ROTOR RESISTANCE ESTIMATION FOR INDUCTION MOTOR USING MODEL REFERENCE ADAPTIVE CONTROLLER

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CERTIFICATE

I, **Kratika Kanwal**, Roll No. 2K14/C&I/22 student of **M. Tech. (Control & Intrumentation)**, hereby declare that the dissertation titled "Rotor Resistance estimation for Induction Motor using model reference adaptive controller" under the supervision of Prof. Madhusudan Singh, Head of the Department, Electrical Engineering Department, Delhi Technological University in partial fulfilment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

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ABSTRACT

Induction motors are widely used machines in domestic and industrial applications due to its simple, low cost and rugged construction. There are many where speed operation of motor is required. Variable speed drives for induction motor cause both fast torque response and wide operating range of speed. Indirect vector control of induction motor is a predictive method, where the speed of the rotor flux is predicted from rotor speed and slip speed variation. The rotor speed may be obtained either from speed sensors or from the estimation method.

Any variation in the rotor time constant due to increase in winding temperature may lead to improper flux orientation and hence deterioration of dynamic performance of the drive. Online estimation of rotor time constant is very essential for the flux orientation which subjected to the change of rotor time constant for variation in temperature. Due to changes in flux orientation and the coupling of flux and torque, the performance of the induction motor drive become sluggish. The estimation of machine parameters using model reference adaptive controller (MRAC) is described and analysed through simulation in MATLAB/Simulink.

Model reference adaptive system controller utilizing the reactive power is presented for the online estimation of the rotor resistance to maintain the flux orientation in an indirect vector control of induction motor drive. The effect of sudden and slow variation in rotor resistance on performance of the indirect vector controlled induction motor (IVCIM). The formation of MRAC with the instantaneous and steady-state reactive power eliminates the estimation of flux. Reactive power based MRAC estimator is less sensitive to integral problems like saturation and drift. Simulation and analytical analysis have been presented in MATLAB/Simulink to validate the capability of the technique.

Index Terms - Indirect vector control, model reference adaptive controller (MRAC), reactive power.

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List of Symbols and Abbreviations

IM	Induction Machine
SVPWM	Space vector pulse width modulation
HCC	Hysteresis current controller
i_{sd}, i_{sq}	d-axis and q-axis stator current expressed in stationary reference frame
i_{rd}, i_{rq}	d-axis and q-axis rotor current expressed in stationary reference frame
V_{sd}, V_{sq}	d-axis and q-axis stator voltage expressed in stationary reference frame
V_{rd}, V_{rq}	d-axis and q-axis rotor voltage expressed in stationary reference frame
	Stator voltage
Ψ_{sd}, Ψ_{sq}	d-axis and q-axis stator flux linkage expressed in stationary reference frame
Ψ_{rd}, Ψ_{rq}	d-axis and q-axis rotor flux linkage expressed in stationary reference frame
P	Pair of poles
J	Motor moment of inertia constant
L_r	Rotor self-inductance
L_s	Stator self-inductance
L_m	Mutual inductance
R_r	Rotor resistance
R_s	Stator resistance
p	Number of pole pairs
T_e	Instantaneous value of electromagnetic torque
T_L	Load torque
T_r	Rotor time constant
ω	Angular speed
ω_r	Rotor speed
$\widehat{\omega_r}$	Estimated rotor speed
ω_e	Synchronous speed
θ_e	Stator voltage angle
σ	Total leakage coefficient

$d^s - q^s$	Direct and quadrature axes Stationary reference frame
$d^e - q^e$	Direct and quadrature axes Rotating reference frame
f	Frequency (Hz)
J	Moment of inertia.
θ_{sl}	Slip angle
Ψ_a	Armature reaction flux linkage
Ψ_f	Field flux linkage
ω_{sl}	Slip frequency

CHAPTER I

INTRODUCTION

1.1 General

The induction motors are most commonly used motor because of high torque, simple, robust structure, low cost and higher reliability. Induction motors have advantages over DC motors, and suitable for high performance drives. Recent advancement in power electronics specially power devices and their control techniques the operation and control of induction machine has become common in industrial applications [1], [2]. Control of induction machine is not simple, because it is not easy to use the rotor quantities which produces torque. Induction machine can have the same characteristics like DC motor if the control of machine is in synchronous frame [2], [3].

Previously DC motors were used where variable speed was required, so that their torque and flux can be controlled by the armature current and field current independently. DC motors are mainly used in applications where four quadrant operation and fast response are needed. DC motors have disadvantages because of the brushes and commutator, results in high maintenance. They are prone to explosion or corrosive environment, and the commutator has limitations with high speed. All these drawbacks can be overcome with the use of AC machines.

Ac motors are designed in such a way that it gives high output power for low rotating mass and low weight machines. Variable speed drives have played major roles in industrial applications in past few years which have prohibited the use of dc machines, and the limitations are also the major reason behind this. AC machines have fast switching frequency of inverter, and they are cost efficient, these low cost AC drive in the field of power electronics have progressed a lot now-a-days the use of cheap and effective power converters for AC drive.

In DC drives, power circuits contain line commutated thyristor or a IGBT based chopper for power devices. In ac drives there are large variety of different converters, which can be used as forced commutation, natural commutation, current source, voltage source, dc link, cyclo-converter, which can be clubbed with different type of ac machines.

ac drives with variable speed drive have become the first choice in many industrial applications where speed control is required. At the same instant of time with the availability of efficient and fast power semiconductor switches (transistors) gives a high frequency control of PWM for the latest drives. The use of AC machine in the industrial applications concludes that the AC motor drive controlled by a PWM has some problems such as: insulation of motors gets damaged because of reflected voltages occurs by long motors, motor bearing mechanism gets failed because of excessive dv/dt and leakage currents to ground. The estimation and control of AC drives are very complex in comparison to DC drives, and with the performance of the machine complexity increases exponentially [1]. The reasons behind the complexity of the machine are the dynamic behavior of the ac machine.

1.2 Parameter Estimations in Induction Motor Drives

FOC (Field oriented control) of induction motor is widely used in industrial application. Both the approaches DFOC (Direct field oriented control) and IFOC (Indirect field oriented control) require parameters of machine. There are many methods for handling problems related to the variation in parameters due to rise in temperature etc. The electrical parameter values changes in different circumstances: both the slip frequency and temperature affects the resistance, magnetic saturation influences mutual inductance and stator and rotor resistances are influenced from the temperature. This has been the major research area devices last many years. The main goal of this research work is to find a suitable method for estimation of online rotor resistance for induction motor drive.

There are many techniques for rotor resistance estimation such as model reference adaptive system, least square recursive method, sliding mode controller, leunberger observer, extended kalman filter, kalman filter. These techniques have grabbed attention an extended kalman filter has attained stability by selecting the positive definite term for riccati equation for the gain designing. This technique has limitation of proper initialization and calculation. Another attractive technique is MRAC in which error is measured from output of the two different models voltage model and current model, the error of these two model should be brought to zero with the help of an adaptation mechanism, the adaptation mechanism is a PI controller which can be tuned accordingly to the need of the system. The control method used here should adapt the system according to the variation in parameters and the uncertainty. This controller is designed with the help of reference model which can describe the characteristics of the controlled plant. Reference model provides the stability to the system. The variable quantity only influences the one model the other has no effect with the variable quantity.

There are two different approaches for MRAC (model reference adaptive controller): direct control and indirect control. In direct control method a controller is selected and its parameter is adjusted accordingly to make the error zero. Indirect control method plant unknown parameters are estimated before the control input is selected. In indirect method it has both adaptive and reference model but in direct method it has only reference model.

1.3 Objective of the thesis

The main aim of this thesis is to identify and implement an estimator for a vector controlled drive. For identifying an observer main focus is on estimator which must be accurate, simple to design, should have wide operating range and can be implemented easily.

1. To study and identify the methods for Estimation of Rotor Resistance in indirect vector controlled drives.
2. To implement the estimator for the parameter variation in Induction motor due to the temperature variation. A reactive power based MRAC Estimator is designed for the estimation of rotor resistance.
3. SVPWM (Space Vector PWM) Inverter fed Induction Motor is considered for Induction Motor drives to implement the estimator technique for the estimation of rotor resistance
4. Adaptive mechanism and speed controller is designed by using PI-Controller, and it computes and transmit output signal of the controller to the control element.

1.4 Organization of the thesis

In this thesis the performance and control of induction motor and estimation of induction motor parameter technique is implemented. Control techniques are implemented and determined in the motor drives. The simulation results have examined using the MATLAB SIMULINK and further variation in rotor resistance with the effect of 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 research papers in last few decades, books and hand books 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 dynamic modeling of induction motor is covered and the transformation through three phase to two phase transformation by using Clarke's and Park's transformation are discussed and the both field orientation control direct and indirect control is discussed.
In this chapter we have discussed about the control techniques used for induction motor such as scalar control, field oriented control or vector control (direct and indirect vector control and sensor-less control techniques) are discussed.

- Chapter IV, Controlling technique for estimation of rotor resistance

In this chapter model reference adaptive system technique has been implemented for the variation in resistance of induction motor due to the increase in temperature for indirect vector control of induction motor drive. And initiation of Power electronics is used (SVPWM inverter), and proportional and integral control technique are used

- Chapter V, Simulation and Results and Discussion

In this chapter analysis and modeling of induction motor with the help of simulation, and variation in rotor resistance with temperature is modeled in MATLAB Simulink and the performance of induction motor drive with the rotor resistance variations is analyzed. The estimation algorithm for rotor resistance is simulated while using the SVPWM controller with the help of proportional and integral control using reactive power. The performance and analysis of algorithm is examined by the accuracy of the results. To show the variation in performance of induction motor drive both sudden and linear change in R_r through MATLAB Simulink demonstrated. The simulation results for MRAS algorithm with changes in resistance are compared and analyzed.

- Chapter VI; Conclusion and Future Scope

In this chapter we concludes the study of variation in rotor resistance with temperature through an algorithm called MRAS for indirect field oriented control while using the SVPWM (Space Vector Pulse Width Modulation) controller .

CHAPTER II

LITERATURE REVIEW

2.1 General

Electrical drives are used in industrial processes for ensuring higher productivity, product quality and efficient operation. With the advancement in intelligent instrumentation, power electronics and digital control techniques has resulted in the design in development of complex larger and efficient industrial systems. Drivers are used for motion control in almost all kind of processes and plants including paper mills, rolling mills, automotive industry, packaging industry, water treatment plant, oil and gas refineries, iron and steel industry, etc. 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.

