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A Variable Speed Sensorless Induction Motor Drive Using DC Link Measurements

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ABSTRACT: The aim of the paper is to implement a new method of Speed Control for a Voltage Source Inverter (VSI) fed Induction Motor. Induction motor is simulated for the indirect vector, sensorless speed control strategy and it to verify the work ability of this strategy with the actual values of speed and electromagnetic torque for different conditions of operation like low speed , change in load, speed reversal etc using MATLAB.

KEYWORDS: Induction Motor, Voltage Source Inverter (VSI), indirect vector control, sensorless speed control, Total Harmonic Distortion (THD)

I. INTRODUCTION

It is known that synchronous speed of induction motor (Ns) depends on supply frequency (f) and number of poles (p). It is also known that 'V' the stator terminal voltage is proportional to the product of air gap flux 'Φ'and the frequency 'f'. Speed control is achieved in inverter driven induction motor by means of variable frequency. Whenever frequency is changed to obtain speed control, stator input voltages have to be changed to maintain air gap flux constant [1]. A number of control strategies have been formulated depending on how the voltage to frequency (volts per hertz) ratio is implemented

a) Scalar control
b) Vector control Or Field Oriented control

Scalar control is easy to implement and is due to magnitude variation of control variables from the set values. Scalar control disregards inherent coupling effect giving sluggish response and system is easily prone to instability. These are low cost applications like volts per hertz control where no particular performance is required. For those applications which require higher dynamic performance than v/f scalar control, vector or field oriented control is preferred and gives fast dynamic response. Field Oriented Control (FOC) of a 3-phase AC motor involves imitating the DC motors' operation. All controlled variables are transformed to DC instead of AC via mathematical transformation. The goal is to control torque and flux independently. There are two methods for Field Oriented Control (FOC):

Direct FOC**:** Rotor flux angle is directly computed from flux estimation or measurement.

Indirect FOC**:** Rotor flux angle is indirectly computed from available speed and slip computation.

This paper presents an indirect vector sensor less speed control where the field angle θ_e is acquired using estimation of stator currents and voltages reconstructed from DC link measurements. The invention of vector control in the beginning of 1970s and the demonstration that an induction motor can be controlled like a separately excited dc motor brought renaissance in the high performance of control of ac drives. Because of dc machine like performance vector control is also known as "decoupling" orthogonal or trans vector control. Field orientation is a technique that provides a method of decoupling the two components of stator current: one producing the air-gap flux and the other producing the torque.

II. VECTOR CONTROL ANALOGY WITH DC MOTOR

In a DC motor the field flux Φ_F produced by the field current I_F is perpendicular to the armature flux Φ_A produced by the armature current I_A. These fields which are stationary in space with respect to each other are orthogonal or decoupled in nature. Therefore when the armature current is controlled to control torque, the field flux remains unaffected enabling a fast transient response as shown in Fig. 1 [2].

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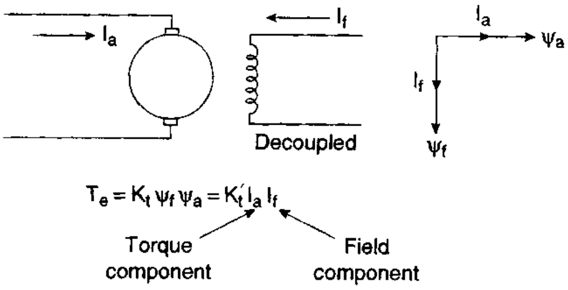

Fig.1. Vector analogy of separately excited dc motor

DC machine like performance can also be extended to an Induction Motor if the machine is considered in a synchronously rotating reference frame where the sinusoidal quantities appear as DC commands as shown in Fig. 2.

