Simulation Investigation of SPWM, THIPWM and SVPWM Techniques for Three Phase Voltage Source Inverter

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ABSTRACT

Pulse width modulation (PWM) technique is one of the vital issues for power electronic circuit control. A number of Pulse width modulation (PWM) techniques are increasingly applied in many new industrial applications that require superior performance. The most widely applied PWM technique for three-phase voltage source inverters are Sine Pulse Width Modulation (SPWM), Third Harmonic Injection Pulse Width Modulation (THIPWM) and Space Vector Pulse Width Modulation (SVPWM). SPWM is the most simple modulation technique that can realize easily in analog circuit. However, it has some drawbacks such as higher total harmonic distortion (THD), lower switching frequency and not capable in over modulation region. THIPWM and SVPWM both provide better THD compared to SPWM. SVPWM shows lower THD in over modulation region and in high frequency application compared to THIPWM. These three techniques are discussed, analyzed and compared in terms of modulation index, switching frequency and inverter input voltage in this paper. The modeling and simulation for all PWM techniques have been done by using MATLAB/SIMULINK and Origin 6.1. From the simulation results, SVPWM shows the best performance and meet IEEE 519 standard of current harmonics level.

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1. INTRODUCTION

Pulse Width Modulation technique produces ac output voltage where the input of the inverter is dc voltage. It is achieved by adjusting the duty ratio of the inverter components. It gives the best results compared to any other external control techniques [1]. Output waveform quality, system loss and efficiency have been directly affected by these techniques [2]. A number of Pulse width modulation (PWM) techniques are used to obtain the variation of output voltage and frequency. SPWM, THIPWM and SVPWM are most attractive control PWM techniques in the real world [3]-[5]. SPWM is the simplest popular control technology which is used widely in the inverters [2]. But it has some drawbacks such as poor output waveform quality, weak modulation ability on active power and reactive power, very narrow linear range, higher total harmonic distortion (THD) and lower effective utilization of DC value [2], [6]. THIPWM is widely used superior performance compared to SPWM in respect of reduced harmonic current ripple, optimized switching sequence and increased voltage transfer ratios [7]. SVPWM provides the highest achievable fundamental output voltage with lower harmonic distortion of the output current,great flexibility to optimise switching waveform and are well suited for hardware implementation [8], [9]. In SVPWM methods, a revolving reference voltage vector is provided as voltage reference as a replacement of three phase modulating waves. The magnitude and frequency of the fundamental component in the line side are controlled by the magnitude and frequency, respectively, of the reference vector. The study of SVPWM reveals that utilizes DC bus voltage more effectively when compared with SPWM. SVPWM and THIPWM can obviously reduce the current harmonic component, comparing with SPWM; the voltage utilization can be raised by 15.5% [10]. SVPWM is probably the best among all the PWM techniques for variable frequency drive application [11]. Because of its superior performance characteristics, it has been finding widespread application in recent year [12]. These three different PWM techniques are discussed and analyzed the performance.

2. GENERAL THEORY OF DIFFERENT PULSE-WIDTH MODULATION TECHNIQUES

2.1. Basic Principle of Sinusoidal Pulse width Modulation

Sine pulse width modulation is the simplest PWM technique and is very popular in industrial applications. A low frequency sine waveform of desired frequency is compared with the high frequency carrier triangular wave. When the instantaneous value of the triangle wave is lesser than that of the sine wave, the PWM output signal is in high level (1). Otherwise it is turned into the low level (0). The level switching edge is produced at every moment of the sine wave intersects with the triangular wave. The ratio of modulating signal amplitude and carrier signal amplitude is called modulation index that controls the amplitude of the applied output voltage. Thus the different tripping positions result in variable duty cycle of the output waveform. The pulses so producedare given to the inverter controls.

