ROTOR RESISTANCE ESTIMATION USING REACTIVE POWER BASED MRAS TECHNIQUE OF VECTOR CONTROL OF INDUCTION MOTOR

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
IN
CONTROL & INSTRUMENTATION
(Electrical Engineering)

Submitted by:

Avinash Sonkar

2K13/C&I/02

Under the supervision of

Prof. Madhusudan Singh

DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CERTIFICATE

I, Avinash Sonkar, Roll No. 2K13/C&I/02 student of M. Tech (Control and Instrumentation), hereby declare that the dissertation titled “Rotor resistance estimation using reactive power based MRAS technique of vector control of induction motor” is a bonafide record of the work carried out by me under the supervision of Prof. Madhusudan Singh of Electrical Engineering Department, Delhi Technological University in partial fulfillment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any degree.

Place: Delhi AVINASH SONKAR

Date:

Prof. MADHUSUDAN SINGH
Supervisor

ACKNOWLEDGEMENT

First and foremost, I express my sense of gratitude to my supervisor Prof. Madhusudan Singh, Head of Department of Electrical Engineering for his guidance, support, motivation and encouragement throughout the period this work was carried out. His readiness for consultation at all times, his educative comments, his concern and assistance has been invaluable.

I also thank all the non-teaching staff of the Electrical Engineering Department for their fullest cooperation.

I would like to thank all those who have directly or indirectly helped me in completion of the thesis well in time.

Finally, I wish to thanks my parents for their moral support and confidence showed in me to pursue M. Tech at an advanced stage of my academic career

Delhi, 2018 AVINASH SONKAR

ABSTRACT

The induction motors are the most famous and widely used machines in most of the industrial as well as in domestic applications due to its simplicity and low cost. When the variable speed applications are required the induction machines are used. For induction machines, variable speed drives requires both fast torque response as well as wide operating range of speed. Indirect vector control of induction motor is somewhat predictive method, where the speed of the rotor flux is predicted from slip speed and rotor speed. The rotor speed may be obtained either from the estimation method or from speed sensors.

If due to a temperature change, there is any variation in the rotor time constant it may lead to uneven orientation of the flux and hence dynamic performance of the drive deteriorates. The continuous online estimation of rotor time constant or rotor resistance is very crucial for the flux orientation which subjected to the change of rotor time constant for variation in temperature. Due to lost in orientation of the flux, the coupling effect makes the performance of the induction motor drive slightly sluggish. Model reference adaptive system (MRAS) method is incorporated for the online estimation of the machine parameter.

Model reference adaptive system controller using the reactive power (Q) is presented here, for the online estimation of the rotor resistance to maintain the flux orientation constant and fixed in an indirect vector control of induction motor drive. The formation of MRAS with the steady-state and instantaneous reactive power eliminates the estimation of flux. Reactive power based MRAS estimator is less prone to the integral problems like drift and saturation. Simulation results have presented to confirm the effectiveness of the technique.

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

IM	Induction Motor
Rs	Stator Resistance
Rr	Rotor Resistance
Rr’	Rotor Resistance Referred to Stator side
Xs	Stator Reactance
Xr	Rotor Reactance
Xr’	Rotor Reactance Referred to Stator side
Xm	Leakage Inductance
I_1	Stator Current
I_2	Rotor Current
I_2’	Rotor Current Referred to Stator side
I_m	Magnetizing Current
V_0	Stator Voltage
s	Slip
ω_s	Synchronous Speed
ω_m	Rotor Speed (Machine Speed)
Ω_s	Average Synchronous Speed (in RPM)
f	Supply Frequency
p	No. of Poles
P_g	Air-gap Power
P_{cu}	Copper loss in the machine
P_m	Mechanical Power output of the machine
T	Torque Developed by the motor
s_m	Slip at maximum torque
T_{max}	Maximum Torque
V_d	DC Link Voltage
ω_{ref}	Reference Speed
ω_{sl}	Slip Speed

ω_f	Rotor Speed at Frequency f
σ	$1-L_m^2/(L_sL_r)$
V_{qs}	q-axis Stator Voltage with stationary frame
V_{ds}	d-axis Stator Voltage with stationary frame
I_{qs}	q-axis Stator Current with stationary frame
I_{ds}	d-axis Stator Current with stationary frame
I_{qr}	q-axis Rotor Current with stationary frame
I_{dr}	d-axis Rotor Current with stationary frame
λ_{ds}	d-axis Stator flux with stationary frame
λ_{qs}	q-axis Stator flux with stationary frame
λ_{dr}	d-axis Rotor flux with stationary frame
λ_{qr}	q-axis Rotor flux with stationary frame
λ_s	q-axis Rotor flux with stationary frame
L_s	Stator Self-Inductance
L_r	Rotor Self-Inductance
L_m	Stator Mutual-Inductance
$I_{s'}$	Complex Conjugate of Stator Current
P_i	Instantaneous Active Power
Q_i	Instantaneous Reactive Power

CHAPTER I

INTRODUCTION

1.1 General

Electric drives have become an inseparable part of the industrial applications, which require high performance. Electric motors have their impact on almost every corner of our modern life. They convert electrical energy into useful mechanical energy. Ranging from everyday household machines like vacuum cleaners, refrigerators, air conditioners to computer hard drives, automatic car windows, and also in various other appliances and devices employ different types of electric motors. They are also responsible for a very large portion of industrial processes. There are various rating sand sizes of induction motor across the world and they altogether consumes about 60% of electricity generated all over the world. These can be utilized in a number of applications, where power requirement ranges from few watts to thousands of kilowatts. Besides these, applications ranges from very precise, high-performance position-controlled drives in the world of robotics to variable-speed drives for adjusting flow rates in pumps, fans and blowers. In the applications discussed above, position and speed control is of utmost importance hence, the drives are controlled by the power electronic converters which acts as an interface between the input supply and the motor.

Because of its special features like ruggedness, simplicity, low inertia, high reliability and low cost induction motor (IM) is considered as the ‘workhorse’ of the modern industry. Based on the rotor construction, the induction motors are Squirrel cage and Slip ring type. Squirrel Cage Induction Motors (SCIM) are widely used in industrial drives because they are reliable, rugged, least expensive motors and require less maintenance. The dynamics of Induction motor is a complex higher-order nonlinear system, strongly coupled, and also a multi-variable system. When these motors are operated directly from the line voltages, they run at an almost constant speed. With the advancement of power electronic converters it is now possible to vary the speed of an induction motors as per the requirement. Due to its wide range of applications torque as well as speed control have remained the focus of our study. Its speed-controller patterns include: slip power feeder, slip power consumer and fixed slip power. In those applications where dynamic control is not our main concern, the controlling of the AC machine drive has been implemented using constant '*voltshertz (V/f)'* technique.

The application of induction motors has shoot up tremendously with the advancement in the field of high performance AC drives. With the development of power electronic devices, microprocessors/digital signal processing, lower loss switching and advancement in modeling, control algorithm the advance features of control in induction motors has been achieved. The high performance AC drives can be broadly classified as, field oriented control (FOC) and direct torque control (DTC) drives. These drives have various applications that were earlier dominated by DC motors and by drive systems. The vector control or FOC belongs to the fixed slip power pattern and a method for higher efficiency. The indirect field oriented (IFO) controlled drives are tremendously used in industrial applications wherever high performance is required [31]-[32]. The field current and the torque current are the two components of the stator current of an induction motors and both these components can be controlled independently to achieve good dynamic response, which is very much similar to the control of dc motors.

In the last few decades there has been a lot of improvement in control techniques and in addition to the advent of power electronic converters it has resulted in better dynamic response of the motor induction motors.

1.2 Parameter Estimations in Induction Motor Drives

Vector control or FOC (Field oriented control) of an induction motor is mostly used in industrial application. Implementation of Direct field oriented control (DFOC) and Indirect field oriented control (IFOC) needs parameters of the motor. There are various methods for suppressing the problems related to the variation in parameters due to rise in motor temperature in long run operation of Induction motor. The electrical parameters changes in different conditions and circumstances. The temperature and slip frequency affects stator resistance as well as rotor resistance, whereas magnetic saturation affects mutual inductance of the motor. In the last few decades this has been a major area for the research in the field of power electronics and drives. Attention has always been focused to enforce field orientation through online estimation of the machine parameters [43]-[46]. Many online parameter estimation techniques have been discussed in [47]-[50]. The main priority of the present research work is to find the most suitable method for the online estimation of rotor resistance of the drive.

There are various techniques discussed in the literature for the estimation of rotor resistance such as Model Reference Adaptive System (MRAS), Kalman filter, Extended Kalman filter, sliding mode controller, leunberger observer, least square recursive method and many others method is reported in literature, and each one these techniques have grabbed the attention of the researchers depending upon the applications. Among these, an extended Kalman filter achieve the stability by properly selecting the positive definite term for riccati equation for the gain designing, but at the same time, this technique suffers from proper initialization and tedious calculation. Another attractive and easy to implement technique is MRAS in which error is measured from the output of two different models i.e., adaptive model and the reference model, and the effort is to make error from these two model to zero with the help of an adaptation mechanism. The adaptation mechanism which is an integral part of MRAS consists of a PI controller which can be tuned according to the requirement. The control method used here should follow the system according to the variation in parameters and the uncertainty. This particular controller is designed with the help of a reference model which describes the characteristics of the plant to be controlled and which also provides the stability to the system. The variable quantity has effect on only one of the model and the other model remains ineffective with the variable quantity.

The two different methods for MRAS (model reference adaptive system) are direct control and indirect control. In direct control method, a controller is selected and its parameter is adjusted in order to make the error as close to zero as possible. In indirect control method, the unknown parameters of the plant are estimated before the control input is selected. Also, this method has both adaptive as well as reference model but in direct method there is only reference model.

1.3 Objective of the thesis

The main objective of this thesis is to identify and finally implement an estimator for a Vector controlled or field oriented control induction motor drive. For identifying observer, the prime focus is on the estimator which must be simple to design, accurate, should have wide operating range and could be implemented easily. The following are the main objectives:

1. To study and identify the methods for the estimation of Rotor Resistance in indirect vector controlled drives.
2. To implement the estimator for the change in parameter of an Induction motor due to the temperature variation. A reactive power (Q) based MRAS estimator is designed for the estimation of rotor resistance.

1.4 Organization of the thesis

In this dissertation, the speed control, performance evaluation, and finally the estimation of an induction motor's rotor resistance is discussed and implemented. To show the authenticity of the technique, simulation results have been examined using the MATLAB SIMULINK and further variation in the rotor resistance due to change in temperature in induction motor drive is analyzed. The outline of the thesis is:

Chapter II, Literature Review
In this chapter a brief review of the books, hand books and some of the latest research papers of the last few decades on rotor resistance estimation techniques of induction motor drive is discussed.

Chapter III, Modeling and Control of Induction Motor
In this chapter, the detailed dynamic modeling of induction motor is covered and three phase to two phase transformation using Clarke's and Park's transformation are discussed.
In this chapter, the control techniques used for induction motor such as scalar control and field oriented control or vector control (direct and indirect vector control) and sensor-less control techniques are described.

Chapter IV, Rotor Resistance Estimation of Induction Motor using MRAS Technique
In this chapter model reference adaptive system technique has been discussed and implemented in brief, for the change in rotor resistance of induction motor due to the

increase in temperature of motor in indirect vector control of induction motor drive and also initialization of use of power electronics devices in the system and proportional plus integral controller technique is discussed.

Chapter V, Simulation results and Discussions

In this chapter, detailed modeling and analysis of induction motor and variation in its rotor resistance with increasing temperature is modeled and simulated, in MATLAB Simulink. The control algorithm for rotor resistance is simulated with the help of proportional plus integral control using reactive power based MRAS. The analysis and performance of control algorithm is examined by the preciseness of the simulation results. To show the effect of change in performance of induction motor drive, both linear and sudden change in rotor resistance is demonstrated. The simulation results for MRAS algorithm with changes in rotor resistance are analyzed.

Chapter VI; Main Conclusion and Future Scope

In the final chapter, main conclusion of the present study of work and future work is discussed. It includes estimation of rotor resistance with increasing temperature through an algorithm called MRAS for indirect field oriented control.

CHAPTER II

LITERATURE REVIEW

2.1 General

Vector control or field oriented control (FOC) has widespread applications in order that the motor speed vary precisely and also follow the specified reference trajectory irrespective of the disturbances. In vector control, the principle of field orientation of an AC induction or synchronous motor helps in achieving control of these motors very much like a separately excited DC motor. The decoupled control of flux and torque in induction motor is obtained through FOC method. The AC motor acts like a DC motor in which the armature flux linkage and the field flux linkage produced by armature (or torque component) current and field current respectively are orthogonally aligned in such a way that, when torque is changed, the field flux is not changed and vice-versa, hence providing fast dynamics to torque and flux in the motor. Now by using axes or coordinate transformation, vector control allows us to decouple the electromagnetic torque from the rotor flux, and hence induction motors performs like a separately excited DC motor. In this type of control, the variables (i.e. stator current or voltage) are transformed into a reference frame (i.e. synchronously rotating frame) in which the dynamic variables acts like DC quantities. The decoupling control between the torque and flux, helps induction motor in achieving fast transient response and therefore, it is globally used in high performance motors applications.

With the advancement in the intelligent instrumentation over past few decades, power electronics and digital control techniques helped in designing and development of complex, larger and efficient industrial systems. In modern times, electrical drives can be seen in almost all kind of industrial process and plants like paper mills, rolling mills, automotive industry, packaging industry, water treatment plant, oil and gas refineries, iron and steel industry, etc to achieve the desired motion control. An extensive literature review of the research and development in the field of modeling and control of induction motor and the rotor resistance estimation are described in this chapter.

2.2 Parameter Estimation Methods in Induction Motor

The concept of vector control of AC motors was given by two Germans. Hasse [2] proposed the theory of indirect vector control in 1968 while Blaschke [1] proposed the theory of direct vector control in early 1970s. Werner Leonhard [3] was further instrumental in developing the FOC techniques. Abbondanti and Brennen et al. [6] in 1975 have designed the slip calculator that depends upon the input quantities such as phase, voltage and current. Allan B. Plunkett et al. [7] have developed means for the measurement of the flux level in an induction motor. With the help of flux and stator current, the electromagnetic torque in an induction motor can be obtained. R. Krishnan et al. [11] suggested that the estimation of flux needed the proper knowledge of induction motor parameters and the indirect vector control was parameter dependent. If there is any change in the temperature of the machine, it affects the machine parameters and indirectly the steady state and dynamic performance of the machine. R Marino et al. [9] concluded that the control algorithm has a nonlinear identification scheme which can asymptotically track the true value of the load torque and rotor resistance which are assumed to be constant but unknown. Once the true value of the load torque and rotor resistance are identified, the two control goals for the regulation of rotor flux and rotor speed amplitudes are decoupled. K. R. Cho et al. [51] studied the detection of broken rotor bars in induction motors. The assumption on which the study was based is that the rotor resistance of an induction motor increases when the rotor bar breaks. For detection of broken rotor bars the measurements of stator current, frequency, voltage, and rotor velocity are taken for a low range of velocity. Measurements can be processed by a least square error estimator to estimate the machine states and parameters. C. Attaianese et al. studied the speed control of induction motor, online estimation of the speed, other parameters of the machine and the comparative study of different motors. H. A. Toliyat et al. [12] in their paper have concluded that the most common machine used in industries is an induction motor and the control scheme for these drives should have to the point knowledge of the machine parameters. The controller deteriorates the performance of the induction machine in case any of the actual parameters changes. C. Kral et al. studied the implementation of estimation of rotor temperature for fan-cooled induction motors with a thermal equivalent circuit. The estimation of rotor resistance becomes inaccurate when the motor is loaded slightly because of the presence of small slip. Estimation of rotor temperature for low-load conditions can be done through a thermal equivalent model. Few machine parameters have to be estimated in advance for the estimation of rotor position and rotor temperature accurately. The iron losses and leakage reactance is calculated through load test of the induction machine. The thermal equivalent model needs a thermal resistance and capacitance. These parameters are derived through a heating test, in which the parameter model is used to give reference temperature in time domain. J. Pedra et al. in their work studied the transient behavior of induction motor by estimating the double-cage model parameters with the help of regression-based equations that depended on the line voltage and mechanical power of the machine. Wei Chen et al. [15] proposed that the estimation of parameters at standstill depends on the static induction machine model. Single phase AC current is injected to the motor, and the parameters like resistance and inductance are estimated through transient response data. The nonlinearity of the system is compensated to improve the estimation precision of the parameters. Hong-yu Zhu et al. [16] in their paper explained the implementation of the parameter estimation method for induction motor using the extended Kalman filter (EKF) theory. Real-time implementation of this method is done on PC-cluster node. Lluís Monjo et al. [17] in their paper proposed the estimation of the parameters of induction motor using a standstill variable frequency test. The estimated resistance and reactance for different frequencies are the data used for the minimization of error for single and double-cage model parameters estimation. In single-cage model it is observed that it measured data for frequencies above tenths of Hertz and in case of double-cage model it fits the data accurately in all the frequency ranges (0 to 150 Hz).

2.3 Speed Estimation Methods in Induction Motor

Problems related to the variation in parameters are handled by different approaches. The electrical parameters value changes in different circumstances: the resistance is affected by both the slip frequency and the temperature. The mutual inductance is influenced by magnetic saturation. Techniques used for the estimation of speed of induction motor includes model reference adaptive system, Extended Kalman filter, sliding mode controller, least square recursive method, leunberger observer, Kalman filter. Extended Kalman filter technique has attained stability by selecting the positive definite term for riccati equation for the gain designing.

T. Iwasaki et al. [18] in their work used an Extended Kalman filter technique for estimating different parameters of the induction motor while using the values of the rotor speed, stator currents and stator voltages. Both the induction motor model and Kalman filter algorithm have a similarity that they are designed in the state space. The filters are used to identify the parameters of an induction motor. F.Z. Peng et al. [19] has proposed the speed identification for a tacholess vector control. Integration of sensed variables is not required here. A tacholess vector control for very high-speed motor drives has been implemented because they have difficulties in mounting speed sensors. L. Ben-Brahim [20] has proposed neural-networks-based method for speed estimation for an induction motor. The back-propagation neural networks technique finds its usage in the real-time based adaptive estimation of the induction motor speed. The proposed theory is used for the improvement in the performance of speed in sensor less drives.