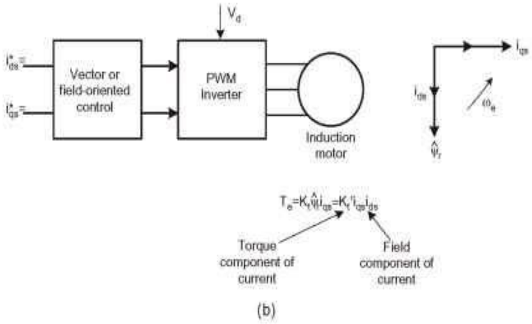

Fig.2. Vector controlled induction motor

From the Fig.2, the Induction Motor with the inverter and vector control is shown with two control current inputs.These currents are the direct axis component and quadrature axis component of the stator current respectively in synchronously rotating reference frame. With vector control, is analogous to field current I_F and is analogous to armature current I_A of a DC machine. From the vector control analogy, it has been established that i_{qs} and i_{ds} of the rotating reference frame can be controlled to provide good dynamic control of the Induction Motor.

Hence in order to obtain the motor values of currents we have to perform transformations on the measured three phase stator currents (a, b, c) into the direct and quadrature (d, q) components of the rotating reference frame. The resulting error terms are then transformed back to three phase quantities and applied to the motor. Assuming the i_a, i_b and i_c are the instantaneous currents in the stator phases, then the complex stator current vector is defined by eqn. (1)

$$i_s = i_a + \alpha i_b + \alpha^2 i_c \qquad (1)$$

where $\alpha = e^{\frac{j2\pi}{3}}$, $\alpha^2 = e^{\frac{j4\pi}{3}}$ represent the spatial operators
The following Fig. 3 and Fig. 4 show the stator current complex space vector where (a,b,c) are the three phase system axes.

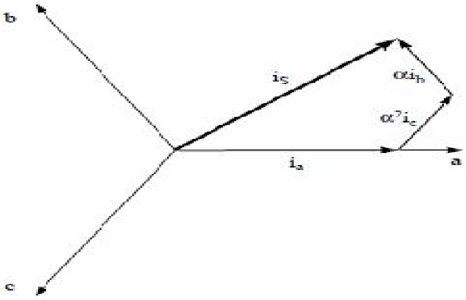

Fig.3. Stator current space vector and its components in (a, b, c)

This transformation can be split into two steps

A) (a, b ,c) to (α, β) (the Clarke transformation) which outputs a two co-ordinate time variant system

B) (α, β) to (d , q) (the Park transformation) which outputs a two co-ordinate time invariant system

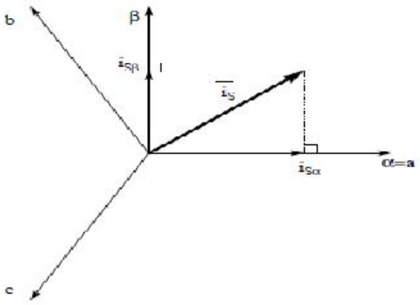

Fig.4. Stator current space vector and its components in (α, β)

The projection that modifies the three phase system into the (α, β) two dimension orthogonal system is presented as eqns. (2 & 3)

$$i_{s\alpha} = i_a \quad (2)$$

$$i_{s\beta} = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \quad (3)$$

The (α, β) to (d , q) projection (Park transformation) This is the most important transformation in the FOC. In fact, this projection modifies a two phase orthogonal system (α, β) into d,q rotating reference frames. The flux and torque components of the current vector are determined by the following eqns. (4 & 5).

$$i_{sd} = i_{sa} \cos\theta + i_{s\beta} \sin\theta \quad (5)$$

$$i_{sq} = i_{s\alpha} \sin\theta + i_{s\beta} \cos\theta \quad (6)$$

We obtain a two co-ordinate time invariant system i_{sq} and i_{sd} which are the control variables in the vector control as shown in Fig. 5.

