

**DESIGN AND ANALYSIS OF THE REDUCTION OF  
HARMONICS AT INVERTER OUTPUT**

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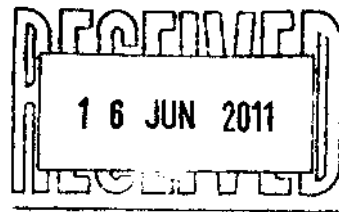
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## ABSTRACT

The aim of this thesis is to present a technique to reduce harmonics in output voltage of single phase inverters. The thesis explains how harmonics is one of the most dangerous threats for the appliances. The thesis also deals with the technique to reduce harmonics. A circuit based on paralleling of two invertors by using interface reactors is investigated. The interface reactor is the harmonic reducing element. Sine Pulse-width modulation is used to generate the gating signals of the inverters. There is a phase difference between the gating signals of parallel branches. By varying the phase difference, an analysis is done to find the best situation when maximum harmonic elements can be reduced. Another two analyses are done by varying frequency ratio and modulation index. A conclusion is made about the finest modulation index depending on RMS value of fundamental component and presence of 3<sup>rd</sup>, 5<sup>th</sup> 7<sup>th</sup> harmonic components. Relation between frequency ratio and specific harmonic components is also studied. It is possible to eliminate all harmonics up to a certain limit by setting the frequency ratio. An equation is established for that. Analysis is carried out by using MATLAB and PSPICE software.

# CHAPTER I

## INTRODUCTION

### INTRODUCTION

In a modern industrialized nation today, an increasingly significant portion of the generated electrical energy is processed through power electronics for various applications in industrial, commercial, residential, aerospace and military environments [1]. Harmonics is always a problem for the power system. So reduction of harmonics is necessary.

When the DC voltage is converted to AC. During this conversion the harmonics affect the power quality a lot. Harmonics occur for the nonlinearity of the load. That is why harmonic reduction in inverters is very important. In early days harmonic distortion was less because the structure of power system was simple. But nowadays the distortion has increased because now the structure of power system is more complex [1]. Every appliance needs pure sinusoidal wave. If the waveform of voltage is not sinusoidal then it is affected by harmonics. The output of the home appliances can be affected by harmonics.

AC-DC conversion is necessary, because only DC can be stored. As Storing AC is not possible an efficient conversion is always desired. There are some techniques which can make this conversion in a desired manner. Full reduction of harmonics is desired, but almost unachievable. Harmonic reduction up to a certain limit is possible. There are some modulation techniques which can reduce the effect of harmonics up to a desired level. In these techniques different types of reference signals are compared with the carrier signal to generate the gating signals. By varying the modulation index, the desired reduction in harmonics can be achieved.

## OBJECTIVE

The objective of this thesis is to design and analysis of the reduction of harmonics at inverter. A single phase inverter is studied to reduce harmonics from its output voltage. The basic is based on paralleling two inverters with a current sharing reactor. The main concern of this thesis is to reduce harmonics as harmonics introduce a lot of difficulties which are also discussed here. The parallel bridges of inverter are operated with shifted gating signals. By varying this shifting angle an analysis is done to get the best shifting angle to reduce harmonics. Specially, elimination of the low order harmonics is preferred. Sine pulse width modulation technique is followed to generate and control the gate voltages. The study of modulation index with respect to the harmonic components is also done here to get a better idea about it. Analysis of the frequency ratio is another objective. A relation between the harmonic components and frequency ratio is established. The relation shows the required frequency ratio to get up to a certain harmonic component.

The objective of the present research work are as follows:

- To analyze the best shifting angle for the proposed circuit to achieve an output voltage of minimum harmonics.
- To analyze the modulation index with respect to fundamental and harmonic components.
- To analyze the relation between the harmonic component and frequency ratio.

It is expected that this study will yield an effective design strategy of single phase inverter with minimum harmonics.



## THESIS LAYOUT

Chapter one of this thesis includes five chapters. Chapter one gives a general introduction and the objective of the work.

Chapter two reviews inverter followed by its operating principle, types and applications.

Chapter three explains the description of the harmonics. Problems due to harmonics and the methods of reduction is also discussed in this chapter.

Chapter four contains the description of the proposed circuit. Analysis using MATLAB for different frequency ratio ( $f_r$ ), modulation index ( $M$ ) and shifting angle ( $\theta$ ) is also shown here.

The results of the output voltages using PSPICE is illustrated in chapter five. The outputs found using MATLAB are reproduced here again for justification.

Chapter six is drawn in chapter six. Some recommendations leading to future scope of work are given here.



## CHAPTER II OVERVIEW OF INVERTER

### INVERTER

An inverter is an electrical circuit that converts direct current (DC) to alternative current (AC). The magnitude and frequency of the alternative current can be changed using different methods [2].

- By changing the DC voltage.
- By changing the gain of the inverter.

If we change the DC voltage then in that case the gain of the inverter will be constant. In this way by changing the DC voltage we can get our desired output.

On the other hand if we change the inverter gain then the DC voltage must have to be constant. In this way by changing the inverter gain desired output AC voltage can be obtained. The gain of the inverter may be defined as the ratio of the AC output voltage to DC input voltage.

In an inverter the output should be pure sinusoidal wave but in practical the output is not ideal. It contains some harmonics.

### OPERATING PRINCIPLE OF INVERTER [2]

Figure 2.1 is the circuit diagram of a single phase bridge voltage source inverter. This is a full bridge inverter. It consists of four choppers. They are Q1, Q2, Q3, Q4. When transistors Q1 and Q2 are turned on simultaneously then the input voltage which is  $V_s$ , appears across the load but on the other hand if transistors Q3 and Q4 are turned on simultaneously then the voltage across the load is reversed. So the voltage across the load becomes  $-V_s$ . These transistors behave as switches. Diodes D1 and D2 are called feedback diodes. When diode D1 and D2 conduct, the energy is fed back to the DC source. Figure 2.2 shows the voltage waveforms of the output voltages. If the upper and one lower switch conduct together the switch state is 1 and the output voltage is

If these are off at the same time then the switch state will be 0. A table is providing to the function of the switch state. Table 2.1 is the switch states for a Single Phase Full-Voltage-Source Inverter.

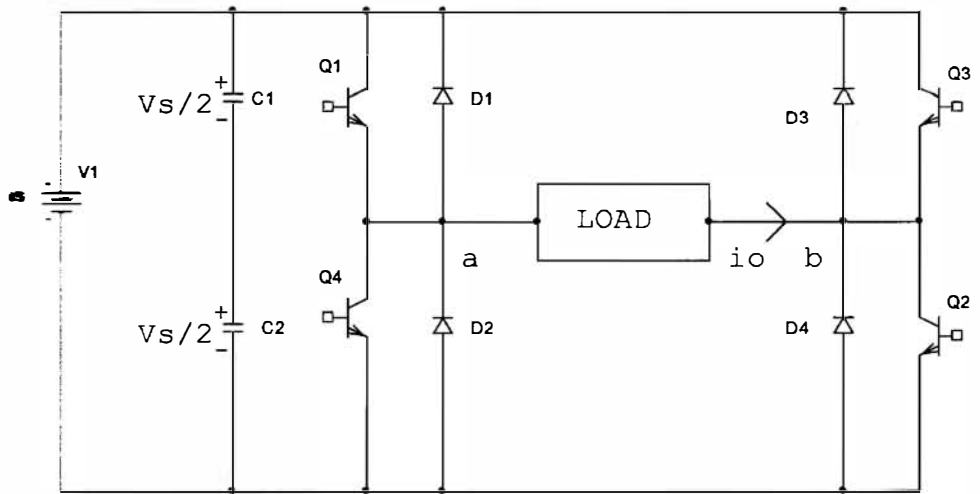


Figure 2.1: Circuit diagram of an inverter.

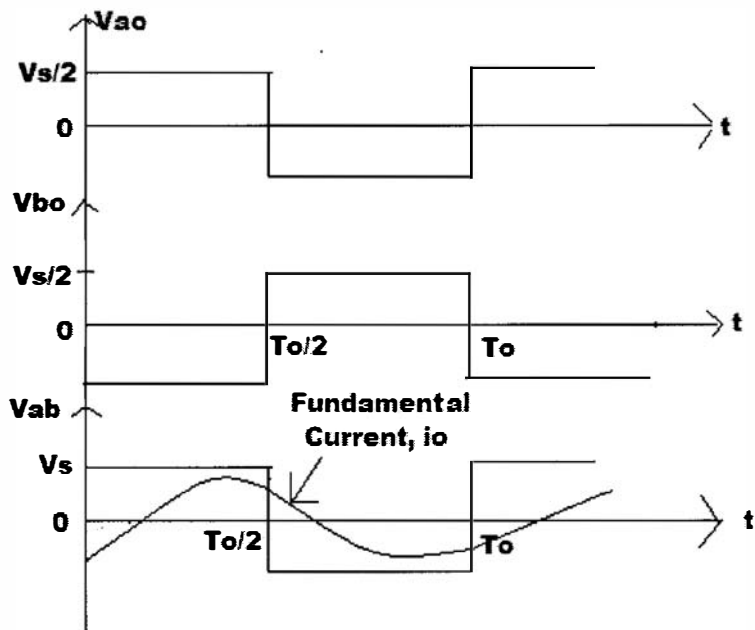


Fig 2.2: Waveforms of the output voltages.

**Table 2.1: Switch states for a Single Phase Full-bridge Voltage-Source Inverter (VSI)**

State	State no	Switch state	V <sub>ao</sub>	V <sub>bo</sub>	V <sub>o</sub>	Components conducting
S1 and S2 are on and S4 and S3 are off	1	10	V <sub>s</sub> /2	-V <sub>s</sub> /2	V <sub>s</sub>	S1 and S2 if i <sub>o</sub> >0 D1 and D2 if i <sub>o</sub> <0
S4 and S3 are on and S1 and S2 are off	2	01	-V <sub>s</sub> /2	V <sub>s</sub> /2	-V <sub>s</sub>	D4 and D3 if i <sub>o</sub> >0 S4 and S3 if i <sub>o</sub> <0
S1 and S3 are on and S4 and S2 are off	3	11	V <sub>s</sub> /2	V <sub>s</sub> /2	0	S1 and D3 if i <sub>o</sub> >0 D1 and S3 if i <sub>o</sub> <0
S4 and S2 are on and S1 and S3 are off	4	00	-V <sub>s</sub> /2	-V <sub>s</sub> /2	0	D4 and S2 if i <sub>o</sub> >0 S4 and D2 if i <sub>o</sub> <0
S1, S2, S3 and S4 are all off	5	off	-V <sub>s</sub> /2 V <sub>s</sub> /2	V <sub>s</sub> /2 -V <sub>s</sub> /2	-V <sub>s</sub> V <sub>s</sub>	D4 and D3 if i <sub>o</sub> >0 D4 and D2 if i <sub>o</sub> <0

Equation of the RMS output voltage is  $V_0 = \left( \frac{1}{T_0} \int_0^{T_0/2} V_s^2 dt \right)^{1/2}$

$$= \frac{1}{T_0} V_s^2 [t]_0^{T_0/2}$$

$$= \frac{1}{T_0} V_s^2 \frac{T_0}{2}$$

$$= V_s^2$$

RMS output voltage is obtained from the above equation.

Instantaneous output voltage can be written as  $V_0 = \sum_{n=1,3,5}^{\infty} \frac{4V_s}{n\pi} \sin n \omega t$

Under load the instantaneous current becomes  $i_0 = \sum_{n=1,3,5}^{\infty} \frac{4V_s}{n\pi \sqrt{R^2 + (n\omega L)^2}} \sin (n\omega t - \theta_n)$

where  $\theta_n = \tan^{-1} (n\omega L/R)$

For inductive load:

The fundamental component of the current is  $i_0(t) = \frac{V_{01}}{V_s} I_0 \cos(\theta_1) - \frac{V_{02}}{V_s} I_0 \cos(2\omega t - \theta_2)$

where  $V_{01}$  = The fundamental r.m.s output voltage

$I_0$  = The r.m.s load current.

$\theta_1$  = The load impedance angle at the fundamental frequency.

From the above equation it is clearly viewed that the current contains second-order harmonics.

These harmonics are injected back into the voltage source thus the design can be guaranteed

to provide a constant DC voltage.

## TYPES OF INVERTERS

There are many types of inverters. But in this thesis we will discuss about three kinds of inverter.

1. Single Phase Voltage Source Inverter

2. Single Phase Full Bridge Inverters

3. Single Phase Square wave or Modified Square wave Inverters

### 2.3.1 SQUARE WAVE INVERTER

This type of inverter produces a square wave at the output. It consists of a DC source, four switches, and the load. The switches are power semiconductors that can carry a large current and withstand a high voltage rating [3]. The operation of the switches should maintain correct on/off sequence. The switch will be on or off at a certain frequency [3]. But it produces the lowest quality of power.

#### Advantages of square wave inverter [4]

1. Simple Design.
2. Least expensive.
3. Less sensitive to noisy power source.
4. Suitable for most electronic devices.

#### Disadvantages of square wave inverter [4]

1. Produces harmonics.
2. Generate electrical noise.
3. Not suitable for high power application.
4. Not suitable for sensitive or specialized equipment, for example certain laser printers.
5. Suitable for resistive load only

### 2.3.2 SINE WAVE INVERTERS

A true/pure sine wave inverter is one type of inverter that produces sine. This sine wave is not identical to the sine wave which is supplied from the power grid. In a sine wave, the voltage rises and falls smoothly with a smoothly changing phase angle and also changes its polarity instantly when it crosses 0 Volts [5].

### **Advantages of true/pure sine wave inverter [5]**

1. Reduces audible and electrical noise in fans, audio amplifiers, TV and some sensitive audio system.
2. Inductive loads like microwave ovens and motors might run faster, quieter and cooler.
3. Suitable for sensitive electrical or electronic items such as certain medical equipment.
4. Prevents crashes in computers, weird print outs and glitches in monitors.
5. The output contains low harmonics.

### **Disadvantages of true/pure sine wave inverter**

1. It is expensive.
2. Complex design.
3. Least efficient.

### **2.3.3 QUASI SQUARE WAVE OR MODIFIED SQUARE WAVE INVERTERS**

The quasi-sine wave is an intermediate approach which can replicate the key characteristics of the AC mains supply if properly controlled. Quasi-sine units are now restricted to very low cost, low end applications and certain very high inrush applications, such as refrigeration. The quasi-sine wave inverter does not give a true sine wave but they can mimic the key voltage parameters fairly well. So the majority of equipment can run successfully [6].

### **Advantages of Quasi Square wave or Modified Square wave Inverters [6]**

1. Cost is low.
2. Majority of loads can be operated successfully.
3. Simple design.
4. More efficient and robust.

## **Disadvantages of Quasi Square wave or Modified Square wave Inverters [7]**

1. The peak voltage varies with the battery voltage.
2. Inexpensive electronic devices with no regulation of their power supply may behave erratically when the battery voltage fluctuates.

## **2.4 APPLICATIONS OF INVERTER**

For low and medium-power applications, square-wave or quasi-square-wave voltages may be acceptable but for high-power applications, low distorted sinusoidal wave-forms are required [2].

Inverters are widely used in different industrial applications [2].

1. Variable-speed ac motor drives.
2. Induction heating.
3. Standby power supplies.
4. Uninterruptible power supplies.
5. Air conditioning.
6. HVDC power transmission.



## CHAPTER III DIFFERENT TECHNIQUES TO ELIMINATE HARMONICS

### 3.1 HARMONICS

Harmonics are undesirable currents and voltages. The frequencies of the harmonics are integer multiple of the fundamental frequency [8]. Harmonics occur when the current flowing through a load is non-linearly related to the applied voltage. The harmonics can arise in three ways [9]

1. Through the application of a non-sinusoidal driving voltage to a circuit containing non-linear impedance.
2. Through the application of a sinusoidal driving voltage to a circuit containing non-linear impedance.
3. Through the application of a non-sinusoidal driving voltage to a circuit containing linear impedance.

Harmonics can be of different order. The harmonics are integer multiples of fundamental frequency. For an example if the fundamental frequency is 'f' then the frequency of the harmonics will be 2f, 3f, 4f etc. Harmonics increase the current of the system. So the current counter higher impedance than the fundamental frequency current. This is due to the Skin effect. Skin effect is the tendency for higher frequency currents to flow near the surface of the conductor [10].

## 2 PROBLEMS OF HARMONICS

Harmonics can create a lot of problem. Some are mentioned below [11]

1. Overheating of transformers, cables, motors, generators and capacitors connected to the same power supply with the devices generating the harmonics.
2. Electronic displays and lighting may flicker
3. False operation of circuit breakers
4. Computers may fail and metering can give false readings. Harmonics can affect the home appliances by damaging it with overvoltage, heat damage due to overheating of wires.
5. Large load currents flow in the neutral wire for a three phase system. This can cause overheating of neutral wire. This can lead to potential fire hazard.
6. Harmonics creates high voltage distortion which can exceed IEEE Standard 1100-1992 "Recommended Practice for Powering and Grounding Sensitive Electronic Equipment" and manufacturer's equipment specifications.
7. Harmonics can create high current distortion and excessive current draw on branch circuits which can exceed IEEE Standard 1100-1992 "Recommended Practice for Powering and Grounding Sensitive Electronic Equipment" and manufacturer's equipment specifications.
8. Harmonics can create high voltage between neutral to ground.
9. Harmonics can also affect the power factor.



Some cause and the effect are mentioned in table 3.1.

**Table 3.1:** List of the different factors and their effects [11]

The causes	The effects
The larger the motor...	The higher the current harmonics
The higher the motor load...	The higher the current harmonics
The larger the DC or AC inductance...	The lower the current harmonics
The higher the number of pulses in the rectifier...	The lower the current harmonics
The larger the transformer...	The lower the voltage harmonics
The lower the transformer impedance...	The lower the voltage harmonics
The higher the short circuit capacity of supply...	The lower the voltage harmonics

### **IMPORTANCE OF REDUCTION OF HARMONICS**

Reduction of harmonics is very important, because those are undesirable. But all devices were designed to run by pure sinusoidal voltage or current. So the distorted voltage or current creates problems. Due to the non-linearity of the load the harmonic problem occurs. Some non-linear loads are mentioned below [11].

1. Motor starters
2. Variable speed drives
3. Computers and some other electrical devices.
4. Personal or notebook computers
5. Laser printers
6. Fax machines
7. Telephone systems
8. Stereos, radios
9. TVs
10. Adjustable speed drives and variable frequency drives
11. Battery chargers
12. UPS

Equipment which is powered by SWITCH MODE POWER SUPPLY that creates harmonics [11]. Problems due to harmonics are discussed in the section [3.2]. So to solve these problems reduction of harmonics is very important.

## 3.4 MODULATION TECHNIQUES

### 3.4.1 SINE PULSE WIDTH MODULATION

Pulse width modulation is a technique which is used for eliminating the lower order harmonics. This technique does not reduce the total harmonics distortion factor of the current or voltage. It reduces the non-zero harmonics of higher order. Sine pulse width modulation technique is used to generate the gating signal. A carrier wave is compared with the reference signal corresponding to a phase to generate the gating signal for that phase [2]. A triangular wave is used as the carrier signal and a sine wave is used as the reference signal. A diagram of sine pulse width modulation is shown in figure 3.1. In this technique a comparator is used. The output of the comparator is pulse width modulated signal. The reference signal is given at the positive terminal of the comparator. The carrier is given at the negative terminal of the comparator. As long as the reference signal is high the pulse will be wider. So the width of the pulse depends on the reference signal. That means when the reference signal is greater than the carrier signal then the output signal will be high. By changing the amplitude of the reference signal the width of the pulse can be varied. The frequency of the carrier signal should be higher than the frequency of the reference signal. By using this technique lower order harmonics can be eliminated [8]. The main advantage of this technique is it provides very low power loss in the switching devices [8]. When the switch is off there is no current. When the switch is on then there is no voltage across the switch. Power is the product of current and voltage. So in both cases the power loss is almost zero.

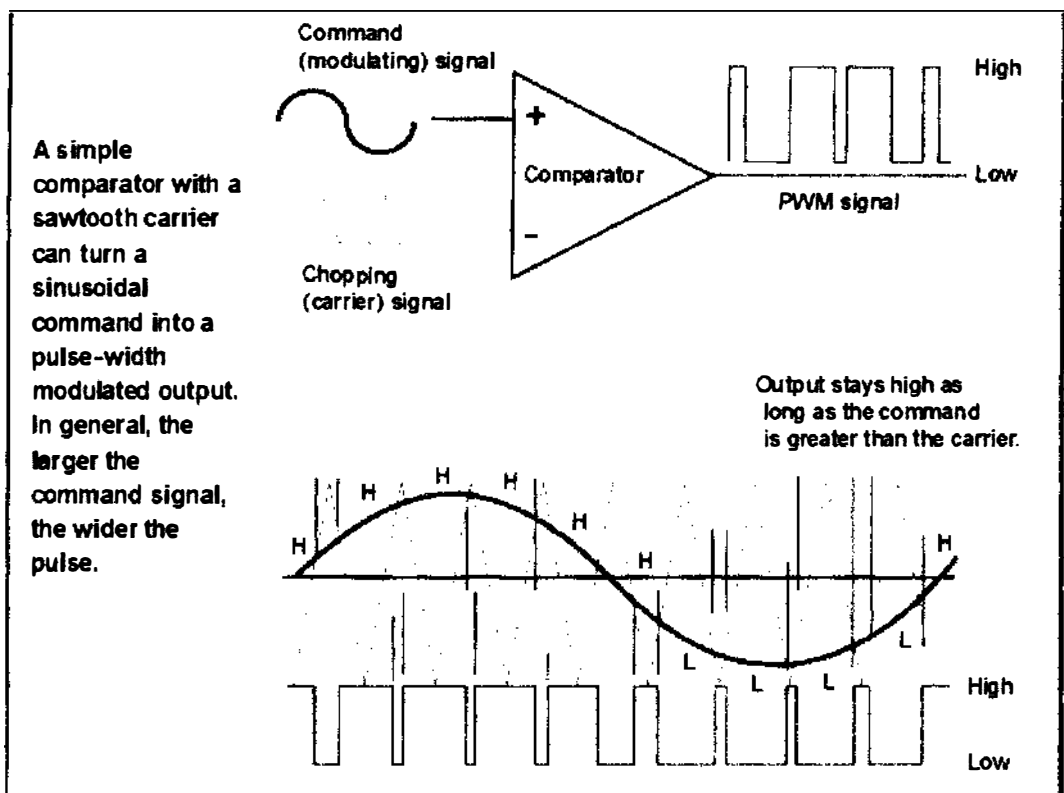


Figure 3.1: Sine Pulse width modulation technique [12]

### 3.4.2 PROGRAMMED PULSE WIDTH MODULATION [8]

Programmed PWM techniques optimize a particular objective function such as minimizing losses, reducing torque pulsations, selective elimination of harmonics etc. More effective result can be obtained by using this technique. The objective functions which are chosen to optimize that reduce the effect of harmonics produced in inverter output. The programmed PWM techniques are generally associated with the difficult task of computing specific PWM switching instants such as to optimize a particular objective function [13]. But in lower-output frequency range this difficulty is encountered. Despite of these difficulties programmed PWM has some advantages too [14].

1. Higher voltage gain can be achieved due to over modulation. This gain contributes to higher utilization of power conversion process.

- 2 About 50% reduction in switching frequency is possible.
- 3 This reduction of switching frequency contributes to the reduction in switching losses of the inverter.
- 4 Elimination of lower order harmonics is possible.
- 5 The use of pre-calculated optimized programmed PWM switching patterns avoids on-line computations and provides straightforward implementation of a high performance technique.
- 6 It is typically a "real time" control technique but programmed PWM is not a "real time" technique. In other words, the switching patterns are not computed and implemented on-line but are pre-calculated using optimization programs. A microprocessor is required for generating the pre-calculated switching instants into gating signals for the relevant inverter.

### **SINGLE-PULSE-WIDTH MODULATION [12]**

In pulse-width modulation technique there is only one pulse per half-cycle. The output of the inverter is controlled by the width of the pulse. The width of the pulse is varied to control the inverter output voltage. The generation of gating signals and output voltage of single bridge inverters is shown in figure 3.2. The gating signals are generated by comparing a reference signal of amplitude  $A_r$  with a triangular carrier wave of amplitude  $A_c$ . The fundamental frequency of the output voltage is determined from the frequency of the reference signal. The output voltage is  $V_o = V_s (g_1 - g_4)$ , here  $g_1$  and  $g_4$  are gating signals for transistor Q1 and Q4. The generation of gating signal is shown in figure 3.2.

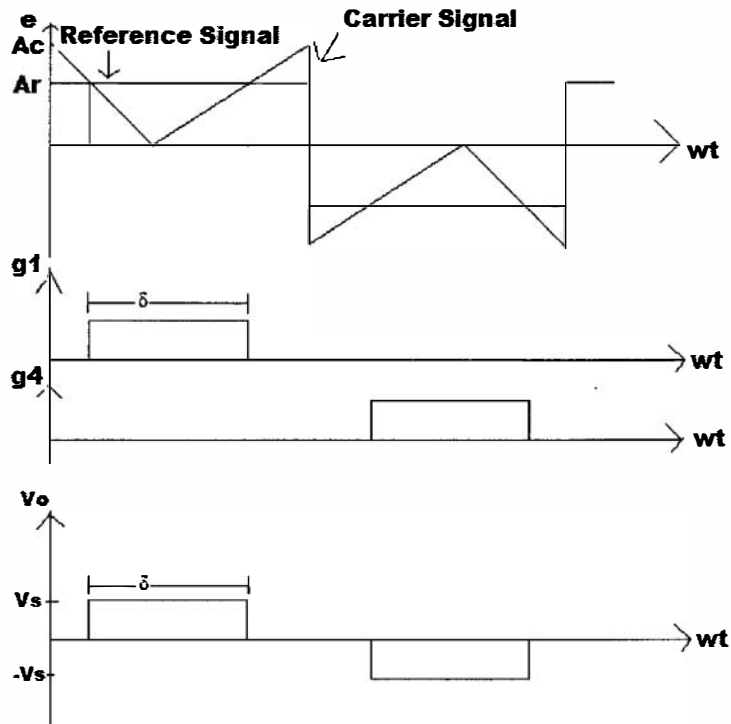


Figure 3.2: Single pulse-width modulation

By varying  $A_r$  from 0 to  $A_c$  the width of the pulse can be modified from  $0^\circ$  to  $180^\circ$  and the RMS voltage  $V_o$  from 0 to  $V_s$ .

There are some algorithms to generate the gating signals. They are

1. Generate a triangular carrier signal  $V_{cr}$ . Then compare the  $V_{cr}$  with a dc reference signal  $V_r$  to produce the difference  $V_e = V_{cr} - V_r$ , which must pass through a gain limiter to produce a square wave of width  $\delta$ .
2. To produce the gating signal  $g_1$ , multiply the resultant square wave by a unity signal  $V_z$ .
3. To produce the gating signal  $g_2$ , multiply the square wave by a logic-invert signal of  $V_z$ .



## 3.4 MULTI-PULSE-WIDTH MODULATION [12]

In single-pulse-width modulation described earlier there is only one pulse in each half-cycle. But in multi-pulse-width modulation there are several pulses in each half-cycle of the output voltage. Here a rectangular reference signal is compared with a triangular carrier wave. The gating signal is generated from this comparison. The generation of gating signal is shown in figure 3.3. The gating signals are shown in figure 3.4. This gating signal is generated for turning on and off of transistors. The frequency of the reference signal ( $f_r$ ) sets the output frequency ( $f_o$ ). The carrier frequency ( $f_c$ ) determines the number of pulses per half-cycle ( $p$ ). The output voltage is controlled by the modulation index. This type of modulation is also known as uniform pulse-width modulation. The number of pulses per half-cycle is found from

$$P = \frac{f_c}{2f_o}$$

$$= \frac{mf}{2}$$

$m_f = \frac{f_r}{f_o}$  is defined as the frequency ratio.



The instantaneous output voltage is  $V_o = V_s (g_1 - g_4)$ . The output voltage is shown in figure 3.5.

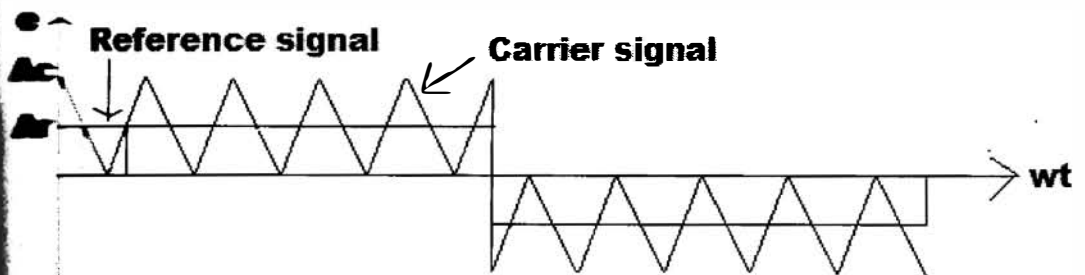


Figure 3.3: Gate signal generation for multi-pulse modulation

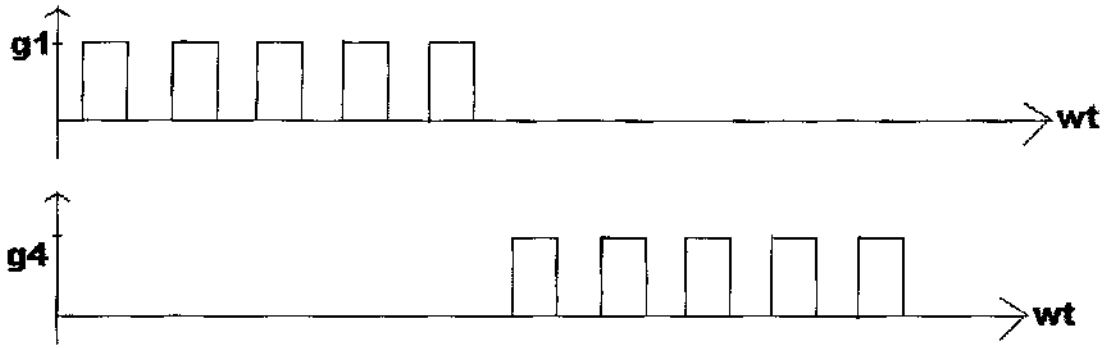


Figure 3.4: Gate signals for multi-pulse modulation

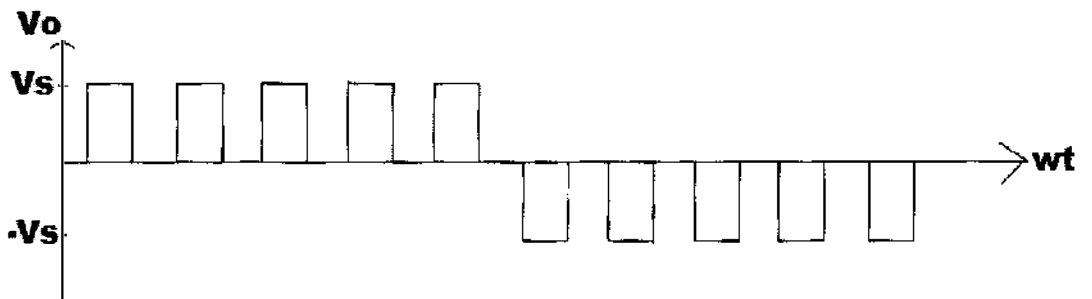


Figure 3.5: Output voltage of multi-pulse modulation

By varying the modulation index from 0 to 1 the output voltage can be controlled as described earlier.

