International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 5, Issue 11, November 2015)

Comparison of Various PWM Techniques for Field Oriented Control VSI Fed PMSM Drive

B. V. R. Uday Kiran
[1]Raghu Institute of Technology, Visakhapatnam, India

***Abstract*-- In this paper, the design of a consistent control strategy for a PMSM. To meet this objective we started our work with the modeling concept and found the modeling equations for a PMSM and later it is converted into a SIMULINK model. Later, the field oriented control (FOC) strategy is modeled using three Pulse Width Modulation (PWM) techniques. Considering the advantages and disadvantages of each method the three methods are compared to each other in various aspects and finally concluded which method of FOC is advantageous in various applications. Simulation and experimental results show the effectiveness of the proposed control methods.**

***Keywords*-- PWM, FOC, SPWM, THIPWM, SVPWM, Three phase Inverter.**

I. Introduction

Permanent magnets have been employed as an alternative to current carrying coils for magnetic field excitation in synchronous machines for over 30 years. The lack of slip rings, brushes and field winding losses have always been viewed as distinct advantages over that of conventional, wound field machines. Early applications included the use of Alnico magnets in small generators. The squirrel cage IM carries current only during starting since steady state operation is at synchronous speed thereby eliminating all steady state rotor I^2R losses which are naturally present in an induction motor. This elimination of rotor conductor loss coupled with a reduced requirement of armature magnetizing current and its associated copper loss was the main impetus for proposing the buried magnet, line start motor as a replacement for high efficiency induction motors in low power applications. Many prototype permanent magnet motors of this type were built and at least one such motor reached the market in early 1970's [14].

Industry automation is mainly developed around motion control systems in which controlled electric motors play a crucial role as heart of the system [3][4]. Therefore, the high performance motor control systems contribute, to a great extent, to the desirable performance of automated manufacturing sector by enhancing the production rate and the quality of products [6].

The popularity of PMSMs comes from their desirable features:

- High efficiency and Lower maintenance cost
- High torque to inertia ratio and High torque to volume ratio
- High air gap flux density and High power factor
- High acceleration and deceleration rates
- Simplicity ,ruggedness and Compact structure
- Linear response in the effective input voltage

In permanent magnet (PM) synchronous motors, permanent magnets are mounted inside or outside of the rotor. Unlike DC brush motors, every brushless DC (so called BLDC) and permanent magnet synchronous motor requires a "drive" to supply commutated current. This is obtained by pulse width modulation of the DC bus using a DC-to-AC inverter attached to the motor windings. The windings must be synchronized with the rotor position by using position sensors or through sensor less position estimation techniques. By energizing specific windings in the stator, based on the position of the rotor, a rotating magnetic field is generated. In permanent magnet ac motors with sinusoidal current excitation (so called PMSM), all the phases of the stator windings carry current at any instant, but in permanent magnet AC motors with quasi-square wave current excitation (BLDC) only two of the three stator windings are energized in each commutation sequence.

In both motors, currents are switched in a predetermined sequence and hence the permanent magnets that provide a constant magnetic field on the rotor follow the rotating stator magnetic field at a constant speed. This speed is dependent on the applied frequency and pole number of the motor. Since the switching frequency is derived from the rotor, the motor cannot lose its synchronism. The current is always switched before the permanent magnets catch up; therefore the speed of the motor is directly proportional to the current switching rate.

II. Pulse Width Modualtion

2.1 Introduction

Pulse-width modulation (PWM) is a technique where the duty ratio of a pulsating waveform 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.

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 5, Issue 11, November 2015)

There is no single PWM method that is the best suited for all applications and with advances in solid-state power electronic devices and microprocessors, various pulse-width modulation (PWM) techniques have been developed for industrial applications. For these reasons, the PWM techniques have been the subject of intensive research since 1970s.

