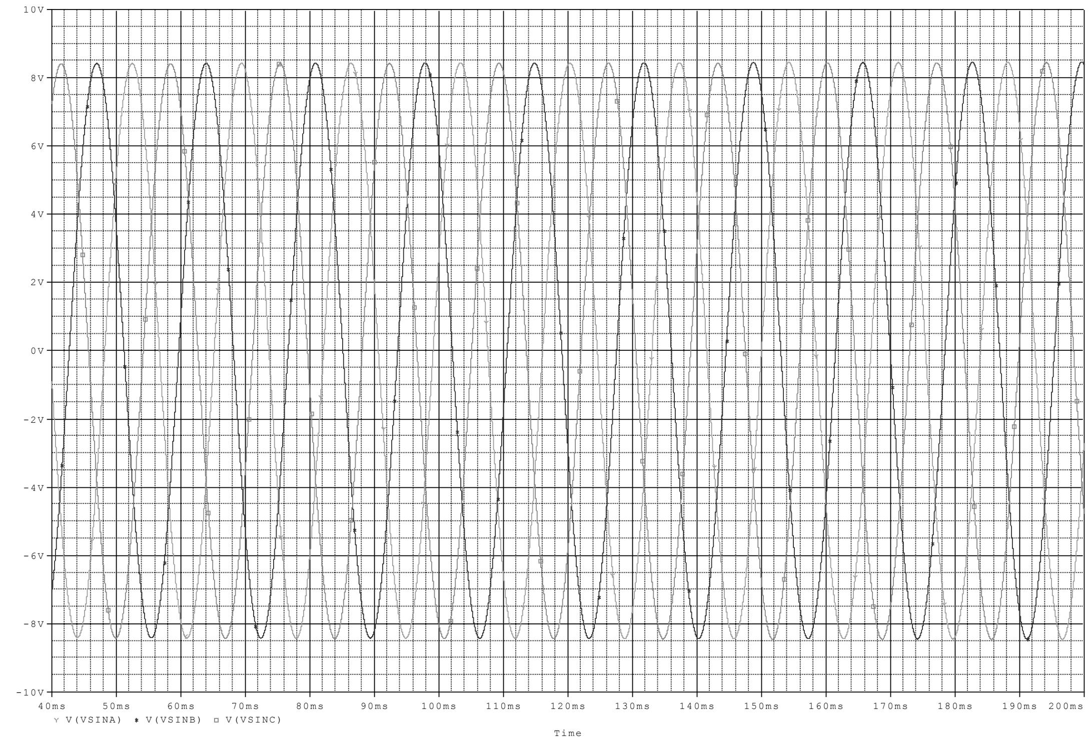

Fig 2.23 (h) Modulating signals for control voltage (V_c=) 3.7 volt

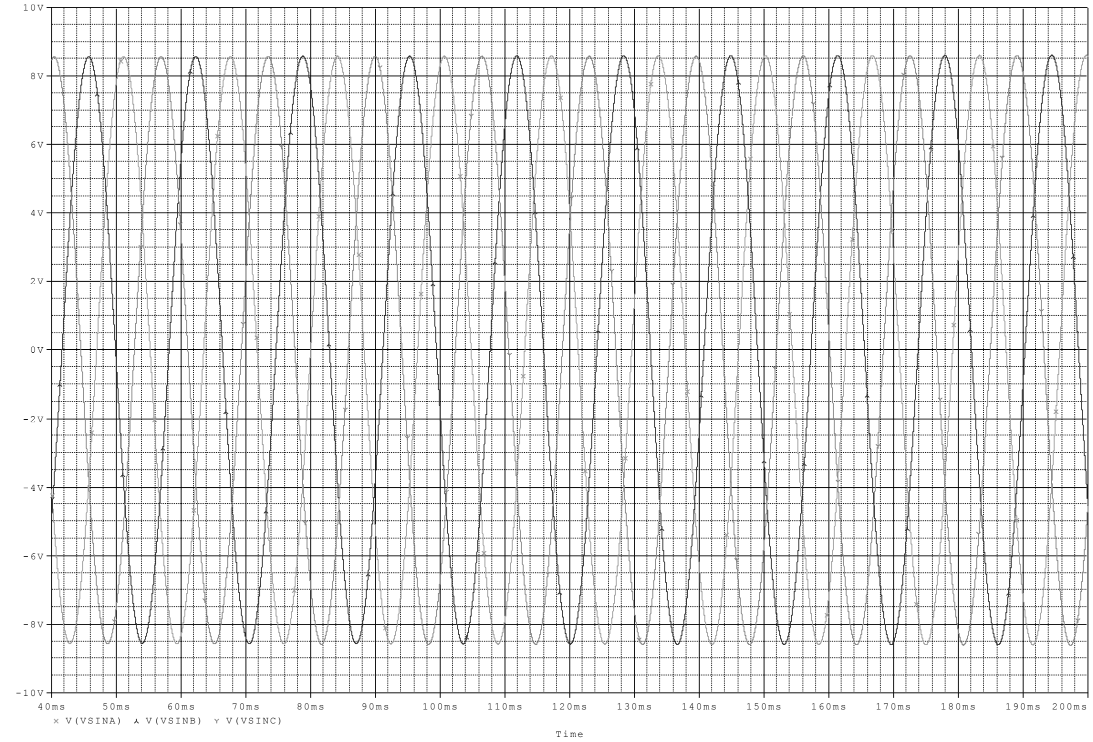

Fig 2.23 (i) Modulating signals for control voltage (V_c=) 3.8 volt

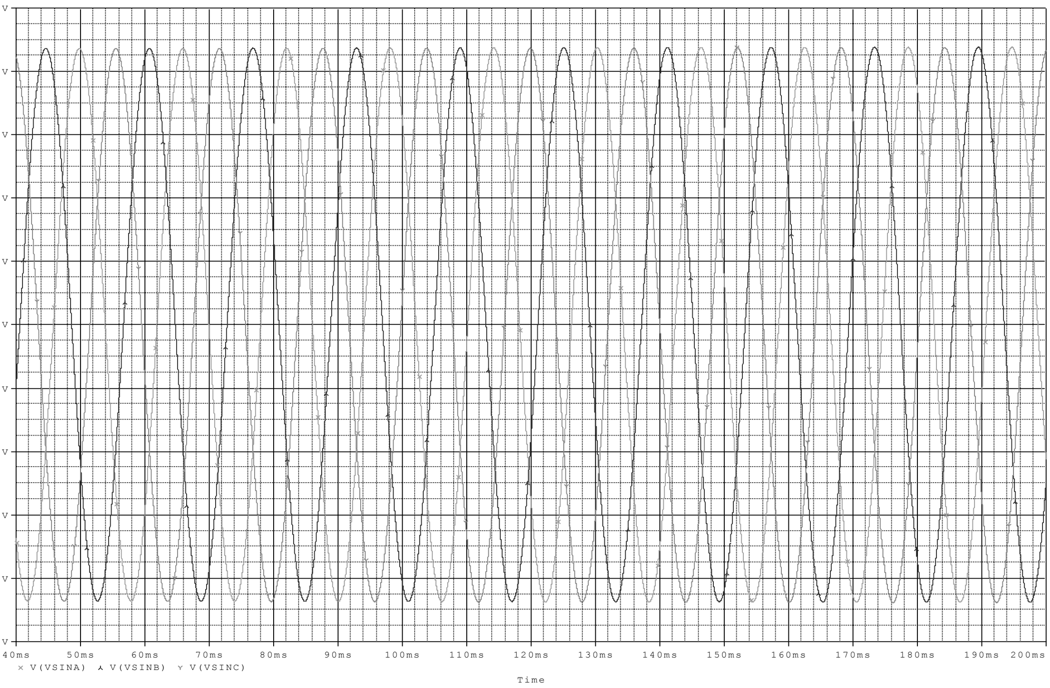

Fig 2.23 (j) Modulating signals for control voltage (V_c=) 3.9 volt

Figure 2.23: Modulating signals generated from modified automatic voltage control oscillator

It is found from figure 2.23 (a-j) that amplitude of the modulating signals produced from modified automatic control circuit for different control voltage is constant.

The output voltages for the modified automatic control circuit have been plotted in figure 3.3. (a-k). It is observed that the output voltage is constant and not distorted.

2.8. Harmonic Standards and Recommended Practices

IEEE Std 519 first introduced in 1981 to provide direction on dealing with harmonics introduced by static power converters and other nonlinear leads so that power quality problems could be averted [11].It is being applied by consulting engineers and enforced by Utilities more frequently in recent years as the use of Variable Frequency Drives and other non-linear leads has grown.

2.8.1. Voltage THD: Total Harmonic Distortion of the voltage waveform. The ratio of the root-sum-square value of the harmonic content of the voltage to the root-mean-square value of the fundamental voltage [11].

$$THD_v = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \ldots\ldots}}{V_1} * 100\% \;\ldots\ldots\ldots\ldots(8)$$

V_1=root-mean-square value of fundamental voltage

V_2, $V_{3,}$ V_4, V_5...........= root-mean-square values of harmonic contents of the voltage.

In order to prevent harmonics from negatively affecting the Utility supply, IEEE Std 519 has been established as the „Recommended Practices and Requirements for adopted, particularly in North America, but has often been misinterpreted and/or misapplied creating installations that have either been expensively overbuilt or critically under designed.

IEEE Std 519 in 1981 gave simple guidelines for limits on voltage distortion. In 1992, it more clearly established limits for both voltage and current distortion. IEEE Std 519 was introduced in 1981 and was revised in 1992. It was intended to provide direction on dealing with harmonics introduced by static power converters and other nonlinear loads. The standard recognizes the responsibility of an electricity user to not degrade the voltage of the Utility by drawing heavy nonlinear or distorted currents. It also recognizes the responsibility of the Utility to provide users with a near sine wave voltage.

The standard was written to establish goals for the design of electrical systems with both linear and nonlinear loads. Distortion limits for both current and voltage are defined in order to minimize interference between electrical equipment. It is presented as a guideline for power system design when nonlinear loads are present and assumes steady-state operation.

IEEE Std 519 was intended to be used as a system standard. The voltage and current harmonics limits presented in the standard were designed to be applied while taking the entire system into consideration, including all linear and non-linear loading.

