SIMULATION AND COMPARISON OF THREE PHASE PULSE WIDTH MODULATED INVERTERS AND REDUCTION OF TOTAL HARMONIC DISTORTION

Sriram Karakana
Assistant Professor, Department of EEE
MVGR College of Engineering (A), Vizianagaram, Andhra Pradesh, India.

Abstract

In the present era with the advancements in solid-state electronics, the use of power electronic devices is playing a vital role in control and conversion of electrical power. These devices are non-linear in nature which accumulated enough space in all the regions of electrical systems. Inverters are playing a major role in industrial and household purposes for converting the direct current power into an alternating current power. Usage of these power electronic devices in inverters is giving a smooth and precise control over conversion of electric power. But on the other hand, usage of these results in the increased level of Total Harmonic Distortion (THD) which has adverse effects on the overall system performance. This paper aims at the reduction of THD for three-phase voltage source inverters by implementing Pulse Width Modulation (PWM) switching techniques. This paper discusses the merits and demerits of two distinct PWM techniques namely the sinusoidal Pulse Width Modulation (SPWM) technique and the third-harmonic- injection Pulse Width Modulation (THIPWM) technique. These two techniques are analyzed and compared by their harmonic spectra of the output voltage and their total harmonic distortion (THD). With an addition to this, this report also discusses three phase inverter with 180 degrees conduction mode. An RL-C filter is also designed in order to filter out the harmonics and to reduce the total harmonic distortion (THD). The models for three-phase inverter with different PWM switching techniques have been simulated using MATLAB Simulink.

Keywords: Harmonics, Total Harmonic Distortion (THD), Pulse Width Modulation(PWM), SPWM, THIPWM.

I. INTRODUCTION

In present days, an electric power converter plays a vital role in industries and power sector. Power converters like, Rectifiers are used for conversion of AC power into DC power; Inverters are used for conversion of DC power into AC power; AC voltage controllers/Cyclo-converters are used for conversion of fixed AC into variable AC with variation in both magnitude/frequency; Choppers are used for converting fixed DC into variable DC. Among these converters, this paper shows focus towards inverters which finds a huge application in industries and household purposes. Usually, an inverter gives a square wave output for given dc input. To make the output sinusoidal, certain techniques are present and some of them have been implemented in this paper. Inverters can be built either by using uncontrolled switches like diodes or controlled switches like SCR’s, MOSFET’s and IGBT’s etc. But to get a variable ac output, it is mandatory to use the controlled switches in inverters. Since these devices are nonlinear in nature, they involve disturbances called harmonics in the sinusoidal waveform. Harmonics are the multiples of fundamental frequency. For example, if fundamental frequency is 50Hz, then the second harmonic will be (2x50) 100Hz; third harmonic will be (3x50) 150Hz and so on. These harmonics will cause several disadvantages in power system like increasing of current, high losses, heating of the equipment and torque pulsations etc. Therefore the reduction of harmonics is compulsory to run the electrical systems smoothly and efficiently. These harmonics are cumulatively leads to a distortion called as Total Harmonic Distortion abbreviated as THD. The THD of a signal is defined as the ratio of the sum of the powers of all individual harmonic components to the power of the fundamental frequency.

$$\mathrm{THD_F} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}$$

THD is used to characterize the power quality of electric power systems. Less the THD, the waveform will be more the sinusoidal. Reduction of THD in inverters can be accomplished by one of the methodologies called pulse width modulation (PWM) switching techniques.

II. PULSE WIDTH MODULATION

Pulse-width modulation (PWM) is a technique where the duty ratio of a pulsating wave-form is controlled by another input waveform. The intersections between the reference voltage waveform and the carrier waveform give the opening and closing times of the switches. The main object of using PWM techniques as switching to inverters is that they result in the decrease of lower order harmonics at the output and increment in higher order harmonics which can be filtered easily by using a low pass filters. This is the major advantage in using PWM techniques for switching purpose. Other than this, there is another advantage in implementing PWM techniques is that there is a scope of getting controllability on output voltage. With regard of both these considerations PWM techniques are widely used for inverters as switching techniques. Pulse-width modulation (PWM) is a technique which is used to control the output of a converter as per requirement. The ON and OFF periods of a controlled switch can be easily changed by adjusting the width of the pulses. Switch turns ON, when the magnitude of reference signal is greater than the carrier signal, and turns OFF when carrier is greater than reference. The width of the pulses can be changed by varying the modulation index. In the other part, PWM switching generates electromagnetic noise as well as voltage spikes. This calls for special measures like filtering, shielding, and the use of spike-hardened components. This is the major drawback.

