IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331,
PP 29-34
www.iosrjournals.org

Closed Loop Speed Control Analysis of FSTPI And SSTPI Inverter Fed PMSM Using SVPWM

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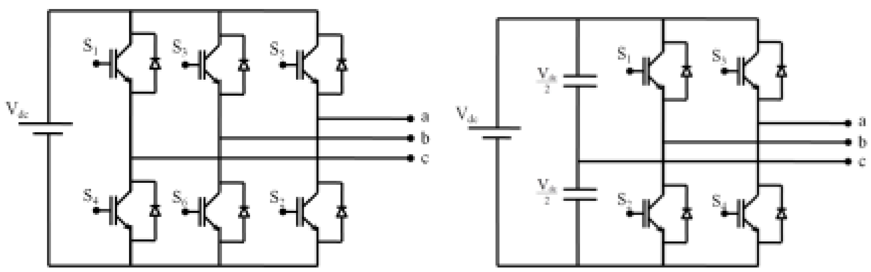
Abstract : *Due to recent developments in the area of power electronics, semi-conductor based inverters have been widely used in variable frequency drive applications. The speed control of various industrial drives is achieved by controlling the power semi-conductor switches in the inverters. Three phase inverters with six switches- Six Switch Three Phase Inverter (SSTPI) have been conventionally used over years. In order to reduce the switch count and thereby switching losses Four Switch Three Phase Inverters (FSTPI) have been introduced. In this paper, a closed loop speed control of SSTPI and FSTPI fed PMSM based on SVPWM is presented. Compared to conventional PWM techniques, SVPWM is the most promising technology in the field of variable frequency drives. SVPWM technique is adopted due to its inherent advantages such as easier digital realization, reduced harmonics, reduced switching losses and better dc bus utilization. The simulation of closed loop speed control of SSTPI and FSTPI fed PMSM using SVPWM is also presented in this paper based on the mathematical modelling in MATLAB/SIMULINK.*
Keywords : *Six Switch Three Phase Inverter (SSTPI), Four Switch Three Phase Inverter (FSTPI), Space Vector Pulse Width Modulation (SVPWM), Permanent Magnet Synchronous Motor (PMSM).*

I. INTRODUCTION

Recently variable frequency drives (VFD) are commonly used in various industrial applications. The recent progress in power semiconductor device technology has reduced VFD cost and size and has improved performance through advances in semiconductor switching devices, drive topologies, and control techniques. Three phase inverters done a major role in variable speed drives, hence it gained increasing popularity in variety of applications. Inverters with reduced number of switches need significant research attention in recent years due to reduction in switching losses, lower electromagnetic interference (EMI), less complexity of control circuitry etc [1]-[4]. A conventional three phase inverter has six switches with two complementary switches on each leg and hence it is known as Six Switch Three Phase Inverter (SSTPI) topology. In order to reduce the switch count, Four Switch Three Phase Inverter (FSTPI) topology is developed by replacing two switches in one leg with two capacitors as shown in Fig. 1(b). In this paper, a comparative closed loop study of SSTPI and FSTPI is presented.