2.2 Parameter Estimation methods in Induction Motor

Vector control was invented in Germany in 1968 and in early starting of 1970's, Hasse [4] has proposed indirect vector control technique and Blaschke has proposed the theory of direct vector control. Werner Leonhard [5] has developed the vector control technique in 1970's. Abbondanti and Brennen et al. [6] in 1975 have discussed about the designing of the slip calculator that depends upon the input quantities as phase, voltage and current. Allan B. Plunkett et al. [7] have been developed for the measurement of the flux level in an induction motor in. With the flux and stator current, the electromagnetic torque can be obtained. R. Krishnan et al. [8] the estimation of flux needs the proper knowledge of induction motor parameters and the indirect vector control is parameter dependent. If any change in the temperature and saturation of the machine its varies the machine parameters and it affects indirectly to the steady state and dynamic performance of the machine. In [9] R marino et al. has concluded that the control algorithm has a nonlinear identification scheme which can asymptotically tracks the true value of the rotor resistance and load torque which are assumed to be constant but unknown. Once those parameters are identified the two control goals for the regulation of rotor flux and rotor speed amplitudes are decoupled. In paper [10] K. R. Cho et al. when the rotor bar breaks the rotor resistance of induction motor increases. For detection of broken rotor bars the measurements of stator current, voltage, frequency, 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 parameters. In [11] C. Attaianese et al. a speed control of induction motor is implemented, and the online estimation the speed and the other parameters of the machine and the comparative study of different motors. H. A. Toliyat et al. [12] have concluded that an induction machine is the most common machine used in industries, control scheme for these drive should have exact knowledge of the machine parameters. In case of any change in the actual parameters or within the controller will deteriorate the performance of the induction machine. In [13] C. Kral et al. estimation of rotor temperature for fan-cooled induction motors with a thermal equivalent circuit is implemented. When the motor is loaded slightly the estimation of rotor resistance becomes inaccurate because of the small slip. Rotor temperature estimation for low-load conditions can be estimated through a thermal equivalent model. For the estimation of rotor and rotor temperature accurately few machine parameters have to be estimated in advance. The leakage reactance and iron losses can be calculated through load test of the induction machine. The thermal equivalent model needs a thermal resistance and capacitance. These parameters can be derived through a heating test, in which reference temperature is given through the parameter model in time domain. J. Pedra et al. [14] the transient behavior of induction motor is studied and the double-cage model parameters are estimated with the regression-based equations that depend on the line voltage and mechanical power of the machine. The starting current, torque, slip and efficiency are calculated with the typical parameters and they are compared with the data of 608 low-voltage induction motors given from the different manufacturers. In [15] Wei Chen et al. the estimation of parameters at standstill depends on the static induction machine model. DC motor or single phase AC current is injected to the motor, and the parameters like resistance and inductance estimates 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] the parameter estimation method for induction motor using the extended Kalman filter (EKF) theory is implemented. This method is implemented in real-time on PC-cluster node which as a controller for an induction motor set-up. Lluís Monjo et al. [17] the parameters of induction motor are estimated 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 the 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 method in Induction Motor

There are many methods for handling problems related to the variation in parameters by different approaches; The electrical parameter values changes in different circumstances: both the slip frequency and temperature affects the resistance, magnetic saturation influences mutual inductance and stator and rotor resistances are influenced from the temperature. There are many techniques for the estimation of speed of induction motor such as model reference adaptive system, least square recursive method, sliding mode controller, leunberger observer, extended kalman filter, kalman filter. These techniques have grabbed attention an extended kalman filter has attained stability by selecting the positive definite term for riccati equation for the gain designing.

T. Iwasaki et al. [18] used an extended Kalman filter to estimates the parameters of an induction motor while using the measurements of the stator currents, voltages and rotor speed. The induction motor model and Kalman filter algorithm are designed in the state space. The filters are used to the parameter identification of an induction motor. A simple and practical method for setting the covariance matrices of the noises are implemented in the Kalman filter algorithm which is very important in designing the algorithm. F.-Z. Peng et al. [19] the speed identification for a tacholess vector control has been proposed. In the instantaneous reactive power of magnetizing inductance in which different from the conventional MRAS schemes based on rotor flux observers is used. It does not require integration of sensed variables and it is robust to rotor resistance temperature variations. 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] A neural-networks-based speed estimation is proposed for induction motor. The back-propagation neural networks technique is used for the real-time based adaptive estimation of the motor speed. The proposed is used for the improvement in the performance of speed sensorless drives

R. Blasco-Gimenez et al. [21] in this paper a real-time slot harmonic speed detector for vector control of induction machines is proposed. Speed accuracy and resolution have been derived for motors of general rotor slot numbers and slot harmonic orders and for windowing and interpolation methods have been proposed Speed tracking and the problems related to that have been discussed. In [22] M.Ta Cao et al. the adaptive speed controller and rotor resistance estimator depends on the fuzzy logic (FL) approach for a high performance indirect vector controlled induction motor drive. In order to achieve the decoupled control of torque and flux a fuzzy logic based rotor resistance estimator is designed. In [23] R. Blasco-Gimenez et al. 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] a set of algorithms 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 stator voltage and current measurements. H.-J. Shieh et al. [25] estimation model based adaptive control for indirect vector control of induction motor is presented. The new reference frame based estimator is designed to adaptively estimate the state variables and the rotor time constant used in indirect vector control.

Y. Zheng et al. [26] have an adjustable-speed drives with induction machines produces an accurate encoder-less operation at very low speed range remains to be less problematic for all control methods, which includes model-reference-adaptive-system(MRAS), nonlinearity compensation, various types of observers, artificial intelligence(AI) or neural network techniques.

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

In [28] B. Karanayil et al. have discussed the two methods of estimation of rotor resistance from indirect vector controlled induction motor. A model reference adaptive scheme is proposed in which adaptation mechanism is executed by using a PI controller and a FL (fuzzy logic) controller. A. Ba-Razzouk et al. [29] in this 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 torque and flux of the drive.

Xing Yu et al. [30] the paper presents the rotor resistance identification method for an IRFO controlled induction drive. A decoupled voltage control scheme is used to achieve a accurate, 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] a vector control of induction drive, by the estimated rotor fux and rotor speed, while using a new extended Kalman filter (EKF) is proposed. In this method, only the rotor flux components are considered as the state variables. Y. Koubaa et al. [32] the estimation of speed is achieved by assuming that the rotor resistance is remaining constant throughout the operating range. In practice, the variation of this resistance depends on the inside temperature of the machine.

S.A.Villazana et al. [33] Rotor resistance estimation of the SCIM (squirrel cage IM) was implemented using support vector machines (SVM) together with the model reference adaptive system. The drive with the variable rotor resistance was simulated and the flux error records were obtained from voltage and current models. Shady M Gadoue et al. [34] presents 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. A multilayer feed forward neural network is implemented for rotor flux estimation which is robust to noise and resistance variation and does not have DC drift problems which are usually associated with this adaptive algorithm.

S.Villazana et al. [35] a comparitive study between the performances of a classical MRAS based observer of the SCIM and the performance of a SVM (Support vector machines) based MRAS observer to estimate the rotor resistance. H. A. Toliyat et al. [36] presents an online rotor time constant estimation scheme of an indirect vector control induction motor for improving the performance and robustness of the drive. The technique neither requires any special test signal nor any complex calculations. Mohamed Rashed et al. [37] sensorless speed control of a PMSM requires an accurate knowledge of rotor flux, speed and position. Many sensorless schemes in which the accurate estimation of rotor fluxes magnitude, speed and, position is by detecting the back electromotive force (back EMF). Suman Maiti et al. [38] Model reference adaptive system (MRAS) techniques for the estimation of rotor time constant and speed for induction motor drive. This method uses both the instantaneous and steady state reactive powers to formulate the error signal.

M. Nandhini Gayathri et al. [39] Vector Control Induction Motor drive with MRAS based Rotor Resistance Estimator using Reactive Power is presented. The rotor resistance changes due to rise in temperature. This variation has a major influence on the vector control performance of an induction motor due to the deviation in slip frequency from its set value. M. Nandhini Gayathri et al. [40] 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] indirect vector control depends on the estimation of the rotor flux and its synchronous angle for decoupling of flux and torque. This estimation is depends on the calculation of current model and slip speed both are prone to detuning of rotor parameters.

Betsy Baby et al [42] the current source inverter (CSI) is suited for high power voltage drive applications. For decoupled control of the machine torque and flux, indirect vector control is preferred because of its less computational complexity and reduced machine parameter dependency. Saji Chacko et al [43] 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. Its compensation is easier and estimation technique is the accurate identification of rotor resistance both during steady state and transient when the drive is operating at full load. Seung-Myung Lee et al. [44] the rotor resistance is associated with the calculation of slip, the estimation of rotor resistance has a major impact on the dynamic behavior of the Indirect vector Control. The proposed rotor resistance estimation parameter is dependent on the rotor flux of the d-axis, where the voltage model of induction motor is reference model, while the current type model in the synchronous reference frame is used to an adjustable model.

2.4 Conclusion

The brief summary of the methods to improve the dynamic performance of Induction motor and estimation of rotor resistance is described. The scope of this research work is focused on the implementation of the control scheme with the suitable algorithm for efficient operation of the drive.

Chapter III

Modeling and Control of Induction Motor

3.1 General

Conventional external resistance is added to rotor through slip rings which gives low starting current, high starting torque, and soft starts, but this will result into loss in resistance. Vector control is used to improve the efficiency and dynamic performance of the drive and it is possible by the transformation by the three dimensional variables to the two dimensional reference frame that can be in stationary, synchronously rotating frame. Dynamic modeling is very complex and it can be implemented with the choice of their different reference frames. Dynamic behavior of induction machine describes various voltages and torque equations that are time-varying. We can reduce the complexity of the model by eliminating all time varying inductances using the change of variables. In that case some transformations are required in order to transform from three phase stationary reference frame to two phase stationary reference frame through a Clarke's Transformation. To transform from two phase stationary reference frame to a two phase rotating reference frame through Park's Transformation is commonly used.

3.2 Dynamic d-q model of Induction Motor

In variable speed drive, it constitutes an element in the feedback loop and with that its transient behavior will be considered in the performance of a machine. Vector control or field oriented control are the high performance machine control, and they depends on the dynamic machine model. The dynamic performance of the motor is complex as the three phase windings of rotor moves w.r.t the three windings of stator as shown in Figure3.1. It can be similar as a secondary winding of the transformer, with the change in the rotor position the coupling of stator and rotor will change continuously. While using the differential equations machine model can be implemented with the time varying mutual couplings. The three phase machine will be represented to a two phase machine though it is simple but the problem remains the same with the time based parameters variations. Now the scientist R.H. Park in 1920 has proposed a theory for the analysis of the machine model to solve the time varying problem. With the Park's transformation the variables of stator will be transformed to synchronously rotating reference frame with the stationary reference frame.[2]

A. Axes transformation

There exist some complexity of the Induction motor model to solve the problems of variation in parameters like time varying inductances and hence in order to reduce the complexity of the system axes transformation is necessary. In this transformation induction machine will be transformed from three phase stationary axes (a-b-c) to two phase stationary axes($d^s - q^s$) is shown in figure 3.1, and then transform stationary axes to two phase rotating axes($d^e - q^e$).

