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Closed Loop Speed Control of Induction Motor using Constant V/F Applying SPWM and SVM Based Inverter

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Abstract—inverter is a type of adjustable-speed drive used to control AC motor speed and torque. With advances in solid-state power electronic devices and microprocessors, various inverter control techniques employing pulse width modulation (PWM) are becoming increasingly popular in AC motor drive application. These PWM-based drives are used to control both the frequency and magnitude of the voltage applied to motors. This paper analysis the speed control system of Induction motor fed by voltage source Inverter with implementation of Proportional Integral (PI) controller in the feedback path utilizing constant volt per hertz ratio with two PWM techniques namely, sinusoidal PWM and Space vector PWM. Comparing the performance of SPWM and SVPWM based inverter has been analyzed in MATLAB/Simulink from the analysis of speed regulation, torque ripple and total harmonic distortion.

Index Terms— Inverter, Pulse Width Modulation (PWM), Closed Loop Control of Induction Motor, Constant V/F.

I. INTRODUCTION

As far as the machine efficiency, robustness, reliability, durability, power factor, ripples, stable output voltage and torque are concerned, three- phase induction motor stands at the a top of the order. Induction motors are widely used in many residential, industrial, commercial, and utility applications [1]. But they require much more complex methods of control, more expensive and higher rated power converters than DC and permanent magnet machines. Various techniques are in practice for induction motor speed control today.

S. Dam and A. Saha were proposed closed loop control of L-matrix based induction motor using V/F method using PID controller [1]. S.V. Ustun tuned the PI coefficients using fuzzy genetic control [3]. Neural network based control of induction motor speed control developed in [4-6]. M. Suetake and I. N. Da Silva were proposed DSP-Based Compact Fuzzy system for V/f control of induction motor in [7]. Artificial Intelligence (AI) techniques, such as Expert Systems, Fuzzy Logic, Neural Networks or Biologically Inspired and Genetic Algorithm have recently been applied in motor drives for V/f speed control [8]. Neuro-Fuzzy controller also designed for induction motor speed control [9, 10].

The most popular technique for induction motor speed control is by generating variable frequency supply, which has constant voltage to frequency ratio. This technique is popularly known as V/F control which has large applications in industry. The control strategy consists of keeping constant the Voltage/Frequency ratio of the induction motor supply source.

In this paper for speed control of induction motors, a closed loop system utilizing PI controller and constant V/F ratio have been used and the performance of two kinds of PWM based inverter including sinusoidal PWM and space vector PWM have been compared.

In this paper, Section 2 explains the basic concept of induction motor speed control technique and constant V/F ratio control. Three phase inverter is discussed in Section 3. SPWM and SVM methods are developed in Section 4. PID controller is summarized in section 5. Simulation results are reported in Section 6 and finally Section 7 concludes the paper.

II. CONSTANT V/F CONTROL

For an induction motor, rotor speed, frequency of the input voltage and number of pair poles are interrelated according to the equation (1):

$$n_s = \frac{120f}{P} \tag{1}$$

Where f is the fundamental frequency of the input voltage and p is the number of pair poles. The induction motor torque in different speeds is obtained from equation (2):

$$T_e = \frac{3}{w_s}\frac{R_r^{'}}{s}\frac{V^2{}_{ph}}{\left(R_s+\frac{R_r^{'}}{s}\right)^2+\left(X_s+X_{r0}^{'}\right)^2} \tag{2}$$

The induction motor torque-speed characteristic applying constant frequency and voltage is illustrated in Fig.1.

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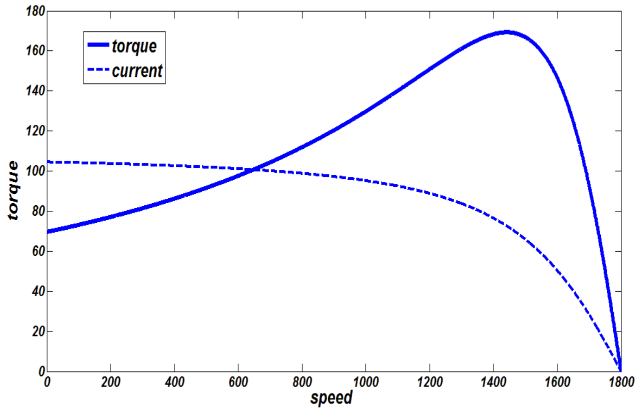

Fig. 1: Induction motor Torque-speed characteristic

The mechanical speed of an induction motor is a function of three parameters including power supply frequency, number of pair poles and slip, thus the change of any of these parameters will cause the motor speed to vary. Since the number of poles is fixed by design, the best way to vary the speed of induction motor is by varying the power supply frequency. Fig.2 shows the typical torque-speed characteristics of an induction motor applying variable frequency and constant voltage.