In this paper for Field Oriented Control (FOC) strategy, three Pulse Width Modulation (PWM) techniques are used. They are :

1. Sinusoidal Pulse Width Modulation
2. Third Harmonic Injection Pulse Width Modulation
3. Space Vector Pulse Width Modulation

2.2. Sinusoidal Pulse Width Modulation

The sinusoidal pulse-width modulation (SPWM) technique produces a sinusoidal waveform by filtering an output pulse waveform with varying width. A high switching frequency leads to a better filtered sinusoidal output waveform. The desired output voltage is achieved by varying the frequency and amplitude of a reference or modulating voltage. The variations in the amplitude and frequency of the reference voltage change the pulse-width patterns of the output voltage but keep the sinusoidal modulation. As shown in figure (2.1), 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 120^0 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 3.4 The outputs of the comparators in Figure (2.1) form 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.

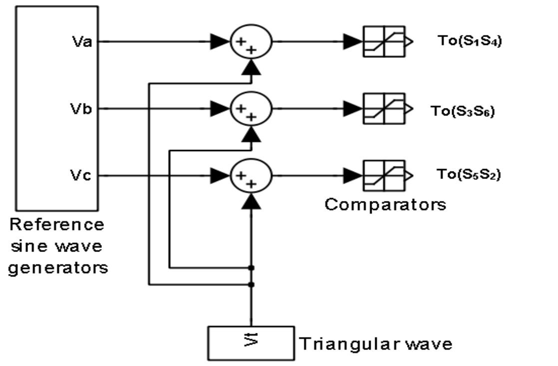

Fig 2.1.Control Signal Generator for SPWM

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 $V_{A0}>V_T$ S_4 is ON when $V_{A0}<V_T$

S_3 is ON when $V_{B0}>V_T$ S_6 is ON when $V_{B0}<V_T$

S_5 is ON when $V_{C0}>V_T$ S_2 is ON when $V_{C0}<V_T$.

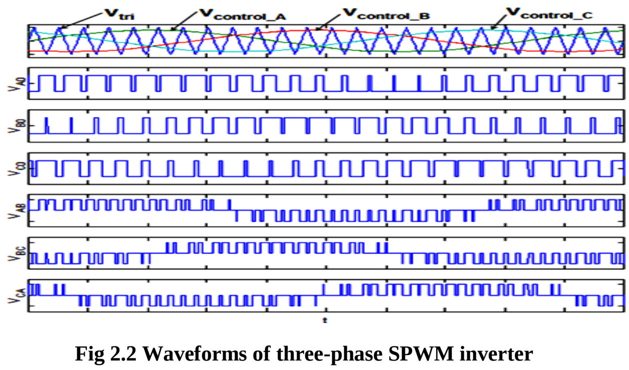

Fig 2.2 Waveforms of three-phase SPWM inverter

As seen in Figure 2.2, the pulse widths depend on the intersection of the triangular and sinusoidal waveforms.

2.3 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.

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 5, Issue 11, November 2015)

Due to this problem, the third-harmonic injection pulse-width modulation (THIPWM) technique was developed to improve the inverter performance. The inverter fundamental voltage V_{AB} can also be increased by adding a third harmonic component to the three-phase sinusoidal modulating wave without causing over modulation. This modulation technique is known as third harmonic injection PWM.

Table2.1

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

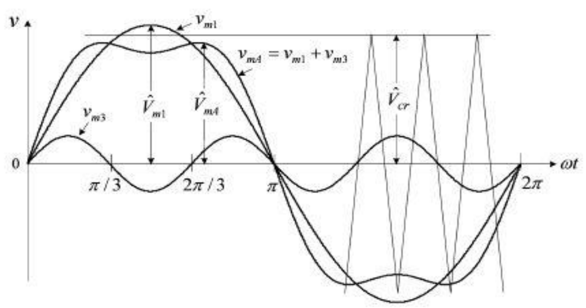

Fig 2.3 Third Harmonic Injected Sine wave

The modulating signal with third and ninth harmonic injections is shown in above figure it should be noted that the injection of third harmonics doesn't affects the quality of the output voltages, because the output of three phase inverter dose not contains triplen harmonics. If only the third harmonics is injected, v_r is given by