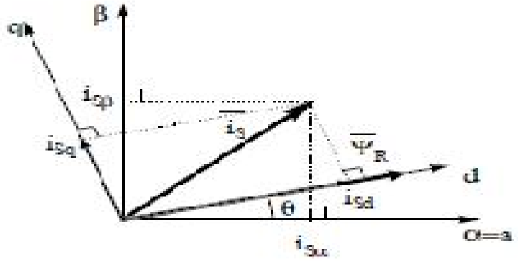

Fig.5. Stator current space vector and its component in (a,b) and in the (d,q) rotating reference frame

With i_a placed coincident with ds, it can be shown that the vector sum of the 3 stator currents i_a, i_b and i_c can be expressed in terms of the quadrature components i_{ds} and i_{qs} in the stator reference frame as shown in eqns. (7 & 8) and in Fig. 6.

$$i_{ds} = i_a \quad (7)$$

$$i_{qs} = \frac{1}{\sqrt{3}} (i_b - i_c) \quad (8)$$

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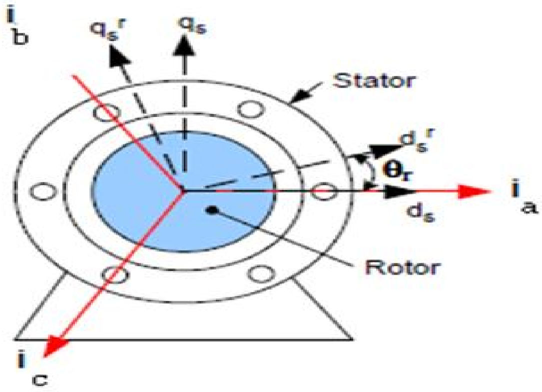

Fig.6. d-q representation of AC induction motor

Equations represent the transformation of the three phase stator currents into a two phase orthogonal vector representation ds and qs. A further transformation is then required in order to relate these components of the stationary stator frame to the rotating reference frame of the rotor. This is achieved using the Park transformation as follows in eqn. (9 & 10)

$$i^r_{ds} = i_{qs}\sin\theta_r + i_{ds}\cos\theta_r \quad (9)$$

$$i^r_{qs} = i_{qs}\cos\theta_r - i_{ds}\sin\theta_r \quad (10)$$

where θ_r represents the angular position of the rotor flux

Hence the Park transformation provides us with the direct axis and quadrature axis components (irds and irqs) of the stator current in a synchronously rotating reference frame that rotate at an angular velocity ω and at an angle θ_r with respect to the ds-qs axes.

III. RECONSTRUCTION OF STATOR VOLTAGES AND CURRENTS FROM DC LINK

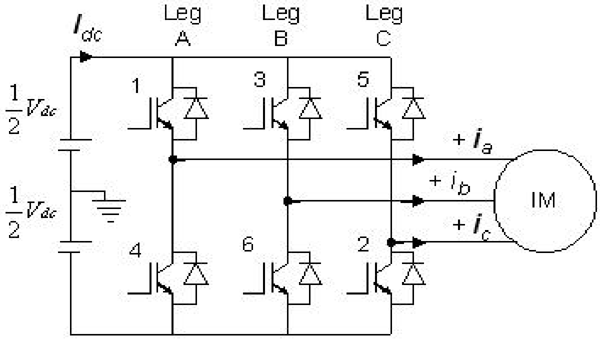

Fig.7. Voltage source inverter-IM drive

In Fig. 7, V_{dc} is the dc link voltage, I_{dc} is the instantaneous dc link current and ia, ib, ic are the instantaneous three-phase winding currents with the stator winding connected in star [3].

During normal state, there are eight switching states of inverter which can be expressed as space voltage vector (S_A,S_B,S_C) such as (0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0) and (1,1,1). S_A =1 means upper switch of leg A is on while the lower one is off, and vice versa. The same logic is applicable to S_B and S_C also. Amongst above eight voltage vectors, (0,0,0) and (1,1,1)

are termed as zero vectors while the other six as active vectors. The switching vectors describe the inverter output voltages.