Section 10 of IEEE Std 519 defines the limits for various harmonic indices that the authors of the standard believe strongly correlate to harmonic effects. The defined indices are:

1. Depth of notches, total notch area, and distortion of the bus voltage by communication notches
2. Individual and total voltage distortion
3. Individual and total current distortion

The philosophy adopted to develop the limits for these indices was to restrict harmonic current injection from individual customers so that they would not cause unacceptable voltage distortion levels when applied to normal power systems.

Table 10.2 in IEEE Std 519 [11] establishes harmonic limits on voltage as 5% for total harmonic distortion and 3% of the fundamental voltage for any single harmonic. This harmonic limit is shown in table 2.1. The reference to medical equipment sensitivity provides some indication as to why the limits are even more severe ($THD_V<3\%$) for special applications such as hospitals and airports. In contrast, the limits are relaxed ($THD_V<10\%$) for dedicated systems. A dedicated system is defined as one that is exclusively dedicated to converter loads assuming the equipment manufacturer will allow for operation at these higher distortion levels.

Table 2.1: Table of voltage distortion limits in IEEE Std 519.

Low-Voltage System Classification and Distortion Limits			
	Special Applications	General System	Dedicated System
THD (voltage)	3%	5%	10%
• Special applications include hospitals and airports • A dedicated system is exclusively dedicated to the converter load			

For applications in the petrochemical industry, the general systems limits are most appropriate [11]. This means that we must design our systems for <5% THD_v and with no single harmonic greater than 3%. These generally will be met at the PCC (point of common coupling) provided the current harmonic limits are met.

2.8.2. Harmonic Elimination

As harmonics have various adverse impacts, reducing the harmonic content of the output voltage or current is one of the important tasks of the designers. On DC-DC converters, the ripple content is easily reduced by post-filtering after the converter. The post converter low pass filter may be designed for cut off frequencies that are several times lower than the switching frequency (usually kilohertz). In the DC-AC inverters, however, the fundamental component of the output voltage or current is either the same or a simple fraction of the switching frequency. Designing an effective low pass filter with cutoff frequency between the fundamental frequency and the first undesired harmonic frequency is a difficult task. Hence, an active harmonic reduction strategy is often desirable. The THD calculation for the designed three phase inverter is described in chapter 3.

In this chapter modifications of power circuit from that of proposed in the single phase application has done for each leg to provide path for four quadrant operation as necessary in the three phase inverter by providing voltage lift circuit in each leg of the DC-DC converter. Three phase differential boost inverter power circuit and it‟s control circuit has been designed where a reduced number of feedback from the power circuit to the control circuit is needed.

Chapter 3

Analysis of the Result of the Proposed Inverter

3.1. Circuit description for the proposed three phase boost inverter

The boost DC-AC converter is shown in Figure. 3.1. It includes dc supply voltage V_{in}, input inductors L_1, L_2 and L_3. Power switches S_1-S_6, transfer capacitors C_1-C_3, freewheeling diodes D_1-D_{14} and load resistances R_1-R_3. In the description of the converter operation, we assume that all the components are ideal and that the converter operates in a continuous conduction mode.

3.2. Control Design Methodology

In the design of the converter, the following are assumed;

- Ideal power switches;
- Power supply free of sinusoidal ripple;
- Converter operating at high-switching frequency.

3.3. Selection of the control parameters

Once the boost inverter parameters are selected, inductances L_1, L_2 and L_3 are designed from specified input and output ripples, capacitors C_1-C_3 are designed so as to limit the output voltage ripple in the case of fast and large load variation. And maximum switching frequency is selected from the converter ratings and switch type.

3.4. The Simulation and Experimental Results

Using the following parameters, the boost inverter was simulated using ORCAD . The parameters are summarized below:

R1-R3=100 ohm

L1-L3=20 mH

L4-L6=10 mH

C1-C3=200 uF

C4-C6=20 uF

C7-C9=10 uF

V_{in}=300 V_{dc}

M_1- M_6=BSV81/PLP, Practical switches (MOSFET);

D_1-D_{14}=MR2406F

With the above parameter set the boost inverter was simulated for different modulating frequency and modulating voltage.

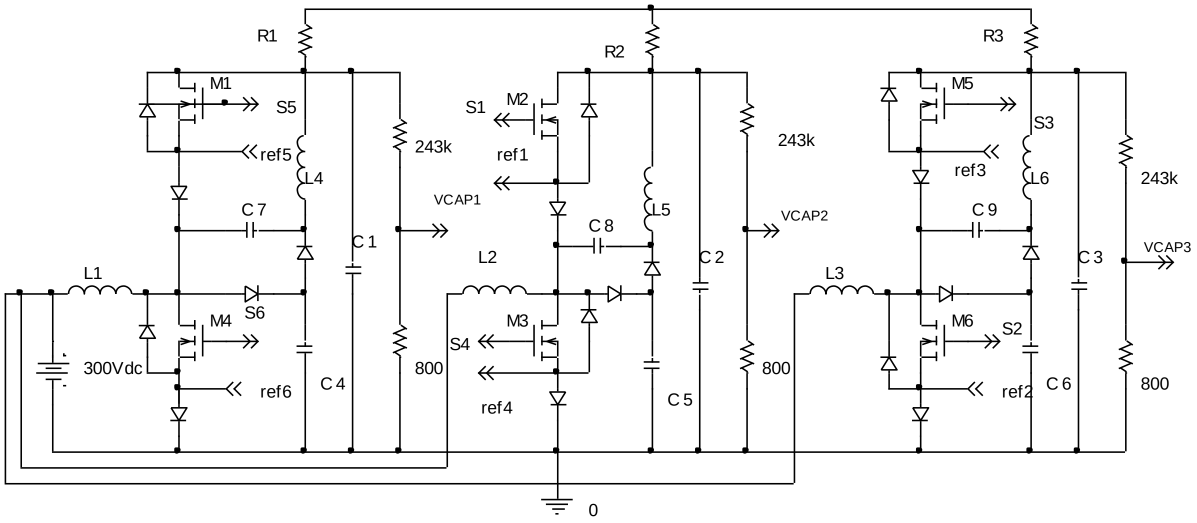

Figure 3. 1: Proposed three phase differential boost inverter circuit

3.5. Variation of Output Voltage for Manual Control Three Phase Boost Inverter

The output voltage for different modulating signals are shown in figure 3.2.

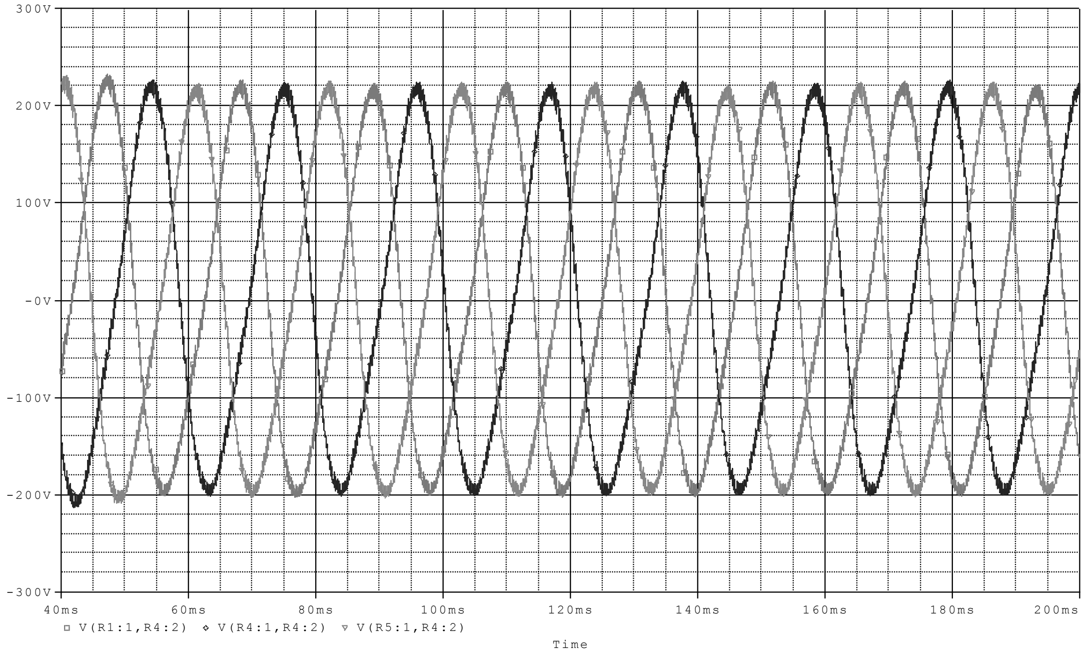

Fig 3.2 (a) Output voltage for modulating frequency (f_m)=48Hz and modulating voltage (V_m)=7.3 volt

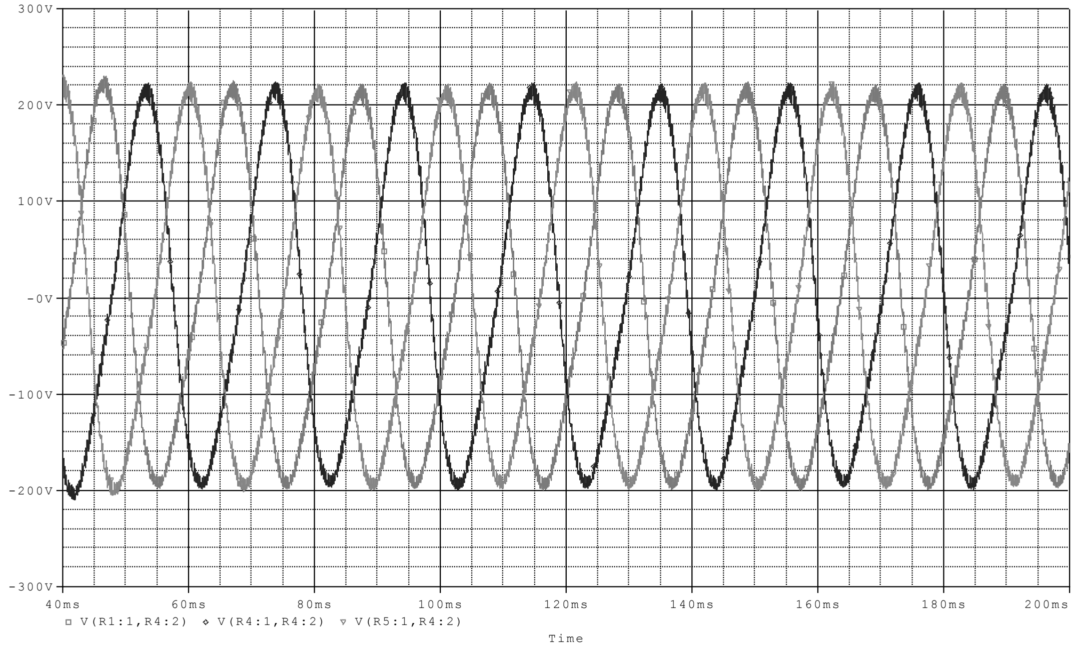

Fig 3.2 (b) Output voltage for modulating frequency (f_m)=49Hz and modulating voltage (V_m)=7.5 volt

