Speed Sensorless Vector Control of Induction Motor Using Reduced Order Extended Kalman Filter

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Abstract

Vector control is a speed control technique used to obtain fast and accurate speed control of induction motor. Speed sensors degrades reliability hence speed sensorless speed control is proposed. This work presents accurate electrical parameter estimation such as flux, torque, theta and speed using reduced order extended Kalman filter based induction motor control is proposed. The Kalman filter is based on the minimization of the estimation error and it is suitable for obtaining high accuracy estimates of state variables and model parameters and eliminating measurement noises. Here no need of speed, torque, flux, rotor position and stator voltage sensors, alternatively the stator current will be measured by three current transformers (CT's) with supporting of mathematical equations. The proposed method has some advantages of saving computation time in comparison with the full order extended Kalman filter. The proposed work is implemented by a hardware using DSPIC30F4011 controller and simulated with help of MATLAB SIMULINK R2010a version.

Keywords—*.Vector control, Extended Kalman filter, Current transformers, Speed sensorless, Coordinate transformation*

1. Introduction

The induction machine is the heart of the most widely used form of electrical AC drive. Induction motor can be considered as the workhorse of the industry. Induction motors are classified into single phase induction motor and three phase induction motor based on given input supply. Three phase induction motors are the most common motors used in industrial control systems and commercial applications. In the past, induction motors were preferred only for constant speed applications. Adjustment of speed of induction motor was very difficult and also needs high cost. But the rapid growth in power electronics and semiconductor technology results, many kinds of induction motor variable speed drives have been developed and now the induction motors are very good alternative for variable speed applications. The robustness, low cost, the better performance and the ease of maintenance make the induction motor advantageous in many industrial applications for general applications. A fast and controlled speed response from an induction motor is obtained most effectively if the principle of vector control is used.

Vector control method is also called as field oriented control method. Vector control method is valid for both steady state as well as dynamic state conditions. In vector control it controls not only the amplitude, frequency but also their phase angle. The main disadvantages are the huge computational capability and accurate measurements of the motor parameters are required. In the direct vector control, information about the actual values of the magnitude and position of the rotor flux and rotor speed is necessary. Vector controlled induction motor drives are widely used in the industrial applications where high performance, like fast torque and speed responses, are demanded. The main concept of vector control is to decouple the control of induction motor's flux and torque via coordinate transformations and to control not only the amplitudes of current and flux but also their phase angle.

The Kalman filter is based on the minimization of the estimation error and it is suitable for obtaining high accuracy estimates of state variables and model parameters and eliminating measurement noises. A lot of researches are carried out to develop accurate speed estimation techniques. To obtain accurate, high performance like fast torque, speed responses and more reliable in three phase induction motor drive system the vector control method has been proposed. The work is mainly focused on speed sensorless speed control of three phase induction motor using vector control technique through reduced order extended Kalman filter. For this purpose of modelling and design of induction motor drive I am developing hardware and simulating with help of MATLAB SIMULINK R2010a version.

2. Modeling of Induction Motor

The IM mathematical model may perhaps be explained in the rotating direct–quadrature (d-q) frame as given below where i_d and i_q, V_d and V_q, ω_r, T_L, ψ_{rd} and θ represents stator currents, stator voltages, rotor speed, load torque, direct-axis rotor flux, and flux angle, correspondingly. Parameter $\tau_r = L_r/R_r$ indicates the rotor time constant and $\sigma = 1 - L_m^2/L_sL_r$ signifies the leakage magnetic coefficient.

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$$\begin{cases} \frac{d_{i_d}}{dt} = -\frac{L_r R_s + L_m^2 R_r}{\sigma L_s L_r^2} + \frac{L_m}{\tau_r \sigma L_s L_r}\psi_{rd} + p\omega_r i_q + \frac{L_m}{\tau_r \psi_{rd}} i_q^2 + \frac{1}{\sigma L_s} V_d \\ \frac{d_{i_q}}{dt} = -\frac{L_r R_s + L_m^2 R_q r}{\sigma L_s L_r^2} i_q - \frac{L_m}{\sigma L_s L_r} p\omega_r \psi_{rd} - p\omega_r i_d + \frac{L_m}{\tau_r \psi_{rd}} i_d i_q + \frac{1}{\sigma L_s} V_q \\ \frac{d\theta}{dt} = p\omega_r + \frac{L_m}{\tau_r \psi_{rd}} i_q \\ \frac{d\psi_{rd}}{dt} = -\frac{1}{\tau_r}\psi_{rd} + \frac{1}{\tau_r} L_m i_d \\ \frac{d\omega_r}{dt} = \frac{pL_m}{L_r}\psi_{rd} i_q - \frac{1}{J} T_L \end{cases} \quad (1)$$