PWM is a technique which is used to change the output parameters by changing the width of the pulses. The width of the pulses is changing by varying the modulation index. If the magnitude of reference signal is greater than the carrier signal, it gives positive pulse and the condition is violated, it gives zero pulse. The below fig 2.1 describes the PWM pulse generation.

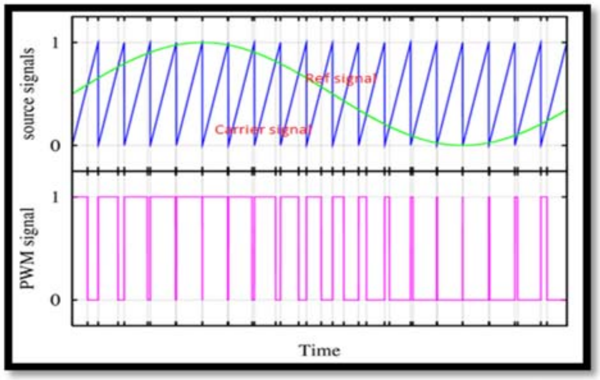


Fig 2.1 Pulse Generation

The amplitude modulation index is given by $m_a = V_{control}/V_{tri}$

Where $V_{control}$ represents the amplitude of the control signal, and V_{tri} represents the amplitude of the triangle signal (carrier). Also the frequency modulation index is the ratio of carrier frequency and control frequency. i.e. $m_f = f_{tri} / f_{control}$.

III. CLASSIFICATION OF PWM TECHNIQUES

Based on switching frequency and type of carrier signal, there are several types of PWM techniques. They are Sinusoidal wave PWM technique; Square wave PWM technique; Triangular wave PWM technique; Trapezoidal wave PWM technique; Third Harmonic Injection PWM; Space Vector PWM technique and etc.

This paper shows focus towards PWM techniques namely the sinusoidal Pulse Width Modulation (SPWM) technique and the third-harmonic- injection Pulse Width Modulation (THIPWM) technique.

A. *Sinusoidal Pulse Width Modulation (SPWM):*

In three-phase Sinusoidal Pulse Width Modulation (SPWM), a triangular voltage waveform (V_T) is compared with three sinusoidal control voltages (V_a, V_b, and V_c), which are 120^0 out of phase with each other and the pulses come out of the comparison are used to control the switching of the devices in each leg of the inverter.

A six-step inverter is composed of six switches S_1 through S_6 with each phase output connected to the middle of each inverter leg as shown in Figure-3.1.

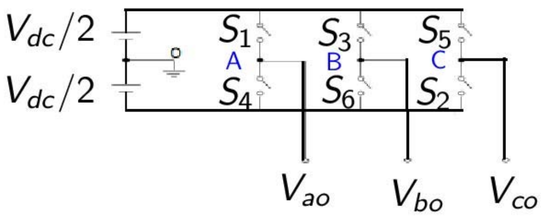


Fig 3.1 Three-Phase Sinusoidal PWM Inverter

The outputs of the comparators in Figure-3.2 form the control signals for the three legs of the inverter.

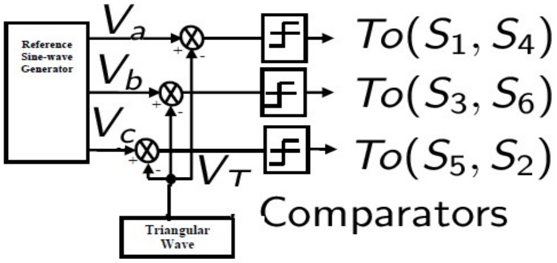


Fig 3.2 Control Signal Generator for SPWM

Two switches in each phase make up one leg and open and close in a complementary fashion. That is, when one switch is open, the other is closed and vice-versa. The output pole voltages V_{ao}, V_{bo}, and V_{co} of the inverter switch between $-V_{dc}/2$ and $+V_{dc}/2$ voltage levels where V_{dc} is the total DC voltage. The peak of the sine modulating waveform is always less than the peak of the triangle carrier voltage waveform. When the sinusoidal waveform is greater than the triangular waveform, the upper switch is turned on and the lower switch is turned off. Similarly, when the sinusoidal waveform is less than the triangular waveform, the upper switch is off and the lower switch is on. Depending on the switching states, either the positive or negative half DC bus voltage is applied to each phase. The switches are controlled in pairs ((S_1, S_4), (S_3, S_6), and (S_5, S_2)) and the logic for the switch control signals is

