SPEED CONTROL OF INDUCTION MOTOR USING VECTOR CONTROL

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ABSTRACT

The Objective of this paper is to control the speed of the induction motor by using vector control method. By controlling the speed of the induction motor power can be saved. Being a non-linear dynamic system with internal coupling, it is necessary to control the speed of an induction motor using vector control techniques. Induction motor model was implemented and the speed torque characteristics were analysed. The speed of the induction motor can be controlled in two ways: Scalar control and Vector control. In scalar control method the dynamic response is not good. Vector control method of speed control of induction motor was superior to scalar control. Two phase voltages are chosen as control variables for vector control. The load torque is varied dynamically to analyse the speed variations during vector control. The vector control model of induction motor was implemented using Matlab-Simulink software.

Key words: Induction Motor; Vector Control.

I. INTRODUCTION

We all know that an electric motor is used for the conversion of electrical energy into mechanical energy. This mechanical energy may be used for the pumping of liquid from one place to other by using pumps or even to blow air by blowers or ceiling fans. The conversion of electrical power to mechanical energy takes place in the rotating part of the motor. In D.C. Motors, the electric power is conducted directly to the armature (the rotating part) through brushes & commutator. Thus we can say a D.C. Motor as a conduction motor. But in case of an A.C. Motor, the rotor does not receive electric power by conduction, but by Induction. Thus they are called as induction motors. This can be compared with the secondary winding of a transformer. These induction motors are also called as rotating transformers. Of all motors, it is generally a 3-phase or a poly-phase induction motor is used in a larger extent in many industries. The Direction of rotation of an Electric motor is given by Fleming's Left Hand rule:

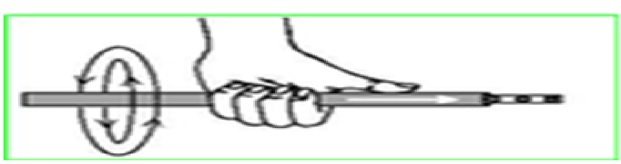

Fig 1.1 Left hand thumb rule

- It shows the relation between the directions of "thrust" on a conductor carrying a "current" in a "magnetic field".
- Keep the Thumb, Index finger & the Middle finger of the left hand at right angles to each other. The first finger or the index finger indicates the direction of the field.
- The second finger or the middle finger represents the direction of the **c**urrent.
- The thumb represents the direction of the thrust or the direction of motion of the conductor.

Also other important Law is the Faraday's Law of Electro Magnetic Induction. There are 3 important rules/laws of electromagnetic induction. They are as follows:

1. An EMF is induced in a coil whenever the flux through the coil changes with time.
2. The magnitude of induced EMF is directly proportional to the rate of change of flux.

The direction of the EMF is such as to oppose the change in flux. These basic Laws govern the working of an electric motor.

A. Construction of Squirrel Cage Induction Motor

Any Induction Motor has a Stator and a Rotor. The construction of Stator for any induction motor is almost the same. But the rotor construction differs with respect to the type which is specified above.

Stator: The stator is the outer most component in the motor which can be seen. It may be constructed for single phase, three phase or even poly phase motors. But basically only the windings on the stator vary, not the basic layout of the stator. It is almost same for any given synchronous motor or a generator. It is made up of number of stampings, which are slotted to receive the windings.
Let us see the construction of a three phase stator. The three phase windings are placed on the slots of laminated core and these windings are electrically spaced 120 degrees apart. These windings are connected as either star or delta depending upon the requirement. The leads are taken out usually three in number, brought out to the terminal box mounted on the motor frame. The insulations between the windings are generally varnish or oxide coated

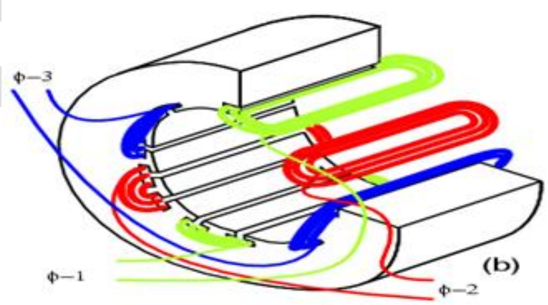

Fig 1.2 Sectional cut-off of Induction Motor Stator

The Rotor (Squirrel Cage Rotor): This kind of rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor conductors, which are not wires, as we think, but thick, heavy bars of copper or aluminum (aluminum) or its alloys. The conductor bars are inserted from one end of the rotor and as one bar in each slot. There are end rings which are welded or electrically braced or even bolted at both ends of the rotor, thus maintaining electrical continuity. These end rings are short-circuited, after which they give a beautiful look similar to a squirrel thus the name.