The torque developed by the motor is directly proportional to the stator magnetic field. According to (3), the voltage applied to the stator is directly proportional to the product of stator flux and frequency. This makes the flux produced by the stator is proportional to the ratio of applied voltage and frequency.

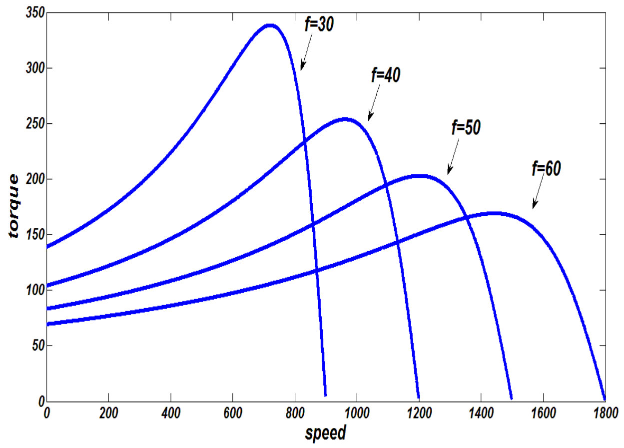

Fig. 2: Induction motor Torque-speed characteristics applying constant voltage and variable frequency

Therefore by varying the voltage and frequency by the same ratio, the torque can be kept constant and independent of the supply frequency throughout the speed range.

$$V_{eff} \propto f.\varphi \Rightarrow \varphi \propto \frac{V}{f} \tag{3}$$

Where V and φ are the stator voltage and flux respectively and f is the input voltage frequency.

This makes constant V/F is the most common speed control of induction motor [11, 12].

The speed control of induction motor is carried out by maintaining constant V/F ratio in order to avoid the air-gap flux variations.

In constant V/F control method, the stator voltage and frequency reaches the maximum value at the base speed. At frequencies higher than the rated value, the stator voltage must not exceed its rated value to avoid insulation break down [13-15]. The constant V/F characteristic has been illustrated in Fig.3.

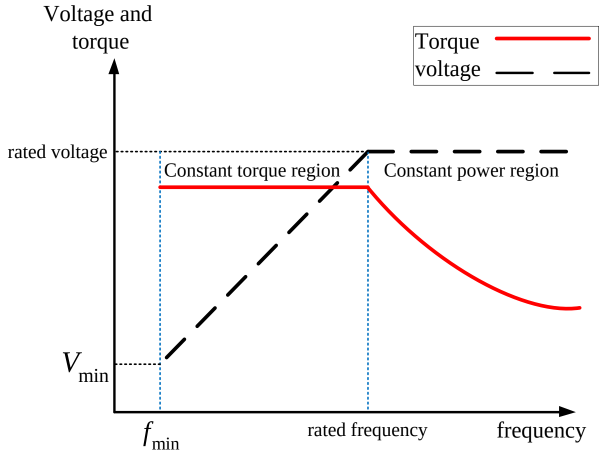

Fig. 3: Constant V/F characteristic [1]

Fig.4 shows the torque-speed characteristics of induction motor with constant V/F ratio control.

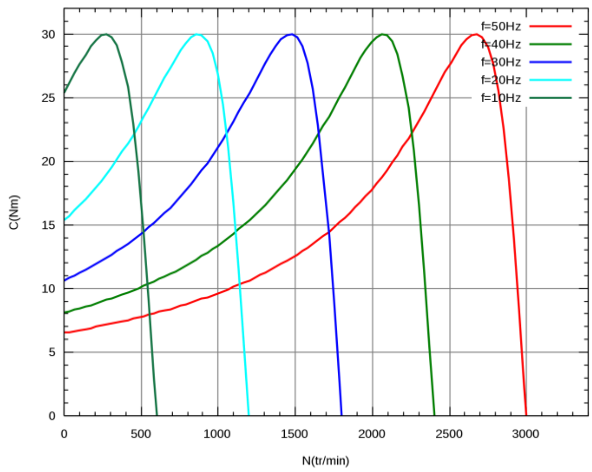

Fig. 4: Induction motor Torque-speed characteristics with constant V/F

As shown in Fig.4, the purpose of the constant V/F control is to maintain the torque constant and independent of frequency, achieving higher efficiency and lower current during run-time.

III. INVERTER

The conventional adjustable speed drive (ASD) system is based on the voltage source inverter, which consists of a diode rectifier front end, dc link capacitor and inverter bridge as shown in Fig.5 [16].