S_1 is ON when $V_a > V_T$
S_4 is ON when $V_a < V_T$
S_3 is ON when $V_b > V_T$
S_6 is ON when $V_b < V_T$
S_5 is ON when $V_c > V_T$
S_2 is ON when $V_c < V_T$

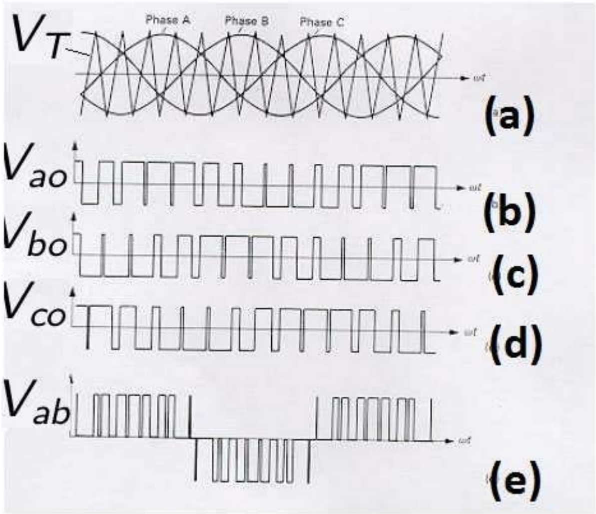


Fig 3.3 Three-Phase Sinusoidal PWM: a). Reference Voltages (a,b,c) and Triangular Wave b). V_{ao}, c) V_{bo}, d) V_{co} e) Line-to-Line Voltages

As seen in Figure-3.3, the pulse widths depend on the intersection of the triangular and sinusoidal waveforms. The inverter output voltages are determined as follows.

If $V_{ao} > V_T$, $V_{ao} = 0.5\ V_{dc}$; $V_{bo} > V_T$, $V_{bo} = 0.5\ V_{dc}$; $V_{co} > V_T$, $V_{co} = 0.5\ V_{dc}$

And if the amplitudes are as follows, then

$V_{ao} < V_T$, $V_{ao} = -0.5\ V_{dc}$; $V_{bo} < V_T$, $V_{bo} = -0.5\ V_{dc}$; $V_{co} < V_T$, $V_{co} = -0.5\ V_{dc}$

The inverter line-to-line voltages are obtained from the pole voltage $V_{ab} = V_{ao} - V_{bo}$; $V_{bc} = V_{bo} – V_{co}$; $V_{ca} = V_{co} – V_{ao}$.

B. *Third Harmonic Injection PWM (THIPWM):*

The sinusoidal PWM is the simplest modulation scheme to understand but it is unable to fully utilize the available DC bus supply voltage. Due to this problem, the third-harmonic injection pulse-width modulation (THIPWM) technique was developed to improve the inverter performance. Following Reference, consider a waveform consisting of a fundamental component with the addition of a triple-frequency term given as $y = \sin\theta + A\sin3\theta$. Where $\theta = wt$ and A is a parameter to be optimized while keeping the maximum amplitude of y(t) under unity. The maximum value of y(t) is found by setting its derivative with respect to q equal to zero.

Thus dy/dθ = cosθ+3Acos3θ = cosθ(12cos^2θ-(9A-1)) = 0

The maximum and minimum of the waveform therefore occur at cosθ = 0 and cosθ = $\left(\frac{9A-1}{12A}\right)^{\frac{1}{2}}$ By solving the equation, the two possible values of are A= -1/3 and A = 1/6. We can see that the negative value of A makes by greater than unity. Therefore, the only valid solution for A is 1/6 and the required waveform is Y = sinθ + 1/6(sin3θ). It is shown that the addition of a third harmonic with a peak magnitude of one sixth to the modulation waveform has the effect of reducing the peak value of the output waveform by a factor of √3/2 without changing the amplitude of the fundamental. It is possible to increase the amplitude of the modulating waveform by a factor K, so that the full output voltage range of the inverter is again utilized. If the modulating waveform is expressed as y = K(sinθ+1/6(sin3θ)). The required factor K for a peak value of unity should satisfy the constraint 1 = K√3/2 and therefore K = 2/√3.