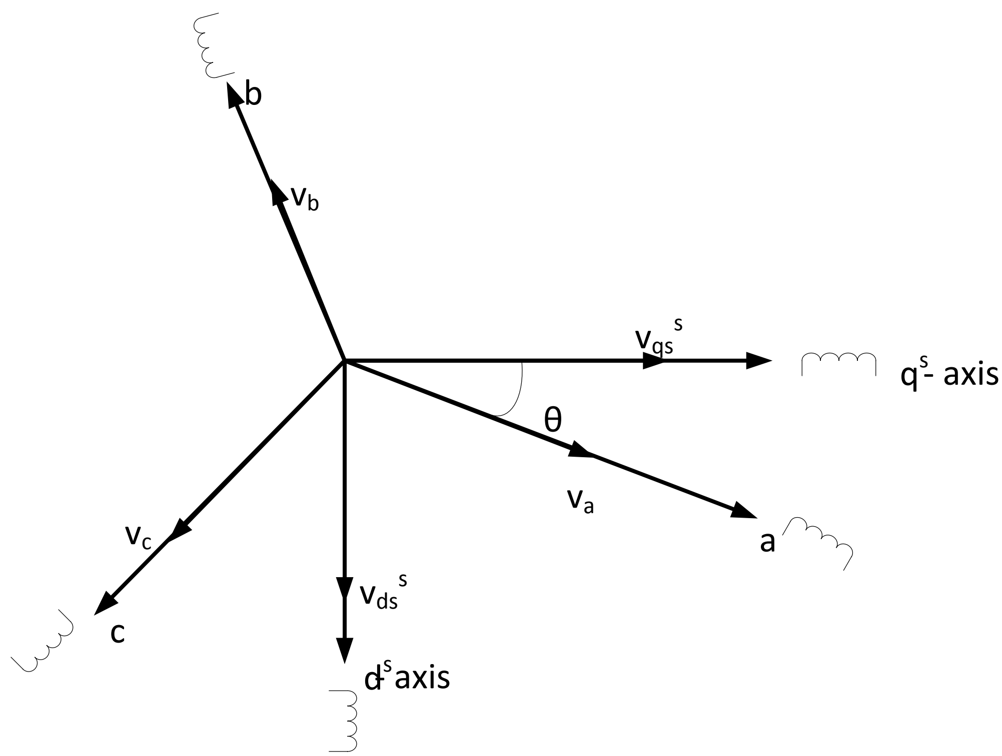


Figure3.1: Transformation from Stationary frame a-b-c to ds-qs frame

The v_{ds}^s and v_{qs}^s components can be resolved into a-b-c component can be in the form of matrix.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120^0) & \sin(\theta - 120^0) & 1 \\ \cos(\theta + 120^0) & \sin(\theta + 120^0) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} \tag{3.1}$$

And the inverse transformation is:

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120^0) & \cos(\theta + 120^0) \\ \sin\theta & \sin(\theta - 120^0) & \sin(\theta + 120^0) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.2}$$

Where,

$v_a, v_b, v_c =$ Line voltage of a,b,c

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

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

v_{0s}^s is the zero sequence component which will not be present at the balanced condition. If we set $\theta = 0$, and 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 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 $\theta = \omega_e t$ angle. Figure 3.2 shows the Transformation from stationary d^s-q^s axis to synchronously rotating $d^e - q^e$ axis.

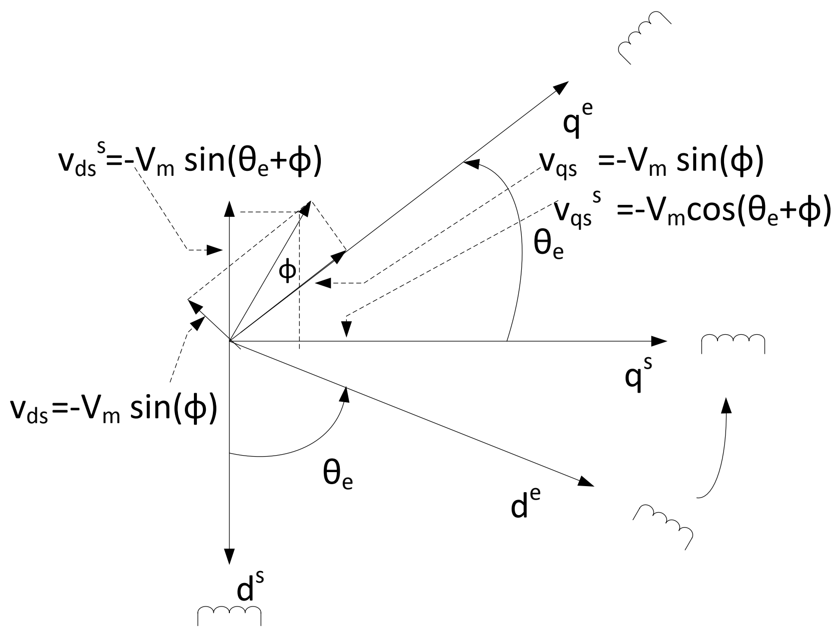


Figure 3.2: Transformation from stationary d^s-q^s axis to synchronously rotating $d^e - q^e$ axis

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

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

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 frame ($d^e - q^e$). Figure 3.3(a,b)shows the equivalent model of induction motor. The Stator equations are as below:

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

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

The rotor equations at the synchronous axes:

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

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

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

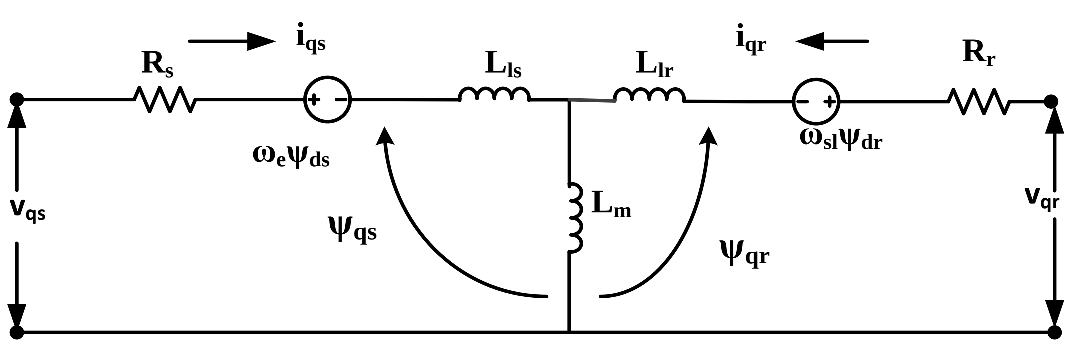


Figure 3.3a dynamic d^e- q^e equivalent circuit of motor (q^e axis)

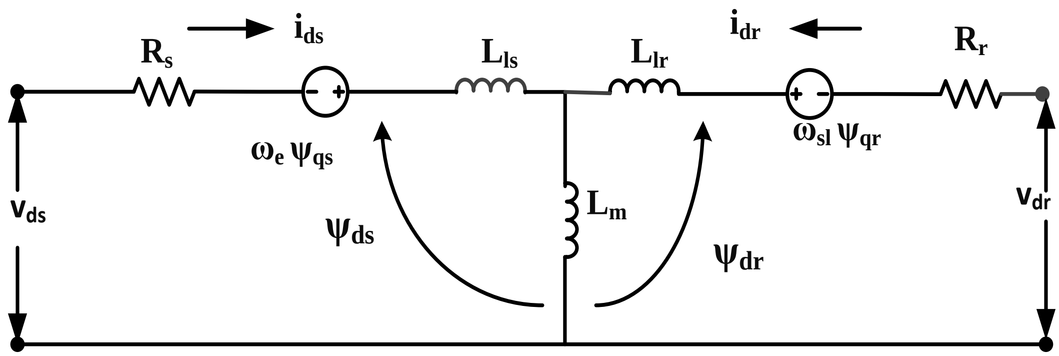


Figure 3.3b dynamic d^e- q^e equivalent circuit of motor (d^e axis)

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

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

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

$$\Psi_{qm} = L_m(i_{qs} + i_{qr}) \quad (3.16)$$

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

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

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

From above equations:

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

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

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

L_m – Mutual inductance

Ψ_{dm}, Ψ_{qm} - Magnetsing 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 casn be written as:

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

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 through 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:

$$T_e = \frac{3}{2}\frac{P}{2}\overline{\Psi}_m \times \bar{I}_r \tag{3.23}$$

The variables can be revolved in $d^e - q^e$ frame, according to figure 3.4 shows the synchronously rotating frame:

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

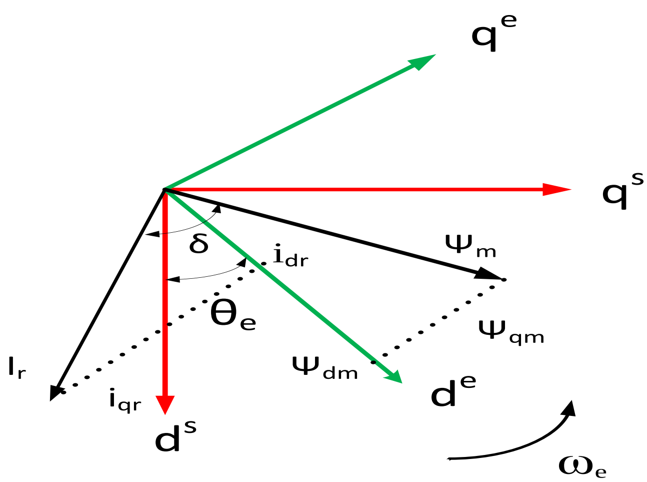


Figure 3.4 Synchronously rotating reference frame

Similarly, other torque equations be derived as shown below:

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

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

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

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

3.3 Vector Control of Induction Motor

Induction machine is simple to implement but produces sluggish response due to the inherent coupling effect. In an induction drive the magnetizing current and the torque-generating current components of stator current are decoupled to the rotor flux like a separately excited dc motor. In vector control the three phase stationary frame (a-b-c) will be converted in two phase stationary frame ($d^s - q^s$) and then to two phase rotating reference frame($d^e - q^e$). For the detection of the rotor flux a hall sensor is directly used in the direct vector control. Indirect vector control is more cost efficient and reliable, it estimates the position of the rotor flux from the motor parameters and it is widely used in industries. In indirect vector control technique a slip frequency command is mandatory for the decoupling for torque-generating and magnetizing currents. This is calculated while using the value of rotor circuit time constant. the variations of this parameter due to variations of saturation of rotor flux ,operating temperature etc., influences the accuracy of the torque and speed performance both in steady state and transient state [45].

