Harmonic Analysis and Application of PWM Techniques for Three Phase Inverter

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Abstract - *This paper presents the advantages and drawbacks of three different PWM techniques the sinusoidal PWM (SPWM) technique, the third-harmonic-injection PWM (THIPWM) technique, and the space-vector PWM (SVPWM) technique. In AC the quality of the sinusoidal waveform is more important than the quantity. In order to achieve that, we need to reduce the harmonic content in the output. For this purpose various pulse width modulation techniques are used. These three methods are compared by discussing their ease of implementation and by analyzing the output harmonic spectra of output voltages (line-to-neutral voltages). The PWM methods are simulated and the results are analyzed using FFT analysis for observing the harmonic distortion. The programs are performed in MATLAB environment*.

Key Words *:* **VSI; PWM; SPWM; THIPWM;SVPWM;FFT**

1. INTRODUCTION

In recent decades there has been a large number of variable speed induction motor drives which serves many industrial applications such as fans, pumps, machine tool cutting, steel rolling mills, etc,. Voltage source inverters are employed for these drives as there is a dramatic increase in the power semiconductor technology which offers power ratings from few hundred watts to several megawatts. The main function of the Voltage source inverters is to convert DC input voltage to an AC output voltage of the desired magnitude. The output voltage waveforms of the Voltage source inverters should be sinusoidal, however the waveform of the practical inverters are non sinusoidal and contains different harmonics. Square wave or quasi-square-wave voltages are acceptable only for low and medium power applications, but for high power applications low distorted sinusoidal waveforms are required. By using high speed power semi conductor devices and by using different switching techniques we can reduce the harmonic content in output voltage. Inverters are widely used in industrial applications (e.g., variable speed AC motors, induction heating, standby power supplies and uninterruptible power supplies). Inverters are broadly classified into two types single phase inverters and three phase inverters Constant or adjustable voltage may be needed for AC loads at their input terminals. It is crucial that output voltage of the inverters is maintained so that we realize the requisite of AC loads when such loads are driven by inverters. The voltage can be controlled by

(i) External control of ac output voltage.

(ii) Internal control of Inverter

1.1 External Control of AC Output Voltage

The control of AC voltage controller through firing angle helps in regulating the voltage input to AC load. However higher harmonic content is seen in the output voltage. Hence the process is seldom used.

1.2 Internal control of Inverter

By having a control within the inverter itself output voltage can be upheld as well from an inverter. The pulse width modulation control employed in an inverter is the most effective method of doing this.

1.3 Pulse Width Modulation

Pulse width modulation (PWM) is a powerful technique for controlling analog circuits with a processor's digital outputs. PWM of a signal or power source involves the modulation of its duty cycle, to either convey information over a communications channel or control the amount of power sent to a load.

1.4 Advantages of Pulse Width Modulation

1) We can obtain the output voltage control foregoing any other additional element.

2) Lower order harmonic can be eliminate or compact beside its output voltage control with this method and as we know higher order harmonics can be filtered easily.

1.5 Pulse Width Modulation Techniques

Switching techniques of pulse width modulation (PWM) have been popular in the area of power electronics and drive systems. PWM is commonly used in applications like motor speed control, converters audio amplifiers etc. PWM is used to adjust voltage applied to the motor. There is no single PWM method which can suite for all applications. As per the advanced technology in solid state power electronic devices and microprocessors, various pulse-width modulation (PWM) techniques have been developed for different industrial applications. For the above reasons, the PWM techniques have been the subject of intensive research since 1970s. The main objective of the PWM is to control the inverter output voltage and to reduce the harmonic content in the output voltage. The pulse width modulation (PWM) techniques are mainly used for voltage control. These techniques are most efficient and they control the drives of the switching devices. The different PWM techniques are:-

1) Sinusoidal Pulse Width Modulation (SPWM)

2) Third Harmonic Injection Pulse Width Modulation (THIPWM)

3) Space Vector Pulse Width Modulation (SVPWM)