Figure-3.4(a) does not have a third harmonic, only a peak value and amplitude of fundamental equal 1. The peak of Figure-3.4(b) is √3/2 with one-sixth of the third harmonic added. The amplitude of the fundamental equals 1. The peak amplitude in Figure-3.4(c) equals 1 while the peak amplitude of the fundamental equals 2/√3 with one-sixth of third harmonic added.

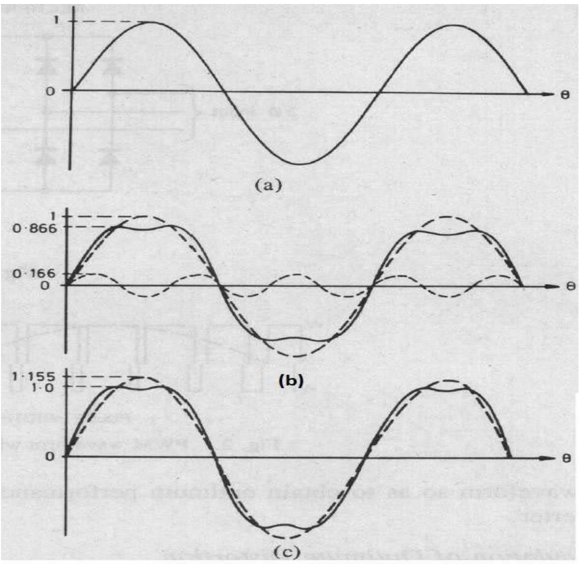


Fig 3.4 One Phase Third-Harmonic Injection PWM

Injecting a third harmonic component to the fundamental component gives the following modulating waveforms for the three-phase

Van = 2√3 (sin(wt)+1/6(sin3wt))

Vbn = 2√3 (sin(wt -2/√3)+1/6(sin3wt))

Vcn =2√3 (sin(wt +2/√3)+1/6(sin3wt))

The THIPWM is implemented in the same manner as the SPWM, that is, the reference waveforms are compared with a triangular waveform. As a result, the amplitude of the reference waveforms do not exceed the DC supply voltage V_{dc}=2, but the fundamental component is higher than the supply voltage V_{dc}. As mentioned above, this is approximately 15.5% higher in amplitude than the normal SPWM.

Consequently, it provides a better utilization of the DC supply voltage. The three reference voltages and triangular waveform of a three-phase THPWM produce the following output pole voltages V_{ao}, V_{bo} and V_{co} as shown in Figure-3.5.

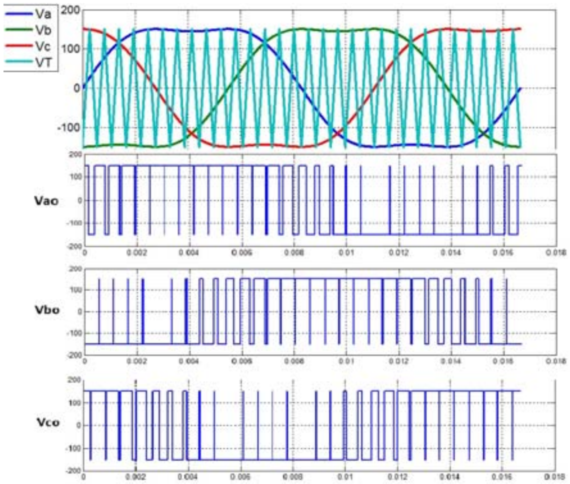


Fig 3.5 Reference Voltages (a,b,c),Triangular Waveforms (V_T), and Output Voltage (V_{ao}, V_{bo}, V_{co})