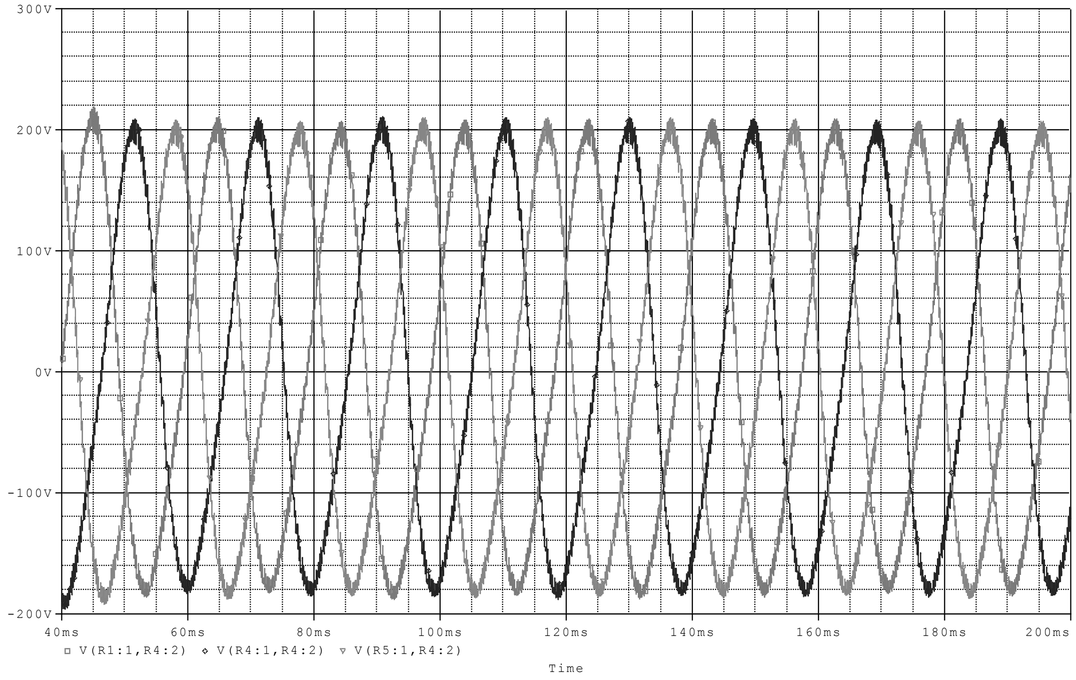

Fig 3.2 (c) Output voltage for modulating frequency (f_m)=51Hz and modulating voltage (V_m)=7.6 volt

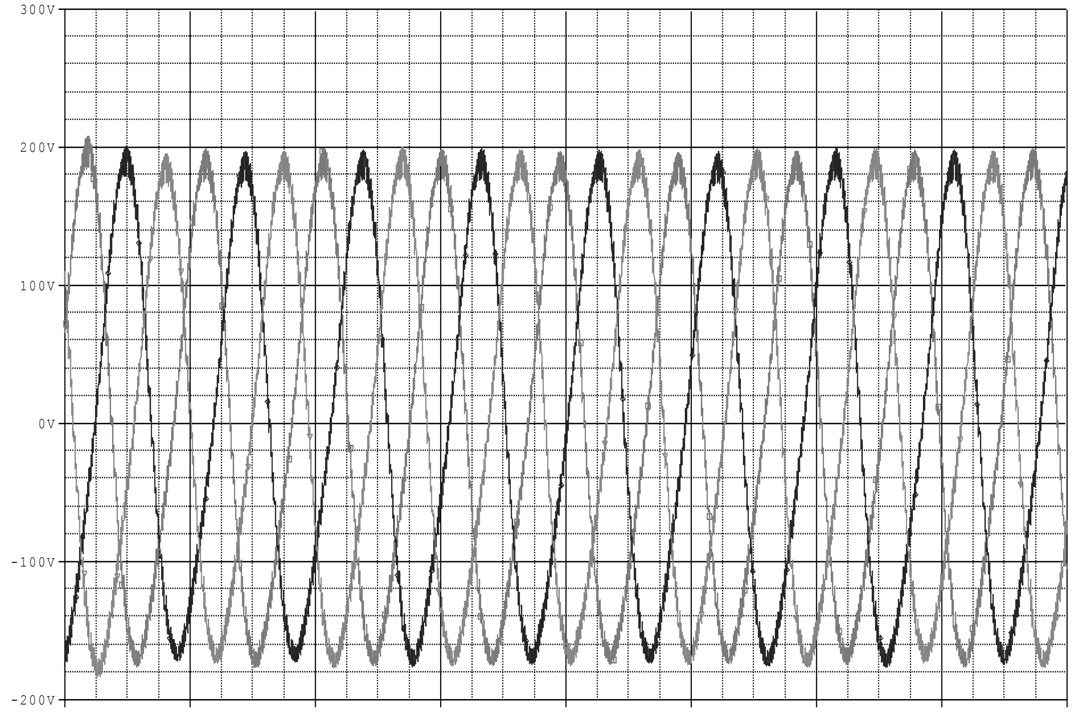

Fig 3.2 (d) Output voltage for modulating frequency (f_m)=53Hz and modulating voltage (V_m)=7.8 volt

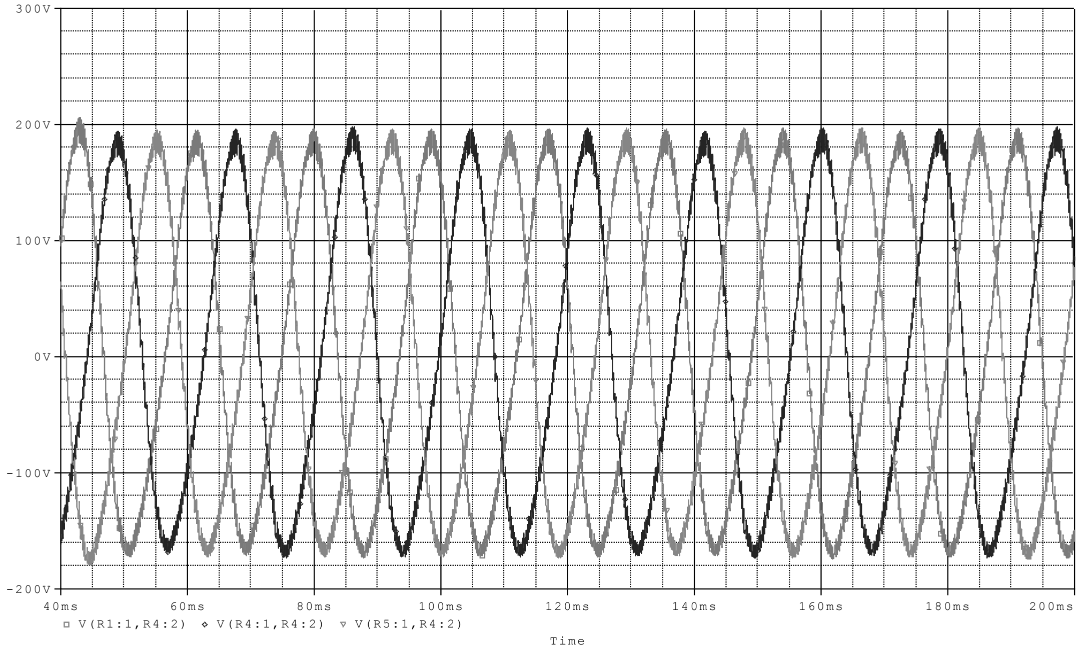

Fig 3.2 (e) Output voltage for modulating frequency (f_m)=54Hz and modulating voltage (V_m)=8 volt

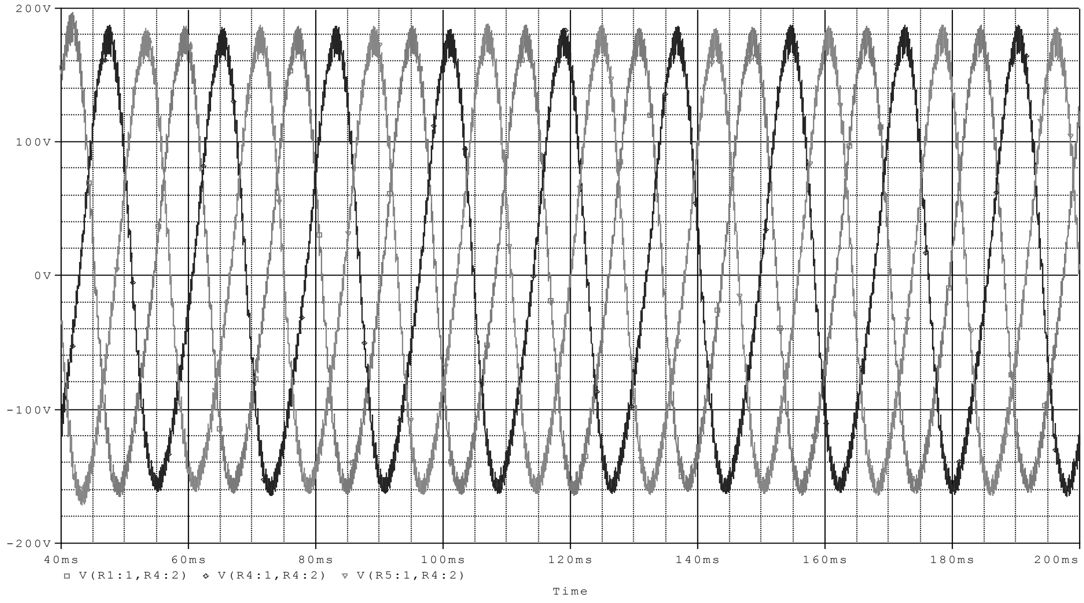

Fig 3.2 (f) Output voltage for modulating frequency (f_m)=56Hz and modulating voltage (V_m)=8.2 volt