2.2. Basic Principle of Third-harmonic-injection Pulse width Modulation

The sinusoidal PWM is unable to fully utilize the DC bus supply voltage and THD is also higher. So, the third harmonic injection pulse width modulation (THIPWM) technique was developed to increase the inverter performance. Phuong Hue Tran [8] consider a waveform comprising of a fundamental component with the accumulation of a triple-frequency term,

$$y = \sin\theta + A\sin 3\theta \tag{1}$$

Where $\theta = \omega t$ and A is a parameter to be optimized while keeping the maximum amplitude of y (t) under unity. Solving equation (1), the required waveform is:

$$y = \sin\theta + 1/6\sin 3\theta \tag{2}$$

All triple harmonics pass through zero at these values of θ. If we substitute the values of $\theta = n\pi/3$ in (2), then we have a maximum amplitude of $\hat{y} = \pm\sqrt{3}/2$ at these angles.

It is probable to increase the amplitude of the modulating waveform by a factor of K so that the full output voltage range of the inverter is again used. If the modulating waveform is expressed as:

$$y = K(\sin\theta + 1/6\sin 3\theta) \tag{3}$$

The vital factor, K for a peak value of unity should satisfy the limit.

$$K = 2/\sqrt{3} \tag{4}$$

Injecting one sixth of the third harmonic component to the fundamental component gives the following modulating waveforms for the three-phase:

$$V_{an} = 2/\sqrt{3}(\sin\theta + 1/6\sin 3\theta) \tag{5}$$

$$V_{bn} = 2/\sqrt{3}(\sin(\theta - \tfrac{2\pi}{3}) + 1/6\sin 3\theta) \tag{6}$$

$$V_{cn} = 2/\sqrt{3}(\sin(\theta + \tfrac{2\pi}{3}) + 1/6\sin 3\theta) \tag{7}$$

The generating PWM technique is the same as SPWM.

2.3. Basic Principle of Space Vector Pulse width Modulation

Space Vector PWM is a special switching scheme of the six power transistors of a three phase power converter. A three-phase voltage source PWM inverter model is shown in Figure 1. S1 to S6 are the six power switches of the inverter that shape the output waveform. When an upper transistor is switched on, i.e. S1, S3 or S5 is 1, the corresponding lower transistor is switched off, i.e. S2, S4 or S6 is 0. Hence, the on and off states of the upper transistors S1, S3 and S5 can be used to control the output waveform [12].

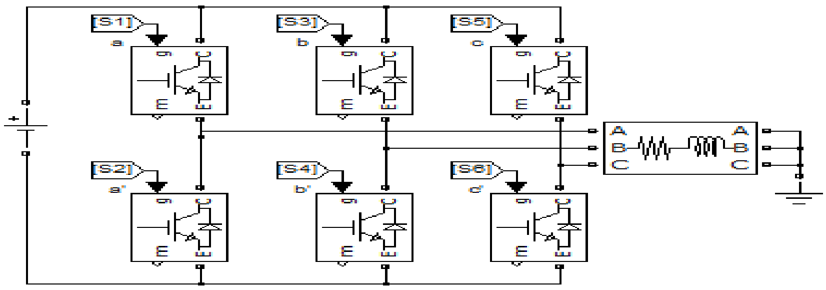

Figure 1. Three-phase voltage source PWM Inverter

The relationship between the switching variable $[a\ b\ c]^T$ and the line-to-line voltage vector $[V_{ab} V_{bc} V_{ca}]^T$ is given as follows:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = Vdc \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (8)$$

The relationship between the switching variable $[a\ b\ c]^T$ and the phase voltage vector $[V_a V_b V_c]^T$ is calculated from the following equation:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (9)$$

For each switching combination a voltage space vector can be constructed using below equation:

$$V^* = \frac{2}{3}(V_a + iV_b + i^2 V_c) \quad (10)$$

According to equations stated above the eight switching vectors, output line to neutral voltage and line-to-line voltages in terms of DC-link V_0 to V_7 are given in Table 1.

