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Close Loop V/F Control of Voltage Source Inverter using Sinusoidal PWM, Third Harmonic Injection PWM and Space Vector PWM Method for Induction Motor

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ABSTRACT

The aim of this paper to presents a comparative analysis of Voltage Source Inverter using Sinusoidal Pulse Width Modulation Method, Third Harmonic Injection Pulse Width Modulation Method and Space Vector Pulse Width Modulation Two level inverter for Induction Motor. In this paper we have designed the Simulink model of Inverter for different technique. An above technique is used to reduce the Total Harmonic Distortion (THD) on the AC side of the Inverter. The Simulink model is close loop. Results are analyzed using Fast Fourier Transformation (FFT) which is for analysis of the Total Harmonic Distortion. All simulations are performed in the MATLAB Simulink / Simulink environment of MATLAB.

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1. INTRODUCTION

A circuit which is used for converting DC power into an AC power at desired output Voltage and Frequency is known as an Inverter. A phase controlled converter, when it is used in inverter mode, are known as line-commutated Inverter, only line-commutated inverter requires at the output terminals an existing AC supply which is used for their commutation it means it required external circuit for commutation. A Force commutated Inverter gives an independent AC output voltage of adjustable Voltage and Frequency therefore its application is so vast. In an Inverter we require Forced commutation for thyristor, therefore we can use other self-commutating device like GTO, MOSFET, and other Transistors to avoiding the commutation circuit. But for high power application we must use thyristor along with the forced commutation circuit. There are major four techniques to reduce the Total Harmonic Distortion in Inverter:

1) Sinusoidal Pulse Width Modulation
2) Third Harmonic Injection Method
3) 60° Pulse modulation
4) Space Vector Pulse Width Modulation

2. TWO LEVEL INVERTER

In this level 180 degree mode each MOSFET conducts for 180° of a periodic cycle. Each phase has a pair S1, S4; S3, S6; S5, S2 and each trigger for 180° of time interval. And S1, S3, and S5 conduct at an interval of 120°. Refer to Figure 1.

0° 60° 120° 180° 240° 300° 360°

S1	S3	S5

S6	S2	S4	S6

Figure 1. Switching period of MOSFET

Specification of each MOSFET 180° mode VSI. Refer to Table 1.

Table 1. For 50 Hz frequency Pulse Generator where amplitude = 230*1.414 and pulse width 50%

S1	Phase Delay = 0 msec
S4	Phase Delay = 10 msec
S3	Phase Delay = 6.667 msec
S6	Phase Delay = 16.667 msec
S5	Phase Delay = 13.33 msec
S2	Phase Delay = 23.33 msec / - 0.0033 sec

3. SINUSOIDAL PULSE WIDTH MODULATION (SPWM)

This technique is very useful for reducing the Total Harmonic Distortion (THD). This technique is characterized by the constant amplitude pulse. And the width of these pulses is modulated to get Inverter output Voltage control and to reduce its harmonic content in the voltage. Force commutation is essential for the pulse width modulation technique. The Switching sequences and topology of the Inverter is same as normal level of Inverter. In this technique the Gate pulses of each MOSFET is modulated and control the Switching of MOSFET to get the desired output voltage at desired frequency for input voltage of Induction motor.

Fourier analysis of the voltage waveform and get the output voltage of an Inverter.

$$V(t)= A_0 + 2*[\sum_{k=1}^{\infty} Ak * coskwt + Bk * sinkwt] \quad \text{(i)}$$

The output voltage wave is odd symmetry. So, A_0 and Ak is zero because it has an even symmetry. So,

$$Bk= (2/\pi)*[\int_{\frac{\pi}{2}-d}^{\frac{\pi}{2}+d} Vs * \sin(nwt) d(wt)]$$

$$=((4*Vs)/(n\pi))*[\sin(n\pi/2)*\sin(nd)] \quad (1)$$

$$V_0=(\sum_{n=1,3,5...}^{\infty}[\left(\frac{4Vs}{n\pi}\right) * \sin\left(\frac{n\pi}{2}\right) * \sin(nd) * \sin(nwt)]) \quad (2)$$

nd is made equal to π. So, d= (π/n)

So, the pulse width is made 2d so it is equal to (2d/n).