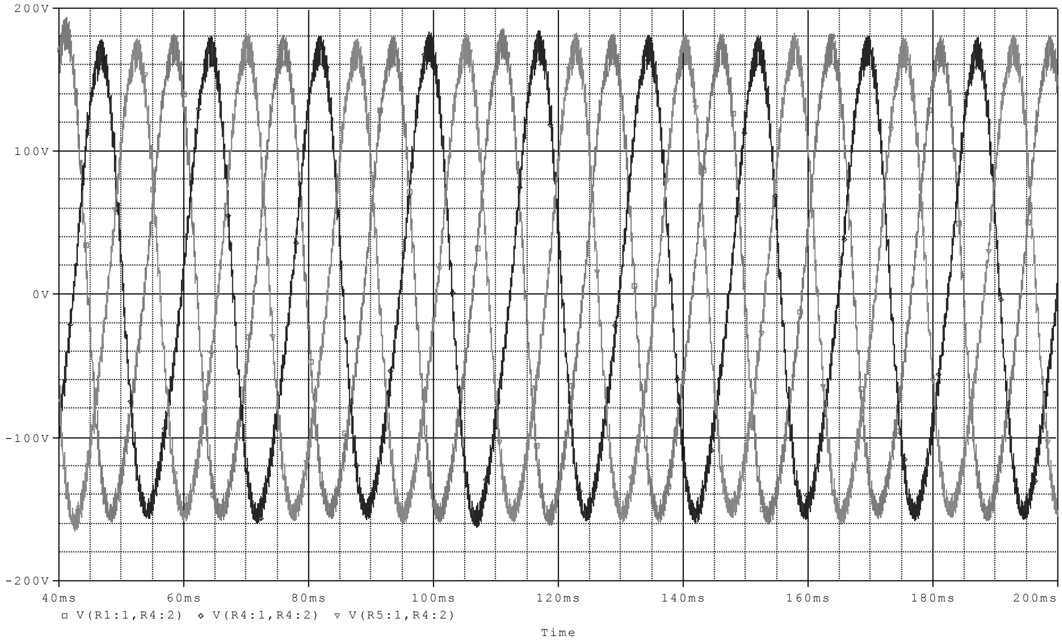

Fig 3.2 (g) Output voltage for modulating frequency (f_m)=57Hz and modulating voltage (V_m)=8.3 volt

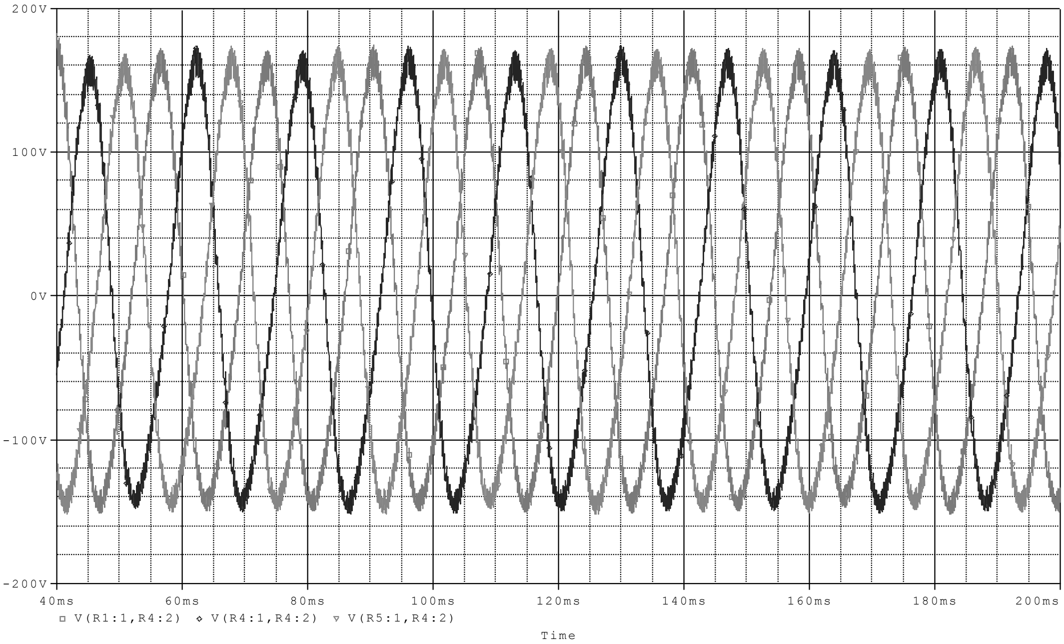

Fig 3.2 (h) Output voltage for modulating frequency (f_m)=59Hz and modulating voltage (V_m)=8.5 volt

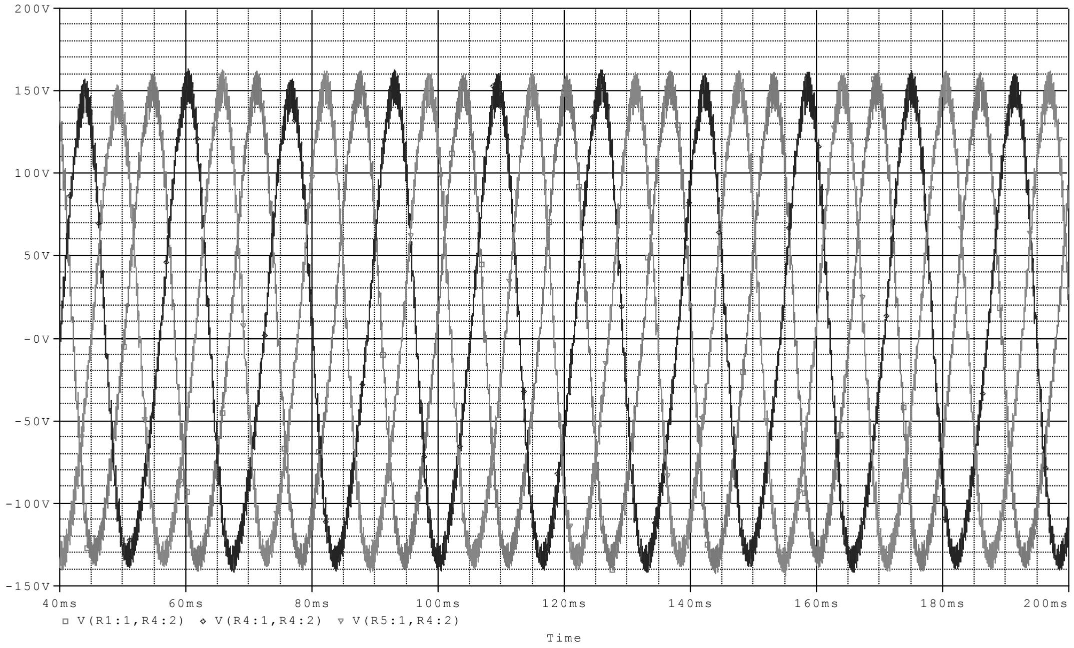

Fig 3.2 (i) Output voltage for modulating frequency (f_m)=61Hz and modulating voltage (V_m)=8.6 volt

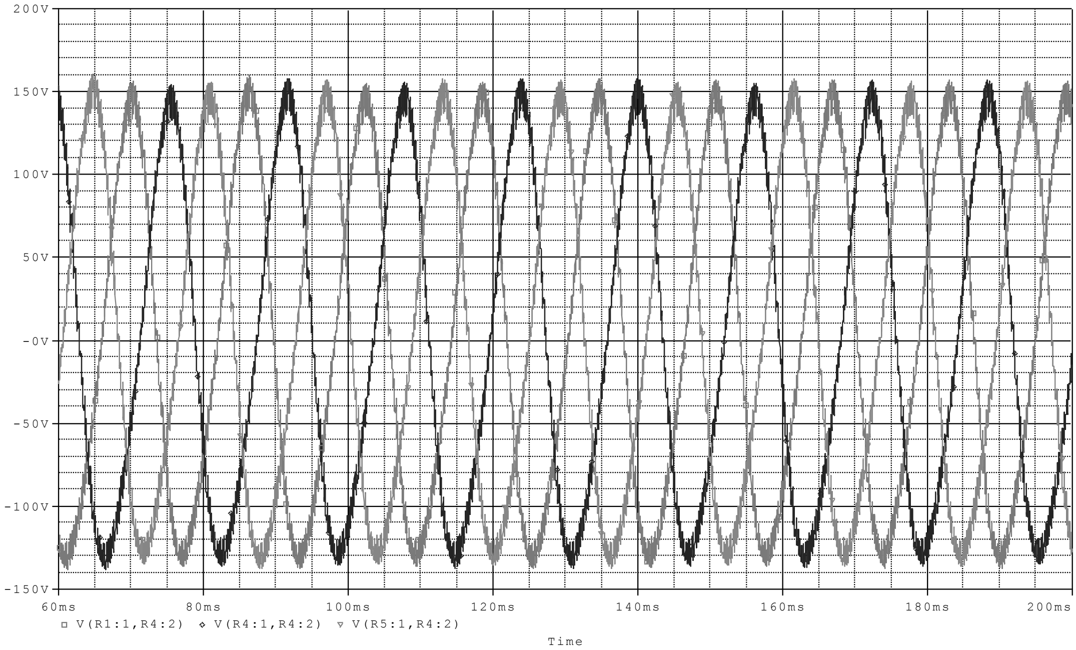

Fig 3.2 (j) Output voltage for modulating frequency (f_m)=62Hz and modulating voltage (V_m)=8.7 volt