C. *Three phase 180 Degrees Conduction Mode:*

In the three phase inverter each SCR conducts for 180 degree of a cycle. Thyristor pair in each arm, i.e. T1, T4; T3, T6 and T5, T2 is turned on with a time interval of 180 degree. It means that T1 conducts for 180 degree and T4 for the next 180 degree of a cycle. Thyristors in the upper group, i.e. T1, T3, T5 conduct at an interval of 120 degree. It implies that if T1 is fired at then T3 must be fired at and T5 at. Same is true for lower groups of SCRs. On the basis of this firing scheme, a table ios prepared as shown. In this table, first row shows that T1 from upper group conducts for 180 degree, T4 for the next 180 degree and then again T1 for 180 degree and so on .In the second row, T3 from the upper group is shown to start conducting 120 degree after T1 starts conducting. after T3 conduction for 180 degree, T6 conducts for the next 180 degree and again T3 for the next 180 degree and so on .further in the third row, T5 from the upper group starts conducting 120 degree after T3 or 240 degree after T1.After T5 conduction for 180 degree, T2 conducts for next 180 degree, T5 for the next 180 degree and so on. In this manner the pattern of firing the six SCRs is identified .T5,T6,T1 should be gated for step 1;T6,T1,T2 for step 2; T1,T2,T3 for step3; T2,T3,T4 for step4 and so on .Thus the sequence of firing the Thyristors is T1,T2,T3,T4,T5,T6;T1,T2…..it is seen from the table that in every step of 60 degree duration, only three SCRs are conducting one from upper group and two from the lower group or two from upper group and one from the lower group. The line voltages waveforms shown in figure-3.6 and it represents a balanced set of three phase alternating voltages .During the six intervals, these voltages are well defined. Therefore, these voltages are independent of the nature of load circuit which may consists of any combination of resistance, inductance, and capacitance and the load may be balanced or unbalanced, linear or non-linear.

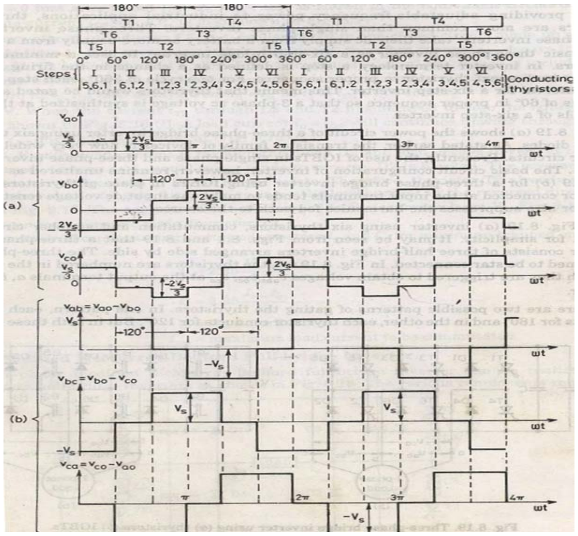


Fig 3.6 Voltage Waveforms for 180degree mode 3-ø inverter

IV. PASSIVE FILTER

Basically a filter is a device which is used to filter the unwanted components in a wave so as to improve the power quality and system performance. The filters are of various types and here for our requirement while using pulse width modulation techniques for the inverters a passive filter will meet the requirement of eliminating the high order harmonic components from the obtained waveforms. A passive filter comprises of only passive elements (resistance, inductance &capacitance) and we have chosen a RLC filter in which an resistor, inductor connected in series and capacitor connected in parallel with the load. The designed filter should remove all the harmonics ie other than fundamental component.

4.1 DESIGN OF FILTER:

Final transfer function of RLC circuit = $\frac{\frac{1}{LC}}{s^2+\frac{R}{L}s+\frac{1}{LC}}$

Comparing with the equation, $\frac{{\omega_n}^2}{s^2+2\varepsilon\omega_n s+\omega_n^2}$

$2\varepsilon\omega_n s = \frac{R}{L}s$ And $2\varepsilon\omega_n = \frac{R}{L}$ (1)

Also we have,

$Q = \frac{1}{2\varepsilon}$ (2)

$Q = \frac{\omega L}{R}$ (3)

And $\omega = 2\pi f$ (4)

Assume $Q = 1$ and substitute in equation (2)

$1 = \frac{1}{2\varepsilon} \Rightarrow 2\varepsilon = 1 \Rightarrow \varepsilon = 0.5$

Taking f=100 hz

$f = \frac{1}{2\pi\sqrt{LC}}$ (5)

Taking c=100 $\mu F$and substitute in (5)

$100 = \frac{1}{2\pi\sqrt{L*220\mu F}}$

$L = 0.0115\ H$

Also,$\omega_n^2 = \frac{1}{LC} \Rightarrow \omega_n = \sqrt{\frac{1}{LC}}$

= 628.69 rad/sec

Substitute ϵ, ω_n & L values in (1)

We get, $2 * 0.5 * 628.69 = \frac{R}{0.0115}$

So R= 7.23 ohm for filter design obtained.