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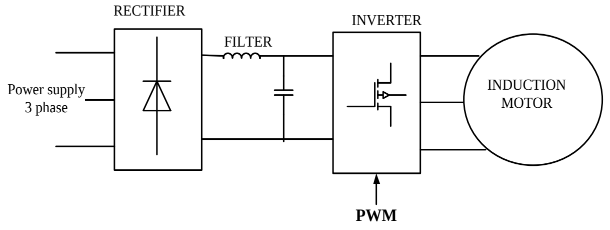

Fig. 5: Conventional variable speed drive system

Different topologies can be used as three phase inverter structure. A typical three phase inverter has been illustrated in Fig.6.

Three phase inverter is composed of 6 switches where each two switches are connected in series with each other to generate three phase voltage output from the input DC bus. The upper and lower switches of the same half bridge should not be switched on at the same time to prevent the DC bus supply from being shorted.

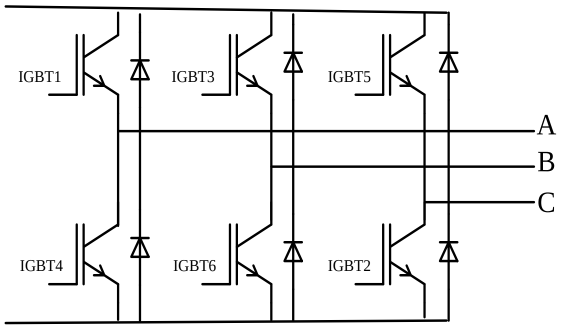

Fig. 6: Topology of a basic three phase inverter

When switches are turned off, the inductive nature of the windings oppose any sudden change in direction of current flow until all of the energy stored in the windings is dissipated. To facilitate this, fast recovery diodes are provided across each switch. These diodes are known as freewheeling diodes.

IV. PULSE WITH MODULATION

Pulse width modulation (PWM) signals control the inverter switches. The amplitude of output voltage is determined by the duty cycle of PWM pulses. The switching pattern produces a rectangular shaped output waveform that is rich in harmonics. The inductive nature of the motor's stator windings filters this supplied current to produce a three phase sine wave with negligible harmonics. The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics. The commonly used PWM techniques to control the output voltage of inverter are Sinusoidal Pulse width modulation (SPWM) and Space vector modulation (SVM)

A. Sinusoidal PWM

The simplest method for producing the PWM pulses is comparing a low power reference sine wave (control signal) with a triangle wave (modulation signal) that is called sinusoidal PWM. The basic concept of SPWM has illustrated in Fig.7.

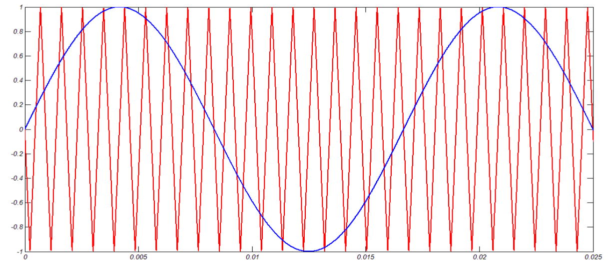

Fig.7: SPWM basic concept

There phase inverter is consist of three reference sine wave with 120 degree out of phase corresponding to each phase to generate the gating pulses for that phase. Comparing the carrier signal with three sin reference waves produces a 2-level PWM pulses for each phase that has been represented in Fig.8.

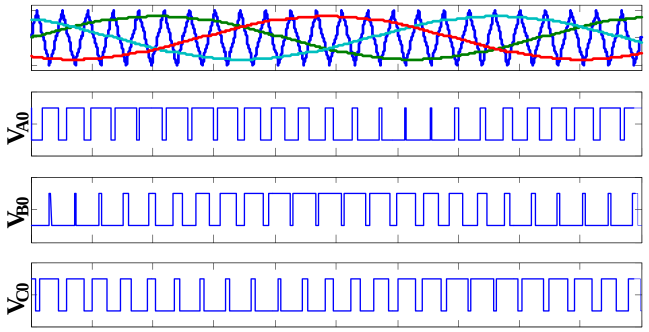

Fig. 8: PWM pulses for three phase inverter

B. Space Vector PWM

Space Vector PWM (SVM) is a special technique for determining the switching sequence of three phase inverter upper switches that provides a higher voltage with lower total harmonic distortion.

The desired three phase voltages at the inverter output could be represented by an equivalent vector rotating in the counter clockwise direction. When reference vector rotates one revolution in space, the inverter output voltage varies one cycle over time. The switching frequency is the same as sampling frequency of the inverter.