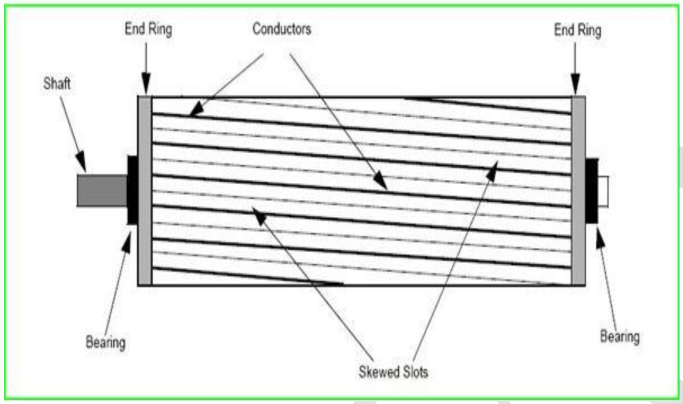

Fig 1.3 Front view of Induction Motor Rotor

II. STATE SPACE REPRESENTATION

In control engineering, a state space representation is a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations. To abstract from the number of inputs, outputs and states, the variables are expressed as vectors. Additionally, if the dynamical system is linear and time invariant, the differential and algebraic equations may be written in matrix form. The state space representation is also known as the time-domain approach. It provides a convenient and compact way to model and analyze the systems with multiple inputs and outputs. Unlike the frequency domain approach, the use of the state space representation is not limited to systems with linear components and zero initial conditions.

A. State variables

The internal state variables are the smallest possible subset of system variables that can represent the entire state of the system at any given time. The minimum number of state variables required to represent a given system is usually equal to the order of the system's defining differential equation. If the system is represented in transfer function form, the minimum number of state variables is equal to the order of the transfer function's denominator.

B. Linear System

The system output varies proportional to the input is called linear system. In mathematics, a linear system f(x) is one which satisfies the both of the following properties.

- Additivity (superposition), f(x+y) = f(x) + f(y);
- Homogeneity, f(ax) = af(x).

The most general state space representation of a linear system with P inputs, Q outputs and state variables is written in the following form.

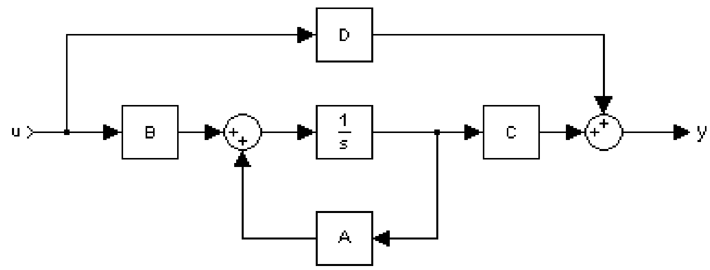

Fig 1.3 Block Diagram of State Space representation

State space representation

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (2.1)$$
$$Y(t) = Cx(t) + Du(t) \qquad (2.2)$$

x(t) is called state vector
Y(t) is called output vector
U(t) is called input vector
A – State matrix
B – Input matrix
C – Output matrix
D – feedforward matrix

C. Nonlinear System

Generally a nonlinear system, in contrast to a linear system, is a system which does not satisfies the superposition principle.ie, the output of a system is not directly proportional to the input either in controlled process or in the controller itself. Nonlinear control theory is concerned with the analysis and design of nonlinear control systems. It is closely related to nonlinear systems theory in general, which provides its basic analysis tools.
Many other techniques from control engineering are applicable to the design of nonlinear systems, some of which may be considered as separate fields of control engineering. Among these we mention:

- **Optimal Control**: Here the control objective is to minimize a pre-determined cost function. The basic solution tools are Dynamic Programming and variational methods (Calculus of Variations and Pontryagin's maximum principle). The available solutions for nonlinear problems are mostly numeric.
- **Model Predictive Control**: An approximation approach to optimal control, where the control objective is optimized on-line for a finite time horizon. Due to computational feasibility this method has recently found wide applicability, mainly in industrial process control.
- **Adaptive Control**: A general approach to handle uncertainty and possible time variation of the controlled system model. Here the controller parameters are tuned on-line as part of the controller operation, using various estimations and learning techniques.
- **Neural Network Control**: A particular class of adaptive control systems, where the controller is in the form of an Artificial Neural Network.