R. Blasco-Gimenez et al. in their paper proposed a real-time slot harmonic speed detector for vector control of induction machines. Resolution and speed accuracy have been calculated for motors of general rotor slot numbers and slot harmonic orders and also for windowing and interpolation methods. The problems associated to Speed tracking have been discussed. In their paper M.Ta Cao et al. proposed that adaptive speed controller and rotor resistance estimator depends on the fuzzy logic (FL) approach for a high performance indirect vector controlled induction motor drive. A fuzzy logic based rotor resistance estimator is designed in order to achieve the decoupled control of torque and flux. [23] R. Blasco-Gimenez et al. in their paper have studied the dynamic performance of a sensorless cage induction motor drive utilizing an MRAS based flux and speed estimator operating within a direct rotor flux orientated vector controller. J. L. Zamora et al. [24] in their paper proposed a set of algorithms that are implemented for online parameter estimation (stator resistance, stator inductance, and leakage inductance) of an induction drive using neither the rotor resistance nor the rotor speed. The estimation procedure is only based on current measurements and stator voltage. H.-J. Shieh et al. [25] proposed estimation model based adaptive control for indirect vector control of induction motor. It involved concept of designing a new reference frame based estimator to adaptively estimate the state variables and the rotor time constant used in indirect vector control.

B. Karanayil et al. [27] in their work have proposed using indirect vector control for estimation of the rotor resistance of the induction motor. The back propagation neural network (NN) technique is used for the adaptive estimation. The error between the actual variable of a neural model and the desired variable of an induction motor is back propagated to adjust the weights of the neural network model, so that the actual variable tracks the desired value.

B. Karanayil et al. [28] have discussed two methods of estimation of rotor resistance from indirect vector controlled induction motor. A model reference adaptive scheme is proposed in which a FL (fuzzy logic) controller and a PI controller are used for executing adaptation mechanism. A. Ba-Razzouk et al. [29] has proposed that implementation of drives insensitive to parameters variations is an important need in the high performance drives. For drives controlled by the indirect rotor flux oriented control (IRFOC), the rotor time constant ($\tau_r = L_r/R_r$) exerts a role in the loss of dynamic performance and its results in an undesirable coupling between flux of the drive and torque.

Xing Yu et al. [30] in their paper presented the rotor resistance identification method for an IRFO controlled induction drive. A decoupled vector control scheme is used to achieve an accurate and fast current control response and indicates the temperature change of the rotor resistance. A model reference adaptive control scheme is used to track the variation of the rotor resistance. Yang Wenqiang et al. [31] proposed a vector control of induction motor drive, by the estimated rotor flux and rotor speed, while using a new extended Kalman filter (EKF). In this method, only the rotor flux components are considered as the state variables. Y. Koubaa et al. [32] proposed that the estimation of speed is achieved by assuming that the rotor resistance is remains constant throughout the operating range. In practical situations, the variation of this resistance depends on the inside temperature of the machine.

S.A.Villazana et al. [33] have proposed that rotor resistance estimation of the SCIM (squirrel cage IM) is implemented using support vector machines (SVM) together with the model reference adaptive system. The drive with the variable rotor resistance was put into simulation and the flux error records were obtained from voltage and current models. Shady

M Gadoue_et al. [34] suggested the neural network based flux observer to solve the low speed problems related to the model reference adaptive speed estimation algorithm which is based on the rotor flux. For rotor flux estimation, a multilayer feed forward neural network is implemented which is robust to noise and resistance variation and does not have DC drift problems which are usually associated with the adaptive algorithm.

S.Villazana et al. [35] presented a comparative study between the performance of a SVM (Support vector machines) based MRAS observer and the performances of a classical MRAS based observer of the SCIM to estimate the rotor resistance. H. A. Toliyat et al. [36] proposed an online rotor time constant estimation scheme of an indirect vector control induction motor for improving the robustness and performance of the drive. The technique neither requires any complex calculations nor any special test signals. Mohamed Rashed et al. [37] proposed that an accurate knowledge of rotor flux, speed and position is required for sensor less speed control of a PMSM. Suman Maiti et al. [38] gave the idea of Model reference adaptive system (MRAS) techniques for the estimation of speed for induction motor drive and rotor time constant. This method uses the instantaneous and steady state reactive powers to formulate the error signal.

M. Nandhini Gayathri et al. [39] in their paper presented Vector Control Induction Motor drive with MRAS based Rotor Resistance Estimator using Reactive Power. Any rise in temperature changes the rotor resistance. Due to the deviation in slip frequency from its set value, it has a major influence on the vector control performance of an induction motor. M. Nandhini Gayathri et al. [40] in this paper proposed that Vector Controlled transforms the control of induction drive to that of a dc motor by creating channels for flux and torque control. Syed Ali Asad Rizvi et al. [41] concluded that indirect vector control depended on the estimation of the rotor flux and its synchronous angle for decoupling of flux and torque. This estimation depends on the calculation of current model and slip speed both are prone to detuning of rotor parameters.

Betsy Baby et al [42] concluded that for high power voltage drive applications, the current source inverter (CSI) is best suited. Indirect vector control is preferred for decoupled control of the machine torque and flux because of its less computational complexity and reduced machine parameter dependency. Saji Chacko et al [43] proposed that the Rotor flux Model Reference Adaptive Controller is used for on line rotor resistance estimation and while improving the steady state performance of the motor. Seung-Myung Lee et al. [44] have proposed that the rotor resistance is associated with the calculation of slip. Also, the estimation of rotor resistance has a major impact on the dynamic behavior of the Indirect vector Control. The proposed rotor resistance estimation technique is dependent on the rotor flux of the d-axis, whereas the voltage model of induction motor is the reference model, while the current type model in the synchronous reference frame is used as an adjustable model.

2.4 Conclusion

This chapter contained the brief summary of the methods to improve the dynamic performance of Induction motor and estimation of rotor resistance. The scope of this research work focuses on the implementation of the vector control scheme and estimation of rotor resistance with the help of suitable algorithm for efficient operation of the drive.

CHAPTER III

MODELING AND CONTROL OF INDUCTION MOTOR

3.1 General

The internal structure of three phase induction motor is shown in figure 3.1. Basically three phase induction motor has two parts a stator and a rotor. The inner periphery of the stator has number of slots on which distributed field windings are placed. The rotor of three phase induction motor is either wound type, which consists of three phase winding whose end terminals are not short circuited or squirrel cage type in which its end terminals are short circuited by end rings. The air gap between stator and rotor structure is kept as small as possible to keep leakage loss low and at the same time to ensure mechanical clearance between the structures. The size of the air gap decides the power rating of the motor. The rotor of induction motor rotates at speed slightly less than the synchronous speed and hence also known as Asynchronous motor. The operating speed of the motor depends upon the slip which comes from the rotational speed of stator field and therefore speed is somewhat lower than the synchronous speed.

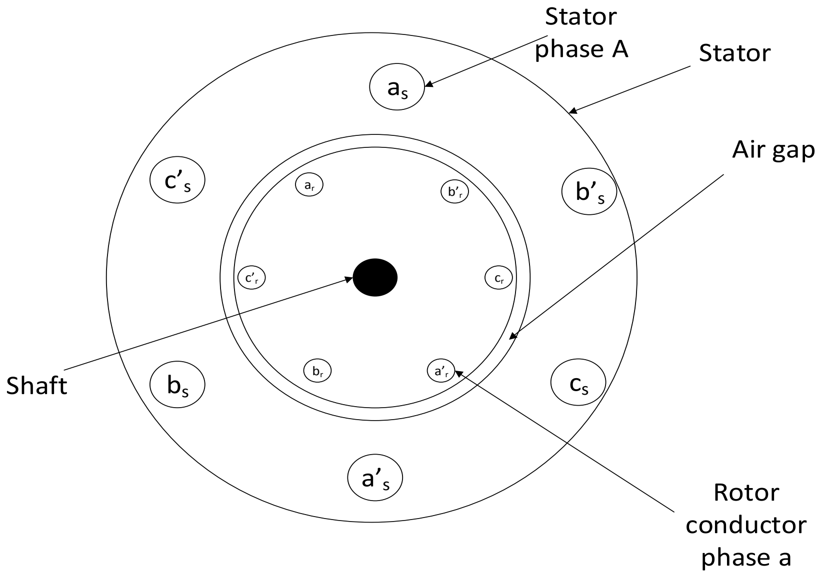


Figure 3.1 Internal structure of three phase induction motor.

In slip ring induction motors external resistance is added to rotor circuit through the slip rings which in turn provides high starting torque, low starting current but results into greater I^2R loss. Vector control is used to improve the dynamic performance as well as the efficiency of the drive and it is possible by transforming the three dimensional variables into two dimensional reference frame that can be in stationary reference frame or in synchronously rotating reference frame. Dynamic modeling is somewhat complex and that can be implemented with the choice of different reference frames. Dynamic properties of induction machine describes various torque and voltage equations that are time dependent. The computational complexity of the model is reduced by reducing all the time varying inductances using change of variables and for that matter some transformations are required in order to transform from three phase stationary reference frame to two phase stationary reference frame which is done by Clarke's Transformation. Again there will be a transformation from two phase stationary reference frame to a two phase rotating reference frame through Park's Transformation.

3.2 Dynamic d-q model of Induction Motor

A variable speed drive constitutes an element in the feedback loop and with that its transient nature will be considered in the performance of a drive. Vector control or field oriented control are the high performance machine drive which critically depends on the dynamic modeling of the machine. The dynamic performance of the motor is tedious and complex as the three phase windings of rotor part moves w.r.t the stationery three phase windings of stator as shown in Figure3.1. It is very much similar to the secondary winding of the transformer. With the continuous change in the rotor position, the coupling between stator and rotor will also change continuously. While using the higher differential equations, machine model can be implemented with the time varying mutual couplings. The three phase ac machine will be represented into a two phase machine. Although it is simple, but the problem remains same with the time based parameters variations. R.H. Park, in the year1920, proposed a theory to solve the time varying problems for the analysis of the machine model. With his transformation theory, the variables of stator are transformed to a synchronously rotating reference frame with the stationary reference frame [2].

A. Axes transformation

There exists complexity in the Induction motor modeling and therefore axes transformation is necessary to solve the problems of variation in parameters like time varying inductances and also to reduce the complexity of the system. In this transformation theory, induction machine will be transformed from three phase stationary axes (a-b-c) to two phase stationary axes($d^s - q^s$) which is shown in figure 3.2, and then transform this stationary axes ($d^s - q^s$) to two phase rotating axes($d^e - q^e$).

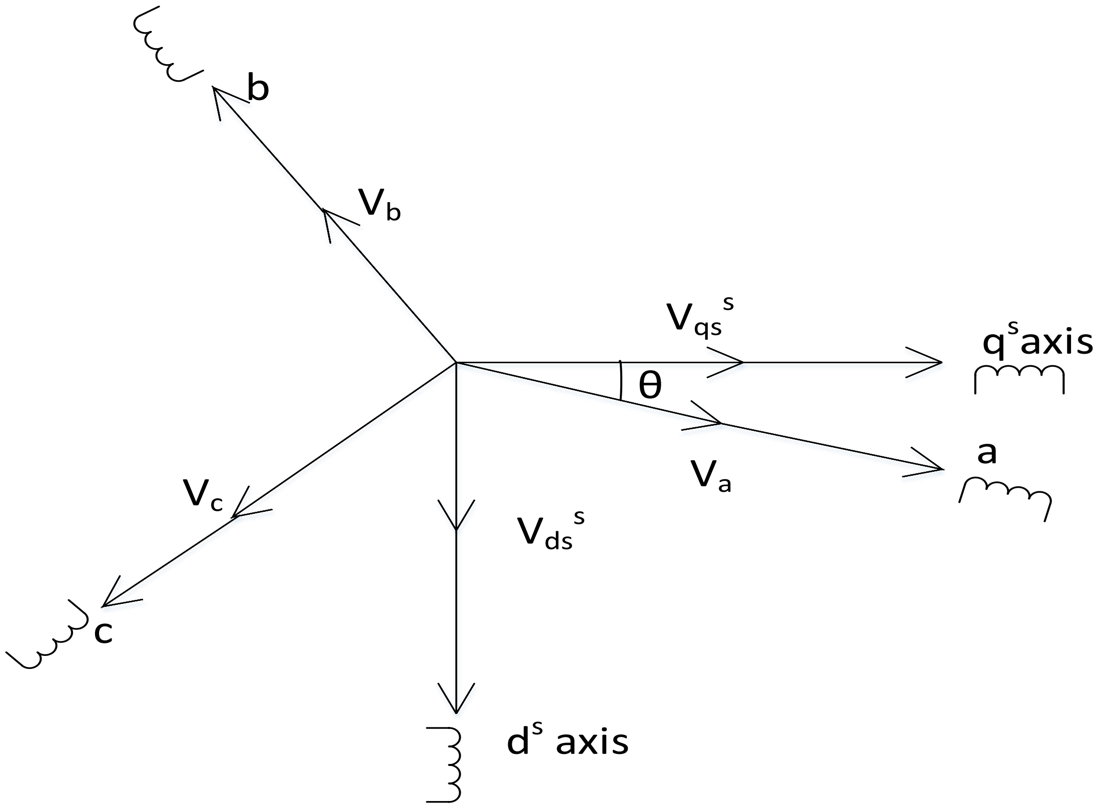


Figure3.2: Transformation from Stationary frame a-b-c to ds-qs frame

The direct axis stator voltage and quadrature axis stator voltage components can be resolved into a-b-c component is written in the form of matrix as given

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} \tag{3.1}$$

And the inverse transformation is:

$$\begin{bmatrix} v_{qs}^{s} \\ v_{ds}^{s} \\ v_{0s}^{s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.2}$$

Where,

v_a, v_b, v_c = Three phase line voltage of a,b,c

v_{qs}^{s} = quadrature axis stator voltage in stationary frame

v_{ds}^{s} = direct axis stator voltage in stationary frame

v_{0s}^{s} = zero sequence component which will not be present in the balanced condition. If we set $\theta = 0$, than q^{s} component is in phase with the phase ‘a’ axis component. While neglecting the zero sequence components.

$$v_a = v_{qs}^{s} \tag{3.3}$$

$$v_b = -\frac{1}{2} v_{qs}^{s} - \frac{\sqrt{3}}{2} v_{ds}^{s} \tag{3.4}$$

$$v_c = -\frac{1}{2} v_{qs}^{s} + \frac{\sqrt{3}}{2} v_{ds}^{s} \tag{3.5}$$

For balanced state:

$$v_a + v_b + v_c = 0$$

The axes transformation from three phase stationary frame a-b-c to two phase stationary frame ($d^{s} - q^{s}$), with the Clarke’s transformation. The synchronously rotating frame($d^{e} - q^{e}$), rotate at the speed of ω_e with the stationary axes. The($d^{s} - q^{s}$) axes can be transformed to the ($d^{e} - q^{e}$) axes with the angle $\theta = \omega_e$t. Figure 3.3 shows the transformation from stationary d^s-q^s axis to synchronously rotating $d^{e} - q^{e}$ axis.

From the phasor diagram ‘v_{qs}’ and ‘v_{ds}’ can be written as:

$$v_{qs} = v_{qs}^{s} * \cos\theta_e - v_{ds}^{s} * \sin\theta_e \tag{3.6}$$

$$v_{ds} = v_{qs}^{s} * \sin\theta_e + v_{ds}^{s} * \cos\theta_e \tag{3.7}$$

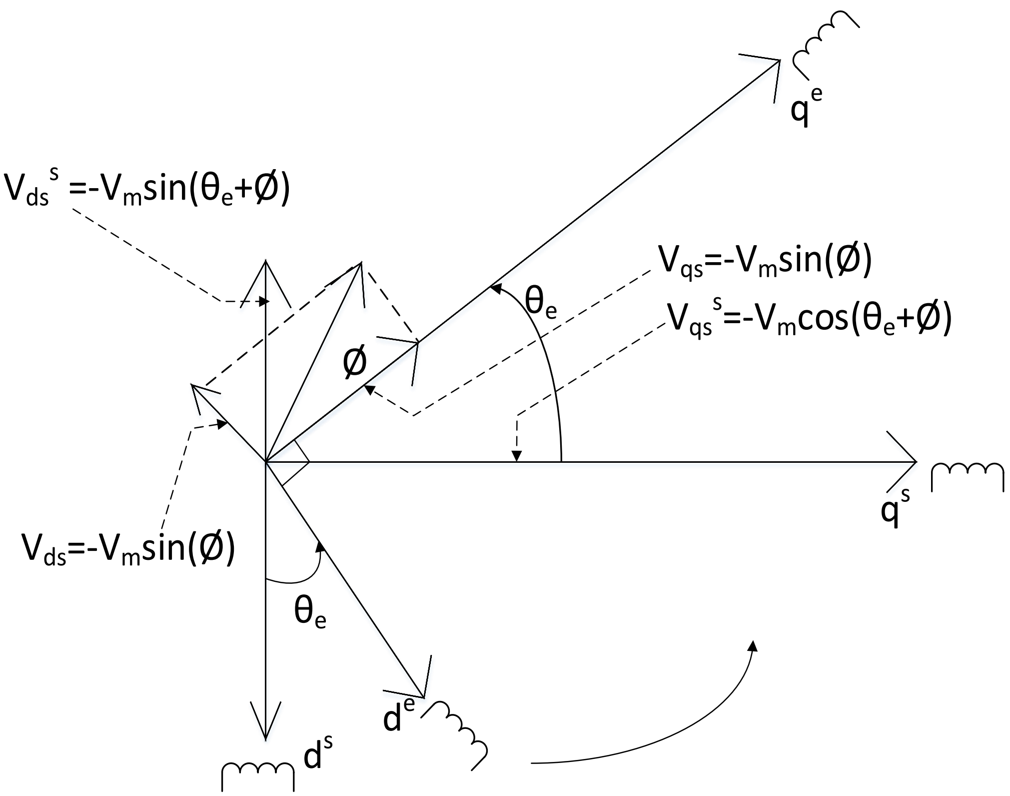


Figure 3.3: Transformation from stationary d^s-q^s axis to synchronously rotating $d^e - q^e$ axis.

It can be represented in the form of matrix:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} \tag{3.8}$$

The components v_{ds} and v_{qs} rotating axes transformation can be transformed through Park’s Transformation.

For the inverse transformation:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos(\theta_e) & -\sin(\theta_e) \\ \cos(\theta_e - 2\pi/3) & -\sin(\theta_e - 2\pi/3) \\ \cos(\theta_e + 2\pi/3) & -\sin(\theta_e - 2\pi/3) \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \tag{3.9}$$

The transformation is achieved from rotating reference frame to stationary frame through the Inverse Park’s transformation.