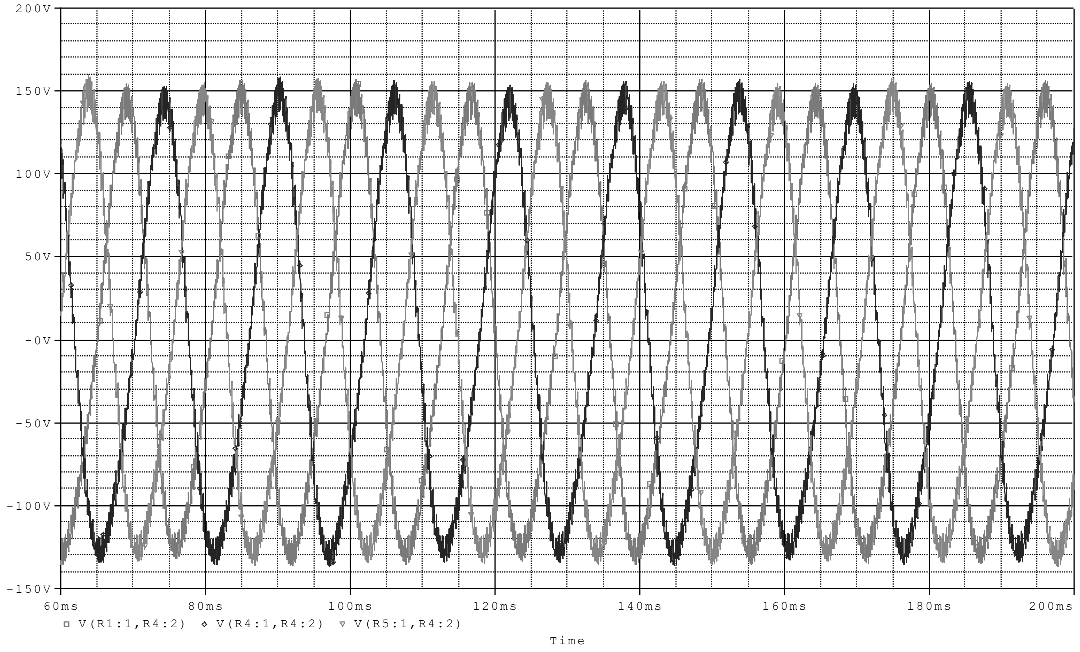

Fig 3.2 (k) Output voltage for modulating frequency (f_m)=63Hz and modulating voltage (V_m)=8.9 volt

Figure 3.2: Output voltage of manual control three phase boost inverter

It is observed from the above figure that output voltage of the proposed three phase boost inverter remain constant and sinusoidal.

3.6. Results and Analysis of Output of Manual Control Three Phase Boost Inverter at different modulating frequency and modulating voltage

To control the output voltage of the proposed three phase boost inverter modulating frequency and voltage is given manually. Output voltages of manual control three phase boost inverter at different modulating frequency and modulating voltage are given in the table 3.1.

Table 3.1: Summary of the Output voltage for manual control three phase boost inverter at different modulating frequency and modulating voltage

Sl. No	Modulating frequency (hz)	Modulating voltage (volt)	Output voltage (volt)
1	48	7.3	225
2	49	7.5	220
3	51	7.6	210
4	53	7.8	200
5	54	8	195
6	56	8.2	190
7	57	8.3	185
8	59	8.5	175
9	61	8.6	165
10	62	8.7	158

It is observed from table 3.1 that the output voltage for manual control three phase boost inverter increases with decreasing modulating frequency and modulating voltage.

3.7. Variation of Output Voltage for Modified Automatic Control Three Phase Boost Inverter

Automatic control three phase boost inverter simplify the control strategy. The output voltage for modified automatic control three phase boost inverter at different control signals are shown in figure 3.3(a-k).