- **Fuzzy Logic Control**: Here the controller implements an (often heuristic) set of logical (or discrete) rules for synthesizing the control signal based on the observed outputs. Defuzzification and fuzzification procedures are used to obtain a smooth control law from discrete rules.

State space representation

$$\dot{x}(t) = f(t, x(t), u(t)) \qquad (2.3)$$

$$y(t) = h(t, x(t), u(t)) \qquad (2.4)$$

D. Controllability

A control system is said to be completely state controllable if it is possible to transfer the system from any arbitrary initial state to any desired state in a finite time period. That is, a control system is controllable if every state variable can be controlled in a finite time period by some unconstrained control signal. If any state variable is independent of the control signal, then it is impossible to control this state variable and therefore the system is uncontrollable. In other words a system is completely controllable if and only if the inverse of Controllability matrix is available. Or the rank of the controllability matrix is *n*.
Controllability matrix

$$Q_c = [A \quad AB \quad A^2B \quad \ldots\ldots A^{N-1}B] \qquad (2.5)$$

A continuous time-invariant linear state-space model is controllable if and only if rank
$|Q_c| = n$
Where rank is the number of linearly independent rows in a matrix.

E. Observability

A system is completely observable if and only if the inverse of observability matrix (Q_o) is available. Or the rank of the observability matrix is *n*.

$$Q_o = [A^T \quad A^T B^T \quad A^{T^2} B^T \ldots\ldots \quad A^{T^{N-1}} B^T] \qquad (2.6)$$

The observability and controllability of a system are mathematical duals .i.e., as controllability provides that an input is available that brings any initial state to any desired final state, observability provides that knowing an output trajectory provides enough information to predict the initial state of the system.

III. MODELING OF INDUCTION MOTOR

A. Three Phase to Two Phase Transformation

A dynamic model for the three-phase induction machine can be derived from the two-phase machine if the equivalence between three and two phases is established. The equivalence is based on the equality of the mmf produced in the two-phase and three-phase windings and equal current magnitudes. Assuming that each of the three-phase windings has Ns turns per phase and equal current magnitudes, the two-phase winding will have 1.5Ns turns per phase for mmf equality.

The three phase equations can be converted into two phase equation using double axis frame theory.

Basically there are three reference frames. They are

1. Stator reference frame.
2. Rotor reference frame.
3. Synchronously rotating reference frame.

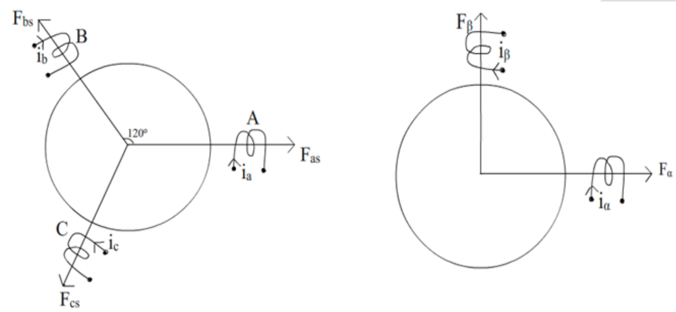

Fig 3.1 Representation of stator currents and stator currents in stationary axis

$$i_{as} = i_m \cos\omega t \quad (3.1)$$

$$i_{bs} = i_m \cos(\omega t - \frac{2\pi}{3}) \quad (3.2)$$

$$i_{cs} = i_m \cos(\omega t + \frac{2\pi}{3}) \quad (3.3).$$

Assuming that each of the three phase winding has N_s turns per phase and equal currents magnitudes, the two-phase winding will have 1.5Ns turns per phase for mmf equality.

$$\frac{3}{2} i_{as} N = N(i_{as}\cos 0^0 + i_{bs}\cos 120^0 + i_{cs}\cos 240^0) \quad (3.4)$$

$$i_{\alpha s} = \frac{2}{3}\left(i_{as} - \frac{1}{2}(i_{bs} + i_{cs})\right) \quad (3.5)$$