2. SINUSOIDAL PULSE WIDTH MODULATION

The sinusoidal pulse-width modulation (SPWM) technique produces a sinusoidal waveform by filtering an output pulse waveform with varying width. As shown in Figure 1, a low-frequency sinusoidal modulating waveform is compared with a high-frequency triangular waveform, which is called the carrier waveform. The switching state is changed when the sine waveform intersects the triangular waveform. The crossing positions determine the variable switching times between states. In three-phase SPWM, a triangular voltage waveform (V_t) is compared with three sinusoidal control voltages (V_a, V_b, and V_c), which are 120 out of phase with each other and the relative levels of the waveforms are used to control the switching of the devices in each phase 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 2. The output of the comparators in Figure 1 forms the control signals for the three legs of the inverter. 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.

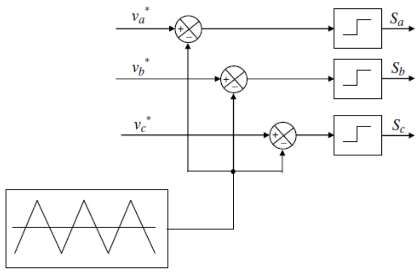

Fig -1: Control Signal Generator for SPWM

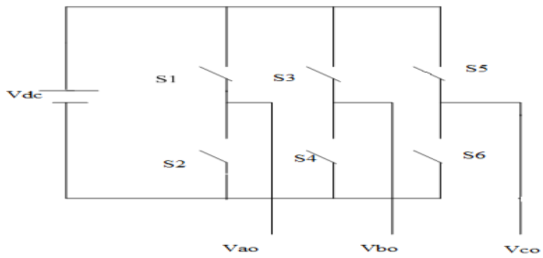

Fig -2: Three-Phase Sinusoidal PWM Inverter

2.1 Switching Strategy

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:-

1) S_1 is ON when $V_a > V_T$, S4 is ON when $V_a < V_T$

2) S_3 is ON when $V_b > V_T$, S6 is ON when $V_b < V_T$

3) S_5 is ON when $V_c > V_T$, S2 is ON when $V_c < V_T$

The pulse widths depend on the intersection of the triangular and sinusoidal waveforms. The inverter output voltages are determined as follows:

If

$V_a > V_{tri}$ Then $V_{ao} = 0.5V_{dc}$

$V_b > V_{tri}$ Then $V_{bo} = 0.5V_{dc}$ [1]

$V_c > V_{tri}$ Then $Vco = 0.5V_{dc}$

And if

$V_a > V_{tri}$ Then Vao = -0.5V_{dc}

$V_b > V_{tri}$ Then Vbo = -0.5V_{dc} [2]

$V_c > V_{tri}$ Then Vco = -0.5V_{dc}

The inverter line-to-line voltages are obtained from the pole voltages as:

$V_{ab} = V_{ao}-V_{bo}$

$V_{bc} = V_{bo}-V_{co}$ [3]

$V_{ca} = V_{co}-V_{ao}$

The inverter line-to-line voltages are obtained from the pole voltages as:

$V_{an}= 2V_{ao}-V_{bo}-V_{co}/3$

$V_{bn}= 2V_{bo}-V_{ao}-V_{co}/3$ [4]

$V_{cn}=2V_{co}-V_{ao}-V_{bo}/3$

3. THIRD HARMONIC INJECTION PULSE WIDTH MODULATION

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. The sinusoidal PWM technique causes decrease maximum achievable output voltage. In this case, an increase of maximum achievable output voltage is studied. Hence, by simply adding a third harmonic signal to each of the reference signals, it is possible to obtain a significant amplitude increase at the output voltage without loss of quality, as represented in Figure 3.

It is remarkable that the reference signal resulting from the addition of the third (V3) and first harmonic (V1) is smaller in amplitude than the first harmonic. At the output, the obtained amplitude of the first harmonic is equal to the amplitude of the first harmonic reference. Note also that the third harmonic is not seen at the output voltage.