$$v_r = 1.15 \sin \omega t + 0.19 \sin 3\omega t$$

The injected third harmonic component *vm*3 will not increase the harmonic distortion for V_{AB}. Although it appears in each of the inverter terminal voltages V_{AN}, V_{BN} and V_{CN}, the third-order harmonic voltage does not exist in the line-to-line voltage V_{AB}. This is because the line-to-line voltage is given by $V_{AB} = V_{AN} - V_{BN}$, where the third-order harmonics in V_{AN} and V_{BN} are of zero sequence with the same magnitude and phase displacement and thus cancel each other.

2.4 Space Vector Pulse Width Modulation

Another method for increasing the output voltage about that of the SPWM technique is the space vector PWM (SVPWM) technique. In the SVPWM technique, the duty cycles are computed rather than derived through comparison as in SPWM. The SVPWM technique can increase the fundamental component by up to 27.39% that of SPWM. The fundamental voltage can be increased up to a square wave mode where a modulation index of unity is reached.

SVPWM is accomplished by rotating a reference vector around the state diagram, which is composed of six basic non-zero vectors forming a hexagon. A circle can be inscribed inside the state map and corresponds to sinusoidal operation. The area inside the inscribed circle is called the linear modulation region or under-modulation region. As seen in Figure 5.1, the area between the inside circle and outside circle of the hexagon is called the nonlinear modulation region or over-modulation region. The concepts in the operation of linear and nonlinear modulation regions depend on the modulation index, which indirectly reflects on the inverter utilization capability.

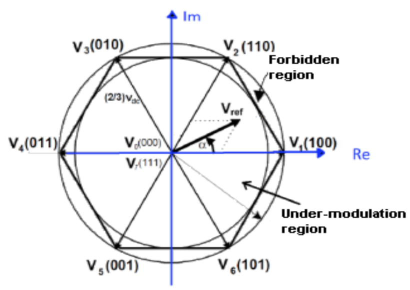

Fig 2.4 Under and Over Modulating regions of Space Vector representation

Principle of Space Vector Pwm

The circuit model of a typical three-phase voltage source PWM inverter is shown in Figure 5.2, S_1 to S_6 are the six power switches that shape the output, which are controlled by the switching variables a, a′, b, b′, c and c′. When an upper transistor is switched on, i.e., when a, b or c is 1, the corresponding lower transistor is switched off, i.e., the corresponding a′, b′ or c′ is 0. Therefore, the on and off states of the upper transistors S1, S3 and S5 can be used to determine the output voltage.

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 5, Issue 11, November 2015)

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

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

Also, the relationship between the switching variable vector $[a, b, c]^T$ and the phase voltage vector $[V_a\ V_b\ V_c]^T$ can be expressed below.

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad \text{--(2)}$$

As illustrated in figure 5.3, there are eight possible combinations of on and off patterns for the three upper power switches. The on and off states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power transistors are determined. According to equations stated above the eight switching vectors, output line to neutral voltage (phase voltage), and output line-to-line voltages in terms of DC-link Vdc, are given in Table 2.1 and figure 2.6 shows the eight inverter voltage vectors (V_0 to V_7).

Note: The respective voltage should be multiplied by V_{dc}

Table 2.1 Switching vectors, Phase voltages and output line to line voltages.

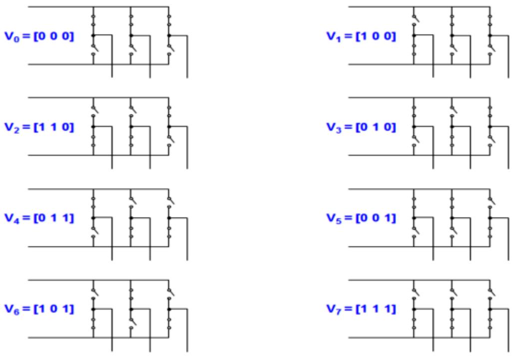

Fig 2.6 The eight inverter voltage vectors (V_0 to V_7)

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 2.6.