Similarly,

$$\frac{3}{2} i_{\alpha s} N = N(i_{as}\sin 0^0 + i_{bs}\sin 120^0 + i_{cs}\sin 240^0) \quad (3.6)$$

$$i_{\beta s} = \frac{2}{3}\left(\frac{\sqrt{3}}{2}(i_{bs} - i_{cs})\right) \quad (3.7)$$

So,

$$\begin{pmatrix} i_{\alpha s} \\ i_{\beta s} \end{pmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{pmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{pmatrix} \quad (3.8)$$

IV. VECTOR CONTROL

Scalar control is so far simple to implement, but the inherent coupling effect (i.e., both torque and flux are functions of voltage or current and frequency) gives sluggish response and the system is easily prone to instability because of a high order (fifth order) system effect. The foregoing problems can be solved by vector or field-oriented control. The invention of vector control in the beginning of 1970's, and the demonstration that an induction motor can be controlled like a separately excited dc motor, brought a renaissance in the high-performance control of ac drives. Because of dc machine-like performance, vector control is also known as decoupling, orthogonal, or transvector control. Vector control is applicable to both induction and synchronous motor drives.

A. DC Drive Analogy

Ideally, a vector-controlled induction motor drive operates like a separately excited dc motor drive, as mentioned above. Fig 5.1 explains this analogy. In a dc machine, neglecting the armature reaction effect and field saturation, the developed torque is given by

$$T_e = K_t^{'} I_a I_f \qquad (4.1)$$

These currents are direct axis component and quadrature axis component of the stator current, respectively, in a synchronously rotating reference frame.

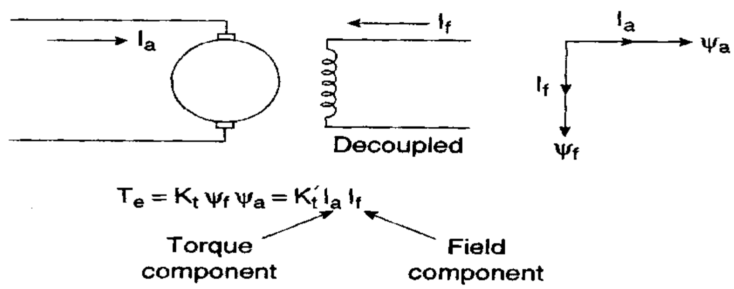

Fig 4.1 Separately excited dc motor

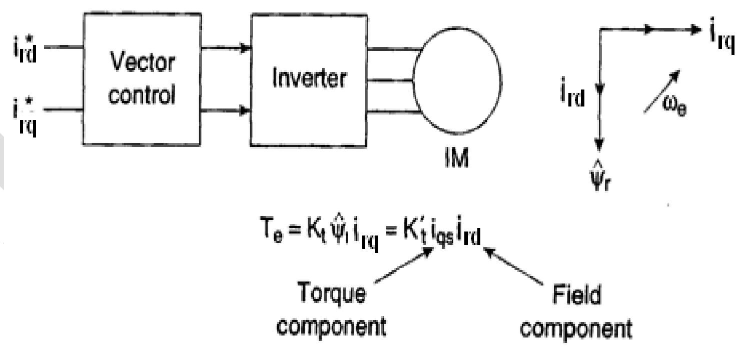

Fig 4.2 Vector-controlled induction motor

With vector control, i_{ds} is analogous to field current I_f and i_{rq} is analogous to armature current I_a of a dc machine. Therefore, the torque can be expressed as

$$T_e = K_p \hat{\psi}_r i_{rq} \qquad (4.2)$$

or

$$T_e = K_t' i_{rd} i_{rq} \qquad (4.3)$$

B. Simulink of Vector Control

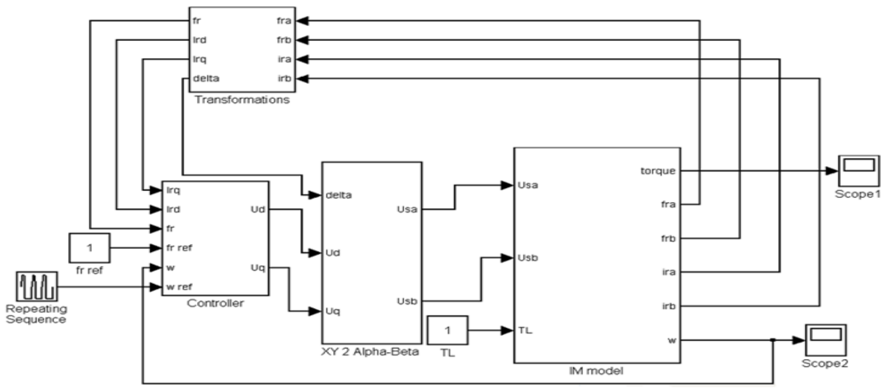

Fig 4.3 Simulink block diagram of vector control induction motor.

