CERTIFICATE

This is to certify that Major project titled **“DESIGN OF KALMAN FILTER FOR INDUCTION MOTOR DRIVE”** submitted by Ms. Kiran Singh in partial fulfillment of requirements for award of the degree of Master of Engineering (Control & Instrumentation) of the Electrical Engineering Department, Delhi college of Engineering, Delhi –110042 is a bonafide record of work that she has carried out under my guidance and supervision.

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ABSTRACT

In this project, design and simulation of standard and extended versions of Kalman's filter (KF) for rotor flux estimation in a voltage source inverter fed vector controlled induction motor drive is presented and described. The complete field oriented control scheme of the induction motor drive incorporating the KF, EKF is simulated in MATLAB for a 50 hp, 460V, 50Hz, 1440rpm squirrel-cage Induction Motor(IM). The performances of the proposed observer based IM drive are analyzed. The estimated results show that the EKF based Flux observer gives better performance of IM drive in comparison to the Standard Kalman's Filter based observer. However its performance depends on an accurate choice of process and measurement noise covariance matrices.

Methodology to create KF, EKF for online identification of induction motor parameters are also described in details.The Extended Kalman Filter can be used for combined state and parameter estimation by treating selected parameters as extra states and forming an augmented state vector. Depending on whether the original state space model is linear or not, the augmented model is nonlinear in multiplication of states .A fifth order augmented state space model is developed when the EKF is applied to the simultaneous estimation of states of stator and rotor d -q current and rotor d -q fluxes.

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List of Symbols

S. No.	Symbols	Description
1	d^s-q^s	Stationary rotating reference frame direct or quadrature axis
2	d^e-q^e	Synchronously rotating reference frame direct or quadrature axis
3	ψ_r	rotor flux linkage
4	ψ_s	stator flux linkage
5	ψ_m	air gap flux
6	ψ_{qs}	q^e-axis stator flux linkage
7	ψ_{qr}	q^e-axis rotor flux linkage
8	ψ_{ds}	d^e*-axis* stator flux linkage
9	ψ_{dr}	d^e*-axis* rotor flux linkage
10	ψ_{dm}	d^e*-axis* air gap flux linkage
11	ψ_{qm}	q^e-axis *air gap* flux linkage
12	ψ_{qs}^s	q-axis stator flux linkages
13	ψ_{ds}^s	d-axis stator flux linkages
14	i_{qs}	q^e-axis stator current
15	i_{qr}	q^e-axis rotor current
16	i_{dr}	d^e-axis rotor current
17	i_{ds}	d^e-axis stator current
18	i_{qs}	q^e-axis stator current
19	L_m	Magnetizing inductance
20	L_{ls}	Stator leakage inductance
21	L_{lr}	Rotor leakage inductance
22	v_{qs}	q^e -axis stator voltage
23	v_{ds}	d^e -axis stator voltage
24	v_{qr}	q^e-axis rotor voltage
25	v_{dr}	d^e-axis rotor voltage

26	R_s	Stator resistance
27	R_r	Rotor resistance
28	L_s	Stator inductance
29	L_r	Rotor inductance
30	ω_e	Stator or line frequency
31	ω_r	Rotor electrical speed
32	ω_{sl}	Slip frequency
33	s	Laplace operator
34	p	Number of pole
35	θ_e	Angle of synchronously rotating frame
36	θ_r	Rotor angle
37	θ_{sl}	Slip angle
38	v_{qs}^s	q^s-axis stator voltage
39	v_{ds}^s	d^s-axis stator voltage
40	i_{qs}^s	q^s-axis stator current
41	i_{ds}^s	d^s-axis stator current

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Chapter I Introduction

1.1 General

The control and estimation of parameters in induction motor drive is an important area of sensorless induction motor drives.The technology of sensorless drive has further advance in recent years. Induction motor drives with cage-type machines have been the workhorses in industry for variable-speed application in a wide power range that covers from fractional horse power to multi-megawatts. These applications include pumps and fans, paper and textile mills, subway and locomotive propulsions, electric and hybrid vehicles, machine tools and robotics ,home appliances, heat pumps and air conditioners, rolling mills, wind generation systems, etc.

1.2 Types of AC Drives

The induction motor drives are broadly classified in two category i.e. scalar control and vector control.

1.2.1 Scalar Control

Scalar control as the name indicates, is due to magnitude variation of the control variable only, and disregards the coupling effect in machine. For example, the voltage of machine can be controlled to control the flux, and frequency or slip can be controlled to control the torque. However flux and torque are also function of voltage and frequency respectively. A scalar controlled drive gives somewhat inferior performance.

Scalar control is easy to implement. Scalar controlled drives have been widely used in industry, but the inherent coupling effect (both torque and flux are function of voltage or current and frequency) gives sluggish response and system is easily prone to instability because of higher order (fifth order) system effect. To make it more clear, if torque is increased by incrementing the slip (the frequency), the flux tends to decrease. Note that the flux variation is also sluggish .The flux decreases then compensated by the sluggish flux control loop feeding an additional voltage. This temporary dipping of flux reduces the torque sensitivity with slip and lengthens the response time. However, their importance has diminished recently because of the superior performance of vector controlled drives.

1.2.2 Vector Control

In DC machine the field flux is perpendicular to the armature flux. Being orthogonal, these two fluxes produce no net interaction on one another. Adjusting the field current can therefore control the DC machine flux, and the torque can be controlled independently of flux by adjusting the armature current. An AC machine is not so simple because of the interactions between the stator and the rotor fields, whose orientations are not held at 90 degrees but vary with the operating conditions. You can obtain DC machine-like performance in holding a fixed and orthogonal orientation between the field and armature fields in an AC machine by orienting the stator current with respect to the rotor flux so as to attain independently controlled flux and torque. Such a control scheme is called flux-oriented control or vector control. Vector control is applicable to both induction and synchronous motors.

Induction Motor drives are used in a multitude of industrial and process control applications requiring high performances. In high-performance drive systems, the motor speed should closely follow a specified reference trajectory regardless of any load disturbances, parameter variations, and model uncertainties. In order to achieve high performance, field-oriented control of induction motor (IM) drive is employed. However, the controller design of such a system plays a crucial role in system performance. The decoupling characteristics of vector-controlled IM are adversely affected by the parameter changes in the motor.

1.3 Indirect Vector Control Induction Motor Drive

The indirect method of vector control was used since it does not require flux sensors in practice and also allows more accurate control at lower speeds. The measurements required are the machine stator voltages and currents as well as the rotor speed/position.

The indirect field-oriented control (IFOC) approach is one of a powerful way to guarantee dynamic performances of induction motor drives. As the crucial point is the knowledge of the instantaneous position of rotor flux, it has been estimated in IFOC based on a real time model of the induction motor. Hence, it is parameter dependent. It is well known that a detuned system leads to poor performances both in steady state and in dynamic operation. The most critical parameter is that the rotor resistance has the wider range of variation due to changes in temperature. In particular, as the stator windings influence cannot be neglected any more due to the low switching frequencies in high power systems, a parameter adaptation in the vector controller using the modified reactive power is needed through simulation and experiment .This introduces a cross-coupling effect we can eliminate by introducing decoupling terms in each axis of the synchronously rotating reference frame. The IFOC method associated with compensation scheme of parameter variation is efficient enough to achieve good dynamic performances of an induction machine drive, due to its simple implementation and its physical approach of the process. Recently, practical investigations are performed on an experimental drive system to validate the IFOC method in a high power application.

1.3.1 Structure of indirect vector control

1.3.1.1 Derivation of indirect vector-control scheme

The indirect field-oriented control method is a powerful way to guarantee dynamic performances of induction motor drives.The crucial point is the knowledge of the instantaneous position of rotor flux. This is estimated in IFOC based on a real time model of the machine. Hence, it is parameter dependent. It is known that a detuned system leads to poor performances both in steady state and in dynamic operation. The most critical parameter which has the wider range of variation due to changes in temperature is the rotor resistance A parameter adaptation control using the vector controller is very useful for induction motor. Especially, in high power systems, due to the low switching frequencies the stator windings influence cannot be neglected any more. That is, we obtain a cross coupling effect we can eliminate by introducing decoupling terms in each axis of the synchronously rotating reference frame.

1.3.1.2. Indirect stator flux-oriented control

In this case of stator flux-oriented control the expression for the error in orientation angle is found to be too cumbersome to be given here. Hence, only equations for the actual to commanded flux and torque ratios are given, in the vector form. The procedure for calculation of commanded torque for given speed and load torque closely parallels the one described.

1.3.1.3. Performance of indirect vector controlled induction motor

The speed of the drive is selected in such a way that operation with rated Hz frequency results for all the four machines when the commanded torque equals rated torque of the machine. Flux command is for each of the machines set to the appropriate rated value for each of the three types of field orientation. All the results include characteristics for all the motors and can be plotted against per unit load torque, which is taken as the independent variable. Due to frequency dependence of the iron loss, the selected value corresponds to the maximum value of iron loss that will take place during operation of the time in the constant flux region. Hence, detuning at lower operating speeds will always be smaller.

1.3.1.4. Implementation of indirect vector control scheme

The PI controller in indirect vector control system should provide the speed and flux requests and generates the commanded values of torque and flux producing components of stator both currents iq and id. The commanded current values are processed through two independent pairs of PI controllers (d and q synchronous frame current control) to generate two sets of command and reference voltage vectors. These reference voltage vectors are used to generate two sets of three phase command and reference voltage vectors and phase shifted by an arbitrary of set value angle, through transformation (d–q synchronous). The commanded voltage vectors in conjunction with the bidirectional triangular waveform provide the switching signals to the base drive of the inverter switches. It will be worthwhile to mention here that the parameter detuning effect is neglected.