In order to simplify the investigation, fix $m = (L_r R_s + L_m^2 R_r)/\sigma L_s L_r^2$, $\gamma = L_m/\sigma L_s L_r$, $\varsigma = 1/\sigma L_s$, $k = 1/\tau_r$, $\rho = pL_m/L_r$, and (1) can be modified as follows:

In this work, only the stator currents are necessary to be computed for control calculations, thus leading to a sensorless induction drive system.

$$\begin{cases} \frac{d_{i_d}}{dt} = -mi_d + k\gamma\psi_{rd} + p\omega_r i_q + k\frac{L_m}{\psi_{rd}} i_q^2 + \varsigma V_d \\ \frac{d_{i_q}}{dt} = -mi_q - \gamma p\omega_r \psi_{rd} - p\omega_r i_d - k\frac{L_m}{\psi_{rd}} i_d i_q + \varsigma V_q \\ \frac{d\theta}{dt} = p\omega_r + k\frac{L_m}{\psi_{rd}} i_q \\ \frac{d\psi_{rd}}{dt} = -k\psi_{rd} + kL_m i_d \\ \frac{d\omega_r}{dt} = \rho\psi_{rd} i_q - \frac{1}{J} T_L \end{cases} \quad \ldots (2)$$

3. Design of Reduced order Kalman filter

In this approach, the three-phase stator currents are the solitary essential measurements, and these are converted from the three-phase reference frame to a diphase reference frame, and subsequently to the frame of the rotating field (d-q) as given below:

$$\begin{cases} i_d = \sqrt[2]{\frac{2}{3}}\left(\cos(\hat{\theta}) i_a + \cos\left(\hat{\theta} - \frac{2}{3}\pi\right) i_b + \cos\left(\hat{\theta} + \frac{2}{3}\pi\right) i_c\right) \\ i_q = \sqrt[2]{\frac{2}{3}}\left(-\sin(\hat{\theta}) i_a - \sin\left(\hat{\theta} - \frac{2}{3}\pi\right) i_b - \sin\left(\hat{\theta} + \frac{2}{3}\pi\right) i_c\right) \end{cases} \quad (3)$$

Where i_a, i_b and i_c signifies the three-phase stator currents, correspondingly and $\hat{\theta}$ represents the estimated flux angle. V_d, V_q and $\hat{\theta}$ are engaged as feedback to the reduced order extended Kalman filter.

The stator flux vector Ψ_{est} and the torque generated by the motor, T_{est}, can be estimated with the help of (1) and (2), correspondingly.

$$\varphi sd = \int (Vsd - Rs.\,isd)\,.\,dt$$
$$\varphi sq = \int (Vsq - Rs.\,isq)\,.\,dt \quad \ldots 4$$

The previous equations only need the stator resistance Rs.
The magnitude of stator flux is decided by

$$\Psi_{est} = \sqrt{(\varphi sd^2 + \varphi sq^2)}$$

At this moment, with the stator flux and the diphase reference frame from the stator currents, together with the motor poles P, Torque is estimated depending on the equation below.

$$T_{est} = \frac{3}{2} P(\varphi sd.\,isq - \varphi sq.\,isd) \quad \ldots (5)$$

Where, φsd and φsq represents the stator flux, isd and isq represents the stator currents Estimated Flux angle can be computed from the equation given below.

$$\theta = \tan^{-1}\left(\frac{\varphi sq}{\varphi sd}\right) \quad \ldots (6)$$

3.1 Speed sensorless speed estimation

With the intention of estimating the sensor less speed, the estimated stator flux has to be transformed into rotor flux depending on the magnetizing inductance in addition to the secondary inductance per phase.