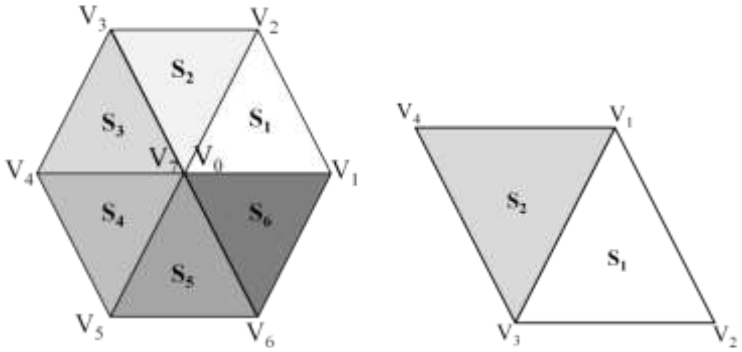
(a) SSTP Inverter (b) FSTP Inverter

Fig.1. Six Switch and Four Switch three phase inverters

Various pulse width modulation (PWM) techniques are utilized for the efficient operation of voltage source inverters [5]-[8]. Commonly used PWM technique is Sinusoidal Pulse Width Modulation where the sine wave is compared with triangular carrier signals. Space Vector PWM (SVPWM) is emerged as most efficient technique due to its inherent advantages of better dc voltage utilization reduced switching losses, lower harmonic distortion and easier implementation. In SVPWM the reference voltage space vector synthesized by switching three nearest voltage space vectors and the pulses are generated by comparing space vector signals with triangular signals [8]-[10]. With the development of advanced DSPs, the implementation SVPWM technique is become simpler. For servo drive applications, Permanent Magnet Synchronous Motors (PMSM) are emerged as an alternative to induction motors, due to the advantages such as high efficiency due to reduced losses, high torque to inertia ratio, high power density and low maintenance. The speed control of PMSM using semi conductor inverters have been the focal point of research in the last few decades. This paper the closed loop speed control of FSTPI and SSTPI fed PMSM using SVPWM is presented.

II. SVPWM FOR SSTPI AND FSTPI

In SVPWM the space vector signal is compared with the triangular carrier signal to generate the pulses which control the ON and OFF states of semiconductor switches in the inverter. The reference space vector is generated by combining three reference phase voltages, hence in SVPWM the inverter circuit is considered as a single unit. The triangle formed by the three voltage space vectors as vertices is known as sector. In SVPWM, the sector is identified first where the reference space vector lies and is synthesized by switching the nearest three voltage space vectors of the sector. Space vector representation of SSTPI and FSTPI are shown in Fig. 2. In SSTPI, only three upper switches are controlled to determine the output voltage, hence total eight voltage space vectors, V_0-V_7 are present as shown in Fig 2(a). Out of this eight vectors, six vectors (V_1 to V_6) are non-zero vectors and two vectors (V_0 & V_7) are zero vectors. All these 8 vectors form 6 sectors (S_1 to S_6) where each sector contains three voltage space vectors as vertices. But in FSTPI two complementary switches in one leg in replaced by two capacitors and the output voltage is controlled by controlling the two upper switches. Hence the total voltage vector space vector is four, V_1 to V_4 and they from two sectors as shown in Fig. 2(b).



a) Space Vector representation of SSTPI (b) Space Vector representation of FSTPI

Fig.2. Space Vector representation of SSTPI and FSTPI

The implementation of SVPWM using proposed algorithm involves the following steps: (i) Identification of sector which encloses the tip of the reference space vector (ii) Determination of inverter switching vectors and corresponding switching states (iii) Computation of duration of the three switching voltage vectors.

SVPWM generation starts with identification of sector in which tip of the instantaneous reference space vector lies. The reference space vector is represented in (α, β) plane and is obtained as the combined effect of three instantaneous reference space voltages V_a, V_b and V_c. . The complete procedure for sector identification without using any look up table is explained in ref [9]. Once the sector is identified, the switching states corresponding to the switching voltage vectors located at the vertices of the identified sectors are also generated simultaneously.

Next step in the generation of SVPWM involves computing the duration of switching voltage space vectors of the identified sector using volt-sec balancing technique [11]. The computed switching time equations for SSTPI and FSTPI are given in Table I and II respectively, where T_1 & T_2 are the duration of the non zero switching voltage space vectors. In SSTPI, duration of the zero vector, T_0 is determined as $T_0 = T_S-(T_1+T_2)$ where T_S is the sampling time period. From the determined T_1, T_2 and T_0 the actual inverter leg switching times, designated as T_{ga}, T_{gb}, and T_{gc}, for SSTPI are also determined as in the Table I. The T_{ga} T_{gb}, and T_{gc} signals are used to generate the three SVPWM signals which is compared with the triangular carrier signal to generate PWM pulses. In FSTPI two complementary switches in one leg is replaced with two capacitors, so only two gating signal time T_{ga} and T_{gb} is required which is compared with triangular carrier to generate SVPWM pulses. No zero vectors are present in FSTPI compared to SSTPI. In addition to this, the number of sectors is reduced to two in FSTPI; hence the circuit complexity is reduced.