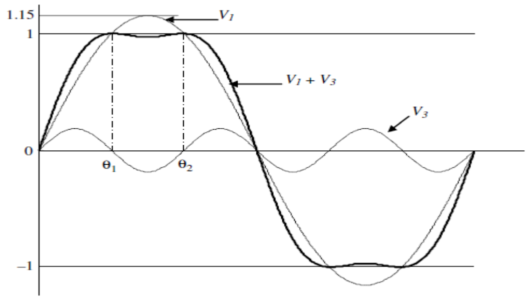

Fig- 3: Third Harmonic Injections to the Reference Signal

On the other hand, the reference signal takes two maxima at t = π/3 and t = 2π/3 equal to 1. The first and third harmonic equations are given by

$V_1=V_{1max}\sin t$ [5]

$V_3 =V_{3max}\sin 3t$ [6]

Therefore, when t= π/3, the first harmonic of the output voltage (line to neutral) takes the value Vbus/2. By substituting in Equation [5] , we find

$V_{bus}/2 = V_{1max} \sin (\pi/3)$ [7]

Consequently, the amplitude of the first harmonic yields

$V_{1max} = V_{bus}/1.732$ [8]

We see that the quality of the voltage waveform has not been significantly degraded. For each phase reference, the third harmonic injected is equal

$V_{1max} \sin (wt) +V_{3max}\sin (3wt)$ [9]

$V_{1max}\sin (wt-2\pi/3) +V_{3max}\sin (3wt)$ [10]

$V_{1max}\sin (wt+2\pi/3) +V_{3max}\sin (3wt)$ [11]

4. SPACE VECTOR PULSE WIDTH MODULATION

Space Vector PWM (SVPWM) refers to a special switching sequence of the upper three Power transistors of a three-phase power inverter. It has been shown to generate less harmonic distortion in the output voltages and or currents applied to the phases of an AC motor and to provide more efficient use of supply voltage compared with sinusoidal modulation technique as shown in Figure 4.This method which is increase the output voltage about that of SPWM technique . This method is used for adjustable speed drives. This technique can increase the fundamental up to 27.3% when compared with SPWM.

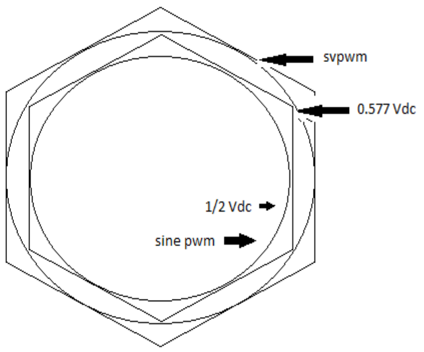

Fig 4: Locus Comparison between SPWM and SVPWM

To implement the space vector PWM, the voltage equations in the *abc* reference frame can be transformed into the stationary *dq* reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Fig. 5.

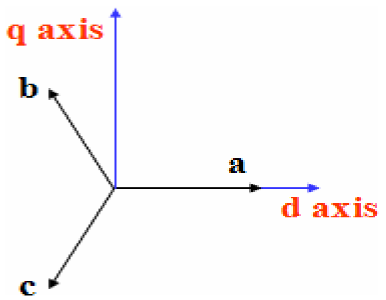

Fig 5: The Relationship of abc Reference Frame and Stationary dq Reference Frame.

As described in Fig. 5, this transformation is equivalent to an orthogonal projection of (a, b, c) ^{t} onto the two-dimensional perpendicular to the vector (1, 1, 1) ^{t} (the equivalent d-q plane) in a three-dimensional coordinate system. As a result, six non-zero vectors and two zero vectors are possible. Six nonzero vectors (V_1 - V_6) shape the axes of a hexagonal as depicted in Fig. 6, and feed electric power to the load. The angle between any adjacent two non-zero vectors is 60 degrees. Meanwhile, two zero vectors (V_0 and V_7) are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by V_0, V_1, V_2, V_3, V_4, V_5, V_6, and V_7. The same transformation can be applied to the desired output voltage to get the desired reference voltage vector V_{ref} in the d-q plane. The objective of space vector PWM technique is to approximate the reference voltage vector V_{ref} using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period, T to be the same as that of V_{ref} in the same period.