**CHAPTER IV**  
**PROPOSED CIRCUIT DIAGRAM AND ANALYSIS OF OUTPUT SIGNAL IN**  
**MATLAB**

**4.1 PROPOSED CIRCUIT DIAGRAM AND MODULATION TECHNIQUE**

**4.1.1 DESCRIPTION OF CIRCUIT DIAGRAM [15]**

In this analysis two inverters are connected parallel by using current sharing reactor. The proposed circuit diagram is shown in figure 4.1. Here two full-bridge single phase inverters are connected in parallel. Switches 1 to 4 belong to first inverter set while switches 1\* to 4\* belong to second inverter set. The biasing circuit is omitted. The circuit is shown in a simplified form. The connection between this two inverter set is established by using a current sharing reactor. The function of the current sharing reactor is described in section [4.1.2]. The operating principle of single phase full-bridge inverter is described in figure 2.1. The operation of this circuit is similar. The difference between the operating principles is that there is a phase displacement between the switching signals of these two inverters. SPWM method is applied for both the inverter sets. The SPWM method is explained section [3.4.1]. The main reason for connecting these two inverters in parallel is by varying the phase shift between the two switching signals the total harmonic distortion can be reduced. Preliminary analysis showed that, as expected, the better harmonic performance was achieved when two bridges were operated in three level mode. Three level mode means the signal has three levels.

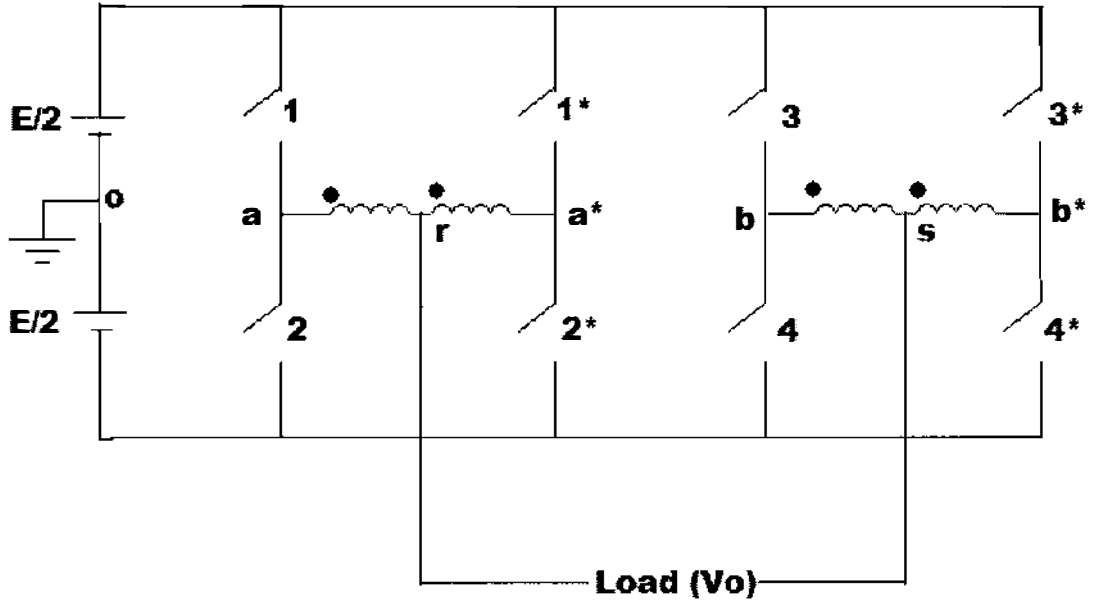


Figure 4.1: Two full-bridge single phase inverters in parallel.

#### 4.1.2 CURRENT SHARING REACTOR

A current sharing reactor is used to operate multiple inverters in parallel. By using an current sharing reactor the inverters share the total current [16]. This is a current equalizing reactor which is connected between two parallel silicon controlled converters [17]. It acts as an inductive voltage divider and provides balanced system operation when both the converters are conducting [17]. This is also known as current sharing reactor. Current sharing with reactor is more efficient method than current sharing with resistance. This reactor improves the transient sharing of currents. The most important magnetic requirements of this kind of reactor are [18]

1. High saturation
2. Low residual flux

It consists of small inductances in order to ensure dynamic and static share of the currents among different switches. Each inductor has its specific current level which is fixed [16].

### Advantages [16]

1. It is cheap.
2. Design is simple.
3. No need of controlling strategy.
4. Independent of device switching time.
5. Reduces the voltage stress across the switching devices.

### Advantages [19]

The current across the reactor has a magnetizing component. The component produces when the DC voltage is applied to the input terminal of the reactor. This magnetizing should be minimized to reduce the current ratings of the switching devices and also to avoid reactor saturation.

## FREQUENCY RATIO AND MODULATION INDEX

### Frequency Ratio

Frequency ratio is the ratio between the carrier wave frequency and reference wave frequency.

$$\text{Frequency ratio, } f_r = f_c/f_m$$

$f_c$  = Frequency of the carrier wave.

$f_m$  = Frequency of the reference signal.

Frequency ratio is higher than the reference signal frequency. So the frequency ratio is greater than 1.

### Modulation Index

The amplitude of the reference signal and the carrier signal is called modulation

index. The modulation index should be greater than one. It can be a fractional value.



Equation of modulation index is given below,

$$\text{Modulation index, } M = A_r / A_c.$$

Amplitude of reference signal

Amplitude of Carrier signal.

## DESCRIPTION OF THE MODULATION TECHNIQUE

Modulation technique that is followed in this design is SPWM is shown in figure 4.2. Here one triangular wave is compared with two sinusoidal waves. The sine waves are  $180^\circ$  shifted from each other. These three waves are shown in figure 4.2. The compared output of triangular wave and sine wave is used to generate the switching signal of switch 1 and 2 i.e. signal  $V_a$ . On the other hand compared output of triangular wave and  $180^\circ$  shifted sine wave is used to generate the switching signal of 3 and 4 i.e. signal  $V_b$ . The other two bridges are operated by a certain amount of phase shifted signals of  $V_a^*$  and  $V_b^*$ . These are labeled as  $V_a^*$ ,  $V_b^*$  and used to generate the switching signal of switch  $1^*$ ,  $2^*$  and  $3^*$ ,  $4^*$  respectively.

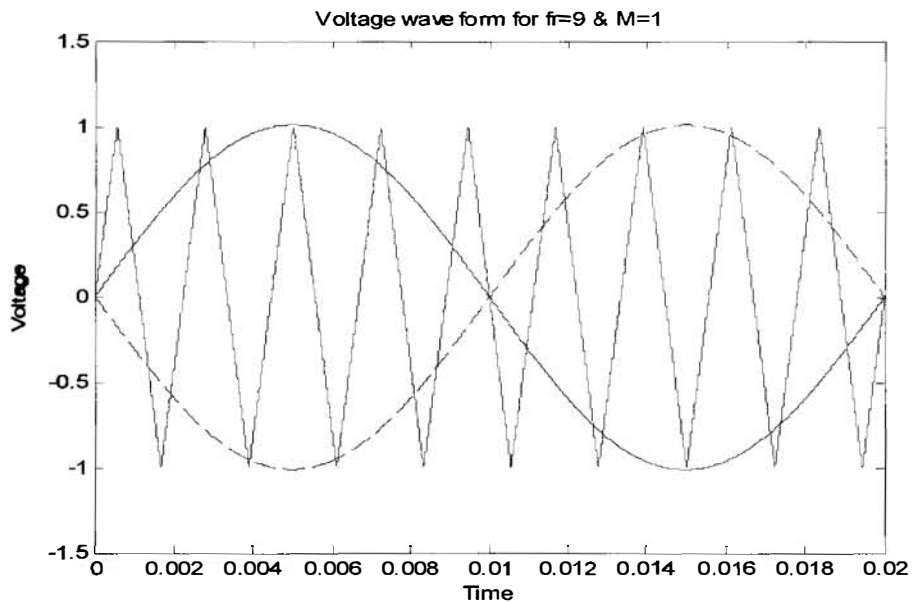


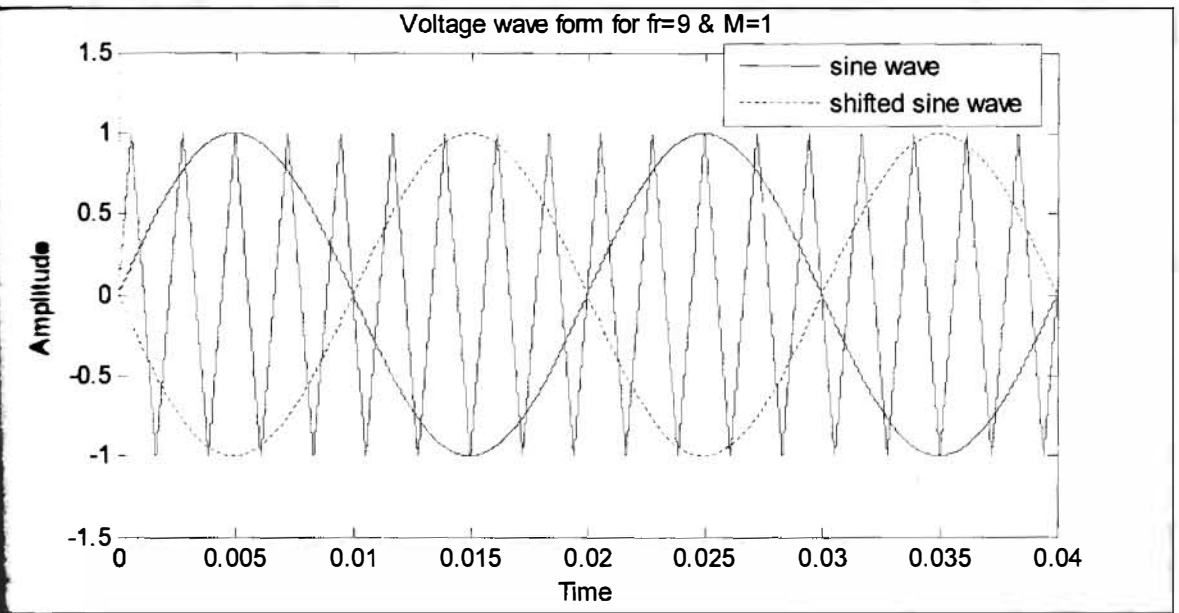
Figure 4.2: Comparison of references with carrier signal

## ANALYSIS AND DISCUSSION OF OUTPUTS IN MATLAB

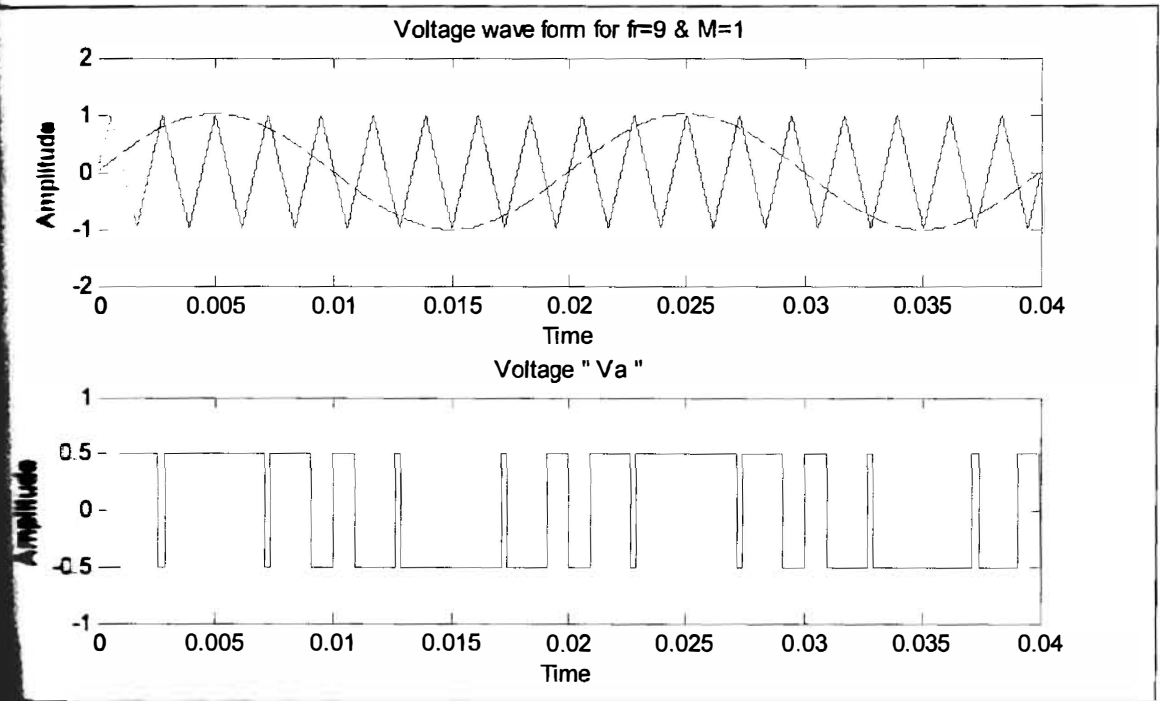
### OUTPUT VOLTAGE ANALYSIS FOR $f_r = 9$ AND $M = 1$

SPWM technique is implemented in MATLAB for different values of  $f_r$  and  $M$ . The sine waves and carrier triangular waves are generated here. When frequency of triangular wave is 9 times higher than the frequency of sine wave and their amplitude ratio is unity shown in figure 4.3. Figure 4.4 shows the signal  $V_a$  along with the reference sine wave and the carrier triangular wave to generate it. Similarly figure 4.5 shows the signal  $V_b$  along with the reference sine wave and the carrier triangular wave to generate it. The theta degree shifted signals  $V_a^*$  and  $V_b^*$  are shown in figure 4.6 and figure 4.7 in similar way. To shift the signal in a specific amount the reference and carrier waves are shifted in that amount. Figure 4.6 shows both  $V_a$  and  $V_a^*$  to visualize the shifting. Similarly figure 4.7 is for the same purpose but for  $V_b$  and  $V_b^*$ .

Output of this inverter is  $V_o$  is the load voltage between point 'r' and 's' which is simply the average of voltages  $V_r$  and  $V_s$ . By means of operation of the current sharing reactor the mean  $V_r$  can be obtained as  $V_r = (V_a + V_a^*)/2$ . This wave form is shown in figure 4.8. The other will provide  $V_s = (V_b + V_b^*)/2$ .  $V_s$  is shown in figure 4.9. The waveforms of  $V_a$ ,  $V_b$ ,  $V_a^*$  and  $V_b^*$  are attached to the figures to justify the results. Figure 4.10 shows the output voltage  $V_o$  for  $f_r = 9$  and  $M = 1$ . Here we see that the output voltage obtained is a five voltage levels. The firing angle theta ( $\theta$ ) is taken  $10^\circ$ , as it gives the best output result with minimum harmonics. It is discussed with the frequency ratio and will be discussed further.

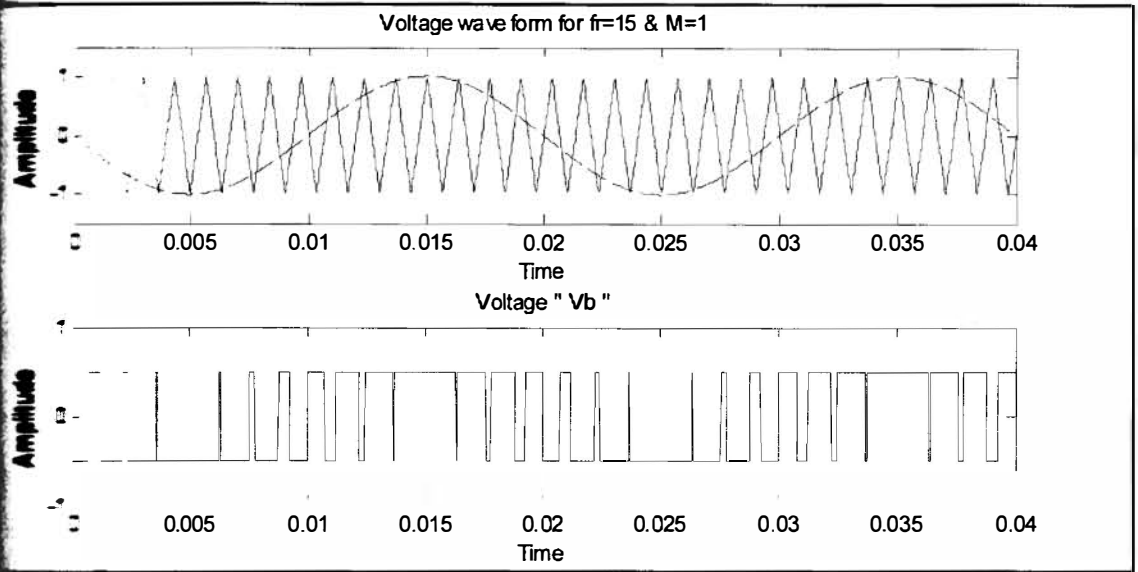


4.3: Comparison of reference sine waves and carrier triangular waves for  $f_r=9$  and  $M=1$ . These waves are generated in MATLAB. One sine wave is  $180^\circ$  shifted from the other.

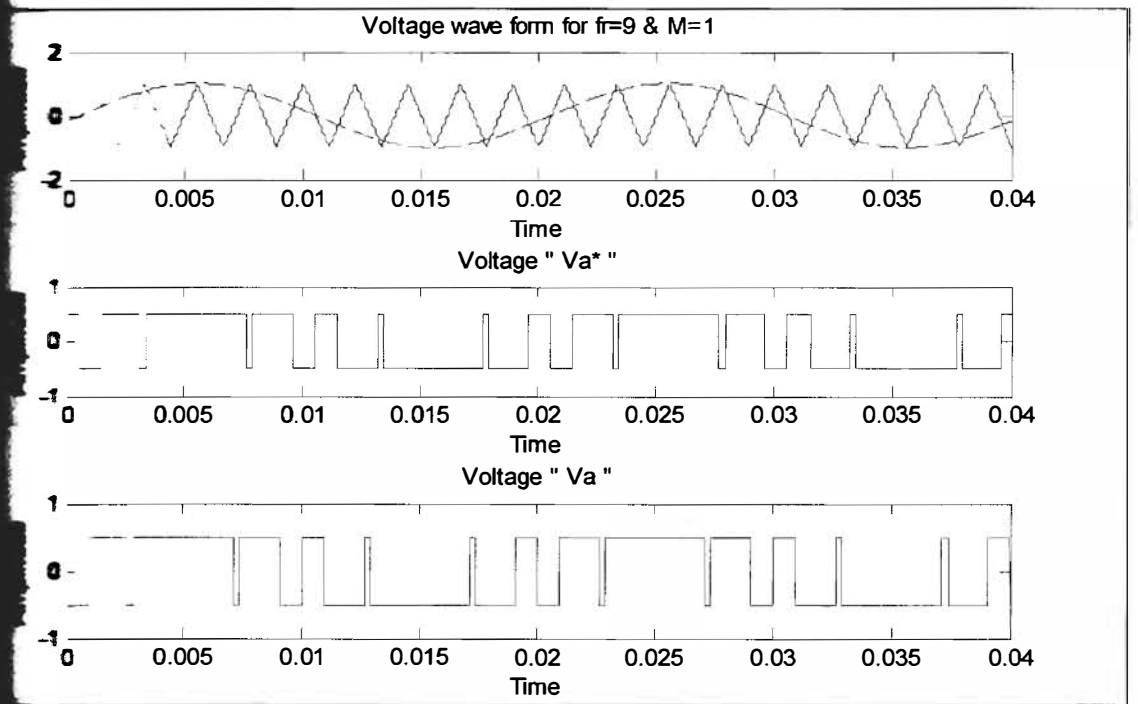


4.4: Signal  $V_a$  for  $f_r=9$  and  $M=1$  along with the reference and the carrier wave to generate  $V_a$  is high when reference sine wave is higher than carrier triangular wave and vice versa.





4.5: Signal  $V_b$  for  $f_r=9$  and  $M=1$ , along with the reference and the carrier wave to  
 This time the triangular wave is compared with  $180^\circ$  shifted sine wave.  $V_b$  is high  
 when reference sine wave is higher than carrier triangular wave and vice versa.



Signal  $V_{a^*}$  for  $f_r=9$  and  $M=1$ . This is  $\theta$  degree shifted from signal  $V_a$ . In this  
 $\theta=10^\circ$ . To shift  $\theta^\circ$  all the reference and carrier waves are shifted in that quantity.

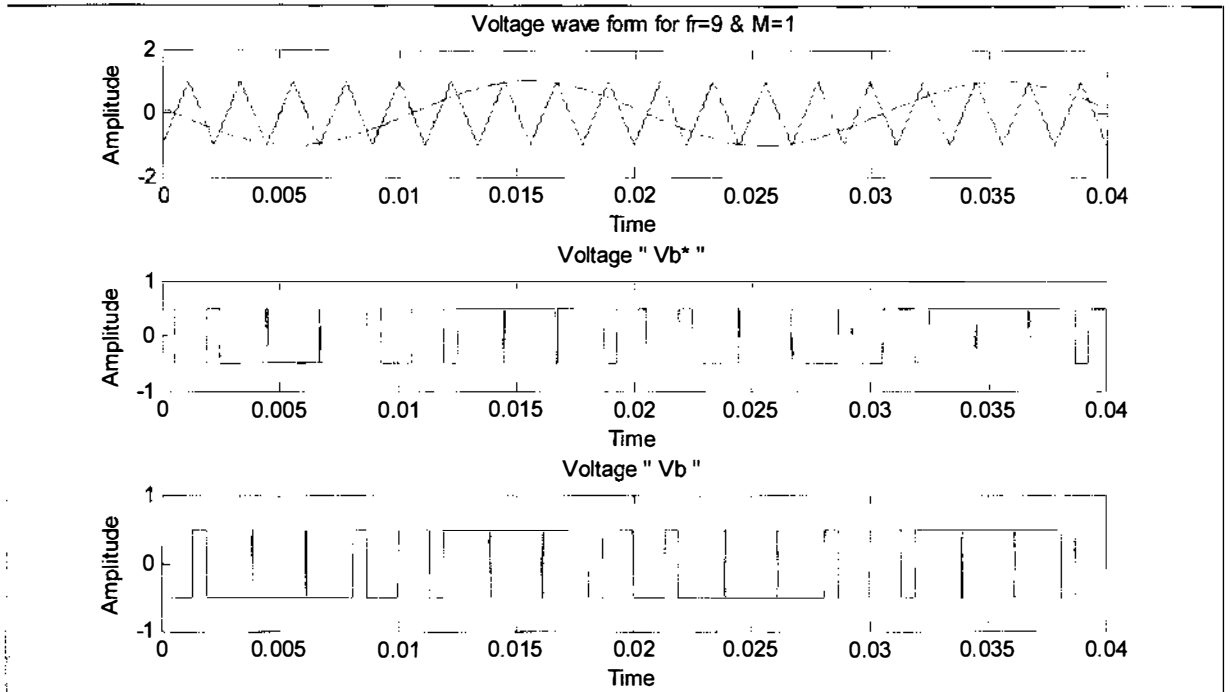


Figure 4.7: Signal  $V_b^*$  for  $f_r=9$  and  $M=1$ . This is  $\theta$  degree shifted from signal  $V_b$ . Also in this case  $\theta=10^\circ$ . To shift  $\theta^\circ$  all the reference and carrier waves are shifted in that quantity.

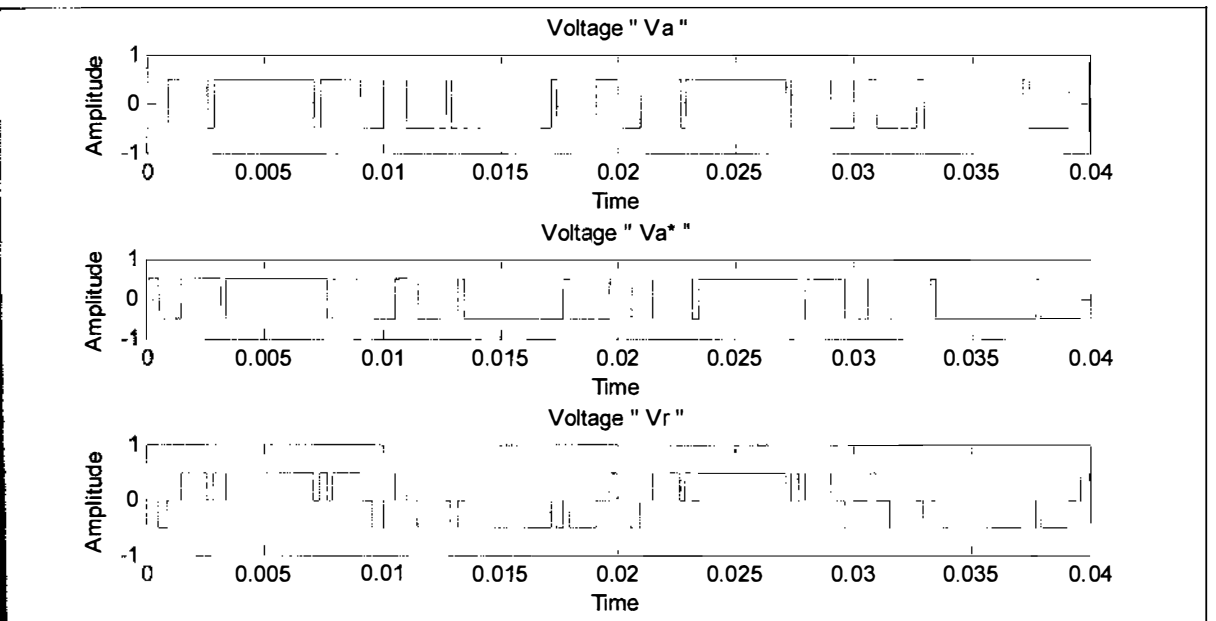


Figure 4.8:  $V_r$  is shown in this figure for  $f_r=9$  and  $M=1$ . It is the average of two signals  $V_a$  and  $V_a^*$ . It varies from  $-0.5$  to  $+0.5$  and has 3 levels of voltages.

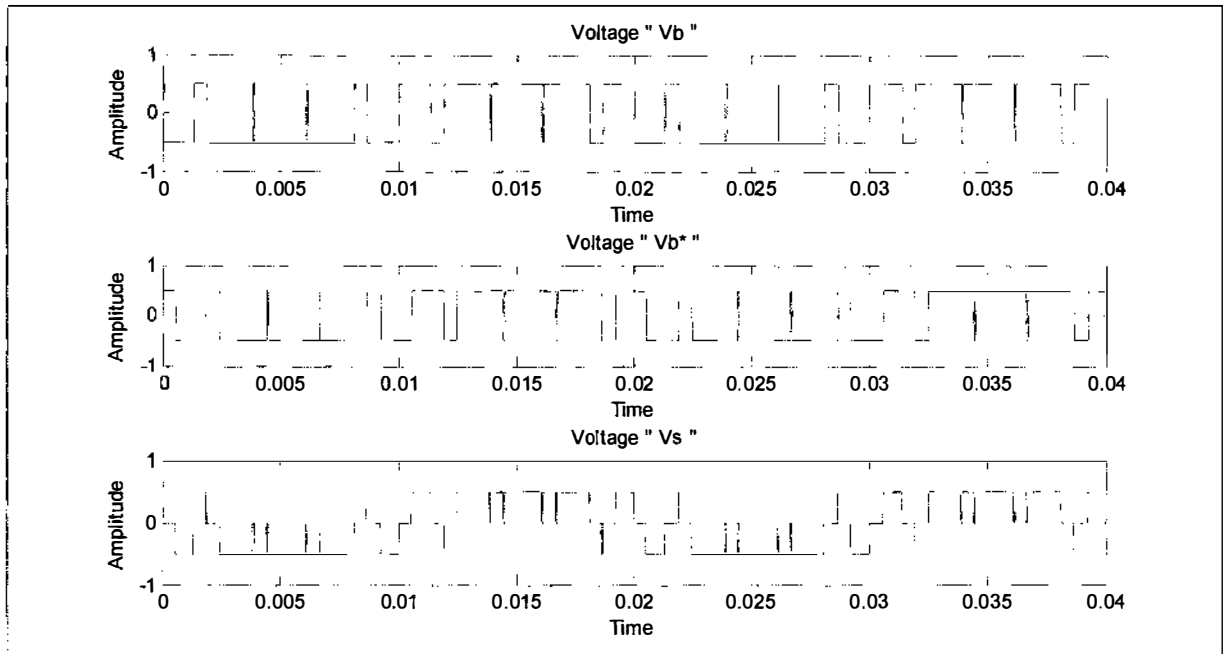


Figure 4.9:  $V_s$  is shown for  $f_r=9$  and  $M=1$ . It is the average of two signals  $V_b$  and  $V_b^*$ . It also varies from  $-0.5$  to  $+0.5$  and has 3 levels of voltages.

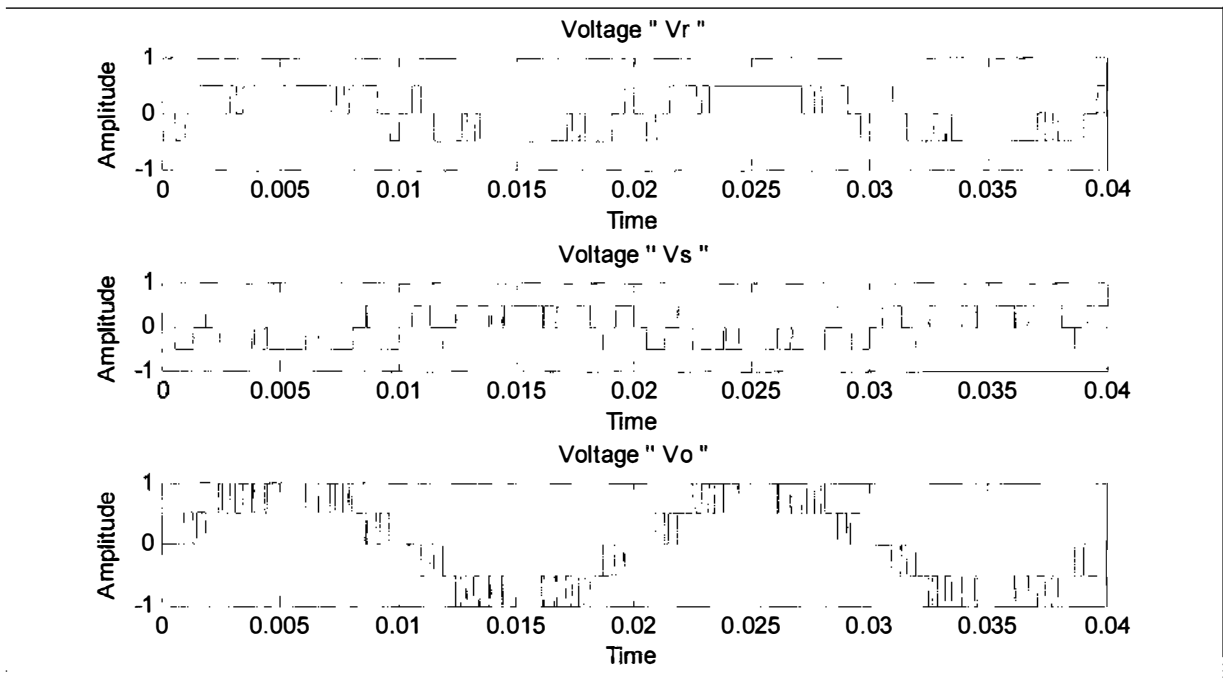
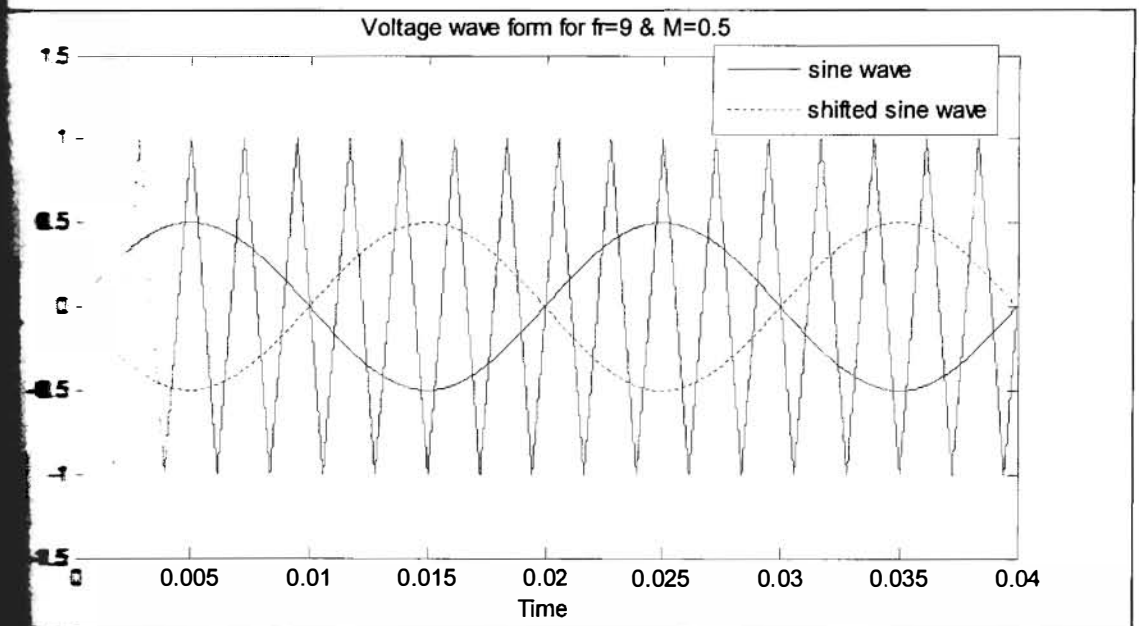


Figure 4.10: The output  $V_o$  is shown for  $f_r=9$  and  $M=1$ . It is the difference of  $V_r$  and  $V_s$ . It varies from  $-1$  to  $1$  and has 5 voltage levels.