$$\varphi rd = \frac{L_m}{L_r}\varphi sd; \qquad \varphi rq = \frac{L_m}{L_r}\varphi sq \quad \ldots\ldots (7)$$

Square of rotor flux, $\varphi rd^2 + \varphi rq^2$

For the purpose of determining the speed of rotor field, the achieved rotor flux has to be transformed into α, β coordinates, by means of the transfer function.

$$\text{Speed of rotor field} = (\varphi rd \times \varphi r\beta) - (\varphi rq \times \varphi r\alpha) \quad \ldots.(8)$$

3.2 Speed control

The error takes place between the estimated and set speed; consequently, it is necessary to design the required torque T_{ref} depending on the speed PI adjuster, i.e.

$$T_{ref} = (\omega_{set} - \omega_{est})\left(K_{p\omega} + \frac{K_{i\omega}}{s}\right) \quad \ldots(9)$$

The function of participation of the PI adjuster is to fine-tune the speed in a small range to make sure the speed tracking precision and the final zero static state error.
In the same way, for the purpose of obtaining the desired Vsq, the obtained reference torque and the estimated torque from sliding mode observer is managed through the torque PI adjuster to achieve the zero static state torque error.

$$Vsq = (T_{ref} - T_{est})\left(K_{pT} + \frac{K_{iT}}{s}\right) \qquad ..(10)$$

Stator Flux Reference

$$\Psi_{ref} = \frac{\varphi ref * \omega b}{\omega_{est}} \qquad ...(11)$$

Where $\omega b = 157\ rad/s$ represents the consider base speed $\varphi ref = 0.95$. ω_{est} is acquired from the sliding mode observer.

$$Vsd = (\Psi_{ref} - \Psi_{est})\left(K_{p\varphi} + \frac{K_{i\varphi}}{s}\right) \qquad ..(12)$$

In the same way for the purpose of obtaining the desired Vsd, the obtained stator flux reference and the estimated stator flux from sliding mode observer is managed through the torque PI adjuster to achieve the zero static state flux error.

The obtained d-q frame voltages V_{sd} and V_{sq} are subsequently given as feedback to the sliding mode observer to approximate the necessary electrical constraints of the induction motor. This evaluation is performed by taking simply stator current. Inverse park transformation is exploited to transform the diphase voltage (V_{sd} and V_{sq}) into a three phase voltage (V_a , V_b and V_c) which is then taken as input to the Space Vector Pulse Width Modulation.

4. Block diagram and its explanation

The figure1 shows the complete block diagram of the proposed work, it consists of three phase diode bridge rectifier, DC link capacitance filter, three phase VSI inverter, reduced order extended Kalman filter (sliding mode observer). The operation of the proposed system is managed by reduced order extended Kalman filter (sliding mode observer) and Pulse Width Modulation. In this proposed system, there is no necessity for speed, torque, flux, position and also voltage measurements. The sliding mode observer has the capacity to perfectly approximate the speed, flux, theta and torque with the help of the phase currents sensing alone.

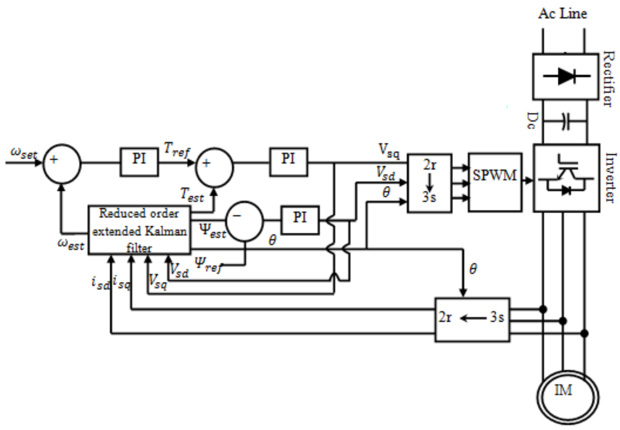

Fig. 1 Block diagram of the proposed system

(13)

The single phase input ac voltage is rectified to dc voltage by means of diode rectifier and then the DC link voltage V_{dc} is given as input to the three phase voltage source inverter. The three phase VSI converts dc supply into three phase ac supply. The SPWM control technique to get the desired output from VSI. Then this three phase ac supply is given to stator of the three phase induction motor. Initially the three phase stator currents are measured through current transformers and then they are converted into two phase by axis or co-ordinate transformation using phase angle(θ) which is generated byreduced order extended Kalman filter and then these two phase stator currents i_{sq} and i_{sd} are given as input to the reduced order extended Kalman filter.