As the vector controlled induction machine is assumed to be current fed from an ideal current controlled PWM inverter, operation with constant, rated flux command would be discussed. As the indirect vector controller is the scheme composed of the appropriate decoupling circuit for each of the three orientation possibilities such as stator, air-gap, and rotor flux-oriented control, it incorporates only PI speed controller. Decoupling circuits neglect iron loss, magnetic saturation and resistance variations and have the well-known form, representation of the induction machine, in terms of space vectors. That is, the indirect vector control system neglects the core loss.

The indirect method of vector control was simulated to investigate the effects of rotor resistance detuning on the induction machine’s torque response. This method also allows the performance of rotor resistance estimation schemes to be evaluated. To implement indirect vector control, measurements required are the induction machine stator currents, as well as the rotor speed or position. These are obtained directly from the induction machine model. A rotor slip calculation is used to find the slip speed that is integrated to give the slip position. Adding this to the rotor position measurement gives the rotor flux position and, hence, the unit vectors required to transform between the stationary frame and rotating frame quantities.

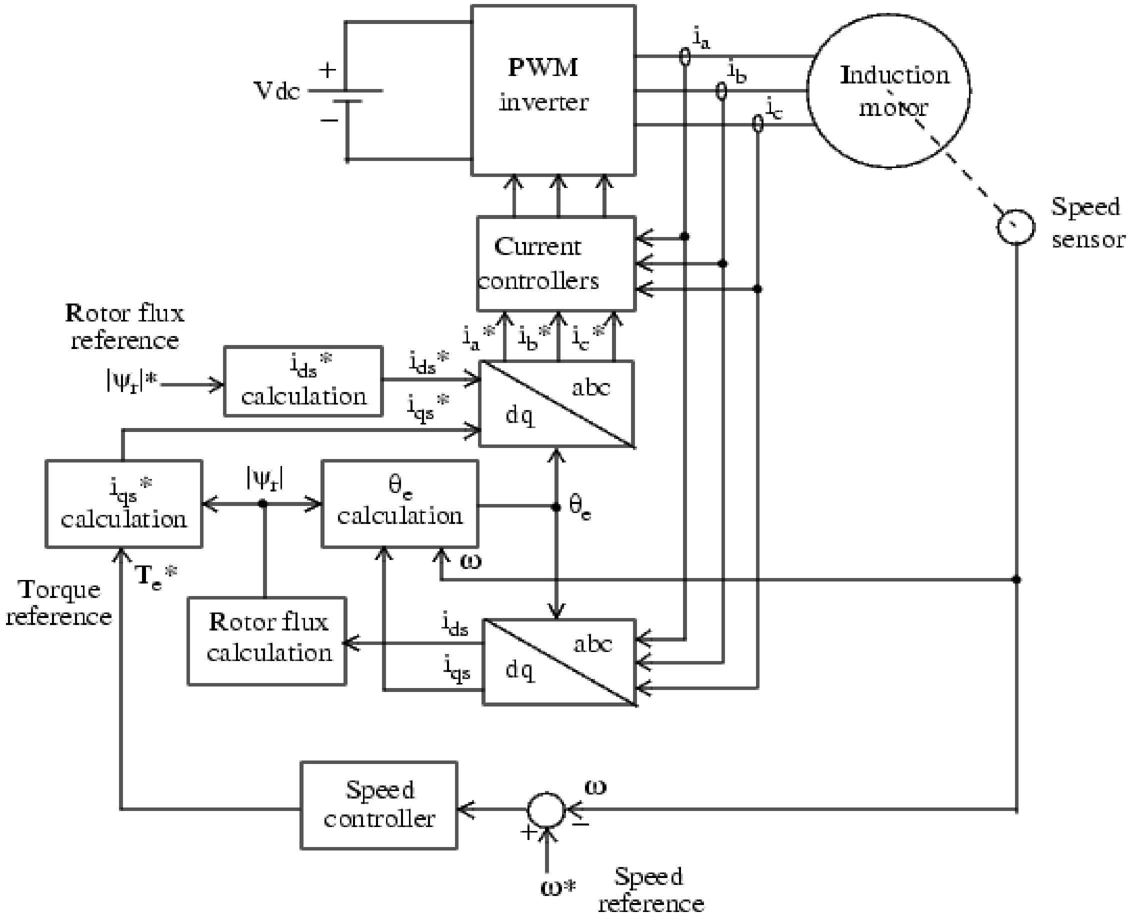


Fig 1.1 Block diagram of indirect vector control induction motor drive

A block diagram of IVICIM drive is shown in fig.1.1.The induction motor is fed by a current-controlled PWM inverter. The motor drives a mechanical load characterized by inertia J, friction coefficient B, and load torque T_L. The speed control loop uses a simple proportional-integral controller to produce the quadrature-axis current reference i_q* which controls the motor torque. The motor flux is controlled by the direct-axis current reference i_d*.Block d-q_ abc is used to convert i_d* and i_q* into current references i_a*, i_b*, and i_c* for the current regulator.

1.4 Observer for Indirect Vector Control of Induction Motor

The observer for IVC of IM requires some internal states of the drive. These state variables are normally not measurable so usually substitute variables are measured. To know these internal state variables for some reason .for example, to control them, there is requirement to calculate them. It is not always possible to calculate these variables directly from the measured outputs.

Consider a system with the following form.

$$\dot{x} = Ax + Bu \tag{1.1}$$

$$y = Cx \tag{1.2}$$

With a very simple approach to realize a system ,that runs parallel to the real system ,and it calculates the state vector, as seen in Fig1.2.This is based on the quite reasonable assumption that the input values of the system are known..

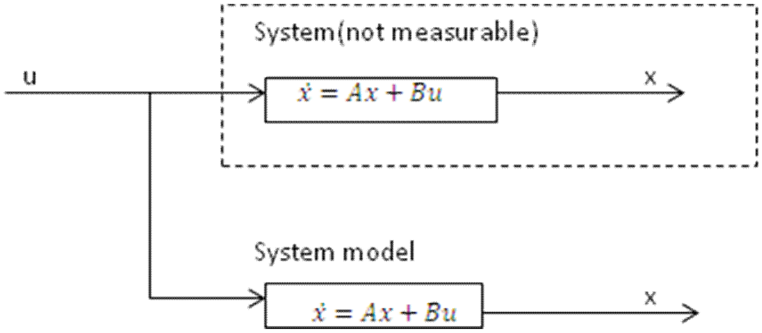


Fig 1.2.Reconstruction of the state vector

This approach however does not take in to account the starting condition of the system. It is unknown. This causes the state variable vector of the system model to be different from that of the real system.

The problem can be overcome by using the principle that estimated output vector based on the estimated state vector.

$$\hat{y} = C\hat{x} \tag{1.3}$$

Which may then be compared with the measured output vector .The difference will be used to correct the state vector of the system model.

Non-linear observers may be designed to give more constant dynamics. One non-linear

Observer, the Extended Kalman Filter, has the advantage of updating the matrix gains recursivly in order to minimise a cost function expressed in terms of system uncertainty and measurement noise.

The Standard Kalman filter (SKF) and the Extended Kalman filter (EKF) have been widely used for state estimation in an induction machine. The EKF has also been used to estimate rotor resistance and rotor speed .Both estimators are stochastic and require information about the process and measurement noise statistics.

1.5 Outline of the Project

This project contains seven chapters. The details of such chapters are as follows.

Chapter I, Present a brief introduction to AC drives and their potential sphere of application. Different types of AC drives and their detail study is presented in this chapter.

Chapter II, This chapter covers an extensive literature review on various topics related to estimation methods in indirect vector controlled drive.

Chapter III, This chapter covers an mathematical modeling of induction motor drive.

Chapter IV, This chapter presents Design of Kalman Filter Based Flux Observer.

Chapter V, This chapter presents MATLAB Model of Indirect Vector Control IM Drive.

Chapter VI, This chapter presents a results and discussion on the design algorithm for Kalman Filter used for IM drive.

Chapter VII, this chapter presents Conclusion and Future Scope of the present Work.

1.6 Conclusion

This chapter gives a state art in vector control of IM and different vector control scheme. The need of observer in indirect vector control induction motor drive and their realizations have been studied and described.

2.1 General

This chapter intends to give a brief literature review of the work being carried out on estimation and filtering technique used for vector control drive during last few decades.

2.2. Induction Motor Speed Control and Applications

B.K Bose et al. [1] mentioned that cage induction motor is one of the most robust motor and widely used. There are many techniques to control the speed of the induction motor such as stator voltage control and frequency control etc. For achieving variable speed operation, the frequency control method of the cage motor is the best method among all the methods of the speed control.

Brian Heber et al. [2] described that, there is a wide variety of applications such as machine tools, elevators, mill drives etc., where quick control over the torque of the motor is essential. Such applications are dominated by DC drives and cannot be satisfactorily operated by an induction motor drive with constant volt/hertz (V/f) scheme.

Hassan Baghgar Bostan Abad et al. [3] pointed out that DC motors are easily controllable than AC motors but they require much cost. In addition, for same rating power, DC motors have higher volume and weight.

2.3 Vector Control

Norman Mariun et al. [4] presented the idea of field oriented control. The vector control or field oriented control (FOC) theory forms the base of a advance control method for induction motor drives. With this theory induction motors can be controlled like a separately excited dc motor. This method enables the control of field and torque of the induction machine independently (decoupling) by manipulating the corresponding field oriented quantities.

Over the last two decades the principle of vector control of AC machines has evolved, by means of which AC motors and induction motors in particular, can be controlled to give dynamic performance comparable to what is achievable in a separately excited DC drive.

Fu-Cai-Liu et al. [5] described that, For high performance control of an induction motor a widely used approach is rotor-flux-oriented vector control, using synchronous frame decoupled stator current. This technique allows an induction motor to achieve similar toque and speed control performance to a dc machine and has led to induction machine replacing the dc machine in many high-performance applications. It is necessary to obtain accuratly the rotor flux magnitude, which is approximately based on flux measurements in the direct VC scheme and estimated in the indirect VC scheme.