Table.1 DC link current and phase voltages

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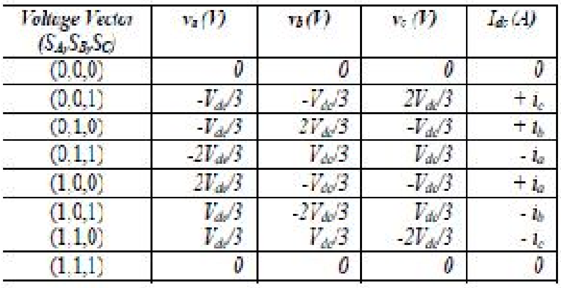

Voltage Vector (S_A, S_B, S_C)	v_a (V)	v_b (V)	v_c (V)	I_{dc} (A)
(0,0,0)	0	0	0	0
(0,0,1)	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$	$+i_c$
(0,1,0)	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$	$+i_b$
(0,1,1)	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$	$-i_a$
(1,0,0)	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$	$+i_a$
(1,0,1)	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$	$-i_b$
(1,1,0)	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$	$-i_c$
(1,1,1)	0	0	0	0

The relationship between the applied active vectors and the phase currents measured from the dc link is shown in Table 1. From this table, the expressions for the reconstruction of three phase voltages are as follows in eqn. (11, 12 & 13)

$$\overline{v}_a = V_{dc}\frac{2S_A - S_B - S_C}{3} \quad (11)$$

$$\overline{v}_b = V_{dc}\frac{-S_A + 2S_B - S_C}{3} \quad (12)$$

$$\overline{v}_c = V_{dc}\frac{-S_A - S_B + 2S_C}{3} \quad (13)$$

The stator voltages are expressed in stationary d-q frame as (14 & 15)

$$\overline{v}_{qs}^{s} = v_a = V_{dc}\frac{2S_A - S_B - S_C}{3} \quad (14)$$

$$(15) \qquad \overline{v}_{ds}^{s} = \frac{\overline{v}_b - \overline{v}_c}{\sqrt{3}} = V_{dc}\frac{S_B - S_C}{\sqrt{3}}$$

In terms of switching states and I_{dc} the three ac line currents can be derived as in eqn. (16, 17 &18)

$$\overline{i}_a = I_{dc}(S_A - \frac{S_B}{2} - \frac{S_C}{2}) \quad (16)$$

$$\overline{i}_b = I_{dc}(\frac{S_A}{2} + S_B - \frac{S_C}{2}) \quad (17)$$

$$\overline{i}_c = I_{dc}(-\frac{S_A}{2} - \frac{S_B}{2} + S_C) \quad (18)$$

The stator currents are expressed in stationary d-q frame where superscript s refer to stationary frame as eqn. (19 & 20)

$$i_{qs}^{s} = -(i_b - i_c) \qquad (19)$$

$$i_{ds}^{s} = (i_b + i_c)/\sqrt{3} \qquad (20)$$

Filter Stage

The dc link current I_{dc} consists of a train of short duration pulses and has information about the stator currents of all the three phases. By using these pulses I_{dc} can be segregated into three ac line currents. The use of band-pass filter with adaptable gain with the transfer function is shown in eqn. (21).

$$y = \left[\left(\frac{sT}{1+sT}\right)\left(\frac{T}{1+sT}\right)\right]x \quad (21)$$

where *x*, *y* and *T* are input, output and time constant of the band-pass filter.

For sT>>1; (1+sT)=1.Therefore, $y = \frac{1}{s}x$

Estimation of feedback signals from reconstructed quantities:

The feedback signals flux, torque and rotor speed are estimated as eqn. (22, 23, 24, 25 and 26)

A) Estimation of Flux

$$\overline{\psi}_{qs} = \int(\overline{v}_{qs}^{s} - R_s\overline{i}_{qs}^{s}) \quad (22)$$

$$\bar{\psi}_{ds} = \int (\bar{v}_{ds}^{s} - R_s \bar{i}_{ds}^{s}) \quad (23)$$

$$|\bar{\psi}_s| = \sqrt{\bar{\psi}_{ds}^{2} + \bar{\psi}_{qs}^{2}} \quad (24)$$

$$\mathrm{Cos}\theta_e = \frac{\bar{\psi}_{ds}}{|\bar{\psi}_s|} \; ; \; \mathrm{Sin}\theta_e = \frac{\bar{\psi}_{qs}}{|\bar{\psi}_s|}$$

where θ_e is the stator flux angle w.r.t the q-axis of stationary d-q frame.