III. CONTROL STRATEGIES FOR PMSM

Synchronous motors have to be driven by a Variable Frequency Drive (VFD) to be able to run at different speeds. Control methods for electric motors can be divided into two main categories depending upon what quantities they control. The control algorithm, Scalar Control controls only magnitude, whereas the Vector Control controls both magnitude and angles. These two main methods can be further divided into a number of different methods depending upon their functionality.

3.1 Field Oriented Control

Early AC machine drives employed the constant volts-per-hertz (constant V/f) operation principle. The performance of the constant volts-per-hertz method was sufficient for fan and pump applications. However, it was not suitable for the applications requiring high motion quality such as high sensitive speed and position controls. The new generation AC machine drives use modern control techniques which provide high motion quality and high bandwidth in torque, speed, and position control. The field oriented control method is used in most of the AC motor drives to obtain high torque bandwidth and control performance.

The principle of field oriented control of electrical drives is based on the control of both the magnitude and the phase of each phase current and voltage waveforms. In the field oriented control (FOC), phase currents and voltages are represented by vectors. In this control technique, some projections which transform a three-phase speed dependent system into a two co-ordinate (*d* and *q* co-ordinates) time invariant system are used to provide great simplification in expression of control equations. These transformations lead to a structure similar to that of a DC machine control

In Field Oriented Control the goal is to control the direct and quadrature-axis current i_d and i_q to achieve the requested torque.. By controlling i_d and i_q independently it's possible to achieve a Maximum Torque Per Ampere ratio (MPTA) to minimize the current needed for a specific torque, which maximizes the motors efficiency.
The torque balance equation,

$$\frac{2}{P} Jp\omega_r = T_e - T_l - \frac{2}{P}\beta\omega_r$$

For a non-salient machine i.e. $L_d = L_q$, the control is easy to implement. From equation it can be seen that a motor without saliency cannot produce any reluctance torque. The i_d has therefore no effect on torque production, and it needs to be zero at all times to reach MPTA. The torque curves will be linear in the *dq0*-plane and the MPTA trajectory will be along the quadrature-axis.

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 5, Issue 11, November 2015)

For a salient machine, i.e. $L_d \neq L_q$ the control is a bit more difficult to implement since the motor produces both electromechanical and reluctance torque. That's why the torque as a function of current in the dq0-plane is no longer linear. To reach MPTA, the minimum distance from the origin to the curve of requested torque has to be calculated.

One of the critical parameters for FOC is the need of correct information of the motors position. The most common way to do this is Indirect FOC (IFO), where a mechanical sensor coupled to the motors shaft is used for positioning. Another type is Direct FOC (DFO) where the position is estimated from the flux- or back EMF vector.

Field oriented controlled machines need two input references. These are the torque component (aligned with the q-axis) and the flux component (aligned with d-axis). The aim of FOC is to perform real time control of torque and flux components separately. As stated above, to perform field oriented control, the control equations are projected from a three-phase non-rotating frame into a two co-ordinate rotating frame by using mathematical transformations. The mathematical transformations have been named as Clarke and Park transformations which simplify the expression of control equations and removes time dependencies. The good torque response, accurate speed control and full torque capability at zero speed are the advantages. The block diagram shown in figure 3.1 illustrates a permanent magnet synchronous motor control scheme based on field orientation principle.