S Wade, M W Dunnigan, et al. [6,7,18] described that These methods are necessary when high performance control is required from an induction machine, with four quadrant control possible computational requirements are quite demanding, requiring a fast microprocessor or digital signal processor. In this system, the stator current space phasor is oriented at an angle which will maintain the flux in the rotor while allowing the required torque to be produced with a fast response time. Transient torque response is excellent, allowing accurate speed and position control. There are two distinct methods of vector control the direct method and the indirect method. The direct method uses flux sensors or estimators, whereas the indirect method uses a speed position sensor with a slip calculation for the synthesis of the unit vectors (which indicate the flux position).The indirect method is employed here since it is more practical to fit a speed position sensor than flux sensors. This method relies on an accurate model of the machine, with parameter inaccuracies or changes being detrimental to the vector control method's ability to maintain correct field orientation. This requires parameter identification if control performance is not to be lost. Parameter inaccuracy can be caused by either poor commissioning or because of run-time parameter variations. Parameters can change on-line due to temperature effects, skin-effect and magnetic saturation. It is likely that all parameters will change to some extent during the machines operation, but those concerned with the rotor time constant (the rotor leakage inductance and the rotor resistance) have the most significant affect on vector control because they are used in the calculation of the rotor flux angle in the indirect method of vector control. when the vector controller has the correct value of the rotor resistance, the torque response is very fast, accurately reproducing the rectangular torque demand. However, when the rotor resistance estimate fed to the vector controller is detuned, the torque response is very poor. this leads to a requirement for parameter identification.

Tan Ruimin et al. [8] described that the vector control system of induction motor, the precision of magnetic field orientation depends on the accuracy of rotor time constant and the precision of field SENSOR constant.

S Wade et al. [9] described that high performance control of torque, speed or position of an induction machine is required, the vector control method is normally used. This requires accurate knowledge of the machine's parameters, which may be time varying due to temperature, skin-effect or magnetic saturation.

P**.** Vas, J. Li, et al. [10] discussed a versatile simulation package (SIMUVEC) for the analysis of vector-controlled induction motor drives which can be used by experts or researchers to investigate various aspects of the design and performance of these drives.

JW Finch et al. [11] discussed main advantage gained from field-orientation is high, controlled transient torque production and therefore fast response to load or demanded speed changes.

W.W.L. Keerthipala et al. [12] discussed an observer needed in field-oriented induction motor control as the phase angle of rotor magnetising current or m.m.f. vector in a standard induction motor cannot be measured by direct means. Two types of observers (linear and non-linear) are used in field-oriented induction motor.

R. H. Osman. et al. [13] defined the terms "field-oriented" and "vector controlled" arise from the behavior of the magnetic fields in the machine.

L. Umanand.et al. [14] pointed out the output feedback approach has been extensively used in aircraft applications such as autopilots.

E. Levi.et al. [15] described the theory of induction machine vector control based on constant parameter induction machine d-q **axis** model that neglects all the parameter variations, flux saturation and iron core loss.

A K Chattopadhyay et al. [16] described that the principle of vector control is used in current regulated PWM inverter (CRPWM), CSI, VSI and cycloconverter fed induction motor drives. The controlled current operation of the motor results in simpler implementation.

The CRPWM inverter is common for high performance servo drives while CSI and cycloconverters are used for larger drives. High frequency PWM transistor inverters (10 kHz), developed around 1979, made it possible to use vector controllers in various kinds of industries including pinch roll drives of continuous casting plates, machine-tool drives and gear-less servo drives as reported by Kume & I wakane (1987).The control method was applied to a large-scale paper mill (Tanaka *etal* 1983) with induction motors of 300-560kW rating using CSI. Application of vector controlled induction motors for high performance servo drives has been brilliantly surveyed by Leonhard (1986). High horsepower vector controlled induction motor servo drive using adaptive rotor flux observer has been recently developed with improved steady state and dynamic response (Huang *et al* 1994). The recent trend is to eliminate the speed and position sensors in high performance vector controlled induction motor drives (Okuyama *eta11990;* Onishi *et al* 1994; Tajima *et al* 1995). Very high power (MW) range cycloconverter-fed induction motors, with vector control for steel mill drive are mature drive systems in Japan (Sugi *et al* 1983; Saito *et al* 1987) and Germany (((Timpe1982; Hasse1977). *Siemens* has recently announced optimised vector controlled SIMOVERT master drives for elevator applications (Scheirling & Schonherr 1995) having many important features.

BPRA043 et al .[17] described that Though the induction motor have a very simple structure, its mathematical model is complex due to the coupling factor between a large number of variables and then on linearities. The Field Oriented Control (FOC) offers a solution to circumvent the need to solve high order equations and achieve an efficient control with high dynamic. This approach needs more calculations than a standard V/f control scheme.

2.4 Scalar Control'

S Wade , M W Dunnigan et al. [6,18], developed a method which is used when a simple, variable speed drive is required from an induction machine. Computational requirements are minimal, and the control can be designed entirely with analogue electronics if desired. In this system, the stator supply frequency is maintained at a value (equal to the rated slip frequency) above the rotor speed. The supply voltage follows a predetermined (usually linear) relationship with frequency, in an attempt to maintain the field at an approximately constant magnitude. This gives poor torque control and response times, making it unsuitable for position servo control. Only a speed sensor is required, there are no current sensors used in scalar control. Although there is speed feedback, the scalar control method is essentially open-loop in regard to the electrical part of the machine system.

2.5 Induction Motor Vector Control Implementation

A K Chattopadhyay et al. [16,19] described that implementation of vector control requires information regarding the magnitude and position of the flux vector and fast control of stator current in both magnitude and phase. Depending upon the method of flux acquisition, the vector control can be direct or indirect.

2.5.1 Direct Field Orientation

A K Chattopadhyay et al.[16,19] described that in the direct method, also known as flux feedback method, the air gap flux is directly measured with the help of sensors such as Hall probes, search coils or tapped stator windings or estimated/observed from machine terminal variables such as stator voltage, current and speed.

Li- Cheng Zai.et al [20] described that in direct method, measured flux fed back to a controller, enabling the rotor flux to be regulated. This method is considered to be expensive because special modifications on the motor are required.

2.5.2 Indirect Field Orientation

A K Chattopadhyay et al.[16,19,21**]** shown an alternative to direct measurement or estimation of the flux position for application of vector control to the induction motor without flux sensors is to employ the slip relation to compute the flux position signal with a commanded slip position signal.

$$\Theta_e = \Theta_{sl} + \Theta_r \tag{2.1}$$

Li-Cheng Zai et al. [20, 22] described that the indirect flux control method regulates the flux indirectly by using the rotor speed and setting the slip frequency as a function of the stator currents.

The indirect scheme, by virtue of its simpler sensing technique, is the favoured method in the industry today. However, its performance strongly depends on the motor parameters, particularly the rotor time constant.

2.6 Sensor-less Vector Control

Young-Real Kim et al. [23] described that in vector-controlled induction motor drives, generally, speed sensors such as shaft-mounted re-solvers or digital shaft position encoders are used to measure the rotor speed. The sensors degrade the systems’ reliability and spoil the general characteristics of ruggedness and mechanical simplicity of the induction motor. This has led to a speed sensor-less vector control.

In most speed and torque controlled drive system,closed loop control is based on the measurement of speed or position of the motor using a shaft encoder. However, some cases it is difficult (e.g. a compact drive system) or extremely expensive (e.g. submarine applications) to use sensors for speed measurement. Eliminating the speed sensor and measurement cables results in a lower cost and at the same time increases the reliability and ruggedness of the overall drive system. Over the past decade, speed sensor-less control strategies have aroused great interest among induction motor control researchers.

In these strategies, the motor speed is estimated and used as a feedback signal for closed loop speed control.

2.7 Observer for Indirect Vector Control of Induction Motor

BPRA057 et al. [24, 26] most of the VCIM drive uses a sensor to measure position of the rotor. In many cases it is impossible to use sensors for speed measurement, perhaps because it is either technically impossible or extremely expensive .As an example, one can mention the pumps used in oil rigs to pump out the oil. Lately, there have been many proposals addressing this problem, and it has turned out that speed can be calculated from the current and voltage values of the AC motor, some of these proposals are open loop solutions, give some estimation of speed, but these solutions normally have a large error. For better results one need an observer or a filter.

F. Chen and M.W. Dunnigan et al. [25] described that the majority of high performance induction machine control strategies are developed with the assumption that either full or partial system state information is available. Example are partial state feedback for field oriented control(FOC), full linearising state feedback control based on differential geometric theory and sliding mode control using state feed-back. The robustness of those controllers depends significantly on accurate knowledge of the system states. In practice, the rotor currents or fluxes are not easily measurable. Therefore an Observer is needed to estimate the unknown states and can also provide, in some circumstances, better estimates of known current states that are contaminated by noise.

2.7.1 Classical and Kalman Estimators

BPRA057 et al. [24, 26] mentioned that the Kalman filter has a good dynamic behaviour, disturbance resistance and it can work even in a standstill position. Implementing a filter is a very complex problem and it requires the model of the AC Motor to be determined in real time. Kalman filter is a statistically optimal observer, if the statistical characteristics of the various noise elements are known.