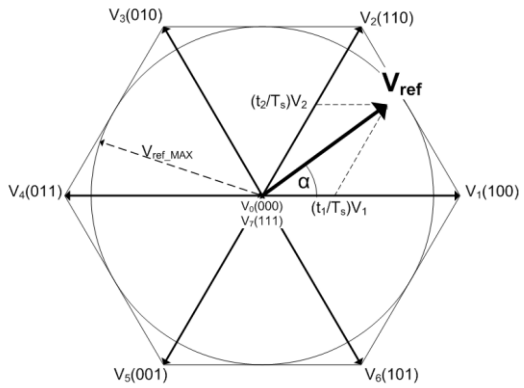

Fig 6 : Basic Switching Vectors and Sectors

The switching time at each sector is summarized inTable1.

Table -1: Switching Time Calculation at Each Sector

sectors	upper switches(s_1,s_3,s_5)	Lower switches(s_2,s_4,s_6)
1	$S_1=T_1+T_2+T_0/2$ $S_3=T_2+T_0/2$ $S_5=T_0/2$	$S_2=T_1+T_2+T_0/2$ $S_6=T_1+T_0/2$ $S_4=T_0/2$
2	$S_1= T_1+T_0/2$ $S_3=T_1+T_2+T_0/2$ $S_5= T_0/2$	$S_4=T_2+T_0/2$ $S_6= T_0/2$ $S_2=T_1+T_2+T_0/2$
3	$S_1= T_0/2$ $S_3=T_1+T_2+T_0/2$ $S_5= T_2+T_0/2$	$S4=T_1+T_2+T_0/2$ $S6= T_0/2$ $S2= T_1+T_0/2$
4	$S_1= T_0/2$ $S_3= T_1+T_0/2$ $S_5=T_1+T_2+T_0/2$	$S4=T_1+T_2+T_0/2$ $S6= T_2+T_0/2$ $S2= T_0/2$
5	$S_1=T_2+T_0/2$ $S_3= T_0/2$	$S4= T_1+T_0/2$ $S6=T_1+T_2+T_0/2$

	$S_5=T_1+T_2+T_0/2$	$S2= T_0/2$
6	$S_1=T_1+T_2+T_0/2$ $S_3=T_0/2$ $S_5= T_1+T_0/2$	$S_4= T_0/2$ $S_6=T_1+T_2+T_0/2$ $S_2= T_2+T_0/2$

5. RESULTS

The PWM techniques (SPWM, THIPWM, and SVPWM) have been evaluated for three-phase VSI. The simulation of voltage waveforms performed by using MATLAB software application at switching frequency 3 KHz. Vdc is 1100 v and no load is connected as analysis is performed only on voltage . Output line to neutral voltage waveforms of SPWM,THIPWM,SVPWM methods are shown in the figure 7,9 and11.Harmonic spectrums of these voltage waveforms which are evaluated by using FFT function are shown in the figure 8,10 and 12.

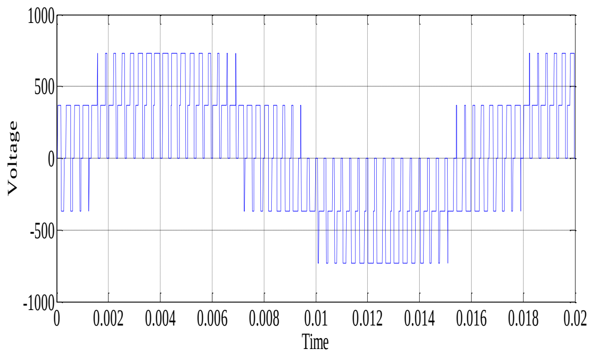

Fig 7 : Line to Neutral Voltage (Van) of SPWM

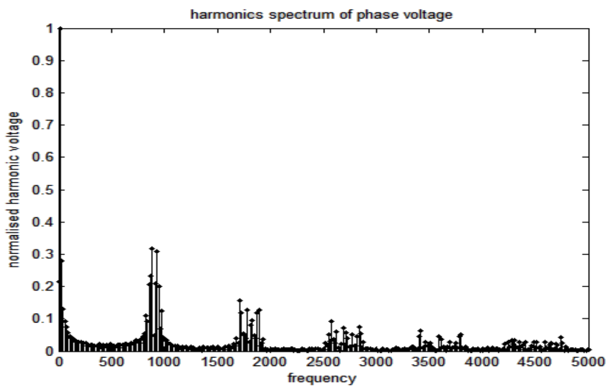

Fig 8: Harmonic Spectrum of Van (SPWM)