Three phase voltage can be transformed to space vector according to (4):

$$\overline{V_{ref}} = |V_{ref}| e^{jwt} = V_\alpha + jV_\beta$$
$$= \frac{2}{3}(V_a + \alpha V_b + \alpha^2 V_c) \qquad (4)$$

Where

$$\alpha = e^{j2\pi/3} \qquad (5)$$

Eq. (4) can also be expressed in matrix format:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (6)$$

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Each state of the output voltage leads to a switching vector in the complex plane. It results 6 active vector and 2 zero vectors. The magnitude of the active vectors is $\frac{2}{3}V_{dc}$.

Six non-zero vectors shape the axes of a hexagonal as depicted in Fig.9.

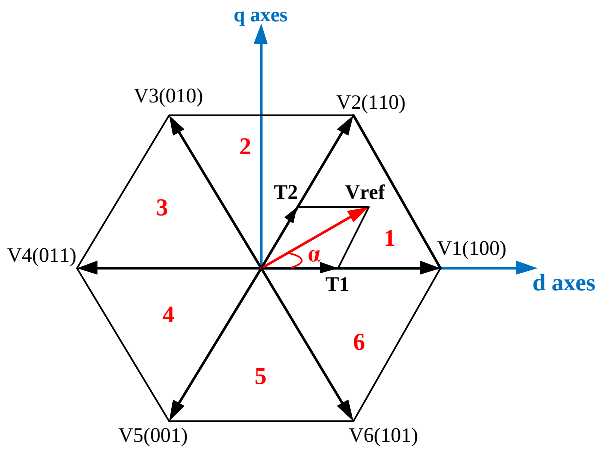

Fig.9: Regular hexagonal space vector

The angle between any adjacent two active vectors is 60 degrees. Three stationary vectors can synthesize the reference vector $\overrightarrow{V_{ref}}$ [18]. The objective of SVPWM technique is to approximate the reference voltage vector using the eight switching patterns. In general case, active vectors dwell time obtained from the following equation:

$$\begin{pmatrix} T_k \\ T_{k+1} \end{pmatrix} = \sqrt{3}\frac{T_s}{V_{dc}} \begin{bmatrix} \sin\frac{k\pi}{3} & -\cos\frac{k\pi}{3} \\ -\sin\frac{(k-1)\pi}{3} & \cos\frac{(k-1)\pi}{3} \end{bmatrix} \begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} \tag{7}$$

Where V_α and V_β are reference vector components along the axis of $\alpha-\beta$.

The dwell time for zero vectors has been also obtained from Eq. (8).

$$T_0 = T_7 = \frac{T_S - T_k - T_{k+1}}{2} \tag{8}$$

If the $\overrightarrow{V_{ref}}$ falls into sector1, for linear modulation range the dwell times can be calculated as:

$$T_1 = \frac{\sqrt{3}V_{ref}}{V_{dc}} T_s \sin(\frac{\pi}{3}-\theta) \tag{9}$$

$$T_2 = \frac{\sqrt{3}V_{ref}}{V_{dc}} T_S \sin\theta \tag{10}$$

$$T_0 = T_7 = \frac{T_S - T_1 - T_2}{2} \tag{11}$$

Where T_s is the sampling period, V_{ref} is the amplitude of reference vector and V_{dc} is input dc voltage.

Assuming the reference vector is located in Sector1, the switching sequence of upper switches has been illustrated in Fig. 10.

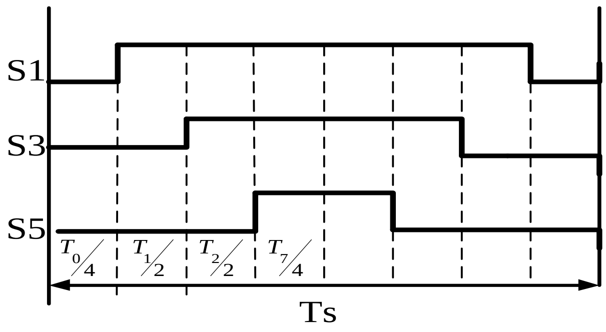

Fig.10: Switching sequence of upper group for sector1

V. PID CONTROLLER

The PID controller is designed to give desired control signals to PWM generator. The motor speed is taken as feedback and it is compared with the set speed. The error signal is given as input to the PID controller. The controller attempts to minimize the error by adjusting the process control inputs. A PID controller is a generic control loop feedback mechanism widely used in industrial control systems.