In the Simulink model sine wave frequency is 50 Hz and the amplitude of the sine wave is 230*1.414 and carrier frequency is sinusoidal with frequency is 10000 Hz.

For a close loop we take the speed as a feedback and compare to the reference speed and then the speed error again added with the rotor speed and its output is change into the Gate Pulse of the MOSFET.

4. THIRD HARMONIC INJECTION PULSE WIDTH MODULATION METHOD (THIM)

This method is also a very useful method for eliminating the harmonic in the system which comes due to the presence of power electronic switches. In this method we inject the third harmonic in the system

and control the pulse of the each MOSFET to get the harmonic free inverter output voltage. Now to find the amplitude of the third harmonic of unknown amplitude of the third harmonic component.
So let us take simple sine wave with the third harmonic sine wave of unknown amplitude x.

$$Y(\alpha) = \sin(\alpha) + x*\sin(3\alpha) \quad (3)$$

For finding the maximum value of the function

$$d/d\alpha\,(Y(\alpha)) = 0$$

Which gives,

$$\alpha = \cos^{-1}\sqrt{((9x-1)/(12x))} \quad (4)$$

From equation (3) and (4)

$$F(x)=Y(\alpha)=[(3x+1)(\sqrt{(3x+1)/(12x)} - 4x^{1.5}\sqrt{((3x+1)/(12x))}] \quad (5)$$

For finding the maximum value of equation (5) using formula d/dx (F(x))
So we get x = -0.334, 0.1667
At x = -0.334
$d^2/dx^2\,(F(x)) = 0$
At x = 0.1667
$d^2/dx^2\,(F(x)) = 10.3923$
Which shows the given function is minimum. At
x = 0.1667 and the value of α is 60°
Now putting the value of α at x = 0.1667
$d^2/dx^2\,(Y(\alpha)) = -2$
This shows the function Y (α) is maximum at x = 0.1667 and the value of α is 60°
So this is clear that the third harmonic should be 0.1667 of this amplitude
Now putting the value of x= 0.1667 and α= 60° in equation (4)
Which gives Y (α) =0.866025 which is the peak of resultant waveform with third harmonic. And the modulation factor of 1/0.866025 is 1.15470053 giving 15.47% more DC utilization.

$$\begin{matrix} Va \\ Vb \\ Vc \end{matrix} = \begin{matrix} V\sin(\alpha) \\ V\sin(\alpha-120°) \\ V\sin(\alpha+120°) \end{matrix} \quad (6)$$

Where,
V is Instantaneous maximum Magnitude of fundamental
And
α is instantaneous phase of fundamental
The above results give the information about the amplitude of the output phase voltage is 1.15 times of the normal output phase voltage. In the Simulink model sine wave frequency is 50 Hz and the amplitude of the sine wave is 230*1.414 and carrier frequency is sinusoidal with frequency is 10000 Hz. And additional sine wave is added to add the third harmonic in the Inverter whose sine wave amplitude is 230*1.414/6 and its frequency is 3 times of rated frequency. For a close loop we take the speed as a feedback and compare to the reference speed and then the speed error again added with the rotor speed and its output is change into the Gate Pulse of the MOSFET.

5. SPACE VECTOR PULSE WIDTH MODULATION (SVPWM)

This technique is very useful for reducing the Total Harmonic Distortion. This technique is characterized by the constant amplitude pulse. And the width of these pulse is modulated to get Inverter output Voltage control and to reduce its harmonic content. The topology of three leg Voltage Source Inverter because of the constraint that the input line must never be shored and the output current must be always be continuous a Voltage Source Inverter can assume only eight distinct sectors. Six out of these eight sectors produces a non-zero output voltage and are known as non-zero switching states and the remaining two sectors produces zero voltage are known as zero switching states.