## OUTPUT VOLTAGE ANALYSIS FOR $f_r = 9$ AND $M = 0.5$

Analysis is done again keeping the same frequency ratio ( $f_r$ ) and different modulation index. Change in modulation index changes the amplitude ratio of reference wave and carrier. This time modulation index is chosen 0.5 i.e. amplitude of reference wave is double of carrier wave. The reference sine waves and carrier triangular waves are shown in figure 4.11. The procedure is similar as before but here outputs are a little bit changed. Figure 4.12 shows the signal  $V_a$  along with the reference sine wave and the carrier triangular wave to generate it. Similarly figure 4.13 shows the signal  $V_b$  along with the reference sine wave and the carrier triangular wave, required to generate it. The theta degree shifted signals  $V_a^*$  and  $V_b^*$  are shown in figure 4.14 and figure 4.15 in similar way.  $V_r$  and  $V_s$  are shown in figure (4.16) and (4.17) respectively. Figure 4.18 shows the output voltage  $V_o$  for  $f_r = 9$  and  $M = 0.5$ .



4.11: Comparison of reference sine waves and carrier triangular waves for  $f_r = 9$  and  $M = 0.5$ . The amplitudes of sine waves are half of triangular wave. Sine waves are  $180^\circ$  shifted from each other.

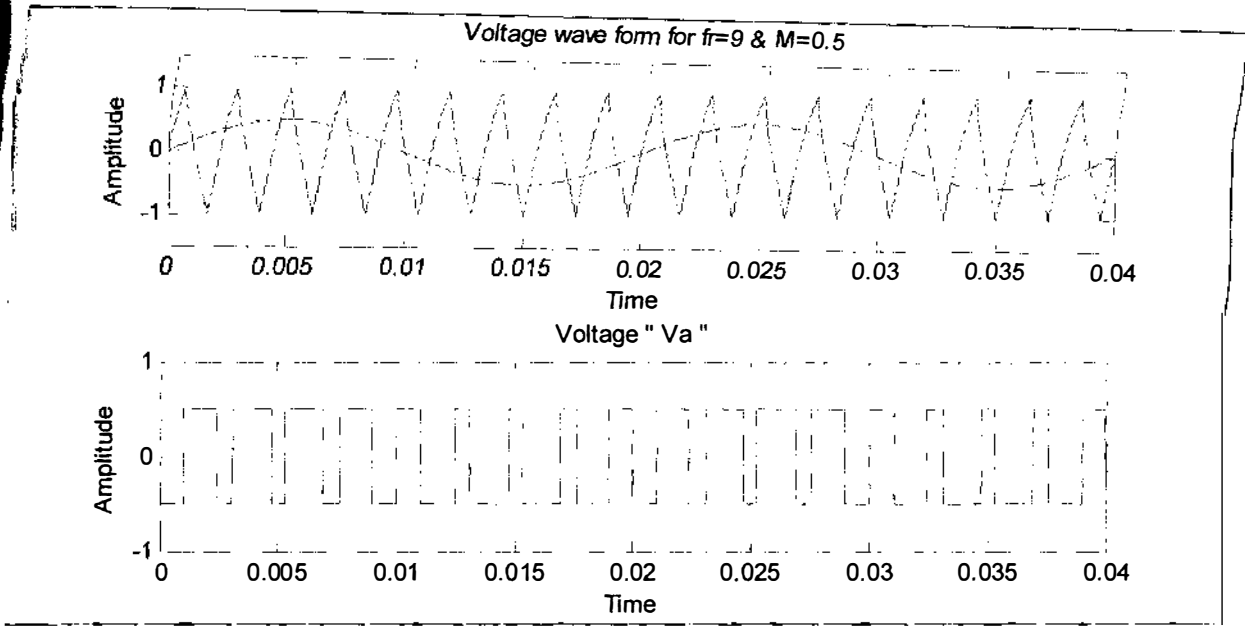


Figure 4.12: Signal  $V_a$  for  $f_r=9$  and  $M=0.5$  along with required reference and the carrier wave to generate it.  $V_a$  is high when reference sine wave is higher than carrier triangular wave and vice versa.

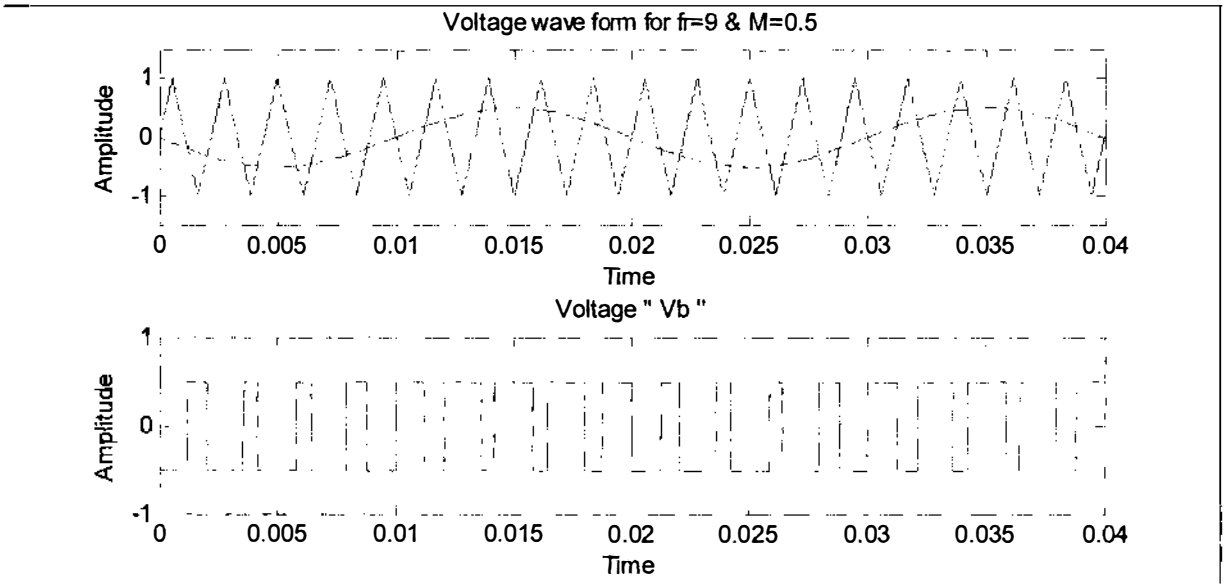


Figure 4.13: Signal  $V_b$  for  $f_r=9$  and  $M=0.5$ , along with the reference and the carrier wave to generate it. This time the triangular wave is compared with  $180^\circ$  shifted sine wave.  $V_b$  is high when reference sine wave is higher than carrier triangular wave and vice versa.

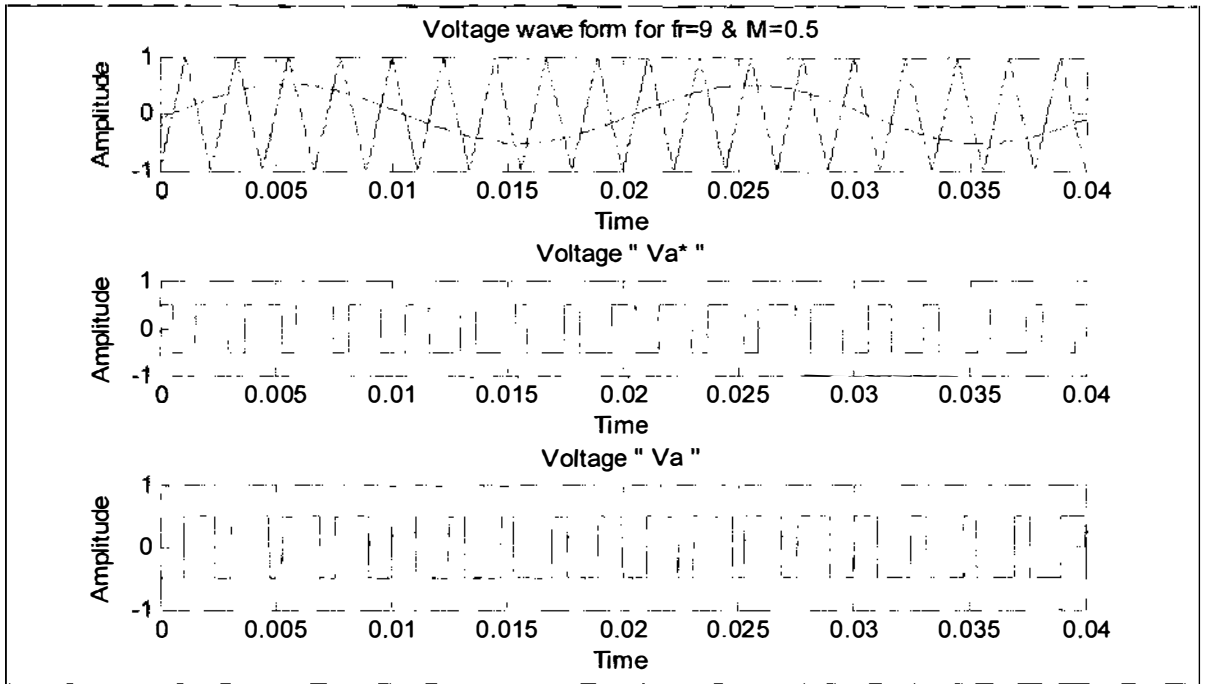


Figure 4.14: Signal  $V_a^*$  for  $f_r=9$  and  $M=0.5$ . This is  $\theta$  degree shifted from signal  $V_a$ . In this case  $\theta=10^\circ$ . To shift  $\theta^\circ$  all the reference and carrier waves are shifted in that quantity.

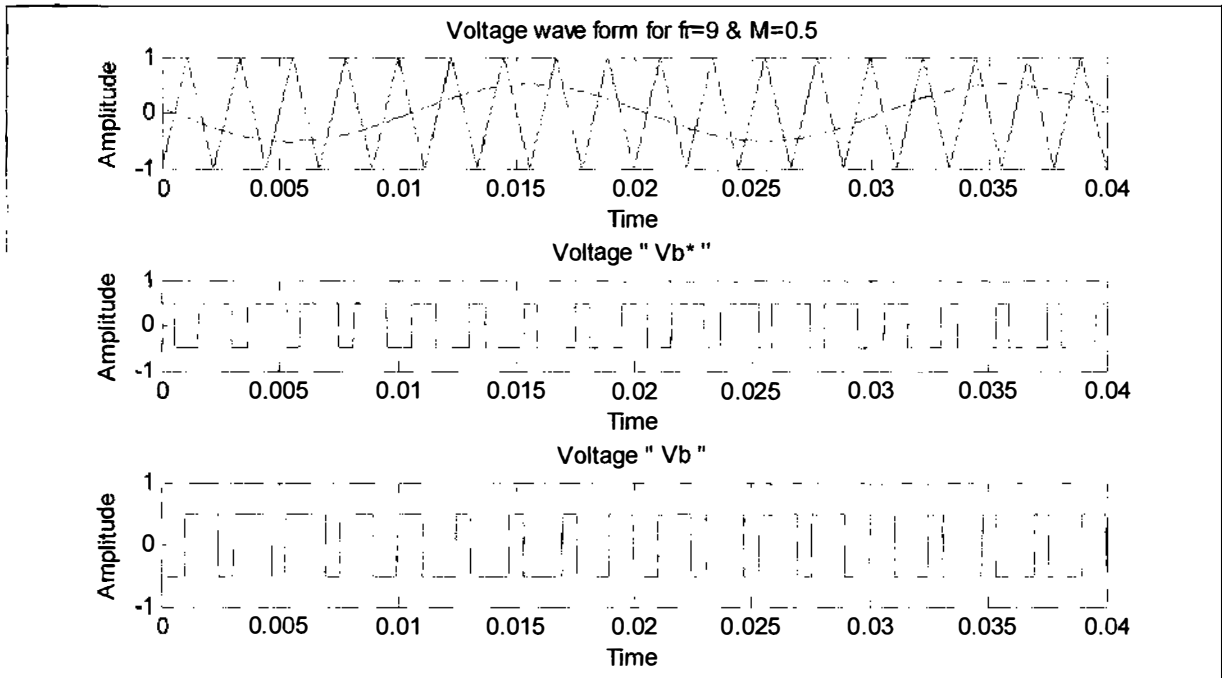


Figure 4.15: Signal  $V_b^*$  for  $f_r=9$  and  $M=0.5$ . This is  $\theta$  degree shifted from signal  $V_b$ . Also in this case  $\theta=10^\circ$ . To shift  $\theta^\circ$  all the reference and carrier waves are shifted in that quantity.

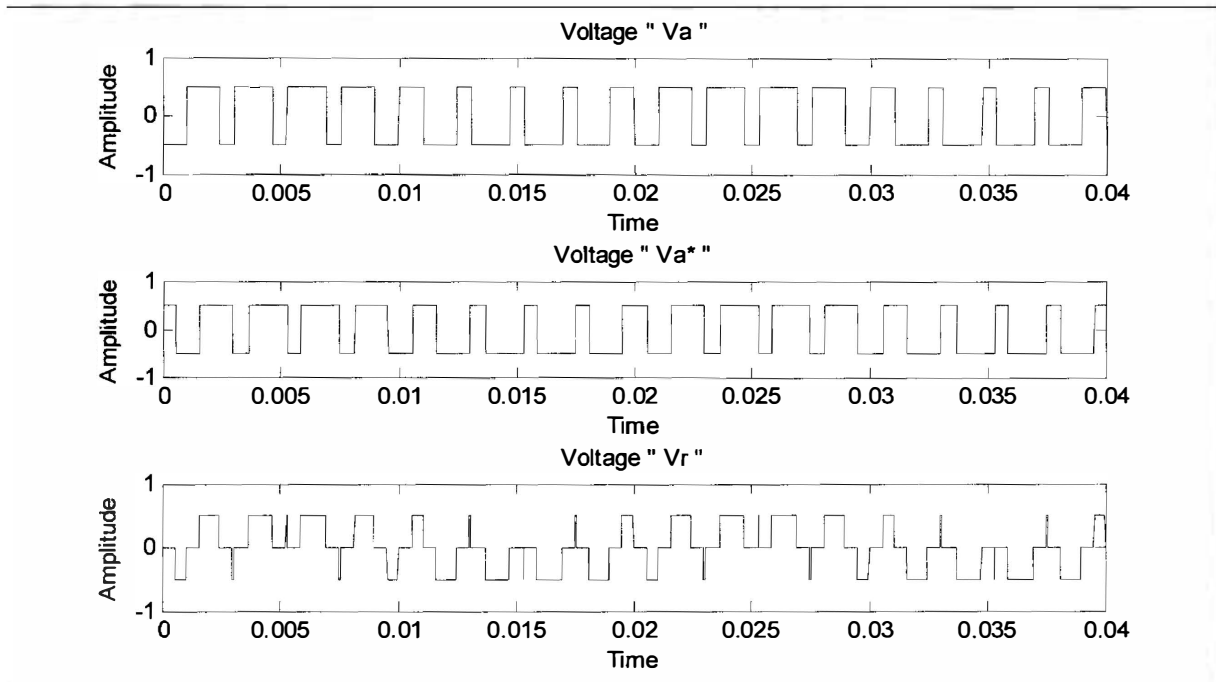


Figure 4.16:  $V_r$  is shown in this figure for  $f_r=9$  and  $M=0.5$ . It is the average of two signals  $V_a$  and  $V_a^*$ . It varies from  $-0.5$  to  $+0.5$  and has 3 levels of voltages.

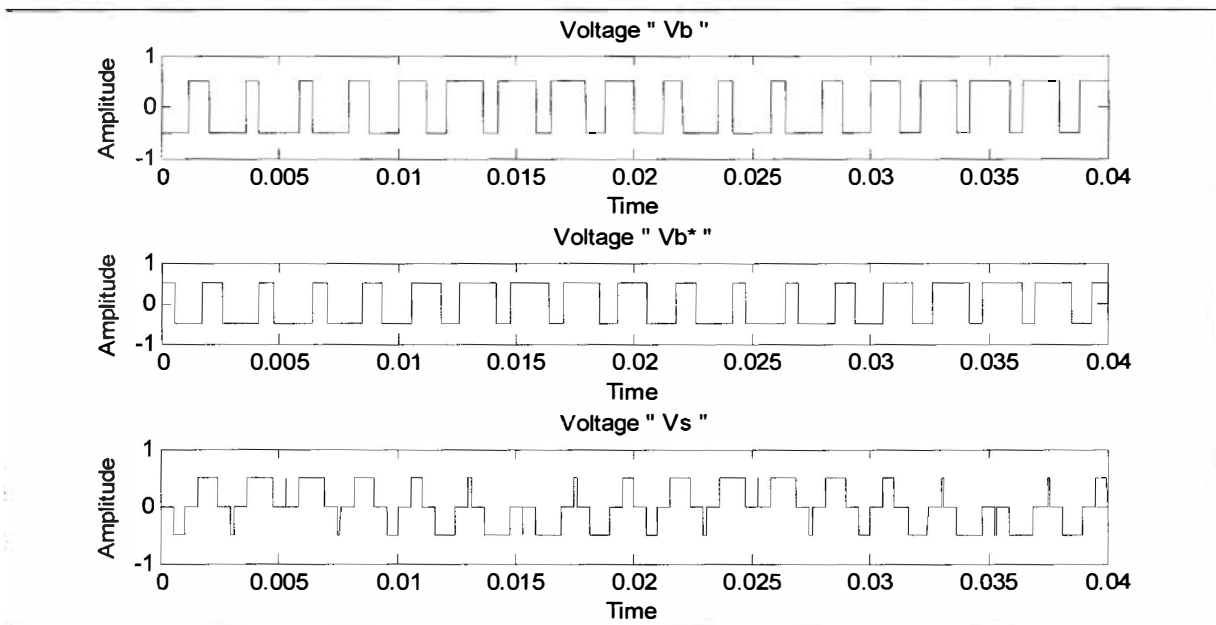


Figure 4.17:  $V_s$  is shown for  $f_r=9$  and  $M=0.5$ . It is the average of two signals  $V_b$  and  $V_b^*$ . It also varies from  $-0.5$  to  $+0.5$  and has 3 levels of voltages.



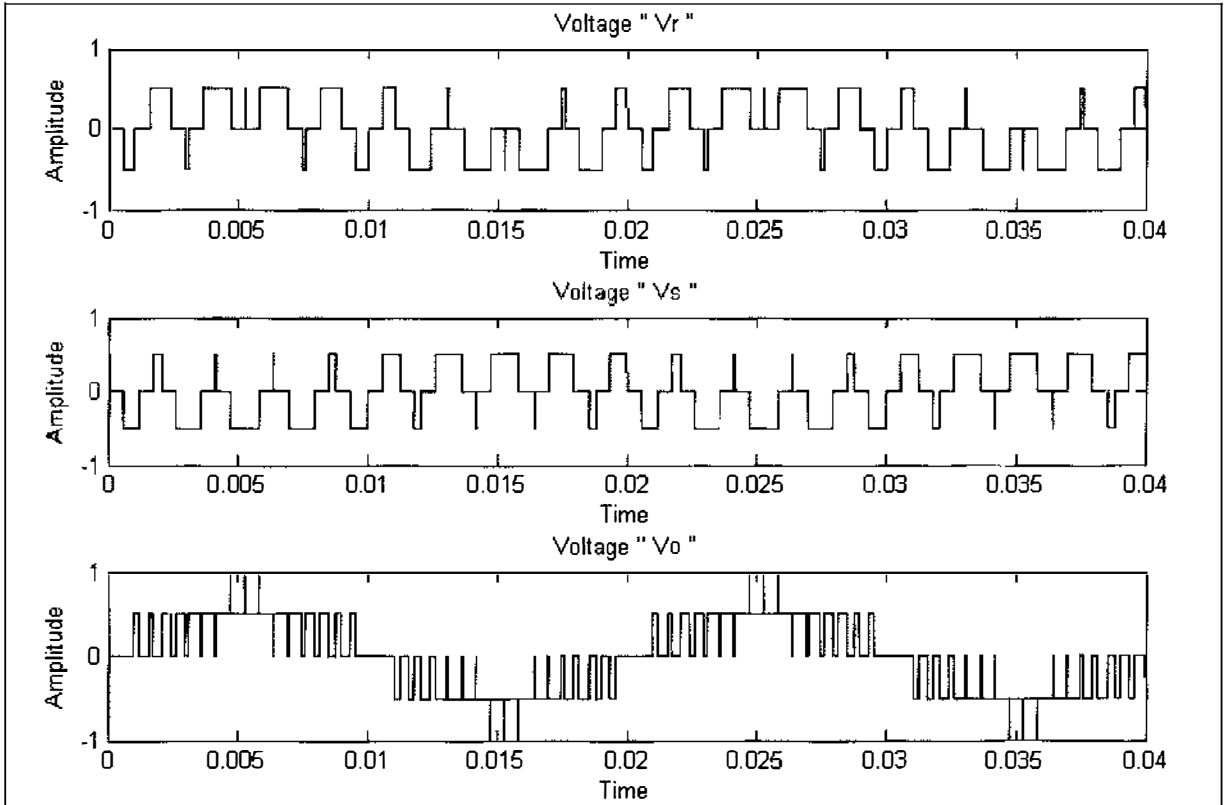


Figure 4.18: The output  $V_o$  is shown for  $f_r = 9$  and  $M = 0.5$ . It is the difference of  $V_r$  and  $V_s$ . It also varies from -1 to 1 and has 5 voltage levels. But in this case duration of having voltage peak 1 is shorter than previous case.



### 4.2.3 OUTPUT VOLTAGE ANALYSIS FOR $f_r = 15$ AND $M = 1$

This time frequency ratio ( $f_r$ ) is changed and modulation index ( $M$ ) is kept unchanged. Frequency ratio is increased to 15. Thus frequency of carrier signal becomes fifteen times higher than frequency of reference signals. The reference sine waves and carrier triangular waves are shown in figure 4.19. The whole procedure is similar as before but here outputs are a little bit changed. Figure 4.20 shows the signal  $V_a$  along with the reference sine wave and the carrier triangular wave to generate it. Similarly figure 4.21 shows the signal  $V_b$  along with the required reference sine waves and the carrier triangular wave to generate it. The theta degree shifted signals  $V_a^*$  and  $V_b^*$  are shown in figure 4.22 and figure 4.23 in similar way.  $V_r$  and  $V_s$  are shown in figure 4.24 and figure 4.25 respectively. Figure 4.26 shows the output voltage  $V_o$  for  $f_r = 15$  and  $M = 1$ .

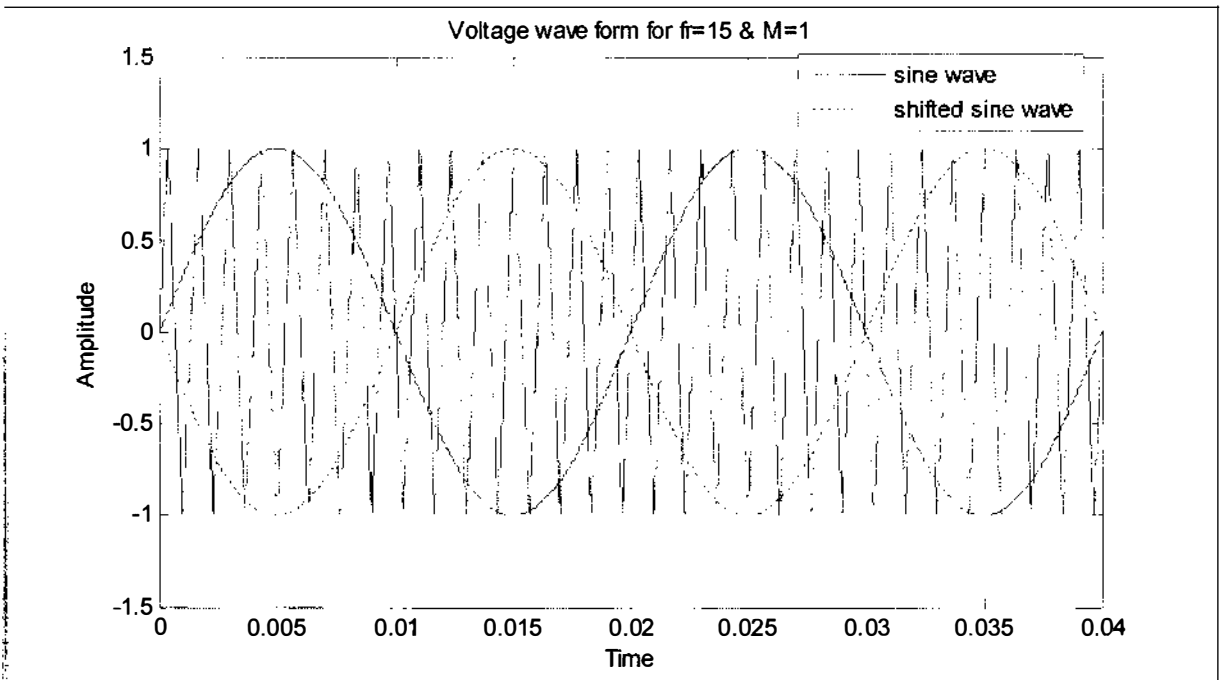


Figure 4.19: Comparison of reference sine waves and carrier triangular waves for  $f_r = 15$  and  $M = 1$ . Thus amplitudes of sine waves are half of triangular wave. Sine waves are  $180^\circ$  shifted from each other.

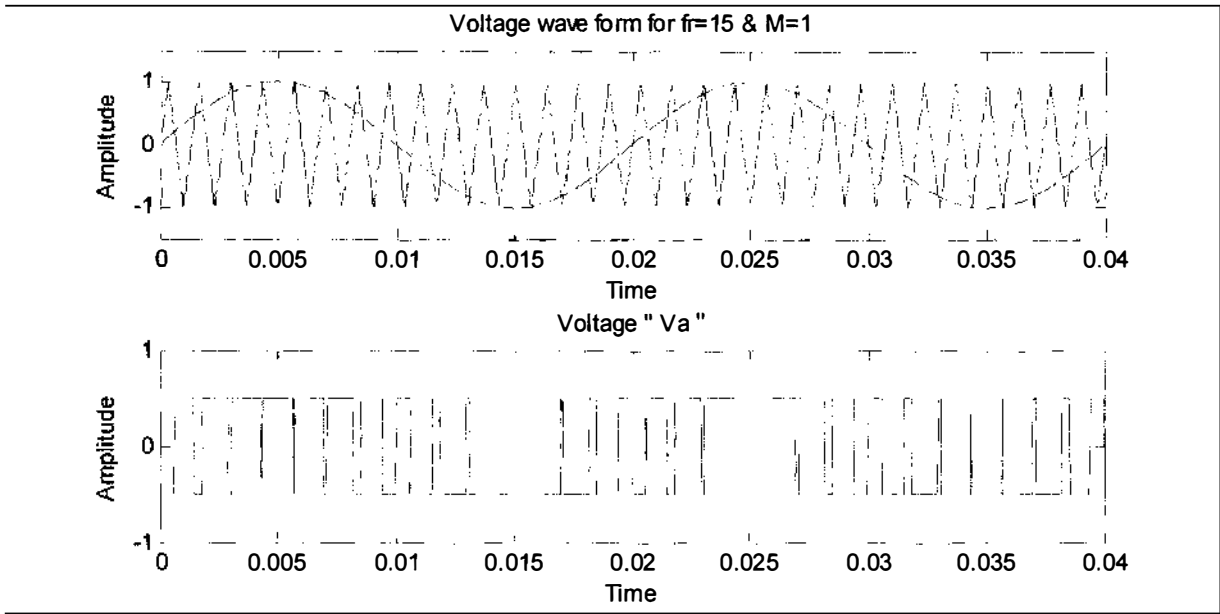


Figure 4.20: Signal  $V_a$  for  $f_r=15$  and  $M=1$  along with required reference and the carrier wave to generate it.  $V_a$  is high when reference sine wave is higher than carrier triangular wave and vice versa.