The PID controller algorithm involves three separate constant parameters: Proportional, Integral and Derivative values. P depends on the present error, I on the accumulation of past errors and D is a prediction of future errors, based on current rate of change.

The PI controller is usually utilized for speed control applications. Block diagram of a closed loop system applying a PI controller has been shown in Fig. 11.

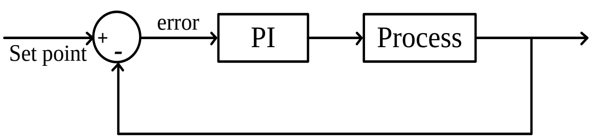

Fig.11: closed loop system applying PI controller

VI. SIMULATION

For analyzing the closed loop speed control of induction motor by three phase VSI using constant V/F ratio and comparing the performance of SPWM and SVPWM based inverters, the MATLAB /Simulink has been used. The simulation model has been illustrated in Fig.12.

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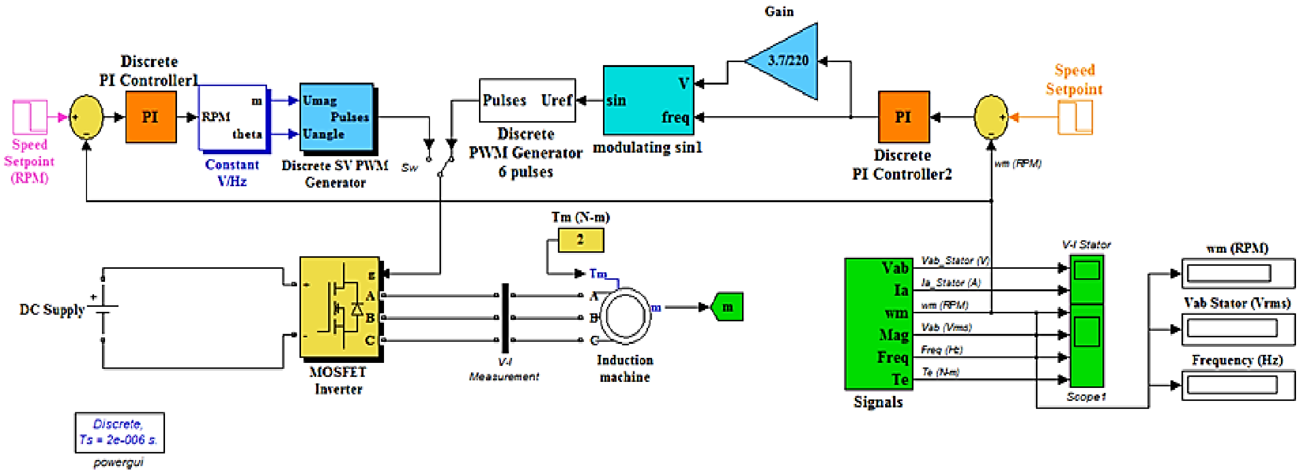


Fig. 12: Simulation Model of SPWM and SVPWM Based Speed Control of induction motor

The input DC voltage to three phase voltage with variable frequency and voltage to control the induction motor speed in different loads. In this paper, two PWM techniques have been utilized for inverter switching: SVM and SPWM. The SVM structure has been illustrated in Fig.13.

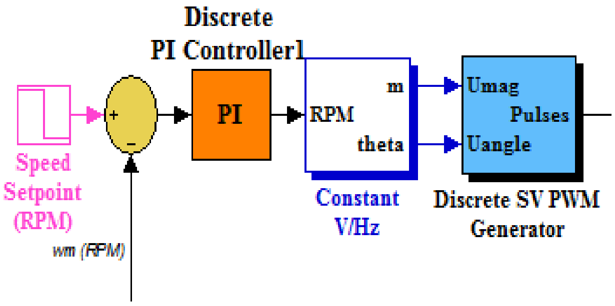


Fig. 13: Space vector PWM structure

Simulation model uses a 3 phase induction motor of 2240 VA, 220 volt and 60 HZ. A three phase inverter transforms Using PI controller and constant V/F blocks, the amplitude and phase of reference voltage vector have been calculated and finally the gating pulses have been generated using discrete SVPWM generator. For evaluating the performance of SPWM based inverter, SPWM structure has been illustrated in Fig.14.

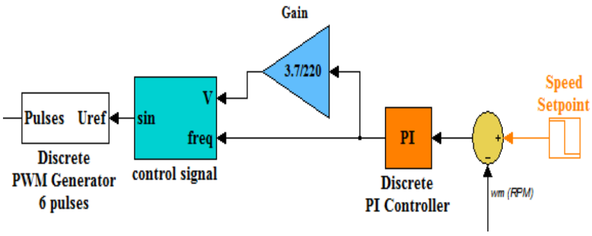


Fig.14: SPWM structure

As shown in Fig.14, after a change in motor speed or load torque, the closed loop system compares the set point and actual speed and calculates the optimal frequency value using PI controller. Amplitude and frequency of sinusoidal control signals required for SPWM generator block have been calculated via constant V/F.