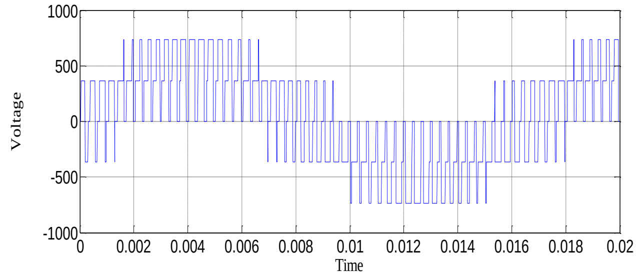

Fig 9: Line to Neutral Voltage (Van) of THIPWM

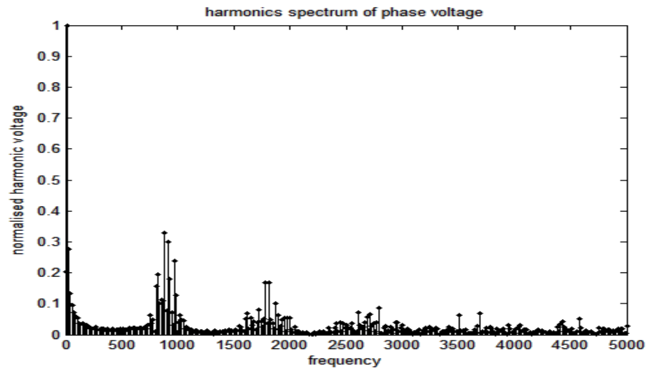

Fig 10: Harmonic Spectrum of Van (THIPWM)

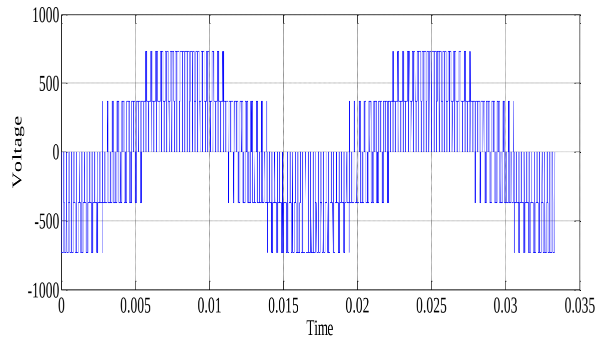

Fig 11: Line to Neutral Voltage (Van) of SVPWM

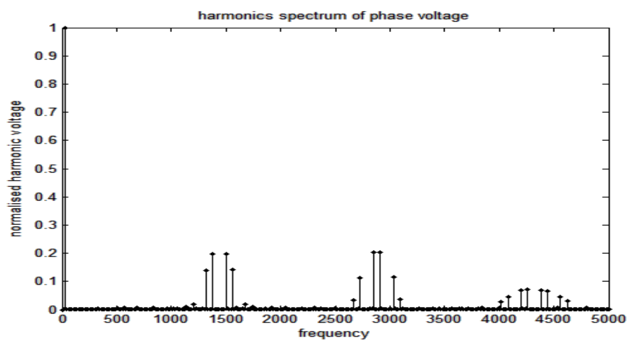

Fig 12: Harmonic Spectrum of Van (SVPWM)

6. Conclusion

This paper discusses about analysis of different PWM techniques. There are few advantages in SVPWM method. When compared to both THIPWM and SPWM. Utilization of DC voltage is more in both SVPWM and THIPWM when compared to SPWM. Maximum output voltage of inverter is increased in both SVPWM and THIPWM when compared to SPWM. From the figures 8, 10, 12 harmonics presence in the inverter voltages is very less in SVPWM method when compared to both SPWM and THIPWM methods in between SPWM and THIPWM methods harmonics are less in SPWM when compared to THIPWM.

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