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PI Control Based Vector Control Strategy for Induction Motor Drive

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***Abstract* — In this paper Proportional and Integral controller is applied to control the speed and flux of induction motor. The new control scheme is proposed which avoids the use of the Sensors to measure the speed. This paper develops a Field Oriented Control Scheme for an induction motor. Using the field-oriented control, a highly coupled, nonlinear, multivariable induction motor can be simply controlled through linear independent decoupled control of torque and flux, similar to separately excited dc motors. By providing decoupling of torque and flux control demand, the vector control can govern an induction motor drive similar to a separate excited dc motor without sacrificing the quality of the dynamic performance. The Speed and Stator flux errors are used to run the PI controller to generate required current and voltage referred to stator side for controlling the speed and flux of Induction motor. Simulation is done in MATLAB and SIMULINK and results are discussed in detail.**

***Key words* — Field vector control, PI control, Sensorless control.**

I. INTRODUCTION

Major improvements in modern industrial processes over the past 50 years can be largely attributed to advances in variable speed motor drives. With the advancement in power electronic devices and the advent of DSP technology fast, reliable and cost effective control of induction motors is now possible. The area of AC motor control has continued to expand because induction motors are excellent candidates for use in Electric or Hybrid Electric Vehicles. Over the past two decades a great deal of work has been done into techniques such as Field Oriented Control, Direct Torque Control and Space Vector Pulse Width Modulation. This paper thoroughly investigated the aforementioned techniques and used them to develop a Field Oriented Vector Control Scheme [9], [10] for controlling the rotor flux and speed control of induction motor. Variable-speed drives for induction motors require both wide operating range of speed and fast torque response, regardless of load variations. The field oriented control is the most successful in meeting the above requirements. The objective of a variable-speed control system for higher productivity is to track the reference speed as fast as possible. Therefore, under the constraints of input voltage and current, a control scheme which yields the maximum torque over the entire speed range can be usefully applicable to minimum-time speed control of induction motors.

Field oriented control [11] method is widely used for advanced control of induction motor drives. However, the field oriented control of induction motor drives presents two main problems that have been providing quite a bit research interest in the last decade. The first one relies on the uncertainties in the machine models and load torque, and the second one is the precise computation of the motor speed without using speed sensors. The decoupling characteristics of the vector control are sensitive to machine parameters variations. Moreover, the machine load characteristics are not exactly known, and may vary during motor operations. Thus the dynamic characteristics of such systems are very complex and nonlinear. To overcome the above system uncertainties, the variable structure control strategy using adaptive control mode [12]-[16] has been focused on many studies and research for the control of the AC servo drive system in the past decades.

In last few decades modern PID control schemes [1]-[8] have been developed for improving the performance of variable speed drives. In this paper, a sensorless vector control scheme with PI controller is presented to improve the performance of a sensorless vector controller in a low speed region. Using the sensorless variable structure control to govern the induction motor drive, the rotor speed becomes insensitive to variations in the motor parameters and load disturbances. Moreover, the proposed control scheme provides a good transient response and exponential convergence of the speed trajectory tracking in spite of parameter uncertainties and load torque disturbances.

II. MATHEMATICAL MODELING OF INDUCTION MOTOR

The three phase induction motor is first converted into corresponding two phase Kron’s model. The voltage equations of the three phase induction motor in synchronous rotating reference frame are:

$$V_{qs}^{s} = R_s i_{qs}^{s} + d\Psi_{qs}^{s}/dt \qquad (1)$$

$$V_{ds}^{s} = R_s i_{ds}^{s} + d\Psi_{ds}^{s}/dt \qquad (2)$$

Where, Ψ_{qs} and Ψ_{ds} are q-axis and d-axis stator flux linkages respectively. The space vectors of the rotor voltages and rotor flux linkages in the general reference frame can be expressed similarly. The motor model voltage equations in the general reference frame can be expressed by using the transformations of the motor quantities from one reference frame to the general reference frame introduced. The Induction motor model is often used in vector control algorithms. The aim of vector control is to implement control schemes which produce high-dynamic performance and are similar to those used to control DC machines. To achieve this, the reference frames may be aligned with the stator flux-linkage space vector, the rotor flux-linkage space vector or the magnetizing space vector. The most popular reference frame is the reference frame attached to the rotor flux linkage space vector with direct axis (*d*) and quadrature axis (*q*). After transformation into d-q coordinates the motor model follows:

These equations in d^e-q^e frame are,

$$V_{qs} = R_s i_{qs} + d\Psi_{qs}/dt + \omega_e \Psi_{ds} \tag{3}$$

$$V_{ds} = R_s i_{ds} + d\Psi_{ds}/dt - \omega_e \Psi_{qs} \tag{4}$$

Where, all the variables are in rotating form. The last term in Equations V_{qs} and V_{ds} can be defined as speed emf due to rotation of the axes. ω_e and ω_r are the speed of the reference frame and the mechanical speed of the rotor in rad/sec. R_s and R_r are the stator and rotor resistances per phase of the motor respectively.

If $\omega_e = 0$, the equations are changed in to stationary form. Note that the flux linkage in the d^e and q^e axes induces emf in the q^e and d^e axes respectively, with Π/2 lead angle. If the rotor is not moving, i.e., $\omega_r = 0$, the rotor equations for a doubly-fed wound-rotor machine will be similar to above two Equations.

$$V_{dr} = R_r\, i_{dr} + d\, \Psi_{dr} /dt - \omega_e {*} \Psi_{qr} \tag{5}$$

$$V_{qr} = R_r\, i_{qr} + d\, \Psi_{qr} /dt + \omega_e {*} \Psi_{dr} \tag{6}$$

Here, all the variables and parameters are referred to the stator. Since the rotor moves at a speed $\omega_e - \omega_r$ relative to the synchronously rotating frame, therefore, in $d^e - q^e$ frame, the rotor equations are modified as,

$$V_{dr} = R_s\, i_{dr} + d\, \Psi_{dr} /dt - (\omega_e - \omega_r)\, \Psi_{qr} \tag{7}$$

$$V_{qr} = R_r\, i_{qr} + d\, \Psi_{qr} /dt + (\omega_e - \omega_r)\, \Psi_{dr} \tag{8}$$

The Electromagnetic Torque is given by

$$T_e = 3P\, (\Psi_{ds} i_{qs} - \Psi_{qs}\, i_{ds})/2 \tag{9}$$

The torque balance equation is:

$$J {*} d\omega_r /dt = T_e - T_L - B\omega_r \tag{10}$$

Where, (5), (6), (7), (8) are all voltages and currents are referred to the arbitrary reference frame.

J is the moment of inertia and B is the coefficient of viscous friction. T_e is the developed torque and T_L is the load torque.

$$T_e = 3PL_m\, (\Psi_{dr}\, i_{qs} - \Psi_{qr}\, i_{ds}) /2L_r \tag{11}$$

III. 2R-2S TRANSFORMATION

The synchronously rotating d^e-q^e axes rotates at synchronous speed ω_e with respect to the d^s-q^s axes and the angle $\theta_e = \omega_e {*} t$. The two phase d^s-q^s windings are transformed in to the hypothetical windings mounted on the d^e-q^e axes. The voltages on the d^s-q^s axes can be converted in to the d^e-q^e frame as follows.

$$V_{qs} = V_{qs}{}^s \cos\theta_e - V_{ds}{}^s \sin\theta_e \tag{12}$$

$$V_{ds} = V_{qs}{}^s \sin\theta_e + V_{ds}{}^s \cos\theta_e \tag{13}$$

Resolving rotating parameters in to stationary parameters, in to a stationary frame, the relations are,

$$V_{qs}{}^s = V_{qs} \cos\theta_e + V_{ds} \sin\theta_e \tag{14}$$

$$V_{ds}{}^s = -V_{qs} \sin\theta_e + V_{ds} \cos\theta_e \tag{15}$$

IV. LOAD TORQUE DISTURBANCE (T_L) COMPENSATION

When a sudden load or disturbance torque T_L can cause a droop in the speed in a speed-controlled drive system, which may not be desirable. The speed droop can be compensated with the help of a disturbance torque observer. The speed and torque are given by the following relation

$$J d\omega_m /dt + B\omega_m = T_e - T_L \tag{16}$$

Where, B = viscous friction coefficient. Therefore, T_L can be estimated by the following equation:

$$T_L = T_e - (JS + B)\, \omega_m \tag{17}$$

The actual speed ω_m is measured with the measurement delay time T_d. The signal is processed through the inverse mechanical model (JS + B) and then subtracted from the effective torque T_e' to generate the estimated torque signal.