The reduced order extended Kalman filter uses recursive algorithm and it takes these two phase stator currents as input and calculates the estimated speed, estimated flux, and estimated torque and phase angle(θ). It compares the reference flux and estimated flux and the result error is processed through a PI controller and it gives the flux controlling component V_{sd}. similarly the reference speed and estimated speed are compared and the result error is processed through a PI controller and it gives the reference torque and again these reference torque and estimated torque are compared and the result error is processed through a another PI controller and it gives the torque controlling component V_{sq} and these flux controlling component V_{sd} and torque controlling component V_{sq} are taken feedback to the reduced order extended Kalman filter.

Then these two phase voltages V_{sq} and V_{sd} are converted back by inverse transformation using phase angle (θ) and these three phase reference voltages are given to PWM driver unit. The driver unit uses sinusoidal PWM technique compares the carrier signal(triangular wave) and the given three phase reference signal(sinusoidal wave) and generates the PWM pulses of width varied according to the three phase reference voltage signal and these PWM signals are given to the MOSFET switches in the VSI for switching action . As the three phase reference voltage is varied according to the set speed and in turn PWM signal pulse width is varied according to the three phase reference voltage and in turn the output of VSI is varied according to the PWM pulses and in turn the input of the motor is the output of VSI and in turn the speed of motor is varied as the input of the motor is varied, hence we will get desired set speed and this type the speed of three phase induction motor is controlled.

4. Simulation results and discussion

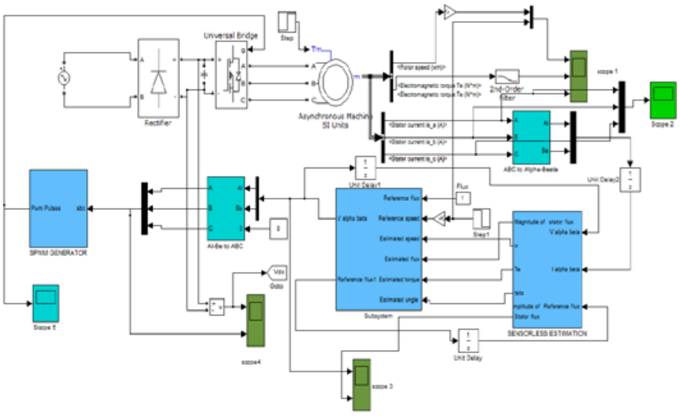

Fig 4.1 Block diagram of complete simulation system

The Block diagram of the complete simulation system is shown in Figure 4.1. The simulation of the work is simulated for the time duration from 0.0 seconds to 2.0 seconds and the results are observed and they are presented below.

CASE: Given step input for a speed 1000r.p.m from 0.0 to1.0 seconds and 600r.p.m from 1.0 second to 2.0 seconds:

Fig 4.2 a) Set speed v/s actual speed, b) Electromagnetic torque, c) Stator current i_a waveforms

From the figure 4.2(a) it is clear that the speed of the induction motor is catching the set speed 1000 rpm from 0.0 to 1.0 sec and 600 rpm from 1.0 to 2.0 seconds.

From the figure 4.2(b) it can be concluded that the torque is remaining constant of magnitude 2N-m.

From the figure 4.2(c) the stator current of magnitude 3.5A, 65 Hz frequency for duration 0.0 to 1.0 second and same magnitude but frequency of 40 Hz for duration from 1.0 to 2.0 seconds hence it is clear that the frequency of stator current is varying according to the change in speed by keeping magnitude constant.