B) Estimation of torque

$$Te = \frac{3P}{4}(\psi_{ds} i_{qs}^{s} - \psi_{qs} i_{ds}^{s}) \quad (25)$$

C) Estimation of synchronous speed and rotor speed

$$\theta_e = \tan^{-1}\left(\frac{\psi_{ds}}{\psi_{qs}}\right) \quad (26)$$

$$\omega_e = \frac{d\theta_e}{dt} \quad (27)$$

To obtain the rotor speed simple slip compensation can be derived using eqn. (28)

$$\omega_{sl} = K_s T_e \quad (28)$$

where K_s is the rated slip frequency and it can be derived from name plate of the machine.

$$\omega_{sl} = \frac{R_r' i_{qs}^{s}}{L_r' i_{ds}^{s}}$$

The rotor speed is then given by $\omega_r = \omega_e - \omega_{sl}$

IV. INDIRECT VECTOR SENSOR LESS SPEED CONTROL

In conventional current-regulated induction motor drive, the phase currents are actually measured by using current sensors which are connected on the stator side. To reduce the number of sensors, the reconstruction of phase currents from dc link current measurements have been implemented [4].

The methods proposed in the recent past years may be classified in two major categories depending upon the way information from dc link was processed to reconstruct the phase currents. The first category includes algorithm using PWM modification approach. The second category deals in estimation of phase currents by employing the machine model based state observer.

An alternative to direct measurement of the two phase currents is measuring the dc link current and based on this signal and pulse-width modulation (PWM) information, the phase currents can be reconstructed. To reconstruct the three phase currents from the dc link, information regarding the inverter switching states is required.

In this paper a new speed sensor less control strategy for Induction motor is proposed that includes the speed control, torque control and current regulation. Unlike conventional close loop estimators, it involves less computation and is less dependent on machine parameters. These have drawbacks like higher switching loss and increased sensitivity to parameter variations.

In indirect vector sensor less speed control, field angle θ_e is acquired using estimation of stator currents and voltages reconstructed from DC link measurements. It presents independent speed & torque control loops and current regulation. For close-loop control, the feedback signals including the rotor speed, flux and torque are not measured directly but are estimated.

The inputs to estimator are the reconstructed waveforms of stator currents and voltages obtained from the dc link and not measured directly on stator side.

Fig. 8 shows the block diagram of the control strategy for VSI fed induction motor [5].

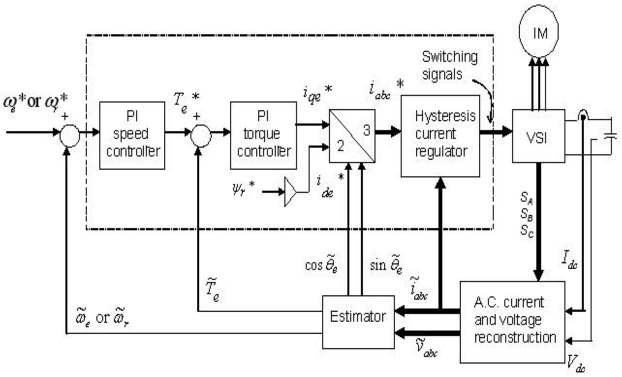

Fig.8. Block diagram of the new control strategy

It has been established that i_{qs} and i_{ds} of the rotating reference frame can be controlled to provide good dynamic control of the Induction Motor
Hence for closed loop control, reference quantities i_{qe}^* and i_{de}^* are compared with the actual values of i_{qe} and i_{de} measured from the motor.

These dc commands i_{qe}^* and i_{de}^* are expressed in synchronously rotating reference after transformation to the three phase current command i_{abc} compared with the actual three phase currents I_{abc} to generate the switching signals for the inverter. The feedback signals i.e. torque T_e and rotor speed ω_e are obtained from the DC link quantities and hence from the reconstructed line currents and phase voltages [6].