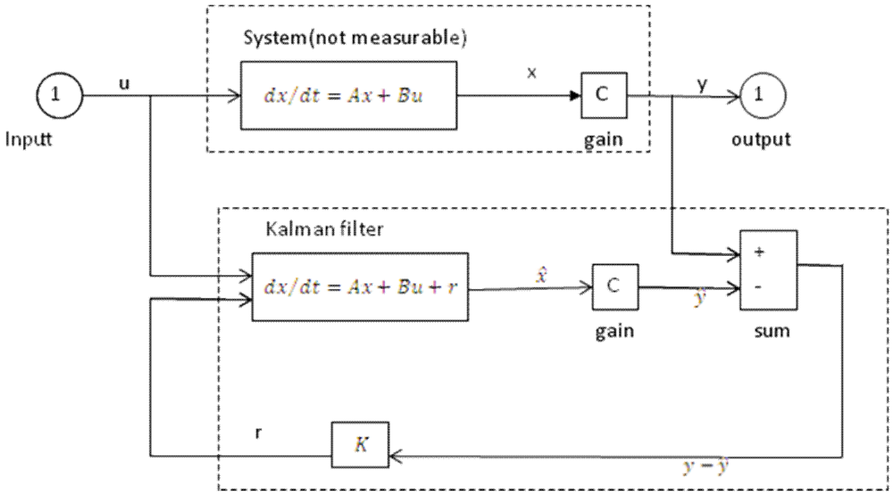


Fig 2.1 Structure of Kalman filter observer

K. L. Shi et al. [27] mentioned that Kalman filter is a special kind of observer, which provides optimal filtering of the noises in measurement and inside the system if the covariance matrices of these noises are known. If rotor speed (as an extended state)is included in the dynamic model of an induction motor, the Extended Kalman filter can be used to relinearize the nonlinear state model for each new estimate as it becomes available. The overall structure of the Kalman filter is shown in Fig 2.1.

Kalman filter directly accounts for the effects of the disturbance noises of a control system and the errors in the parameters will also be handled as noise. The Kalman filter is implemented by the following equation, the system being expressed as a state model:

$x = Ax + Bu + G(t)w(t)$(System) (2.2)

$y = Cx + v(t)$ (Measurement) (2.3)

Where

G(t) =weighting matrix of noise

w(t) =noise matrix of state model (system noise). v(t) =noise matrix of output model (measurement noise) G(t) ,w(t)and v(t) are assumed to be stationary ,white ,and Gaussian noise and their expectation values are zero. The covariance matrices Q and R of these noises are defined as:

Q = cov(w) = E{ww’} (2.4)

R = cov(v) = E{vv’} (2.5)

Where E {.} denotes the expected value.

2.7.2 Extended-Kalman Filter Estimator

T. Du, **P.** Vas et al. [28] mentioned that there are specific components characteristic of EKF FLUX OBSERVER support a design procedure. In the block diagram shown in Fig.2.2, the observer is between a pre-processing block and a post-processing block.

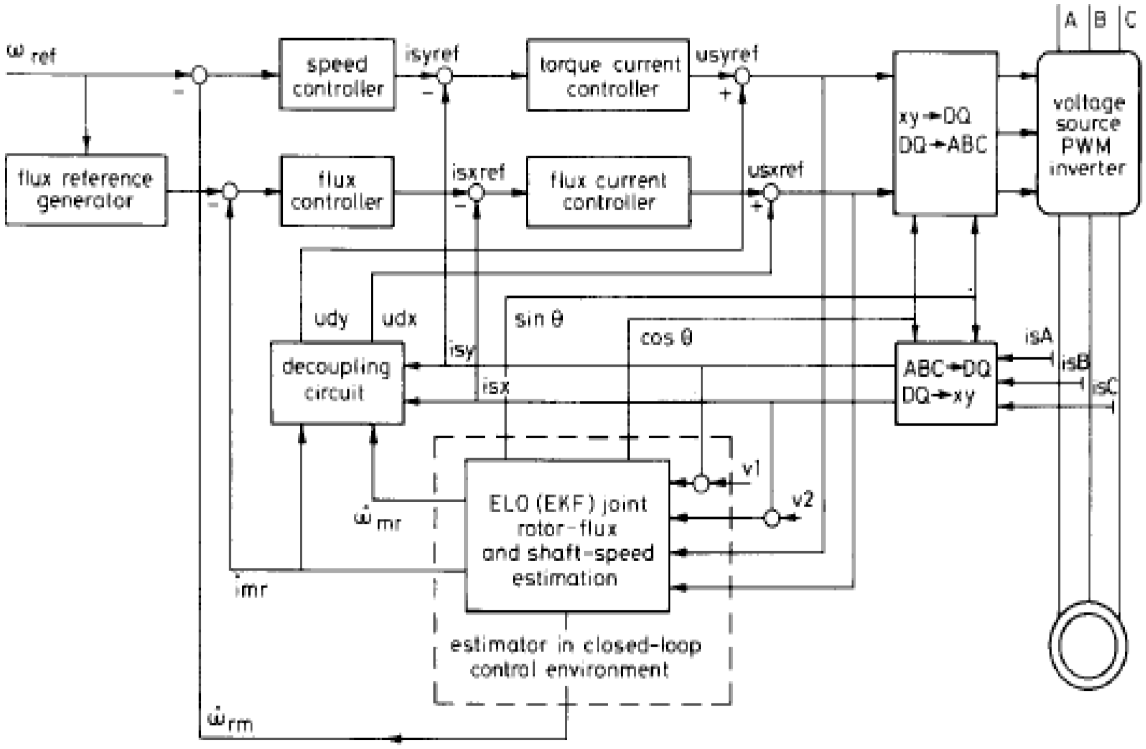


Fig 2.2 Block diagram of EKF flux observer

The design of an accurate EKF Observer requires a discrete model of the system together with a set of recursive equations that continuously update the Kalman gain matrix **K** and the system covariance matrix **P.**

2.8 Conclusion

An extensive literature study is made on the topic Sensor-less, Vector control, Scaler control and Observer for induction motor drives and a brief summary of different research papers are presented.

Chapter III Mathematical Modelling of Induction Motor Drive

3.1 General

Estimation techniques are based on the principle of observers, in which a mathematical model of the motor is operated in parallel with the motor itself. The model and the motor receive the same inputs and the outputs are compared, any error being used to correct the model behavior .Therefore it is necessary to begin with a suitable mathematical model of the motor.

A dynamic model of the machine subjected to control must be known in order to understand the design of vector controlled drives. Due to the fact that every good control has to face any Possible change of the plant, it could be said that the dynamic model of the machine could be just a good approximation of real plant. Nevertheless, the model should incorporate all the important dynamic effects occurring during both steady-state and transient response.

Furthermore, it should be valid for any changes in the inverter's supply such as voltages or currents.

In an adjustable-speed drive, the machine normally constitutes an element within a feedback loop, and therefore its transient behaviour has to be taken in to consideration. Besides, high-performance drive control, such as vector-or field oriented control, is based on the dynamic d-q model of the machine. Therefore, to understand vector control principles, a good understanding of the d-q model is mandatory.

The dynamic performance of an AC machine is somewhat complex because the three-phase rotor windings move with respect to the three-phase stator winding.

3.2 Mathematical Model of Induction Motor

The d-q model of an induction motor in synchronously rotating d^e-q^e frame using Fig.3.1are as follows.

$$v_{qs}^{s} = R_s i_{qs}^{s} + \frac{d}{dt}\psi_{qs}^{s} \tag{3.1}$$

$$v_{ds}^{s} = R_s i_{ds}^{s} + \frac{d}{dt}\psi_{ds}^{s} \tag{3.2}$$

Where ψ_{qs}^{s} and $\psi_{ds}^{s}$are q-axis and d-axis stator flux linkages, respectively.When these equation are converted to $d^e - q^e$ frame the following equation can be written as.

$$v_{qs} = R_r i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e \psi_{ds} \tag{3.3}$$

$$v_{ds} = R_r i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e \psi_{qs} \tag{3.4}$$

where all the variables are in the rotating form. The last term in equation (3.3) and (3.4) can be defined as speed emf due to rotation of the axis, that is, when ω_e =0 ,the equation revert to stationary frame. The flux linkage in the d^e and q^e axes induce emf in the q^e and d^e axes, respectively with $\pi/2$ lead angle.

If the rotor is not moving, that is, $\omega_e = 0$ the rotor equation for a double fed wound rotor machine will be similar to equation (3.3)-(3.4)

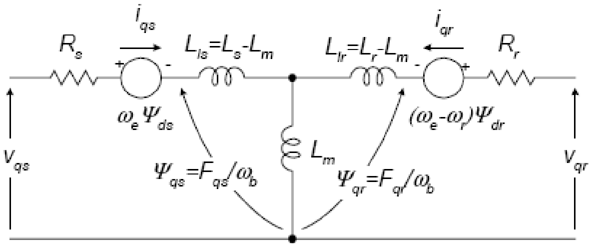
$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \omega_e \psi_{dr} \tag{3.5}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_e \psi_{qr} \tag{3.6}$$

Where, all the variables and parameters are referred to stator. Since the rotor actually moves at speed ω_r the d-q axes fixed on the rotor move at speed $\omega_e - \omega_r$ relative to the synchronously rotating frame. Therefore, in d^e-q^e frame, the rotor equations should be modified as

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \tag{3.7}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \tag{3.8}$$



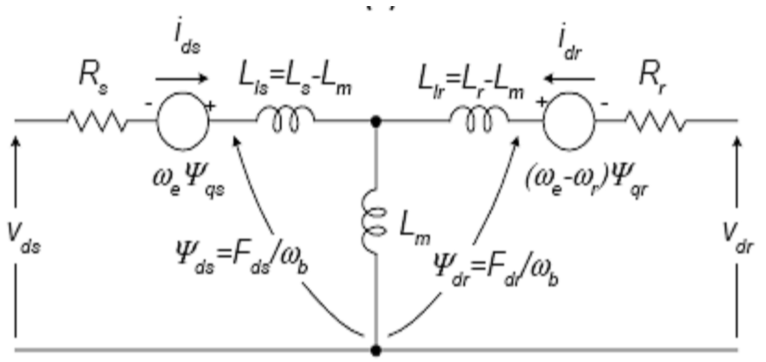


Fig 3.1 d^e-q^e equivalent circuit of induction machine

Fig 3.1 shows the d^e-q^e equivalent circuit that satisfy the equations (3.3)-(3.4) and (3.7)-(3.8). A special advantage of the d^e-q^e dynamic model of the machine is that all the sinusoidal variables in stationary frame appears as dc quantities in synchronous frame.