Table 1. Switching Vectors, Phase Voltages and Output Line to Line Voltages in terms of Vdc

Voltage Vectors	Switching vectors			Line to neutral voltages			Line to line voltages		
	A	B	C	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

The switching diagram shown in Figure 2 is achieved when these space vectors are plotted on a set of real and imaginary axes. The switching space vectors divide the axes into 6 equally sized sectors. The two null vectors V_7 (000) and V_8 (111) are located at the origin. The objective of SVPWM is to estimate a reference space vector V somewhere within the transcribed circle using a combination of the eight switching vectors.

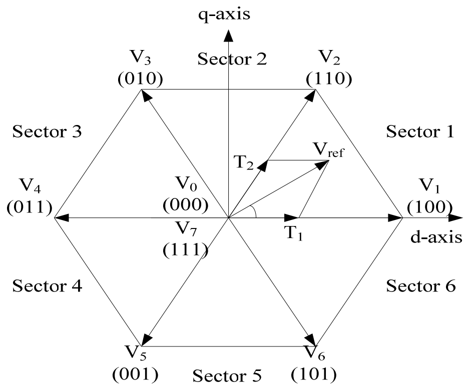

Figure 2. Determination of the switching sequences in the three phase inverter

In this modulation technique the three phase quantities can be transformed to their equivalent two-phase quantity either in synchronously rotating frame (or) stationary frame by Clarke equation. The transformation of two phase quantity is represented as [13]:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{11}$$

From these two-phase components, the reference vector magnitude can be found and used for modulating the inverter output. The magnitude of the reference voltage vector is:

$$\left|\vec{V}_{ref}\right| = \frac{2}{3}.M_i\sqrt{\alpha^2 + \beta^2} \tag{12}$$

Where M_i is the modulation index. The angle, θ is defined in trigonometric function as:

$$\theta = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \tag{13}$$

The operation sector number, for any given reference vector, is given by [14]:

$$s = floor\left(\frac{\theta}{\pi/3}\right) + 1 \tag{14}$$

The dwelling time can be evaluated using the equations [12]:

$$T_1 = \frac{\sqrt{3}T_s|\vec{V}_{ref}|}{V_{dc}}\left[sin\left\{\frac{\pi}{3} - \alpha + \frac{(s-1)\pi}{3}\right\}\right] \tag{15}$$

$$T_2 = \frac{\sqrt{3}T_s|\vec{V}_{ref}|}{V_{dc}}\left[sin\left\{\alpha - \frac{(s-1)\pi}{3}\right\}\right] \tag{16}$$

$$T_0 = T_s - (T_1 + T_2) \tag{17}$$

Where Ts is the switching period and Vdc is the inverter input voltage. Calculation of switching time for each sector is shown in table 2.2

3. MODELING OF CONTROL TECHNIQUES

The switching signal generation model for SPWM, THIPWM and SVPWM are shown in Figure 3, 4 and 5 respectively. The switching delays and the forward drop of the power switches and the dead time of the inverter are all ignored in these modeling. My proposed H-Bridge inverter topology requires six switching devices, single DC source of 220V; three phase RL-load of 50Ω and 20mH in each phase. The fundamental frequency is 50Hz .