V. SIMULATIONS AND RESULTS

5.1 THREE-PHASE INVERTER WITH 180 DEGREE CONDUCTION MODE:

Circuit diagram and simulation results of 180 degree conduction mode are shown in figures 5.1 to 5.4. In order to reduce the THD value filter is used. The output voltage and THD values obtained without filter are 110.3v and 31.08%. And the output line-line voltage and THD values obtained with filter are 104.2v and 3.99%. But by using 180 degree conduction mode the output is not controllable, so we use PWM techniques to get controllability.

5.1.1 THREE PHASE INVERTER-180 DEGREE CONDUCTION MODE WITHOUT FILTER:

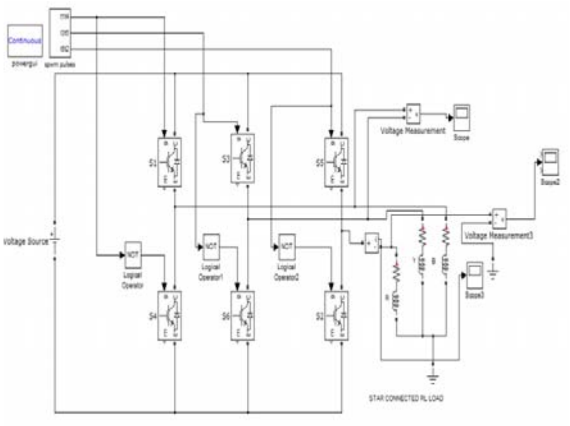


Fig 5.1 Circuit Diagram of 180 Degree Conduction Mode without Filter

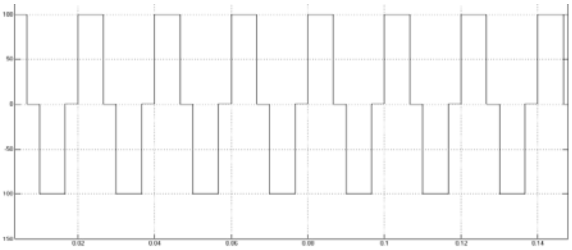


Fig 5.2 Output Line-Line Voltage Waveform of 180 Degree Conduction Mode without Filter

5.1.2 THREE PHASE INVERTER-180 DEGREE CONDUCTION MODE WITH FILTER

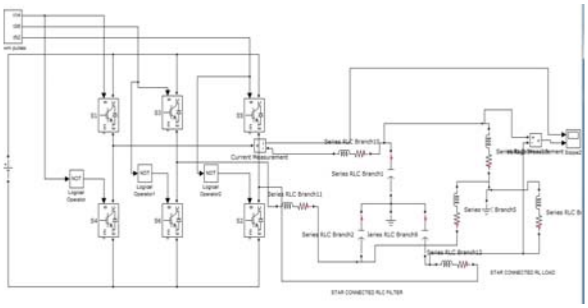


Fig 5.3 Circuit Diagram of 180 Degree Conduction Mode with Filter

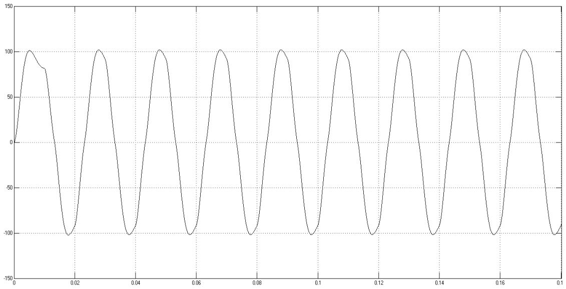


Fig 5.4 Output Line-Line Voltage Waveform of 180 Degree Conduction Mode with Filter

5.2 THREE-PHASE INVERTER WITH SINUSOIDAL PWM TECHNIQUE (SPWM):

Circuit diagram and simulation results of 3 phase sinusoidal PWM technique are shown in figures 5.5-5.9. The output line-line voltage and THD values obtained without using filter are 86.58v and 68.58%. By using a suitable filter THD can be reduced to 0.44% and the output line-line voltage is 81.48v. But by using this method the DC bus voltage is reduced, which can be improved by using third harmonic injection method.