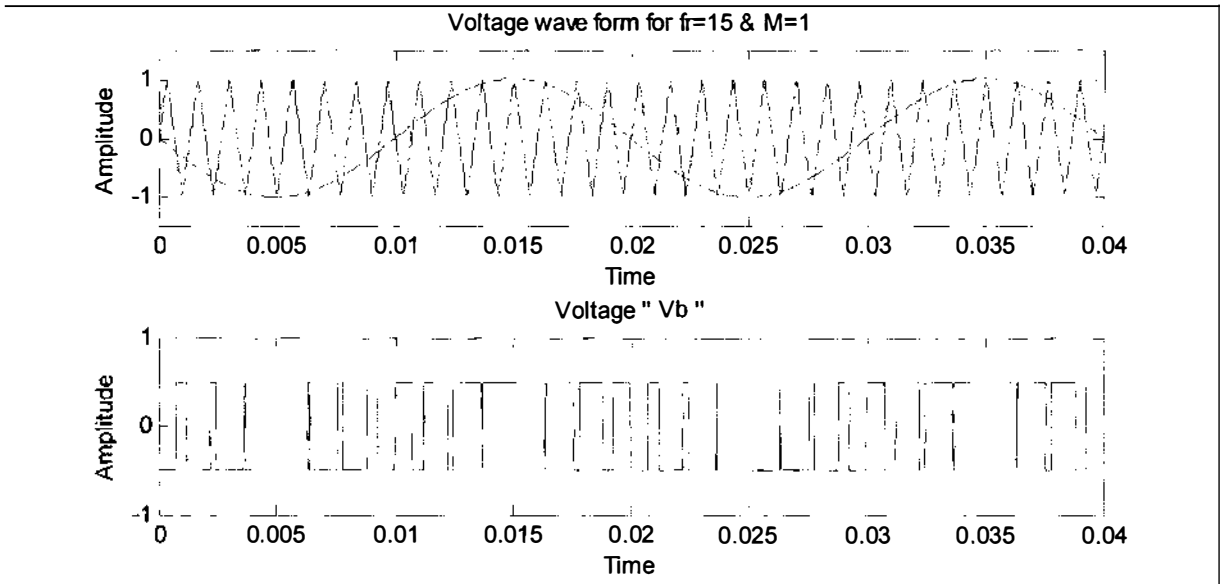
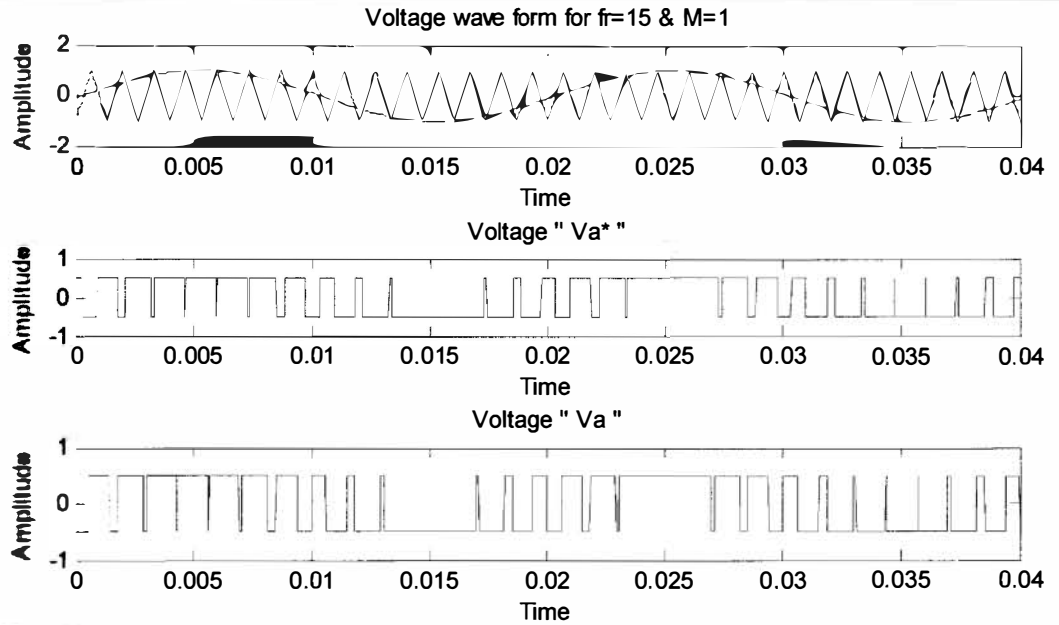
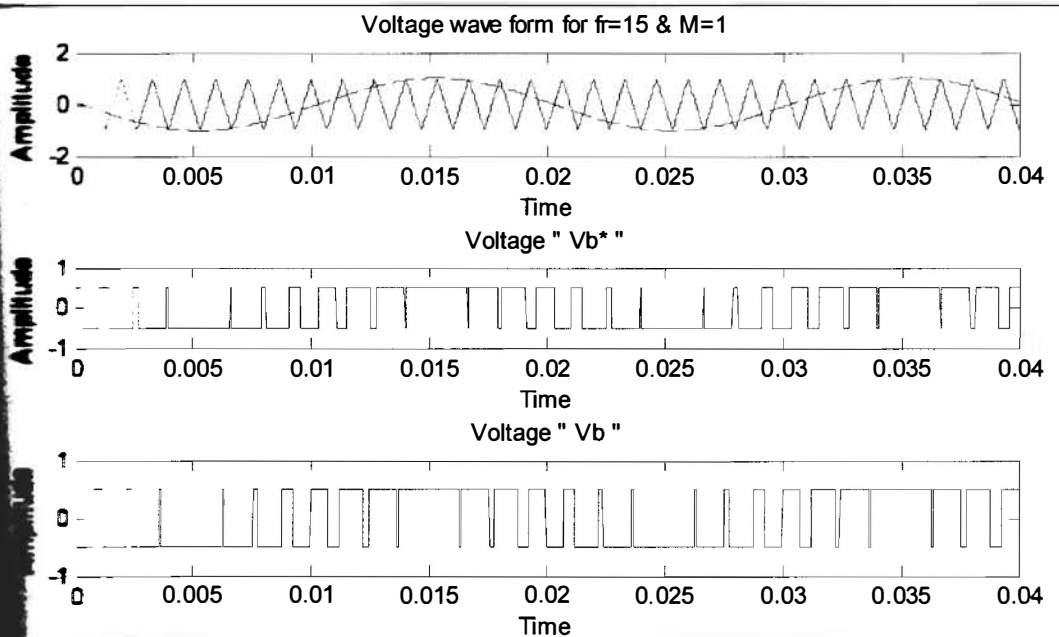


Figure 4.21: Signal  $V_b$  for  $f_r=15$  and  $M=1$ , along with required reference and the carrier wave to generate it. This time the triangular wave is compared with 180° shifted sine wave.  $V_b$  is high when reference sine wave is higher than carrier triangular wave and vice versa.



4.22: Signal  $V_a^*$  for  $f_r = 15$  and  $M = 1$ . This is  $\theta$  degree shifted from signal  $V_a$ . In case  $\theta = 6^\circ$ . To shift  $\theta^\circ$  all the reference and carrier waves are shifted in that quantity.



4.23: Signal  $V_b^*$  for  $f_r = 15$  and  $M = 1$ . This is  $\theta$  degree shifted from signal  $V_b$ . Also case  $\theta = 6^\circ$ . To shift  $\theta^\circ$  all the reference and carrier waves are shifted in that quantity.

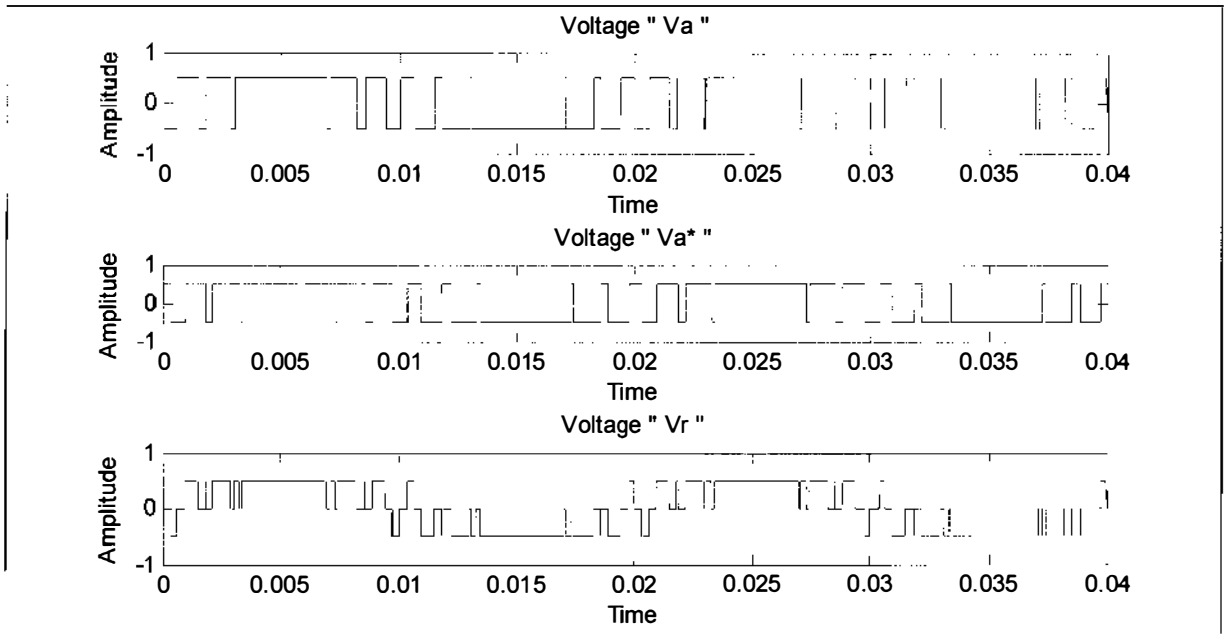


Figure 4.24:  $V_r$  is shown in this figure for  $f_r=15$  and  $M=1$ . It is the average of two signals  $V_a$  and  $V_a^*$ . It varies from  $-0.5$  to  $+0.5$  and has 3 levels of voltages.

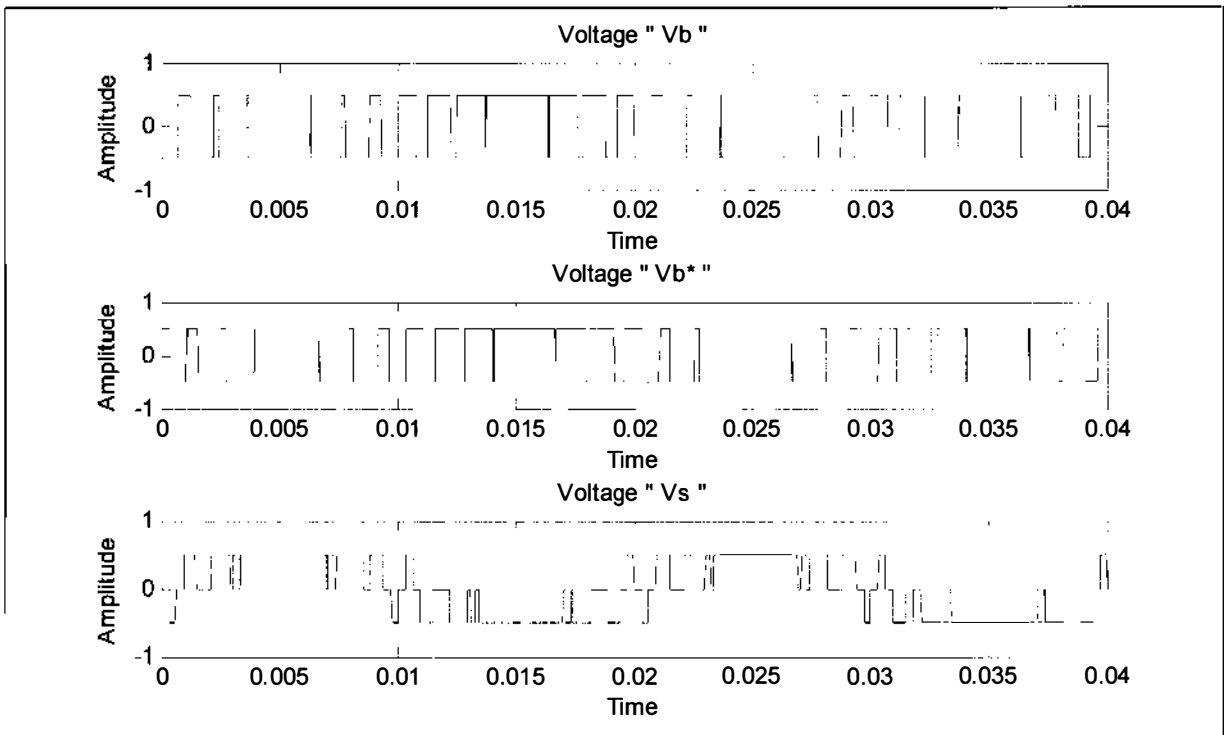
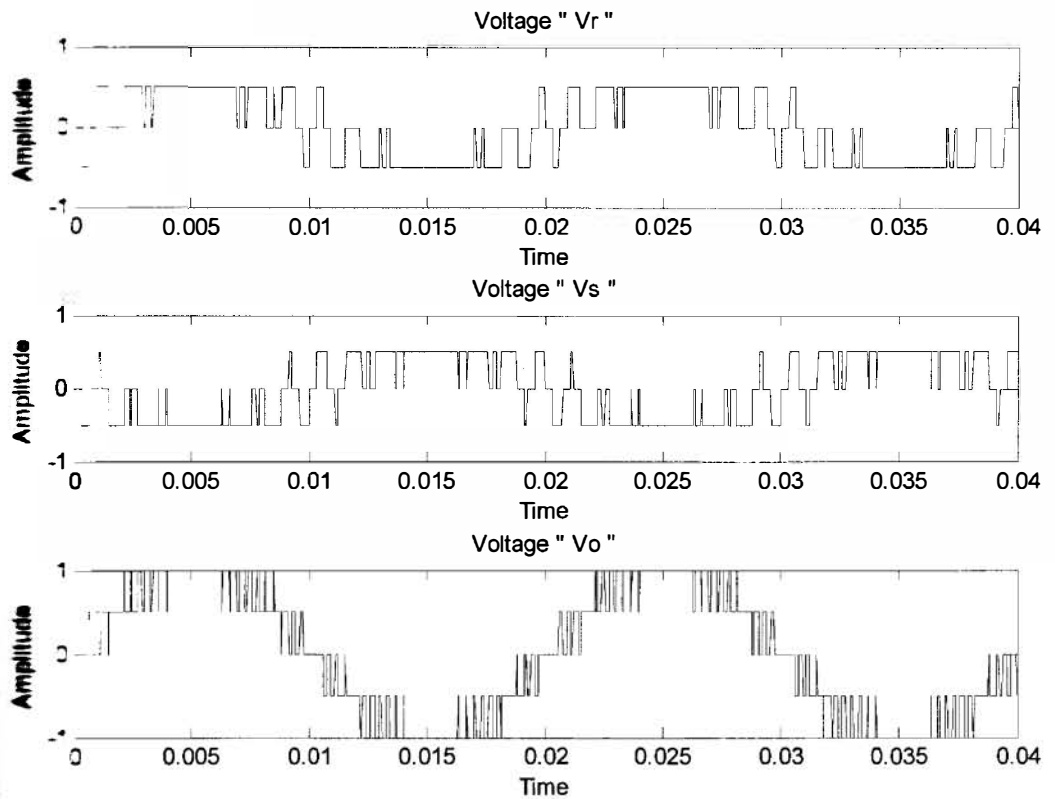


Figure 4.25:  $V_s$  is shown for  $f_r=15$  and  $M=1$ . It is the average of two signals  $V_b$  and  $V_b^*$ . It also varies from  $-0.5$  to  $+0.5$ .



4.26: The output  $V_o$  is shown for  $f_r=15$  and  $M=1$ . It is the difference of  $V_r$  and  $V_s$ . It from -1 to 1 and has 5 voltage levels. But in this case duration of having voltage peak 1 is larger than any of the previous case.



#### 4.2.4 HARMONIC SPECTRA OF OUTPUT WAVEFORMS

Since the output voltage is always a odd-quarter wave symmetry formulae for the Fourier series coefficients is [19]:

$$a_n = (4/n\pi) \times \sum J_s \cos (nx_s) \dots\dots\dots(4.1)$$

$$b_n = 0 \quad \text{for odd } n$$

And  $a_n = b_n = 0$  for even  $n$

Where,  $J_s$  is the jump in the voltage at angle  $x_s$  and  $m$  is the number of jumps in quarter wave cycle. Figure (4.27) shows the voltage harmonic spectra up to 39<sup>th</sup> harmonic for  $f_r = 9$  and  $M = 1$ . As already said the shifting angle  $\theta$  is chosen  $10^\circ$  in this case. The even harmonics becomes zero and odd harmonic remain almost zero up to 13<sup>th</sup> harmonic. 15<sup>th</sup> and 21<sup>st</sup> harmonics have a value less than 0.1V. The RMS value of fundamental component is 0.7V if DC voltage is 1V.

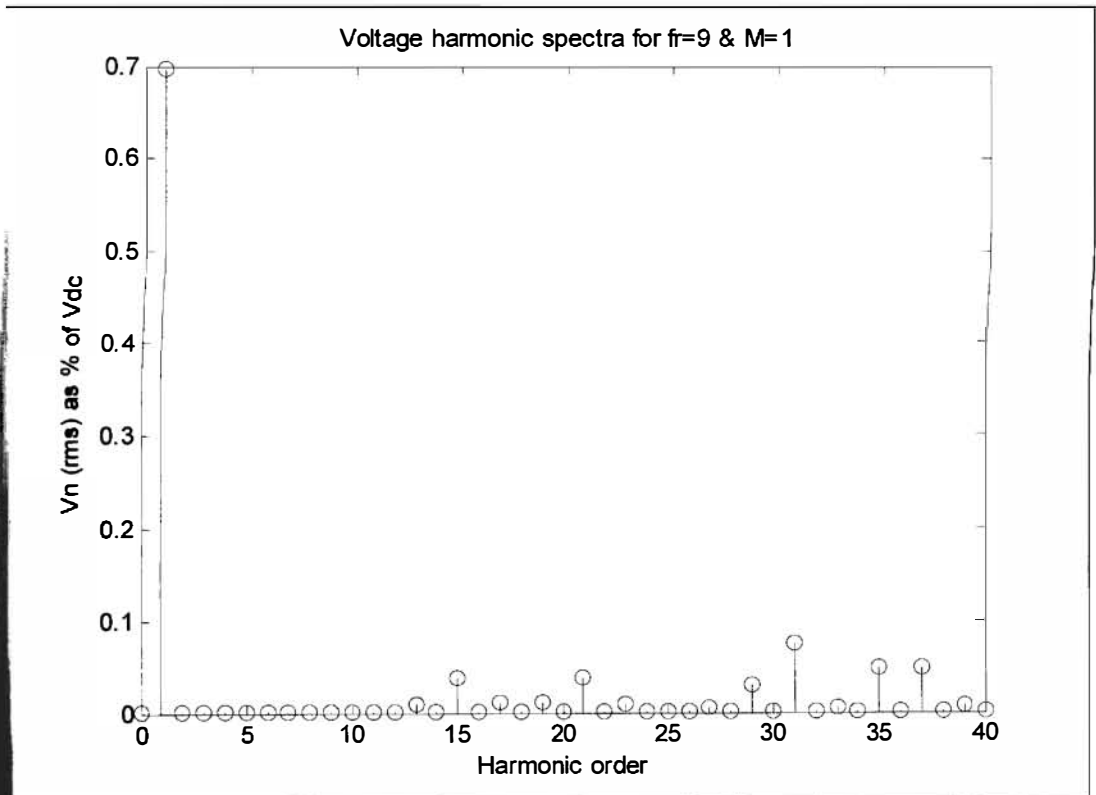


Figure 4.27: Voltage harmonic spectra up to 39<sup>th</sup> harmonic for  $f_r = 9$  and  $M = 1$ .

Figure (4.28) shows the voltage harmonic spectra up to 39<sup>th</sup> harmonic  $f_r = 9$  and  $M = 0.5$ . This time shifting angle  $\theta$  is chosen  $10^\circ$  again as frequency ratio remains unchanged. This value of  $\theta$  is the best possible case for  $f_r = 9$  which is discussed later. From the figure it is clear that for reducing the modulation index RMS value of fundamental component reduces from 0.7V to 0.35V and 33<sup>rd</sup>, 35<sup>th</sup>, 37<sup>th</sup> and 39<sup>th</sup> harmonic increases than previous setting. However, the harmonic components up to 15<sup>th</sup> harmonic are still close to zero. Thus changing the modulation index low order harmonic doesn't increase but RMS value of fundamental harmonic decreases.

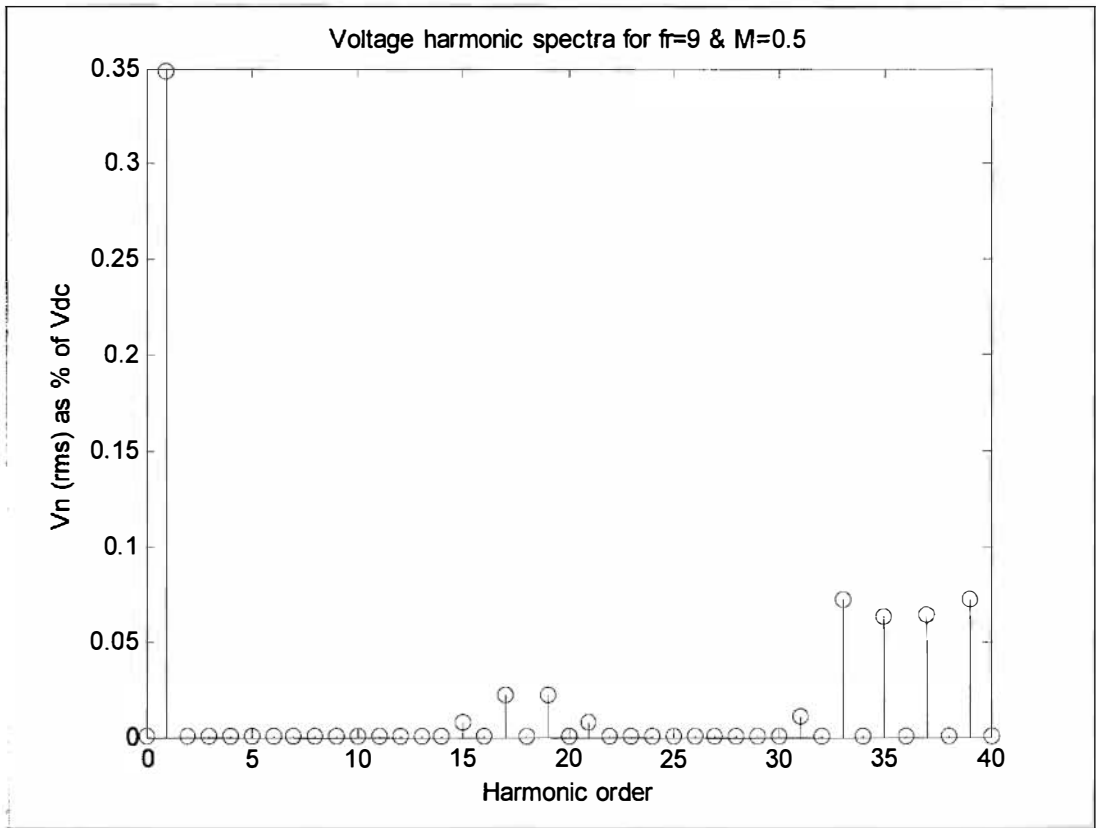


Figure 4.28: Voltage harmonic spectra up to 39<sup>th</sup> harmonic for  $f_r = 9$  and  $M = 0.5$ .

Figure (4.29) shows the harmonic spectra for  $f_r = 15$  and  $M = 1$ . Again up to 39<sup>th</sup> harmonic is plotted. If this is compared with the output for  $f_r = 9$  and  $M = 1$  it is observed that increase in frequency ratio has a positive effect in harmonic reduction. Except 27<sup>th</sup> and 33<sup>rd</sup> harmonic all other harmonic components become zero. The RMS value of fundamental harmonic doesn't change and remains 0.7V.

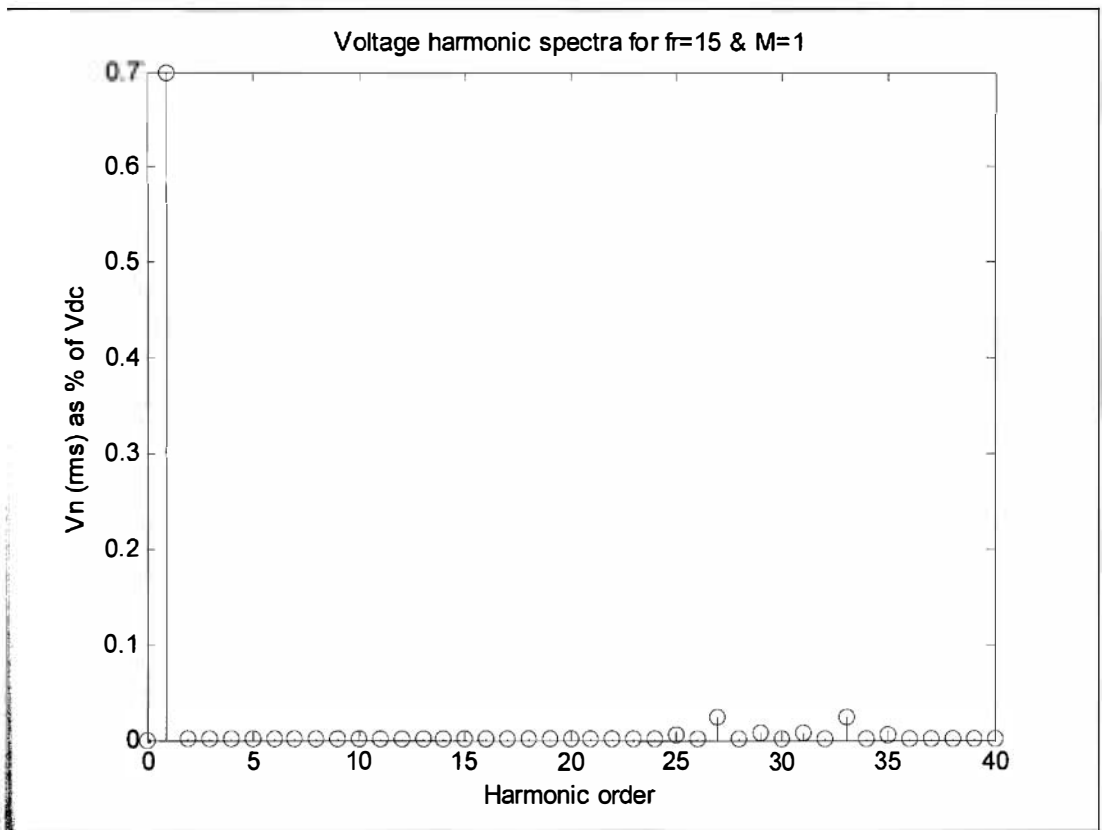
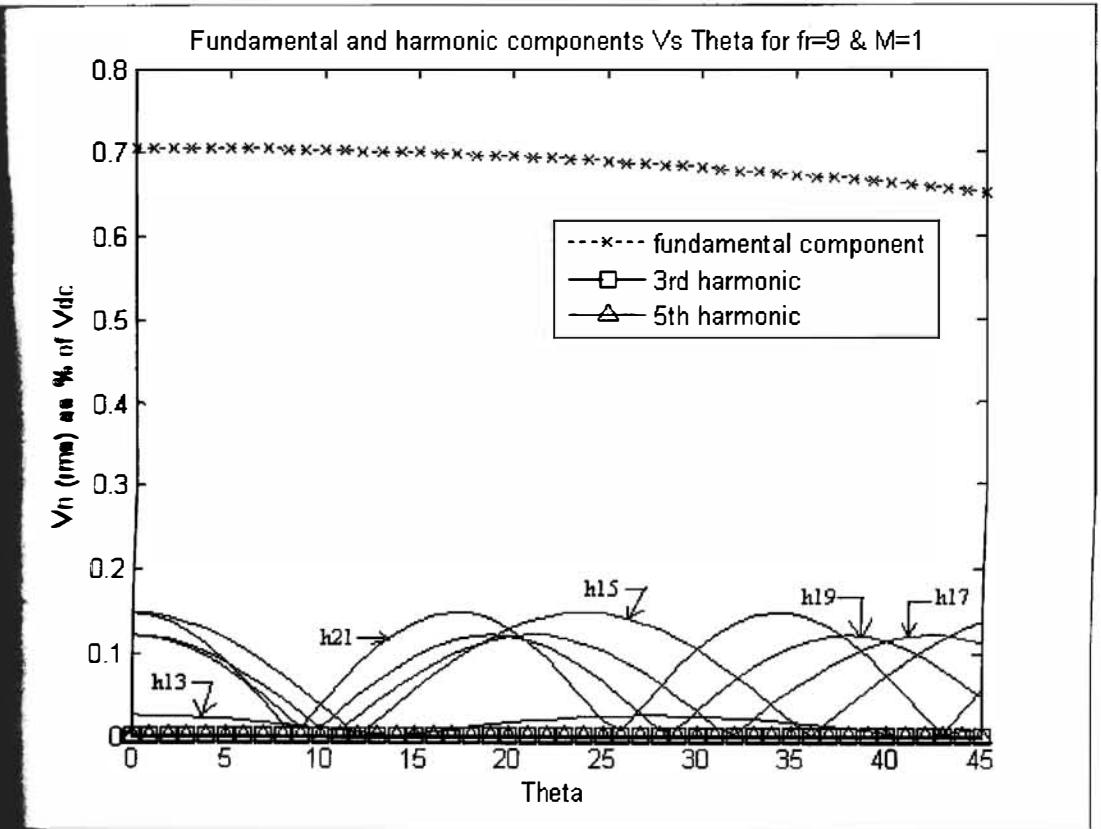


Figure 4.29: Voltage harmonic spectra up to 39<sup>th</sup> harmonic for  $f_r = 15$  and  $M = 1$ .



## 2.5 VARIATION OF HARMONIC COMPONENTS WITH SHIFTING ANGLE ( $\theta$ )

In previous sections a fixed shifting angle is chosen depending on the frequency ratio. This section deals with the best shifting angle for harmonic components with minimum value. To find the best shifting angle fundamental and harmonic voltages versus theta ( $\theta$ ) is plotted. Figure 4.30 shows the fundamental and harmonic component versus theta for  $f_r = 9$  and  $M = 1$  (up to 21<sup>st</sup> harmonic order). The figure shows that fundamental component reduces a little with the increase of shifting angle. The most important finding is at  $\theta = 10^\circ$ , the lowest RMS value of other harmonics is achieved.



4.30: Fundamental and harmonic components Vs shifting angle ( $\theta$ ) for  $f_r = 9$  and  $M = 1$ .

When  $\theta = 10^\circ$ , the lowest harmonics is achieved.

The same procedure is done for  $f_r = 9$  and  $M = 0.5$ . Harmonic components up to 21<sup>st</sup> is shown in figure 4.31. Here the RMS values of 17<sup>th</sup> increases a lot and RMS value of fundamental component decreases. But still at  $\theta = 10^\circ$  all harmonic components except fundamental component are minimum. So change in modulation index doesn't have that much effect on the best shifting angle.

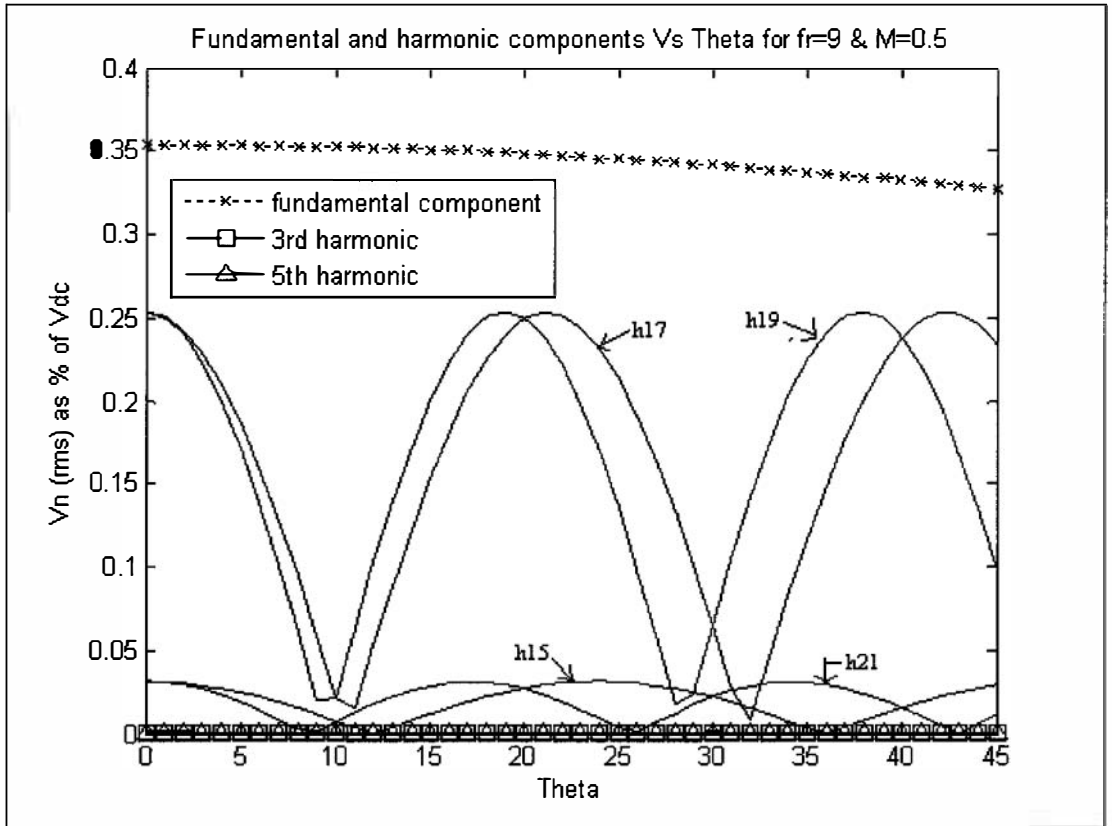


Figure 4.31: Fundamental and harmonic components Vs shifting angle ( $\theta$ ) for  $f_r = 9$  and  $M = 0.5$ .  
When  $\theta = 10^\circ$ , the lowest harmonics is achieved.