Table 2. Switching Time Calculation at Each Sector

Sector	Switching Time	Upper switches (S1, S3, S5)	Lower Switches (S2, S4, S6)
1	Ta	$T_1+T_2+T_{0/2}$	$T_{0/2}$
	Tb	$T_2+T_{0/2}$	$T_1+T_{0/2}$
	Tc	$T_{0/2}$	$T_1+T_2+T_{0/2}$
2	Ta	$T_1+T_{0/2}$	$T_2+T_{0/2}$
	Tb	$T_1+T_2+T_{0/2}$	$T_{0/2}$
	Tc	$T_{0/2}$	$T_1+T_2+T_{0/2}$
3	Ta	$T_{0/2}$	$T_1+T_2+T_{0/2}$
	Tb	$T_1+T_2+T_{0/2}$	$T_{0/2}$
	Tc	$T_2+T_{0/2}$	$T_1+T_{0/2}$
4	Ta	$T_{0/2}$	$T_1+T_2+T_{0/2}$
	Tb	$T_1+T_{0/2}$	$T_2+T_{0/2}$
	Tc	$T_1+T_2+T_{0/2}$	$T_{0/2}$
5	Ta	$T_2+T_{0/2}$	$T_1+T_{0/2}$
	Tb	$T_{0/2}$	$T_1+T_2+T_{0/2}$
	Tc	$T_1+T_2+T_{0/2}$	$T_{0/2}$
6	Ta	$T_1+T_2+T_{0/2}$	$T_{0/2}$
	Tb	$T_{0/2}$	$T_1+T_2+T_{0/2}$
	Tc	$T_1+T_{0/2}$	$T_2+T_{0/2}$

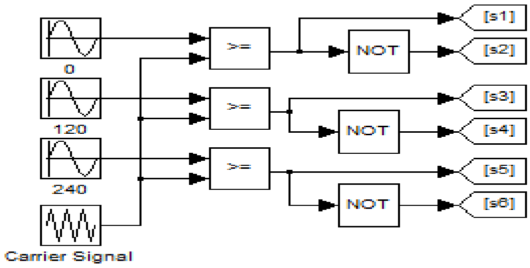

Figure 3. Switching signal generation model for SPWM

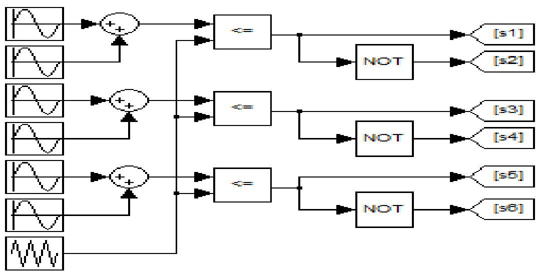

Figure 4. Switching signal generation model for THIPWM

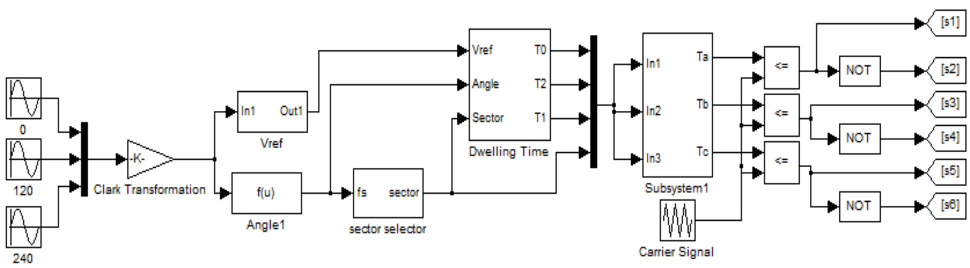

Figure 5. Switching signal generation model for SVPWM

4. RESULT AND DISCUSSION

Three-Phase modulating signals are generated which are displaced from each other for SPWM, THIPWM and SVPWM are shown in Figure 6, 7 and 8 respectively. Their three phase output current waveforms are shown in Figure 9, 10 and 11 respectively. THD measurement of the corresponding three phase output currentsare shown in Figure 12, 13 and 14 respectively where the switching frequency is fixed to 4KHz. THIPWM shows the reduced THD by 6.67% compared to SPWM and hence THIPWM is better than SPWM. SVPWM shows the reduced THD by 0.18% compared to THIPWM and hence SVPWM is better than THIPWM. The output line-line voltages are shown in Figure 15, 16 and 17 respectively. THD measurement of the corresponding output line-line voltagesare shown in Figure 18, 19 and 20 respectively. SVPWM shows the reduced THD by 16.4% than SPWM and 18.51% than THIPWM. Hence SVPWM shows the better performance i.e better quality of output waveform than any others.