These estimated feedback signals are given to two separate PI controllers for comparing with reference values of torque and rotor speed that are obtained from the motor forming independent loops for both speed and torque.The output of the PI regulators forms the q-axis reference in a synchronously rotating reference frame.

V. RESULTS & ANALYSIS

In order to predict the behavior of the drive during steady-state and transient conditions, detailed simulation studies of the are carried out on a Induction motor by using Simulink software. The simulation was carried out for different operating conditions using Simulink software.

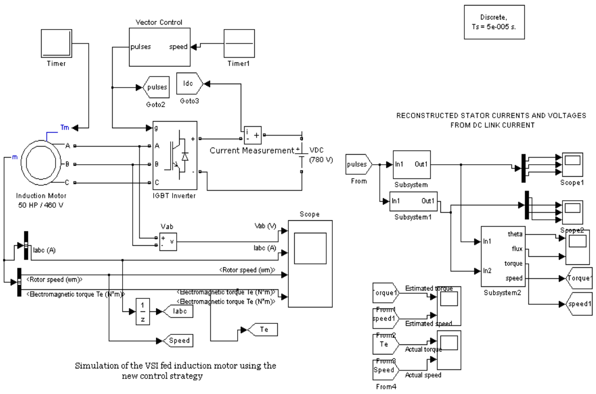

Fig.9. Simulink model of the VSI fed Induction motor speed control using DC link measurements

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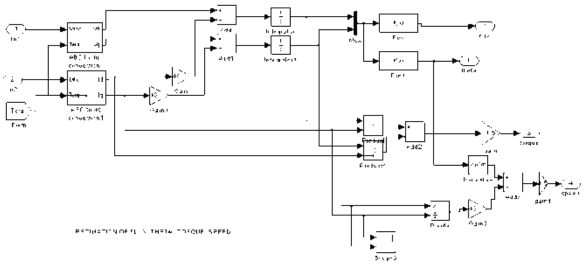

Fig.10. Estimation of the feedback signals

The simulation results are presented for the indirect vector sensor less speed control using DC link measurement for different operating conditions and those results are compared with actual values.