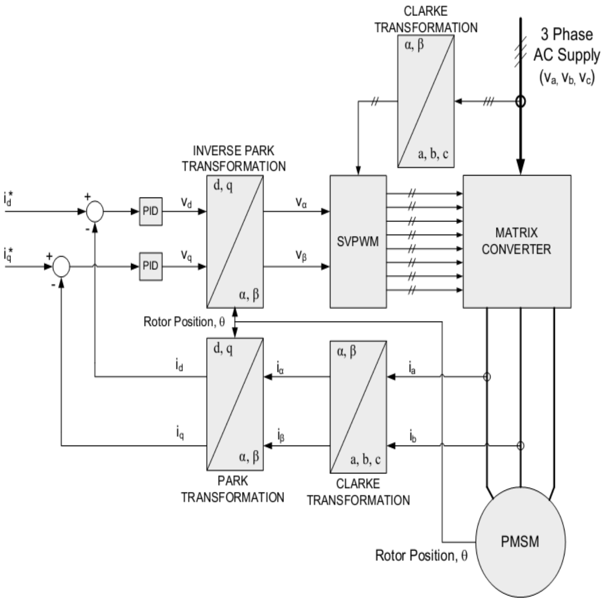

Fig 3.1 Scheme of SVPWM based on FOC for PMSM

As illustrated in the figure3.2, there are eight possible combinations of on and off patterns for the three upper power switches. The on and off states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power transistors are determined. According to equations stated above the eight switching vectors, output line to neutral voltage (phase voltage), and output line-to-line voltages in terms of DC-link V_{dc}, are given in Table2.1 and figure 3.2 shows the eight inverter voltage vectors (V_0 to V_7).

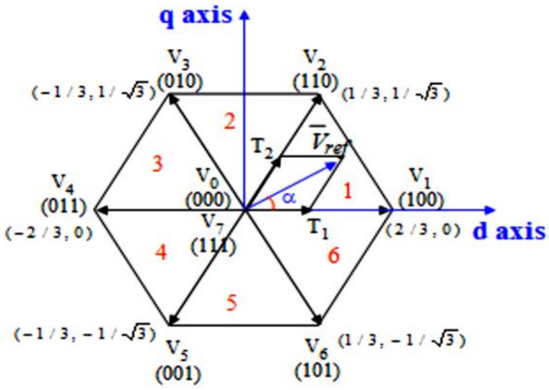

Fig 3.2 Basic switching vectors and sectors

IV. Simulation And Result Analysis

3.1 Simulation Models Of Field Oriented Control For Pmsm Based On Various Pwm Techniques

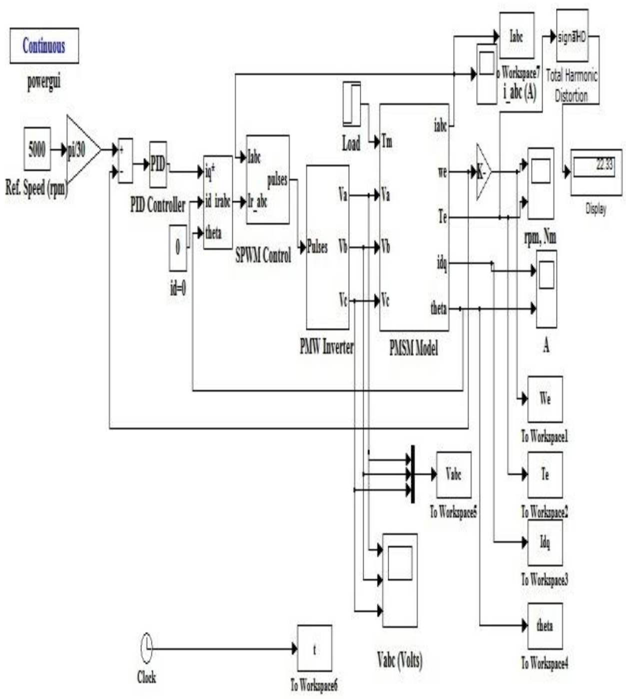

Fig 4.1 Simulation model of FOC for PMSM based on SPWM technique

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 5, Issue 11, November 2015)