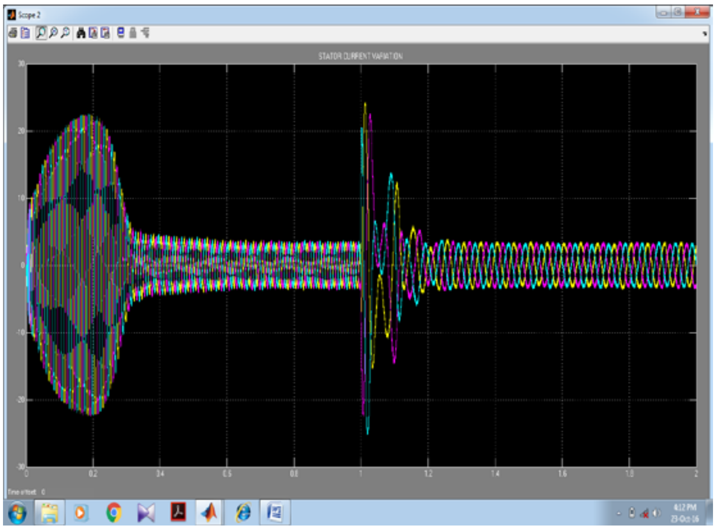

Fig 4.3 Three phase stator current variation waveform

From the figure 4.3 the three phase stator currents of magnitude 3.5A, 65 Hz frequency for duration 0.0 to 1.0 second and same magnitude but frequency of 40 Hz for duration from 1.0 to 2.0 seconds. The three phase stator currents are sinusoidal in shape and are balanced that is all three phase have same magnitude with 120^0 phase difference and the frequency of three phase stator current is varying according to the change in speed by keeping magnitude constant.

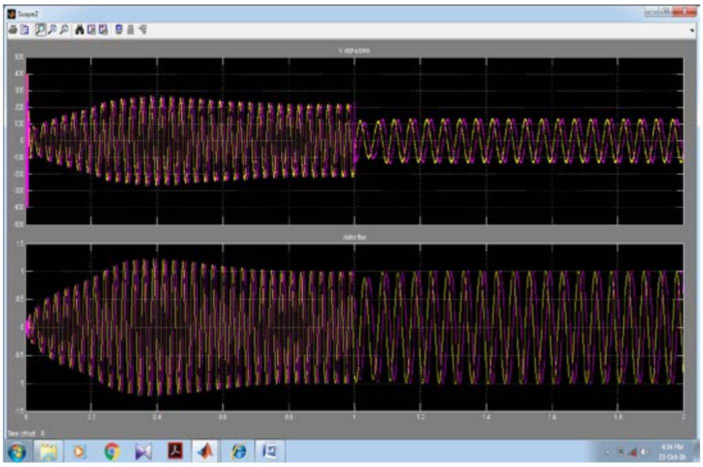

Fig 4.4 a) $V_{alpha\ beta}$, b) Stator flux waveforms

From the figure 4.4(a) $V_{alpha\ beta}$ is of magnitude 220 volts for duration 0 to 1.0 second and magnitude of 130 volts for duration 1.0 to 2.0 seconds. The two phase stator voltage $V_{alpha\ beta}$ is two phase sinusoidal voltage and whose magnitude is varying according to the speed change.

From the figure 4.4(b) it can be concluded that the stator flux is remaining constant of magnitude of 1 Weber. The stator flux is sinusoidal and two phase containing both quadrature and direct components of stator flux and it is maintained to constant magnitude of 1 Weber irrespective of speed change.