Figure 4.32 is for a different frequency ratio. This time  $f_r = 15$  and  $M = 1$ . As modulation index is again one, the RMS value of fundamental component becomes same as  $f_r = 9$  and  $M = 1$ . But here other harmonics becomes the minimum at different shifting angle. This time the best shifting angle is  $\theta = 6$ . From the previous analysis it can be said that RMS value of fundamental component changes with modulation index but the best shifting angle varies with the frequency ratio. Referring the previous results the relation between frequency ratio  $f_r$  and shifting angle  $\theta$  for minimum harmonics can be given by [19];

$$\theta = 90 / f_r$$

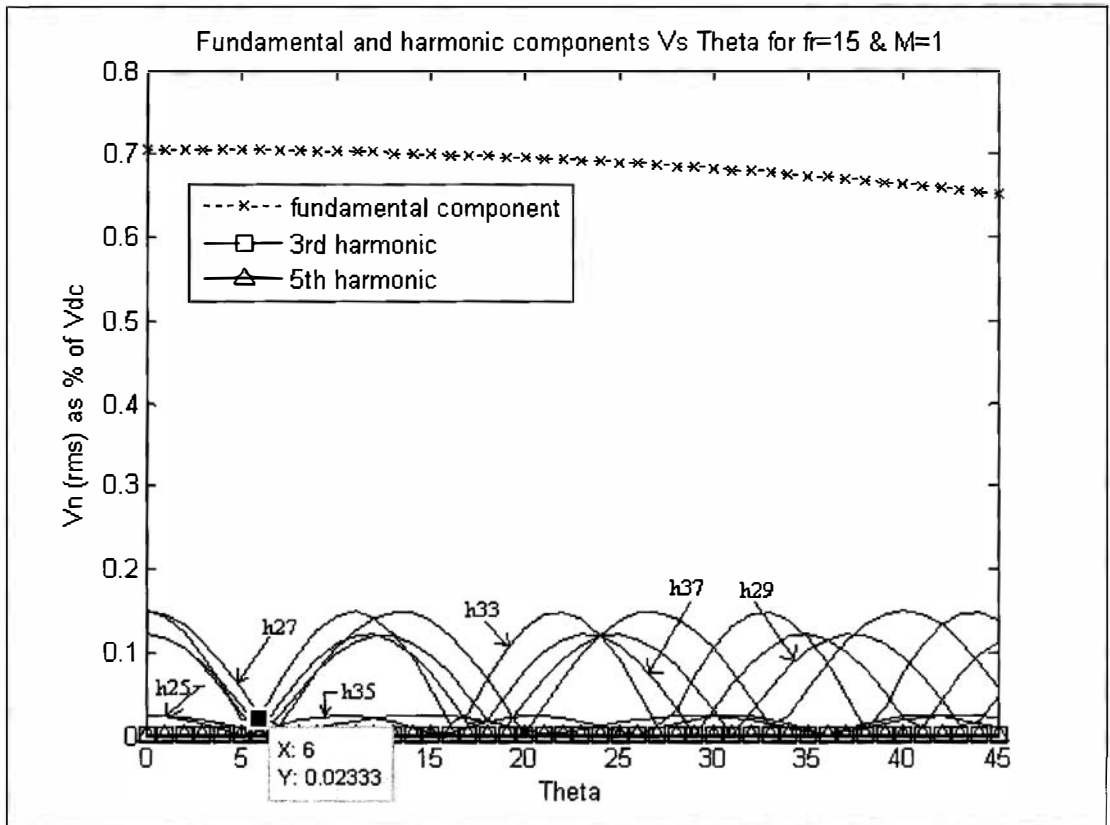


Figure 4.32: Fundamental and harmonic components Vs shifting angle ( $\theta$ ) for  $f_r = 10$  and  $M = 1$ . The lowest harmonics is achieved when  $\theta = 6^\circ$ .

#### 4.2.6 VARIATION OF HARMONIC COMPONENTS WITH MODULATION INDEX (M)

In previous sections it is observed that change in modulation index has an effect on RMS value of fundamental component. In this section analysis is done on effect of modulation index on fundamental component. It is also observed how the other harmonic components changes and at the end a conclusion is made for the best modulation index in respect of fundamental component and other harmonic components.

Figure 4.33 shows fundamental and harmonic components (up to 21<sup>st</sup> component) versus modulation index. The modulation index is varied from 0 to 1.6. Fundamental component increases almost linearly when modulation index increases from 0 to 1. When modulation index is 0.7 the RMS, values of fundamental component and highest harmonic are 0.528V and 0.022 V respectively. On the other hand when modulation index is 1 their value becomes 0.703V and 0.038 respectively. Here if 0.016V increase in harmonic value is considered fundamental component increases 0.175V. Up to this the 3<sup>rd</sup> and 5<sup>th</sup> harmonic components are zero. When modulation index increases from 1 the 3<sup>rd</sup> and 5<sup>th</sup> harmonics don't remain zero. They start to increase which is completely undesired. Because it is hard to avoid this harmonics and lots of works has been done just to get rid of these harmonic components. The introduction of 3<sup>rd</sup> and 5<sup>th</sup> harmonics (for  $M > 1$ ) is clear in figure 4.33. Though the 5<sup>th</sup> harmonic again starts to get low after little increase, the 3<sup>rd</sup> harmonic continues to increase. Considering RMS value of fundamental component, highest harmonic component and the presence of 3<sup>rd</sup>, 5<sup>th</sup> harmonics it can be said that  $M=1$  is the best setting to get rid of harmonic components as well as well fundamental component.

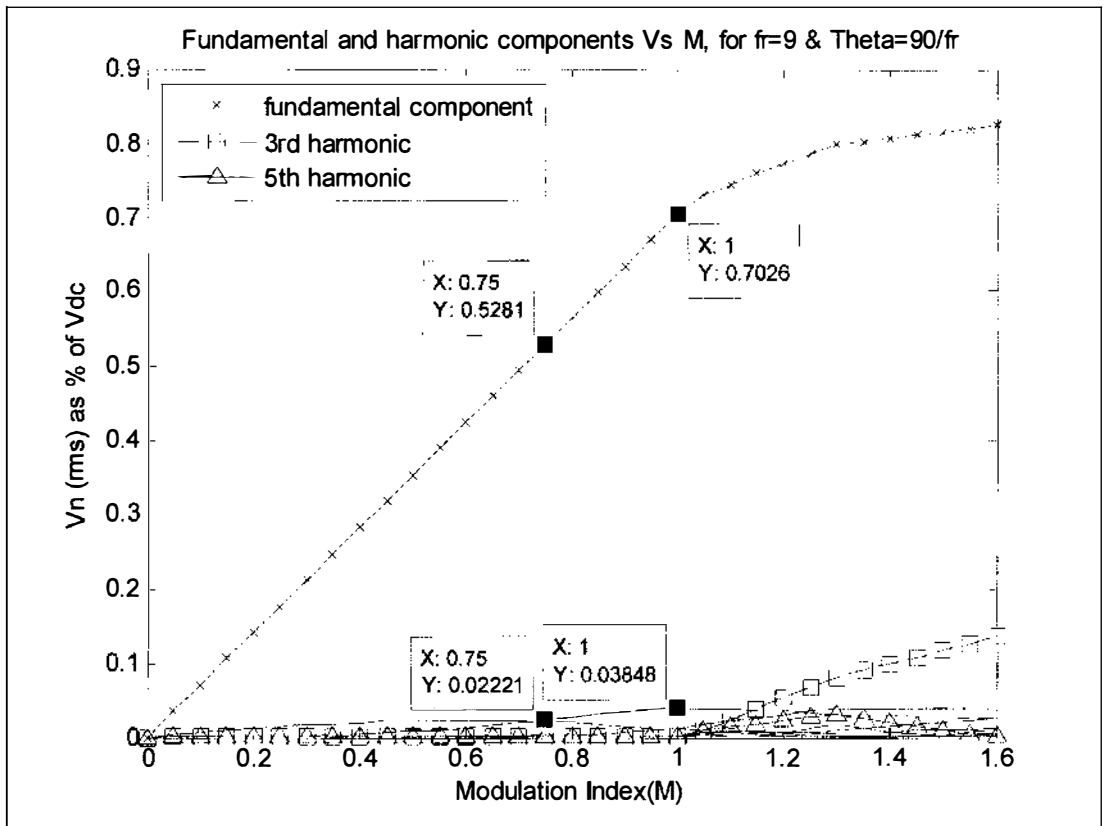


Figure 4.33: Fundamental and harmonic components Vs modulation index (M). In this case  $f_r=9$  and  $\theta = 90 / f_r$ . 3<sup>rd</sup> and 5<sup>th</sup> harmonics initiate when  $M > 1$ .

Figure 4.34 shows the variation of 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, 9<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup> harmonics with respect to modulation index. The fundamental component is not shown here so that the change of these harmonics can be seen noticeably. Now it is clearly observable that the of 3<sup>rd</sup> and 5<sup>th</sup> harmonics begin when  $M > 1$ . 9<sup>th</sup> and 11<sup>th</sup> harmonic also start from this point. 13<sup>th</sup> harmonic starts to increase before that point but its value is not that much high.

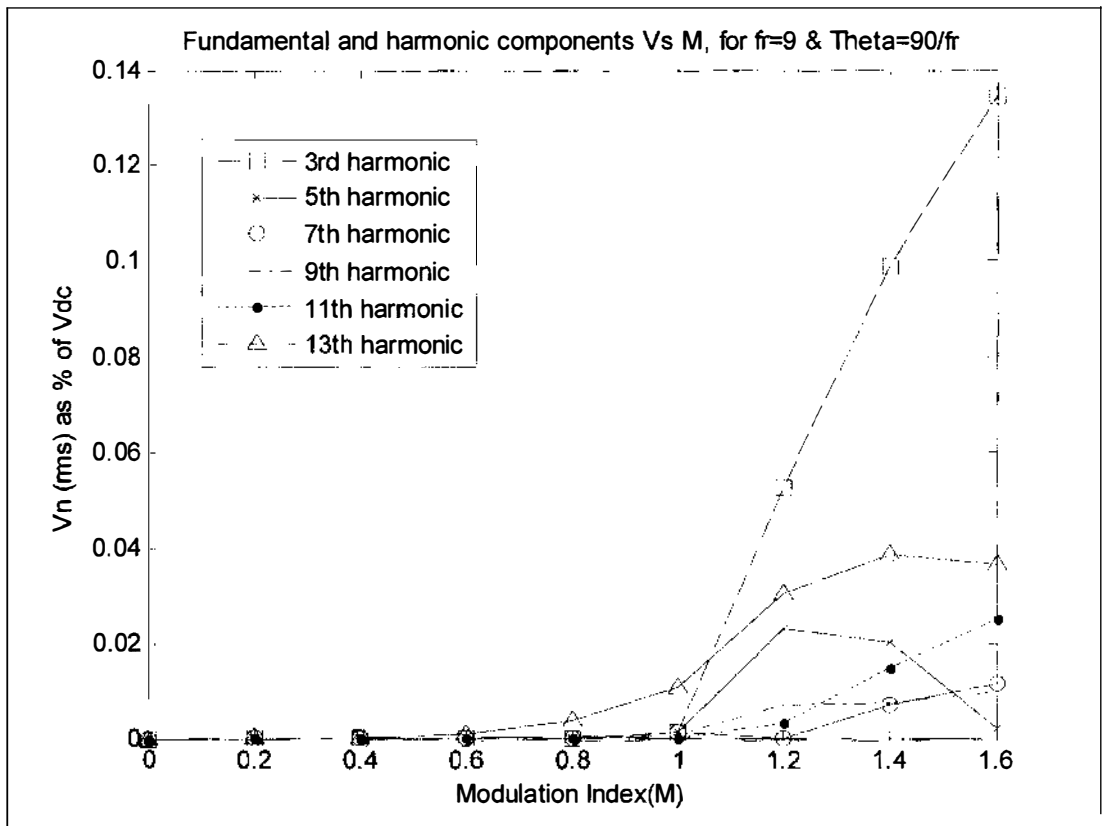


Figure 4.34: Fundamental and harmonic components Vs modulation index (M). 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, 9<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup> harmonics are shown here.

Figure 4.35 shows the variation of 3<sup>rd</sup>, 5<sup>th</sup>, 17<sup>th</sup>, 19<sup>th</sup> and 21<sup>th</sup> harmonics with respect to modulation index (M). 15<sup>th</sup>, 19<sup>th</sup> and 21<sup>st</sup> harmonic components incorporate before modulation index increases to 1 but as they are higher order harmonics they can be easily omitted. Thus there inclination is not important issue. So a conclusion can be drawn that modulation index, M=1 is the much suitable for harmonic reduction.

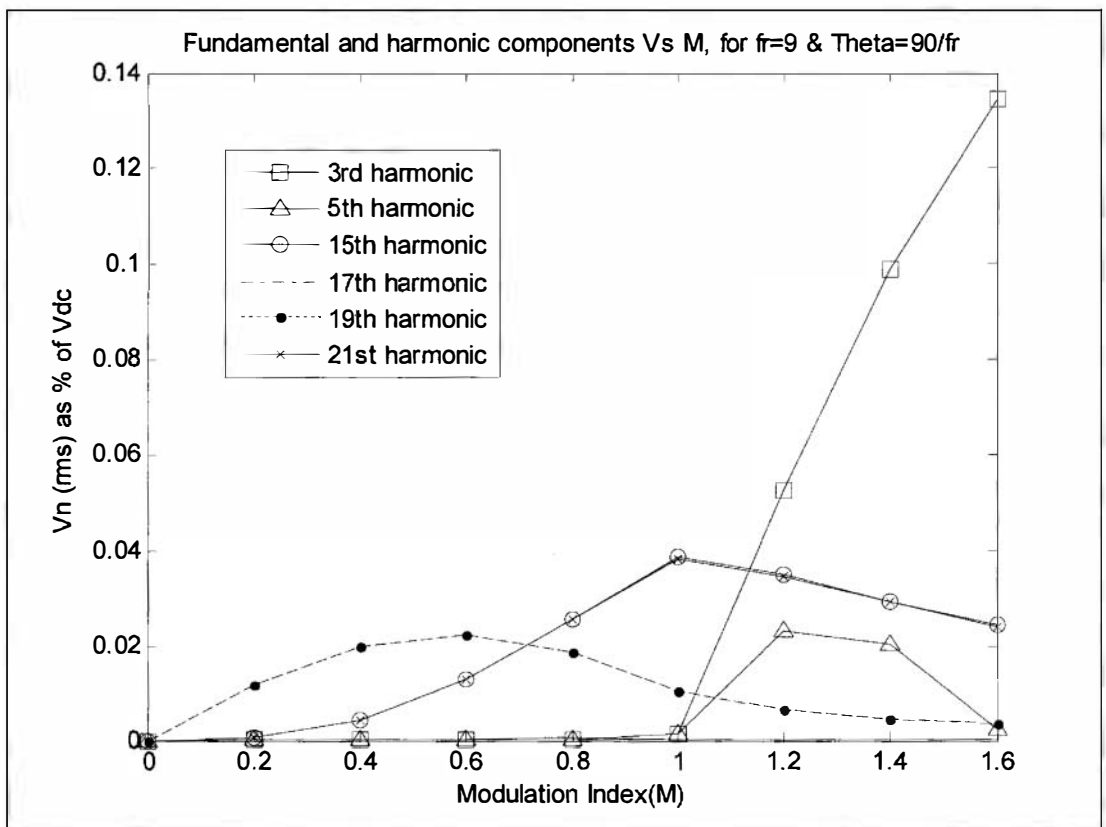


Figure 4.35: Fundamental and harmonic components Vs modulation index (M). 3<sup>rd</sup>, 5<sup>th</sup>, 17<sup>th</sup>, 19<sup>th</sup> and 21<sup>th</sup> harmonics are shown here.



#### 4.2.7 VARIATION OF HARMONIC COMPONENTS WITH FREQUENCY RATIO ( $f_r$ )

This chapter contains analysis on the change of harmonic components with respect to frequency ratio ( $f_r$ ). Here modulation index is fixed to 1 as already it is considered to be the best setting to get minimum harmonics. Figure 4.36 shows variation of harmonic components (up to 23<sup>rd</sup> harmonics). For analysis frequency ratio is varied from 1 to 1.6. Fundamental component reduces when  $f_r$  increases from 1 to 2. After that it again starts to increase and holds 0.7V in further increase of  $f_r$ . From figure 4.36 it is visible that though the value of harmonics is higher at the beginning, successively they become zero with the increase of frequency ratio. When  $f_r = 15$ , all 23<sup>rd</sup> harmonic are eliminated.

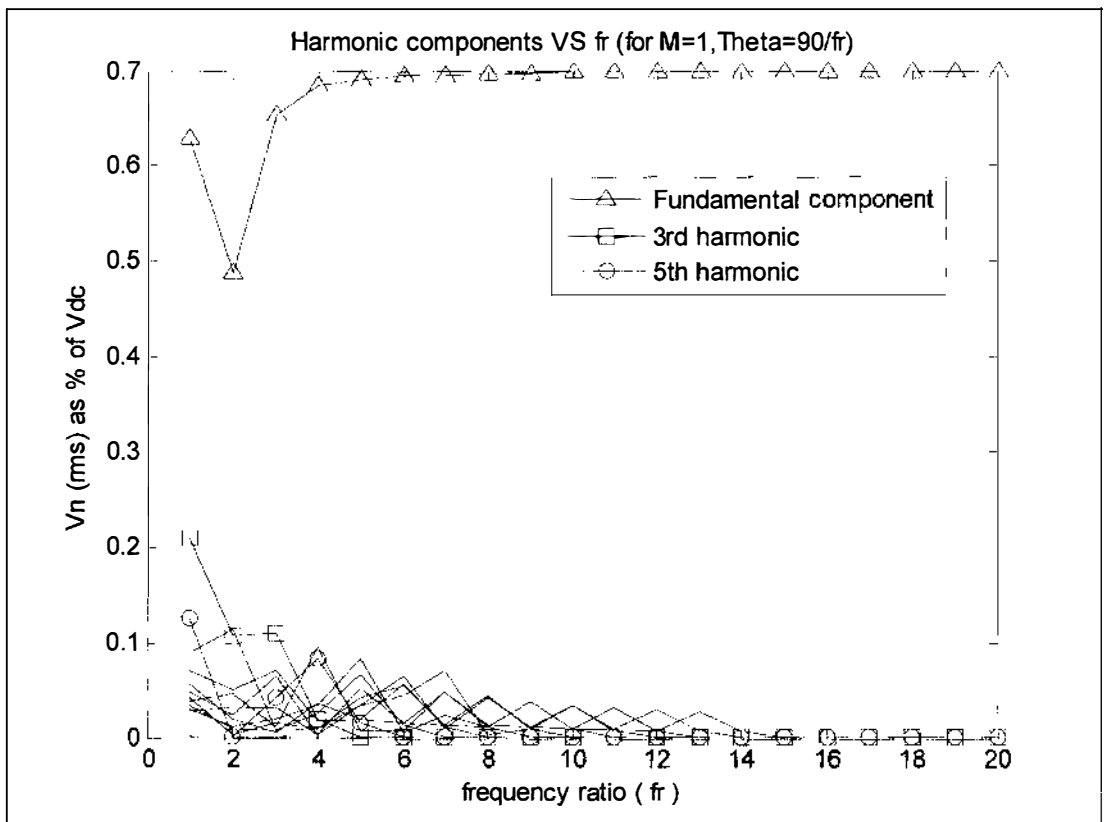


Figure 4.36: Fundamental and harmonic components Vs frequency ratio ( $f_r$ ). Harmonic components up to 23<sup>rd</sup> harmonics is shown. All harmonics are eliminated when  $f_r$  is 15 or above.



All harmonic components are plotted individually then. Figure 4.37 shows fundamental, 3<sup>rd</sup> and 5<sup>th</sup> component. 3<sup>rd</sup> and 5<sup>th</sup> harmonics are eliminated when  $f_r = 5$  and  $f_r = 6$  respectively. 5<sup>th</sup> harmonic is also close to zero at  $f_r = 2$ . But with increase of  $f_r$  it again increases and becomes zero at  $f_r = 6$ . Figure 4.38 shows the 7<sup>th</sup>, 9<sup>th</sup> and 11<sup>th</sup> harmonic components. They become eliminated when value of  $f_r$  is 7, 8, and 9 respectively. Figure 4.39 shows the 13<sup>th</sup>, 15<sup>th</sup> and 17<sup>th</sup> harmonic components and they become eliminated when  $f_r$  is 10, 11.2 and 13. The 19<sup>th</sup>, 21<sup>st</sup>, and 23<sup>rd</sup> harmonics are shown in figure 4.40 and they are eliminated when  $f_r$  is 13, 14 and 15 respectively. Specific harmonic component and specific frequency ratio for which they become negligible are shown in table 4.1. Referring the previous results of table 4.1, it can be said that relation between harmonic component and required harmonic component to eliminate up to that harmonic is:

$$f_r = (h + 7) / 2; \dots\dots\dots(4.1)$$

$f_r$  is the required frequency ratio to eliminate up to  $h^{\text{th}}$  harmonics. The value of  $h = 3, 5, 7, 11, \dots$  as even harmonics are zero.

**Table 4.1: Elimination of specific harmonic component with specific frequency ratio ( $f_r$ )**

Harmonic component	Required frequency ratio to eliminate
3 <sup>rd</sup>	5
5 <sup>th</sup>	6
7 <sup>th</sup>	7
9 <sup>th</sup>	8
11 <sup>th</sup>	9
13 <sup>th</sup>	10
15 <sup>th</sup>	11
17 <sup>th</sup>	12
19 <sup>th</sup>	13
21 <sup>st</sup>	14
23 <sup>rd</sup>	15

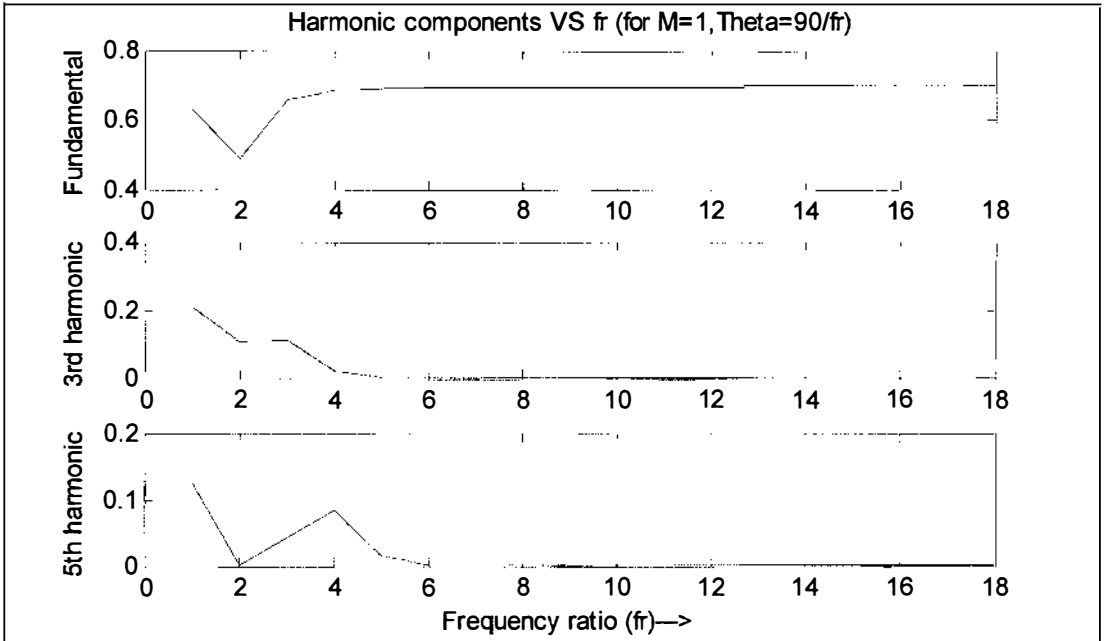


Figure 4.37: Fundamental, 3<sup>rd</sup> and 5<sup>th</sup> harmonic components Vs frequency ratio ( $f_r$ ). 3<sup>rd</sup> and 5<sup>th</sup> harmonics are eliminated at  $f_r = 5$  and 6 respectively.

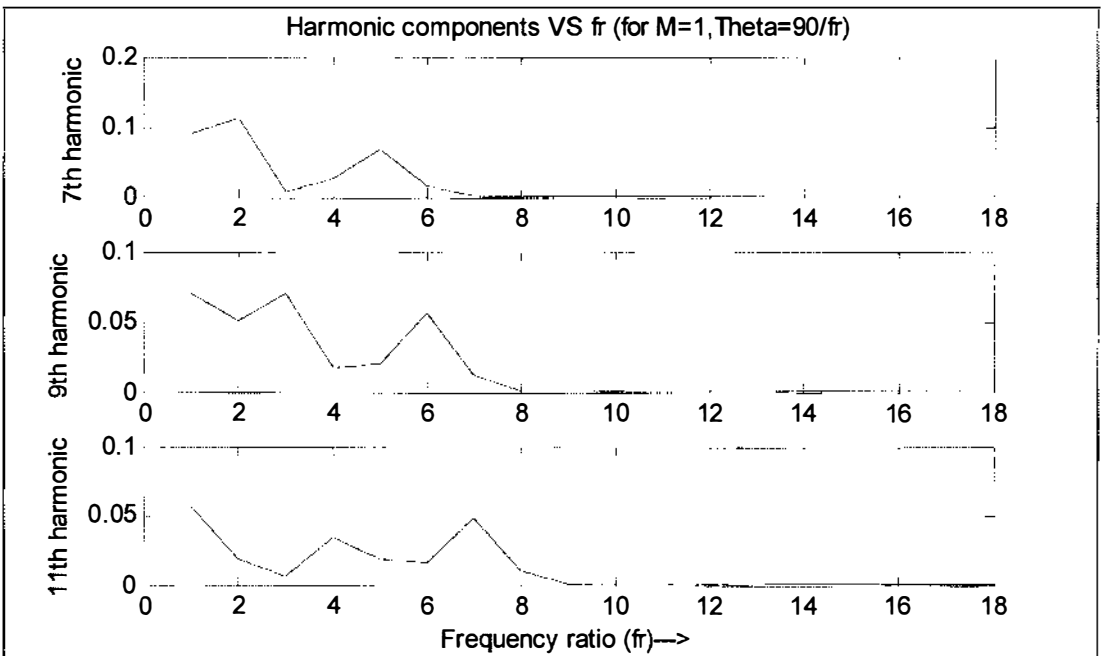


Figure 4.38: 7<sup>th</sup>, 9<sup>th</sup> and 11<sup>th</sup> Harmonic components Vs frequency ratio ( $f_r$ ). They become eliminated at  $f_r = 7, 8$  and 9 respectively.

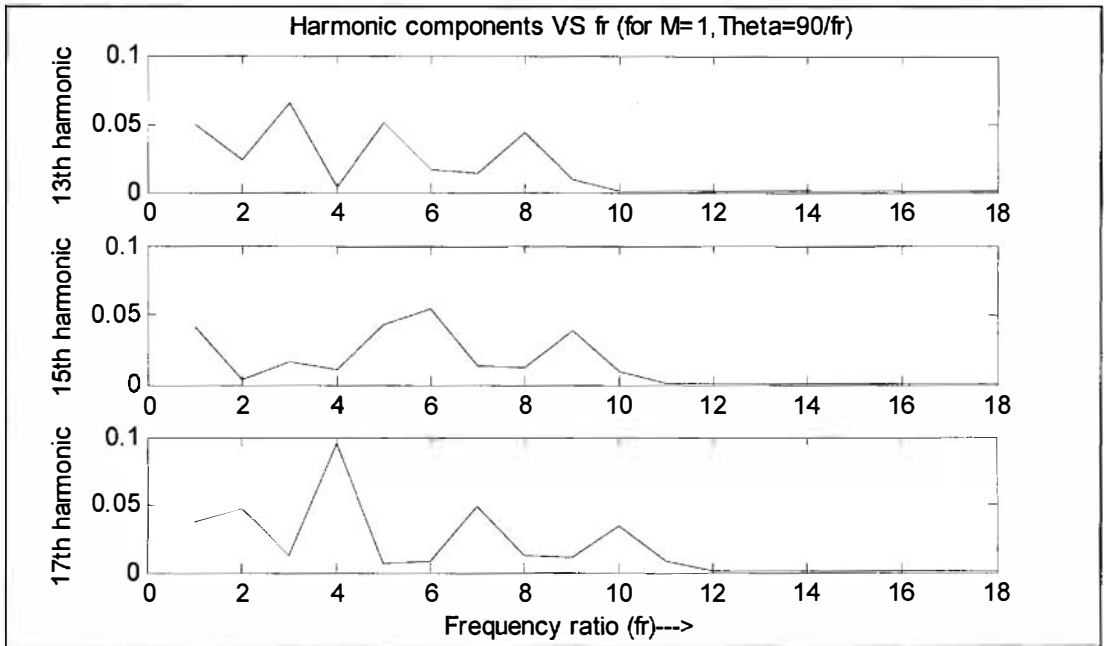


Figure 4.39: 13<sup>th</sup>, 15<sup>rd</sup> and 17<sup>th</sup> Harmonic components Vs frequency ratio ( $f_r$ ). They become eliminated at  $f_r = 10, 11$  and  $12$  respectively.

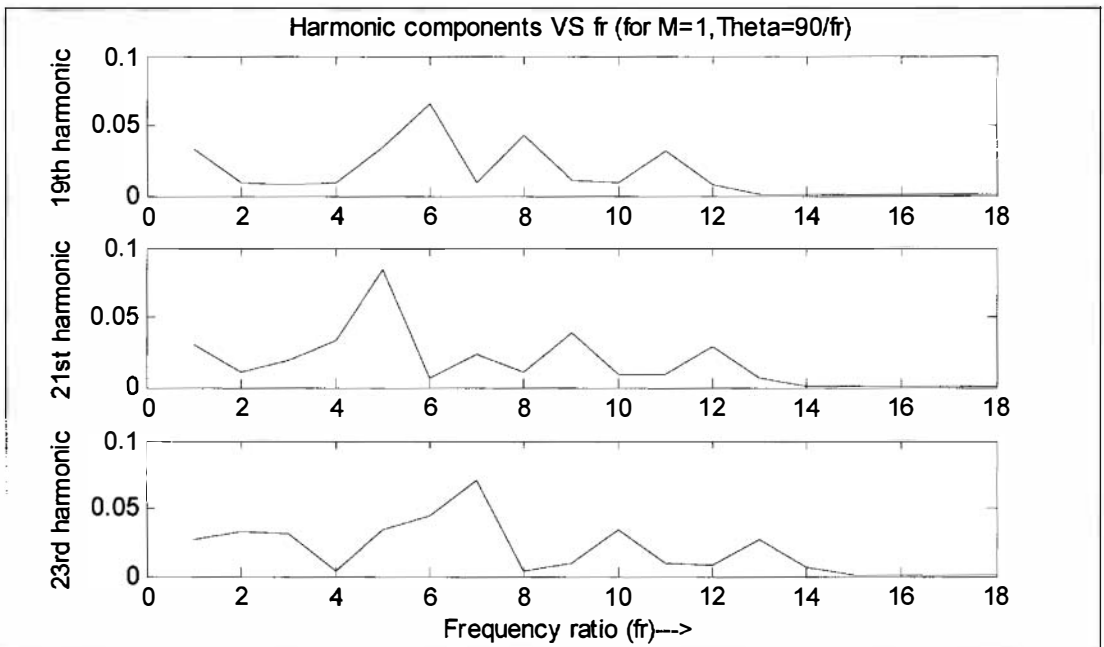


Figure 4.40: 19<sup>th</sup>, 21<sup>st</sup> and 23<sup>rd</sup> Harmonic components Vs frequency ratio ( $f_r$ ). They become eliminated at  $f_r = 13, 14$  and  $15$  respectively.

## CHAPTER V

### ANALYSIS OF THE OUTPUT SIGNALS IN PSPICE

#### 5.1 CIRCUIT DESCRIPTION

In this chapter, SPWM is implemented on PSPICE for different values of  $f_r$  &  $M$ , like the previous chapter which was done in MATLAB. The Chapter V (Analysis in MATLAB) concludes that for some particular values of  $f_r$  &  $M$ , the output voltage harmonic reduces. Because the values of  $f_r$  &  $M$  is known, so a circuit can be implemented in PSPICE. The main work of this chapter is to design , analysis & simulation of a switching circuit for inverter & to compare the simulated output with the output of MATLAB & to check the similarities & discrepancies (if available) of the simulated outputs.