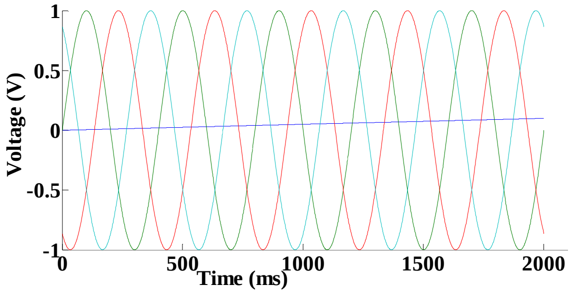

Figure 6. Three phase modulating signal for SPWM

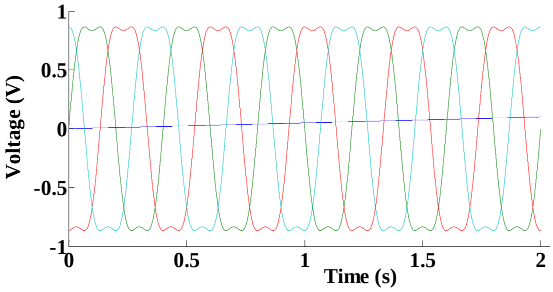

Figure 7. Three phase modulating signal for THIPWM

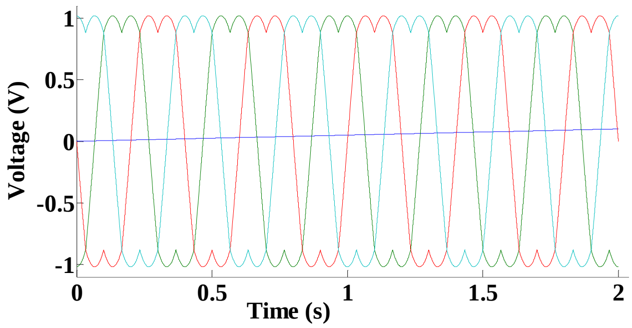

Figure 8. Three phase modulating signal for SVPWM

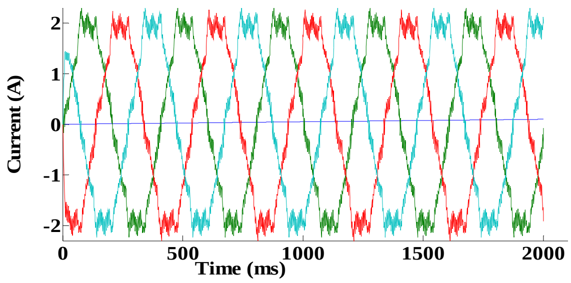

Figure 9. Three phase output current for SPWM

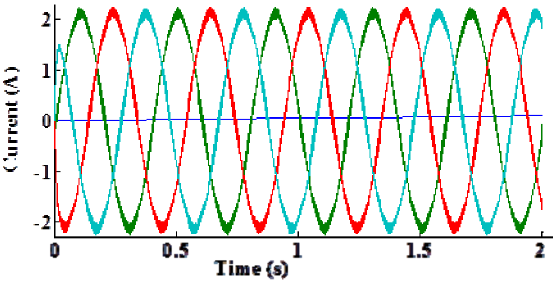

Figure 10. Three phase output current for THIPWM

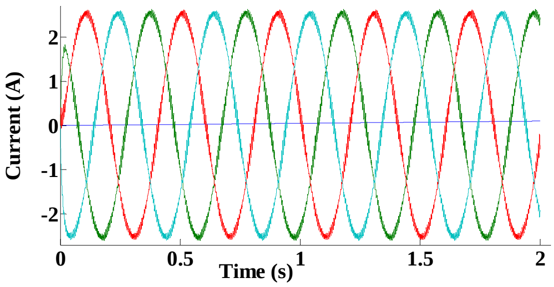

Figure 11. Three phase output current for SVPWM

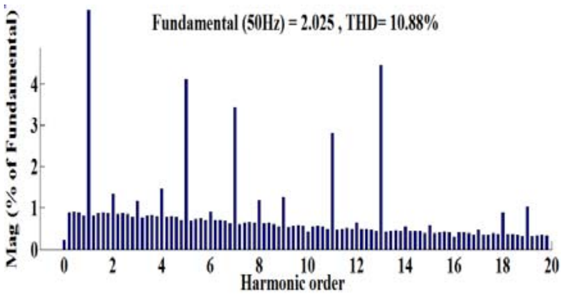

Figure 12. Current THD measurement for SPWM

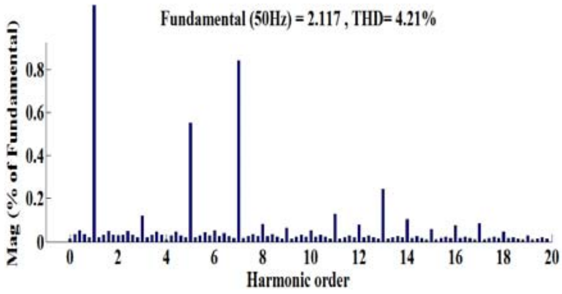

Figure 13. Current THD measurement for THIPWM

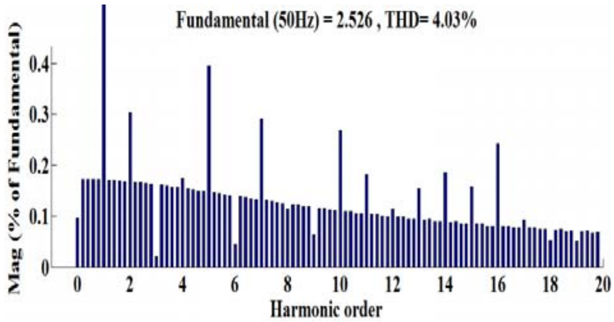

Figure 14. Current THD measurement for SVPWM

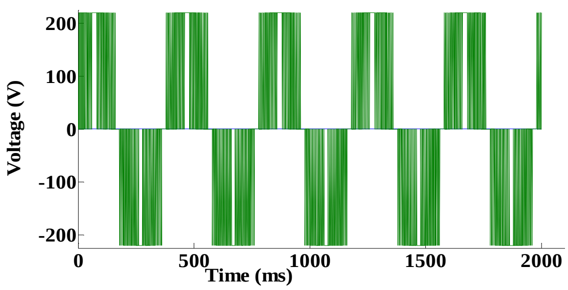

Figure 15. Output Line-Line voltage for SPWM

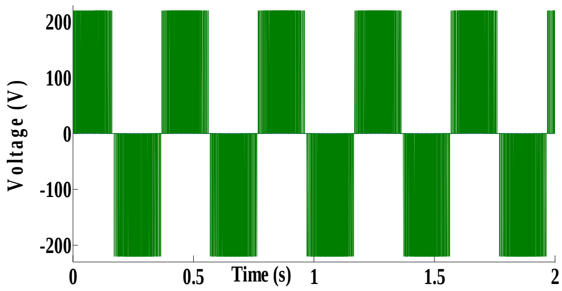

Figure 16. Output Line-Line voltage for THIPWM