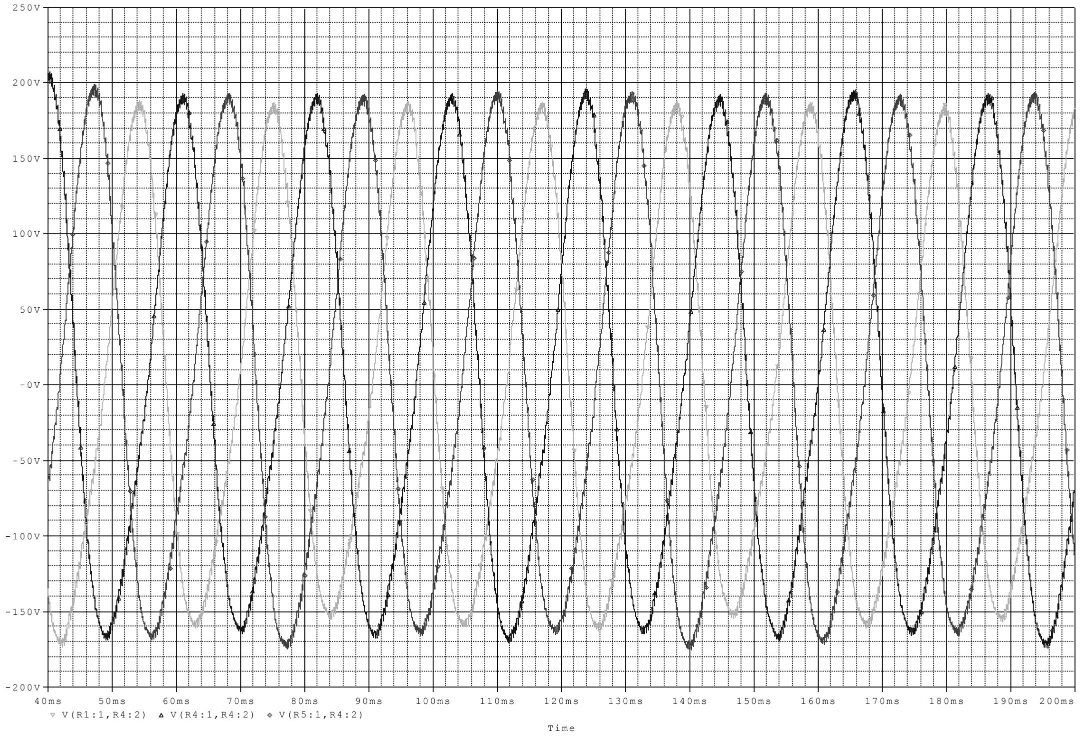

Fig 3.3 (a) Output voltage (V_o=) 192 volt for control voltage (V_c=) 3 volt

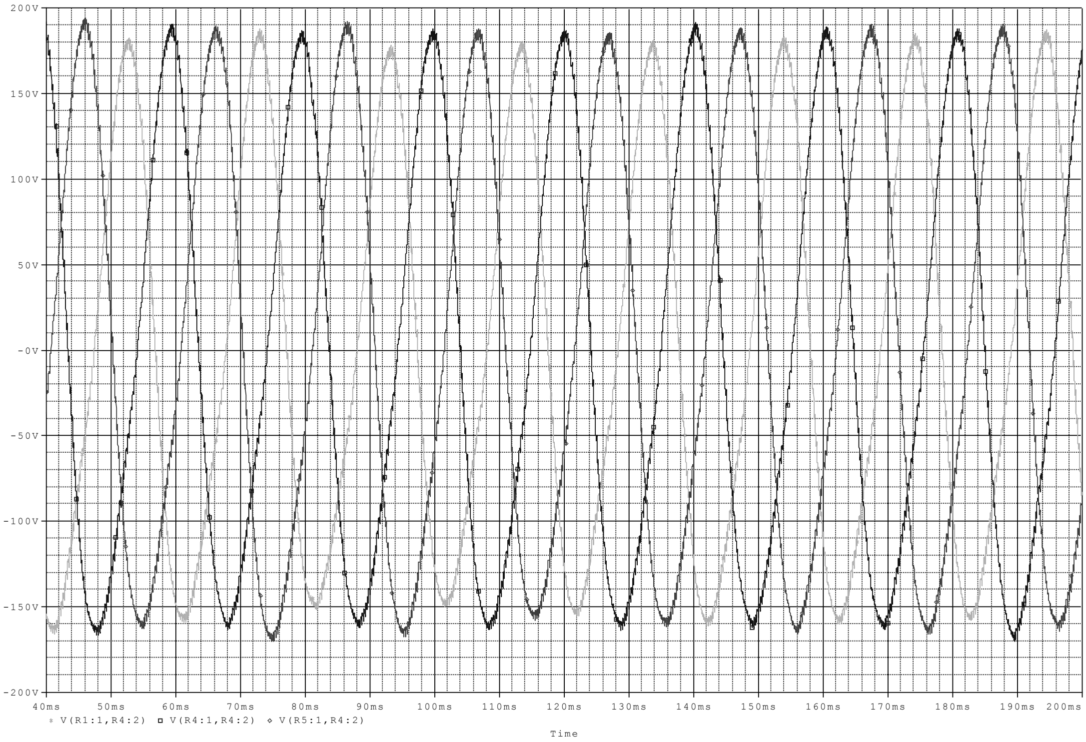

Fig 3.3 (b) Output voltage (V_o=) 190 volt for control voltage (V_c=) 3.1 volt

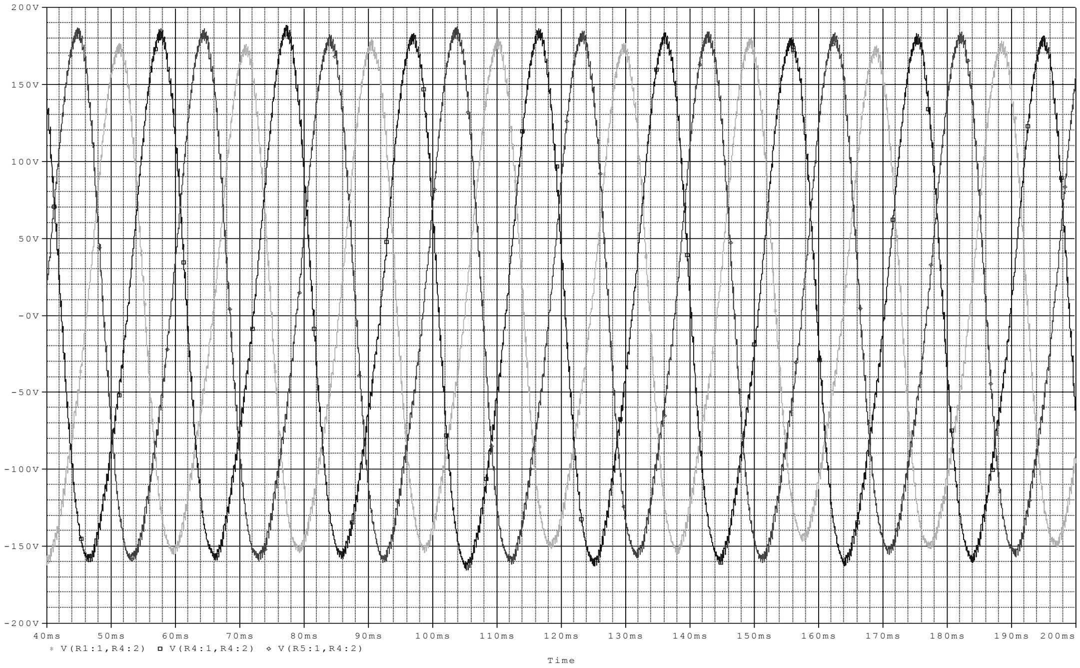

Fig 3.3 (c) Output voltage (V_o=) 186 volt for control voltage (V_c=) 3.2 volt

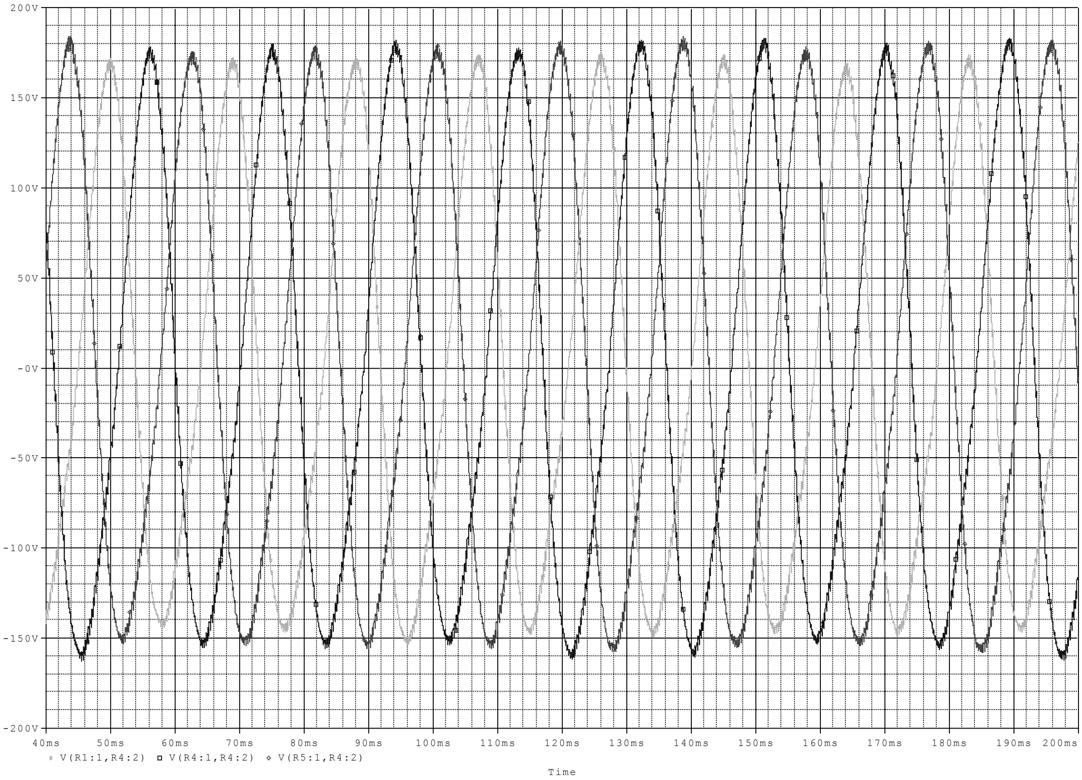

Fig 3.3 (d) Output voltage (V_o=) 185 volt for control voltage (V_c=) 3.3 volt

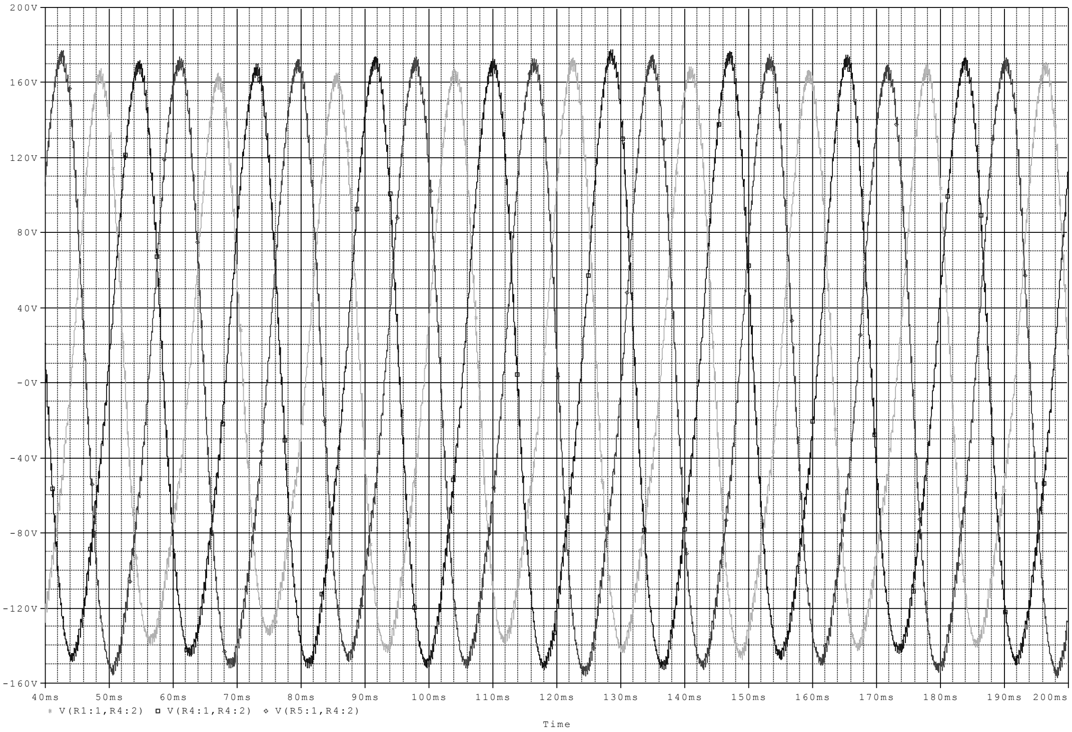

Fig 3.3 (e) Output voltage (V_o=) 175 volt for control voltage (V_c=) 3.4 volt

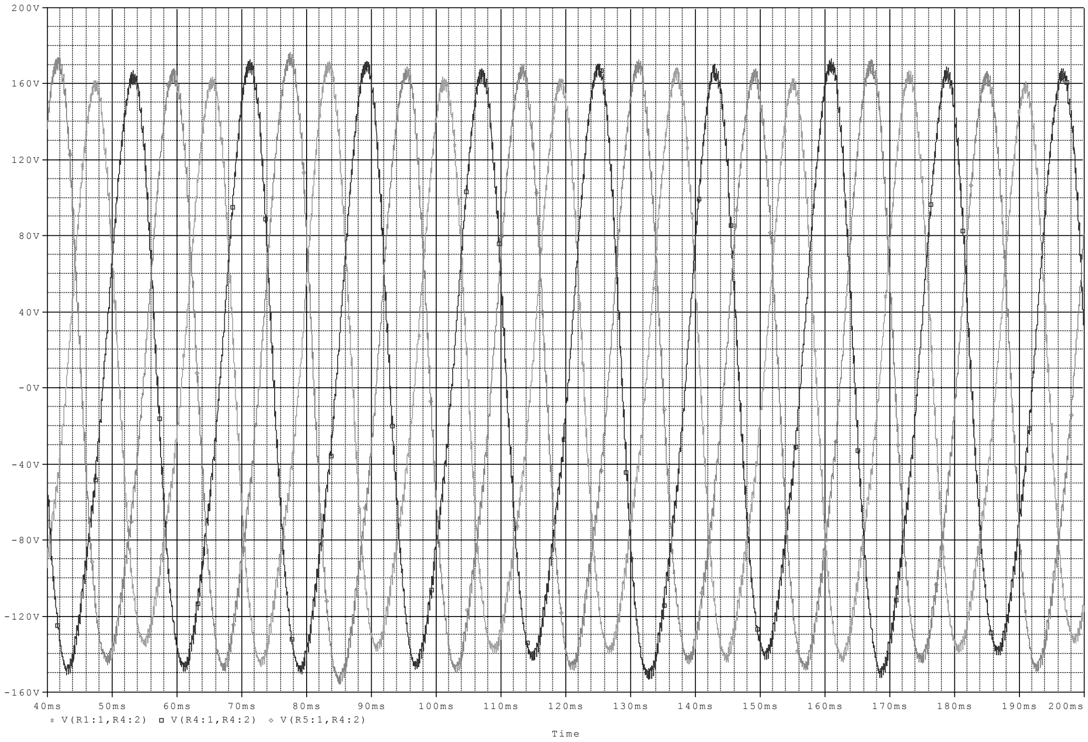

Fig 3.3 (f) Output voltage (V_o=) 172 volt for control voltage (V_c=) 3.5 volt

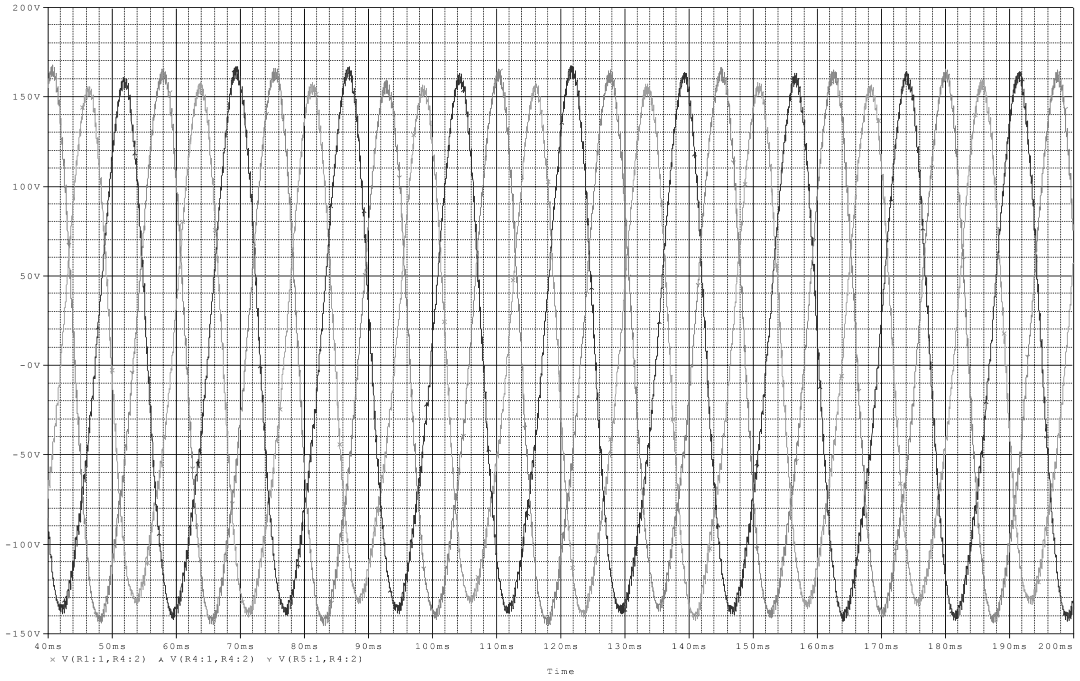

Fig 3.3 (g) Output voltage (V_o=) 166 volt for control voltage (V_c=) 3.6 volt