V. VECTOR CONTROL OF INDUCTION MOTOR

Field angle is calculated by using terminal voltages and currents. The control parameters i_{ds} and i_{qs} which are dc values in synchronously rotating reference frame converted to stationary frame by using unit vectors generated from flux vector signals Ψ_{dr} and Ψ_{qr}. These flux signals are generated from the machine terminal voltages and currents with the help of the voltage model estimator. For precision control of flux, control loop should be added. The torque component of current i_{qs} is generated from the speed control loop through i_{qs} aligning of current i_{ds} in the direction of flux Ψ_r and the current i_{qs} perpendicular to it is $d^e - q^e$ will rotate at synchronous speed (ω_e) with respect to stationery frame $d^s - q^s$. The angular position of the d^e axis with respect to the d^s axis is θ_e.

$$\Psi_{dr}{}^s = \Psi_r \cos \theta_e \tag{18}$$

$$\Psi_{qr}{}^s = \Psi_r \sin \theta_e \tag{19}$$

$$\Psi_r = \sqrt{\,[(\Psi_{dr}{}^s)^2 + (\Psi_{qr}{}^s)^2]} \tag{20}$$

Ψ_r vector is represented by magnitude Ψ_r. This unit vector signal, when used for vector rotation, gives currents i_{ds} on d^e axis and i_{qs} on q^e axis. When $\Psi_{qr} = 0$ and $\Psi_{dr} = \Psi_r$, then the torque expression will be same as dc machine expression. In direct vector control, the generation of a unit vector signal is from feedback flux vector. In Induction motor the effective Time Constant under electrical transients is small (looking at the stator). So by manipulating stator MMF independent control can be achieved for Torque and Flux components of stator current. Induction motors can now be used for the applications requiring high dynamic performances like a separately excited DC motors.

VI. ESTIMATION OF SPEED

The speed of the motor is estimated by estimating the synchronous speed and subtracting the command slip speed. The synchronous speed is estimated using the stator flux components, because of its higher accuracy compared to estimation based on rotor flux components. The rotor speed of an induction motor is expressed in terms of synchronous and slip (angular) frequencies is as follows

$$\omega_r = (\omega_e - \omega_{sl})/p \qquad (21)$$

The estimation of rotor speed is accomplished by an estimation of either synchronous, or slip frequency, with the other being known. In the proposed speed estimation scheme, the synchronous frequency is estimated and slip frequency is assumed as command. So the estimated rotor speed of the sensorless drive is obtained from the above equation as:

$$\omega_r = (\omega_e - \omega^*_{sl})/p \qquad (22)$$

Where,

ω_r = estimated rotor frequency in rad/sec.

ω^*_{sl} = command value of slip frequency in rad/sec.

The estimated synchronous frequency is derived based on the rotor flux model, or the stator flux model.

The stator resistance can be measured fairly accurately. Hence, stator flux can be estimated more accurately compared to the rotor flux. Therefore the estimated stator flux can be used to derive the synchronous frequency.

VII. INDUCTION MOTOR WITH PI CONTROLLER

In a PI controlled drive, the tuning of the proportional and integral gains of a simulated or experimental system can be done in the past, several commercial auto tuned PID controllers for general purpose and higher order linear controlled systems were available. In this paper, simulation diagram of vector controlled drive system where the PI controller gains k_p and k_i are being tuned in the speed control loop. The expert controller contains the knowledge base for tuning the controller. It is assumed that initially, the PI parameters will be loaded such that the system will remain within the stability limit. The initial parameters can be derived from the knowledge of the plant parameters. A square wave auxiliary test signal is injected as the speed command ω_r^* and the pattern of the error response e is retrieved. From the knowledge base, the controller can look in to the error response and determine how the k_p and k_i parameters are to be modified to get the correct tuning. Since, $k_p + (k_i /s) = k_i /s\ (1+s/k)$ where, $k=k_i / k_p$. It is evident that the second order drive system, reducing k_i will reduce the loop gain constant as well as reduce the cross over frequency. Whereas reducing k_p will only decrease the cross over frequency with a constant gain. In this paper the vector controlled induction motor is attached with a PI controller for improving the steady state characteristics in term of speed and flux.