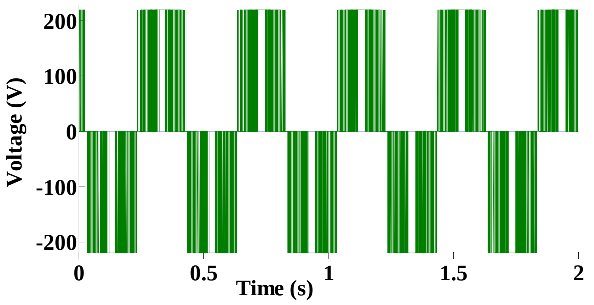

Figure 17. Output Line-Line voltage for SVPWM

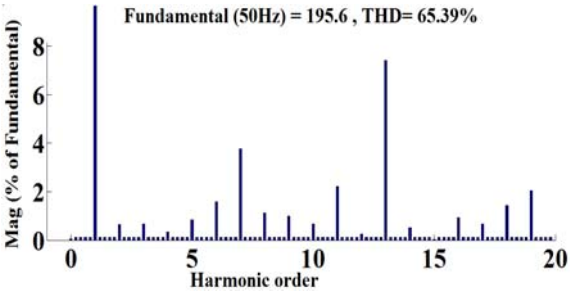

Figure 18. Voltage THD measurement for SPWM

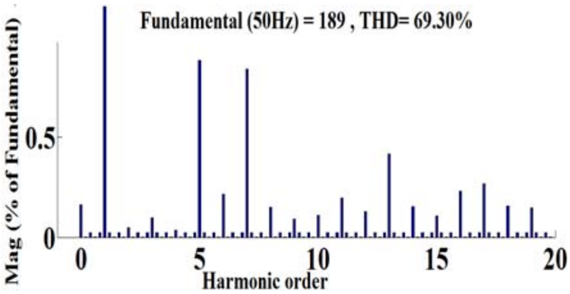

Figure 19. Voltage THD measurement for THIPWM

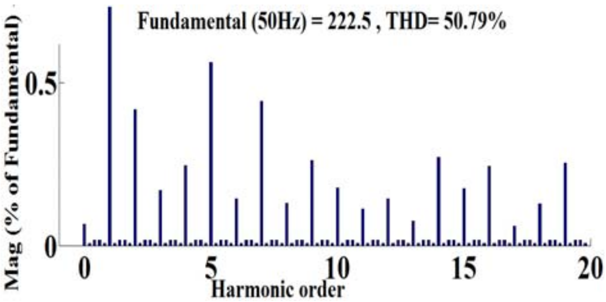

Figure 20. Voltage THD measurement for SVPWM

In this section, output performance is analized in terms of modulation indices, switching frequencies and inverter input voltage. Variation of THD with modulation indices are shown in Figure 21 and 22. The current THD is continuously decreased up to modulation index 1 for SPWM but it shows increasing nature exceeding modulation index 1. Hence, SPWM is not suitable in over modulation region. THIPWM and SVPWM both show better THD compared to SPWM. The THD is continuously decreased up to modulationindex 1.15 for SVPWM and it shows the lowest THD than others. Hence SVPWM can run in over modulation region but over modulation is limited up to modulation index 1.15 because THD increases exceeding modulation index 1.15.Variations of THDs with switching frequencies are shown in Figure 23 and 24. The THD is continuously decreased up to switching frequency 4KHz for SPWM and it shows unexpected results exceeding 4KHz. Hence, SPWM is not capable in high switching application. THIPWM and SVPWM both show continuous reduction of THD up to 15KHz but they show increasing behavior exceeding 15KHz. Hence, they are applicable up to 15KHz. Variation of THDs with inverter input voltages are shown in Figure 25 and 26. THD remains constant with the variation of inverter input voltage for SPWM and THIPWM. The current THD is continuously decreased up to 220V but increased exceeding this value and voltage THD is proportional to input voltage for SVPWM. Hence, the optimized modulation index is 1.15, optimized switching frequency is 15KHz and optimized inverter input voltage is 220V.