For generating sinusoidal control signals required for PWM generator, the following configuration in Fig.15 has been used.

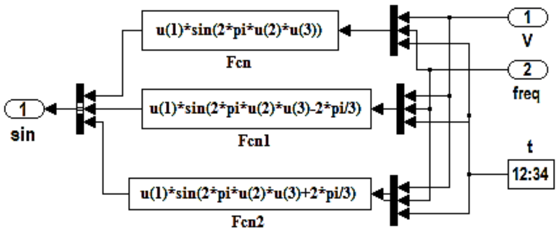


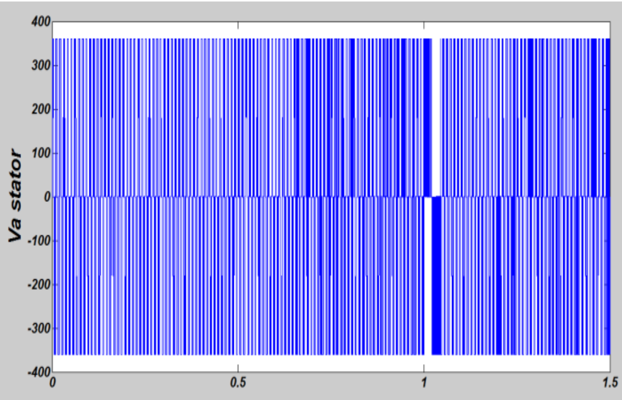
Fig.15: generating three phase sinusoidal control signal

A. Comparative Analysis

For analyzing the performance of SPWM and SVPWM based inverters and closed loop PI controller, two separate scenarios have been considered.

For the first scenario and comparing the simulation results, motor speed has been changed from 1725 rpm to 1300 rpm at t=1 sec. For both PWM based inverters, switching frequency and sampling time has been considered 1080 HZ and 1us respectively.

Simulation results have been illustrated in Fig. 16 and Fig. 17.



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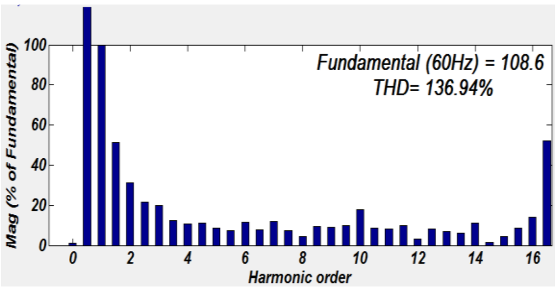

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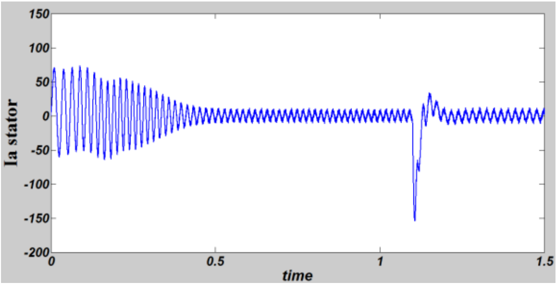

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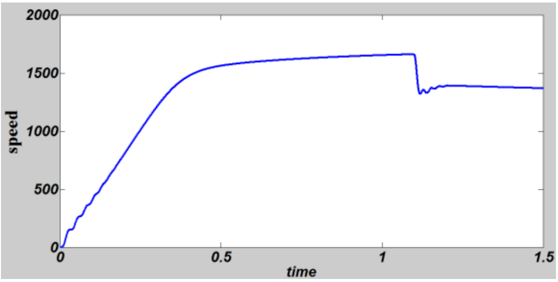

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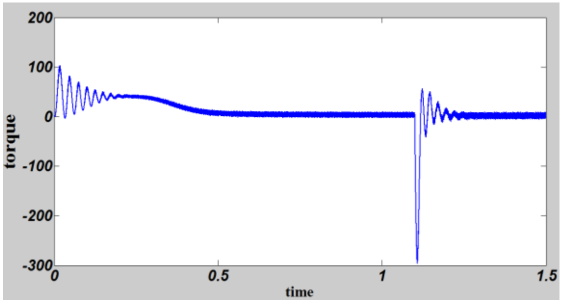