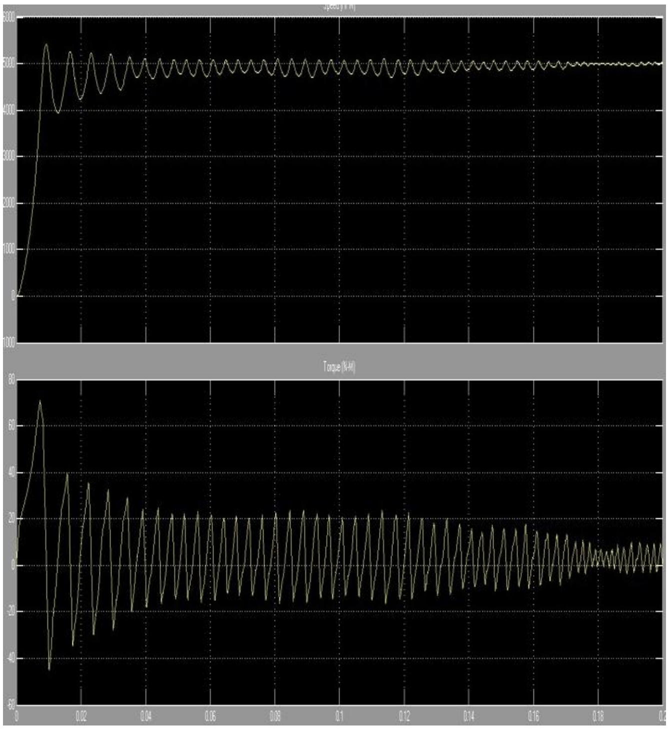

Fig 4.2 Speed-Torque characteristics for SPWM based FOC of PMSM

The torque characteristics for SPWM based FOC of PMSM has more number of oscillations and in speed characteristics it take more time to attain steady state position which can be seen in the figure 4.2