B. Synchronously rotating reference frame

To represent the two phase machine components at stator $d^s - q^s$ and rotor $d^r - q^r$ at the synchronously rotating reference frame ($d^e - q^e$). Figure 3.4(a,b) shows the equivalent model of an induction motor. The stator equations are:

$$v_{qs} = i_{qs}R_s + \frac{d}{dt}\Psi_{qs} + \omega_e\Psi_{ds} \tag{3.10}$$

$$v_{ds} = i_{ds}R_s + \frac{d}{dt}\Psi_{ds} - \omega_e\Psi_{qs} \tag{3.11}$$

The rotor equations at the synchronous axes:

$$v_{qr} = i_{qr}R_r + \frac{d}{dt}\Psi_{qr} + (\omega_e - \omega_r)\Psi_{dr} = 0 \tag{3.12}$$

$$v_{dr} = i_{dr}R_r + \frac{d}{dt}\Psi_{dr} - (\omega_e - \omega_r)\Psi_{qr} = 0 \tag{3.13}$$

Where,

R_s - Stator resistance

R_r - Rotor resistance

i_{ds}, i_{qs} - direct and quadrature axis component of stator current

i_{dr}, i_{qr} - direct and quadrature axis component of rotor current

Ψ_{ds}, Ψ_{qs} - direct and quadrature axis component of stator flux linkage

Ψ_{dr}, Ψ_{qr} - direct and quadrature axis component of rotor flux linkage

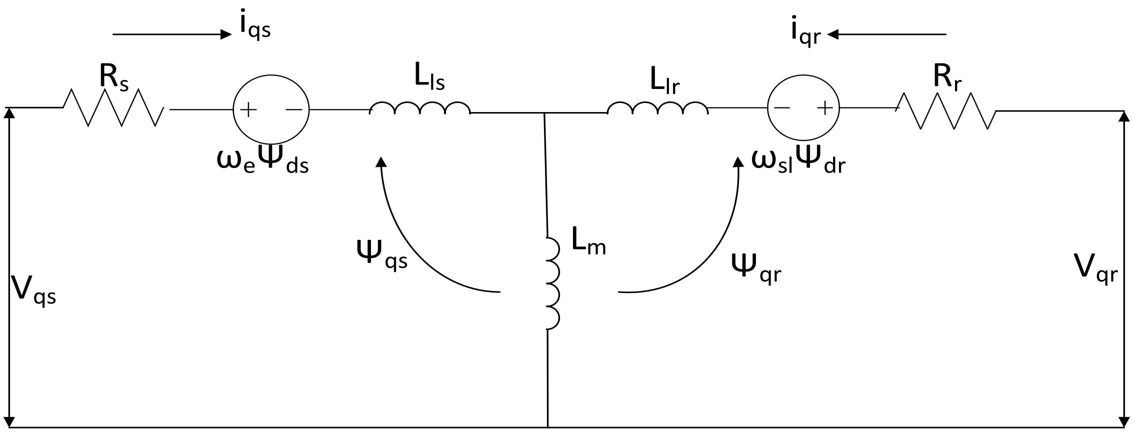


Figure 3.4(a) dynamic d^e- q^e equivalent circuit of motor (q^e axis)

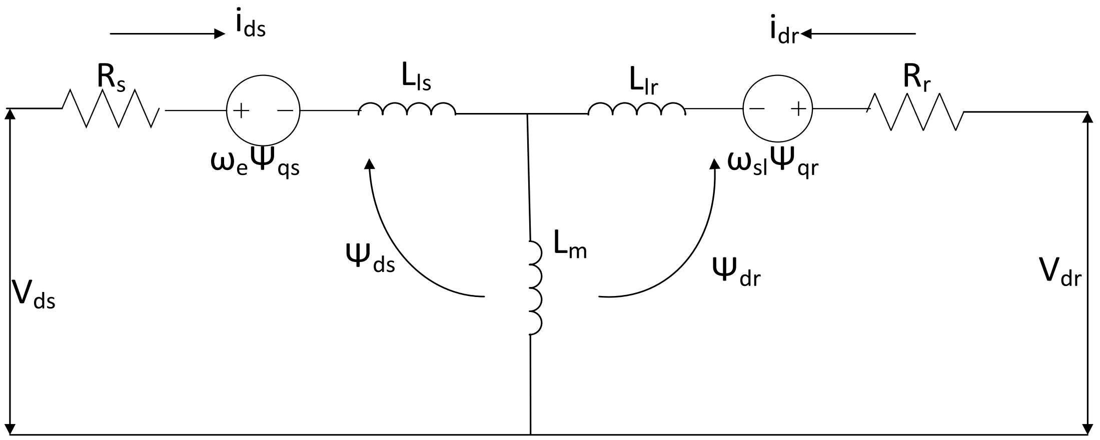


Figure 3.4(b) dynamic d^e- q^e equivalent circuit of motor (d^e axis)

The flux linkage equations can be in the form of voltage and current as given below:

$$\Psi_{qs} = i_{qs}L_{ls} + L_m\left(i_{qs} + i_{qr}\right) = L_s i_{qs} + L_m i_{qr} \tag{3.14}$$

$$\Psi_{qr} = i_{qr}L_{lr} + L_m\left(i_{qs} + i_{qr}\right) = L_r i_{qr} + L_m i_{qs} \tag{3.15}$$

$$\Psi_{qm} = L_m\left(i_{qs} + i_{qr}\right) \tag{3.16}$$

$$\Psi_{ds} = i_{ds}L_{ls} + L_m(i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr} \tag{3.17}$$

$$\Psi_{dr} = i_{dr}L_{lr} + L_m(i_{ds} + i_{dr}) = L_r i_{dr} + L_m i_{ds} \tag{3.18}$$

$$\Psi_{dm} = L_m(i_{ds} + i_{dr}) \tag{3.19}$$

From above equations:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + sL_s & \omega_e L_s & sL_m & \omega_e L_m \\ -\omega_e L_s & R_s + sL_s & -\omega_e L_m & sL_m \\ sL_m & (\omega_e - \omega_r)L_m & R_r + sL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & sL_m & -(\omega_e - \omega_r)L_r & R_r + sL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{3.20}$$

$L_{ls,}L_{lr}$ – Stator and rotor leakage inductance

$L_{s,}L_r$ – Stator and rotor inductance

L_m – Mutual inductance

Ψ_{dm}, Ψ_{qm} – Magnetizing flux linkage

The electromagnetic torque T_e is determined as:

$$T_e - T_L = J\frac{d\omega_m}{dt} \tag{3.21}$$

In case of electrical speed (ω_r), the above equation can be written as:

$$T_e - T_L = \frac{2}{P} J \frac{d\omega_r}{dt} \qquad (3.22)$$

T_L – Load torque

ω_m – Mechanical speed of the rotor

J – Inertia of the machine

P – Number of poles of machine

The developed torque T_e due to the interaction of air gap flux (Ψ_m) and the rotor MMF that is dependent on the rotor current (I_r) is expressed in the form of vector:

$$T_e = \frac{3}{2}\frac{P}{2}\bar{\Psi}_m \times \bar{I}_r \qquad (3.23)$$

The variables can be revolved in $d^e - q^e$ frame, according to figure 3.5 shows the synchronously rotating frame:

$$T_e = \frac{3}{2}\frac{P}{2}\left(\Psi_{dm} i_{qr} - \Psi_{qm} i_{dr}\right) \qquad (3.24)$$

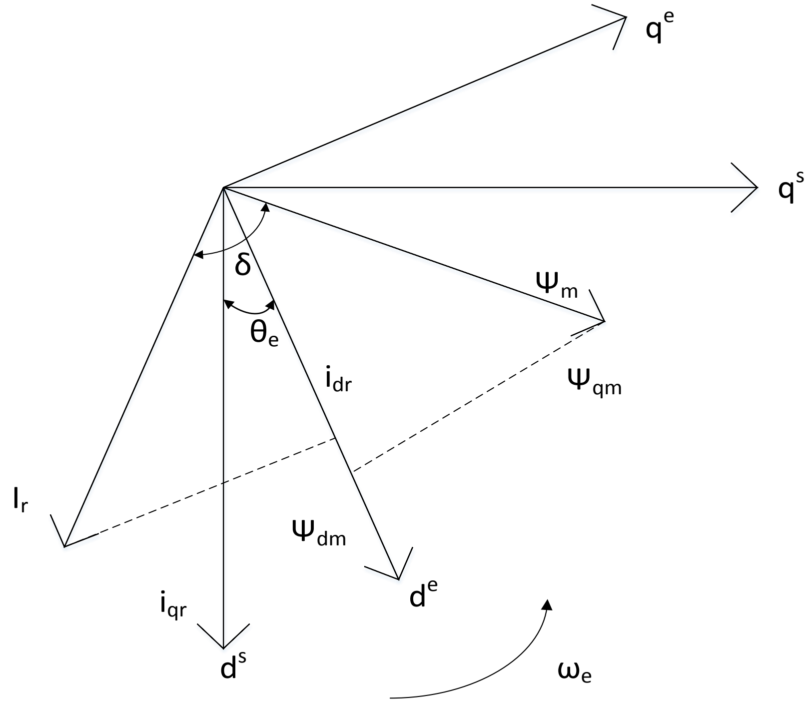


Figure 3.5 synchronously rotating reference frame

Similarly, other torque equations be derived as shown below:

$$T_e = \frac{3}{2}\frac{P}{2}\left(\Psi_{dm} i_{qs} - \Psi_{qm} i_{ds}\right) \tag{3.25}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}\right) \tag{3.26}$$

$$T_e = \frac{3}{2}\frac{P}{2} L_m\left(i_{qs} i_{dr} - i_{ds} i_{qr}\right) \tag{3.27}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\Psi_{dr} i_{qr} - \Psi_{qr} i_{dr}\right) \tag{3.28}$$

3.3 Vector Control of Induction Motor

Induction machines in comparison to other machines are simpler and easy to implement but because of the inherent coupling effect in its characteristics, it produces sluggish response in its performance. In a Vector control of Induction motor, the magnetizing component as well as the torque generating current component of stator are decoupled exactly in the same fashion like a separately excited dc motor. In vector control, the three phase stationary frame (a-b-c) is transformed in two phase stationary frame ($d^s - q^s$) and further to two phase rotating reference frame$(d^e - q^e)$. To know the exact location and angle of the continuously rotating rotor flux, hall sensors are directly employed in the direct vector control. On the other hand, indirect vector control is more economical and reliable which gives the exact position and angle of the rotor flux from the motor parameters. In indirect vector control technique, a slip frequency command (ω_{sl}^*) is necessary for the orthogonal type control of torque-generating and magnetizing component of the currents. The calculation requires the value of rotor circuit time constant. The variation of rotor time constant due to saturation of rotor flux, increasing temperature etc., affects the accuracy of the torque and speed performance both in steady state and transient state [45] to a greater extent.

Vector control is not only applicable to induction motor but it is extended for synchronous machine drives also. In modern sensor less drive system, vector control is implemented with feedback signal which is complex so the use of modern digital signal processors (DSP) and microcomputers are essential. Vector control has almost discarded the use of scalar control in various industrial application.

3.3.1 Indirect Vector Control

The two methods of vector control or field oriented control are the direct or feed-back method and the feed forward control or indirect method. The feed-back or direct method was proposed by **Blaschke** [1] and on the other hand the indirect or feed forward method by **Hasse** [2]**.** The method of knowing the position of rotor flux or simply the method of determining the rotor angle distinguishes both the methods. In direct method, the angle is calculated by the terminal voltages and currents and also from search coils and Hall effect devices induced into the air gap of the machine and on the other hand, in indirect FOC, the same angle is obtained by machine's parameter estimation and by using rotor position measurement.

The dynamic performance of current source or voltage source inverters supplying induction motors or supplying synchronous motors can be compared to that of a four quadrant converter fed dc drives. The orientation of field is a very powerful and an important tool for controlling such type of AC machines. Although, FOC requires a very complex function to perform but a large number of intelligent controllers such as digital signal processor (DSP) and microcontrollers can execute the required complex function of FOC which also results in a great deal of minimization of control hardware [4,7].

Employing arrangements in the field oriented controller so that the motor parameters coincide with the true parameters of the motor, a satisfying control performance can be achieved. A new and a unique identification method utilizing injected negative sequence components was described by **Takayoshi** [4]**.** The leakage impedance, stator resistance as well as rotor resistance can be determined on line while the motor is driving the load. A full-scale hybrid simulation model in a MATLAB software of a field-oriented controlled PWM inverter based induction motor drive verified this theory. The gating pulses feeding the IGBT switches of an IGBT based inverter determines the performance of an induction motor and as a result, the output current produced by the inverter. For determining the pattern of the pulse, a hysteresis current control technique [5,9] can be applied. Load parameter is not essential and above all quick response current loop can be obtained by this method. Undesirable harmonic generation as well as variable switching frequency of the inverter is obtained by this method. A new Space vector current control technique for induction motor is proposed by **Ting–Yu et.al** [16] which shows better result and performance. The complicated, complex calculation and time varying coordinate transformation are eliminated. Moreover, even a simpler 8751 microprocessor can be employed for a high performance drive system. Also to reduce the switching frequency, the proposed space vector-based current controller also uses the extra information of error derivative. The conventional proportional plus integral control method is generally used to control the speed. But, in recent years, the technical advancement in control strategies has produced a number of efficient controllers. The use of H2 and H∞ control technique was proposed by **Yau-Tze et.al** [13] for implementation in vector control scheme. This particular scheme has shown a better disturbance rejection capability than the conventional PI and other controllers and, especially H∞ controller that resulted a better performance. Although, fixed gain controllers are very sensitive to load disturbances, parameter variations etc. The other techniques like fuzzy logic controller which involves the use of soft computing technique is also available. In many applications, fuzzy logic controllers are more advantageous in comparison to the conventional PI, PID and at some places to adaptive controllers also. **Gilberto et.al** [20] gave a fuzzy logic theory based on-line efficiency optimization control for an indirect vector controlled drive system whereas a fuzzy adaptive control scheme for vector controlled induction motor drive was proposed by **Emanuele** [29]**.**

Yi-Hwa Liu et.al [30] designed and implemented a new space vector based current regulated PWM inverter (SVPWM) with somewhat new switching tables and because of fully utilizing all the voltage vectors that are available, the harmonic contents in the current have been improved by the proposed switching table in the angular coordinate. Some new optimization techniques are also proposed in [42, 45].

Figure 3.6 shows the block diagram representing Indirect vector control. This method has find it place deeper in industries for its efficiency and performance. Indirect vector control also known as feed forward control mainly depends on the machine parameters such as stator and rotor resistance which gets changed with the change in temperature. Obviously, both the resistances can change upto approximately 80-100% of their actual values due to temperature change. Figure explains the phasor diagram of induction motor drive

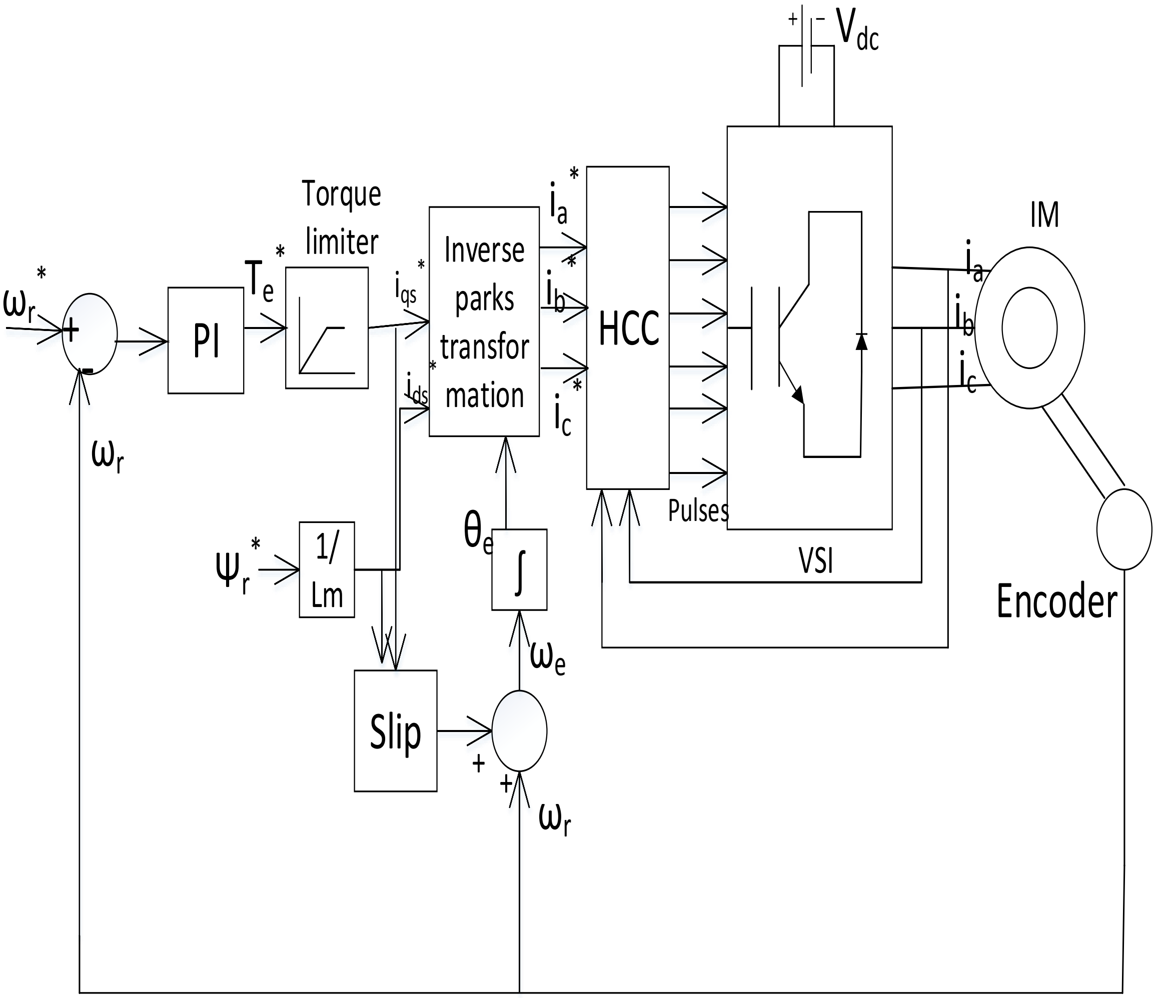


Figure 3.6: Block diagram representation of Indirect vector control

The $d^s - q^s$ and $d^r - q^r$ axes are fixed to the stator and the rotor terminals of the machine. Figure 3.7 shows the phasor representation of Indirect Vector Control scheme. The $d^r - q^r$ axes is fixed to the rotor which is constantly revolving at a speed of ω_r. And the synchronously rotating $d^e - q^e$ axes which is moving ahead of the rotor flux with slip angle θ_{sl} from the $d^r - q^r$ axes.[2]