The flux linkage expression in term of can be written from figure as follows

$$\psi_{qs} = L_{ls}i_{qs} + L_m(i_{qs} + i_{qr}) \quad (3.9)$$

$$\psi_{qr} = L_{lr}i_{qr} + L_m(i_{qs} + i_{qr}) \quad (3.10)$$

$$\psi_{ds} = L_{ls}i_{ds} + L_m(i_{ds} + i_{dr}) \quad (3.11)$$

$$\psi_{dr} = L_{lr}i_{dr} + L_m(i_{ds} + i_{dr}) \quad (3.12)$$

$$\psi_{dm} = L_m(i_{ds} + i_{dr}) \quad (3.13)$$

$$\psi_{qm} = L_m(i_{qs} + i_{qr}) \quad (3.14)$$

Combining the above expressions with equations (3.3), (3.4), (3.7) and (3.8) the electrical transient model in terms of voltage and currents can be given in the matrix form as

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s + SL_s & \omega_e L_s & SL_m & \omega_e L_m \\ -\omega_e L_s & R_s + SL_s & -\omega_e L_m & SL_m \\ SL_m & (\omega_e - \omega_r)L_m & R_r + SL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & SL_m & -(\omega_e - \omega_r)L_r & R_r + SL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (3.15)$$

Where S is the Laplace operator.For a cage motor, $v_{qr} = v_{dr} = 0$

3.3 Continuous-Time Linearised Induction Machine Model for Estimation

The continuous-time linearised mathematical model of the induction machine can be described in state-space form,with rotor speed treated as a time-varying parameter.

$$\dot{x}_i = f_i(x,t) + Bu \tag{3.16}$$

Where i= 1 ,….4

The definitions of the vector x of state variables and the input voltage vector u are:

x =[ids iqs ψ_{dr} ψ_{qr}] ^{T} u = [uds uqs]^T .The subscript s and r stand for stator and rotor; d and q

denote the components of a vector with respect to a fixed stator reference frame.The states x3 and x4 are the d-q axis rotor fluxes,which are not easily measurable and require estimation. Sometimes,the measured stator currents are contaminated by noise,and require to be estimated as well. In some circumtances the estimates can be more reliable.

The four first order differential equations resulting from the expansion of eqn (3.16) are:

$$\dot{x}_1 = -\left(\frac{R_s}{L_\sigma} + \frac{R_r}{L_r^2}\frac{L_m^2}{L_\sigma}\right) x_1 + \frac{R_r}{L_r^2}\frac{L_m}{L_\sigma} x_3 + \frac{\omega_r}{L_r}\frac{L_m}{L_\sigma} x_4 + \frac{1}{L_\sigma} u_{ds} \tag{3.17}$$

$$\dot{x}_2 = -\left(\frac{R_s}{L_\sigma} + \frac{R_r}{L_r^2}\frac{L_m^2}{L_\sigma}\right) x_2 - \frac{\omega_r}{L_r}\frac{L_m}{L_\sigma} x_3 + \frac{R_r}{L_r^2}\frac{L_m}{L_\sigma} x_4 + \frac{1}{L_\sigma} u_{qs} \tag{3.18}$$

$$\dot{x}_3 = \frac{R_r}{L_r} L_m x_1 - \frac{R_r}{L_r} x_3 - \omega_r x_4 \tag{3.19}$$

$$\dot{x}_4 = \frac{R_r}{L_r} L_m x_2 + \omega_r x_3 - \frac{R_r}{L_r} x_4 \tag{3.20}$$

where *L,* is the redefined leakage inductance, defined as

$$L_\sigma = L_s - \left(\frac{L_m^2}{L_r}\right) \tag{3.21}$$

L_s, L_r , L_m is respectively stator,rotor and magnetising inductances,henery

R_s , R_r is respectively stator and rotor resistances, ohm.

ω_r rotor speed,rad/sec.

The input matrix B, is

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}^T$$

The above modelling equation obtained from following equation.

1. Dynamic Model (Kron equation)

$$v_{ds}^s = R_s i_{ds}^s + \frac{d}{dt}\psi_{ds}^s \tag{3.22}$$

$$v_{qs}^s = R_s i_{qs}^s + \frac{d}{dt}\psi_{qs}^s \tag{3.23}$$

2. Flux-Vector Estimation Equation

(a) Voltage Model

$$\psi_{dr}^s = \frac{L_r}{L_m}\psi_{dm}^s - L_{lr}\ i_{ds}^s \tag{3.24}$$

$$\psi_{qr}^s = \frac{L_r}{L_m}\psi_{qm}^s - L_{lr} i_{qs}^s \tag{3.25}$$

(b) Current Model

$$\frac{d}{dt}\psi_{dr}^s = \frac{L_m}{T_r} i_{ds}^s - \omega_r \psi_{qr}^s - \frac{1}{T_r}\psi_{dr}^s \tag{3.26}$$

$$\frac{d}{dt}\psi_{qr}^s = \frac{L_m}{T_r} i_{qs}^s + \omega_r \psi_{dr}^s - \frac{1}{T_r}\psi_{qr}^s \tag{3.27}$$

3.4 Conclusion

This chapter deals with a need of mathematical model for estimation of induction motor drive, complete mathematical model of indirect VCIM drive and continuous-time linearised Induction machine model for estimation is described.

Chapter IV Design of Kalman Filter Based Flux Observer

4.1 General

The Kalman filter was developed by R.E. Kalman in 1960. Due to advances in the development of digital computing, the Kalman filter is a subject of extensive research and application. Kalman filtering has been applied in the areas of aerospace, navigation, manufacturing, and many others.

The discrete-time Kalman filter recursive generation can be expressed in five different forms, State Estimate Extrapolation (Propagation), Covariance Estimate Extrapolation (Propagation) Filter Gain Computation, State Estimate Update and Covariance Estimate Update.

4.2 Discrete Induction Motor Model

Estimation of rotor current is based on a discrete time varying linear model of the induction motor.

$$x(k+1)=F(k)x(k)+G(k)u(k) \tag{4.1}$$

$$y(k)=H\,x(k) \tag{4.2}$$

where

F(k),G(k),and H(k) may vary and can be given different values at each time step k. This is because the KF will deal with a time varying system.

$$F(k)=\begin{bmatrix} 1-a_1\,t_s & a_2\,t_s\,\omega_r & a_3\,t_s & a_4\,t_s\,\omega_r \\ -a_2 t_s\,\omega_r & 1-a_1\,t_s & -a_4\,t_s\,\omega_r & a_3\,t_s \\ a_6\,t_s & -a_7\,t_s\,\omega_r & 1-a_8\,t_s & -a_9\,t_s\,\omega_r \\ a_7 t_s\,\omega_r & a_6\,t_s & a_9\,t_s\,\omega_r & 1-a_8\,t_s \end{bmatrix} \tag{4.3}$$

$$G(k)=\begin{bmatrix} a_5 t_s & 0 \\ 0 & a_5 t_s \\ -a_{10} t_s & 0 \\ 0 & -a_{10} t_s \end{bmatrix} \tag{4.4}$$

And

t_s=is the discrete sampling interval

$$x(k) = [i_{ds(k)} \quad i_{qs(k)} \quad i_{dr(k)} \quad i_{qr(k)}]^T \tag{4.5}$$

$$u(k) = [v_{ds}(k) \quad v_{qs}(k)]^T \tag{4.6}$$

also

$$a_0 = L_1\,L_2 - L_m^2$$

$$a_1 = \frac{R_1 L_2}{a_0}$$

$$a_2 = \frac{L_m^2}{a_0}$$

$$a_3 = \frac{R_2 L_m}{a_0}$$

$$a_4 = \frac{L_m L_2}{a_0}$$

$$a_5 = \frac{L_2}{a_0}$$

$$a_6 = \frac{R_1 L_m}{a_0}$$

$$a_7 = \frac{L_1 L_m}{a_0 a_8}$$

$$a_8 = \frac{R_2 L_1}{a_0}$$

$$a_9 = \frac{L_1 L_2}{a_0 a_{10}} = \frac{L_m}{a_0}$$

$$a_{10} = \frac{L_m}{a_0}$$

An output or observation equation is required by the state space model and for the practical case in which stator currents are chosen as measurements:

$$y(k) = [i_{ds} \quad i_{qs}]^T \qquad (4.7)$$

which gives an output matrix

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (4.8)$$

It has been assumed that the plant can be represented perfectly by a deterministic state space model. In practice this is not the case, due to the presence of disturbances for which modeling would be difficult and results in complex equations. For handling plant uncertainties of this nature a stochastic model is used. As the induction motor is best served by the state space model, this is extended to a stochastic case by adding Gaussian white-noise vectors. The resulting stochastic state space model is:

$$x(k+1)=F(k)x(k)+G(K)u(k)+w(k) \qquad (4.9)$$

$$y(k)=H(k)x(k)+v(k) \qquad (4.10)$$

the process noise w(k) is characterized by

$$E\{w(k)\} = 0 \qquad (4.11)$$

$$E\{w(k)w(j)^T\} = Q\delta_{kj} \qquad Q\geq 0 \qquad (4.12)$$

The measurement noise v (k) is characterized by

$$E\{v(k)\} = 0 \qquad (4.13)$$

$$E\{v(k)v(j)^T\} = R\delta_{kj} \qquad R\geq 0 \qquad (4.14)$$

The initial state is characterized by

$$E\{x(0)\} = \hat{x}_0 \tag{4.15}$$

$$E\{(x(0) - \hat{x}_0)(x(0) - \hat{x}_0)^T\} = P_0 \tag{4.16}$$

4.3 Kalman Filter

The main value of the Kalman filter is its ability to produce estimates of states that are not measurable. This feature is particularly important for estimation problems associated with the cage induction motor as the rotor quantities are not directly accessible.