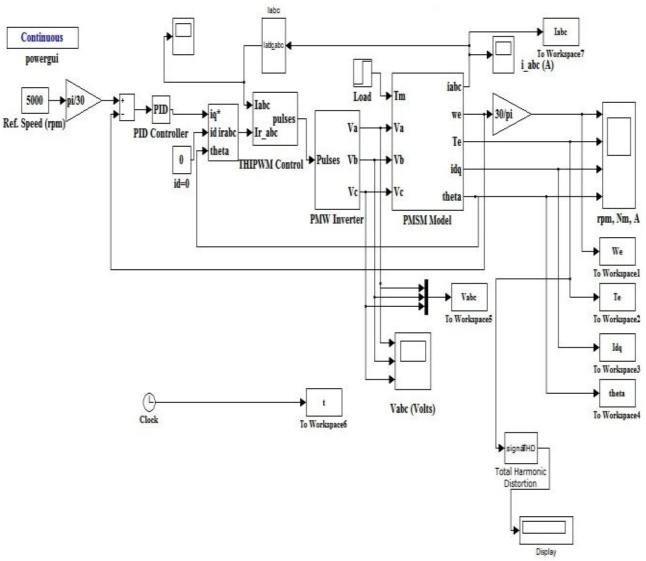

Fig 4.3 Simulation model of FOC for PMSM based on THIPWM technique

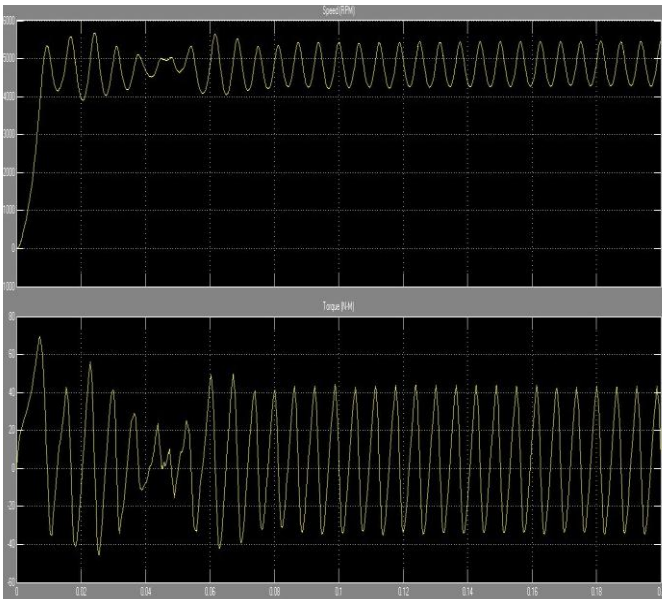

Fig 4.4 Speed-Torque characteristics for THIPWM based FOC of PMSM

The torque characteristics for Third Harmonic Injection PWM based FOC of PMSM has more number of oscillations compared to Sine PWM and in speed characteristics it has never attained a steady state position, as shown in the figure 4.4.

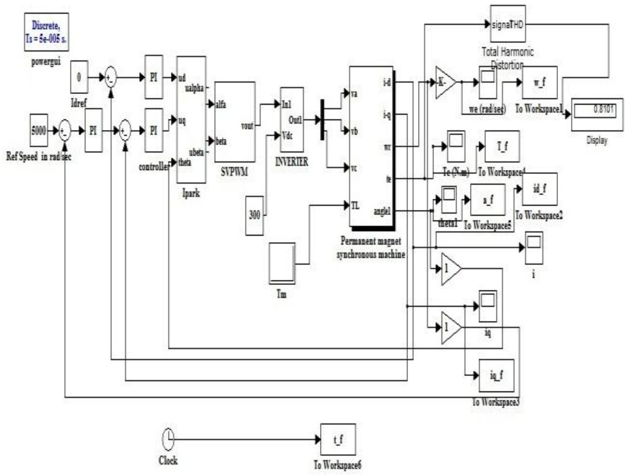

Fig 4.5 Simulation model of FOC for PMSM based on SVPWM technique

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 5, Issue 11, November 2015)

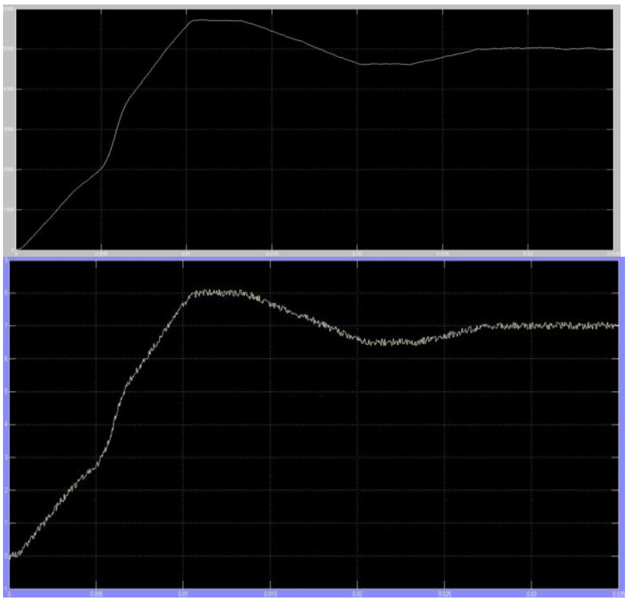

Fig 4.6 Speed-Torque characteristics for SVPWM based FOC of PMSM

The torque characteristics for Space Vector PWM based FOC of PMSM has less number of oscillations compared to Sine PWM and in speed characteristics it has attained a steady state position with in no time, as shown in the figure 4.6

Comparison of Total Harmonic Distortion of various PWM techniques for FOC of PMSM

Table 4.1

PWM technique	Sine PWM	Space Vector PWM	Third Harmonic Injection PWM
THD	28.79	12.47	4.59

V. Result

In this paper the field oriented control strategies of VSI fed PMSM drive using various PWM methods are studied. First the sinusoidal PWM technique is used and the speed torque characteristics, total harmonic distortion are calculated. Second the third harmonic injection PWM technique is used and the speed torque characteristics, total harmonic distortion is calculated. Finally the space vector PWM technique is used and the speed torque characteristics, total harmonic distortion are calculated. All the results obtained are compared with each other to know the best PWM technique for field oriented control strategy.