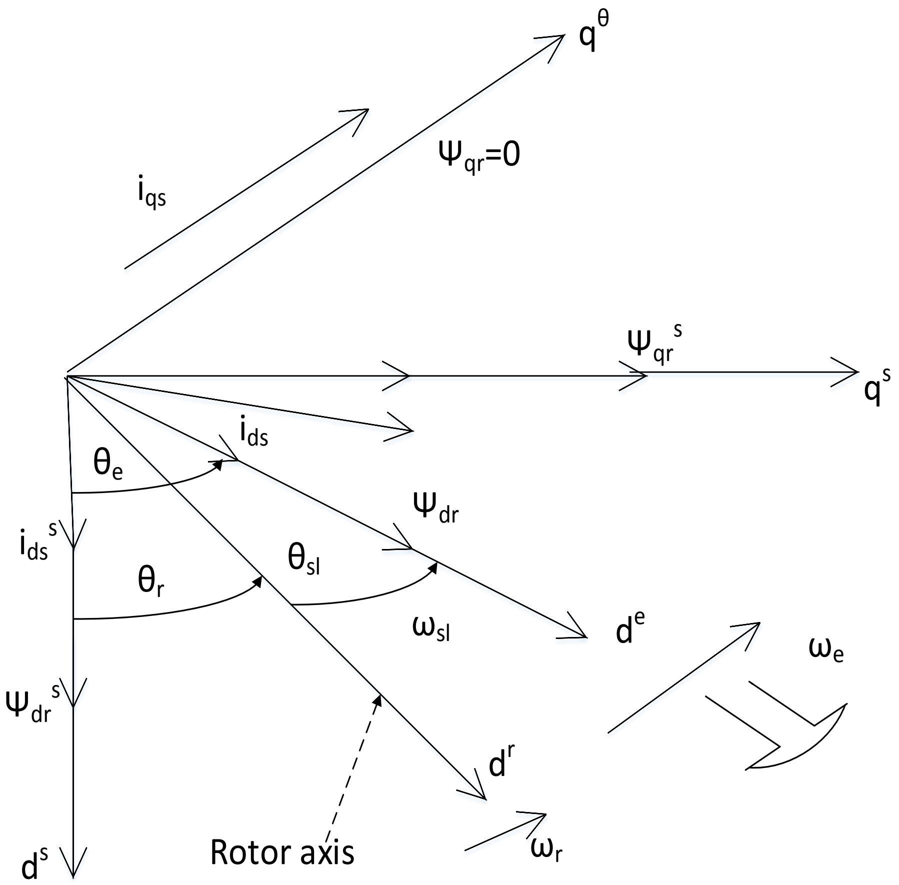


Figure 3.7, Phasor representation of Indirect Vector Control

When the rotor pole is directed towards the d^{e} axes and then ω_e will be:

$$\omega_e = \omega_r + \omega_{sl} \tag{3.29}$$

Where,

ω_{sl} = Slip speed of the rotor

We write equation:

$$\theta_e = \int \omega_e dt = \int (\omega_r + \omega_{sl}) dt = (\theta_r + \theta_{sl}) \tag{3.30}$$

The control equations will be implemented for indirect control scheme by the decoupling the circuit with the help of $d^e - q^e$ equivalent circuit and the equations for rotor will be as given below:

$$\frac{d\Psi_{dr}}{dt} + R_r i_{dr} - (\omega_e - \omega_r)\Psi_{qr} = 0 \tag{3.31}$$

$$\frac{d\Psi_{qr}}{dt} + R_r i_{qr} + (\omega_e - \omega_r)\Psi_{dr} = 0 \tag{3.32}$$

The flux equations for the rotor are as given below:

$$\Psi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{3.33}$$

$$\Psi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{3.34}$$

The current equations can be evaluated by arranging the above equations:

$$i_{dr} = \frac{1}{L_r}\Psi_{dr} - \frac{L_m}{L_r} i_{ds} \tag{3.35}$$

$$i_{qr} = \frac{1}{L_r}\Psi_{qr} - \frac{L_m}{L_r} i_{qs} \tag{3.36}$$

Rotor currents component can be eliminated from the equations 3.31 and 3.32 while substituting the values of the equation 3.35 and 3.36 in equation 3.31 and 3.32 which is shown as follows:

$$\frac{d\Psi_{dr}}{dt} + \frac{R_r}{L_r}\Psi_{dr} - \frac{L_m}{L_r} R_r i_{ds} - \omega_{sl}\Psi_{qr} = 0 \tag{3.37}$$

$$\frac{d\Psi_{qr}}{dt} + \frac{R_r}{L_r}\Psi_{qr} - \frac{L_m}{L_r} R_r i_{qs} - \omega_{sl}\Psi_{dr} = 0 \tag{3.38}$$

Where $\omega_{sl} = \omega_e - \omega_r$ (3.39)

For decoupling control these conditions should be fulfilled:

$\Psi_{qr} = 0$, And

$$\frac{d\Psi_{qr}}{dt} = 0$$

while substituting the above conditions we will get:

$$\frac{L_r}{R_r}\frac{\widehat{d\Psi}_r}{dt} + \widehat{\Psi}_r = L_m i_{ds} \tag{3.40}$$

$$\omega_{sl} = \frac{L_m R_r}{L_r \hat{\Psi}_r} i_{qs} \tag{3.41}$$

$$\widehat{\Psi}_r = \Psi_{dr}$$

$$\widehat{\Psi}_r = L_m i_{ds} \tag{3.42}$$

Where,

$\widehat{\Psi}_r$ = Estimated rotor flux

In steady state condition the current i_{ds} will be directly proportional to the rotor flux $\widehat{\Psi}_r$

3.3.2 Direct vector control

Blaschke [1] firstly, proposed the theory of direct vector control, which is also termed as feedback vector control scheme. Directly using flux estimators obtained from the terminal voltages and currents, the method of rotor angle or control vector is obtained in direct vector control. For enhancing the performance of the drive some other various controllers have also been designed and implemented on direct vector control scheme.

Although, this method is the most favourable control scheme, but it suffers from few drawbacks like unreliability of the flux measurement as well as high cost. On the other hand, the indirect method can level the performance of the direct control measurement scheme, but the major drawback or weakness of this particular scheme, is based upon the accuracy of the control gains which indirectly depends heavily upon the machine parameters assumed in the feed forward control algorithm [4].

In this control method, the values of synchronously rotating reference frame will be transformed into a stationary frame with the help of unit vectors (θ_e) as a vector rotation (VR), generated through the flux signals Ψ^s_{dr} and Ψ^s_{qr}.These stationary frame signals is than applied to the input side of the inverter. Figure 3.8 shows the block diagram representation of direct vector control. The voltage and current signals from the machine terminals will be used for the voltage model of the estimator or to the flux estimator model to generate the flux signals Ψ^s_{dr} and Ψ^s_{qr}.

The current i_{ds} is properly aligned with the direction of rotor flux $\overline{\Psi_r}$. The quadrature axes current i_{qs} is orthogonally (or perpendicularly) apart from the rotor flux $\overline{\Psi_r}$. With the help of phasor diagram figure 3.9 fluxes are explained, and the rotating reference frame $d^e - q^e$ is moving at the speed $'\omega_e'$ w.r.t the stationary axes $d^s - q^s$. The angle between the d^e-axis and the d^s-axis is θ_e and hence we can write the following equations.

$$\Psi^s_{dr} = \overline{\Psi_r} \cos \theta_e \tag{3.43}$$

$$\Psi^s_{qr} = \overline{\Psi_r} \sin \theta_e \tag{3.44}$$

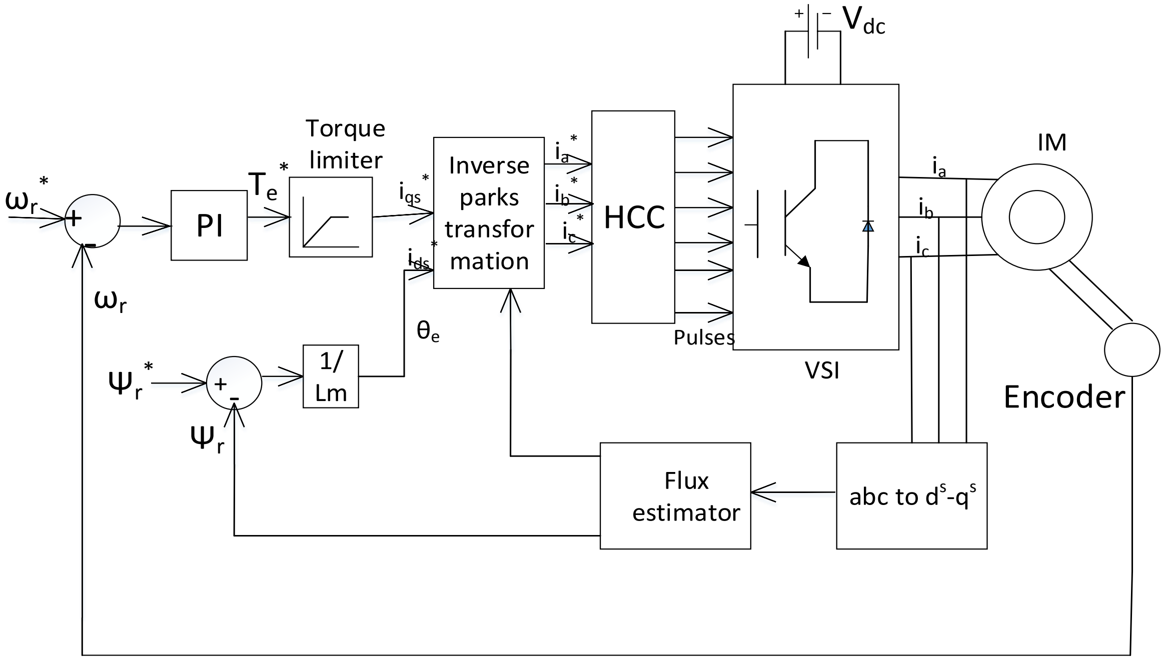


Figure 3.8, Block diagram representation of Direct Vector Control

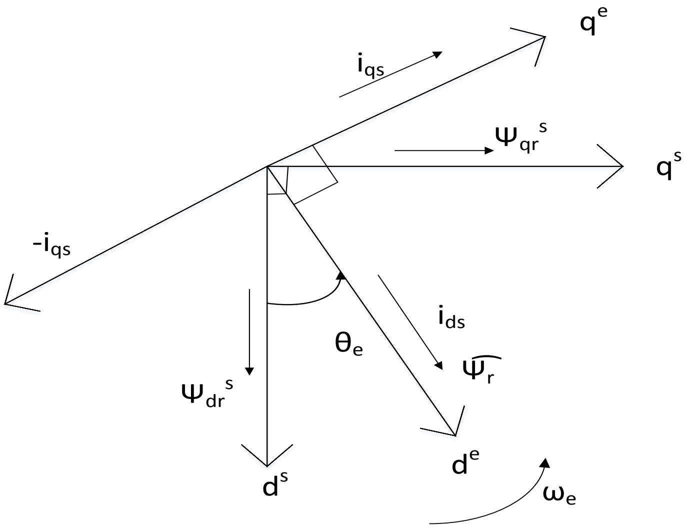


Figure 3.9, Phasor diagram of Direct vector control

$$cos\ \theta_e = \frac{\Psi^s_{dr}}{\widehat{\Psi_r}} \tag{3.45}$$

$$sin\ \theta_e = \frac{\Psi^s_{qr}}{\widehat{\Psi_r}} \tag{3.46}$$

$$\widehat{\Psi_r} = \sqrt{{\Psi^s_{dr}}^2 + {\Psi^s_{qr}}^2} \tag{3.47}$$

- For very low frequencies, V^s_{ds} and V^s_{qs} voltage signals are very low
- The dynamic behavior of the machine gets affected due to variation in machine parameters which results in the reduction of the accuracy of the system. Increase in temperature has a dominant effect on the machine parameters. But in case of higher voltage values the parameter variations of machine [2] can be neglected.

3.3.3 Direct Torque Control

Takahashi and Toshihiko Noguchi proposed a control technique termed DTC or direct torque control in an IEEE paper presented in September 1984 and in an IEEE paper published in late 1986 [7]. In this method, motor's magnetic flux and torque is estimated by the calculation based on measured voltage and current of the motor which is used to control the speed of the motor. Limit cycle control of both torque and flux is achieved, by using an optimum PWM output voltage and also to attain a fast torque response, low inverter switching frequency and low harmonic losses, a switching table is employed for selecting the optimum inverter output voltage vectors. In the steady state operation, the efficiency optimization is also considered which can be attained by controlling the amplitude of the flux in accordance with the torque command **Isao Takahashi** in 1989 [8] proposed another DTC control scheme, which has better performance. In the system, instantaneous values of the torque as well as of the flux are calculated from primary variables and they are controlled independently by using an optimum switching table. Hence, apart from achieving fastest torque response it also has lowest acoustic noise and harmonic losses.

In the year 1995, **Marian** [22] showed that by the injection of an additional carrier signal to the torque controller input, performance is improved at the starting and robust operation at low speed region can be achieved. Also, no current regulation loops, no separate voltage modulation block, no coordinate transformation and no voltage coupling network is required. For a variable speed control of an open-end induction motor drive **Chintan et.al** [64] proposed a torque control scheme, based on a direct torque control (DTC) algorithm using a 12-sided polygonal voltage space vector. Among the 12 vectors, the proposed DTC scheme selects eight switching vectors based on the sector information of the estimated fundamental stator voltage vector and its relative position with respect to the stator flux. The exact positions of the fundamental stator voltage vector and stator flux vector is utilized by the proposed scheme to select the optimal switching vector for fast control of torque with small variation of stator flux within the hysteresis band. The full load torque control with fast transient response to very low speeds of operation is achieved and the switching frequency has also decreased with the present DTC scheme.

3.3.4 Sensor less Vector Control

As name suggests, in sensor less vector control speed sensors are absent. A speed encoder enhances the reliability problems as well as the cost. The speed of the motor can be estimated from the machine terminal voltages and currents. Although, sensor less vector control increases the computational complexity, but with the help of various other available estimation algorithms, reliability can be achieved. As its name implies, speed sensor less estimation is the method of determining the speed signal from an Induction motor without using the rotational sensors in the rotor. The dynamic equations of an IM are used to calculate the component of rotor speed for various control purposes. The calculation is carried out by using the terminal voltages and currents which are easily available using sensors. Hence, sensor less vector control induction motor drive essentially means vector control without using any speed sensors. Usually an optical type incremental shaft mounted speed encoder is required for closed loop speed or position control in both scalar controlled and vector controlled drives. A speed signal is also required in direct vector control for the low speed range, including the zero speed startup operation and in indirect vector control in the wide operating range of the speed. Without using the mechanical speed sensors at the shaft of the controlled induction motor, drives have found their application where low cost high reliability is required. Speed sensors cannot be mounted where the drives are operating in extremely high speed and in hostile environment. To replace the sensors, at the motor terminals, the information on the rotor speed is taken out from already measured stator voltages and currents. The schematic diagram for the control strategy of an induction motor with sensor less control is shown in Fig 3.9. The inherent coupling of an IM is eliminated by vector control method, very much identical to the case of a separately excited dc motor. Switching pulses for the control of the motor is obtained from the inverter. The speed and flux estimators are used to calculate the speed and flux respectively. Both these signals are then compared with reference signals and finally with the help of PI controllee it is controlled.

Tsugutoshi [12] gave a theory on Vector control scheme whichis based on a rotor flux speed control, which involves rotor flux and torque producing current, calculated from the stator current and voltage. A lag circuit is employed In the proposed rotor-flux estimator, to which both rotor flux command and motor induced voltage are imposed, and as a result, it is possible to calculate even a very low frequency down to stand still. Figure 3.10 shows the block diagram representation of Sensor less vector control drive.

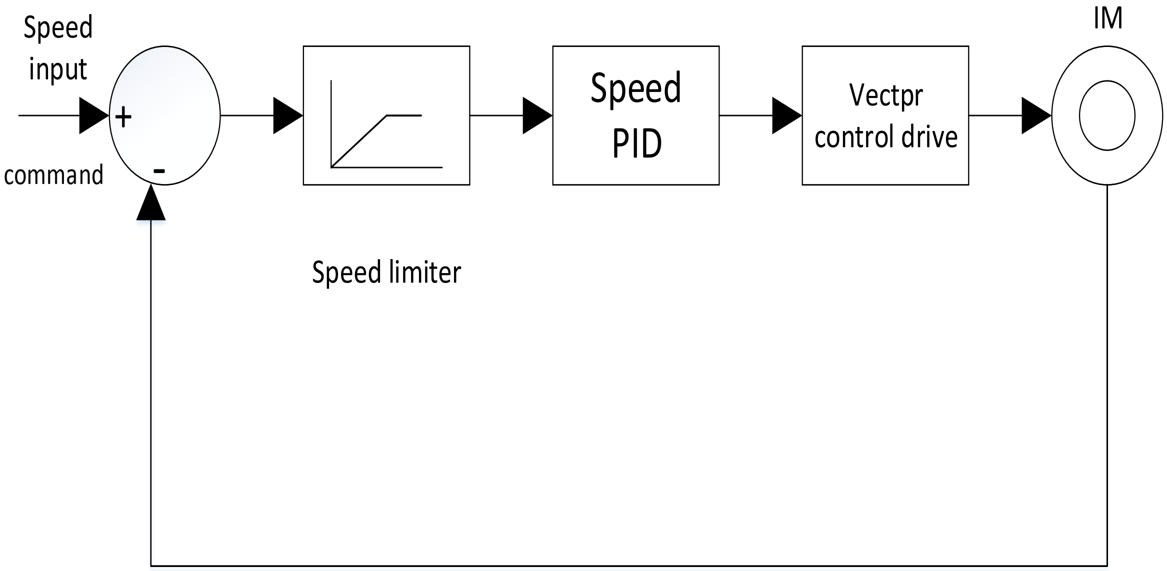


Figure 3.10: Sensor less vector control drive

Voltages and currents are obtained from machine terminals whereas flux estimator estimates the d-q rotor flux. From the d-q axes flux components the rotor flux Ψ_r will become:

$$\Psi_r = \sqrt{(\Psi^s_{qr})^2 + (\Psi^s_{qr})^2} \qquad (3.48)$$

And for the estimating speed the speed estimator 'ω_r' will be:

$$\omega_r = \frac{1}{\Psi_r^2}\left(\left[\Psi^s_{dr}\Psi'^s_{qr} - \Psi^s_{qr}\Psi'^s_{dr}\right] - \frac{L_m R_r}{L_r}\left[\Psi^s_{dr} i^s_{qs} - \Psi^s_{qr} i^s_{ds}\right]\right) \qquad (3.49)$$

Where Ψ'^s_{qr} and Ψ'^s_{dr} quantities are the first derivatives of Ψ^s_{qr} and Ψ^s_{dr}

3.4 MATLAB model and simulations

3.4.1 MATLAB model of Indirect Vector Control

A Simulink model of the Vector Control is developed using components from the MATLAB Simulink Power Systems Block set. It contain models for the various power electronics devices and for the control elements of vector control drive also. The control scheme simulated is in discrete time form and the blocks used the designing are already available in the Simulink library. Figure 3.11 and 3.12 shows the MATLAB simulation of voltage source inverter and Vector control of Induction motor respectively.