Vector control is not only applicable for induction motor but it is also used for synchronous machine drives. In modern sensor less drive vector control is implemented with feedback signal it is complex and the use of DSP and microcomputer are mandatory to use. Vector control has expelled the use of scalar control in industrial application.

3.3.1 Indirect Vector Control

In Indirect vector control the unit vector signals ($\cos\theta_e$, $\sin\theta_e$) will be generated in feed-forward technique. Figure 3.5 shows the block diagram representation of Indirect vector control This method is very popular in industries for its performance and efficiency. Indirect vector control is a feed forward scheme, it mainly depends on the machine parameters that is rotor resistance which gets changed with the increase in temperature. Stator and rotor resistances are the most critical parameters which will get affected by the increase in temperature variation, the variation in these values can be 100% of their actual values. Figure explains the phasor diagram of induction motor drive.

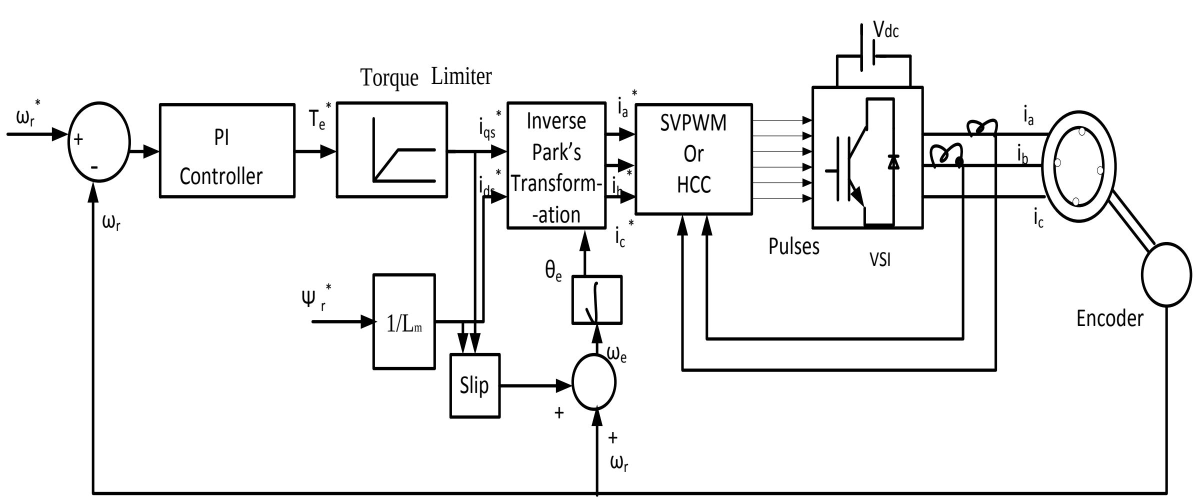


Figure 3.5: Block diagram representation of Indirect vector control

The $d^s - q^s$ and $d^r - q^r$ axes are fixed at the stator and the rotor terminal of the machine. Figure 3.6 shows the phasor representation of Indirect Vector Control The $d^r - q^r$ axes is at the rotor which is moving at a speed of ω_r. And the synchronously rotating $d^e - q^e$ axes which is moving ahead of slip angle θ_{sl} from the $d^r - q^r$ axes.[2]

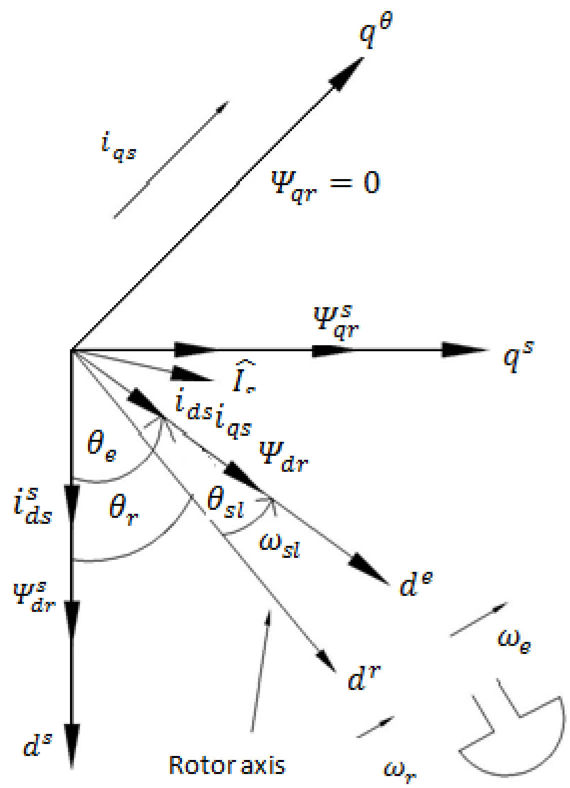


Figure 3.6, Phasor representation of Indirect Vector Control

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:

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

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

The flux equations for the rotor are as given below:

$$\Psi_{dr} = L_r\, i_{dr} + L_m\, i_{ds} \quad (3.33)$$

$$\Psi_{qr} = L_r\, i_{qr} + L_m\, i_{qs} \quad (3.34)$$

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

$$i_{dr} = \frac{1}{L_r}\Psi_{dr} - \frac{L_m}{L_r} i_{ds} \quad (3.35)$$

$$i_{qr} = \frac{1}{L_r}\Psi_{qr} - \frac{L_m}{L_r} i_{qs} \quad (3.36)$$

Rotor currents component can be eliminated from these equations 3.33 and 3.34 while substituting the equation 3.35 and 3.36 are as follows :

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

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

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:

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

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

$$\widehat{\Psi_r} = \Psi_{dr}$$

$$\widehat{\Psi_r} = L_m i_{ds} \tag{3.42}$$

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

Direct vector control or the feedback control was invented by Blashke in 1968. In this control the values of synchronously rotating reference frame will be converted into synchronously stationary frame with the help of unit vectors as a vector rotation (VR), generated through the flux signals Ψ_{dr}^{s} *and* Ψ_{qr}^{s}. Then these stationary frame signals will be applied to the input end of the inverter. Figure 3.7 shows the block diagram representation of direct vector control. The voltage and current from the machine terminal will be used for the voltage model of the estimator or to the flux estimator model to generate the flux signals Ψ_{dr}^{s} *and* Ψ_{qr}^{s}.

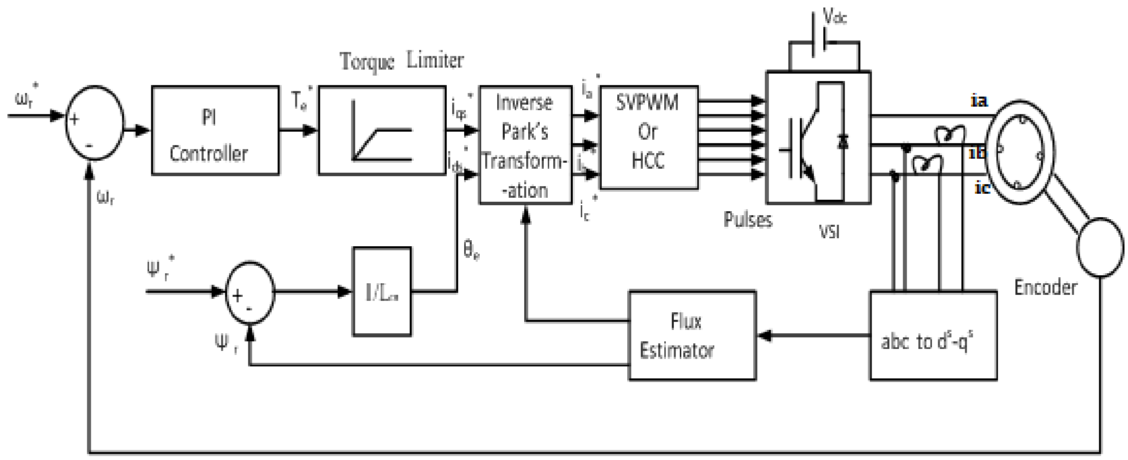


Figure 3.7, Block diagram representation of Direct Vector Control

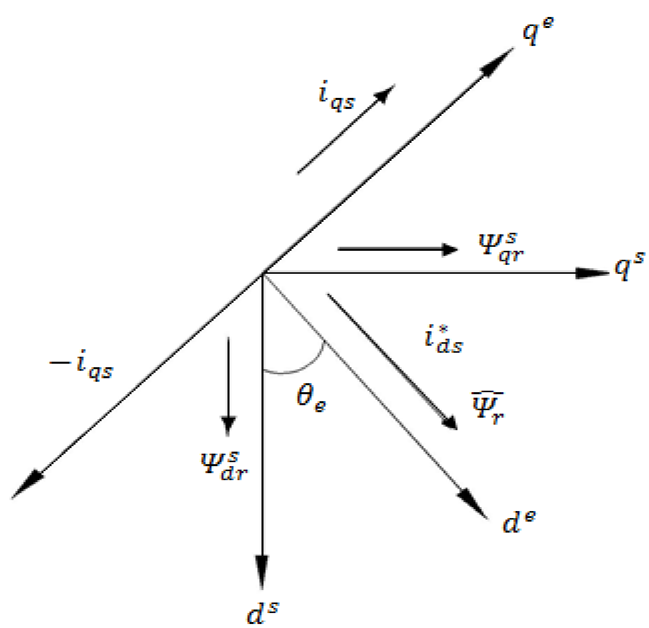


Figure 3.8, Phasor diagram of Direct vector control

The current i_{ds} is correctly aligned with the direction of flux $\widehat{\Psi_r}$. The quadrature axes current i_{qs} will be perpendicularly apart from the flux $\widehat{\Psi_r}$. with the help of phasor diagram figure 3.8 shows the fluxes will be explained, and the rotating reference frame $d^e - q^e$ is moving at the speed ω_e w.r.t the stationary axes $d^s - q^s$. The angular position between the d^e-axis and the d^s-axis is θ_e we can write following equations.

$$\Psi_{dr}^{s} = \widehat{\Psi_r} \cos\theta_e \tag{3.43}$$

$$\Psi_{qr}^{s} = \widehat{\Psi_r} \sin\theta_e \tag{3.44}$$

$$\cos\theta_e = \frac{\Psi_{dr}^{s}}{\widehat{\Psi_r}} \tag{3.45}$$

$$\sin\theta_e = \frac{\Psi_{qr}^{s}}{\widehat{\Psi_r}} \tag{3.46}$$

$$\widehat{\Psi_r} = \sqrt{{\Psi_{dr}^{s}}^{2} + {\Psi_{qr}^{s}}^{2}} \tag{3.47}$$