VIII. SIMULATION RESULTS

The model for vector control Induction motor with PI controller using vector control scheme is simulated in MATLAB.

I. NO LOAD CHARACTERISTICS:

1) No load Characteristics without any controller:

(i) Rotor Speed characteristic:

Scaling: X-axis: 1 Unit = 1 sec
Y-axis: 1 Unit = 150 rad/sec

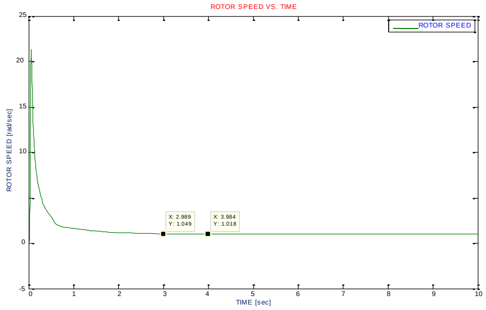

Fig. 1. Rotor Speed (rad/sec) Vs. Time (Sec) Without any Controller

(ii) Rotor Torque characteristic:

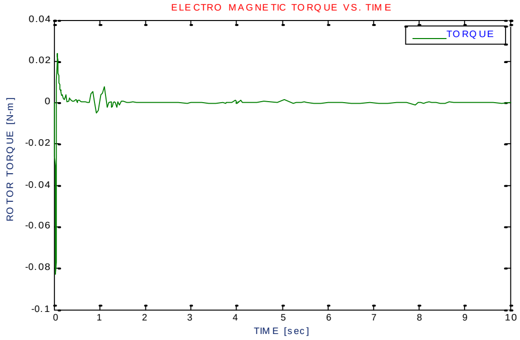

Fig. 2. Electro Magnetic Torque [Te] (N-m) Vs. Time (Sec) Without any Controller

(iii) Rotor Flux characteristic:

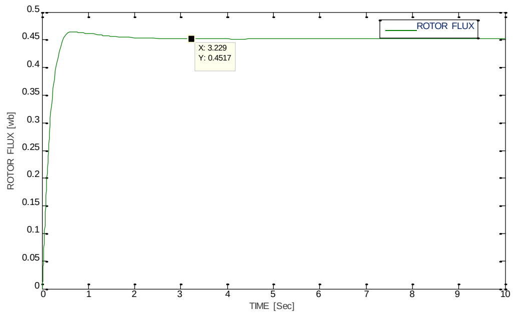

Fig. 3. Rotor Flux (wb) Vs. Time (Sec) without any Controller

2) No load Characteristics with PI Controller

(i) Rotor Speed characteristic:

Scaling: X-axis: 1 Unit = 1 sec

Y-axis: 1 Unit = 150 rad/sec

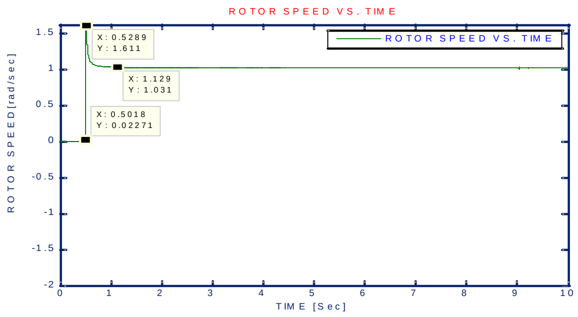

Fig. 4. Rotor Speed (rad/sec) Vs. Time with PI Controller

(ii) Rotor Torque characteristic:

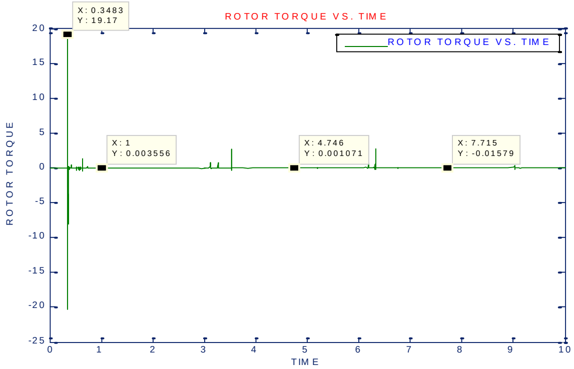

Fig. 5. Electromagnetic Torque (T_e) (N-m) Vs. Time (Sec) With PI Controller

(iii) Rotor Flux characteristic:

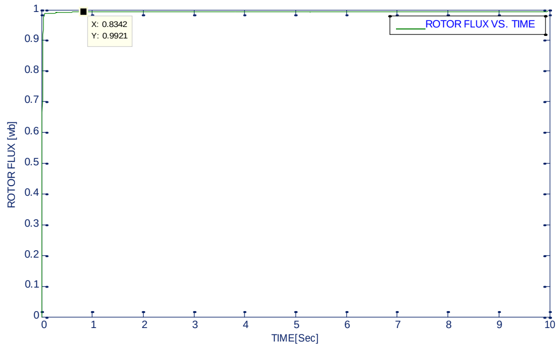

Fig. 6. Rotor Flux (wb) Vs. Time (Sec) with PI Controller

(iv) d-axis and q-axis flux with reference to the stator side

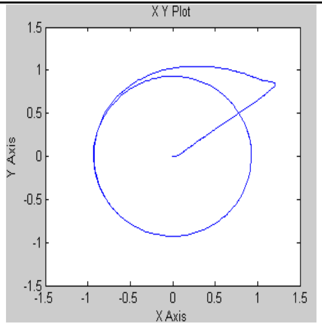

Fig. 7. d-axis flux with Reference to Stator Side Using PI Controller

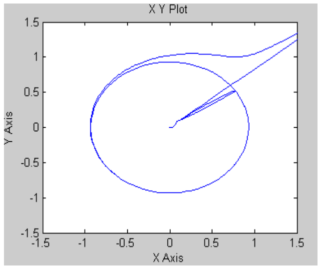

Fig. 8. q-axis Flux with Reference to Stator Side Using PI Controller

II. CHARACTERISTICS FOR CONSTANT LOAD [WITH CONSTANT DISTURBANCE]:

The ideal Load torque versus time characteristic is shown in Fig 9.

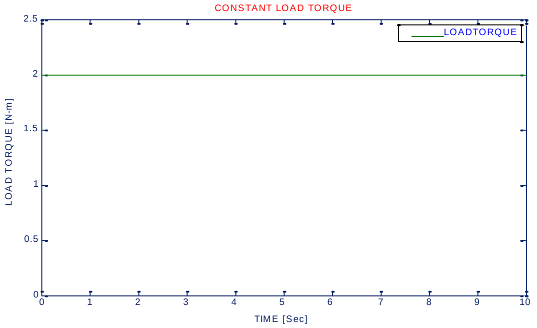

Fig. 9. Constant Load Torque (N-m) Vs. Time (Sec)

1) Constant load characteristic without any controller:

(i) Rotor Speed characteristic:

Y-axis: 1 Unit = 150 rad/sec

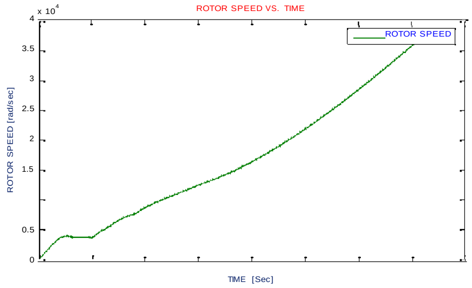

Fig. 10. Rotor Speed (rad/sec) Vs. Time Without any Controller

(ii) Rotor Torque characteristic:

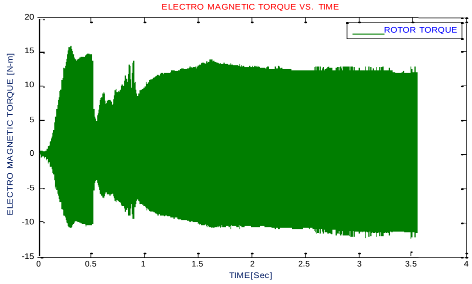

Fig. 11. Electro Magnetic Torque Vs. Time Without any Controller

(iii) Rotor Flux characteristic:

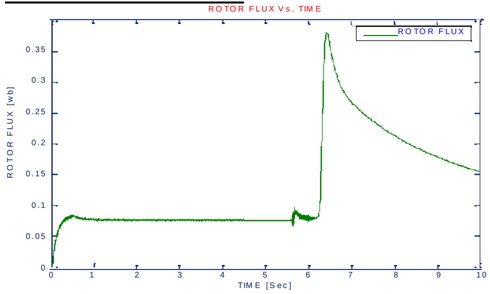

Fig. 12. Rotor Flux Vs. Time Without any Controller

2) Constant load characteristic with PI Controller:

(i) Rotor Speed characteristic:

Scaling: X-axis: 1 Unit = 1 sec
Y-axis: 1 Unit = 150 rad/sec

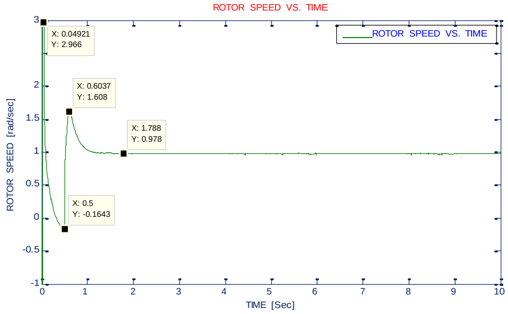

Fig.13. Rotor Speed (rad/sec) Vs. Time with PI Controller

(ii) Rotor Torque characteristic:

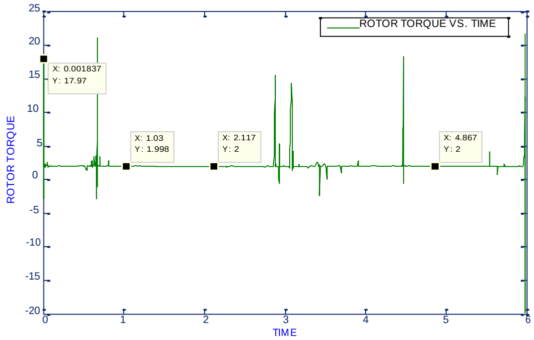

Fig. 14. Electromagnetic Torque Vs. Time with PI Controller

(iii) Rotor Flux characteristic:

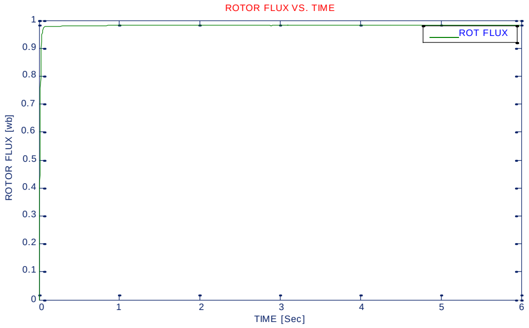

Fig.15. Rotor Flux Vs. Time with PI Controller

(iv) d-axis and q-axis flux with reference to the stator side

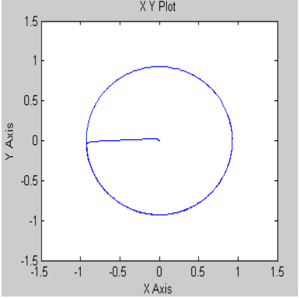

Fig. 16. d-axis Flux with Reference to Stator Side Ising PI Controller

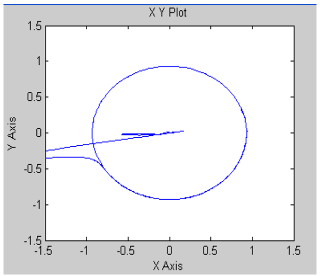

Fig. 17. q-axis Flux with Reference to Stator Side Using PI Controller

III. CHARACTERISTICS OF VARIABLE LOAD [WITH VARYING DISTURBANCE]:

The Load torque versus time characteristic is shown in Fig 18.