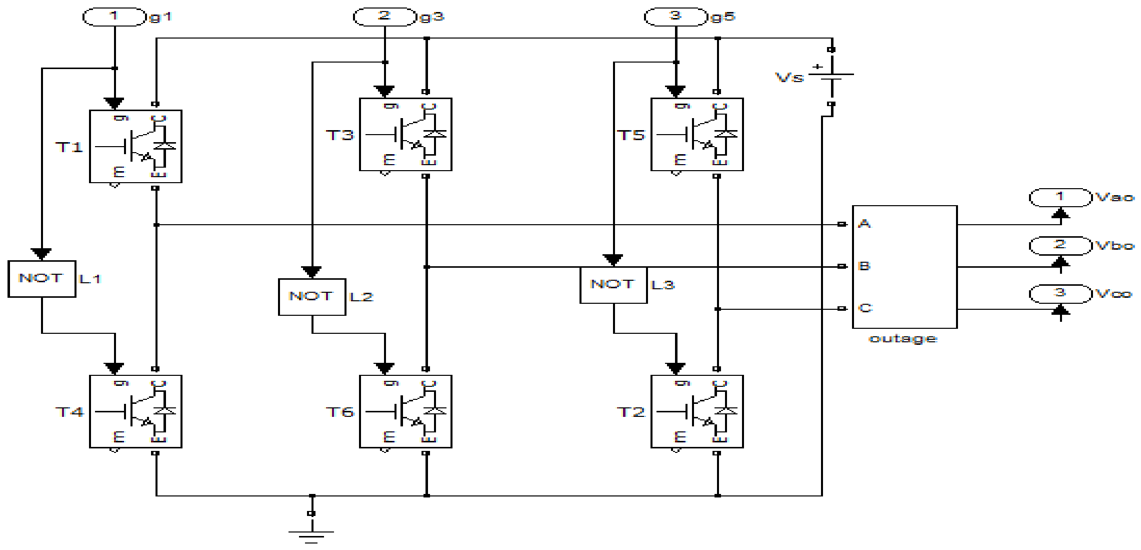


Figure 3.11 MATLAB model of voltage source inverter

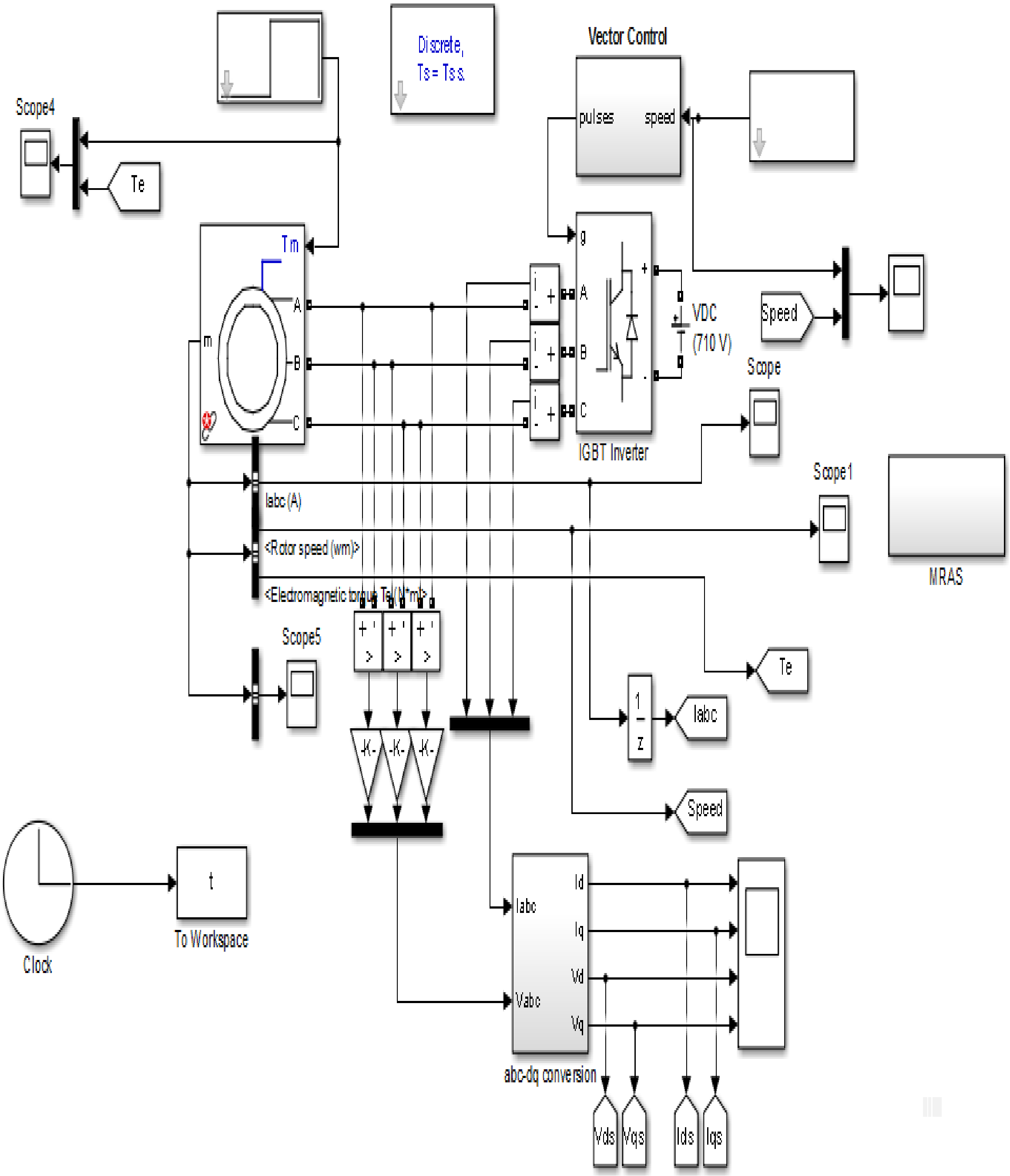


Fig 3.12 MATLAB Simulink model of vector control of Induction motor

3.4.2 Simulation Results

A Vector control scheme with indirect vector control is implemented in MATLAB Simulink for a 5.4 HP, 50 hz, 400V induction motor. Hysteresis current controller is designed to analyze the dynamic performance of the machine in indirect vector control. Induction motor is started with the speed of 100 rad/sec. The starting stator current I_{abc} (A) drawn by the motor is abruptly high and as a result motor starts with high starting torque. The load torque is kept zero from t=0sec to t=0.35sec after that the load torque is changed to 7N-m and with that the stator current again increases but lesser than the starting current. The speed of induction motor is changed to 100 rad/sec to -100 rad/sec at t=1sec with the reversal in speed, the phase of the stator current gets reversed during this interval and after that when the phase reversal of current is completed the speed reversal attains its set value.

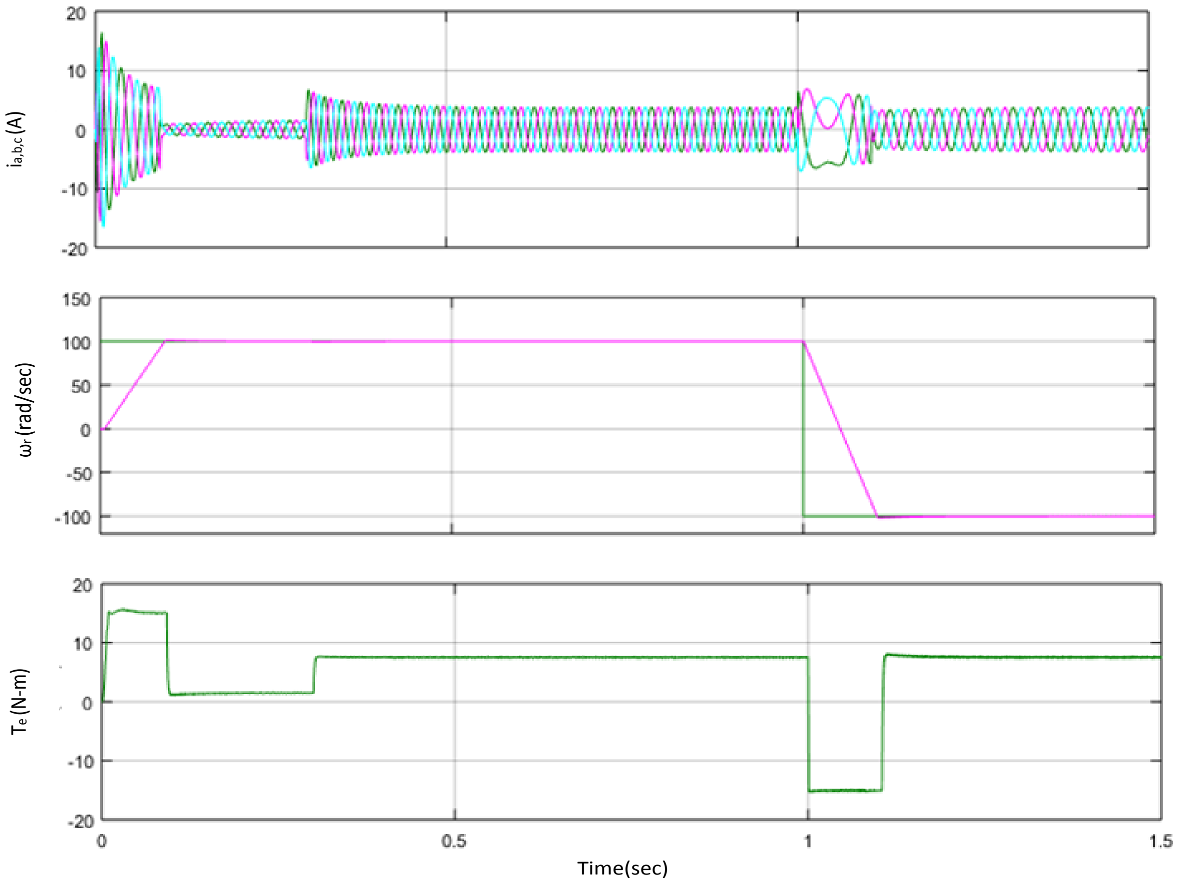


Figure 3.13: Dynamic response of Indirect vector control of induction motor on Stator current I_{abc} [A], Rotor Speed ω_r [rad/s] and Torque [N/m]

3.5 Conclusion

In this chapter, the dynamic performance of the induction motor has been thoroughly discussed and all the time varying inductances that are present in various equations of torque and voltages have been eliminated by analyzing the model in the synchronously rotating reference frame. A MATLAB model for Vector control of Induction Motor is described in this chapter.

CHAPTER IV

ROTOR RESISTANCE ESTIMATION OF INDUCTION MOTOR USING MRAS TECHNIQUE

4.1 General

Model reference adaptive system (MRAS) deals with the problems associated with the parameter variations e.g., temperature variations, disturbances, etc. An adaptive controller is basically designed for the problems associated to varying parameters and are neutralized in such a way that they try to eliminate the uncertainties and the parameter variations of the plant. The adaptive controllers have found their use from last few decades only and this time dependent controller provides robustness and a great extent of stability in various control techniques.

4.2 MRAS Controller

In rotor resistance (*R*r) estimation scheme of model reference adaptive controller (MRAC), the basic concept which is common in every MRAC technique is that one quantity is produced in two different ways. One of them depends on *R*r whereas the other one is independent on *R*r. The two quantities that are calculated separately are further used to produce the error signal. The error signal is then fed as an input to an adaptation mechanism, which is predominantly a PI-controller. The output of the adaptation mechanism is the estimated quantity. Depending upon the quantity (reactive power in this case) used for the production of the error signal, various kinds of MRAC are available, e.g., electromagnetic torque based [40], rotor flux based [41], outer product of stator current and back EMF based [42], reactive power based [43]–[45], etc. Among them, the reactive power-based method is the most popular method because of the fact that it is independent of stator resistance.

The theory of the Model Reference Adaptive System (MRAS) states that, it makes sure that the plant should follow the response of a reference model whenever there is disturbance and variation in the plant parameter. The output error from the two models i.e. the reference model and the adjustable model is directly fed to the adaptation control mechanism and as a result, controller updates the error every single time till the parameters converges to the ideal plant values in order to obtain the similar response as of the reference model as shown in figure 4.1. The system dynamics are nonlinear in nature and they are linearized by obtaining the linear controller. The resultant linear model and parameters varies in accordance with the operating conditions applied, parameters can be varied with ageing, changes in the loading conditions and disturbances.

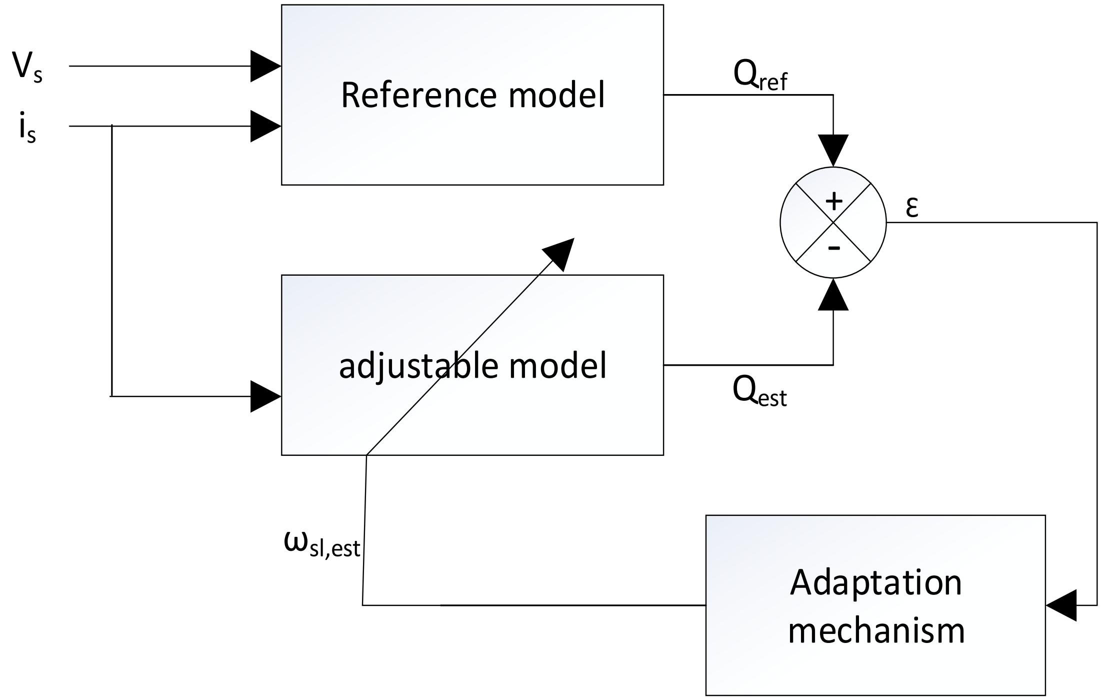


Figure 4.1 model reference adaptive system

In this paper, the performance capability of a new modified reactive power based MRAC which is a more stable version than the basic MRAC discussed above, is studied in detail for the calculation of rotor resistance. The modified MRAC also is presented in such a way that rotor flux estimation is not necessary. It is important to note that [35] and [36] have thoroughly reviewed such MRAC-based schemes; however, a detailed study including sensitivity and stability analysis were not available in those papers. Most of the MRAC-based systems [43]–[45] requires the necessity of flux estimation. As a result, they suffer from integrator-related problems at very low speed and achieve less accuracy in estimation. The most eye catching property of the MRAS presented in this thesis is, that steady state reactive power is used in the adjustable model whereas, the instantaneous reactive power is used in the reference model.