- For the low frequencies V_{ds}^{s} and V_{qs}^{s} voltage signals are very low, but now due to problem of integrating arises at the output of integrator that dc offset will get build up.
- Variation in machine parameters will affect the dynamic behavior of machine and that will reduce the accuracy of the system. Increase in temperature will dominate the machine parameters. But in case of higher voltage values we can neglect the parameter variations of machine.[2]

3.4 Sensorless vector control

Speed sensors attached to machine drives increases the cost and decreases the reliability of the machines. For moderate performance in application drives sensorless drives are the best options. Figure 3.9 shows the block diagram representation of Sensorless vector control drive. In this control estimated speed signal from machine voltage and current. As speed is observe and estimated depends upon the machine parameters, in that case special care has been taken with the variations in the parameters. Figure 3.9 shows the sensorless vector control drive.[46]

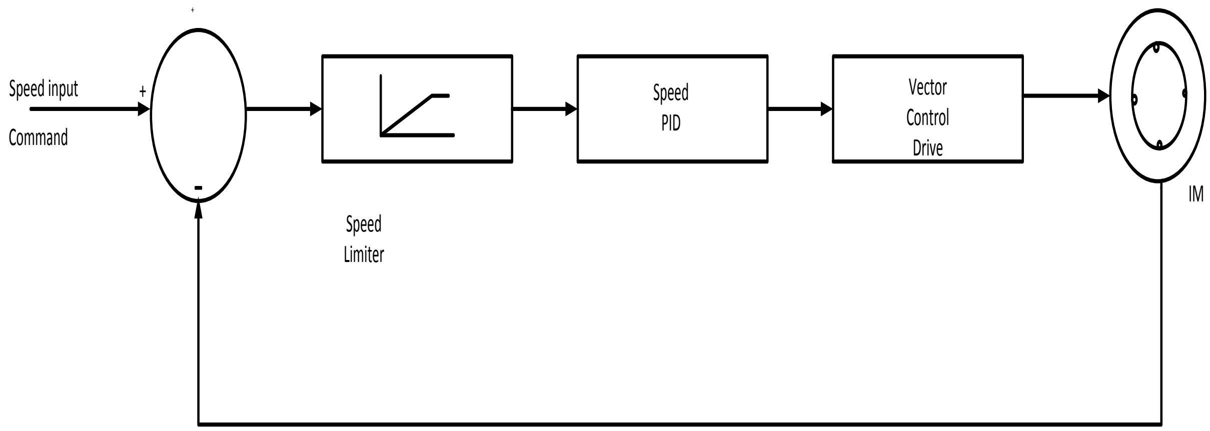


Figure 3.9: Sensorless vector control drive

We get voltage and current from machine terminals and flux estimator will estimates the d-q rotor flux. From the d-q axes flux components the rotor flux Ψ_r will become:

$$\Psi_r = \sqrt{(\Psi_{qr}^s)^2 + (\Psi_{qr}^s)^2} \tag{3.48}$$

And for the estimating speed the speed estimator ω_r will be

$$\omega_r = \frac{1}{\Psi_r^2}(\left[\Psi_{dr}^s \Psi_{qr}'^s - \Psi_{qr}^s \Psi_{dr}'^s\right] - \frac{L_m R_r}{L_r}\left[\Psi_{dr}^s i_{qs}^s - \Psi_{qr}^s i_{ds}^s\right] \tag{3.49}$$

Where $\Psi_{qr}'^s$ and $\Psi_{dr}'^s$ quantities are the first derivatives of Ψ_{qr}^s and Ψ_{dr}^s

3.5 MATLAB model and simulations

3.5.1 MATLAB model of Indirect Vector Control

A Simulink model of the Vector Control is developed while using the components from the MATLAB Simulink Power Systems Block set. They provides models for the power electronics devices and for the control structures of vector control drive. The control scheme simulated is in discrete time and the blocks used in the designing are already available in the Simulink library. Some blocks which are not available in the library are constructed. Figure 3.10 shows the MATLAB simulation of Vector control of Induction motor.

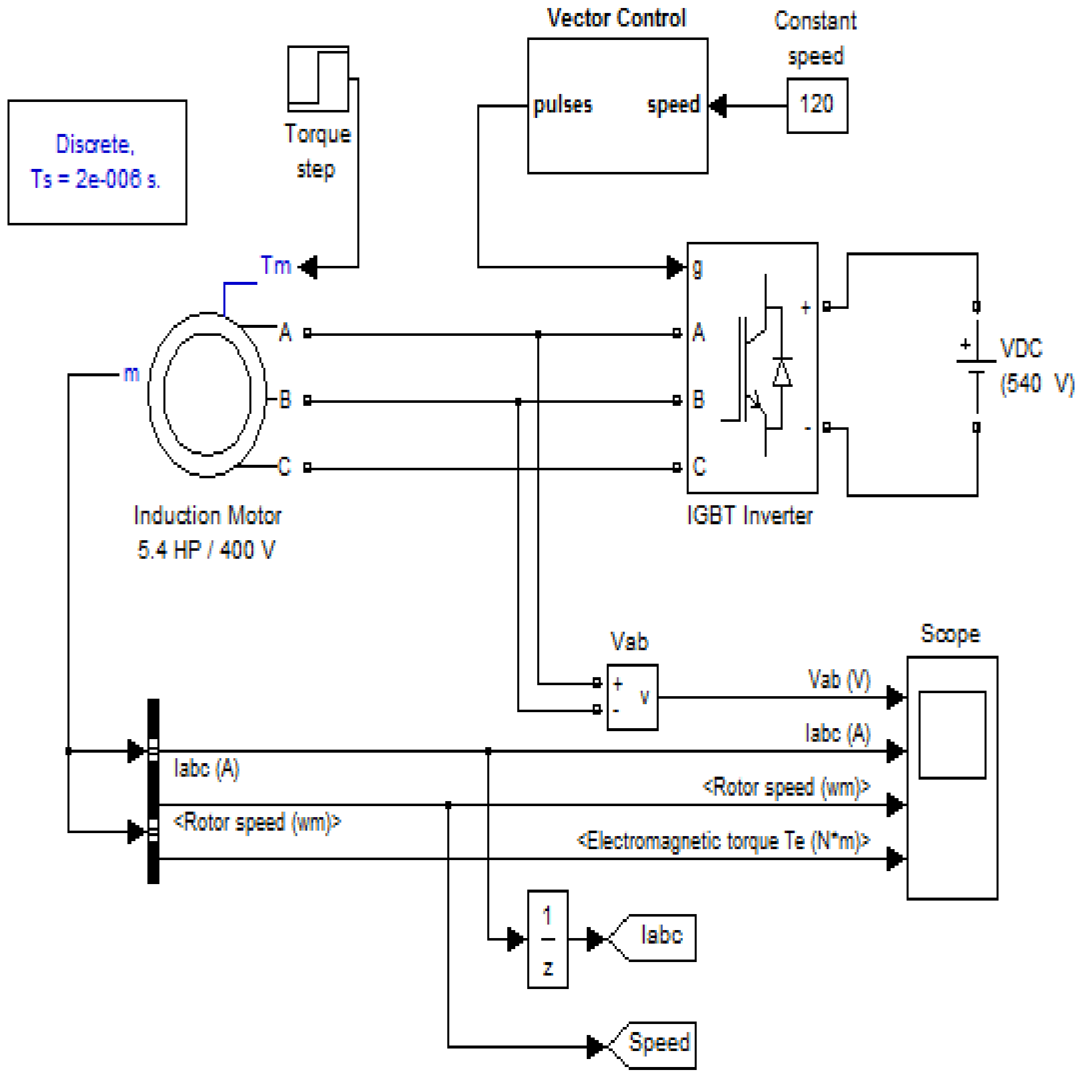


Fig 3.10 MATLAB Simulink model of vector control of Induction motor

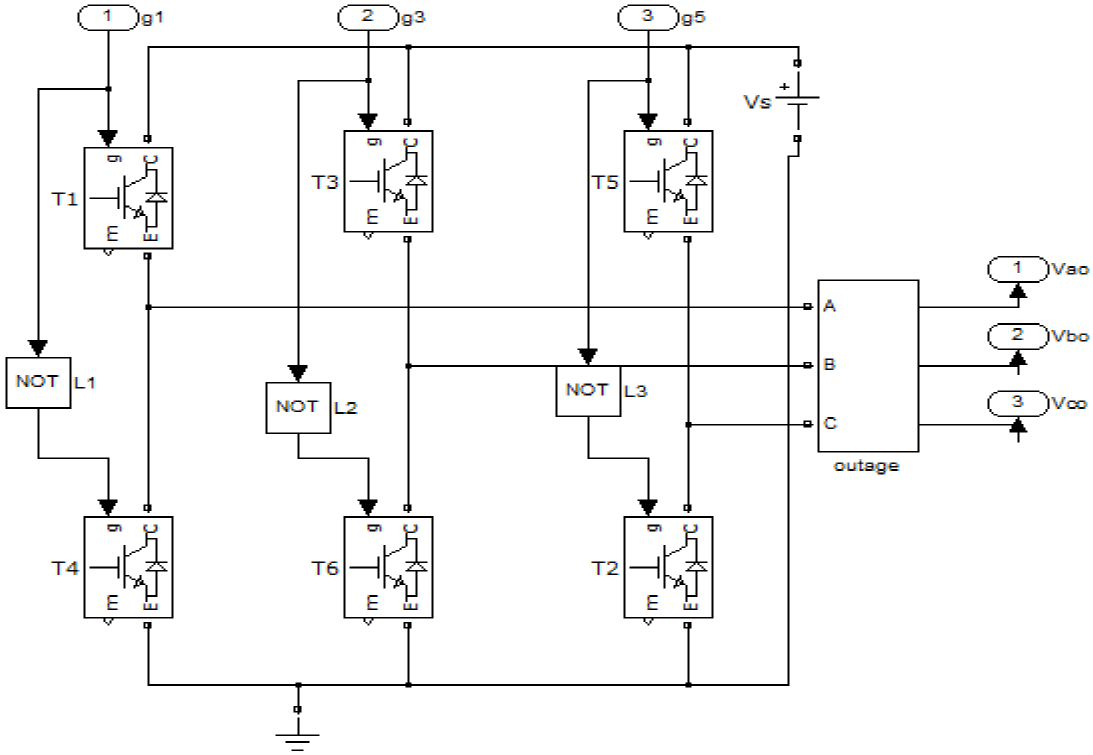


Figure 3.11 MATLAB model of voltage source inverter

3.5.2 Simulation Results

Indirect vector control of induction motor using the hysteresis current controller is designed to see the dynamic performance of the machine, induction motor was started with the speed of 100 rad/sec. The starting stator current i_{abc}(A) drawn by the motor is high and with that motor has 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 increases. The speed of induction motor is changed to 100 rad/sec to -100 rad/sec at t=1sec with the reversal in speed the stator current phase gets reversed after that when the phase reversal of current is completed the speed reversal attains its set value.