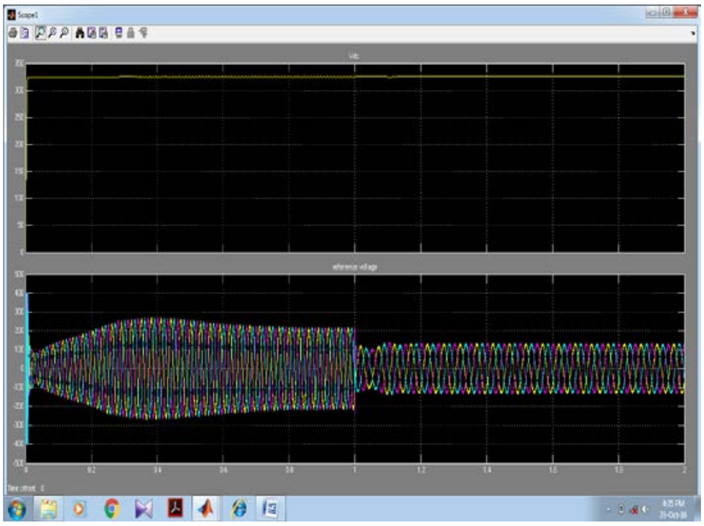

Fig 4.5 a) V_{dc} , b) Three phase reference voltage waveforms

From the figure 4.5(a) it is clear that the V_{dc} is the pulsating dc voltage approximately magnitude of 325 volts remaining constant.

From The figure 4.5(b) three phase reference voltage is of magnitude 220 volts for duration 0.0 to 1.0 second and magnitude of 130 volts for duration 1.0 to 2.0 seconds. The three phase reference voltage is sinusoidal voltage and whose magnitude is varying according to the speed change.

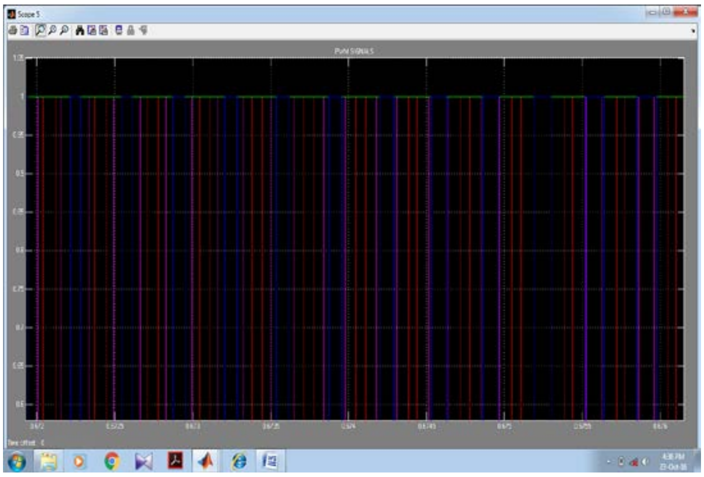

Fig 4.6 PWM signal waveform

From the figure 4.6 it can be concluded that the continuous square wave PWM pulses are generating and are supplied to VSI.

5. Experimental setup and its results

Fig. 5.1 Experimental set up of hardware

The figure 5.1 shows the experimental set up of the hardware unit. It consists of single phase ac power supply, three phase diode bridge rectifier, dc link capacitor filter, three phase voltage source inverter, current transformers, control relay circuit, DSPIC30F4011 Controller, MOSFET driver unit and three phase induction motor.

The hardware is connected as shown in figure 5.1. The required supplies are turned on then the motor starts to run. The speed of motor is set to 1000 rpm and the three parameters are measuring through Digital Storage Oscilloscope are stator voltage, stator current and PWM pulses and they are represented below

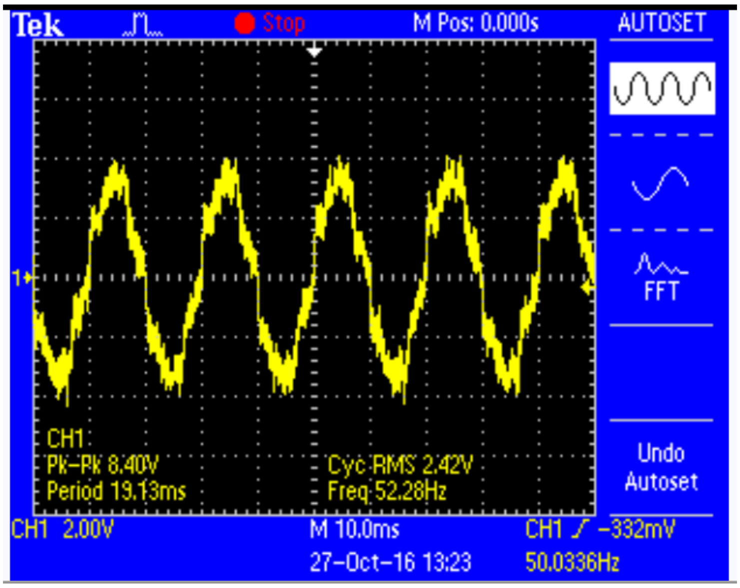

Fig 5.2 stator voltage waveform

The figure 5.2 shows the stator voltage waveform of peak to peak magnitude of 8.4 volts and rms magnitude of 2.42 volts with frequency 52.28 Hz.