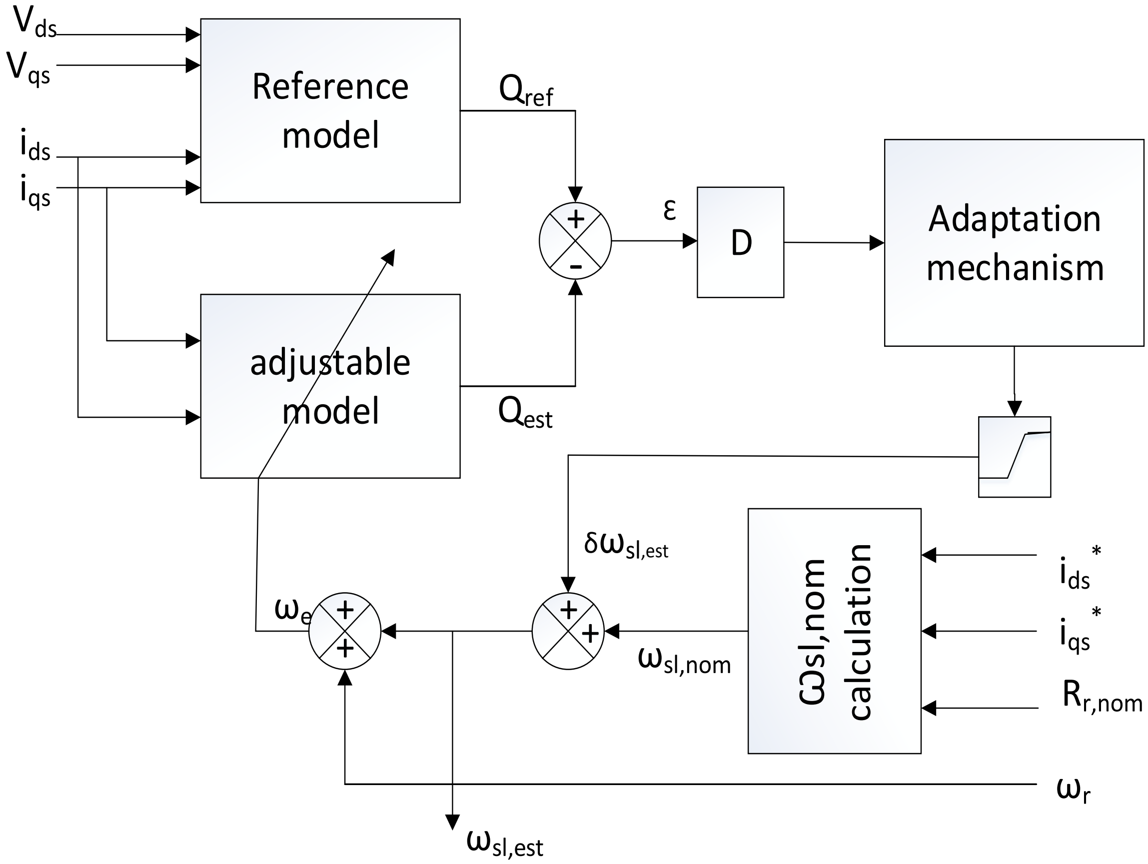


Fig. 4.2 Modified structure of MRAC

The two different methods for model reference adaptive system controller are direct vector control and indirect vector control. Only the reference model is used in the controller of the direct vector control technique and their parameters are adjusted to diminish the error (output) of the plant but in indirect vector control technique the unknown parameters of the plant are calculated from the adjustable model and the reference model both. In MRAS controller, the reference model is reactive power based and this has the advantages of removing pure integrators and also are very less sensitive to the variations of parameter.

4.2.1 MRAS in control applications

The speed of the induction motor drive is extracted from the rotor speed assuming it as an unknown quantity in the adaptive controller. The rotor resistance of the machine is also calculated by taking the rotor time constant as an unknown quantity. Both the models depends upon on different parameters of the motor and finally, the error coming out from both the models is fed to an adaptive controller. Some of the advantages of MRAS technique are:

1. The implementation of the model is simple and easy.
2. This technique has a potential to change the dynamic characteristics of the plant (say if it is poor) into a high performance drive. .
3. Technique gives flexibility and it is also reliable in achieving the required goals.

4.2.2 Stability of the MRAS estimator

The state error equations of the MRAS technique are assured to be asymptotically stable. The adaptation mechanism is derived below from the state error equations, which are produced by subtracting the adjustable model equations from the reference model equations.

Let

$$\varepsilon = Q_{ref} - Q_{est} \tag{4.1}$$

$$v_{ds} = R_s i_{ds} + \sigma L_s i_{ds} \dot{+} \frac{L_m}{L_r} \frac{d\Psi_{dr}}{dt} - \sigma L_s \omega_e i_{qs} - \omega_e \frac{L_m}{L_r} \Psi_{qr} \tag{4.2}$$

$$v_{qs} = R_s i_{qs} + \sigma L_s i_{ds} \dot{+} \frac{L_m}{L_r} \frac{d\Psi_{dr}}{dt} - \sigma L_s \omega_e i_{ds} - \omega_e \frac{L_m}{L_r} \Psi_{dr} \tag{4.3}$$

The instantaneous reactive power expressed as:

$$Q_1 = (v_{qs}\, i_{ds} - v_{ds}\, i_{qs}) \tag{4.4}$$

Substituting (4.2) and (4.3) in (4.4), the new expression of Q is

$$Q_2 = \sigma L_s\left(\dot{i}_{qs} i_{ds} - \dot{i}_{ds} i_{qs}\right) + \sigma L_s \omega_e\left(i_{ds}^2 + i_{qs}^2\right) - \frac{L_m}{L_r}\left(\dot{\Psi}_{dr} i_{qs} - \dot{\Psi}_{qr} i_{ds}\right) + \omega_e \frac{L_m}{L_r}\left(\Psi_{qr} i_{qs} + \Psi_{dr} i_{ds}\right) \quad (4.5)$$

In steady state condition the derivative terms will be zero, so the expression of Q is

$$Q_3 = \sigma L_s \omega_e\left(i_{ds}^2 + i_{qs}^2\right) + \omega_e \frac{L_m}{L_r}\left(\Psi_{qr} i_{qs} + \Psi_{dr} i_{ds}\right) \quad (4.6)$$

Substituting the condition $\Psi_{dr} = L_m i_{ds}$ and $\Psi_{qr} = 0$ for the indirect vector control induction motor drive. In equation 4.6, the more simplified expression of Q will be:

$$Q_4 = \sigma L_s \omega_e\left(i_{ds}^2 + i_{qs}^2\right) + \omega_e \frac{L_m^2}{L_r}\left(i_{ds}^2\right) \quad (4.7)$$

$$R_r^* = \omega_{sl}^* \frac{3P}{4} {\Psi_r^*}^2 \quad (4.8)$$

The Proportional plus Integral controller is used in adaptive mechanism for the estimation of rotor time constant.

$$\beta_r = (K_p + K_i/p).\varepsilon \quad (4.9)$$

$Q_1 = Q_{ref}$ = Actual reactive power

$Q_4 = Q_{est}$ = Estimated reactive power

β_r= Output of the Adaptive mechanism

K_p= Proportional controller

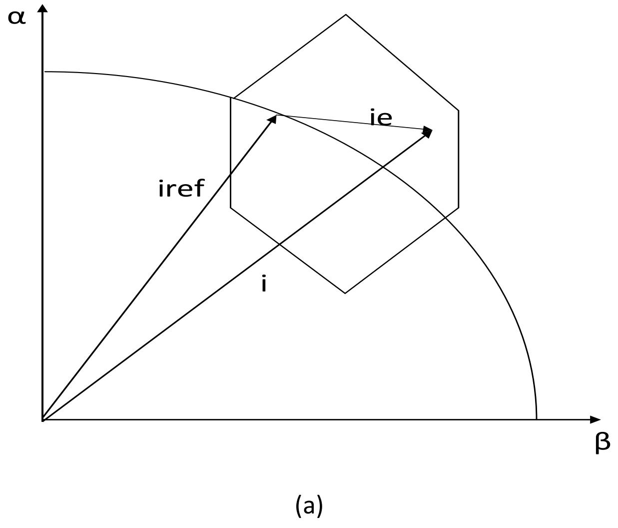
K_I= Integral controller

And Ψ_r^*= Estimated flux linkage

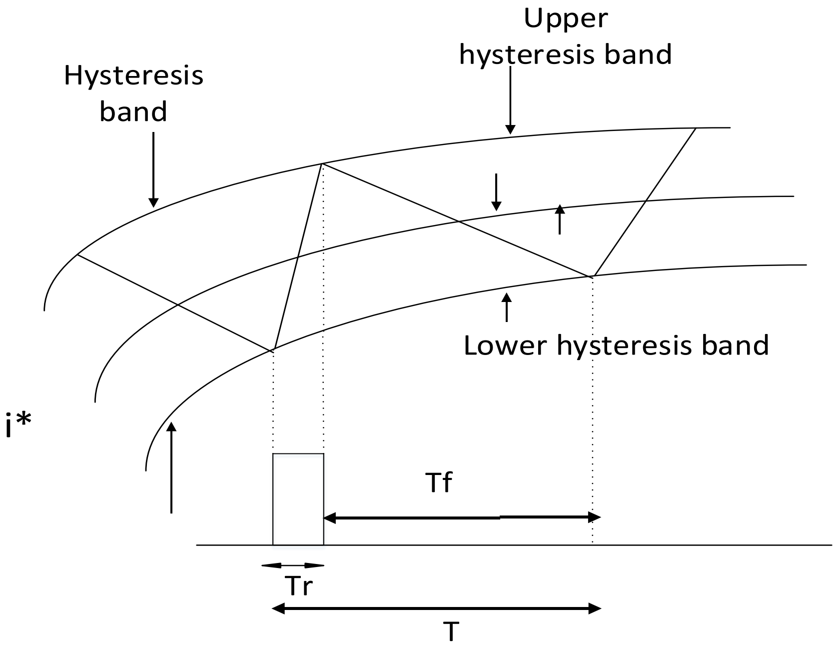
4.3 Hysteresis Current Controller

The hysteresis current controller technique is extensively used method and is easy to implement. In this method, hysteresis comparators are used to superimpose a hysteresis or fixed dead band around the reference current. The most basic principle of hysteresis current control is based on the fact that the switching signals are derived from the comparison of the error of the current with a fixed tolerance band. When the magnitude of the current is more than the tolerance band, the switching pattern of the inverter changes. This type of control is negatively affected by the interactions of phase currents which is in three-phase systems. The current control of PWM-VSI has been implemented in the stationary (α, β) reference frame.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{4.10}$$



(a)



(b)

Figure 4.3(a),(b): Principle of hysteresis-band current control

The main task is to maintain the actual values of the current within the hysteresis band throughout the process. The three currents are not completely independent from each other, and hence, the system will be transformed further into (α, β) coordinate system. Now, the transformation of three phase coordinate into two phase (α, β) coordinate system in the hysteresis band results in a hysteresis hexagonal area. In this, the reference current 'I_{ref}' is directed towards the mean point of the hysteresis as shown in in figure 4.3(a). In steady state condition, the reference current moves on a circular path around the origin of the (α, β) coordinate system. Therefore, the hexagon also moves on this circle.

4.4 Proportional plus Integral controller

The PI (proportional plus integral) controller is the most often used controller in practical and industrial applications. The PI controller can be made from an existing PID (proportional plus integral plus derivative) controller with the D-term (i.e. derivative) inactivated. Most of the time, the D-term is kept deactivated because it causes abrupt variations in the control signal and amplifies random high frequent measurement noise. The schematic diagram of proportional and integral controller is shown in figure 4.4. The continuous-time PI controller function is as follows:

PI output, $e_o = K_P e(t) + \frac{K_I}{T_I} \int e(t)\,dt$ (4.11)

Where,

$e(t)$ = (reference speed – estimated speed)

K_p = Proportional control gain

K_p = Integral control gain

ω_{ref} = Reference speed

ω_{est} = Estimated speed

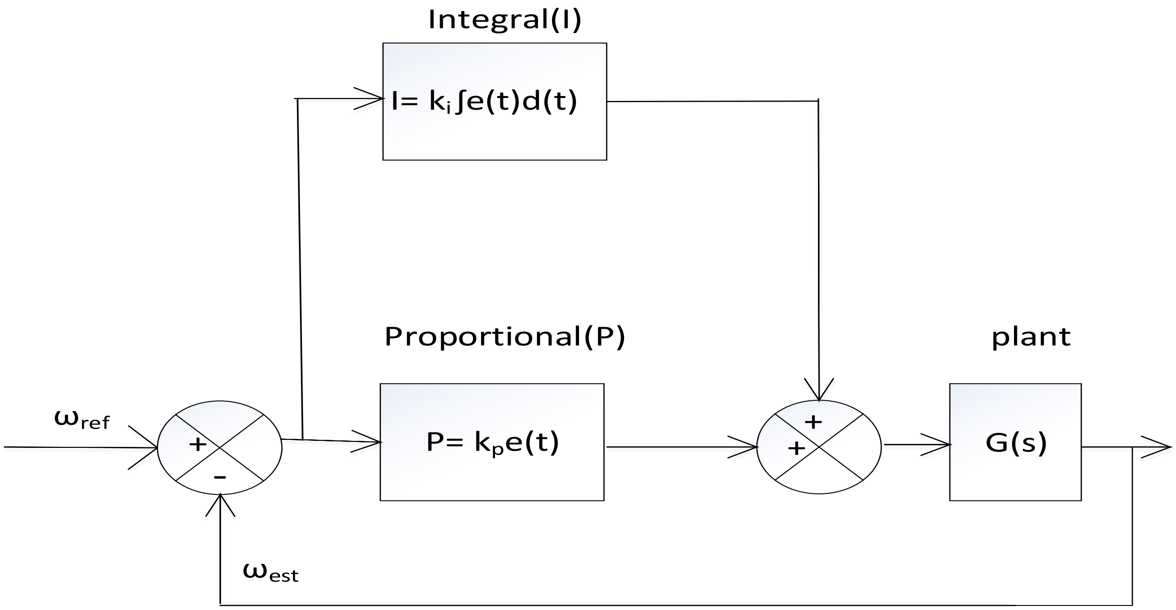


Figure 4.4 Proportional and integral controller

PI controller is also termed as feedback controller. Apart from various advantages proportional controller suffers from a major drawback. It produces an offset error and to eliminate this offset, the integral controller is used but makes the overall response bit of sluggish. The output of the PI speed controller produces the electromagnetic torque, which is then further used for calculating the command stator current i_{qs}^{*}. For the constant rotor flux and torque values, the stator quadrature current i_{qs}^{*} is also constant. Also the stator direct current i_{ds}^{*}component should be constant and as a result, the magnitude of the stator current should be constant. Error signal $(i_{qs}^{*} - i_{qs})$ and $(i_{ds}^{*} - i_{ds})$ serves as the inputs to the PI controller and there outputs are v_{q}^{*} and v_{d}^{*} [50].

4.5 Conclusion

This chapter present the detailed idea of different controlling techniques of an induction machine and different methods for rotor resistance estimation also. It concludes that vector control assures a good dynamic performance in comparison to a scalar control. The stability of the MRAS control technique is discussed here. This technique is implemented in the MATLAB simulink.

CHAPTER V

SIMULATION RESULTS & DISCUSSIONS

5.1 General

Simulation study of a Vector control Induction motor for rotor resistance estimation is carried out in MATLAB/Simulink. The very first step for designing and modeling of a controller is to implement a block diagram depicting all its algorithm. The block diagram representation can be done with the help of Simulink library blocks and the blocks which are implemented by the users. The block diagram which is now developed can be simulated with the help of different solvers. These solvers used to solve the internal variables with the help of lower order differential equations. By choosing a suitable solver, it can actually lessen the computational time and can improve the accuracy of the simulation.

It totally depends on the controller which type can be implemented in continuous time using the Laplace variable and in discrete time using the complex ‘z’ variables. The difference between the continuous model and the discrete model is that a discrete model responds to the change in inputs with a constant time period and hold their outputs fixed between the successive samples and in case of continuous model state variable can be calculated at any instant of time. A solver is required which actually follows the transient nature of the dynamic model. Now to implement this it requires a variable step solver which not only do the complex calculations but also calculates the step size which decides the occurrence of the steps. The step size improves the speed by avoiding the repeated and unnecessary calculations.

5.2 Block Diagram of Vector Control Drive with Rotor Resistance Estimation and Simulink Model of MRAS technique

The schematic diagram of vector control drive with rotor resistance estimation block has been shown in figure 5.1. The indirect vector controlled induction motor drive is simulated using the PWM signal generation for the three phase voltage source inverter. The reference current and actual current compares in the MRAS controller and the output of that controller that is estimated slip speed ω_{sl}^* is used for the estimation of rotor resistance in an estimator block.

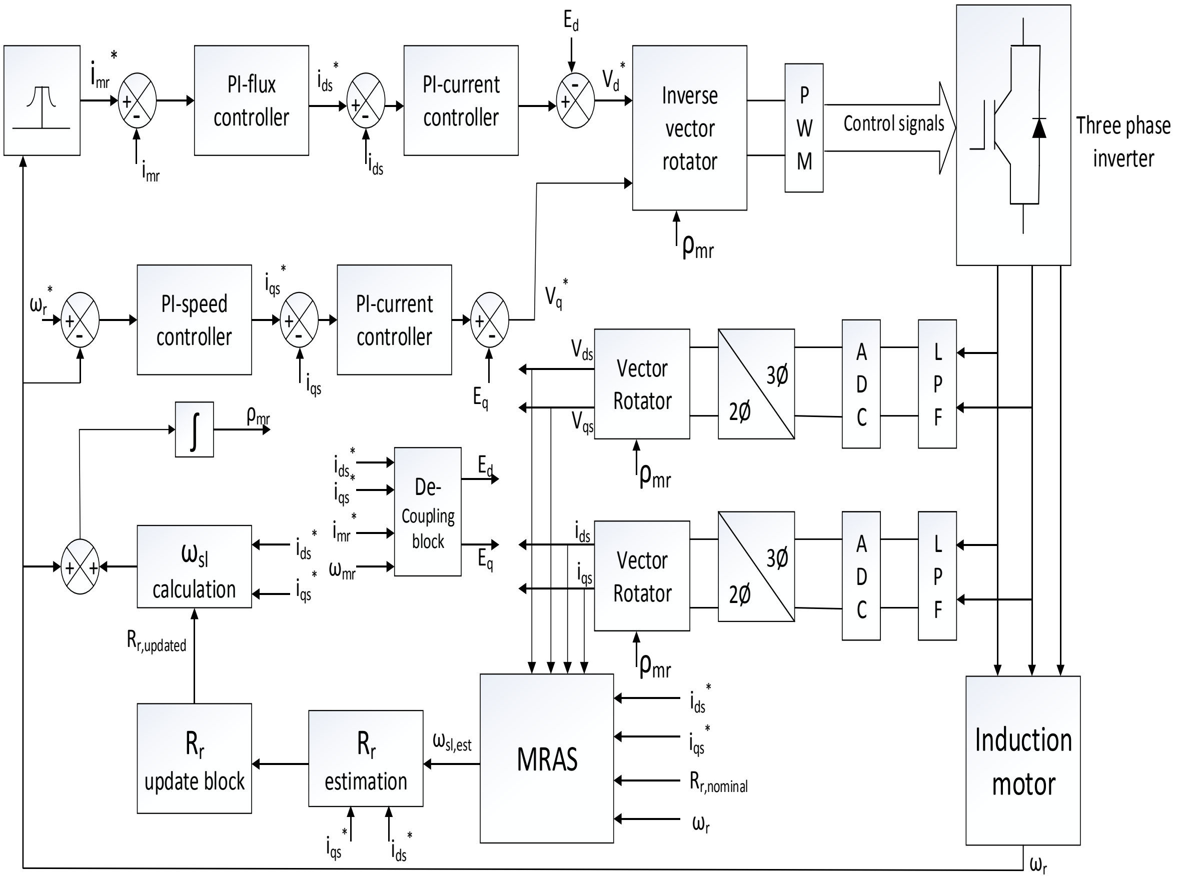


Figure 5.1 Block diagram of rotor resistance estimation of Induction motor

In this block diagram, figure 4.2 is included as a whole in the MRAS block shown above which produces estimated slip speed at its output. Now this slip speed acts as an input to the rotor resistance estimation block. After estimating the updated value of rotor resistance is fed to the slip speed calculation block. There are total four PI controller blocks that has been used in the above diagram. The PI speed controller block uses the error of the speed to produce the stator quadrature axis current. The first PI current controller block uses the error of the stator quadrature axis currents to produce the reference quadrature axis voltage. The PI flux controller block uses the error of the rotor currents to produce the reference direct axis stator current. Now this reference current is compared with the actual direct axis stator current and the error is fed to the second PI current controller block that produces the reference direct axis voltage. PWM control signals are produced by inverse vector rotator block to trigger the gating pulses to the switches of a three phase inverter. The controlled three phase currents coming out of the inverter is directly given to the induction motor whose rotor speed is fed back for the calculation of synchronous speed and also to produce the error which is used by the PI speed controller block. The MRAS block uses the reference direct and quadrature axis stator current, the actual rotor resistance of the motor and the actual speed of the motor to produce estimated slip speed.