Table I: Switching time equations for SSTPI

Sector	T_1	T_2	T_{ga}	T_{gb}	T_{gc}
S_1	$\left[V_\alpha - \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$\frac{2}{\sqrt{3}}V_\beta\, T_s$	$T_1+T_2+(T_0/2)$	$T_2+(T_0/2)$	$(T_0/2)$
S_2	$\left[-V_\alpha + \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$\left[V_\alpha + \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$T_2+(T_0/2)$	$T_1+T_2+(T_0/2)$	$(T_0/2)$
S_3	$\left[\frac{2}{\sqrt{3}}V_\beta\right]T_s$	$-\left[V_\alpha + \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$(T_0/2)$	$T_1+T_2+(T_0/2)$	$T_2+(T_0/2)$
S_4	$\left[-\frac{2}{\sqrt{3}}V_\beta\right]T_s$	$\left[-V_\alpha + \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$(T_0/2)$	$T_2+(T_0/2)$	$T_1+T_2+(T_0/2)$
S_5	$-\left[V_\alpha + \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$\left[V_\alpha - \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$T_2+(T_0/2)$	$(T_0/2)$	$T_1+T_2+(T_0/2)$
S_6	$\left[V_\alpha + \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$\left[-\frac{2}{\sqrt{3}}V_\beta\right]T_s$	$T_1+T_2+(T_0/2)$	$(T_0/2)$	$T_2+(T_0/2)$

Table II: Switching time equations for FSTPI

Sector	T_1	T_2	T_{ga}	T_{gb}
S_1	$\left[-V_\alpha + \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$\left[\frac{1}{2} + V_\alpha + \frac{1}{\sqrt{3}}V_\beta\right]T_s$	T_2	T_1+T_2
S_2	$\left[V_\alpha - \frac{1}{\sqrt{3}}V_\beta\right]T_s$	$\left[\frac{1}{2} + \frac{2}{\sqrt{3}}V_\beta\right]T_s$	T_1+T_2	T_2

III. MODELLING OF PMSM

Recently permanent magnet motors needs more attention where stator is a classical three phase induction motor and rotor has permanent magnets. The permanent magnet motors are classified in to two based on the induced back-emf. Permanent magnet motor with sinusoidal back-emf is known as Permanent Magnet Synchronous Motors (PMSM) and with trapezoidal back-emf is known as Brushless DC Motor (BLDC). The circuit of inverter fed PMSM is shown in the Fig. 3.

The electrical equation of the motor is, $V_{an} = Ri_a + (L-M)\frac{di_a}{dt} + e_a$

$$V_{bn} = Ri_b + (L-M)\frac{di_b}{dt} + e_b$$

$$V_{cn} = Ri_c + (L-M)\frac{di_c}{dt} + e_c$$

Where V_{an}, V_{bn}, V_{cn} are per phase voltages, i_a, i_b, i_c are per phase currents, e_a, e_b, e_c are per phase back-emf, R is per phase resistance and L, M are per phase self and mutual inductance respectively.

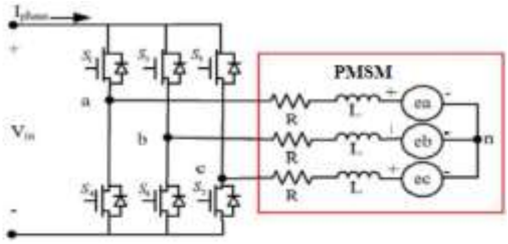


Fig.3. Inverter fed PMSM

The developed electromagnetic torque T_e is obtained as:

$$T_e = \frac{1}{\omega_r}\,(e_a i_a + e_b i_b + e_c i_c)$$

Where, ω_r is the mechanical speed of the rotor.

The mechanical equation of the motor with moment of inertia J, friction coefficient B and load torque T_L is:

$$J\frac{d\omega_r}{dt} + B\omega_r = T_e - T_L$$

$$\frac{d\omega_r}{dt} = \frac{1}{j}\,(T_e - T_L - B\,\omega_r)$$

The electrical rotor speed related to the mechanical speed for a motor with number of pole pairs, P:

$$\omega_e = P\,\omega_r$$

The rotor angle θ_r is:

$$\theta_r = \int \omega_e\, dt$$

The instantaneous induced EMFs can be written as given in equation:

$$e_a = \sin(\theta_r)\ K_b\ \omega_r$$

$$e_b = \sin\left(\theta_r - \frac{2\pi}{3}\right)\ K_b\ \omega_r$$

$$e_c = \sin\left(\theta_r + \frac{2\pi}{3}\right)\ K_b\ \omega_r$$

Where, K_b is the back-emf constant.