APPENDIX

Motor Data

$R_s = 1.6$;

$L_d = 0.006365$;

$L_q = 0.006365$;

Flux = 0.1852;

J = 0.0001854;

P = 8;

f = 50;

$V_{rms} = 220$;

REFERENCES

[1] M. S. Merzoug, and F. Naceri "Comparison of Field-Oriented Control and Direct Torque Control for Permanent Magnet Synchronous Motor (PMSM)" World Academy of Science, Engineering and Technology 21 2008

[2] Raja Ram Kumar, Sunil Kumar, Alok Yadav "Comparison of PWM Techniques and Inverter Performance," IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE), ISSN: 2278-1676 Volume 4, Issue 1 (Jan. - Feb. 2013), PP 18-22.

[3] Kiran Boby, Prof.Acy M Kottalil, N.P.Ananthamoorthy "Mathematical Modeling of PMSM Vector Control System Based on SVPWM with PI Controller Using MATLAB" International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering Vol. 2, Issue 1, January

[4] M. Malek, J. Vittek, V. Vavrúš, M. Štulrajter "Application Of Space Vector Modulation in Direct Torque Control Of PMSM" Advances in Electrical and Electronic Engineering.

[5] M. Malek, J. Vittek, V. Vavrúš, M. Štulrajter "Application Of Space Vector Modulation in Direct Torque Control Of PMSM" Advances in Electrical and Electronic Engineering.

[6] Joachim Boecker, 'Modeling and Control of Permanent Magnet Synchronous Motors', Tutorial Proposal EPE-PEMC, 2006.

[7] P. Brandstetter, P. Rech, and P. Simonik, 'Sensorless Control of Permanent Magnet Synchronous Motor Using Luenberger Observer', PIERS Proceedings, Cambridge, USA, July 5-8, 2010.

[8] Pradeep K. Nandam, AND Paresh C. Sen, 'A Comparative Study of a Luenberger Observer and Adaptive Observer-Based Variable Structure Speed Control System Using a Self-Controlled Synchronous Motor', IEEE transactions on industrial electronics, APRIL 1990.

[9] P.Ramana, B.Santhosh Kumar, K.Alice Mary and M.Surya Kalavathi "Direct Torque Control Inverter Fed PMSM Drive using SVM" IJAIEM, Vol.2, Issue.7, pp.2928-2936.

[10] P.Ramana, B.Santhosh Kumar, K.Alice Mary and M.Surya Kalavathi "Comparison Of Various PWM Techniques For Field Oriented Control VSI Fed PMSM Drive" IJAREEIE, Vol.2, Issue.7, pp.2928-2936.

[11] Junfeng Xu, Yinglei Xu, Jiangpin Xu, Jianghua Feng and Fengyan Wang, 'Direct torque control of Permanent Magnet Synchronous Machines using Stator flux Full order State Observer, IEEE transactions, 2004.

[12] Khwaja M. Rahman and Silva Hiti, 'Identification of Machine parameters of a Synchronous Motor', IEEE transactions, 2003.

[13] K. Alice Mary, 'Speed Control of An SPWM inverter Driven Non Linear PMSM Drive with Pole Placement Technique-11', IEEE International conference on Electrical energy systems and power electronics in emerging economics ICEESPEEE 2009. SRM University, Chennai 16-17 April 2009

[14] K. Alice Mary, 'Design performance of the speed control systems for inverter driven Nonlinear Permanent magnet synchronous motor using exact feedback linearization', 1st international conference on computer communications, control and information technology" C3it, 2009, Academy of technology,Calcutta,06-07-feb2009.

[15] P. S. Bimbra, 'Generalized theory of Electrical machines', Khanna Publishers.

[16] Paul C. Krause, 'Analysis of Electrical Machinery and drive systems', 2nd edition, Wiley Inter science A John wiley and sons; INC Publications.