Discrete-Time Kalman filter

The discrete-time linear system can be modeled as;

$$x_k = A_{k-1}\ x_k + Bu_{k-1} + w_{k-1} \tag{4.17}$$

The measurement equation can be modeled as;

$$y_k = C_k x_k + v_k \tag{4.18}$$

where k is the time index.

The system noise is white and zero-mean:

$$E(w_k) = 0 \tag{4.19}$$

$$E(w_k w'_k) = Q_k \tag{4.20}$$

$$E(w_k\ w'_j) = 0\ (k \neq j) \tag{4.21}$$

The measurement noise is white, zero-mean and uncorrelated with the system noise:

$$E(v_k) = 0 \tag{4.22}$$

$$E(v_k v'_k) = R_k \tag{4.23}$$

$$E(v_k v'_j) = 0\ (k \neq j) \tag{4.24}$$

$$E(v_k w'_j) = 0 \tag{4.25}$$

The KF equations are as follows:

$$\hat{x}(k+1/k) = F(k)\,\hat{x}(k/k) + G(k)u(k) \tag{4.26}$$

$$P(k+1/k) = F(k)P(k/k)F(k)^{T} + Q \qquad (4.27)$$

$$\hat{x}(k+1/k+1) = \hat{x}(k+1/k) + K(k+1)[y(k+1) - H(k+1)\hat{x}(k+1/k) \qquad (4.28)$$

$$K(k+1) = P(k+1/k)H(k+1)^{T}[H(k)(P(k+1/k)H(k)^{T} + R]^{-1} \qquad (4.29)$$

$$P(k+1/k+1) = P(k+1)/k) - K(k+1)H(k+1)P(k+1/k) \qquad (4.30)$$

Where

$K(.)$ is the Kalman gain matrix

$\hat{x}(.)$ *is the state estimate*

and the estimation error covariance is

$$P(k/k) = E\{(x(k) - \hat{x}(k))(x(k) - \hat{x}(k))^{T}\} \qquad (4.31)$$

Where k/k denotes a prediction at time k based on data up to and including time k. Similarly,(k+1)/k denotes a prediction at time k +1 based on data up to and including time k.

NOTES:

1)Equation (4.27),(4.29)and(4.30),which are all involved in propagating P(k),are collectively known as the Riccati difference equation(RDE).

2) The plant model matrices F(k),G(k)and H(k) may vary and can be given different values at each time step k. This is because the KF will deal with a time varying system.

3) Although the noise covariances Q and R are shown to be constant, in general they can be time varying.

4) The process noise covariance Q can be zero, representing a perfect state model with no noise, or it must be positive definite.

5) The estimator is time varying and can therefore operate with rotor speed variations.

6) The KF requires measurements of plant input and plant output together with a ω_r measurement to give a time-varying F (k) matrix in its plant model. The measurements have noise sources added to account for imperfections in an experimental system. The outputs of the KF are estimates of stator and rotor currents.

4.4 Extended Kalman Filter

The Extended Kalman Filter is direct extension of the standard Kalman algorithm to nonlinear system.
Consider the discrete nonlinear state space model:

$$x(k+1)=F(k)x(k)+G(K)u(k)+w(k) \tag{4.32}$$

$$y(k) =H(k)x(k)+v(k) \tag{4.33}$$

The associated EKF equations are given as follows:

$$\hat{x}(k+1) = f\ (\hat{x}(k), u(k) + K(k)[y(k) - H\hat{x}(k)] \tag{4.34}$$

$$K\ (k) = F\ (k)\ P\ (k)H^{T}\ [HP(k)H^{T} + R]^{-1} \tag{4.35}$$

$$P(k+1)= F(k)P(k)F(k)^{T}+Q-K(k)[HP(k)H^{T}+R]K(k) \tag{4.36}$$

$$F(k) = \frac{\partial f(\cdot)}{\partial x(k)}\ \Big|_{\hat{x}(k),u(k)} \tag{4.37}$$

4.4.1 Rotor Resistance Estimation:

The EKF theory is also applied to the simultaneous estimation of stator and rotor currents together with rotor resistance .This produces a fifth-order augmented state space model with the following stator vector:

$$x(k) = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5]^T=[i_{ds}(k) \quad i_{qs}(k) \quad i_{dr}(k) \quad i_{qr}(k) \quad R_2(k)]^T \qquad (4.38)$$

$$x_1(k+1)=a_{11}x_1(k)+ a_{12}\ \omega_r(k)\ x_2(k) + a_{13}\ x_5(k)x_3(k)+a_{14}\omega_r(k)x_4(k)+a_{15}u_1(k)+w_1(k) \qquad (4.39)$$

$$x_2(k+1)=a_{21}\omega_r(k)\ x_1(k)+ a_{22}\ x_2(k) + a_{23}\ \omega_r(k)\ x_3(k)+a_{24}\ x_5(k)x_4(k)+a_{25}u_2(k)+w_2(k) \qquad (4.40)$$

$$x_3(k+1)=a_{31}x_1(k)+ a_{32}\ \omega_r(k)\ x_2(k) + x_3(k)+ a_{33}x_5(k)x_3(k)+a_{34}\omega_r(k)x_4(k)+a_{35}u_1(k)+w_3(k) \qquad (4.41)$$

$$x_4(k+1)=a_{41}\omega_r(k)\ x_1(k)+ a_{42}\ x_2(k) + a_{43}\ \omega_r(k)\ x_3(k)+ x_4(k)+ a_{44}x_5(k)x_4(k)+a_{45}u_2(k)+w_4(k) \qquad (4.42)$$

$$x_5(k+1)=x_5(k)+n(k) \qquad (4.4.3)$$

The coefficients are

$a_0 = L_1\ L_2 - L_m^2$

$a_{11} = 1 - R_1\ L_2\ t_s / a_0$

$a_{12} = L_m^2\ t_s / a_0$

$a_{13}=L_m t_s/a_0$

$a_{14}= L_m\ L_2 t_s / a_0$

$a_{15}=L_2 t_s/a_0$

$a_{21} = -L_m 2 t_s / a_0$

$a_{22} = 1 - R_1 L_2 t_s / a_0$

$a_{23} = - L_m L_2 t_s / a_0$

$a_{24} = L_m t_s / a_0$

$a_{25} = L_2 t_s / a_0$

$a_{31} = L_m R_1 t_s / a_0$

$a_{32} = -L_m L_1 t_s / a_0$

$a_{33} = -L_1 t_s / a_0$

$a_{34} = -L_1 L_2 t_s / a_0$

$a_{35} = -L_m t_s / a_0$

$a_{41} = L_m L_1 t_s / a_0$

$a_{42} = L_m R_1 t_s / a_0$

$a_{43} = L_1 L_2 t_s / a_0$

$a_{44} = -L_1 t_s / a_0$

$a_{45} = -L_m t_s / a_0$

$u_1(k) = v_{ds}(k)$

$u_2(k) = v_{qs}(k)$

Terms $w_1(k) - w_2(k)$ and $n(k)$ are the zero mean process noise sequences.

The Jacobian or partial derivative matrix for the induction motor is:

$$F(K) = \begin{bmatrix} a_{11} & a_{12}\omega_r(k) & a_{13}x_5(k) & a_{14}\omega_r(k) & a_{13}x_3(k) \\ a_{21}\omega_r(k) & a_{22} & a_{23}\omega_r(k) & a_{24}x_5(k) & a_{24}x_4(k) \\ a_{31} & a_{32}\omega_r(k) & 1 + a_{33}x_5(k) & a_{34}\omega_r(k) & a_{33}x_3(k) \\ a_{41}\omega_r(k) & a_{42} & a_{43}\omega_r(k) & 1 + a_{44}x_5(k) & a_{44}x_4(k) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.44}$$

4.5 MATLAB Model of Vector Control IM Drive

The MATLAB model of the indirect vector control induction motor is shown in Fig.4.1.It comprises of three phase IM,of 50 hp, 460 V, 60 Hz, 1440 r.p.m driven by a three phase PWM inverter. A hysteresis current controller is used to control the PWM inverter, according to the difference in actual and estimated motor line current.