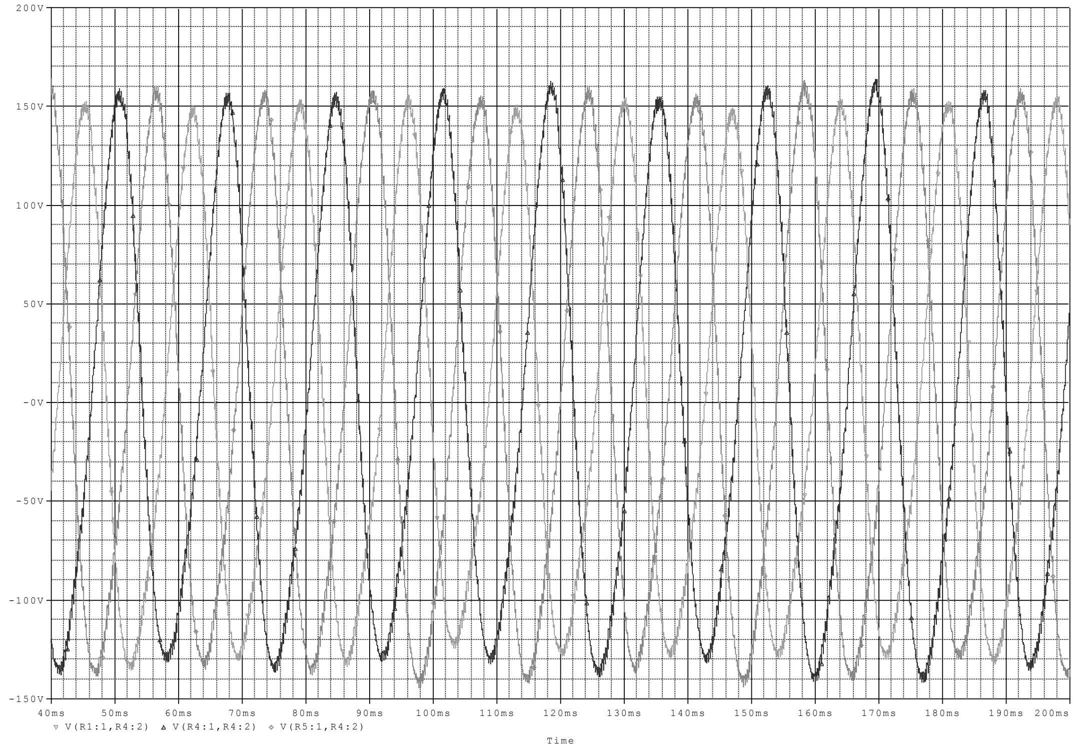

Fig 3.3 (h) Output voltage (V_o=) 162 volt for control voltage (V_c=) 3.7 volt

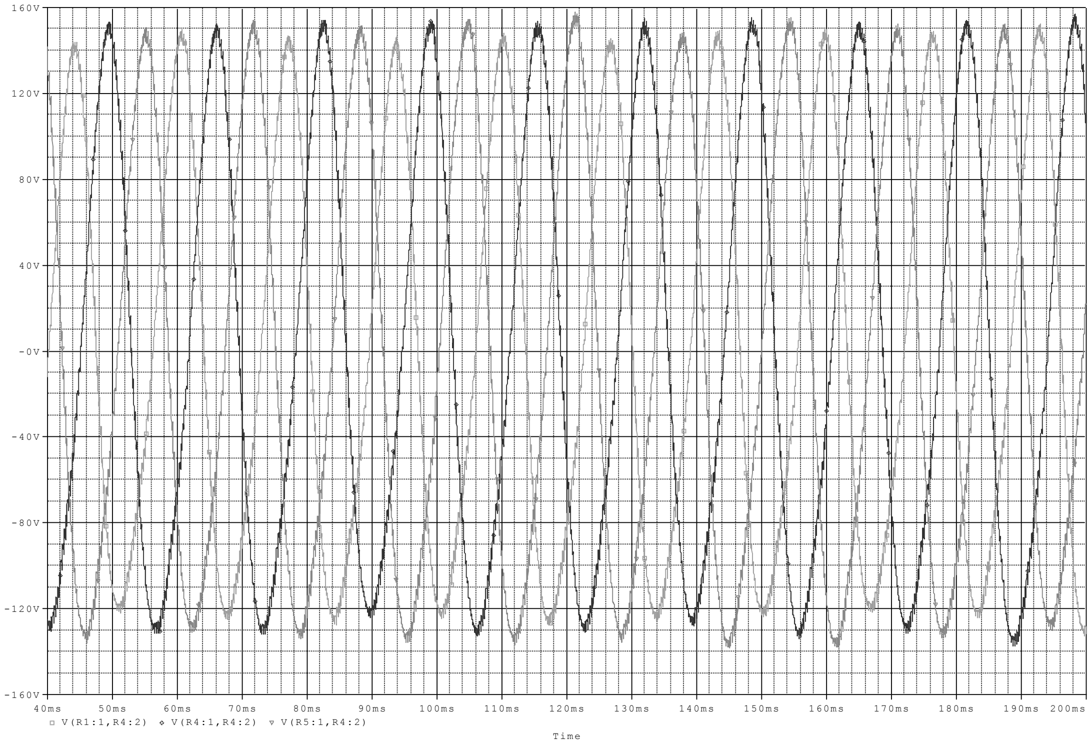

Fig 3.3 (i) Output voltage (V_o=) 158 volt for control voltage (V_c=) 3.8 volt

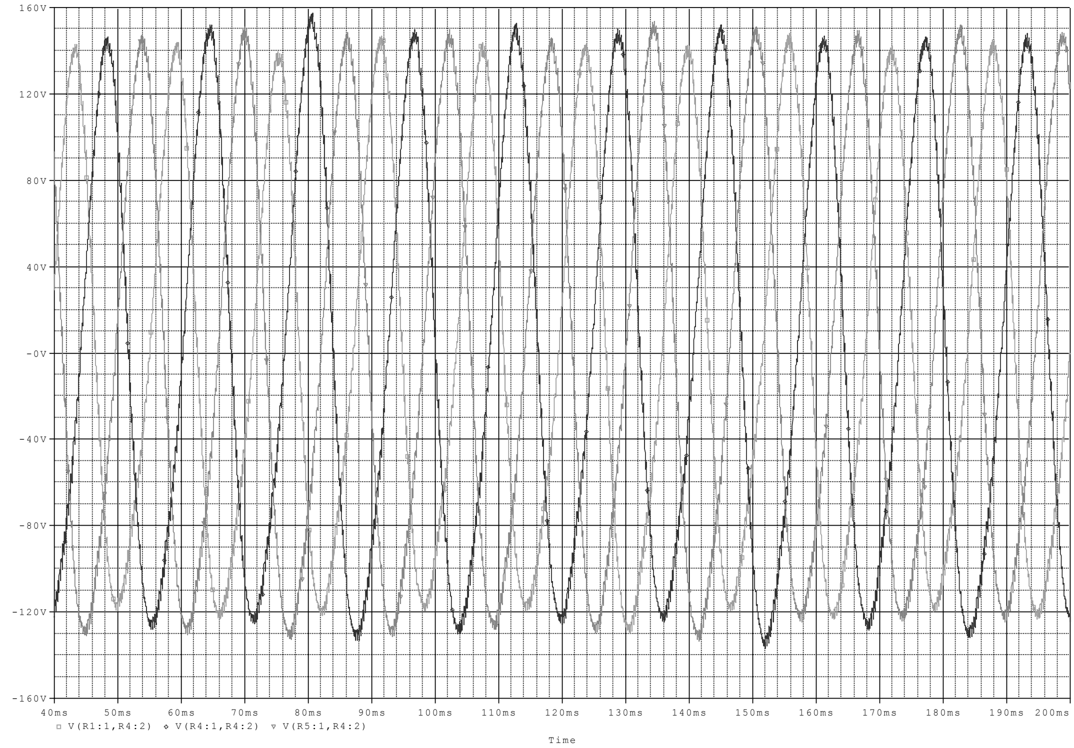

Fig 3.3 (j) Output voltage (V_o=) 155 volt for control voltage (V_c=) 3.9 volt

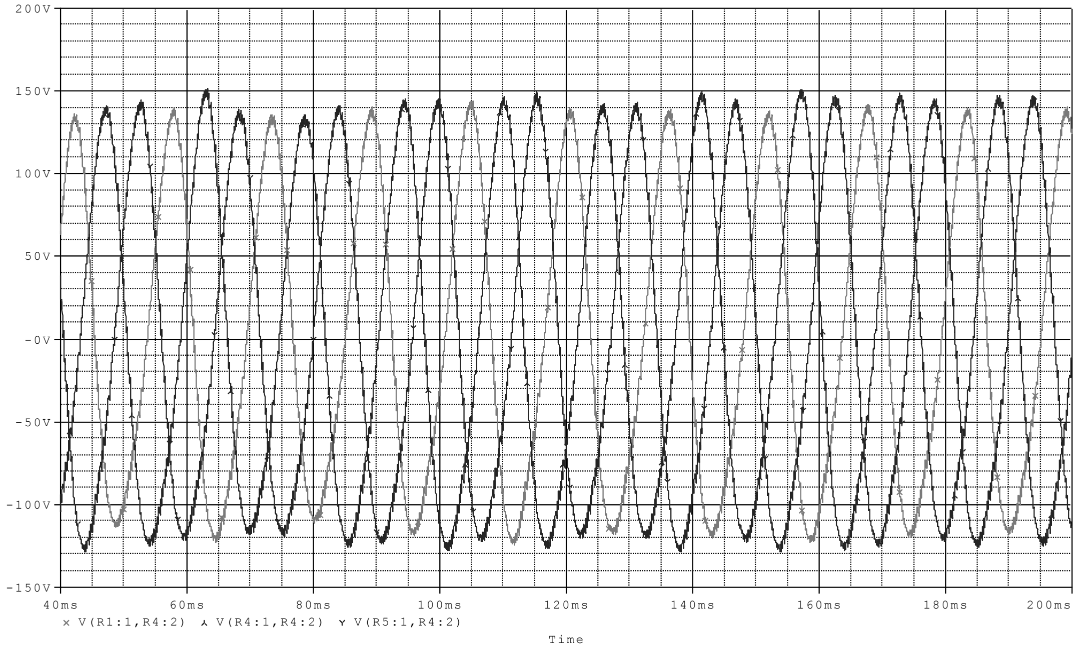

Fig 3.3 (k) Output voltage (V_o=) 145 volt for control voltage (V_c=) 4 volt

Figure 3.3: Output voltage of modified automatic control three phase boost inverter

It is observed from the figure 3.3 that output voltages of modified automatic control three phase boost inverter are constant and sinusoidal upto 60 hz (V_c= 3.9 volt). The output voltages remain sinusoidal above 4 volt control voltage but it is not constant.