The SVPWM can be implemented by using wither sector selection algorithm or by using a carrier based space vector algorithm.
The types of SVPWM implementations are:
a) Sector selection
b) Reduced switching
c) Carrier based
d) Reduced switching carrier based

- Sector selection of SVPWM : -

Step1. Determine V_d, V_q, V_{ref}, and angle μ
Step2. Determine time duration T1, T2, T0
Step3. Determine the switching time of each IGBT (S1 to S6)
For Step 1, Refer Figure 2

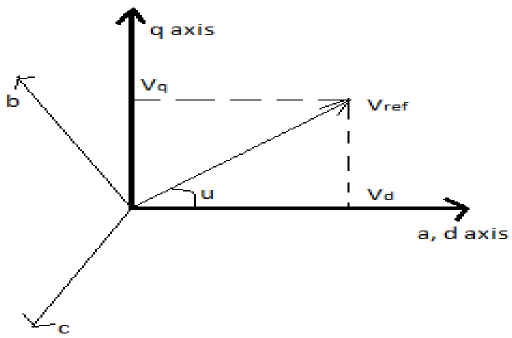

Figure 2. V_d, V_q, V_{ref}, and μ can determine

$$V_d=V_{an}-0.5*V_{bn}-0.5*V_{cn} \tag{7}$$

$$V_q=0+0.866*V_{bn}-0.866*V_{cn} \tag{8}$$

$$V_{ref}=\sqrt{(V_d^2+V_q^2)} \tag{9}$$

$$\mu=\tan^{-1}(V_q/V_d)=wt=2\pi ft \tag{10}$$

For Step 2, Refer Figure 3 which shows the switching time during a sector1

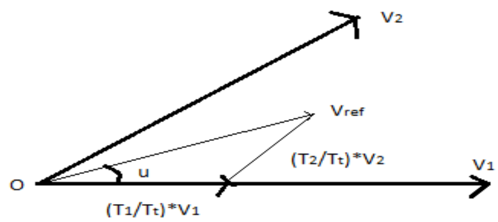

Figure 3. Reference vector as a combination of adjacent vectors at sector

Switching time duration at sector 1

$$\int_0^{Tt} Vref\ dt=\int_0^{T1} V1\,dt+\int_{T1}^{T1+T2} V2\,dt+\int_{T1+T2}^{Tt} V0\,dt \tag{11}$$

$$T_t*V_{ref} = (T_1 *V_1 + T_2* V_2) \quad (12)$$

$$T_{t*} |V_{ref}|* \cos (\mu) = T_1* 2/3*V_{dc} + V_2*2/3 *\cos (\pi/3) \quad (13)$$

$$T_{t*}|V_{ref}|*\cos (\mu) = V_2*0.667*\sin(\pi/3) \quad (14)$$

Where, $(0 <= \mu <= 60^o)$

$$T_1 = T_t*\mu*(\sin (\pi/3-\mu) / \sin (\pi/3)) \quad (15)$$

$$T_2 = T_t*\mu*(\sin (\mu) / \sin (\pi/3)) \quad (16)$$

$$T_0 = T_t – (T_1 + T_2) \quad (17)$$

Where, $T_t = 1/f_t$ and $\mu= |V_{ref}| / (0.667*V_{dc})$
For step 3 refer Table 2

Table 2. Switching Time Calculation at Each sector

Sector	Upper Switches (S1, S3, S5)	Lower Switches (S4, S6, S2)
1	$S1=T_1 + T_2 + T_0/2$ $S3= T_2 + T_0/2$ $S5= T_0/2$	$S4= T_0/2$ $S6= T_1 + T_0/2$ $S2= T_1 + T_2 + T_0/2$
2	$S1= T_1 + T_0/2$ $S3= T_1 + T_2 + T_0/2$ $S5= T_0/2$	$S4= T_2 + T_0/2$ $S6= T_0/2$ $S2= T_1 + T_2 + T_0/2$
3	$S1= T_0/2$ $S3= T_1 + T_2 + T_0/2$ $S5= T_2 + T_0/2$	$S4= T_1 + T_2 + T_0/2$ $S6= T_0/2$ $S2= T_1 + T_0/2$
4	$S1= T_0/2$ $S3= T_1 + T_0/2$ $S5= T_1 + T_2 + T_0/2$	$S4= T_1 + T_2 + T_0/2$ $S6= T_2 + T_0/2$ $S2= T_0/2$
5	$S1= T_2 + T_0/2$ $S3= T_0/2$ $S5= T_1 + T_2 + T_0/2$	$S4= T_1 + T_0/2$ $S6= T_1 + T_2 + T_0/2$ $S2= T_0/2$
6	$S1= T_1 + T_2 + T_0/2$ $S3= T_0/2$ $S5= T_1 + T_0/2$	$S4= T_0/2$ $S6= T_1 + T_2 + T_0/2$ $S2= T_2 + T_0/2$

6. SIMULATION MODEL PARAMETER

Specification of model. Refer Table 3.