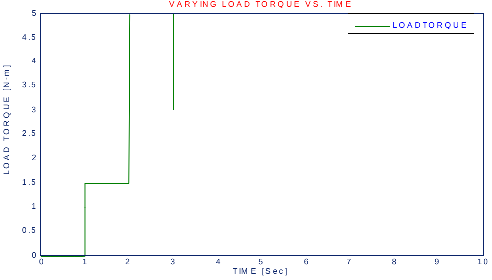

Fig.18. Varying Load Torque Vs. Time

1) Without any Controller

(i) Rotor Speed characteristic:

Scaling: X-axis: 1 Unit = 1 sec
Y-axis: 1 Unit = 150 rad/sec

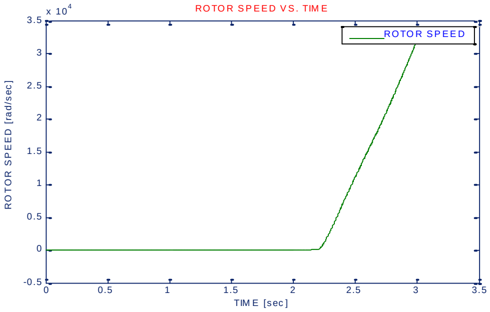

Fig.19. Rotor Speed Vs. Time without any Controller for Varying Load

(ii) Rotor Torque characteristic:

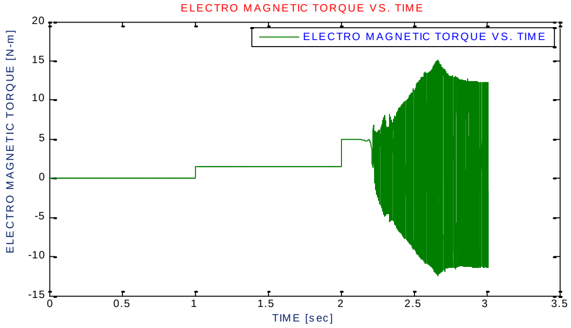

Fig.20. Electro Magnetic Torque Vs. Time Without any Controller

(iii) Rotor Flux characteristic:

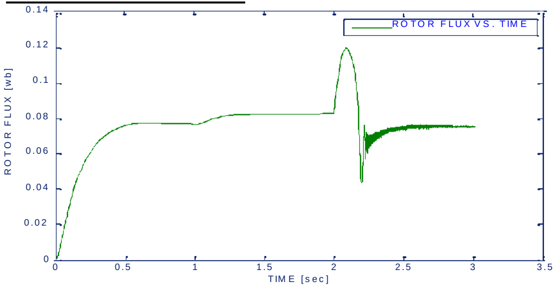

Fig.21. Rotor Flux Vs. Time Without any Controller

2) Variable load characteristic with PI Controller:

(i) Rotor Speed characteristic:

Scaling: X-axis: 1 Unit = 1 sec
Y-axis: 1 Unit = 150 rad/sec

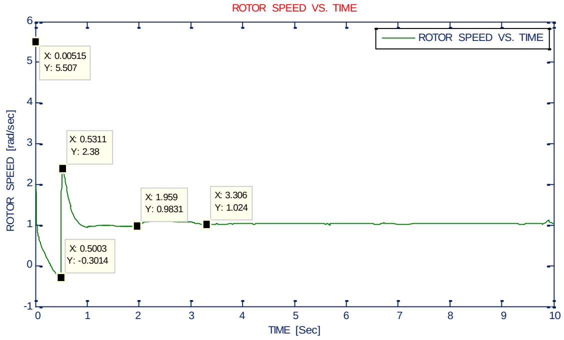

Fig.22. Varying Load Rotor Speed (rad/sec) Vs. Time (Sec) with PI Controller

(ii) Rotor Torque characteristic:

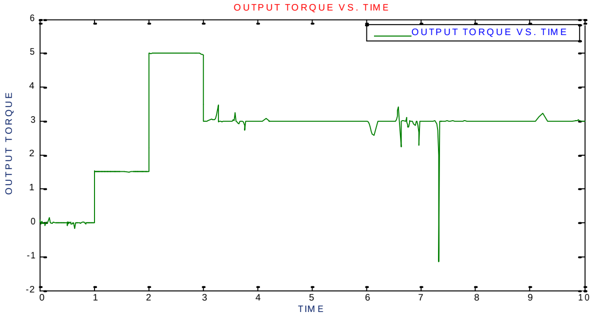

Fig.23. Electro Magnetic Torque (T_e) in N-m Vs. Time (Sec) with PI Controller

(iii)Rotor Flux characteristic:

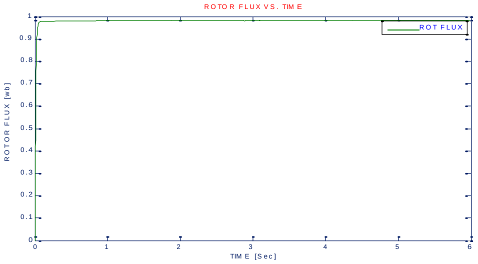

Fig.24. Rotor Flux Vs. Time (Sec) with PI Controller

(iv) **d-axis and q-axis flux with reference to the stator side**

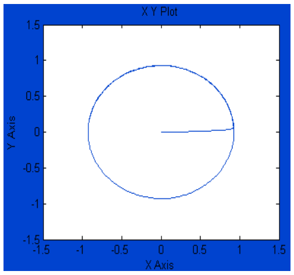

Fig.25. d-axis Flux with Reference to Stator Side Using PI Controller

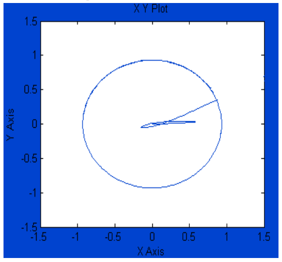

Fig.26. q-axis Flux with Reference to Stator Side Using PI Controller

IX. CONCLUSION

Comprehensive study on dynamic d-q model and vector control has been made. To study the dynamic performance of an induction motor, MATLAB SIMULINK toolbox is used. It is observed that during transients, the Induction motor without any controller becomes unstable. Its dynamic characteristics are improved with the application of PI controller Tables I and II give the comparison of Induction motor performance without any controller and with PI controller. This comparison is carried out for different loading conditions. Firstly the motor is at no load condition then it is loaded with constant load and finally it is loaded with variable load. Under these conditions the speed and flux of induction motor are calculated and their characteristics are shown in Fig.s. The specifications which are taken for the comparison are maximum Overshoot, settling time, steady state value and steady state error. From the simulation results, it can be concluded that the performance of Induction motor is improved drastically with the application of PI controller for field oriented Induction motor drive. It is most capable scheme for reducing the spikes, maximum overshoot, and Steady state error.

TABLES

I. COMPARATIVE ANALYSIS OF INDUCTION MOTOR PERFORMANCE FOR SPEED AS A PARAMETER

	WITHOUT ANY CONTROLLER			**PI CONTROLLER**		
Description	*No Load*	*Constant Load*	*Variable Load*	*No Load*	*Constant Load*	*Variable Load*
% Max. Overshoot	20.5	Unstable	Unstable	0.611	1.966	4.507
Settling Time (Sec)	3.984	Unstable	Unstable	1.121	1.788	3.306
Steady State Speed	1.018	Unstable	Unstable	1.031	0.978	1.024
Steady State Error	-0.018	Unstable	Unstable	-0.031	0.022	-0.024

II. COMPARATIVE ANALYSIS OF INDUCTION MOTOR PERFORMANCE FOR FLUX AS A PARAMETER

	WITHOUT ANY CONTROLLER			PI CONTROLLER		
Description	*No Load*	*Constant Load*	*Variable Load*	*No Load*	*Constant Load*	*Variable Load*
% Max. Overshoot	0	Unstable	Unstable	0	0	0
Settling Time (Sec)	3.229	Unstable	Unstable	0.8342	0.98	0.982
Steady State Flux	0.4517	Unstable	Unstable	0.9921	0.982	0.983
Steady State Error	0.5483	Unstable	Unstable	0.0097	0.018	0.017

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