5.2.1 THREE-PHASE SINUSOIDAL PWM INVERTER WITHOUT FILTER:

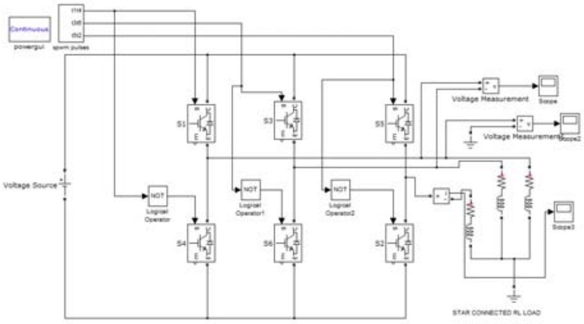


Fig 5.5 Circuit Diagram of 3-Phase Sinusoidal PWM Inverter without Filter

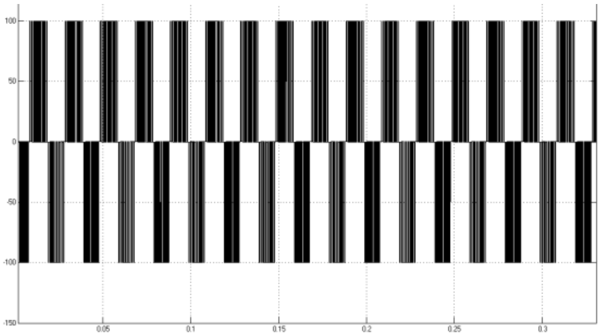


Fig 5.6 Output Line-Line Voltage of 3-Phase Sinusoidal PWM Inverter without Filter

5.2.2 THREE-PHASE SINUSOIDAL PWM INVERTER WITH FILTER:

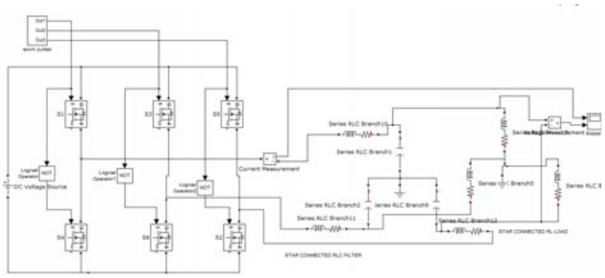


Fig 5.7 Circuit Diagram of 3-Phase Sinusoidal PWM Inverter with Filter

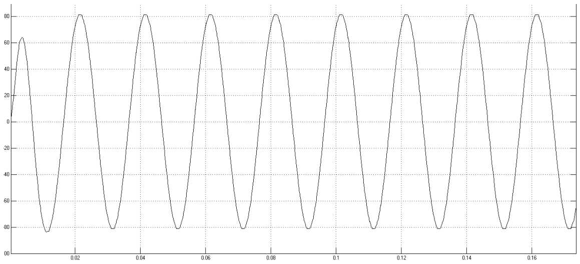
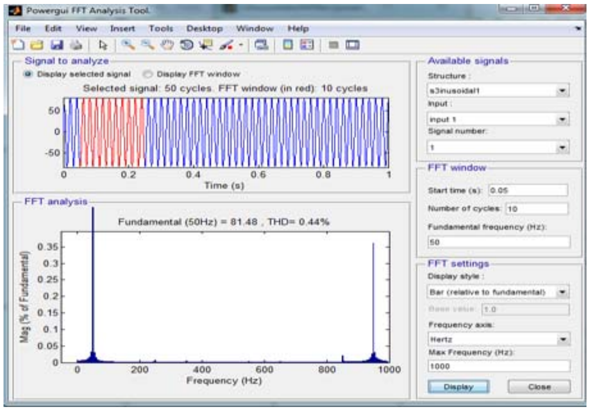


Fig 5.8 Output Line-Line Voltage of 3 Phase SPWM Inverter with Filter



● Display selected signal ○ Display FFT window

Selected signal: 50 cycles. FFT window (in red): 10 cycles

Fundamental (50Hz) = 81.48 , THD= 0.44%

Structure : s3inusoidal1

Input : input 1

Signal number: 1

Start time (s): 0.05

Number of cycles: 10

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig 5.9 Harmonic Spectra of 3 Phase SPWM Inverter with Filter

5.3 THREE-PHASE INVERTER WITH THIRD HARMONIC INJECTION METHOD (THIPWM):

MATLAB schematic diagrams for both SPWM and THIPWM are similar for with/without filter. Only difference is that, the third harmonic content is added to the fundamental and applied to pulse generating block. The simulation results of 3 phase third harmonic injection method are shown in figures 5.10-5.12. The output voltage and THD values obtained without using filter are 97.08v and 56.38%. By using filter the THD is decreased to 0.45% and the output line- line voltage is 94.39V.