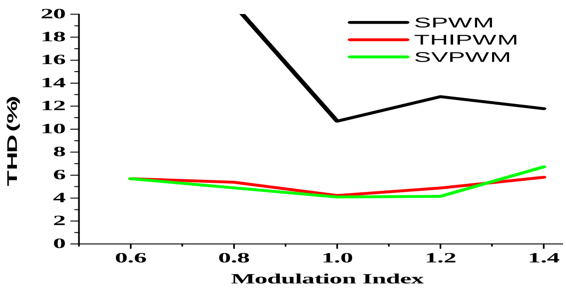

Figure 21. Variation of Current THD with MI

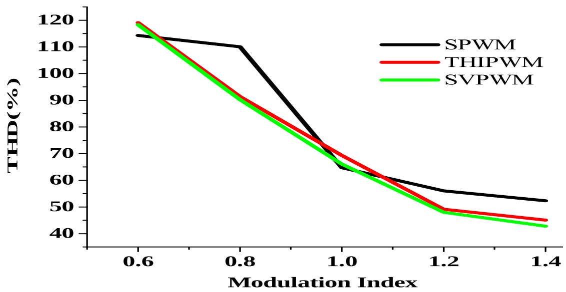

Figure 22. Variation of Voltage THD with MI

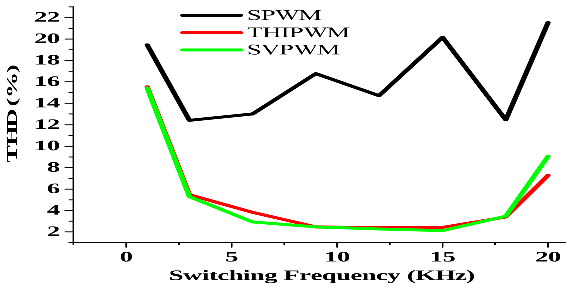

Figure 23. Variation of Current THD with Switching Frequency

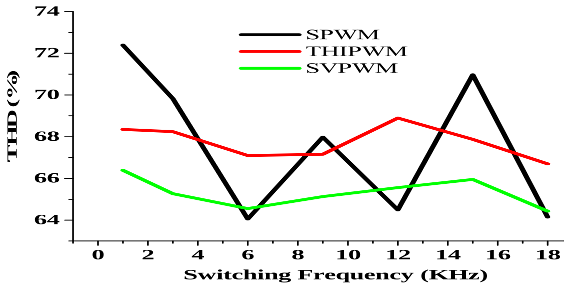

Figure 24. Variation of Voltage THD with Switching Frequency

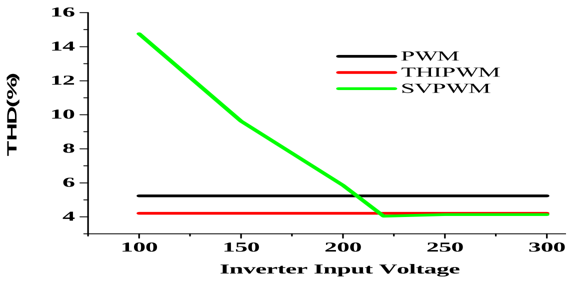

Figure 25. Variation of Current THD with Input Voltage

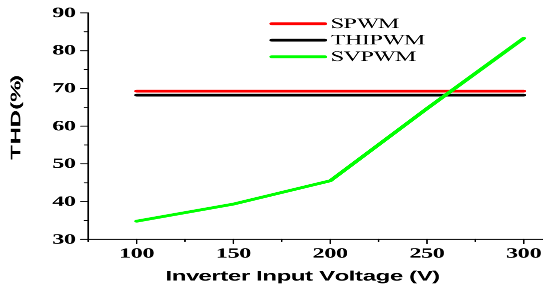

Figure 26. Variation of Voltage THD with Input Voltage

5. CONCLUSION

In this paper, the comparative analysis of SPWM, THIPWM and SVPWM for a three phase voltage source inverter is performed and their performance has been presented in terms of modulation index, switching frequency and inverter input voltage. From the simulation results, SPWM cannot capable in over modulation region and in high switching frequency application. THIPWM and SVPWM both show better THD up to 15KHz. THD remains constant with the variation of inverter input voltage for SPWM and THIPWM. The current THD is continuously decreased up to 220V and voltage THD is proportional to input voltage for SVPWM. It can be concluded that SVPWM gives enhanced fundamental output with better quality i.e. lesser THD compared than others.

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