Figure 5.1 shows the circuit diagram of the switching circuit of the inverter. Here VSIN & VPULSE is used for generating sine wave & triangular wave respectively. There might be a question that why VSIN & VPULSE are used to generating waves in place of sine wave & triangular wave generator circuit, the answer is that the objective or the main focus of this project is to reduce output voltage harmonics of the inverter, wave generating circuits are not a subject of concern. To do that the switching circuit is designed to reduce output voltage harmonics of the inverter. The circuit has two arrangements of similar components including two sine wave generator, triangular wave generator & two comparator circuits. One sine wave generator generates a  $0^\circ$  sine wave & the other generates  $180^\circ$  phase shifted sine wave. One (upper part of the figure 5.1 part of the circuit compares the  $0^\circ$  sine wave &  $180^\circ$  phase shifted sine wave with triangular wave. The other part (lower part of the figure 5.1) does the same job but the whole arrangement is  $\theta^\circ$  shifted from the first one. For a fixed value of  $f_r$ ,  $\theta$  is fixed. In this circuit uA771 op-amp ICs are used from the PSPICE library, which is a fast switching op-amp IC.

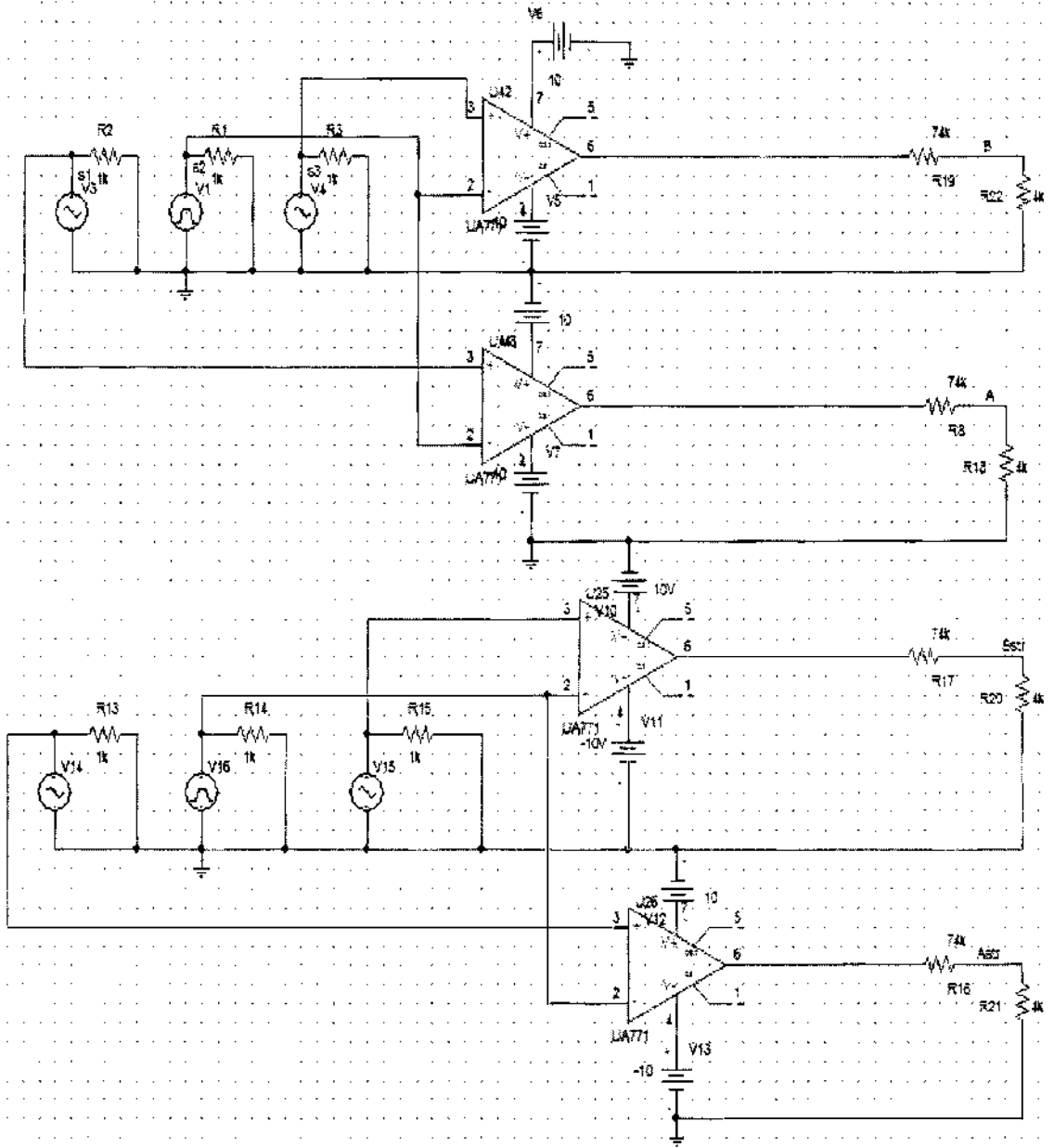
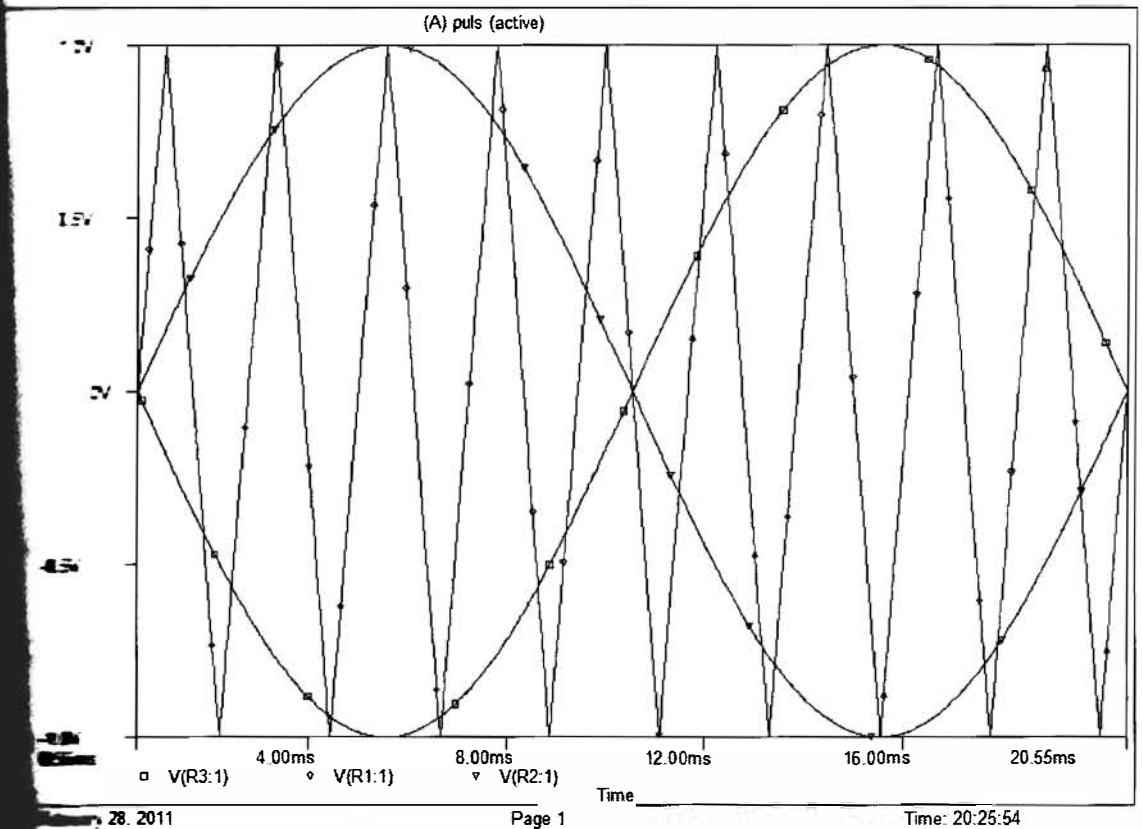


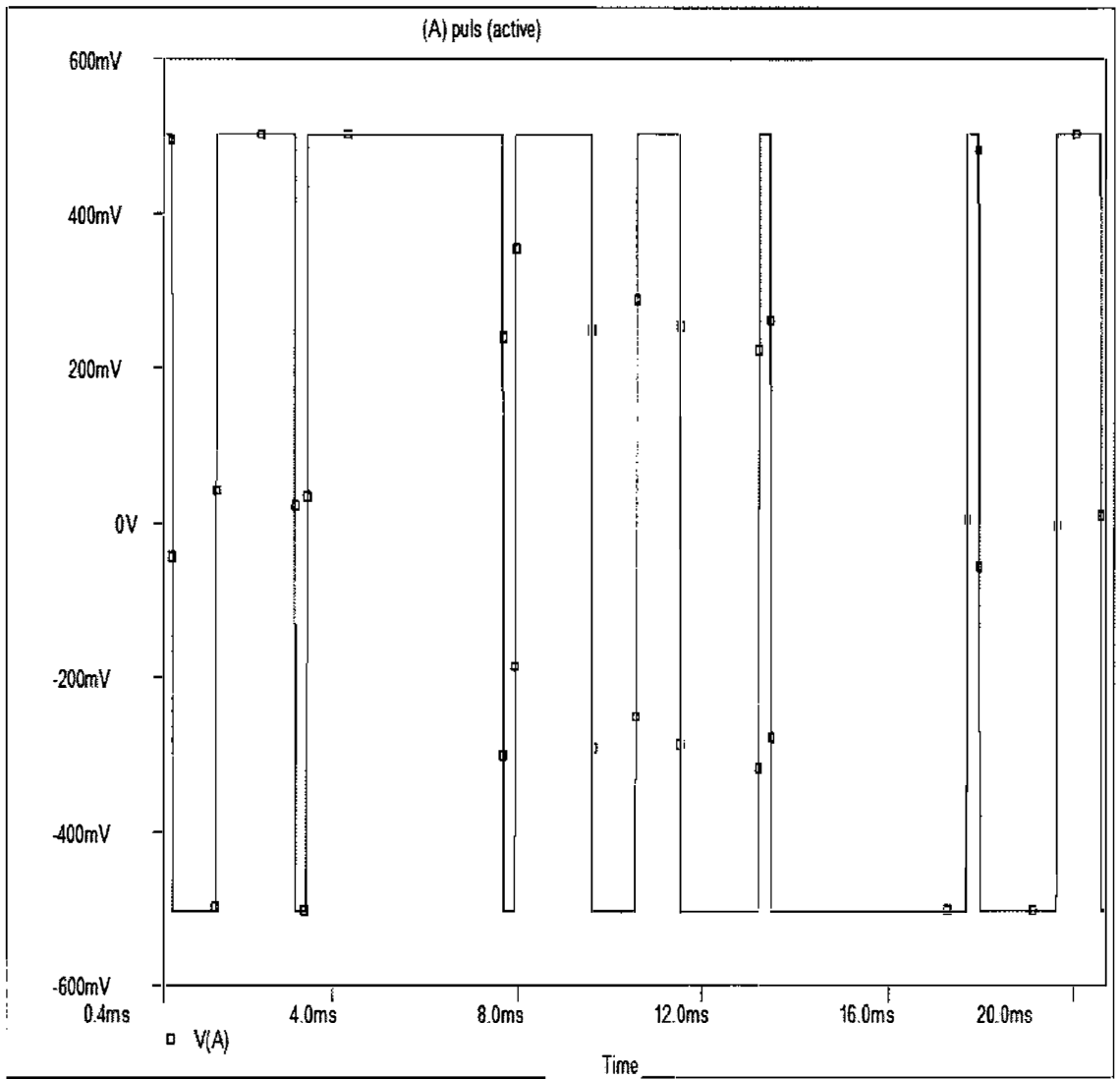
Figure 5.1: The Circuit diagram of the switching circuit of the inverter designed in PSPICE shown in figure 5.1. The circuit contains VSIN to generate sine wave, VPULSE to generate triangular wave & uA771 op-amp ICs.

## OUTPUT VOLTAGE ANALYSIS FOR $f_r = 9$ AND $M = 1$

In this section the circuit is simulated for  $f_r=9$  &  $M=1$ . To do that the frequency of Sine waves (at  $180^\circ$  shifted) are set at 50 Hz which is the frequency of the power line of Bangladesh. On the other hand the frequency of the triangular wave is set at 450Hz because the frequency ratio is 9. The value of  $\theta$  is set at  $10^\circ$  because  $\theta=(90^\circ/f_r)=10^\circ$  where  $f_r=9$ . The amplitude of all waves is 1V because modulation index is 1. In the plots of PSPICE V(A) , V(B), V(Astr) & V(Bstr) are used in place of  $V_a$ ,  $V_b$ ,  $V_a^*$  &  $V_b^*$  respectively &  $V_r$ ,  $V_s$  & the final output  $V_o$  is used with the following expressions i.e.  $(V(A) + V(Astr))/2$ ,  $(V(B) + V(Bstr))/2$  &  $((V(A) + V(Astr))/2) - ((V(B) + V(Bstr))/2)$  is used in place of  $V_r$ ,  $V_s$  &  $V_o$  respectively.



Plot of three waves in PSPICE for  $f_r=9$  &  $M=1$ . The plot of the figure 5.2 includes a phase of  $0^\circ$  &  $180^\circ$  shifted sine wave which will be compared with a triangular wave. The sine wave have same amplitude of 1V & frequency of 50 Hz. The triangular wave has same amplitude of 1 volt but the frequency is 9 times of sine waves.

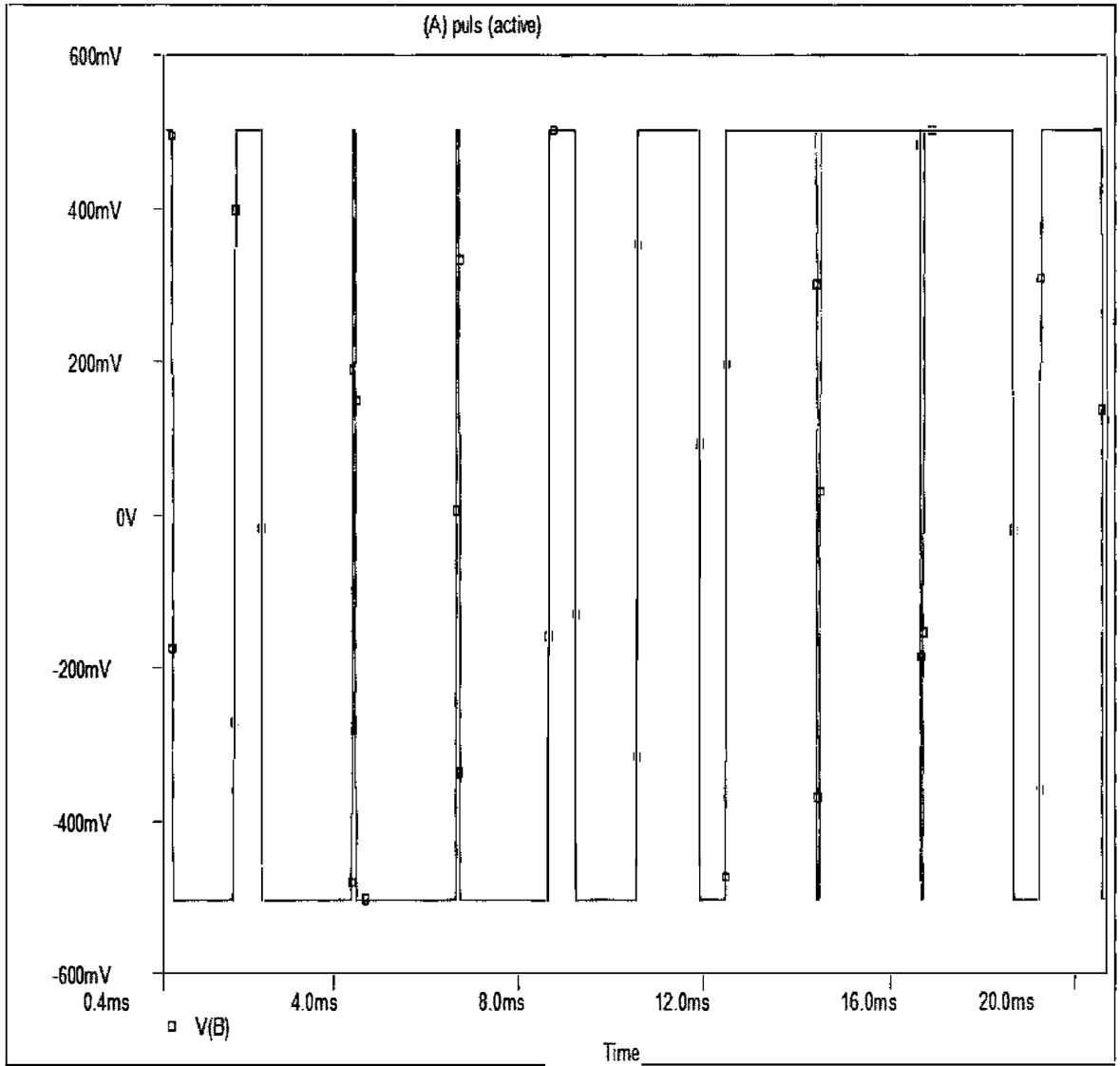


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Figure 5.3: Plot of  $V_a$  as  $V(A)$  in PSPICE for  $f_r=9$  &  $M=1$ . The signal of the figure 5.3 is found after comparing the  $0^\circ$  sine wave & the triangular wave i.e. it's  $V(A)$  which was previously denoted as  $V_a$  in MATLAB.



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Figure 5.4: Plot of  $V_b$  as  $V(B)$  in PSPICE for  $f_r=9$  &  $M=1$ . The signal of the figure 5.4 is found after comparing the  $180^\circ$  phase shifted sine wave & the triangular wave i.e. it's  $V(B)$  which was previously denoted as  $V_b$  in MATLAB.



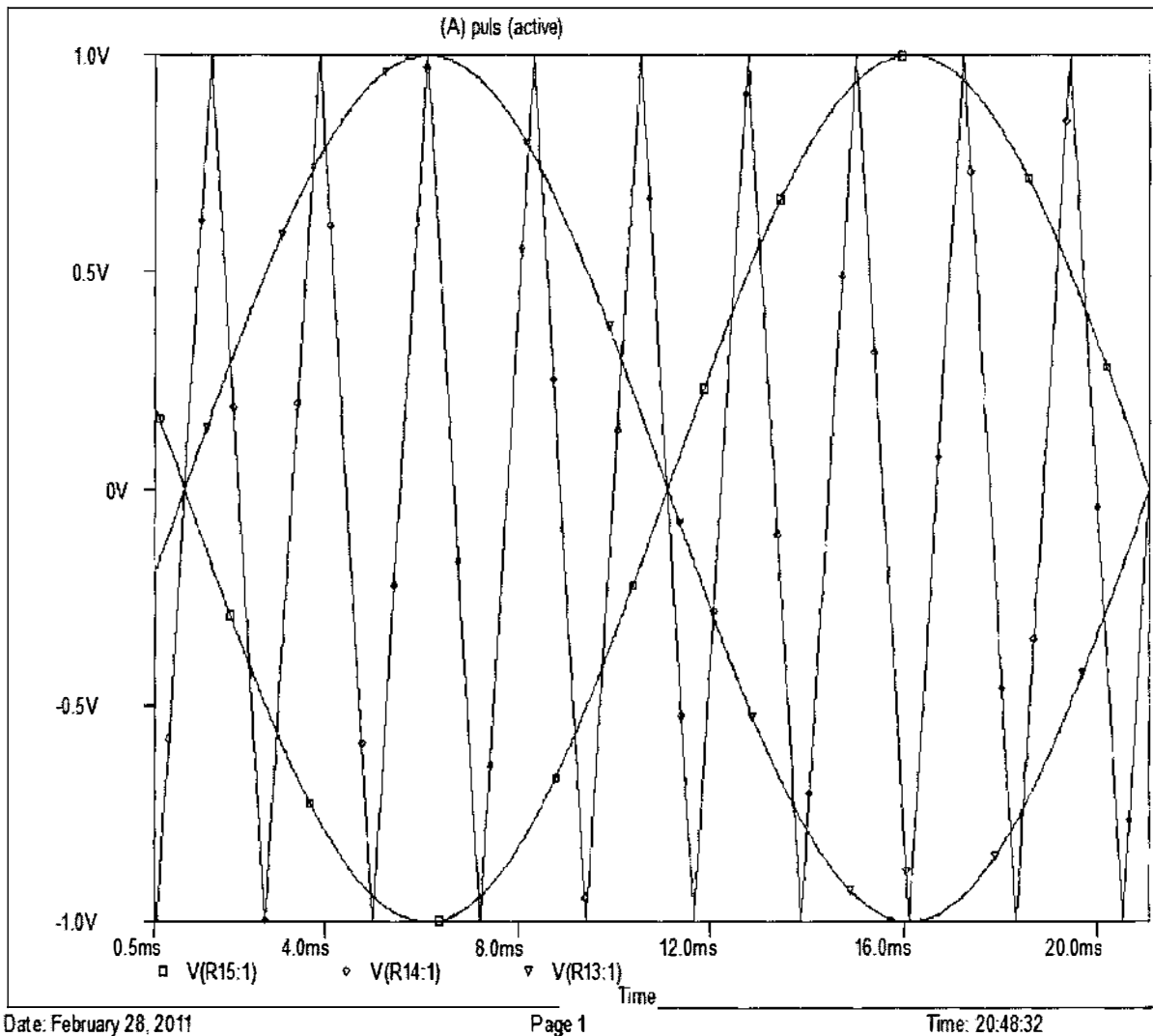


Figure 5.5: Plot of  $10^\circ$  phase right shifted three waves in PSPICE for  $f_r=9$  &  $M=1$ . Figure 5.5 shows the plot of three waves i.e. two sine waves & a triangular wave which is  $\theta^\circ$  right shifted from the signal of Figure 5.2. Here  $\theta=(90^\circ/f_r)=10^\circ$  where  $f_r=9$ .

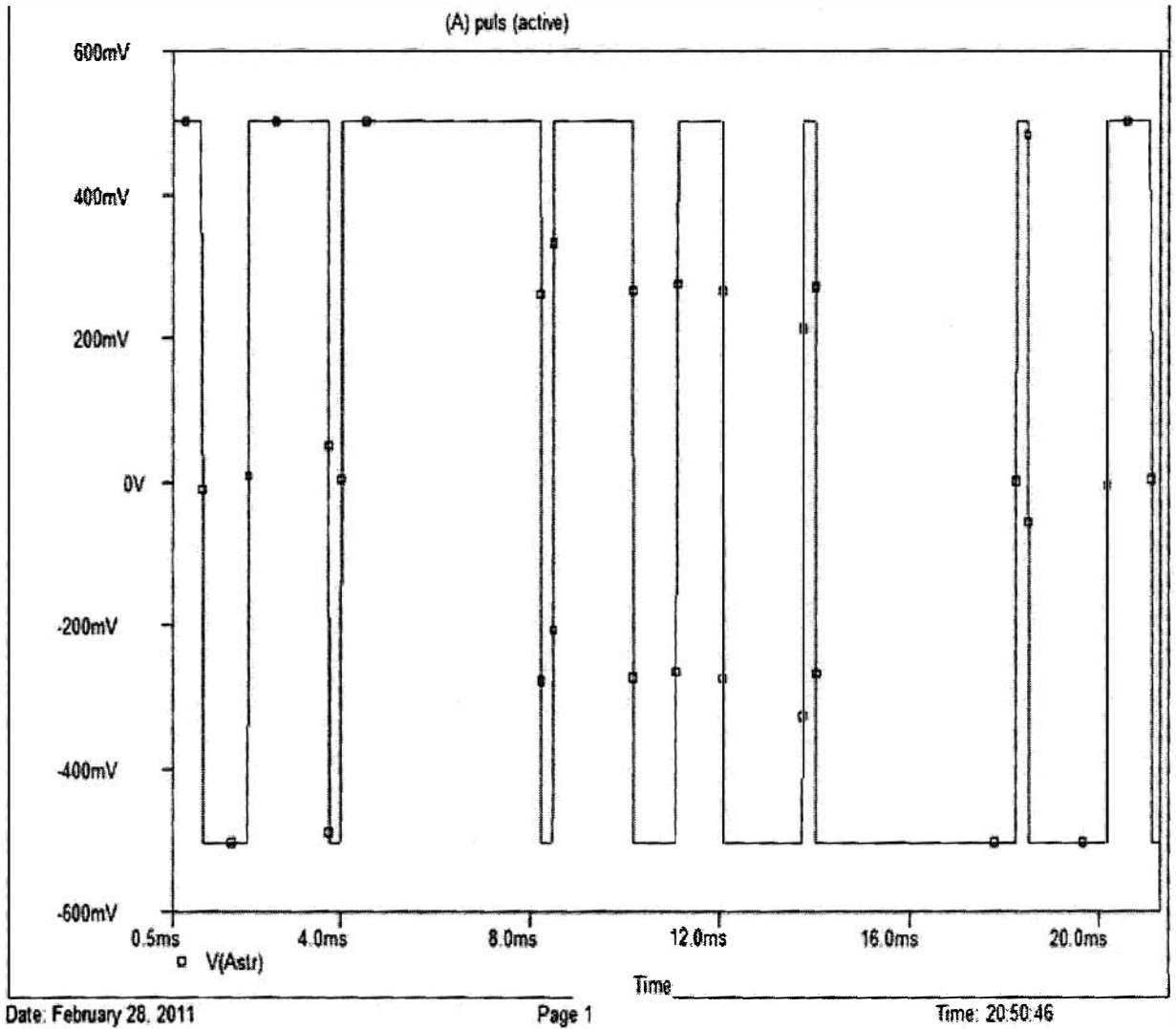


Figure 5.6: Plot of  $V_a^*$  as  $V(\text{Astr})$  in PSPICE for  $f_r=9$  &  $M=1$ . Figure 5.6 shows the plot of  $10^\circ$  phase right shifted signal from the signal shown in fig 5.3 i.e.  $V(\text{Astr})$  which was previously denoted as  $V_a^*$  in MATLAB.



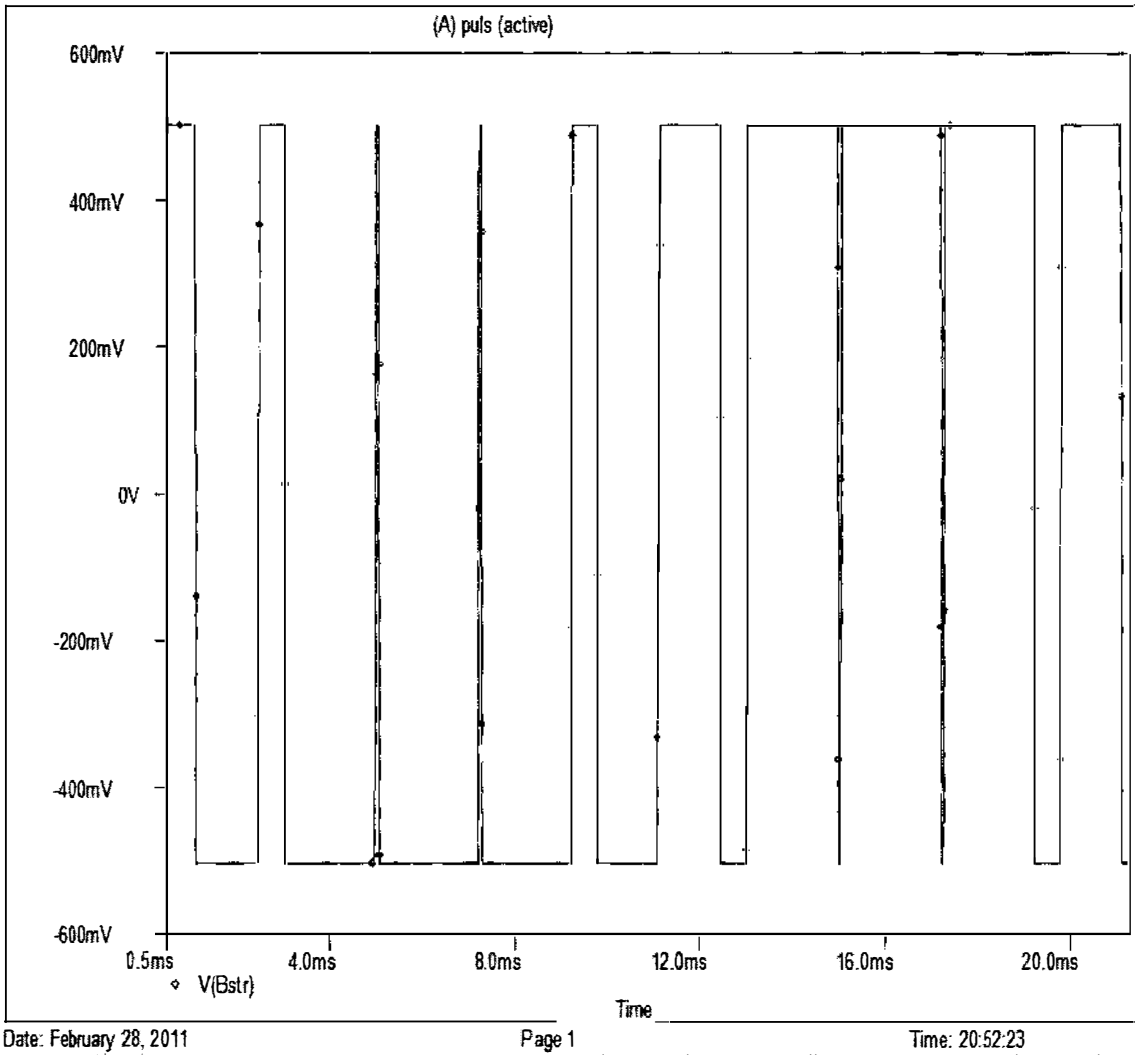


Figure 5.7: Plot of  $V_b^*$  as  $V(Bstr)$  in PSPICE for  $f_r=9$  &  $M=1$ . Figure 5.7 shows the plot of  $10^\circ$  phase right shifted signal from the signal shown in fig 5.4 i.e.  $V(Bstr)$  which was previously denoted as  $V_b^*$  in MATLAB.