5.3.1 THREE-PHASE INVERTER WITH THIRD HARMONIC INJECTION WITHOUT FILTER

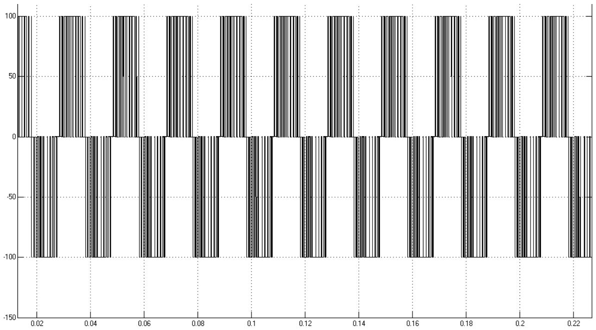


Fig 5.10 Output Line-Line Voltage of 3 Phase Third Harmonic Injection PWM Inverter without Filter

5.3.2 THREE-PHASE INVERTER WITH THIRD HARMONIC INJECTION WITH FILTER

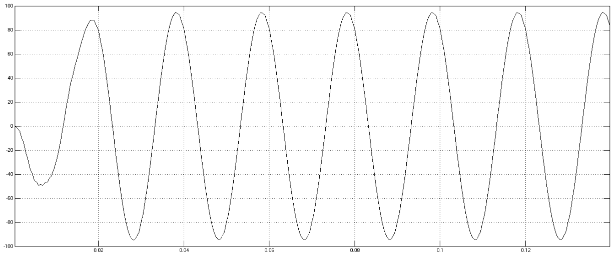
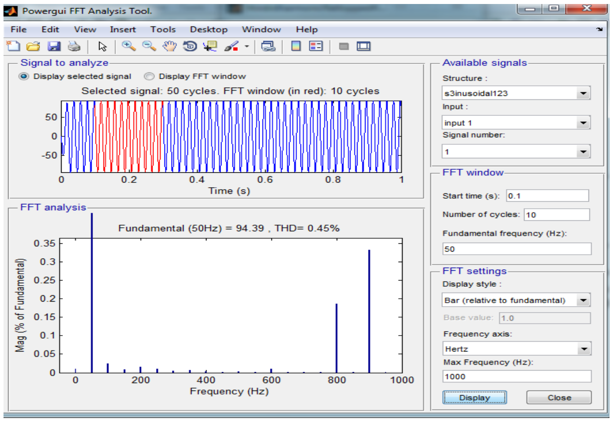


Fig 5.11 Output Line-Line Voltage of 3 Phase Third Harmonic Injection PWM Inverter with Filter



● Display selected signal ○ Display FFT window

Selected signal: 50 cycles. FFT window (in red): 10 cycles

Fundamental (50Hz) = 94.39 , THD= 0.45%

Structure : s3inusoidal123

Input : input 1

Signal number: 1

Start time (s): 0.1

Number of cycles: 10

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig 5.12 Harmonic Spectra of 3 Phase Third Harmonic Injection PWM Inverter with Filter

VI. CONCLUSION

In this work, a three phase inverter is simulated using 180 degrees conduction mode, SPWM and THIPWM techniques and the results are as follows.

TABLE I. Results of output and Total harmonic distortion

TECHNIQUE	OUTPUT VOLTAGE (L-L)		THD	
	WITH OUT FILTER	WITH FILTER	WITH OUT FILTER	WITH FILTER
180 DEGREE CONDUCTION MODE	110.3V	104.2V	31.08%	3.99%
SINUSOIDAL PWM METHOD	86.58V	81.48V	68.58%	0.44%
THIRD HARMONIC INJECTION METHOD	97.08V	94.39V	56.38%	0.45%

The third harmonic injection method is proved to have major advantage in aspects of Dc bus voltage and THD reduction over sinusoidal PWM and 180 degree conduction mode. Though the THD value is numerically less in 180 degree conduction mode, it has more amounts of lower order harmonics and the output voltage is not controllable. By using PWM techniques the output voltage control is possible. The disadvantage of PWM technique is high switching frequency results in high switching loss.

The design of passive filter is also a crucial factor which was done in this paper and this further enables to design the filter for various power electronic converter circuits.

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