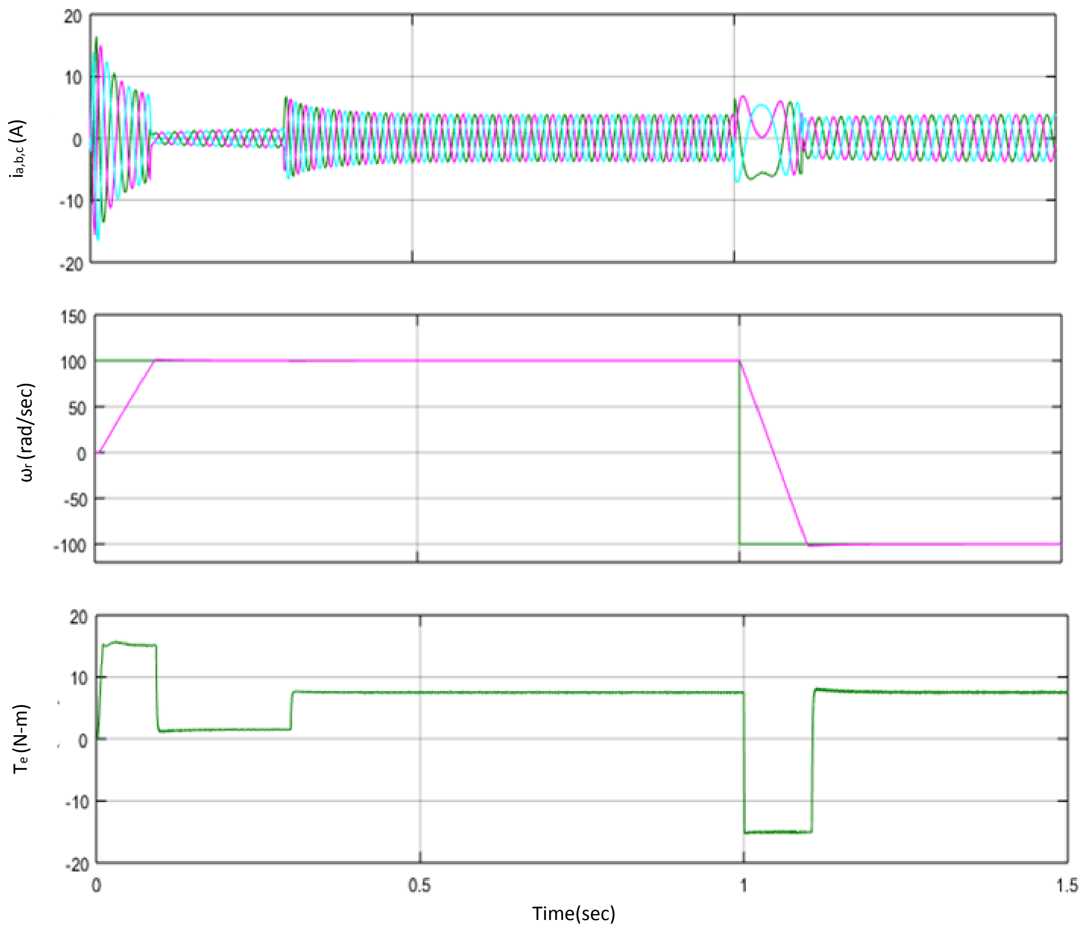


Figure 3.12: Dynamic response of Indirect vector control of induction motor (a)Stator current I_{abc} [A],(b) Rotor Speed ω_r [rad/s] (c)Torque [N/m]

3.6 Conclusion

In this chapter, the dynamic modeling of the induction motor has been discussed and all the time varying inductance that are present in various equations of voltages and torque have been eliminated by exploiting the model in the synchronously rotating reference frame.

CHAPTER IV

CONTROLLING TECHNIQUE FOR ESTIMATION OF ROTOR RESISTANCE

4.1 General

The main aim of this controller is to keep the output of a dynamic system within the specified limit. In the field of control (or adaptive control) model reference adaptive controller (MRAC) deals with the problems related to the parameter variations (temperature variations, disturbances, etc.). An adaptive controller is designed for the problem arises due to varying parameters, they are adjusted such a way that they adapt the uncertainties and the parameter variation of the plant. Adaptive controller provides a time varying solutions to the nature and magnitudes of uncertainties in the plant the closed loop controller gives the better performance. The adaptive controllers are in use from last few decades, this time varying controller provides a stability and robustness in various control techniques.

4.2 Model Reference Adaptive Controller

The concept of the Model Reference Adaptive controller (MRAC), is that it forces the plant to track the response of a reference model to the adjustable model when the variation in plant parameters and disturbance effect occurs. The output error of the two models i.e. the reference model and the adjustable model is fed to an adaptation control mechanism and controller updates the error till the parameters converges to the ideal plant values to obtain similar response as the reference model as shown in figure 4.1. The system dynamics are nonlinear and they are linearized by obtaining the linear controller. The resultant linear model and parameters varies with the operating conditions applied, Parameters can be varied with ageing, changes in the loading conditions and disturbances.

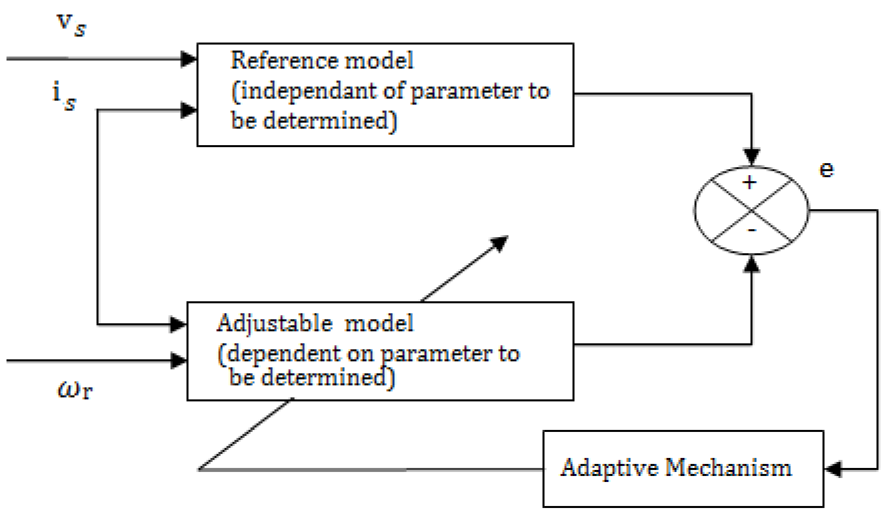


Figure 4.1 model reference adaptive controller

There are two different approaches for model reference adaptive controller such as: direct vector control and indirect vector control. In direct vector control technique only the reference model is used in this controller their parameters are adjusted to minimize the error (output) of the plant. In indirect vector control technique the unknown parameters of the plant are estimated through the adjustable model and the reference model. In MRAC controller the reference model is based on the actual reactive power model and this has the advantages of avoiding pure integration and very less sensitive to parameter variations. The adjustable model is based on estimated reactive power and the input to the adjustable model is stator voltage, previous value of stator current, rotor flux and rotor speed.

4.2.1 MRAC in control applications

The induction drive speed can be estimated with rotor speed considering as an unknown quantity of the adaptive controller. The rotor resistance is estimated by considering the rotor time constant as an unknown quantity. Both the models are dependent on different parameters of the motor and the error of both the models is fed to an adaptive controller. MRAC have some advantages such as:

1. The model implementation is easy and simple and has direct interpretation.

2. It has a potential for implementing a high performance control, when dynamic characteristics of a plant are bad.

3. Technique gives flexibility in achieving the goals.

4.2.2 Stability of the MRAC estimator

The estimated values to the actual values can be attained with the suitable dynamic characteristics and it provides a stable and quick response. The state error equations of the MRAC technique are assured to be asymptotically stable.

The adaptation mechanism will be derived from the below state error equations which are produced by subtracting the adjustable model equations from the reference model equations.

Let

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

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

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

The instanteous 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

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

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

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

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

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

$$R_r^* = \omega_{sl}^* \frac{3P}{4} \Psi_r^{*2} \frac{1}{T_e^*} \tag{4.8}$$

The PI controller is used in adaptive mechanism for the estimation of rotor time constant. $\beta_r = (K_p + K_i /p).\varepsilon$ (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