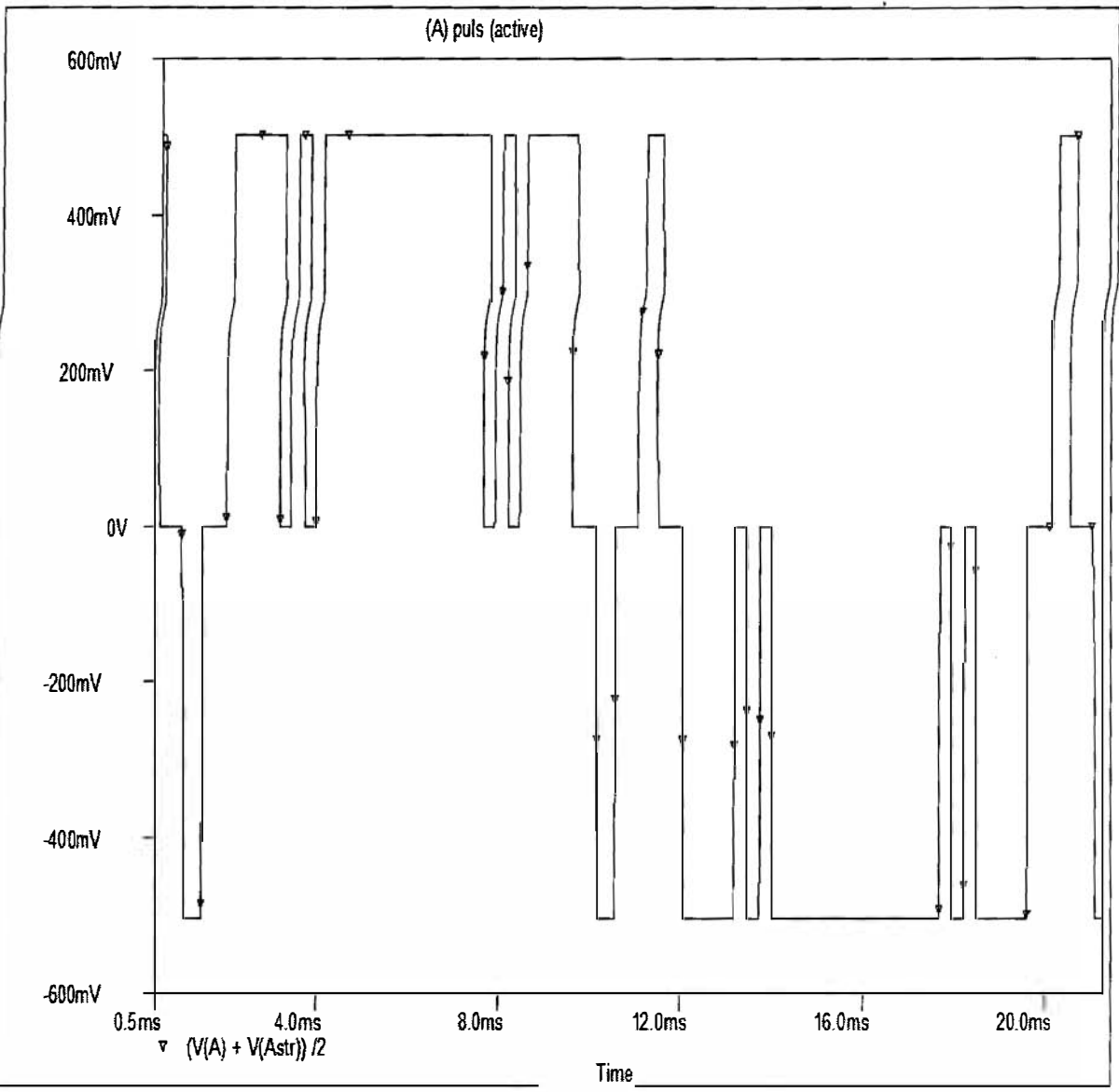
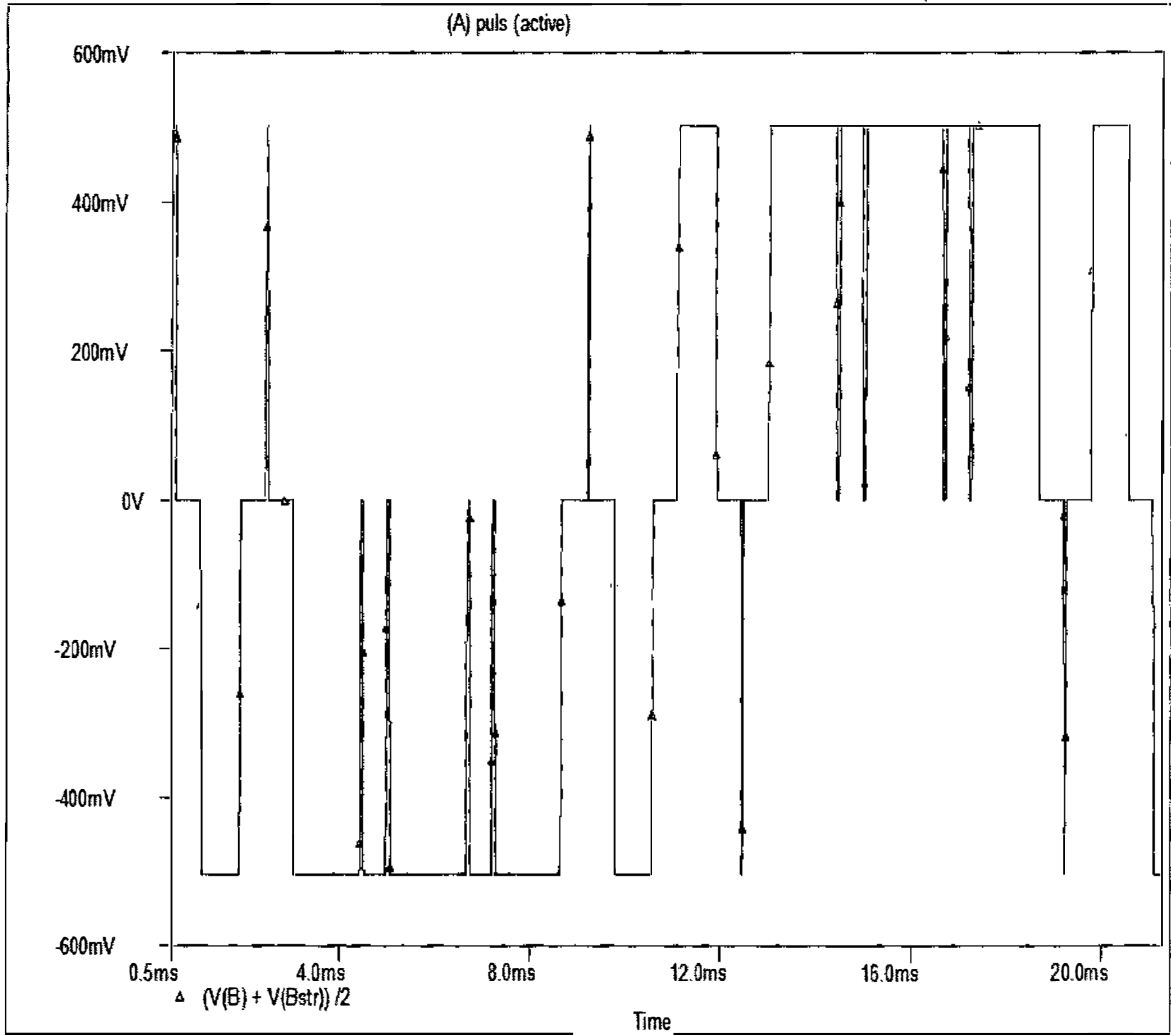


Figure 5.8: Plot of  $V_r$  as  $(V(A) \& V(Astr))/2$  in PSPICE for  $f_r=9$  &  $M=1$ . The signal is found by adding the signal of fig 5.3 & fig 5.6 then dividing by 2 i.e.  $(V(A) \& V(Astr))/2$  which was previously denoted as  $V_r$  in MATLAB & where  $V_r = (V_a + V_a^*)/2$ .



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Figure 5.9: Plot of  $V_s$  as  $(V(B) \& V(Bstr))/2$  in PSPICE for  $f_r=9$  &  $M=1$ . The signal of the figure 5.9 is found after adding the signal of fig 5.4 & fig 5.7 then dividing by 2 i.e.  $(V(B) \& V(Bstr))/2$  which was previously denoted as  $V_s$  in MATLAB & where  $V_s = (V_b + V_b^*)/2$ .

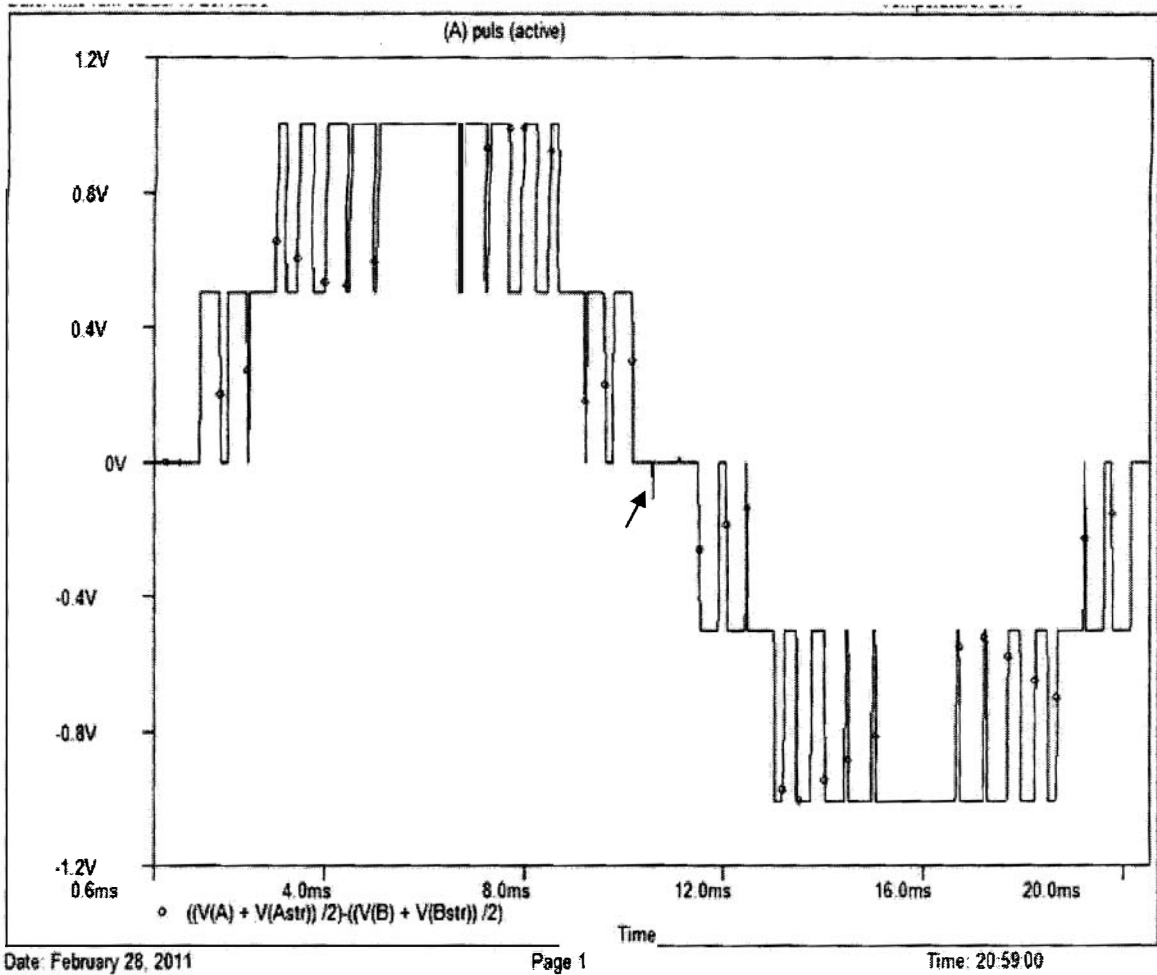


Figure 5.10: Plot of final output  $V_o$  as  $((V(A) + V(Astr))/2) - ((V(B) + V(Bstr))/2)$  in PSPICE for  $f_r=9$  &  $M=1$ . The plot of the figure 5.10 shows the final output. This signal is found by subtracting from the signals of fig 5.8 to the signal of fig 5.9 i.e.  $((V(A) + V(Astr))/2) - ((V(B) + V(Bstr))/2)$  which is previously denoted as  $V_o$  in MATLAB & where  $V_o = V_r - V_s$ . This output is very similar to the output of the MATLAB but has a theoretically undesired small spike (indicated by an arrow).

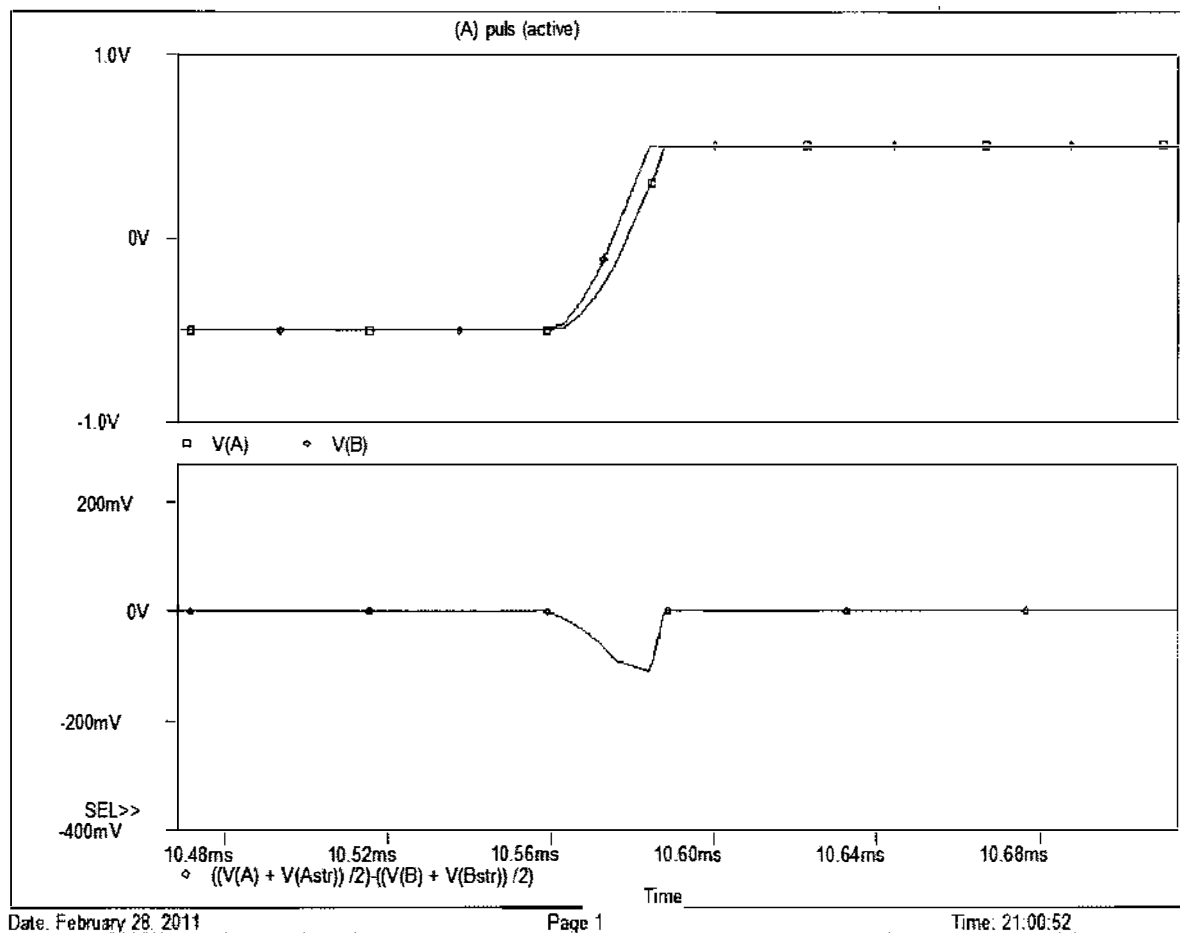


Figure 5.11: Zoomed plot at where the problem occurs in PSPICE for  $f_r=9$  &  $M=1$ . It is clearly seen from the upper plot of the figure 5.11, the two signals are not rising at a same time but theoretically these two signals should rise with a same race & time.

This type of problem is very common & usual problem for the practical circuits because the actual ICs may not be identical. But in software simulation it shouldn't occur because the ICs are from the same library.

The explanation of this small spike was not found because of time limitation. It may occur because of a mismatch issue of ICs although the ICs are used from the same PSPICE library. So finding out the correct reason behind this problem is suggested as a future work.

### 5.3 OUTPUT VOLTAGE ANALYSIS FOR $Fr = 9$ AND $M = 0.5$

Now changing the modulation index  $M$  from 1 to 0.5 & keeping the same frequency ratio of 1, the circuit is simulated. All the simulation output signals are very similar to the output found from the MATLAB but there is a little mismatch at the output signal. This mismatch issue is discussed at the end of this section.

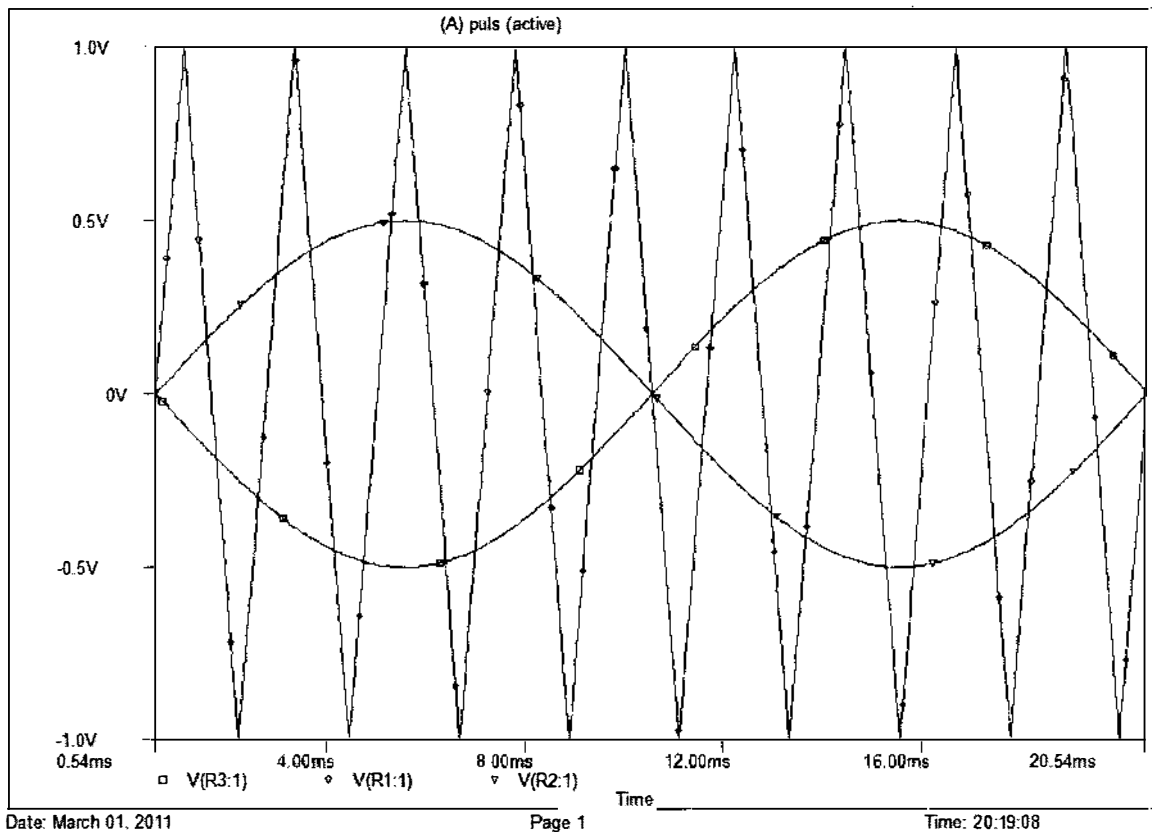
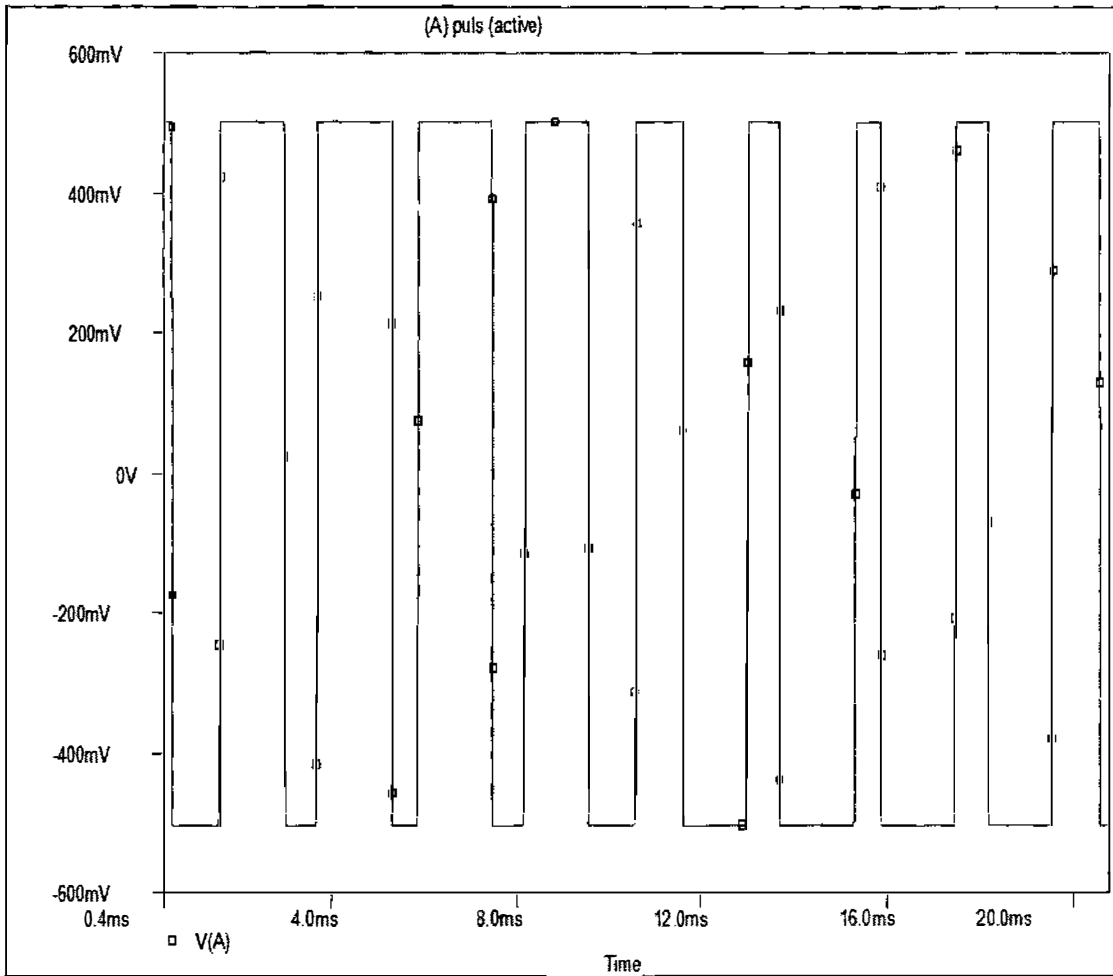


Figure 5.12: Plot of three waves in PSPICE for  $f_r=9$  &  $M=0.5$ . The plot of the figure 5.12 includes a sine wave phase of  $0^\circ$  &  $180^\circ$  shifted sine wave which will be compared with a triangular wave. The both sine wave have same amplitude of 0.5 volt & frequency of 50 Hz. The triangular wave has same amplitude of 1 volt but the frequency is 9 times of sine waves.



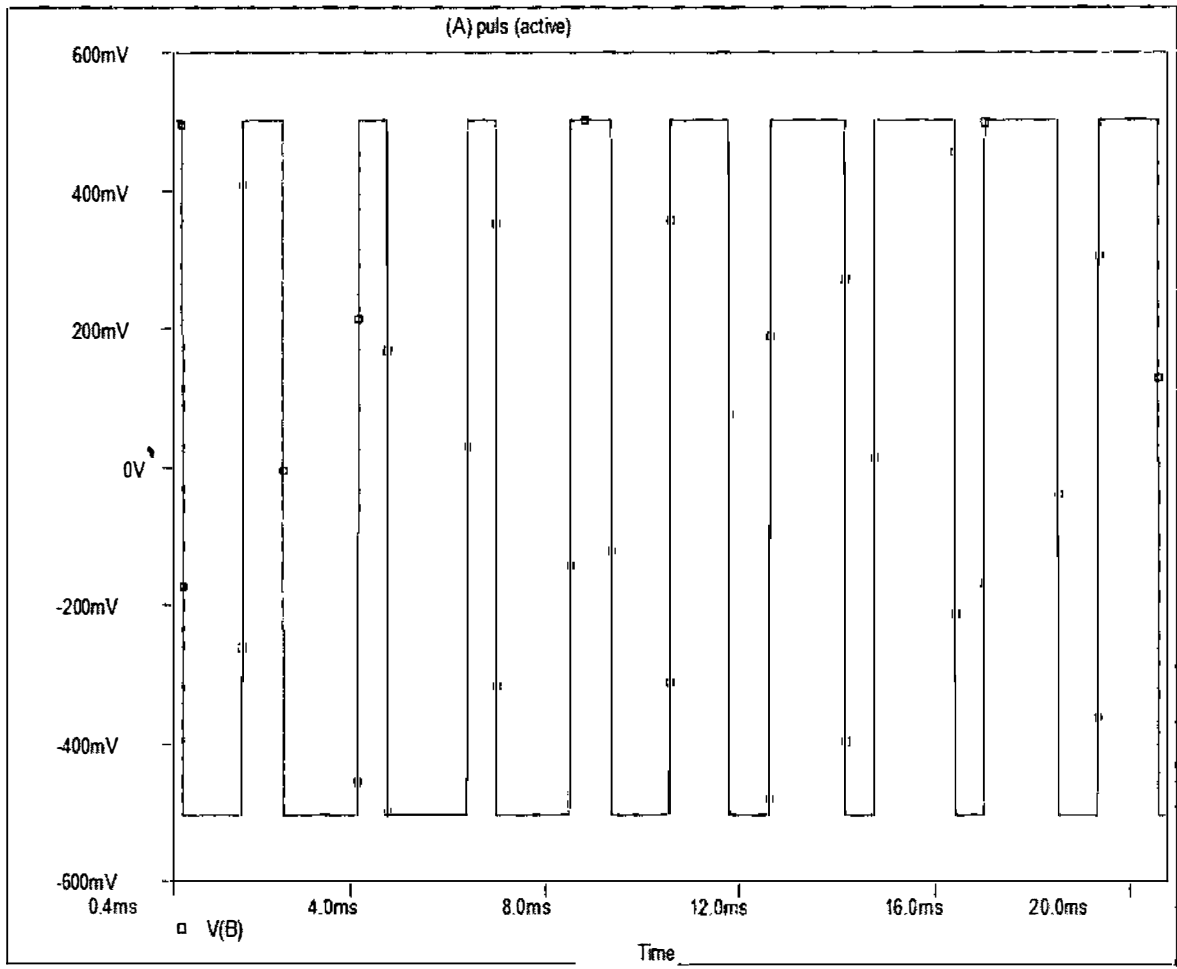


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Figure 5.13: Plot of  $V_a$  as  $V(A)$  in PSPICE for  $f_r=9$  &  $M=0.5$ . The signal of the figure 5.13 is found after comparing the  $0^\circ$  sine wave & the triangular wave i.e. it's  $V(A)$  which was previously denoted as  $V_a$  in MATLAB.



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Figure 5.14: Plot of  $V_b$  as  $V(B)$  in PSPICE for  $f_r=9$  &  $M=0.5$ . The signal of the figure 5.14 is found after comparing the  $180^\circ$  phase shifted sine wave & the triangular wave i.e. it's  $V(B)$  which was previously denoted as  $V_b$  in MATLAB.

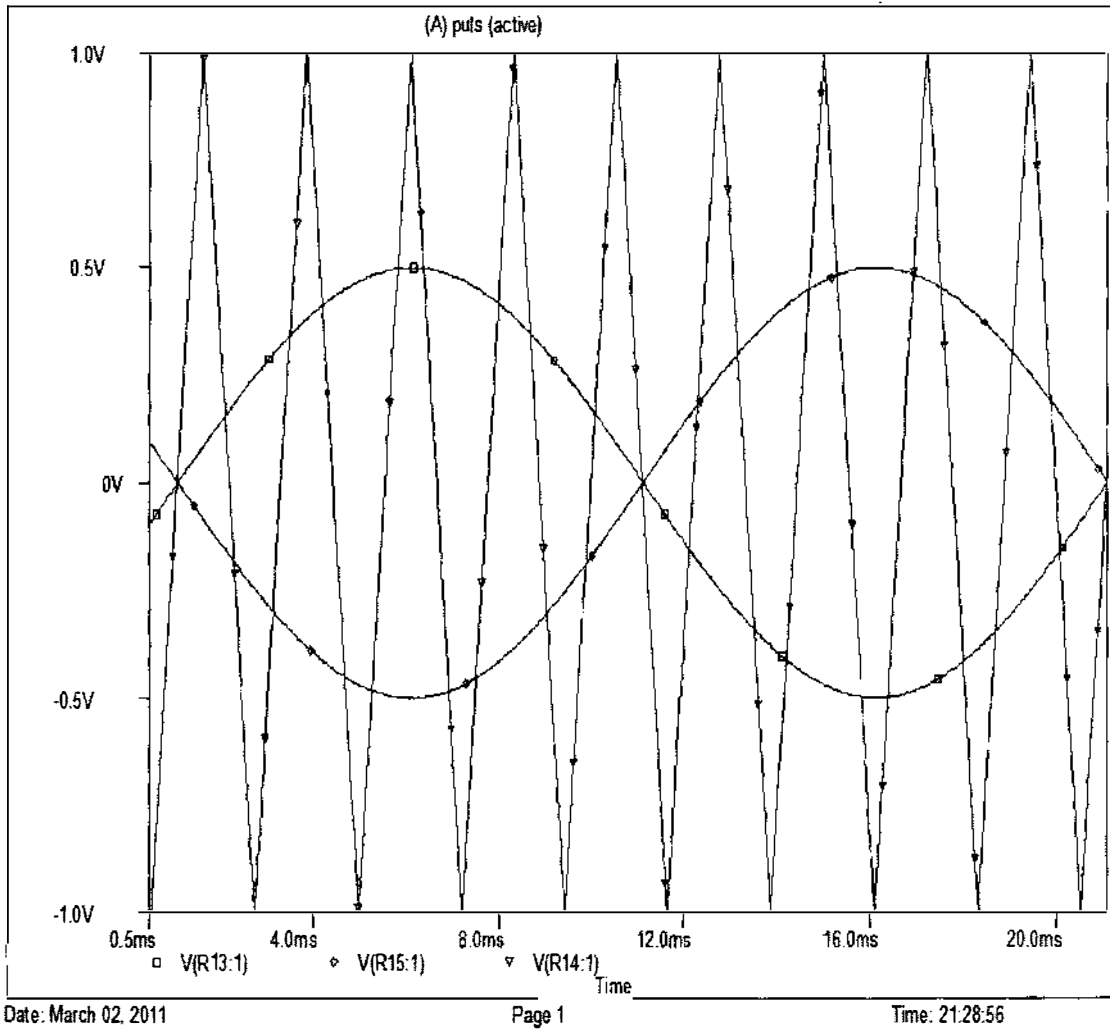
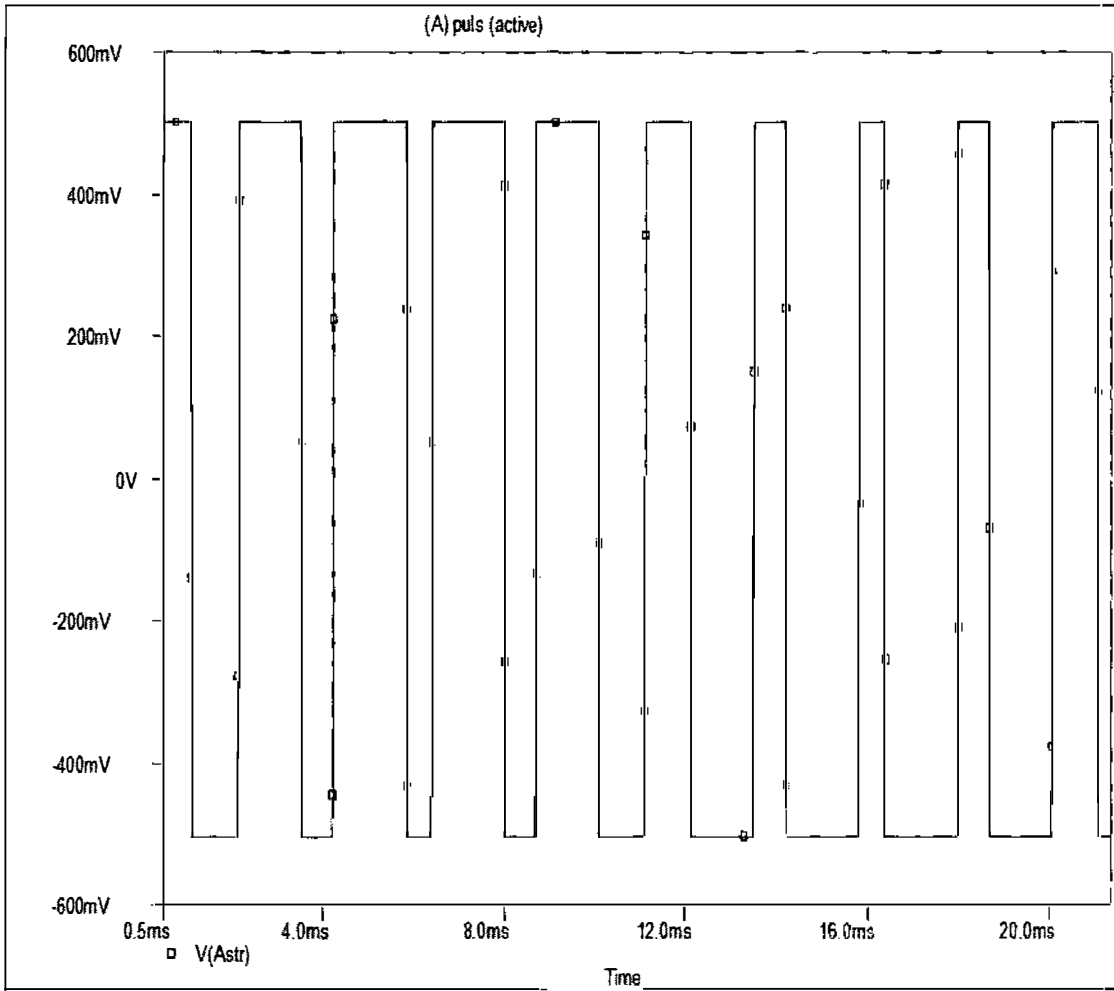


Figure 5.15: Plot of  $10^\circ$  phase right shifted three waves in PSpice for  $f_r=9$  &  $M=0.5$ . The plot of the figure 5.15 shows the three waves i.e. two sine waves & a triangular wave which is  $0^\circ$  right shifted from the signal of Figure 5.12. Here  $\theta=(90^\circ/f_r)=10^\circ$  where  $f_r=9$ .