V. SIMULATION RESULTS

A. For Scalar Control

The induction motor was simulated using scalar control method and the below results were obtained. The initialization file for this model is given in appendix-1.

(a) Comparison of Actual and Reference Speed

Speed of the induction motor is controlled using scalar control. The reference speed is given as 150 rad/sec and we can observe that speed has settled to 150 rad/sec after a settling time of 2.5 sec. It has a peak value of 240 rad/sec and the rise time is 0.7 sec.

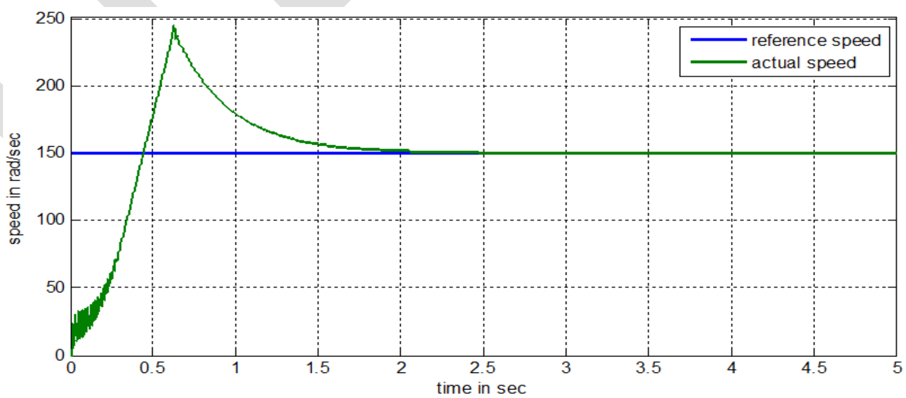

Fig 5.1 speed characteristics during scalar control

There were more transients during first 02 sec and gradually the transients die out and actual speed was obtained at 2.5 sec

(b) Torque vs Time Characteristics

Torque during scalar control of induction motor is shown in Fig 5.2, the settling time of the torque is 2 sec and it is settled equal to the load torque value. The torque is oscillating from 300 N-m to -200 N-m before getting settled to required load torque value.
Transients are more in the load torque with scalar control

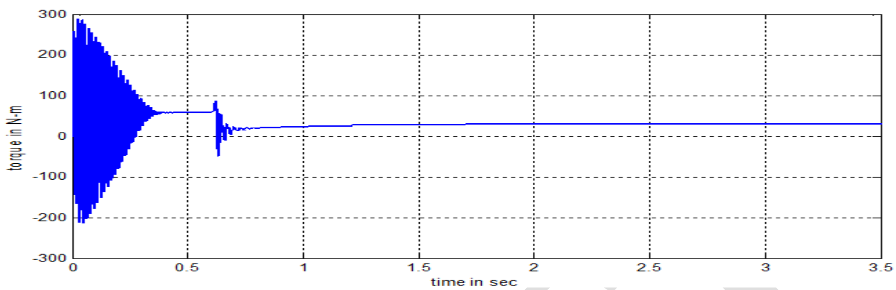

Fig 5.2 Torque characteristics with scalar control

B. Vector Control

(a) Speed-Torque Characteristics:

The reference speed is given as 100 rad/sec and the actual speed is settled down nearly to 100 rad/sec after a settling time of 0.1 sec (Fig 5.3). The parameters chosen are as per the appendix 1. The vector controlled induction motor when simulated with appendix-2 values has the speed characteristics as in Fig 5.4. Here the settling time is 0.5 sec and the speed settled exactly at 100 rad/sec.
When the speed of the motor was changed from positive value to negative value, the speed also varied dynamically from positive speed to negative speed as per the requirement (reference speed). Thus by using vector control speed can be controlled in both clockwise and anti-clockwise direction. Transients are very few though the speed changes suddenly, so we can use vector control for sudden load changing conditions such that we have smooth variation in speeds. The characteristics are given in Fig 5.5.