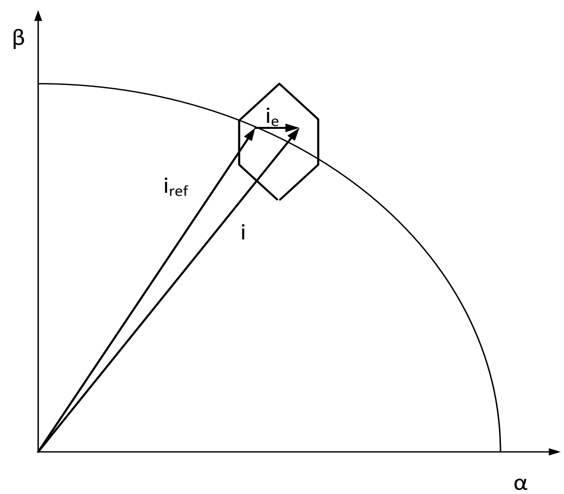
K_I= Integral controller

Ψ_r^*= Estimated flux linkage

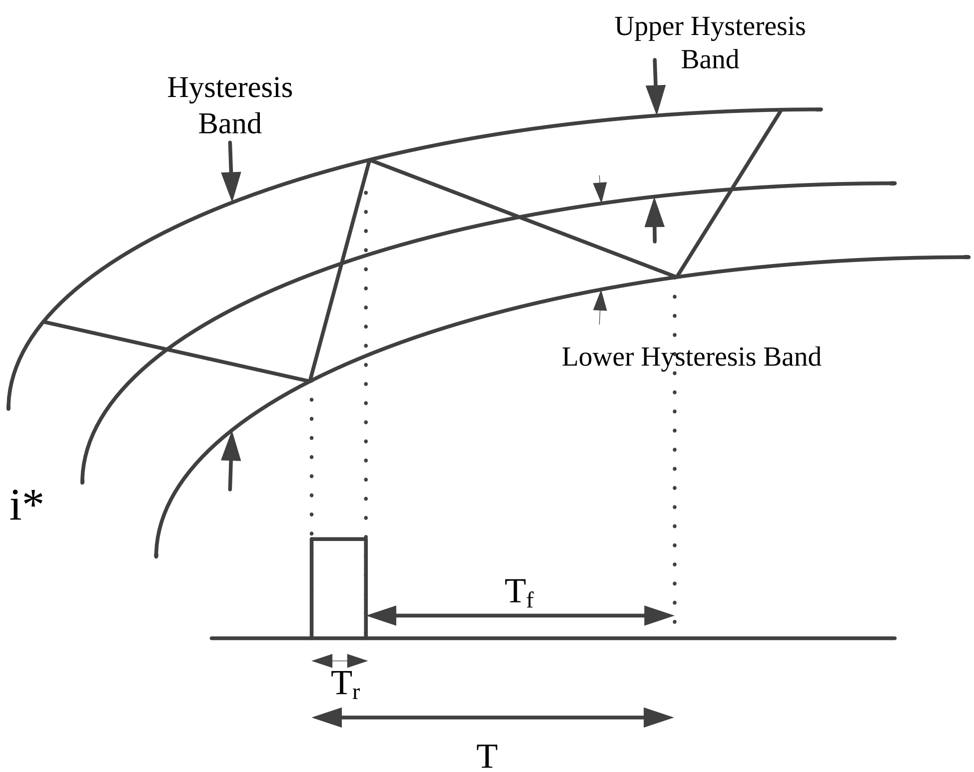
4.3 Hysteresis Current Controller

The hysteresis current control is the simple and extensively used methods. In this, hysteresis comparators are used to impose a hysteresis or fixed dead band around the reference current. The basic implementation of hysteresis current control is based on deriving the switching signals from the comparison of the current error with a fixed tolerance band. When the magnitude of the current exceeds the tolerance band, the switching pattern of the inverter will change. This type of band control is negatively affected by the interactions of phase current 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 4.2(a),(b): Principle of hysteresis-band current control

The main aim is that the actual value of the currents remains in their hysteresis band throughout the time. The three currents are not independent from each other, and the system will be transformed into (α, β) coordinate system. The transformation of three phase coordinate into two phase (α, β) coordinate system in the hysteresis band the result lies in an hysteresis hexagon area. In this the reference current i_{ref} points toward the center of the hysteresis as shown in in figure 4.2a. In steady state condition the reference current will moves on circle around the origin of the (α, β) coordinate system. Hence the hexagon also moves on this circle.

4.4 SPACE VECTOR PULSE WIDTH MODULATION

Space Vector Pulse Width Modulation (SVPWM) is an algorithm that translates phase voltage references (phase to neutral) coming from controller into duty cycles and it is applied to the switches i.e. IGBT's or MOSFET's. In general, this technique is used for three phase loads especially motor control. SVPWM maximizes the DC voltage utilization that is applied to inverter and it reduces the harmonic content as it uses nearest vectors and the three phase inverter is shown in figure 4.3. But, at the same time SVPWM has to do a lot of sampling, calculating and waveform manipulation.

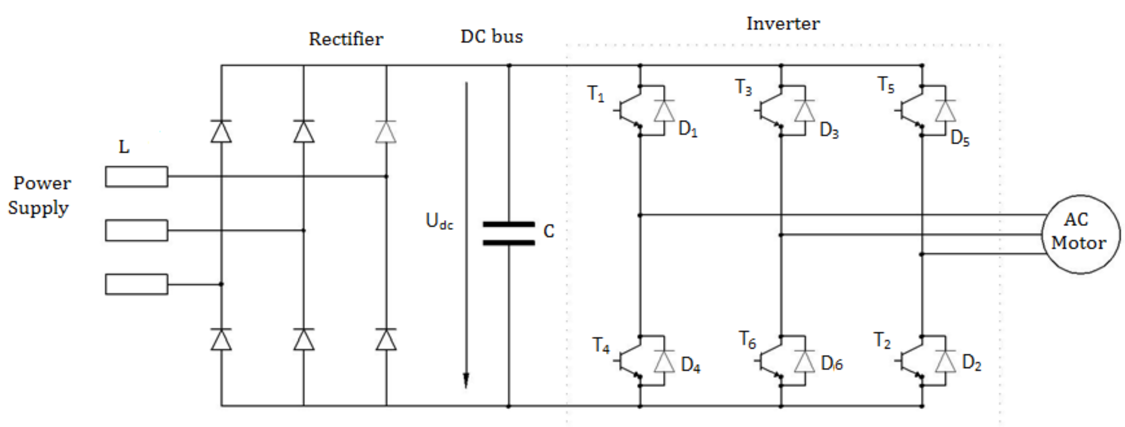


Figure 4.3 Three phase voltage source inverter

The classical application of SVPWM is vector motor control, which is based on the control of currents / voltages projection on two orthogonal coordinates ($d - q$). Hence, SVPWM takes voltages v_d and v_q as input quantities from controller and generates PWM waves accordingly. The basic concept of SVPWM can be understood by SVM (Space Vector Modulation) Technique. SVM is an algorithm that is used for the control of Pulse Width Modulation and it is generally used in case of three phase inverter.

The controlling of six switches will be done so that no two switches of the same arm gets simultaneously closed, otherwise short circuit of input DC voltage will occur. Hence, both the switches in the same arm must complement to each other and on doing so, eight switching vectors will be generated. SVM basically allows a three phase bridge PWM drive to supply about 15% higher peak voltage to a motor than the standard sine triangle modulation scheme by allowing the neutral point of the motor to move away from the nominal half of the supply. The characteristic voltage output of an SVM-modulated sine wave is a sine wave with a double-hump on the peaks.[47]

The graphical depictions of all combinations of hexagon form as shown in figure 4.4. In which six non zero states (v_0, v_{60}, v_{120}, v_{180}, v_{240}, v_{300}) and two zero states (O_{000}, O_{111}). Table 4.1 shows the combinations which contains six non zero states and two zero states.

Table 4.1 Switching combinations of Space Vector Pulse Width Modulation

S_{At}	S_{Bt}	S_{Ct}	v_a	v_b	v_c	v_{ab}	v_{bc}	v_{ca}	Vector
0	0	0	0	0	0	0	0	0	O_{000}
1	0	0	$2v_{d/3}$	$-v_{d/3}$	$-v_{d/3}$	v_d	0	v_d	v_0
1	1	0	$v_{d/3}$	$v_{d/3}$	$-2v_{d/3}$	0	v_d	v_d	v_{60}
0	1	0	$-v_{d/3}$	$2v_{d/3}$	$-v_{d/3}$	$-v_d$	v_d	0	v_{120}
0	1	1	$-2v_{d/3}$	$v_{d/3}$	$v_{d/3}$	$-v_d$	0	v_d	v_{180}

0	0	1	$-v_{d/3}$	$-v_{d/3}$	$2v_{d/3}$	0	$-v_d$	v_d	v_{260}
1	0	1	$v_{d/3}$	$-2v_{d/3}$	$v_{d/3}$	v_d	$-v_d$	0	v_{300}
1	1	1	0	0	0	0	0	0	O_{111}

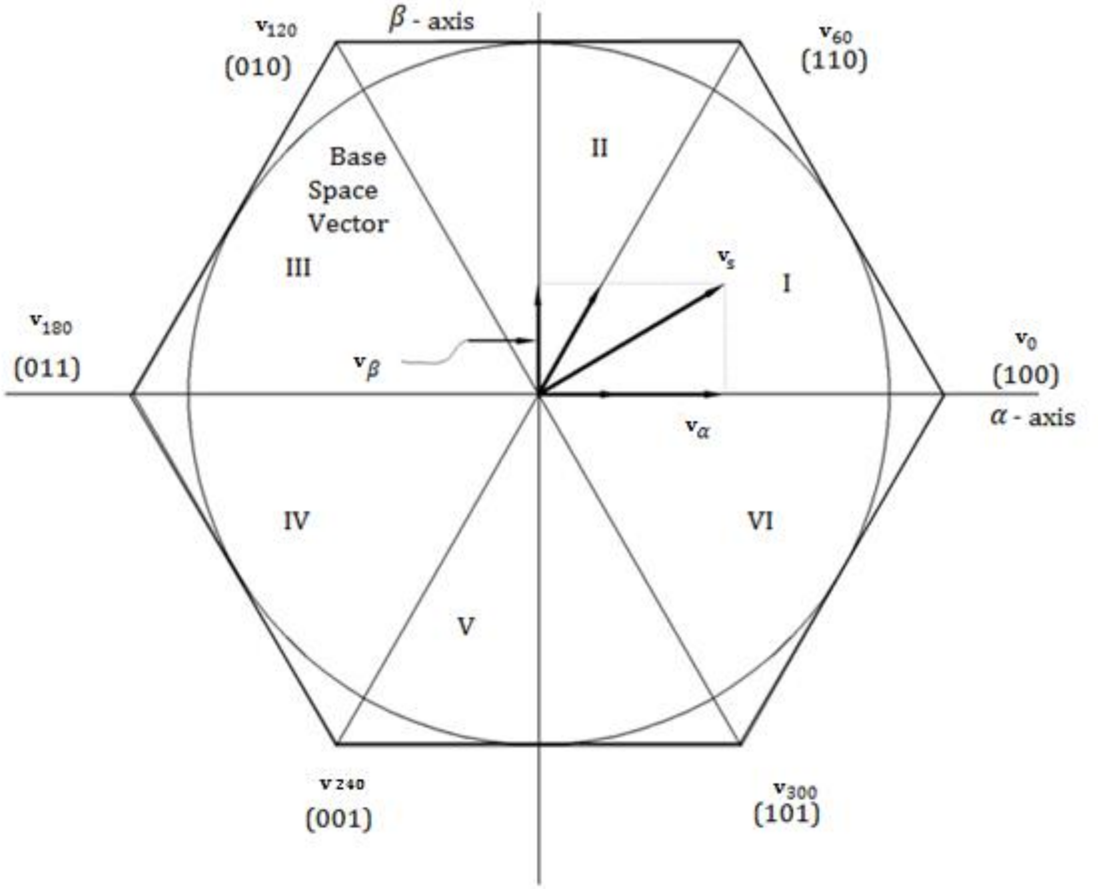


Figure 4.4 The graphical depiction of all combinations is in hexagon form

4.4.1 Space Vector Pulse Width Modulation Control Algorithm

Space vector pulse width modulation is applied to output voltage and input current control. This method has an advantage because of increased flexibility in the choice of switching vector for both input current and output voltage control. It can yield useful advantage under unbalanced conditions. The three phase variables are expressed in space vectors. For a sufficiently small time interval, the reference voltage vector can be approximated by a set of stationary vectors generated by a matrix converter.