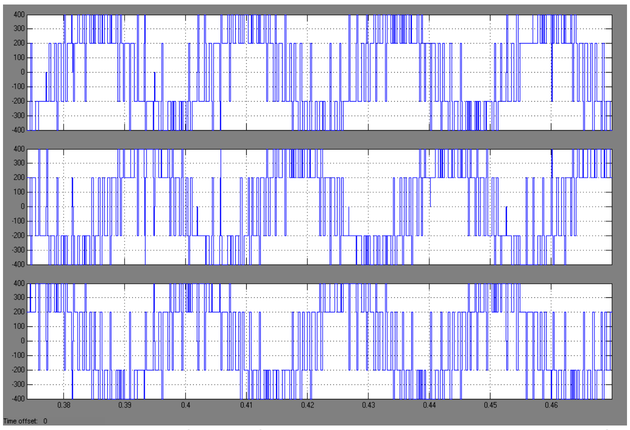

Fig.11. Reconstructed waveform of three phase voltages separated from DC link

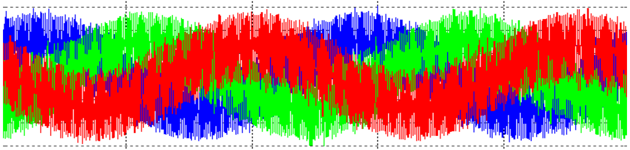

Fig.16. Stator reconstructed ac line currents at rated load

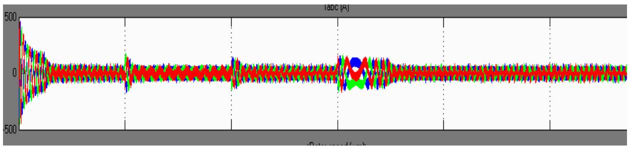

Fig.12. Stator currents during speed reversal at no-load reconstructed waveform

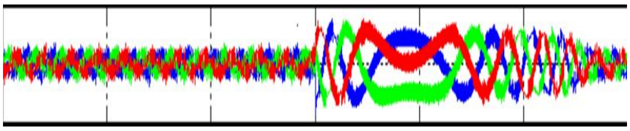

Fig.13. Stator currents during speed reversal at no-load actual waveform

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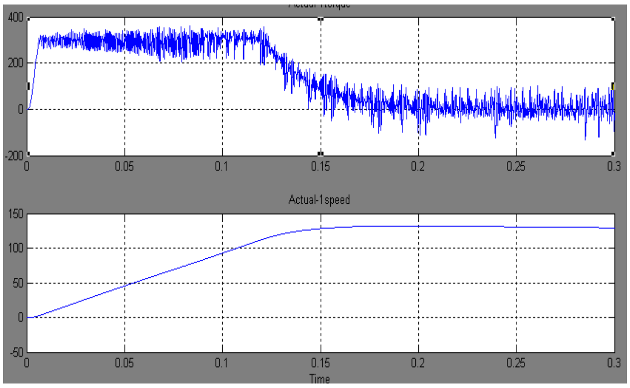

Fig.14. Free acceleration characteristics of actual torque and speed

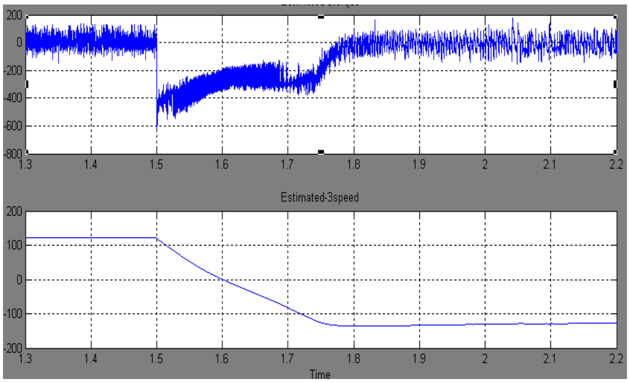

Fig.15.Variation of speed reversal for estimated values

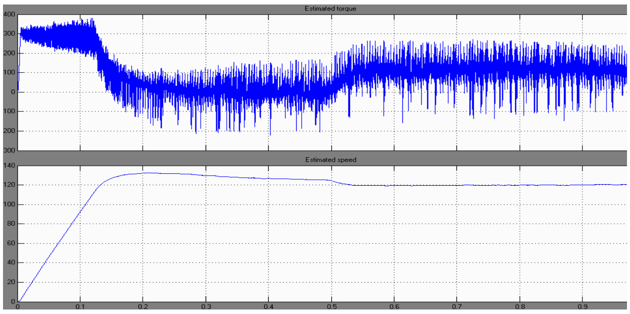

Fig.16. Variation in rotor speed and electromagnetic torque with step rise in load for estimated values

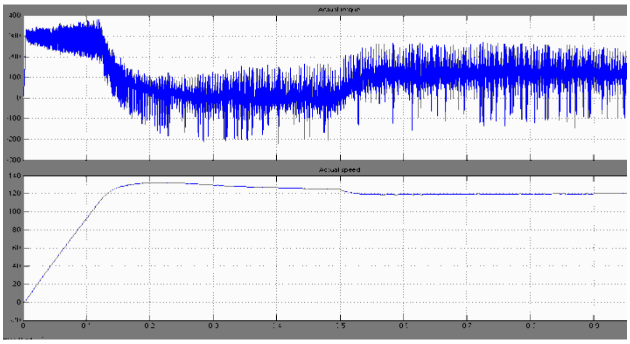

Fig.17. Variation in rotor speed and electromagnetic torque with step rise in load for actual values

VI. CONCLUSSION

From these results of the proposed conditions it is concluded that the speed of the given induction motor is varied with good steady state and dynamic conditions. These results are compared with actual values. It shows good agreement between actual and estimated values with fast performance and hence can be regarded as an improvement.

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