IV. SIMULATION AND ANALYSIS

The PMSM control system has dual closed loop control with outer loop for speed control and inner loop for current control. Simulation of closed loop speed control using SSTPI and FSTPI fed PMSM based on SVPWM is carried out using MATLAB/SIMULINK. Fig. 4 shows the simulink model of closed loop control of three phase inverter fed PMSM based on SVPWM.

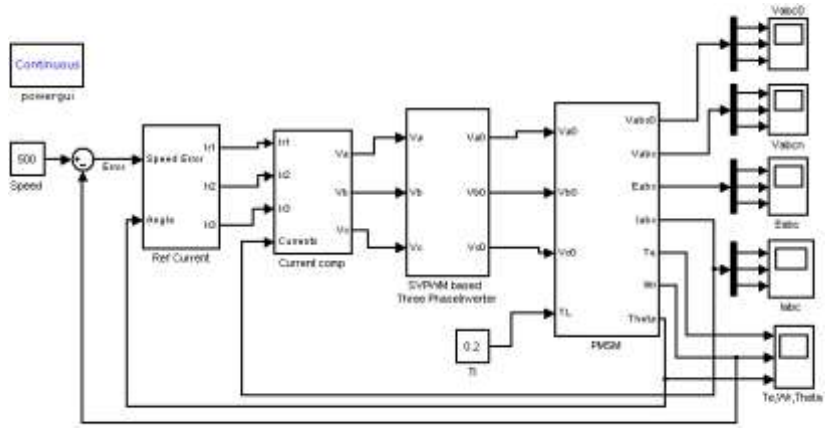
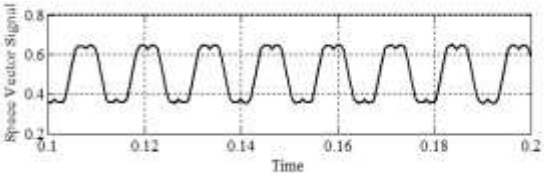
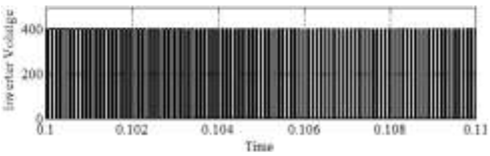


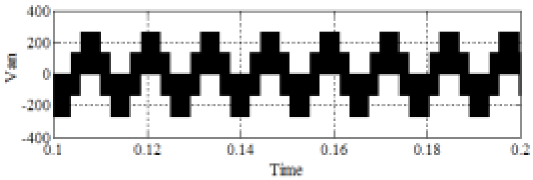
Fig.4. Simulink model of speed control of three phase inverter fed PMSM based on SVPWM

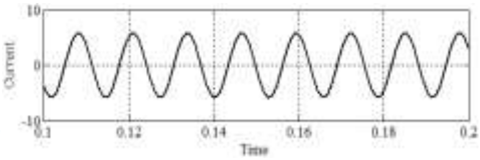
The performance results of SSTPI and FSTPI are shown in Fig. 5 and Fig. 6 respectively. Fig. 5(a) shows the space vector signal generated for 'phase a' using SVPWM technique and is compared with the triangular carrier signal to generate pulses for controlling the switching states of inverters. The inverter output voltage, motor phase voltage and current for 'phase a' are shown in Fig. 5(b), (c) and (d) respectively. The generated back-emf in SSTPI fed PMSM is shown in Fig. 5(e) and speed is as shown in Fig. 5(f) respectively. The corresponding waveforms of FSTPI fed PMSM are as shown Fig. 6 (a) to Fig. 6(f). Fig. 7(a) and (b) shows the FFT analysis of 'phase a' current with SSTPI and FSTPI. The THD of SSTPI is small compared to FSTPI.