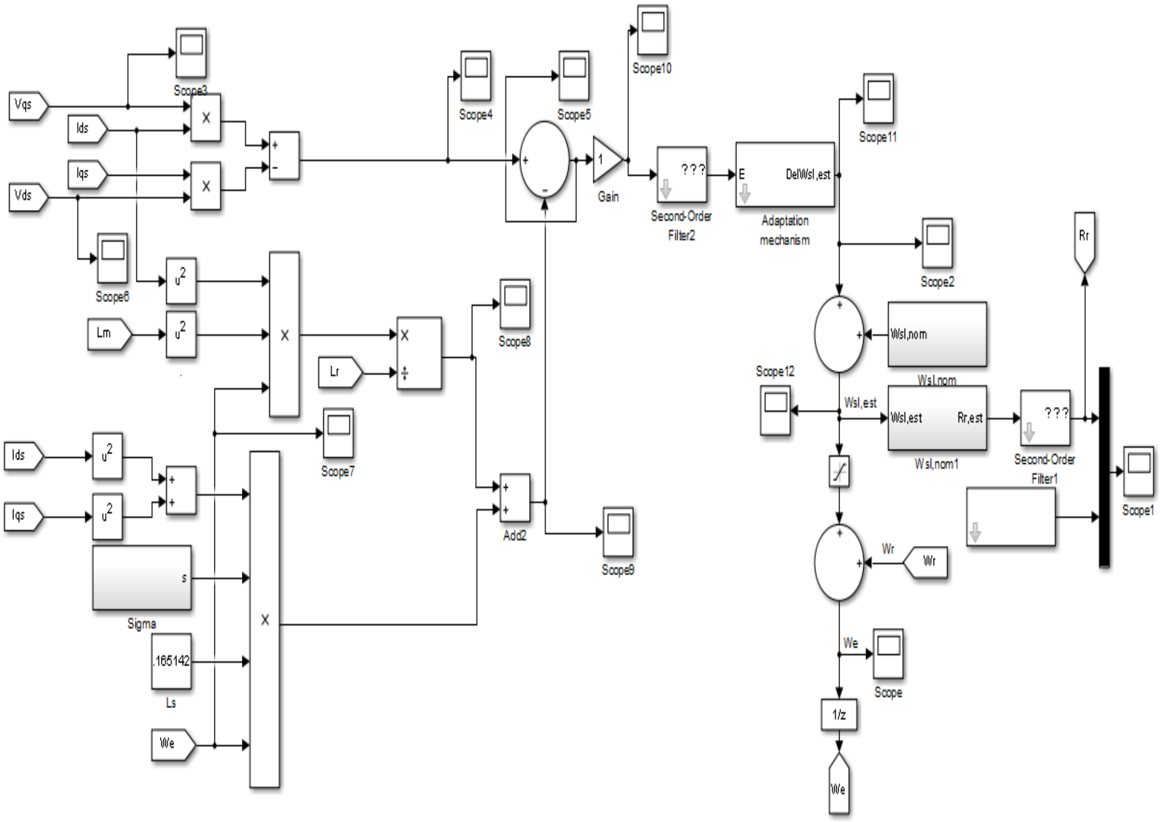


Figure 5.2 MATLAB model of MRAC technique of Induction motor

Figure 5.2 shows the MRAS subsystem of the actual simulation model of Indirect Vector control of Induction motor shown in figure 3.10.

5.3 Simulation results

The MRAS controller is implemented for the estimation of the rotor resistance in induction motor, the trapezoidal and step change in rotor resistance is given to the dynamic model of induction motor and with that the designed MRAS controller tracks the actual rotor resistance of the machine.

5.3.1 Dynamic performance of indirect vector controlled induction motor and trapezoidal change in rotor resistance

A. Trapezoidal reference resistance is used here for the study of machine tracking performance as the resistance increases linearly and decreases linearly in trapezoidal change.

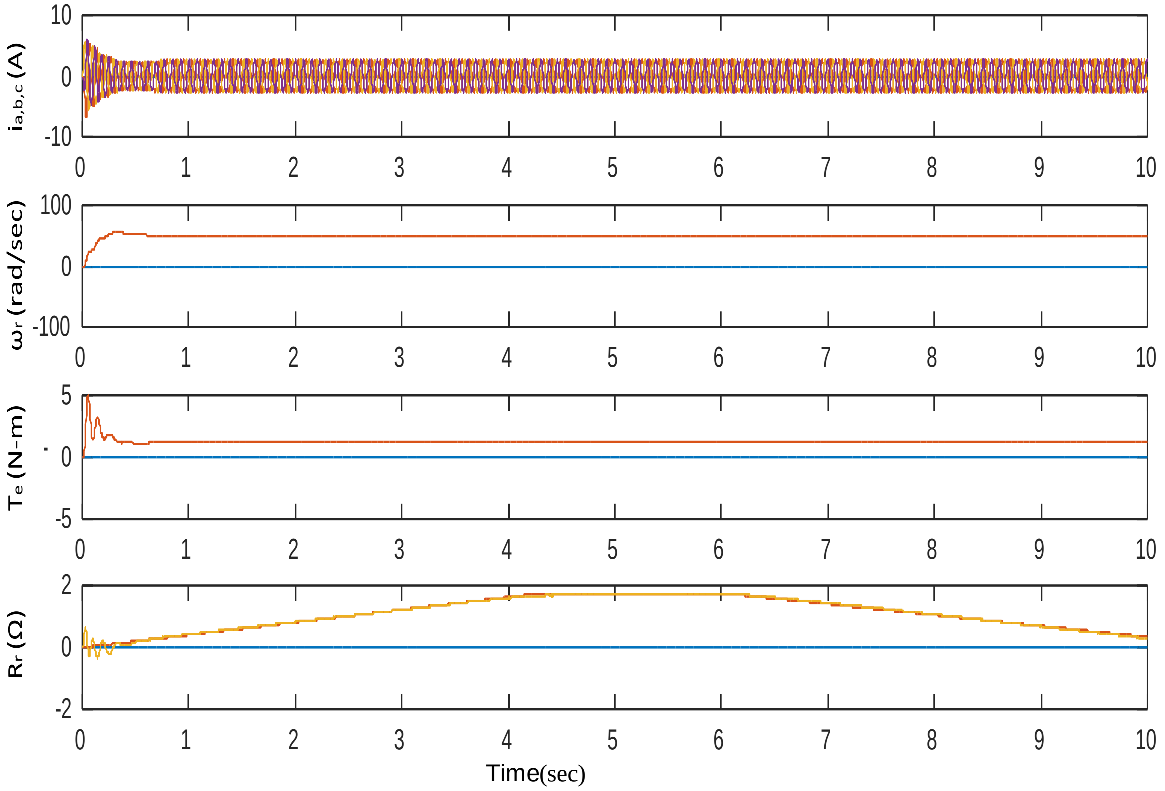


Figure 5.3 Dynamic response of Indirect vector control of induction motor on trapezoidal change in rotor resistance and effect on Stator current I_{abc} [A], Rotor Speed ω_r [rad/s], Torque T_e [N/m], Rotor Resistance R_r [ohm]

The induction motor is started with the speed set point at 50 rad/sec, In figure 5.3 shows that the initial current drawn by motor is high and the initial torque is also high. When motor reaches the set speed, the current attains the steady state value of 3Amp. The trapezoidal change is a linear change in rotor resistance and it has a very minute effect on speed and torque of the induction motor which is negligible. The rotor resistance experiences the transients from t=0sec to t=0.35sec and after that it tracks the actual rotor resistance with the minimum error. The starting stator current $i_{a,b,c}$ (A) of the motor is high for t=0sec to t=0.4sec and after t=0.4sec to t=10sec it attains the steady state stator current level. Due to high starting current the initial torque of the motor has transients from t=0sec to t=0.6 sec after that t=0.6 to t=10sec the torque attains the steady state condition.

B. Estimation of rotor resistance for Indirect vector control of Induction motor

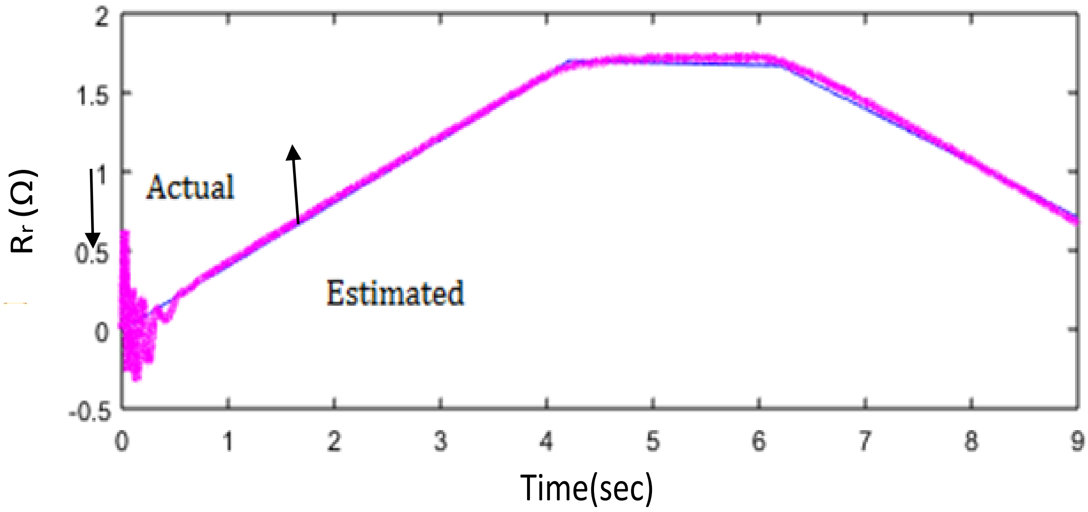


Figure 5.4 Trapezoidal Change in the Rotor Resistance of Induction motor

In figure 5.4 estimated rotor resistance experiences the transients from t=0 sec to t=0.5 sec after that the estimated rotor resistance tracks the actual machine resistance given in the trapezoidal form. The estimated rotor resistance increases linearly from t=0 sec to t=4 sec and from t=4 sec to t=6 sec it gives the constant value of 1.6Ω resistance after that at t=6sec to t=9 sec resistance decreases linearly, the estimated rotor resistance tracks the actual rotor resistance with the minimum error.

C. Dynamic response of indirect vector control of induction motor for the speed reversal

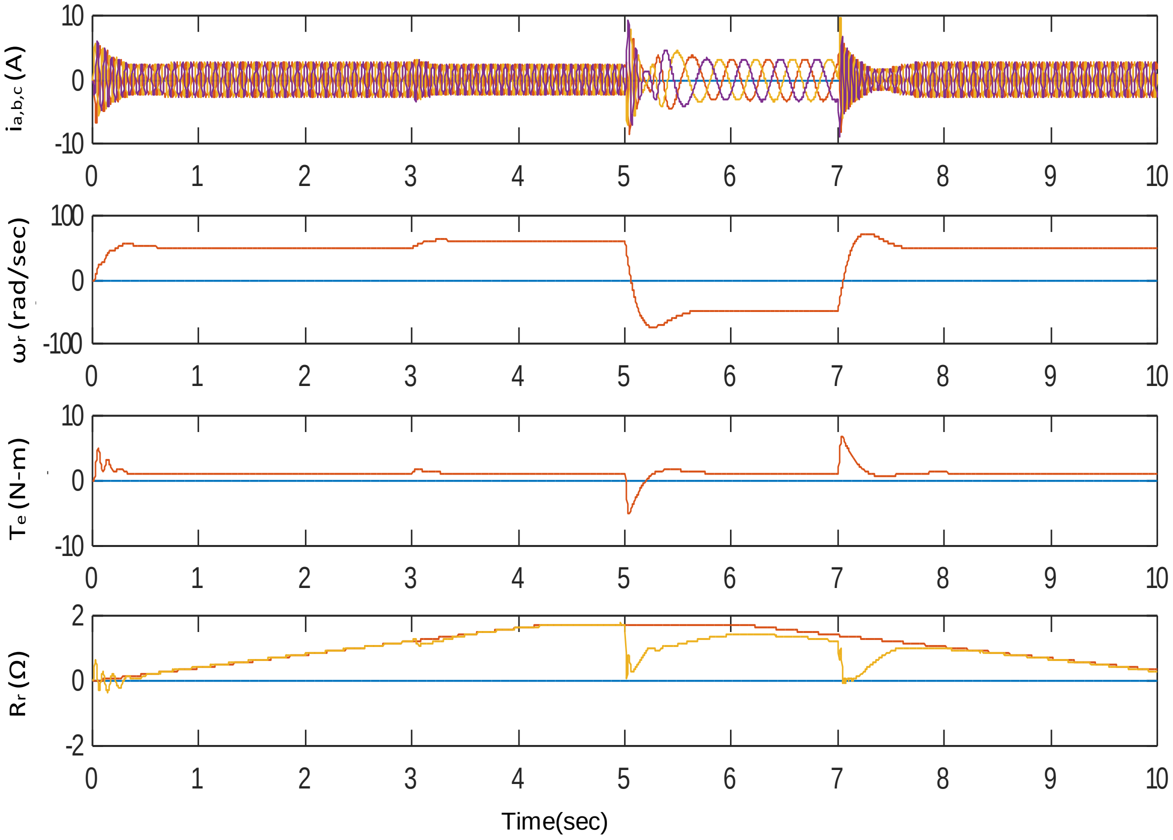


Figure 5.5 Dynamic response of Induction motor on trapezoidal change in rotor resistance for speed reversal and its effects on Stator current I_{abc} [A], Rotor Speed ω_r [rad/s], Torque T_e[N/m] and Rotor Resistance R_r [ohm]

Initially the induction motor speed is set at 50 rad/sec. Figure 5.5 shows that the initial current of the motor is high and due to that the initial torque is also high. When motor attains the set speed, the current attains the steady state value of 3Amp. The motor speed changes to -50rad/sec at t=3sec, when the speed gets reversed the phase reversal of current is observed and the torque value decreases as the speed attains it final value torque again comes in steady state. Change in motor speed from -50rad/sec to +50rad/sec at t=7sec the current attains its steady state when speed reaches its set point.

D. Dynamic response of indirect vector control of induction motor for step torque

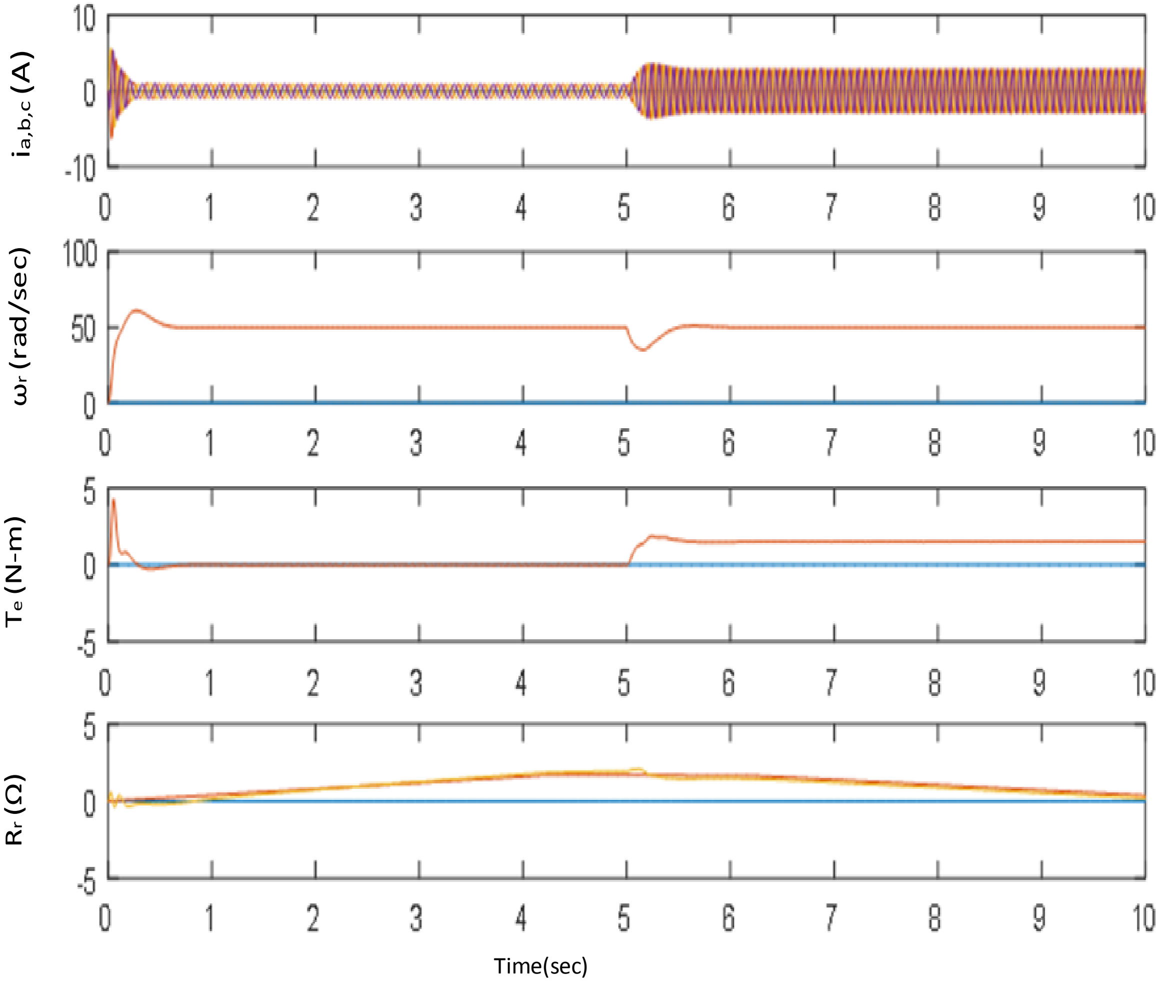


Figure 5.6 Dynamic response of Indirect vector control of Induction motor for step change in torque and effects on Stator current I_{abc} [A], Rotor Speed ω_r [rad/s], Torque T_e [N/m] and Rotor Resistance R_r [ohm]

Initially the induction motor is started with the speed set point 50 rad/sec, Figure 5.6 shows that when motor attains the set speed, the current attains the steady state value of 1.5Amp. At t=5sec the step change in torque from 0 N-m to 1.25 N-m the stator current increases to 5Amp. Due to the increase in torque, speed experiences the dynamic change and attains steady state level. Due to increase in torque the rotor resistance decreases from its actual value because torque is indirectly proportional to the rotor resistance.