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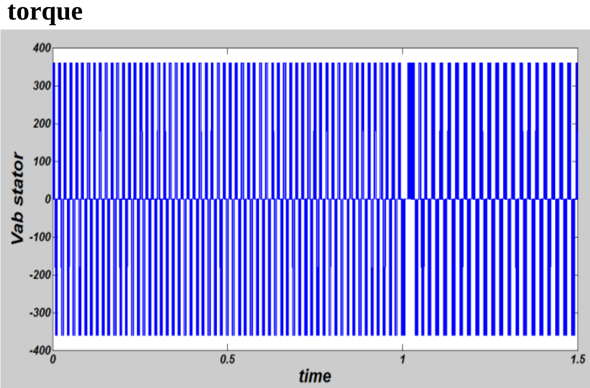
Fig.16: induction motor responses to speed change from 1725 to 1300 rpm at t=1.1sec applying SPWM based inverter. (a) Vab stator. (b) Harmonic spectrum of the inverter voltage waveforms, (c) Ia stator, (d) Rotor speed, (e) torque



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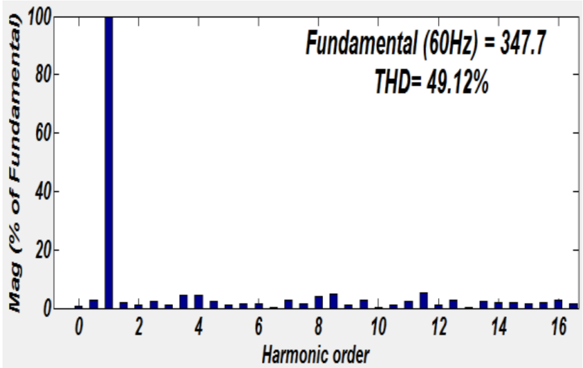

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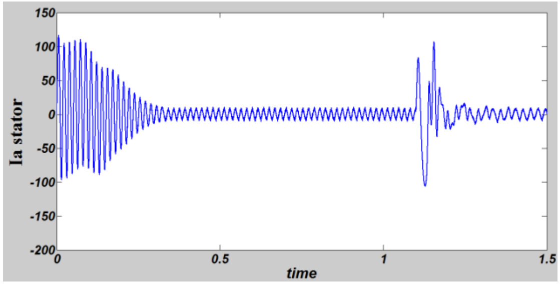

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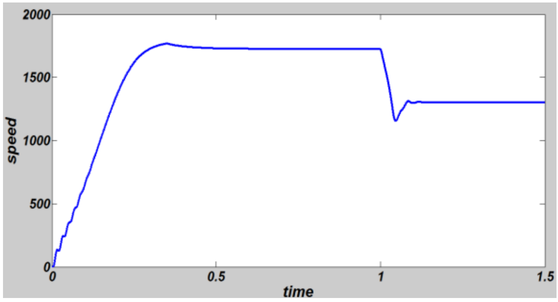

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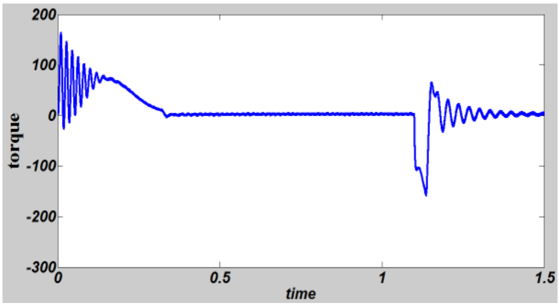

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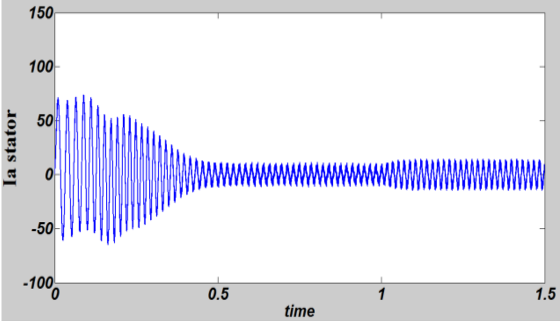
Fig.17: induction motor responses to speed change from 1725 to 1300 rpm at t=1.1sec applying SVPWM based inverter. (a) Vab stator, (b) harmonic spectrum of the inverter voltage waveforms, (c) Ia stator, (d) Rotor speed, (e) torque

For second scenario and evaluating the induction motor closed loop speed control using SPWM and SVPWM based inverter, the load torque has been changed from 2 n.m to 10 n.m at t=1 sec. during torque change, rotor speed will kept constant 1720 rpm.