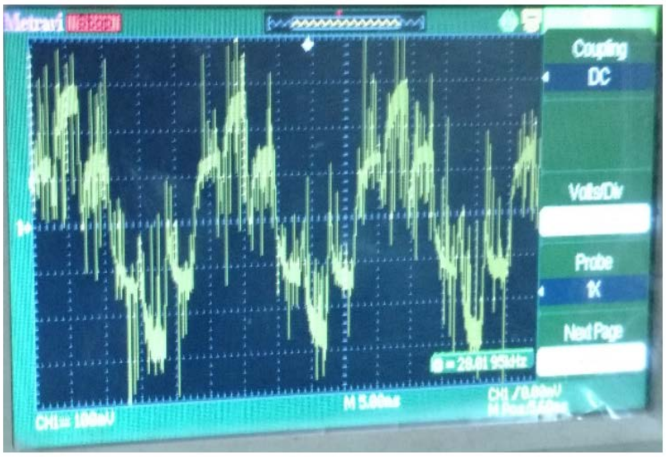

Fig 5.3 Stator current waveform

The above figure represents the stator current waveform. The magnitude of stator current is approximately 0.3 amps, 50 Hz.

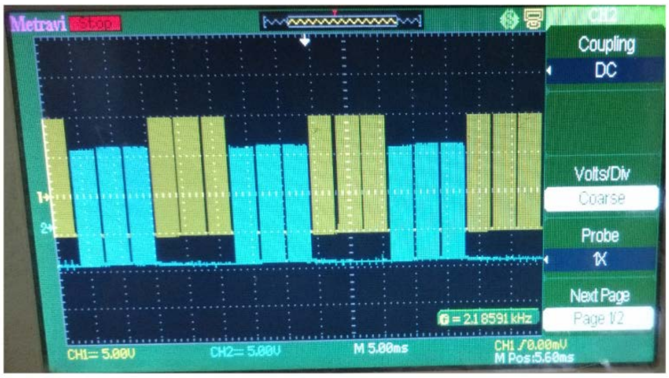

Fig 5.4 PWM pulses waveform

The above figure represents the PWM pulse signal waveform. These waveforms are the PWM pulses generated by driver circuit and are given to the MOSFET switches for switching action. The PWM pulse is of magnitude 260 volts.

6. Conclusion

A model to control the speed of three phase induction motor by vector control method using reduced order extended Kalman filter has been successfully implemented for ½ HP, 440V, 0.75A, 50Hz three phase induction motor. The hardware of proposed work is implemented by using DSPIC30F4011 controller and the work is simulated with help of MATLAB SIMULINK R2010a version. The outputs of simulation and hardware are taken and are found quite satisfactory. The stator voltage of peak to peak magnitude of 8.4 volts and r.m.s magnitude of 2.42 volts with frequency 52.28 Hz is obtained. The magnitude of stator current is approximately 0.3 amps, 50 Hz and the PWM pulse is of magnitude 260 volts. The accurate and fast speed control is achieved. The accuracy of speed control is achieved by minimizing estimation errors by using reduced order extended Kalman filter. A fast control is achieved by saving computation time compared with full order Kalman filter. The accuracy and reliability of system is improved by replacing the speed sensors with current transformers. The problem as dynamic response and coupling effect of scalar control are solved. The problem of speed sensors as error in measurement itself and low reliability are solved. Easy of maintenance due to not present of mechanical commutators, bushes, slip rings and speed sensors. Performance of proposed drive has been found quite satisfactory by accurate and fast controlling the speed of three phase induction motor. This type of speed control of three phase induction motor can be used in industries where a high performance drive like fast and accurate speed control and high reliability is required.

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