5.3.2 Dynamic performance of indirect vector controlled induction motor and step change in rotor resistance.

A. Step Change in rotor resistance of induction motor

The MRAS controller is implemented for the estimation of rotor resistance, the step change in rotor resistance is given to the dynamic model of induction motor and with that the designed MRAS controller tracks the actual rotor resistance of the machine.

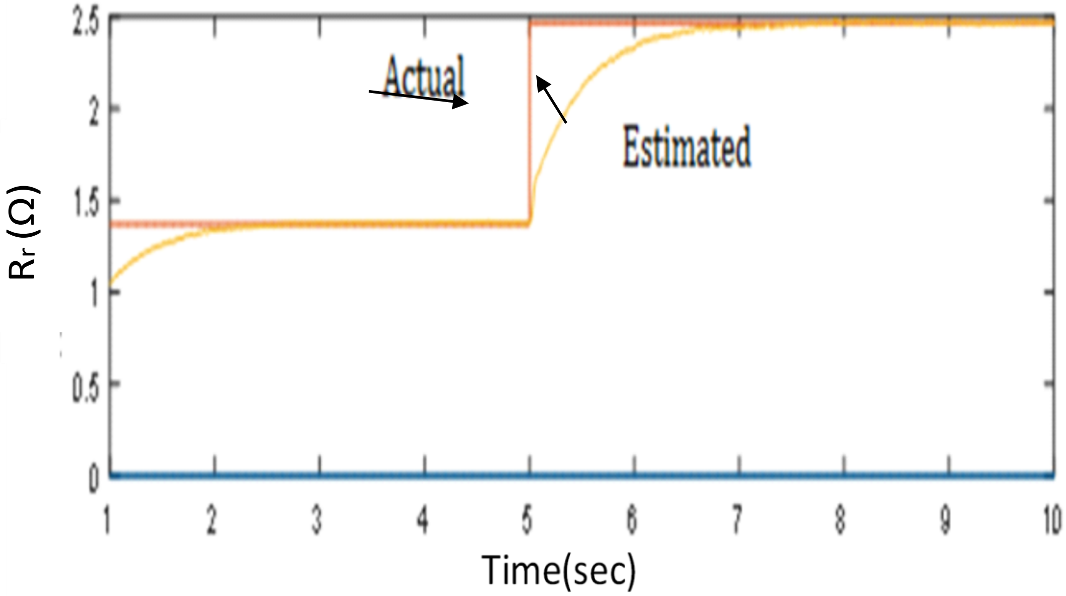


Figure 5.7 Step change in Rotor resistance of Induction motor

As shown in Figure 5.7 The resistance is changed 85% to its actual value, the step change in rotor resistance from 1.405 ohm to 2.5 ohm at time t=5 sec . The estimated rotor resistance experiences the transients from t=0sec to t=2sec after that it tracks the actual rotor resistance of the machine.

B. Dynamic performance of indirect vector control of induction motor for the estimation of rotor resistance

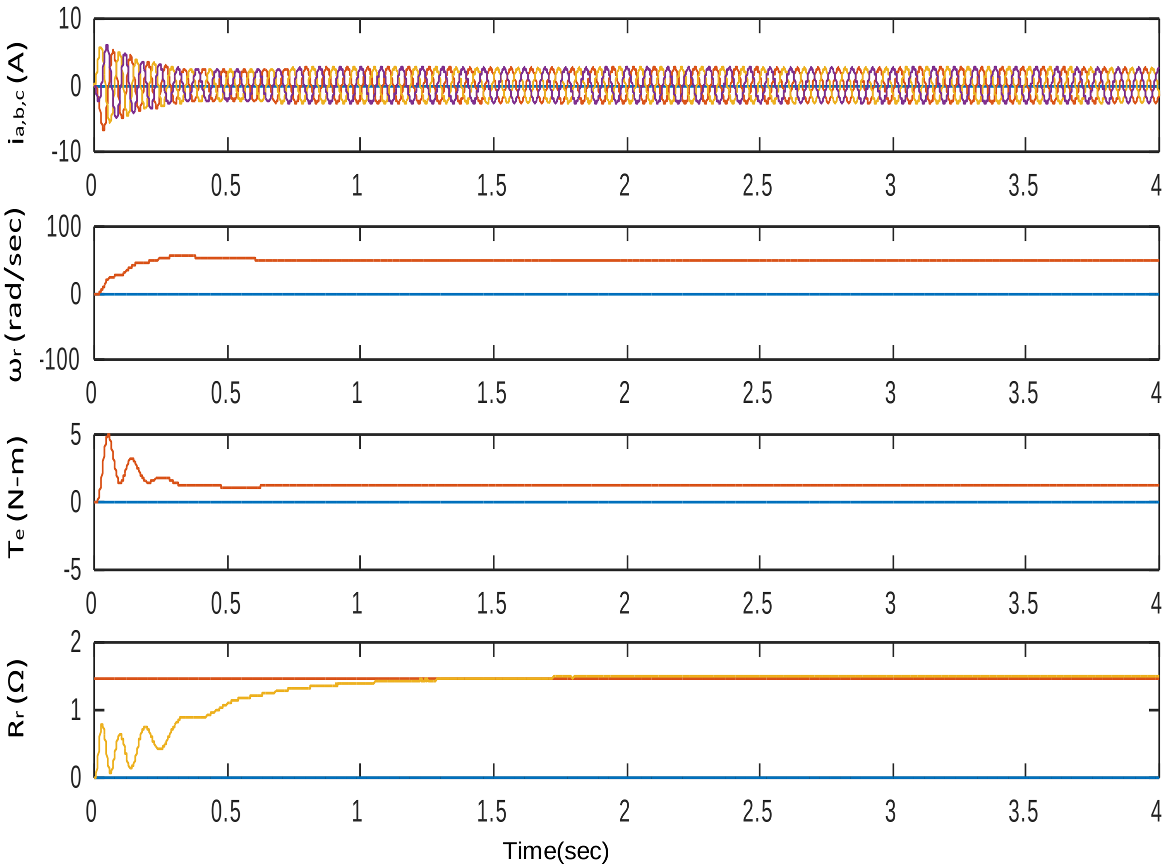


Figure 5.8: Dynamic response of Indirect vector control of Induction motor and estimation of rotor resistance and its effects on Stator current I_{abc} [A], Rotor Speed ω_r [rad/s], Torque T_e [N/m] (d) Rotor Resistance R_r [ohm]

The induction motor is set to the 50 rad/sec and the change in the rotor resistance is implemented on the dynamic model of induction motor as shown in figure 5.8. The initial current of induction motor is high with that the initial torque becomes high. When the motor reaches to its actual speed 50 rad/sec the stator current i_{abc} (A) attains the steady state. The change in the rotor resistance value from R_r =1.38Ω to R_r =1.51 Ω , it experiences the starting transients from t=0sec to t=1.34 sec and after that it tracks the actual rotor resistance of the motor.

C. Dynamic response of indirect vector control of induction motor for the speed reversal

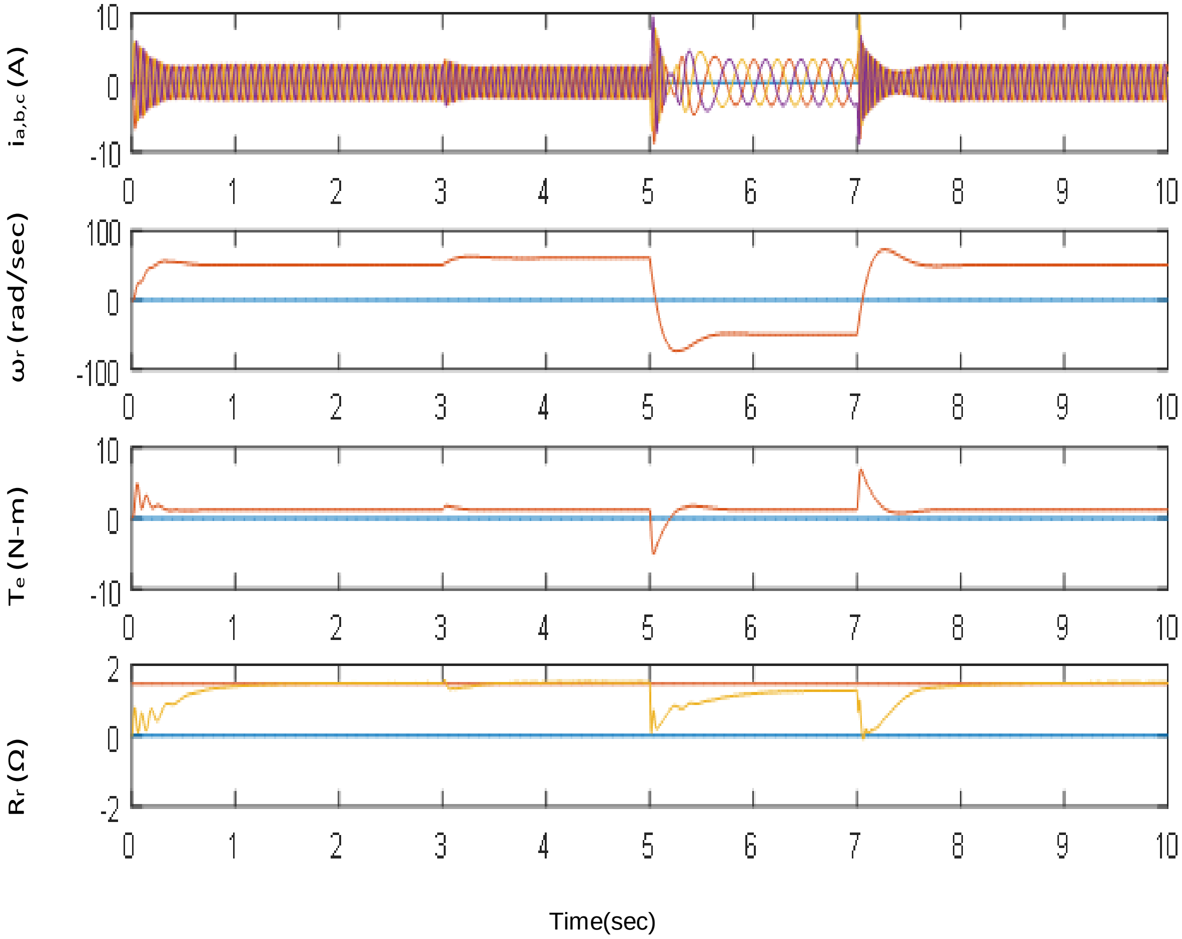


Figure 5.9: Dynamic response of Indirect vector control of Induction motor for speed reversal and its effects on Stator current I_{abc} [A], Rotor Speed ω_r [rad/s], Torque T_e [N/m] and Rotor Resistance R_r [ohm]

Induction motor is started with the set speed of 50 rad/sec, In figure 5.9 shows that the initial current of the motor is high and due to that the initial torque is also high. When motor attains the set speed, the current attains the steady state value of 3Amp. The motor speed changes to -50rad/sec at t=3sec, when the speed gets reversed the phase reversal of current is observed and the torque value decreases as the speed attains it final value torque again comes in steady state. Change in motor speed from -50rad/sec to +50rad/sec at t=7sec the current attains its steady state when speed reaches its set point.

D. Dynamic response of indirect vector control of induction motor for step torque

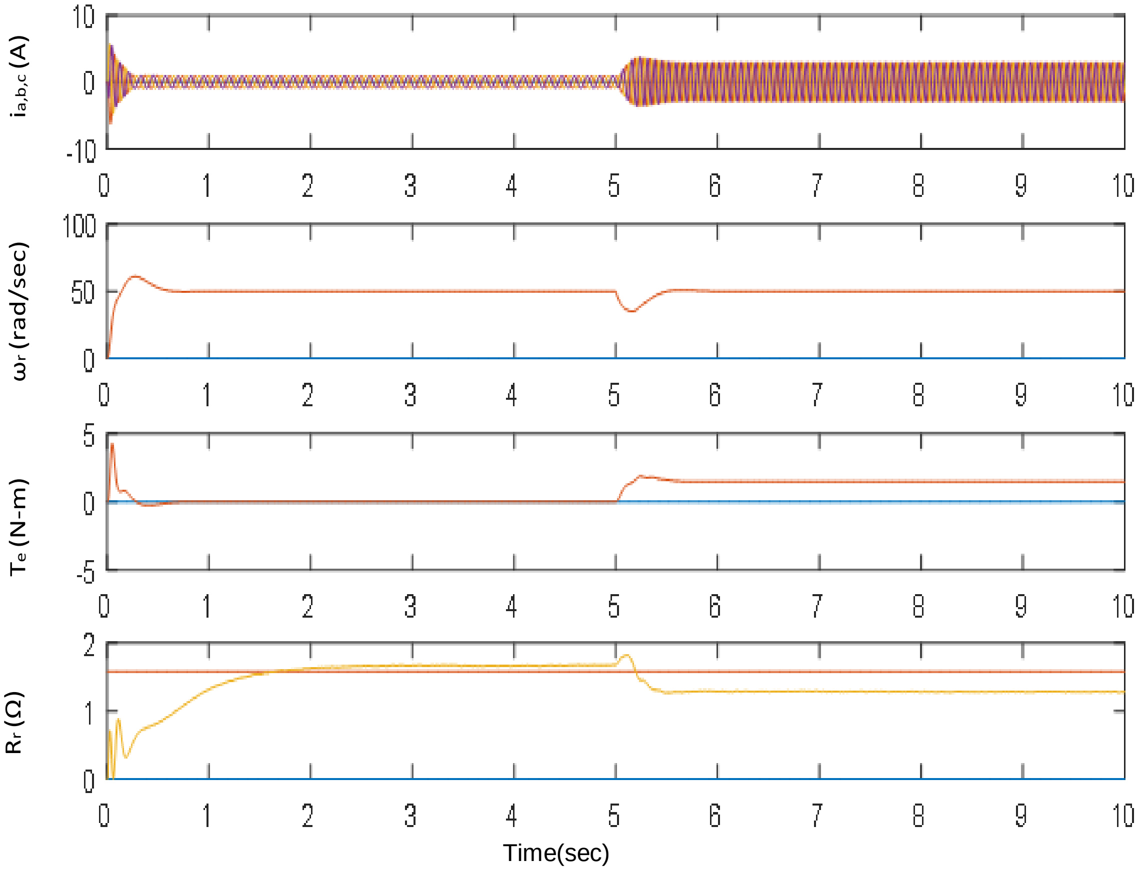


Figure 5.10: Dynamic response of Indirect vector control of Induction motor on step change in rotor resistance and its effects on Stator current I_{abc} [A], Rotor Speed ω_r [rad/s], Torque T_e [N/m] (d) Rotor Resistance R_r [ohm]

The induction motor is started with the speed set at 50 rad/sec, In figure 5.10 shows that when motor attains the set speed, the current attains the steady state value of 1.5Amp. At t=5sec the step change in torque from 0 N-m to 1.25 N-m with that the stator current increases to 5Amp. Due to the increase in torque, speed experiences the dynamic change and attains steady state. Due to increase in torque the rotor resistance decreases from its actual value because torque is indirectly proportional to the rotor resistance.

5.4 CONCLUSION

In this chapter, the rotor resistance is estimated and calculated for two variations i.e., for trapezoidal change and for step change in rotor resistance through the required gate pulses for the voltage source inverter (VSI) using MRAC technique. In this chapter, different variations with speed and torque were calculated and corresponding results were produced and analyzed in detail. Reactive power based MRAC technique is found out to be one of the best among all the R_r estimation techniques in the literature.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Main Conclusions

The main objective of the dissertation was to estimate and calculate the rotor resistance of the Induction motor drive using MRAS controller through simulation study in MATLAB/Simulink. The research work in the thesis developed an estimator for the sudden (i.e., step change) as well as linear change (i.e., trapezoidal change) for the estimation of the rotor resistance of the drive. Different speed and torque control methods of Induction motor such as direct, indirect, direct torque control, sensor less control are discussed and their dynamic performance for the induction motor is analyzed. The indirect vector control model of induction motor based on hysteresis current controller is simulated in MATLAB/Simulink and the dynamic performance in terms of speed, torque, current waveforms are described.

6.2 Future scope of work

In the present work rotor resistance estimation using MRAS method is described. Moreover, the performance of Vector control drive can be evaluated under varying rotor resistance condition. In the future scope of work, the controller can be applied to other machine model with the higher rating and where the parameter variations is large and is of great concern. Intelligent controller such as Genetic Algorithm, Fuzzy logic and Artificial Neural Network Controller can be incorporated to MRAC control technique instead of proportional and integral controller to make it more efficient and more robust. Sliding mode controller can be implemented for the speed control of a Vector control Induction motor drive.

Appendix

Table A.1 System Parameters

Rated Power (P)	5.4 hp
Rated Voltage (V)	400 V
Stator Resistance (R_s)	1.405 Ω
Stator Inductance (L_s)	0.17803 H
Rotor Resistance (R_r)	1.395 Ω
Rotor Inductance (L_r)	0.17803 H
Mutual Inductance (L_m)	0.1722 H
Frequency (f)	50 Hz
Rotor friction co-efficient (F)	0.002985 N.m.s
Rotor Inertia (J)	0.0131 $kg.m^2$
Pole pairs (p)	2
Rated Torque	26.88 N-m
Rated Speed	149.74 rad/s

PI speed controller

k_p= 0.160

k_I = 1

PI adaptive mechanism

k_p= 0.2

k_I = 2.5

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