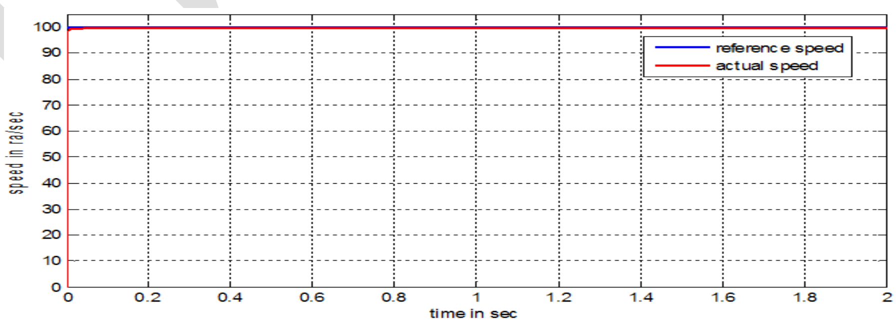

Fig 5.3 speed characteristics with Appendix-1 parameters

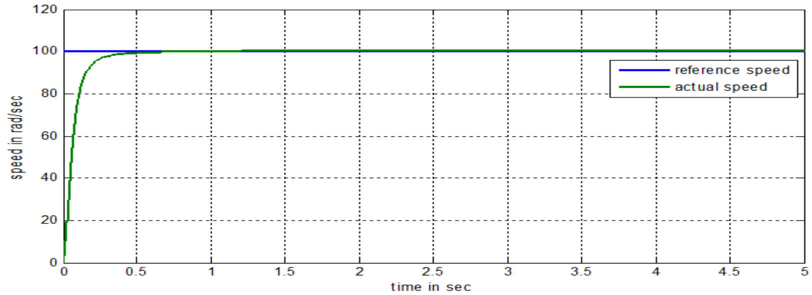

Fig 5.4 Speed characteristics with Appendix-2 parameters

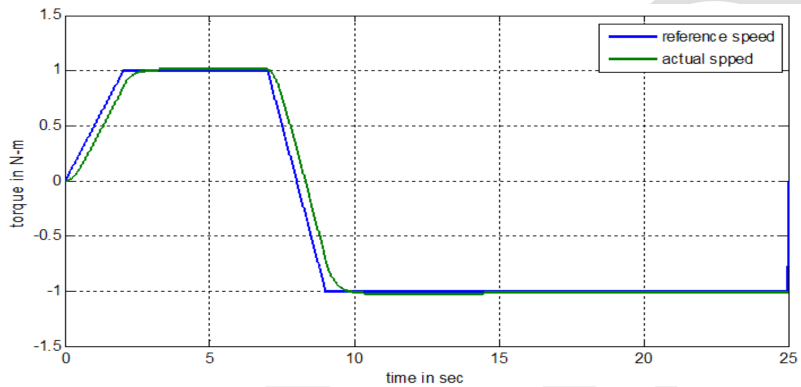

Fig. 5.5 speed characteristics in positive and negative references

(b) Torque vs Time Characteristics:

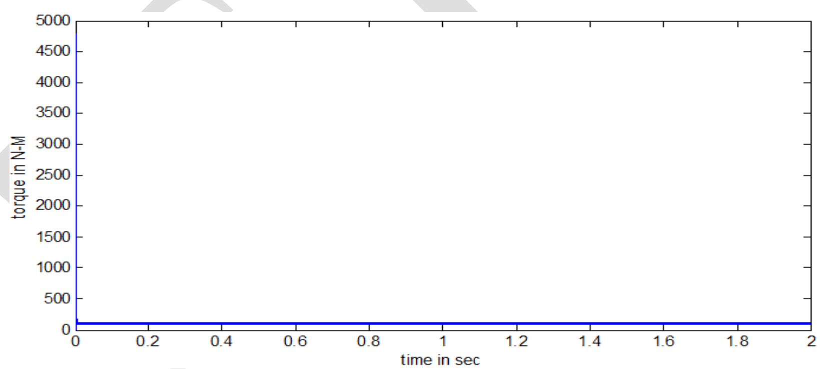

Fig 5.6 Torque characteristics with appendix-1 parameters

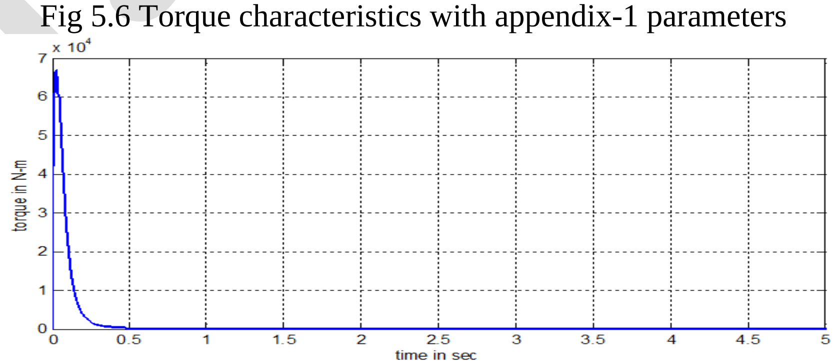

Fig 5.7 Torque characteristics with appendix-2 parameters

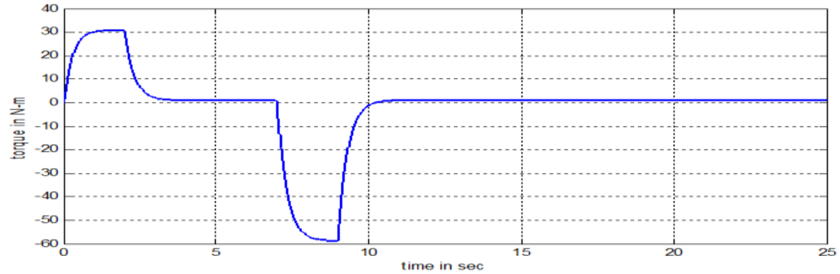

Fig 5.8 Torque characteristics with change in speed

(c) Current Characteristics

Inrush currents of the induction motor are high (10%-20%). When load is applied the value of inrush current is 20kA. The final value of current is 0.5 p.u.

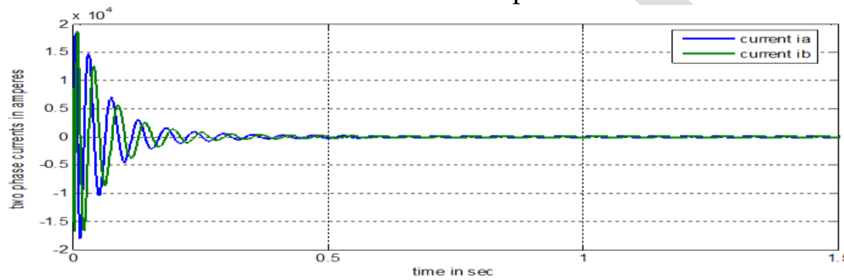

Fig 5.9 current characteristics

When speed changed suddenly current value is increased. It changed from positive peak to negative peak and settled to 1p.u.

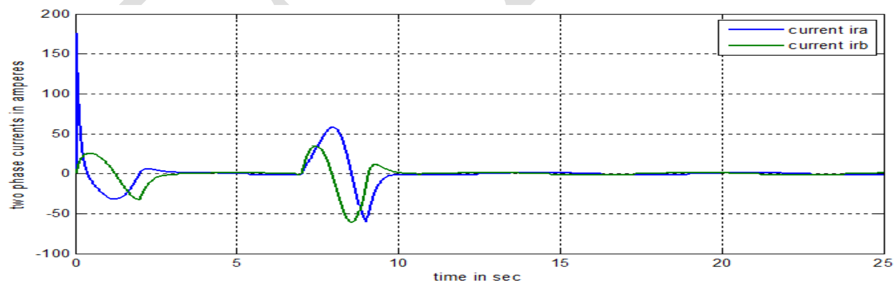

Fig 5.10 current characteristics with change in speed

C. Flux Characteristics

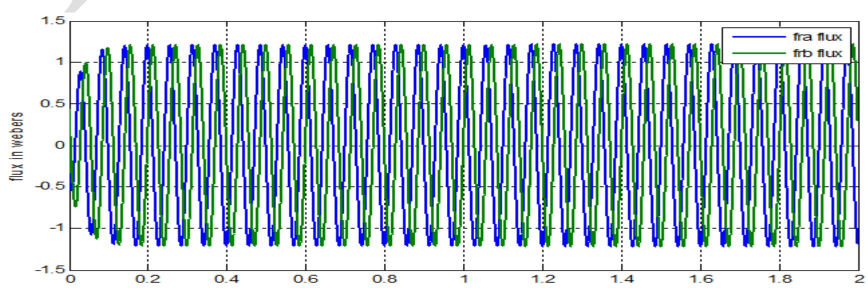

Fig 5.11 Flux characteristics with appendix-1 parameters

The magnitude of flux remains always constant but the frequency and initial flux is varied as the parameter values are changed. The steady flux is always 1.2 webers, thus transformer action of induction motor is observed.