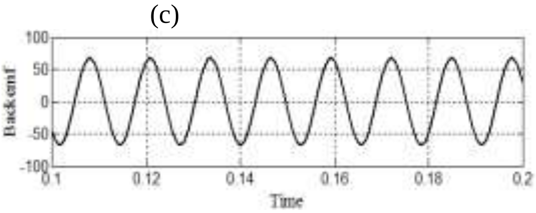


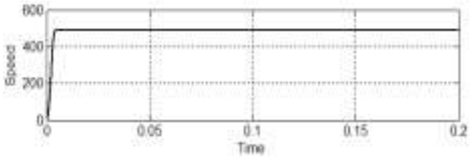
(a) (b)





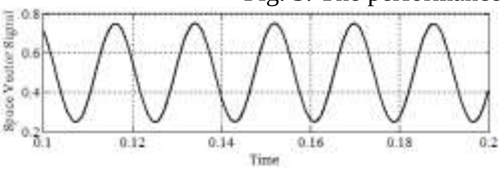
(c) (d)

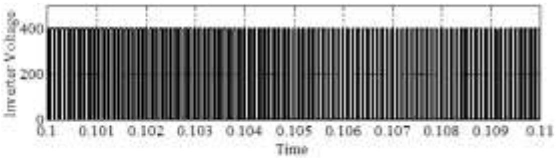




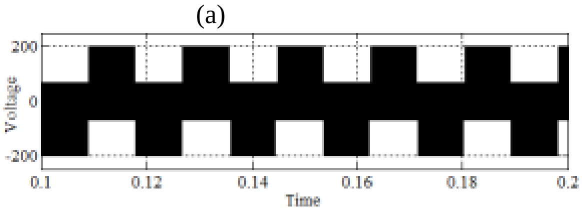
(e) (f)

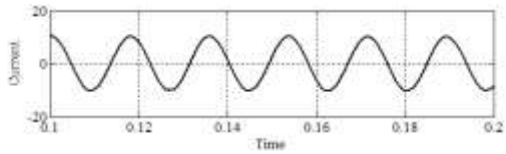
Fig. 5. The performance results of SSTPI fed PMSM



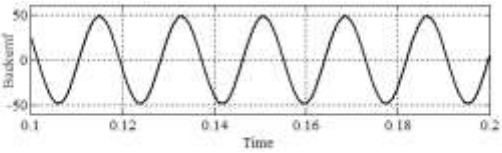


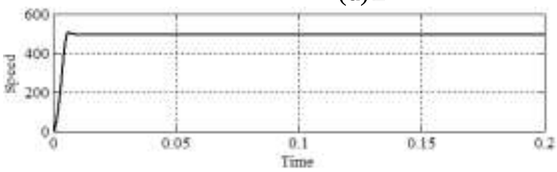
(a) (b)





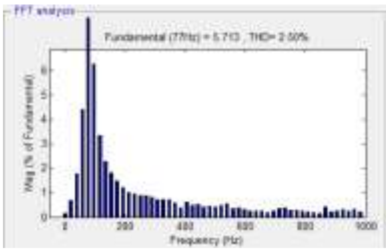
(c) (d)



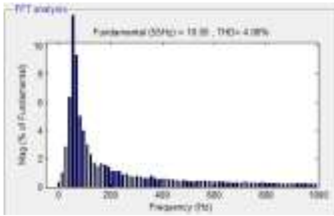


(e) (f)

Fig. 6. The performance results of FSTPI fed PMSM



(a)



(b)

Fig. 7 FFT analysis of (a) SSTPI and (b) FSTPI

V. CONCLUSION

SSTPI and FSTPI are the most promising inverter topologies used in variable speed drive applications. Compared to SSTPI, FSTPI has less number of switches, hence switching losses are reduced. Thereby complexity of circuitry can be reduced in FSTPI. FSTPI topology is adopted in applications where reduced switching losses and less complex switching circuitry are the main objective. Whereas when the focus is to reduce harmonics, SSTPI is more preferred as the THD analysis of current waveform shows 2.5% when compared to 4.6% in FSTPI. In this paper closed loop speed control of PMSM using SSTPI and FSTPI based on SVPWM is established in MATLAB/SIMULINK.

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APPENDIX

Parameters of PMSM

Stator resistance	0.02Ω
Stator inductance	2.5mH
Back-emf constant	0.13658V/rad/sec
Moment of inertia	0.0002kgm^2
Damping coefficient	0.002Nms/rad