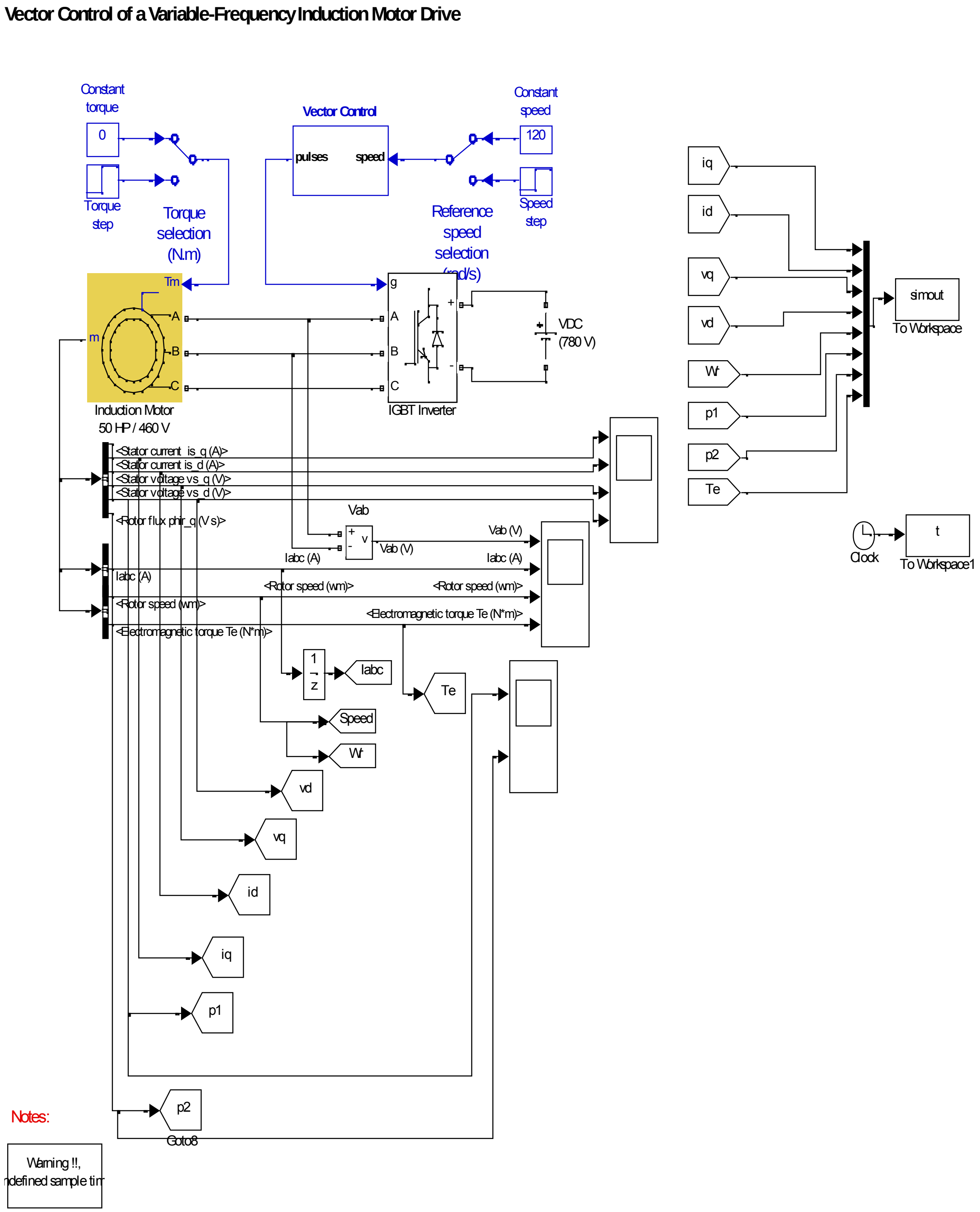


Fig.4.1Simulation Block Diagram of Indirect Vector Control using P-I Controller

4.6 Conclusion

This chapter presented design of Kalman and Extended Kalman filter in detail for state estimation of induction motor. Here the state which is estimated is rotor current (hence rotor flux).Rotor current required discrete induction motor model. A Simulink Model of indirect vector control using P-I controller is developed to obtain various parameter of induction motor through simulation. Various parameter of induction motor are stator d-q axis voltages and currents, rotor d-q axis fluxes, rotor speed and torque. These parameters are used from Matlab Workspace.

Chapter V Results and Discussions

5.1 Simulation Results

An indirect vector controlled IM with PI speed controller is simulated in MATLAB simulink.

The performance of indirect vector control drive using P-I speed control and KF, EKF are described. A comparison of both estimated result of KF and EKF observers are presented

5.2 Performance of Indirect Vector Control IM Using P-I Control

Fig.5.1and 5.2 show the performance characteristic of a 50 hp, 460 V, 60 Hz IM, operating at no load with a PI speed controller. The reference speed setting is 120 rad/sec. it is observed that motor pick up the reference speed at t = 0.55 sec and also it draw high starting current.

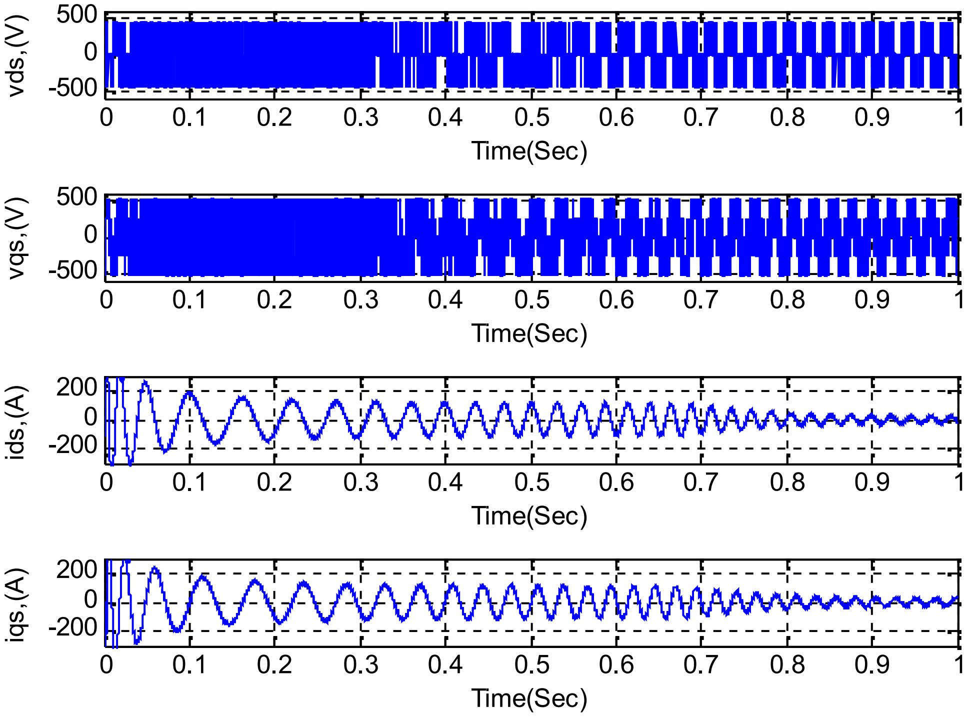


Fig 5.1 Performance of Indirect Vector Control (IVC) using P-I Speed Control at No Load

With Reference Speed 120 rad/sec

Fig.5.2 shows the performance characteristic of motor, when a sudden change in torque at t = 0.7 sec, the reference speed from 120 to 140 rad /sec is made ,it is observed for the waveform of the motor speed tracks the change in speed slowly and even in steady state, there is significant offset about 10 rad/sec.

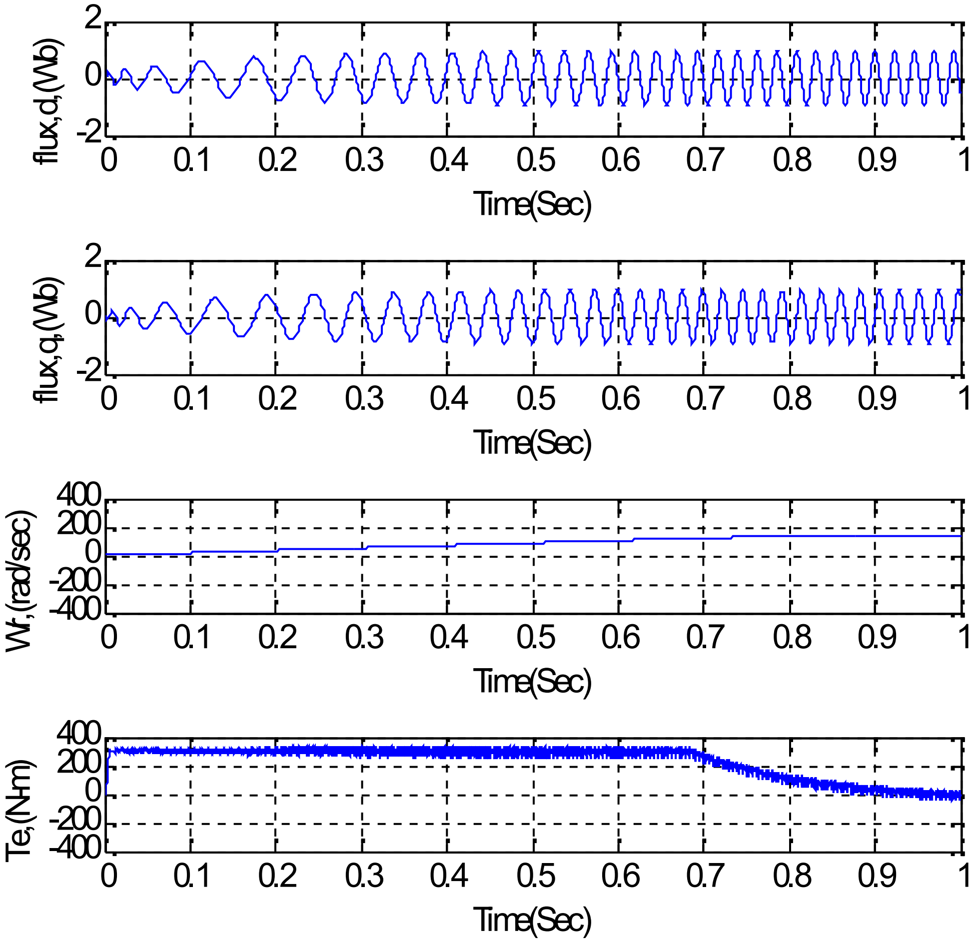


Fig 5.2 Response of IVC with a sudden change in torque at t = 0.7sec, with reference speed is (120 to 140 rad/sec)

5.3 Estimation of Performance of Indirect Vector Control IM Using Kalman filter Observer

Fig.5.3 shows the performance characteristic of a 50 hp, 460 V, 60 Hz IM, operating at no load with a Kalman Filter observer. The purpose of Kalman filter is to estimate rotor fluxes. &it is observed from the waveform of rotor flux that more variation in starting due to high starting current drawn by the IM with sudden change at t=0.2sec. After t=0.2 sec it starts go to steady state and at last become constant.