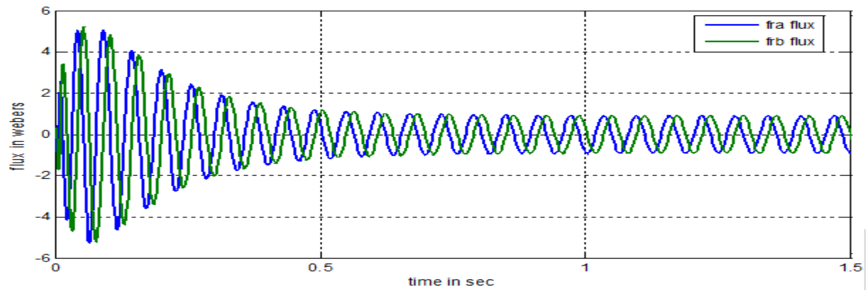

Fig 5.12 Flux characteristics with appendix-2 parameters

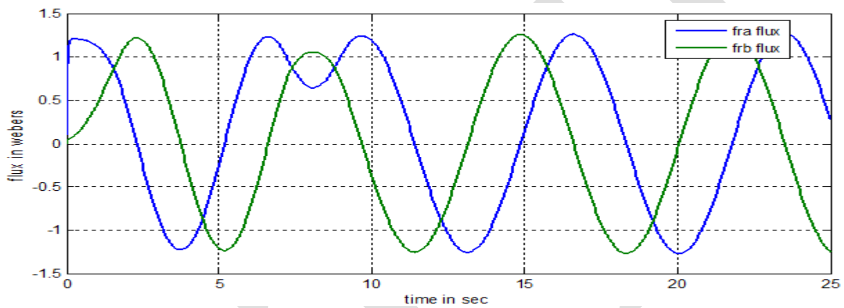

Fig 5.13 Flux characteristics with change in speed

CONCLUSION

In this paper, implementation of a matlab-simulink model for an induction motor has been introduced. By analyzing the results vector control of induction motor model has superior performance than scalar control of induction motor. With vector control the rise time, the settling time, the peak over shoot is decreased and the dynamic behavior of induction motor is well performed. Unlike, other modular implementation, with simulink model the user has access to all the internal variables for getting an insight into the machine operation.
In future, this project can be extended by the hardware implementation of the induction motor with vector control and can also be extended by simulink model with advanced nonlinear controllers like backsteepping control, adaptive control, fuzzy logic etc.

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APPENDIX-1

Induction motor data

R_s	Stator resistance	0.18 Ω
R_r	Rotor resistance	0.15 Ω
i_s	Stator current	
ψ_s	Stator flux linkage	
i_r	Rotor current	
ψ_r	Rotor flux linkage	1.3 Wb
U	Voltage input	
W	Angular speed	220 rad/sec
n_p	No of pole pairs	3
δ	Angle of rotation	
L_s	Stator inductance	0.0699 H
L_r	Rotor inductance	0.0699 H
M	Mutual inductance	0.068 H
J	Rotor inertia	0.0586 Kg-m^2
T_L	Load torque	70 N-m
T	Electric motor torque	Rated power 15 KW

APPENDIX -2

Induction motor data

R_s	Stator resistance	0.045p.u.
R_r	Rotor resistance	0.045p.u.
ψ_r	Rotor flux linkage	1 p.u.
U	Voltage input	
W	Angular speed	1 p.u.
L_s	Stator inductance	1.927p.u.
L_r	Rotor inductance	1.927 p.u.
M	Mutual inductance	1.85 p.u.
J	Rotor inertia	59 Kg-m^2
T_L	Load torque	0.7 p.u.
T	Electric motor torque	Rated power 15 KW
n_p	No of pole pairs	1
K_p	Proportional constant	200
K_I	Integral constant	10