3.8. Results and Analysis of Output of Modified Automatic Control Three Phase Boost Inverter at different Control Voltage

Output voltages of automatic control three phase boost inverter at different control voltage are given in the table 3.2.

Table 3.2: Summary of the Output voltage for automatic control three phase boost inverter at different control voltage

Sl. No	Control voltage	Modulating frequency	Modulating voltage	Output voltage
1	3	48	7.3	192
2	3.1	49	7.5	190
3	3.2	51	7.6	186
4	3.3	53	7.8	185
5	3.4	54	8	180
6	3.5	56	8.2	170
7	3.6	57	8.3	166
8	3.7	59	8.5	162
9	3.8	61	8.6	158
10	3.9	62	8.7	155

The magnitude of modulating frequency and voltage produced from automatic control oscillator for different control voltage is listed on the table 3.2. The magnitude of modulating frequency and voltage for control voltage 3 volt to 4 volt are listed on the table. It is observed from table 3.2 that the output voltage increase with decreasing modulating frequency and voltage.

3.9. Comparision of Output Voltage of Manual and Automatic Control Circuit

The output voltages of manual and automatic control three phase boost inverter at different modulating frequency and modulating voltage is summarized in the table 3.3 and figure 3.4.

Table 3.3: Analysis of the Output voltage for manual and automatic control three phase boost inverter at different modulating frequency and modulating voltage

Sl. No	Modulating frequency	Modulating voltage	Output voltage (Manual)	Output voltage (Automatic)
1	48	7.3	225	192
2	49	7.5	220	190
3	51	7.6	210	186
4	53	7.8	200	185
5	54	8	195	180
6	56	8.2	190	170
7	57	8.3	185	166
8	59	8.5	175	162
9	61	8.6	165	158
10	62	8.7	158	155

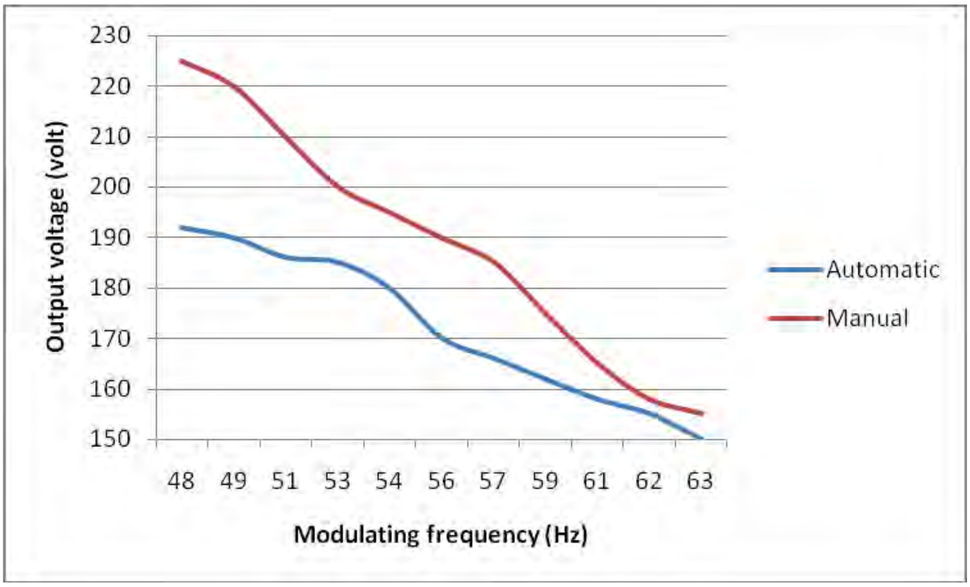

Figure 3.4: The output voltages of manual and automatic control three phase boost inverter at different modulating frequency

From table 3.3 and figure 3.4 it can be concluded that variation of output voltage of automatic control three phase boost inverter is almost same as manual control three phase boost inverter. Output voltage of both manual and automatic control three phase boost inverter decrease with increasing modulating frequency and modulating voltage.

3.10. Calculation of THD

At 48 Hz modulating frequency and 7.3 volt modulating voltage of automatic control three phase boost inverter we found that Fourier components of transient response $V(R\_R_3)$

Table 3.4: Foufier Analysis

HARMONIC NO	FREQUENCY (Hz)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	4.800E+01	1.732E+02	1.000E+00	1.494E+02	0.000E+00
2	9.600E+01	2.660E+01	1.536E-01	8.293E+01	2.159E+02
3	1.440E+02	1.771E+00	1.023E-02	1.245E+02	3.238E+02
4	1.920E+02	1.243E+00	7.176E-03	6.795E+01	5.298E+02
5	2.400E+02	7.169E-01	4.140E-03	9.134E+01	6.558E+02
6	2.880E+02	2.161E-01	1.248E-03	1.715E+02	7.251E+02
7	3.360E+02	1.214E-01	7.013E-04	4.742E+01	1.093E+03
8	3.840E+02	3.396E-01	1.961E-03	1.694E+02	1.026E+03
9	4.320E+02	3.132E-01	1.809E-03	1.534E+02	1.191E+03
10	4.800E+02	8.685E-02	5.016E-04	1.525E+02	1.342E+03

From the equation (8) we know that

$$THD_v = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \dots\dots\dots}}{V_1} *100\% \;\dots\dots\dots\dots(8)$$

$$\mathrm{THD_v} = \frac{\sqrt{(2.660\mathrm{E}+01)^2+(1.771\mathrm{E}+00)^2+(1.243\mathrm{E}+00)^2+\cdots\ldots\ldots\ldots+(8.685\mathrm{E}-02)^2}}{1.732\mathrm{E}+02} *100\%$$

$=0.15417$

Total Harmonic Distortion (THD) = 1.542213E+01 %

Table 3.5: THD value of manual and automatic coltrol three phase boost inverter at diffeent modulating frequency and voltage

Sl. No	Modulating frequency	Modulating voltage(auto)	Modulating voltage(manual)	THD%(auto)	THD%(manual)
1	48	7.3	6.3	15.5	16.8
2	49	7.5	6.7	16.2	16.5
3	51	7.6	6.9	15	15.3
4	53	7.8	7.3	16.2	14.8
5	54	8	7.4	13.7	15.4
6	56	8.2	7.7	13.8	14.8
7	57	8.3	7.8	12.8	14.8
8	59	8.5	8.1	14.7	14
9	61	8.6	8.2	12.9	14.4
10	62	8.7	8.4	14.4	13.6

From table 3.5 it is observed that the THD output of automatic and manual control three phase boost inverter is almost same.

The variation of the output voltage of automatic and manual control three phase boost inverter at different modulating frequency and voltage is nearly equal. The output voltages of both manual and automatic control three phase boost inverter are constant and sinusoidal.

Chapter 4

Conclusion and Suggestions for Future Works

4.1. Conclusion

A three phase differential boost inverter is designed and analyzed in this thesis. A brief review of the single phase and three phase boost inverter with different control technique was done. There relative merits and demerits are discussed. A three phase differential boost inverter is designed as a single phase differential boost inverter with modifications of power circuit to simplify the control strategy with reduced number of feedback from the power circuit to the control circuit.

In the thesis we have made a three phase boost inverter circuit with 3 leg inverter for 3-phase conversion which is composed of 6 MOSFETs and the control unit.

Connecting the load differentially across two BOOST DC-DC converters switched by sinusoidally modulated waves of opposite phase provides AC voltage across the load. The frequency and voltage of the inverter depend on the frequency of the modulating wave and the modulation index of modulation, three-phase AC can be achieved by introducing three DC-DC boost converter along with modulated switching wave produced from reference sine wave with 120° phase shift. However, modifications of power circuit from that of proposed in the single phase application will be necessary for each leg to provide path for four quadrant operation as necessary in the inverters. This will be done by providing voltage lift circuit in each leg of the DC-DC converter.

Three legs of the DC-DC converters of the three phase inverter will be controlled using voltage mode PWM technique by comparing a saw tooth ramp carrier with a reference sine wave and standard feedback technique from the load voltage. Reduction of the feedback will be the result of use of voltage lift circuit, which makes output voltage input current insensitive.

The control unit generates control pulses to drive the MOSFETs. The pulse generator gives a digital signal to the MOSFETs. When the signal from the pulse generator is not zero then it reacts as a switch and opens. This consists the basic operation in order to convert the DC to AC, with the technique of the Pulse Width Modulation (PWM). Different modulating signals (amplitude and frequency) can be used to control the system. Modulating signal with different amplitude and frequency is given to the manual control system to generate modulated signal and to control the output of the inverter. In automatic control circuit modulating signal is generated by controlling only the control voltage to simplify the control strategy.

4.2. Suggestions for Future Works

Reviewing the works of this thesis we can conclude that there are several opportunities for future works.

- From the preliminary simulation study the efficiency of the inverter is not satisfactory. Further study can be done to increase the efficiency of the inverter

- From the THD calculation it is observed that the THD value is high. Investigation can be done to lower the THD values as much as possible.

- The inverter is designed by ORCAD simulation. Further work can be done to practically design t0he inverter.

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