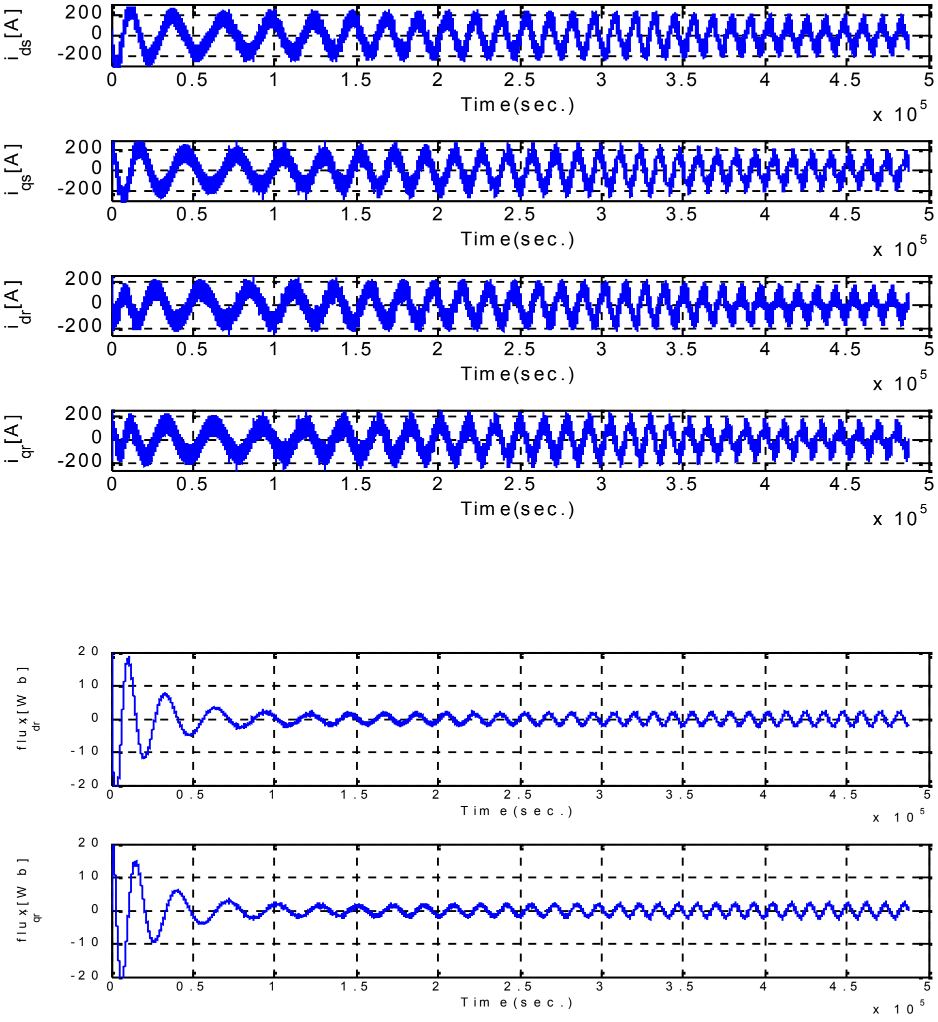


Fig 5.3 Estimation Performance of Kalman Filter for Rotor Flux Estimation of IVCIM.

5.4 Estimation Performance of Indirect Vector Control IM Using Extended Kalman filter Observer

Fig.5.4 shows the performance characteristic of a 50 hp, 460 V, 60 Hz IM, operating at no load with a Extended Kalman filter observer. The purpose of extended Kalman filter is rotor flux estimation, it is observed from the waveform of rotor flux it has less variation in starting, till t=1.6sec, After that it starts slowly increasing, but almost waveform has less variation in compare to Kalman filter.

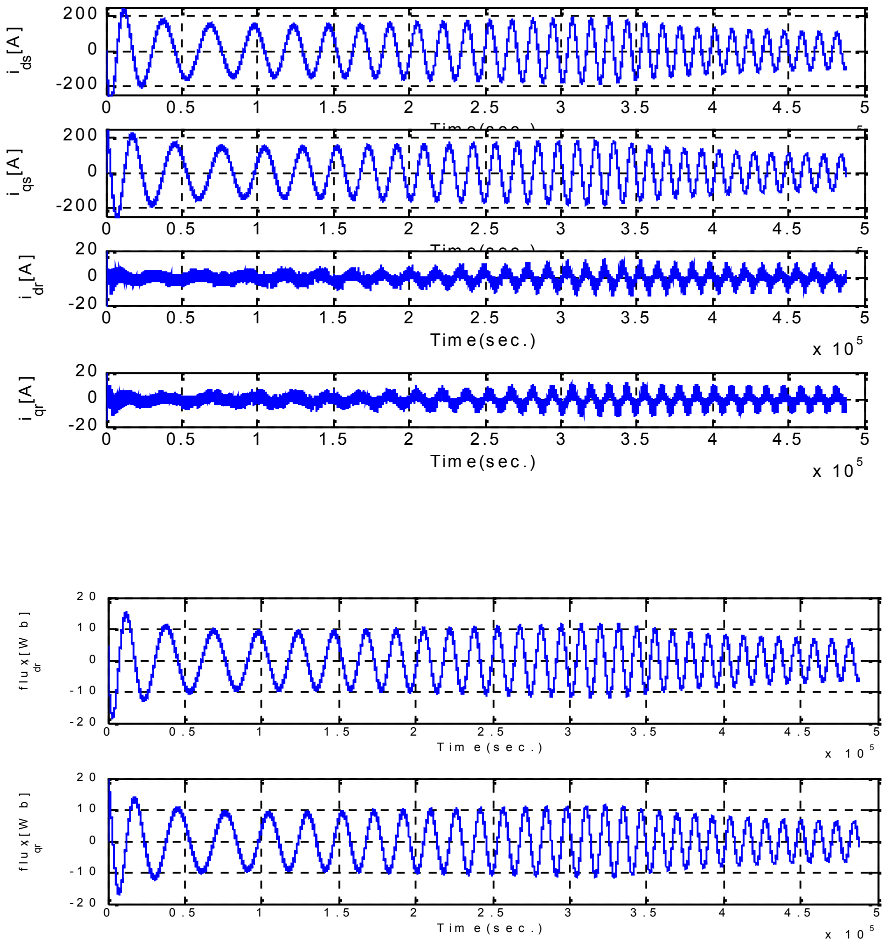


Fig5.4 Estimation Performance of Extended Kalman Filter for Rotor

Flux Estimation of IVCIM

5.5 Conclusion

In this present project, a continuous-time linearised mathematical model of indirect vector control of induction motor drive is developed and simulated in MATLAB/ Simulink. The KF, EKF based flux observer for indirect vector control drive is studied and a comparison of estimated parameter for conventional P-I controller based drive is obtained through simulation and their relative merits and demerits are described.

Due to change in the parameter such as rotor resistance and moment of inertia, performance of the system will be disturb such as torque will decreases or increases depending on the condition.

d-q axis rotor fluxes,which are not easily measurable and require estimation.sometimes,the measured stator currents are contaminated by noise and require to be estimated as well.In some circumtances the estimates can be more reliable.

The performances has been investigated at different dynamic operating conditions both simulated and estimated result. It is concluded that the proposed EKF has shown superior performances over KF observer.

Chapter VI Conclusion and Future Scope of Work

6.1 Conclusion

This project has successfully demonstrated that a properly designed Extended & Kalman filter can be traditional non linear observer. Performance and features of EKF algorithms for induction motor rotor flux estimation inserted in a field oriented control scheme are compared, the following conclusions are made.

- It is effective for application in industrial systems which can be regarded as being strongly stochastic in nature.
- Its performance can be tuned by adjusting the covariance matrices.
- Its design incorporates no flexibility owing to the fact that a constraint implying Optimality must be satisfied. Thus no additional prescribed performance criteria such as speed of response, speed of convergence, robustness against parameter drift etc. can be accommodated directly into the design procedure;.
- In contrast to the basic Kalman filter, ***ad*** *hoc* covariance matrix-tuning adjustments, and the nonlinear nature of the observed plant results in a non-optimal estimator ***ad hoc*** covariance matrix adjustments may also result in a bias problem.

6.2 Future Scope of Work

- Induction motor drive systems with a field-oriented controller are presently considered as viable alternatives for replacing dc motor drives.
- In recent years, the Kalman filter algorithm has been used for the parameter estimation of an induction motor or for the speed estimation of a synchronous and an induction motor. In the speed estimation of an induction motor using an extended Kalman filter algorithm, not only the angular speed of rotor, but also the angular frequency of rotor flux and the angle of rotor flux have to be augmented in the Extended Kalman filter.
- The original kalman filter is applicable only to a linear system. the Kalman filter based algorithm has demonstrated to be the best one for processing noisy discrete measurements and obtaining high accuracy estimates.
- The Kalman filter is a tool that can estimate the variables of a wide range of processes. In mathematical terms we would say that a Kalman filter estimates the

states of a linear system. The Kalman filter not only works well in practice, but it is theoretically attractive because it can be shown that of all possible filters, it is the one that minimizes the variance of the estimation error.

- For nonlinear problems, the KF is not strictly applicable since linearity plays an important role in its derivation and performance as an optimal filter. The EKF attempts to overcome this difficulty by using a linearized approximation where the linearization is performed about the current state estimate

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APPENDIX

Induction Motor Parameters Used For Simulation

Machine type	3-phase induction motor
Rotor type	squirrel cage
Stator and Rotor	Y-connection to an internal neutral point
Reference Frame	stationary
Power	50-hp
L-L Voltage	460V
Frequency	60Hz
Stator resistance	0.087Ω
Rotor resistance	0.228Ω
Stator inductance	0.8mH
Rotor inductance	0.8mH
Mutual inductance	34.7mH
Inertia	1.662Kg.m^2
Friction factor	0.1N.m.s
No of pole	4

Inverter parameters used for simulation

Power electronics device	IGBT
Number of bridge arms	3
Snubber resistance	1000Ω
Snubber capacitance	inf
Internal resistance	1mΩ
Forward vltage	0.8V
Fall time	1μs
Tail time	1μs