Table 3. Model parameter and Specification

Inverter Power Supply	400 V DC	
Induction Motor parameter	Stator Resistance	1.5ohm
	Stator Inductance	0.0354 Henry
	Rotor Resistance	0.5 ohm
	Rotor Inductance	0.0354 Henry
	Mutual Inductance	0.0104 Henry
	Nominal Power	5.15 hp
	Rated RMS Voltage	330±10 VOLTS
	Rated Speed	1500 rpm
	Pole	4
	Slip	2%
	Moment of Inertia	0.0488 Kg*m^2
	Load Torque (Step in Nature)	25 Nm

7. SIMULINK MODEL AND WAVEFORM

Figure 4 shows the complete Simulink model of Close loop control of Induction Motor with different different Inverter technique. Figure 5, 7, and 9 shows the Torque and Speed Characterstics with respect to time and Figure 6, 8, and 10 shows the Stator current of the Induction Motor THD when SPWM, THIPWM, and SVPWM technique is employed respectively.

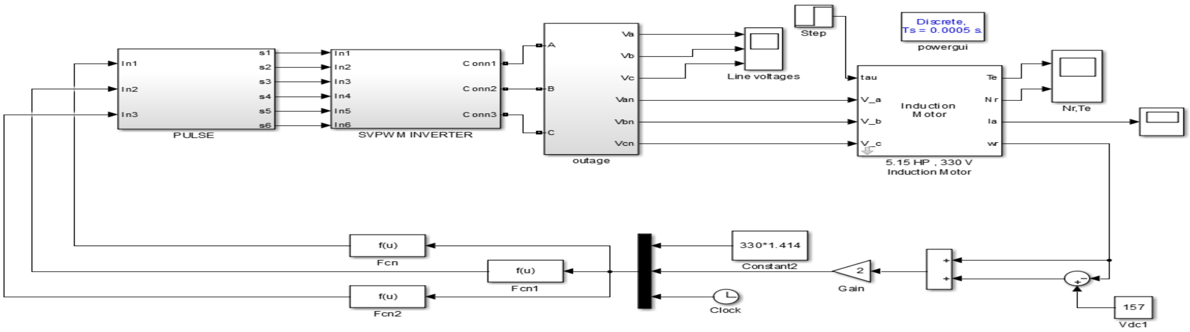

Figure 4. Close loop Inverter with IM Load

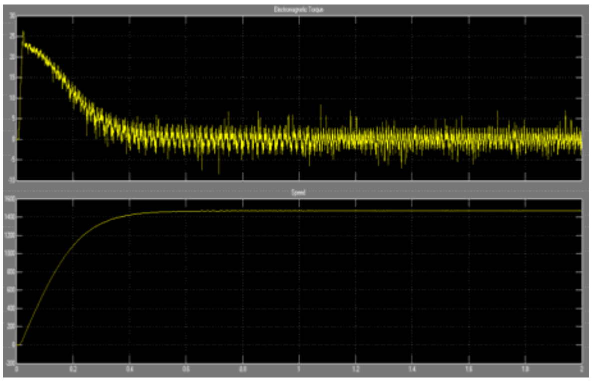

Figure 5. Two level SPWM INVERTER Torque and Speed

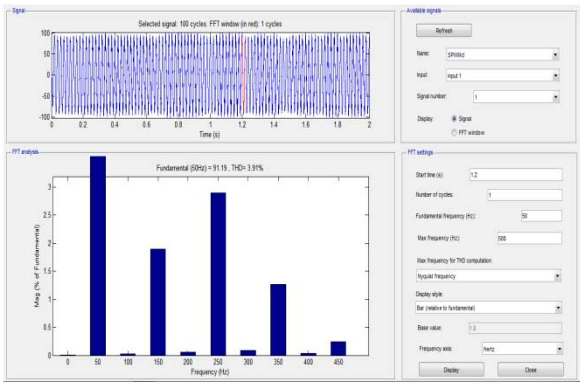

Figure 8. SPWM Stator current THD

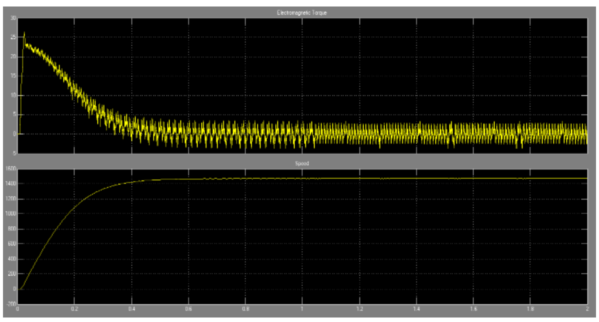

Figure 6. Two level THIPWM INVERTER Torque and Speed

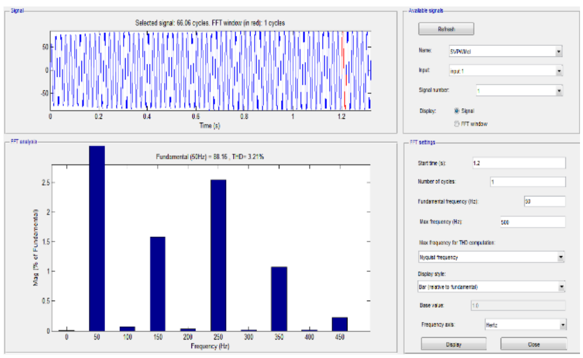

Figure 9. THIPWM Stator current THD

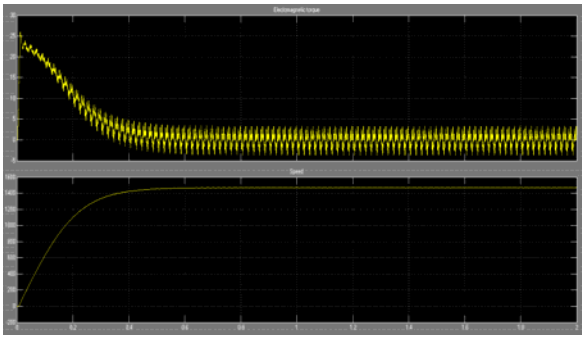