The results of simulation applying SPWM and SVPWM based inverter have been illustrated in Fig. 18 and Fig. 19.



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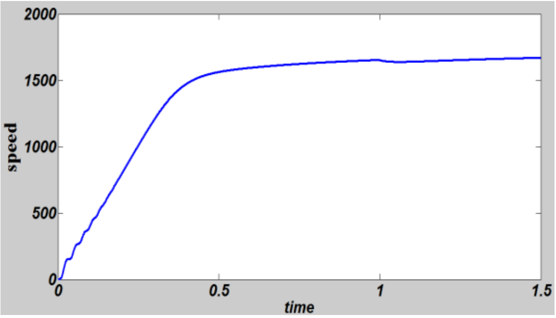

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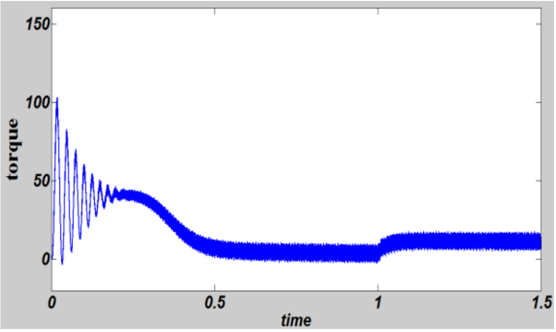

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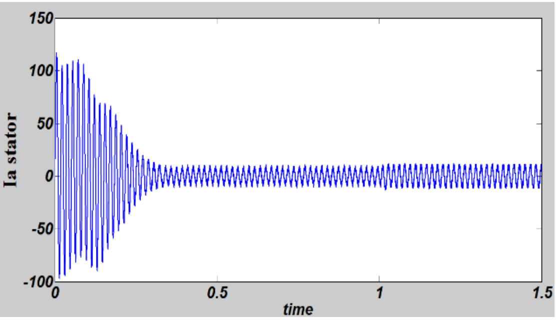
Fig.18: induction motor responses to speed change from 1725 to 1300 rpm at t=1s applying SPWM based inverter: (a): Ia stator- (b): Rotor speed- (c): torque



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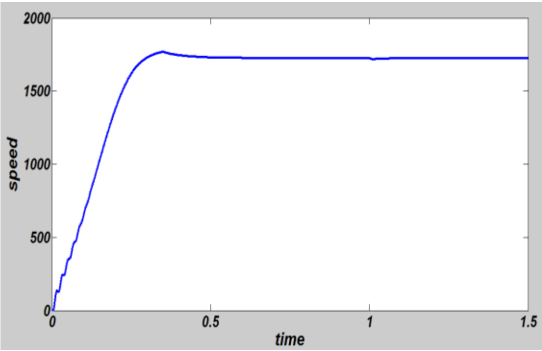

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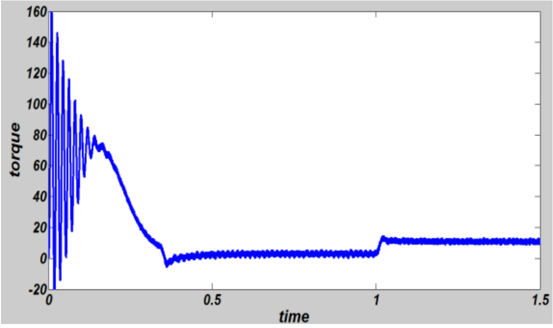

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Fig.19: induction motor responses to speed change from 1725 to 1300 rpm at t=1s applying SVPWM based inverter: (a): Ia stator- (b): Rotor speed- (c): torque

By comparing the simulation results of closed loop speed control of induction motor applying SPWM and SVPWM based inverter it is clear that the closed loop PI controller satisfactorily follow the speed change applying both PWM based inverters because of optimal adjustment of PI variables, but analysis of Total Harmonic Distortion specifies that the SVPWM based inverter produces less THD than SPWM based inverter and therefore has a superior performance as compared to SPWM.

VII. CONCLUSION

In this paper, the performance of two different type of PWM based inverter including SPWM and SVPWM have been compared for closed loop speed control of induction motor applying constant V/F method. The analysis has been simulated in MATLAB\Simulink. For evaluating the performance of PWM based inverters, two separate scenarios have been considered including speed change from 1725 rpm to 1300 rpm in t=1.1 sec and torque change from 2 n.m to 10 n.m in t=1 sec . The results have been compared and it is clear that the application of SVPWM based inverter has a superior performance as compared to SPWM because the motor variables such as voltage, current, speed and torque have fewer harmonics and ripples applying SVPWM.

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