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Figure 5.16: Plot of  $V_a^*$  as V(Astr) in PSPICE for  $f_r=9$  &  $M=0.5$ . The plot of the figure 5.16 shows  $10^\circ$  phase right shifted signal from the signal shown in fig 5.13 i.e. V(Astr) which was previously denoted as  $V_a^*$  in MATLAB.

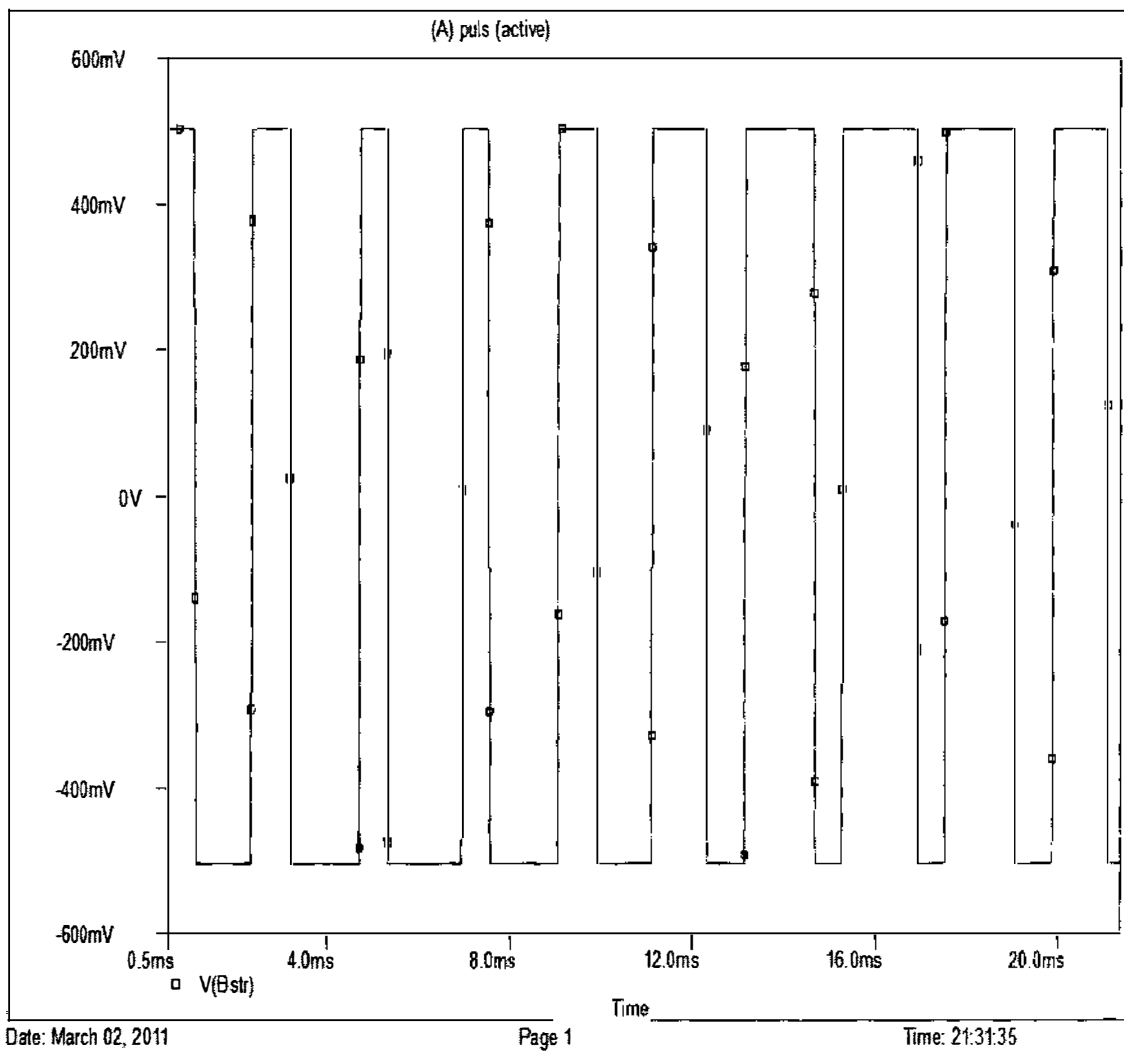
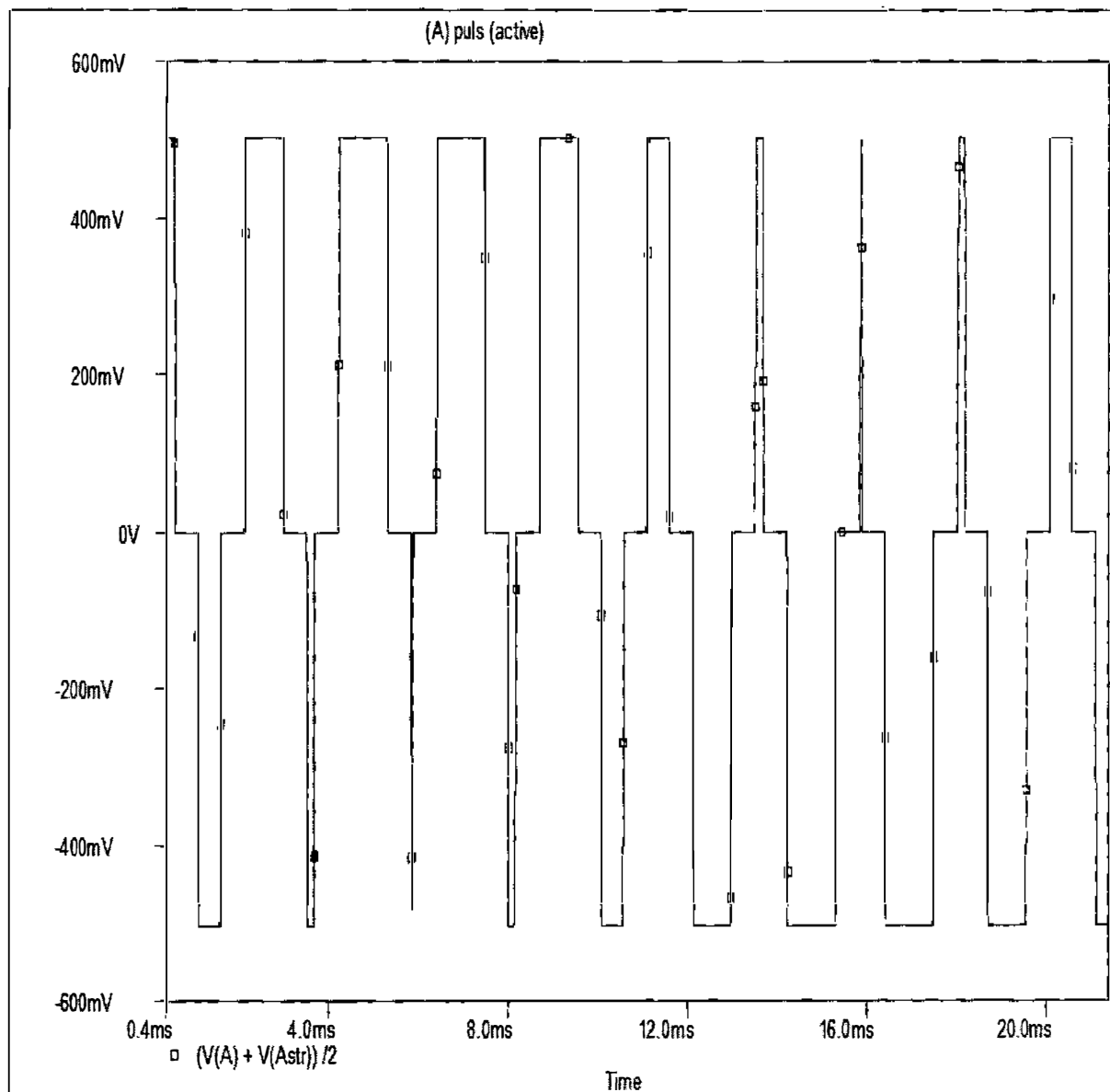


Figure 5.17: Plot of  $V_b^*$  as V(Bstr) in PSPICE for  $f_r=9$  &  $M=0.5$ . The plot of the figure 5.17 shows  $10^\circ$  phase right shifted signal from the signal shown in fig 5.14 i.e. V(Bstr) which was previously denoted as  $V_b^*$  in MATLAB.

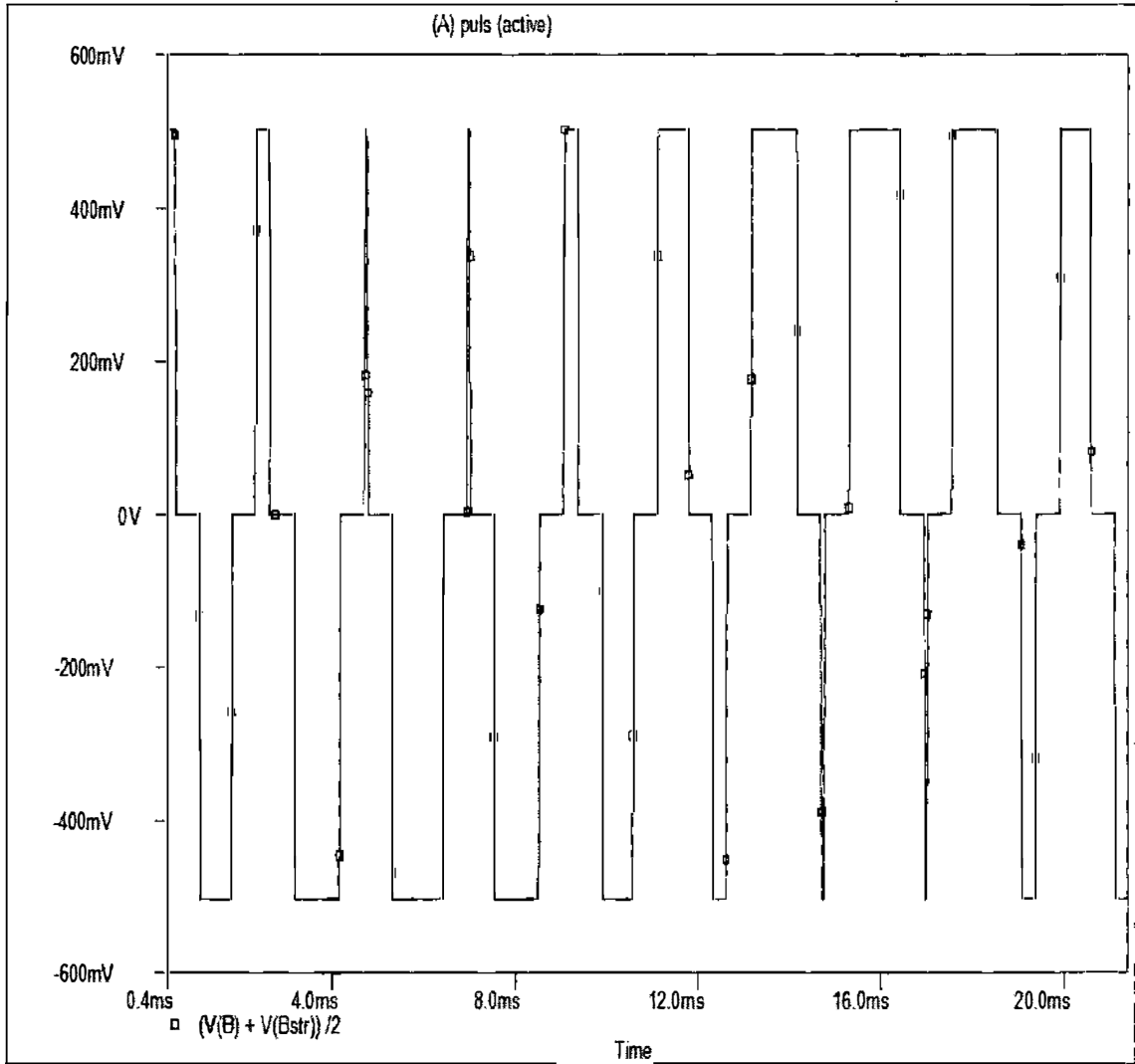


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Figure 5.18: Plot of  $V_r$  as  $(V(A) \& V(Astr))/2$  in PSPICE for  $f_r=9$  &  $M=0.5$ . The signal of the figure 5.18 is found after adding the signal of fig 5.13 & fig 5.16 then dividing by 2 i.e.  $(V(A) \& V(Astr))/2$  which was previously denoted as  $V_r$  in MATLAB & where  $V_r = (V_a + V_a^*)/2$ .



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Figure 5.19: Plot of  $V_s$  as  $(V(B) \& V(Bstr))/2$  in PSPICE for  $f_r=9$  &  $M=0.5$ . The signal of the figure 5.19 is found after adding the signal of fig 5.14 & fig 5.17 then dividing by 2 i.e.  $(V(B) \& V(Bstr))/2$  which was previously denoted as  $V_s$  in MATLAB & where  $V_s = (V_b + V_b^*)/2$ .

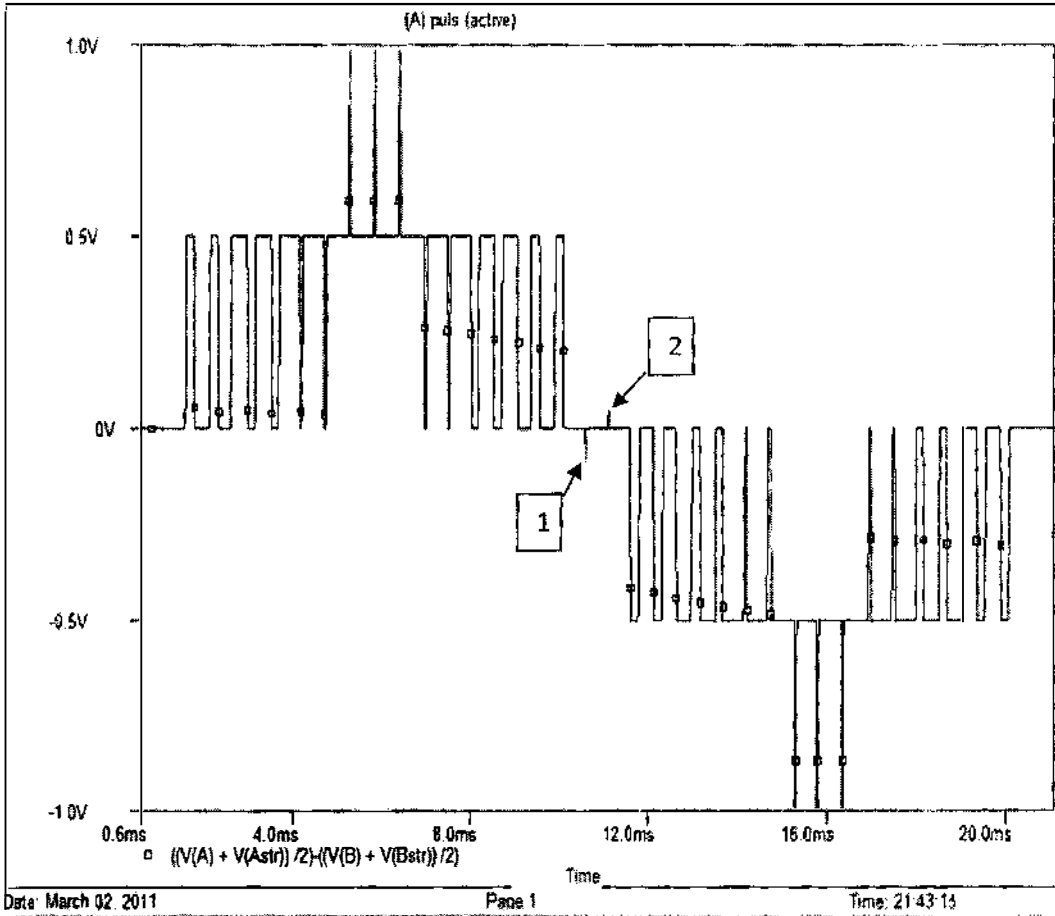


Figure 5.20: Plot of final output  $V_o$  as  $((V(A) + V(Astr))/2) - ((V(B) + V(Bstr))/2)$  in PSPICE for  $f_r=9$  &  $M=0.5$ . The plot of the figure 5.20 shows the final output. This signal is found by subtracting from the signals of fig 5.18 to the signal of fig 5.19 i.e.  $((V(A) + V(Astr))/2) - ((V(B) + V(Bstr))/2)$  which is previously denoted as  $V_o$  where  $V_o = V_r - V_s$ . This output is very similar to the output of the MATLAB but has two theoretically undesired small spikes (indicated by arrows).



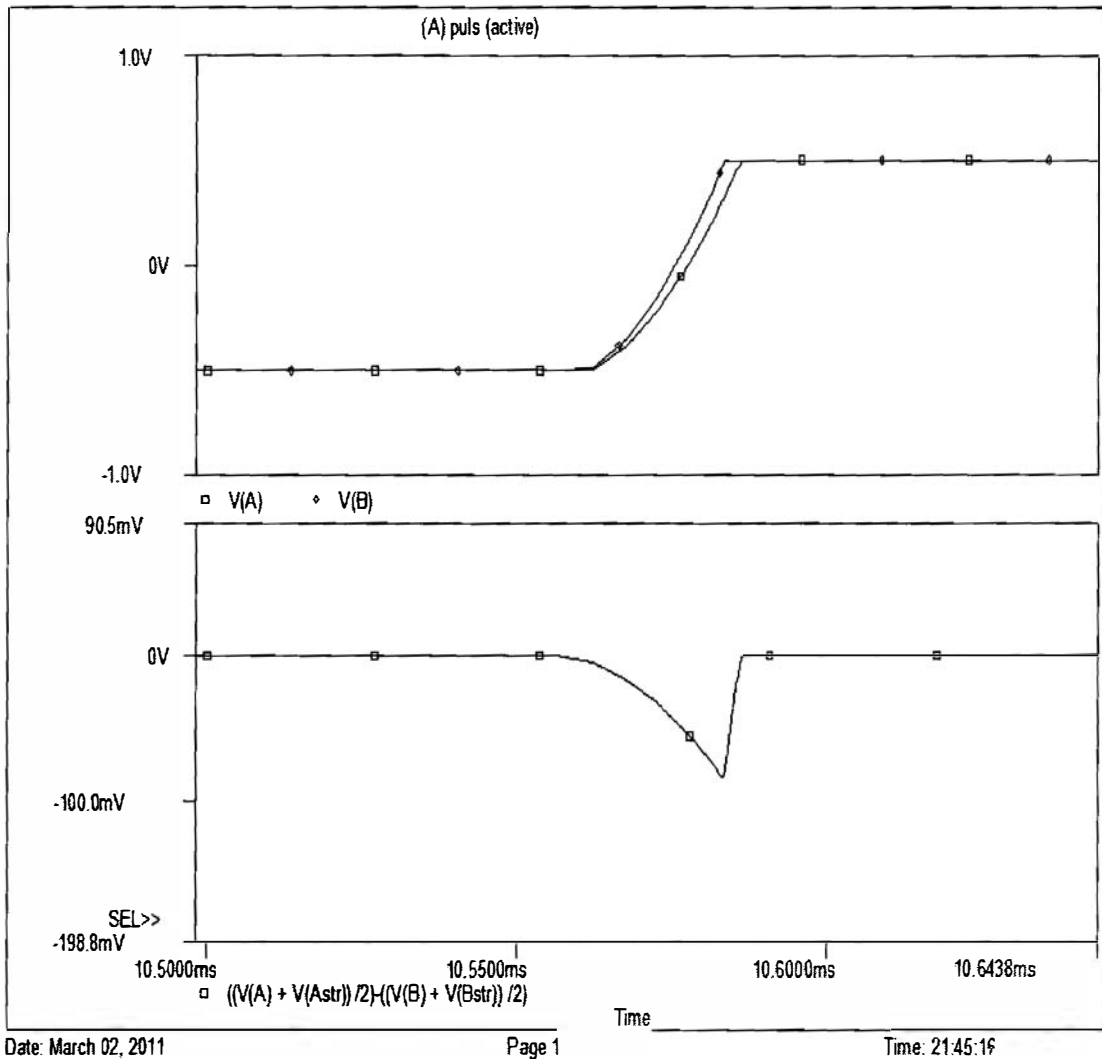


Figure 5.21: Zoomed plot at where the 1<sup>st</sup> spike occurs in PSPICE for  $f_r=9$  &  $M=0.5$ . It is clearly seen from the upper plot of the figure 5.21, the two signals are not rising at a same time but theoretically these two signals should rise with a same race & time i.e. there shouldn't be any time gap at this stage.



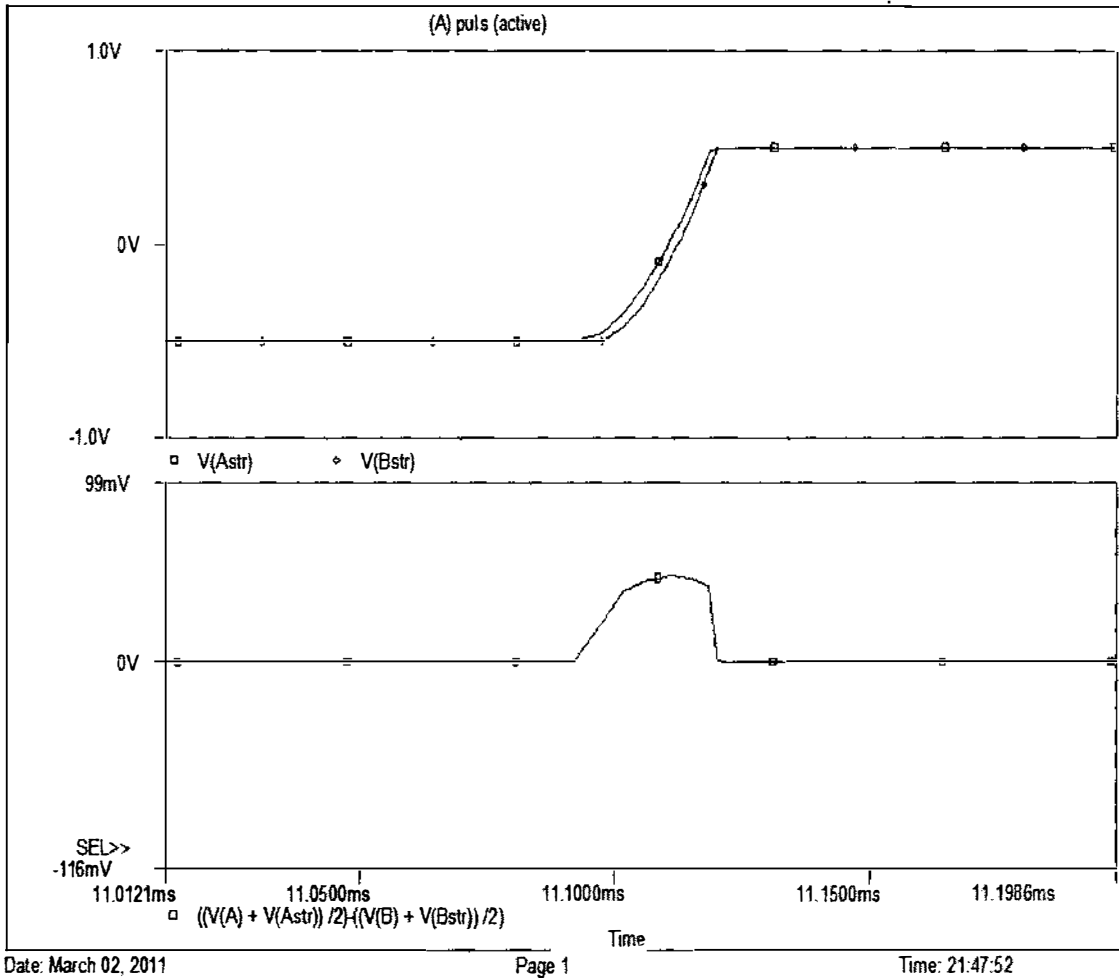


Figure 5.22: Zoomed plot at where the 2<sup>nd</sup> spike occurs in PSPICE for  $f_r=9$  &  $M=0.5$ . It is clearly seen from the upper plot of the figure 5.22, the two signals are not rising at a same time but theoretically these two signals should rise with a same race & time.

This type of problem is very common & usual problem for the practical circuits because the practical ICs may not be identical. But in software simulation it shouldn't occur because the ICs are from the same library.

The explanation of these small spikes was not found because of time limitation. It may occur because of a mismatch issue of ICs although the ICs are used from the same PSPICE library. So finding out the correct reason behind this problem is suggested as a future work.

## CHAPTER VI

### CONCLUSION & RECOMMENDATIONS FOR FURTHER WORK

#### 6.1 CONCLUSION

It is difficult to get pure sinusoidal AC voltage from a DC voltage because of the presence of harmonics. This is an important issue as it causes difficulties in many ways. Lot of analysis are done to get rid of these harmonics in different types of inverters. This thesis investigates the parallel operation and Sinusoidal pulse width modulation (SPWM) technique to reduce harmonics from output voltage of single phase inverter. The analysis is done by both MATLAB and PSPICE. The effect of phase difference of two parallel bridges on harmonic components is investigated. Effect of changing Frequency ratio ( $f_r$ ) and Modulation depth (M) are investigated also.

The main concern of the investigation is to have control over harmonic components by observing their variation with change in parameters:  $\theta$ ,  $f_r$  and M. For a defined frequency ratio  $f_r$  the best shifting angle  $\theta$  is found. In MATLAB  $f_r$  and M are varied against the harmonic order and it is seen that with the increase of  $f_r$  more harmonic components become eliminated. In case of M the best output considering value of fundamental and other harmonic components is found when its value is 1. With the known best value of  $\theta$  (for a fixed  $f_r$ ) a circuit is designed in PSPICE using VSIN, VPULSE and uA771 op-amp ICs. Then the circuit is simulated and compared with outputs of MATLAB. The main finding of this thesis is the equation relating different harmonic components for different values of  $f_r$ . In practical applications all harmonics may not affect the output of a particular application. By this equation a designer can easily choose the suitable value of  $f_r$  to eliminate up to particular harmonic order for a particular application.

## **6.2 RECOMMENDATIONS FOR FURTHER WORK**

Throughout the thesis analysis is done by using MATLAB and PSPICE software. The conclusions drawn are depending on the simulation results. So it can be practically implemented to verify the theoretical outcomes.

In PSPICE simulation some undesired spikes in output voltage are found, which are not present in MATLAB outputs. More analysis can be done on the origin of these spikes.

## REFERENCE

1. B. K. Bose, "Power Electronics and Motion Control – Technology Status and Recent Trends," IEEE Trans. Ind. Appl., vol-29, No.5, September/October 1993.
2. M. H. Rashid. "Power Electronics" Pearson Education Pte. Ltd, Singapore, 2004 3<sup>rd</sup> edition.
3. [http://www.daviddarling.info/encyclopedia/S/AE\\_square\\_wave\\_inverter.html](http://www.daviddarling.info/encyclopedia/S/AE_square_wave_inverter.html)
4. <http://www.webanswers.com/science/engineering/what-is-the-use-advantages-disadvantages-square-wave-and-sine-wave-inverters-0ac550>
5. [http://www.samlexamerica.com/customer\\_support/faq\\_02.htm](http://www.samlexamerica.com/customer_support/faq_02.htm)
6. <http://www.atares.co.uk/glossary%20quasi%20sine.htm>
7. <http://www.energyalternatives.ca/SystemDesign/inverters1.html>
8. R. Kumar, "Programmed Harmonic Reduction In Single Phase A Three Phase Voltage-Source Inverters," M.sc Thesis, Ohio University, pp1-76, August 1996.
9. T. M. Gruz, "A Survey of Neutral Currents in Three- Phase Computer Power systems," IEEE Trans Ind. Appl., Vol. 26, No. 4, pp. 719-715, July 1990.
10. [http://ecmweb.com/powerquality/electric\\_harmonics\\_made\\_simple/](http://ecmweb.com/powerquality/electric_harmonics_made_simple/) Date of visit 27-02-2011
11. The Electric Online <http://tjaroonline.blogspot.com/p/harmonic-reduction.html>
12. PTD design. [www.motionsystemdesign.com](http://www.motionsystemdesign.com) , October 2000
13. F. C. Zach, R. Martinez, S. Keplinger, and A. Selser, "Dynamically Optimal Switching Patterns for PWM inverters Drives (for minimization of torque and speed ripple)," IEEE Trans. Ind. Appl., vol. IA-21, No. 4, pp.975-986, July/Aug. 1985
14. P. N. Enjeti, P. D. Ziogas and J. F. Lindsay, "Programmed PWM Techniques to Eliminate Harmonics: A Critical Evaluation," IEEE Trans. Ind. Appl., Vol. 26 No.2, pp. 302-316, March/April 1990
15. A. M. Kamel and T. H. Ortmeier, "Harmonic reduction in single-phase inverter using a parallel operation technique," /IEEE Applied Power Electronics Conference/, pp. 101-108, 1989.
16. H. Braga and I. Barbi, "A new technique for parallel connection of commutation cells: Analysis, design and experimentation" in *Proc.PESC '95*, pp. 81–87

17. <http://www.answers.com/topic/interphase-reactor>
18. [http://books.google.com/books?id=mRC5z7yOeT0C&pg=PA127&lpg=PA127&dq=what+is+current+sharing+reactor&source=bl&ots=lQwV-XjaMI&sig=-qmoWnBrMopjWn65nKJvHJL\\_sLg&hl=en&ei=mCuOTZroC46fOuab!KEC&sa=X&oi=book\\_result&ct=result&resnum=4&sqi=2&ved=0CDsQ6AEwAw#v=onepage&q=what%20is%20current%20sharing%20reactor&f=false](http://books.google.com/books?id=mRC5z7yOeT0C&pg=PA127&lpg=PA127&dq=what+is+current+sharing+reactor&source=bl&ots=lQwV-XjaMI&sig=-qmoWnBrMopjWn65nKJvHJL_sLg&hl=en&ei=mCuOTZroC46fOuab!KEC&sa=X&oi=book_result&ct=result&resnum=4&sqi=2&ved=0CDsQ6AEwAw#v=onepage&q=what%20is%20current%20sharing%20reactor&f=false)
19. P. Xiao, K. A. Corzine, and G. K. Venayagamoorthy, "A novel sevenlevelshunt active filter for high-power drive systems," in *Proc. IEEE Ind. Electron. Soc. Conf.*, Paris, France, Nov. 2006, pp. 2262–2267.