Figure 7. Two level SVPWM INVERTER Torque and Speed

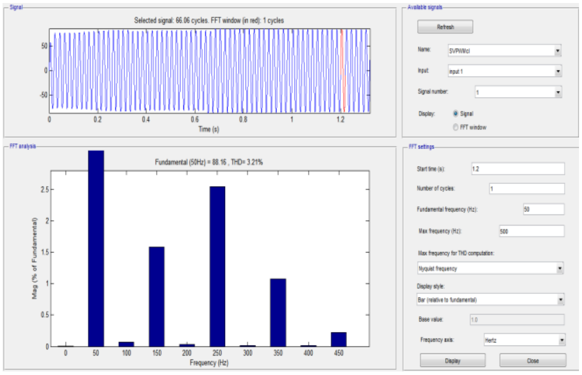

Figure 10. SVPWM Stator Current THD

8. RESULTS

Table 4 shows the Stator Current of Induction Motor THD with respect there techniques which are employed. And the result shows the SVPWM technique has better waveform as compre to SPWM and THIPWM.

Table 4. THD results

LEVEL	TECHNIQUE	LOAD	THD%
	SPWM	**IM**	3.91
TWO	**THIPWM**	**IM**	3.61
	SVPWM	**IM**	3.21

9. CONCLUSION

With the help of simulation result we can conclude that SVPWM (Space Vector Pulse Width Modulation) technique is better than the THIPWM (Third Harmonic Injection Pulse Width Modulation) technique and SPWM (Sinusoidal Pulse Width Modulation) technique. The THD of Stator current of SVPWM Inverter is less so its industrial application is better than the THIPM Inverter and SPWM Inverter. But the rise time of SVPWM Inverter is more as compare to THIPWM and SPWM Inverter that is 1.5 sec, 0.385sec and 0.4 sec simulation time respectively. The system is free from the PID controller. So the controlling cost of the Induction Motor is cheap. We know that PID controller is 85% efficient. But this Simulink model is 90-95% efficient.

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