If this time interval is the sample time for converter control, then at the next sampling instant when the reference voltage vector rotates to a new angular position, it may correspond to a new set of stationary voltage vectors. Carrying this process by sampling the waveform of the desired voltage vector being synthesized in sequence, the average output voltage would closely emulate the reference voltage.

Modulation of the line to line voltage naturally gives an extended output voltage capability. The computational procedure required by SVPWM method is less complex than that for Venturini method because of the reduced number of sine function computations (Kolar et al 1991). The number of switch commutations per switching cycle for SVPWM method is 20% less than that of Venturini method.

Roots of vectorial representation of three-phase systems are presented in the research contributions of Park and Kron, but the decisive step on systematically using the Space Vectors was done by Kovacs and Racz (Park 1933). They provided both mathematical treatment and a physical description and understanding of the drive transients even in the cases when machines are fed through electronic converters [48].

SVPWM refers to a special switching sequence of the upper three power transistors of a three-phase power inverter. It has been shown to generate less harmonic distortion in the output voltages and or currents applied to the phases of an AC motor and to provide more efficient use of supply voltage. The objective of space vector PWM technique is to approximate the reference voltage vector V_{ref} using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period, T to be the same as that of V_{ref} in the same period. Therefore, space vector PWM can be implemented by the following steps:

Step 1 : Determine v_d, v_q, and angle between v_s and v_α.

Step 2 : Determine time duration T_1, T_2, T_0. The concerned formulae have been shown.

Step 3 : Determine the switching time of each transistor (S1 to S6)

All sectors in SVPWM are shown in Figure 4.4. It uses a set of vectors that are defined as instantaneous space vectors of the voltages and currents at the input and output of the inverter. These vectors are created by various switching states that the inverter is capable of generating.

$$T1 = \frac{|v_{SX}|}{|v_X|} T_{PWM}\ for\ vectors\ v_X \tag{4.11}$$

$$T_2 = \frac{|v_{SX}|}{|v_{X\pm 60}|} T_{PWM}\ for\ vectors\ v_{X\pm 60} \tag{4.12}$$

$$T_0 = T_{PWM} - (T_1 + T_2)\ for\ either\ (\ O_{000}\ or\ O_{111}) \tag{4.13}$$

T_0, T_1, T_2 = Time periods

v_d, v_q = direct and the quadrature axis voltage

S_1, S_2, S_3, S_4, S_5, S_6= Switching time of transistors

4.5 MATLAB model of vector control of Induction motor with SVPWM controller

Matlab model of indirect vector control of induction motor with the space vector pulse width modulation technique is developed in the MATLAB/Simulink environment as shown in figure 4.5. The speed, torque and currents graphs are plotted, with the step change in load torque at t=3.5sec and the speed reversal at t=1 sec is observed and discussed below in figure 4.6

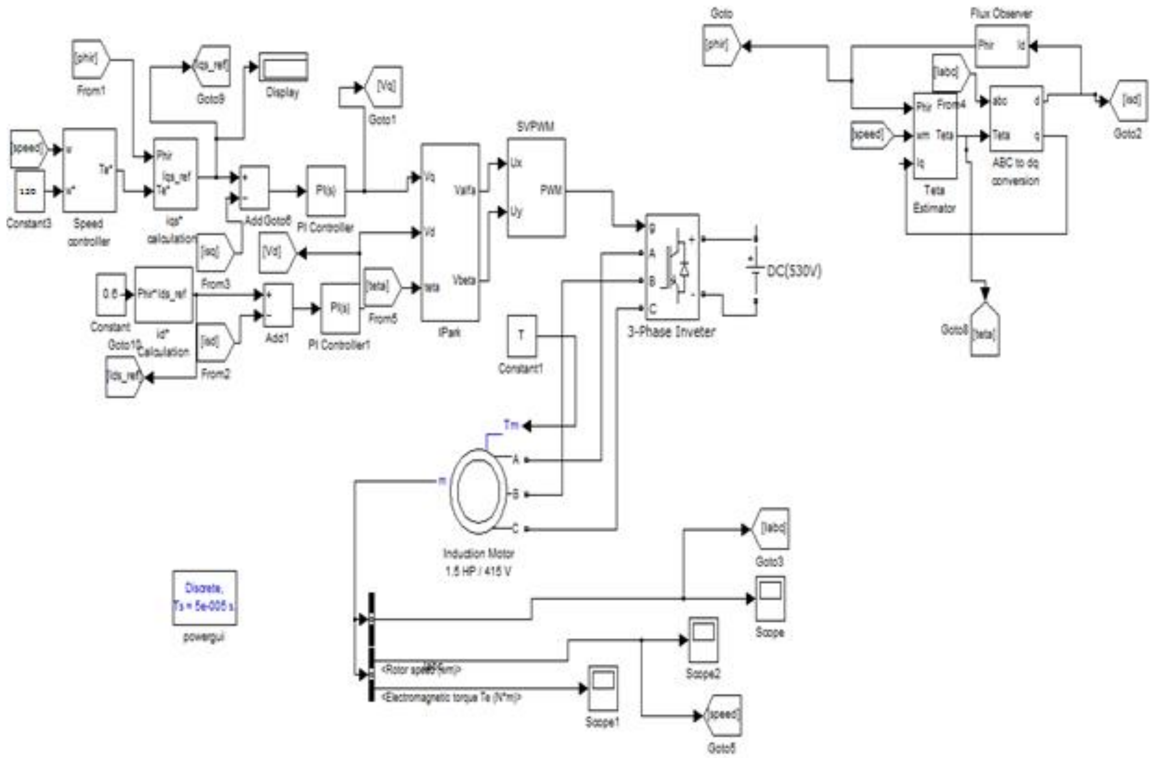


Figure 4.5 MATLAB model of vector control with SVPWM inverter

4.5.1 Simulation results

Indirect vector control of induction motor using the SVPWM controller is implemented, initially induction motor was started with the speed of 100 rad/sec. The starting stator current i_{abc}(A) drawn by the motor is high and with that motor has high starting torque. The load torque is kept zero from t=0sec to t=0.35sec after that the load torque is changed to 4N-m and with that the stator current increases to 3 ampere. The speed of induction motor is changed to 100 rad/sec to -100 rad/sec at t=1sec as the speed changes the stator current phase gets reversed, when the phase reversal of current is completed the speed reversal attains its set value.

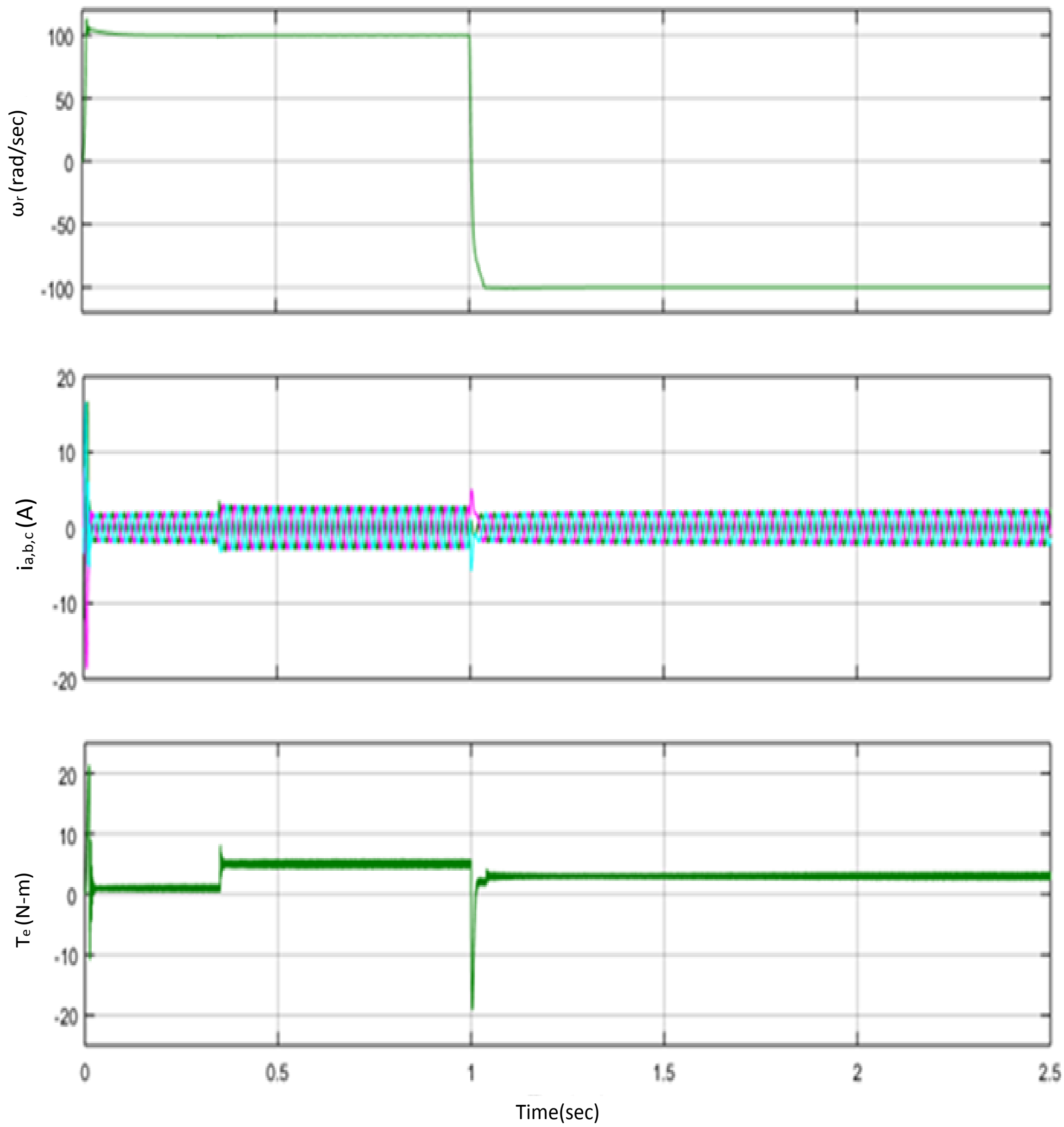


Figure 4.6: Dynamic response of Indirect vector control of induction motor (a)Stator current I_{abc} [A],(b) Rotor Speed ω_r [rad/s] (c)Torque [N/m]

4.6 Proportional and Integral controller

The PI (proportional plus integral) controller is the most frequently used controller in practical applications. The PI controller stems from a PID controller with the D-term (derivative) deactivated. The D-term is often deactivated because it amplifies random (high-frequent) measurement noise, causing abrupt variations in the control signal. The schematic diagram of proportional and integral controller is shown in figure 4.7. The continuous-time PI controller function is as follows:

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

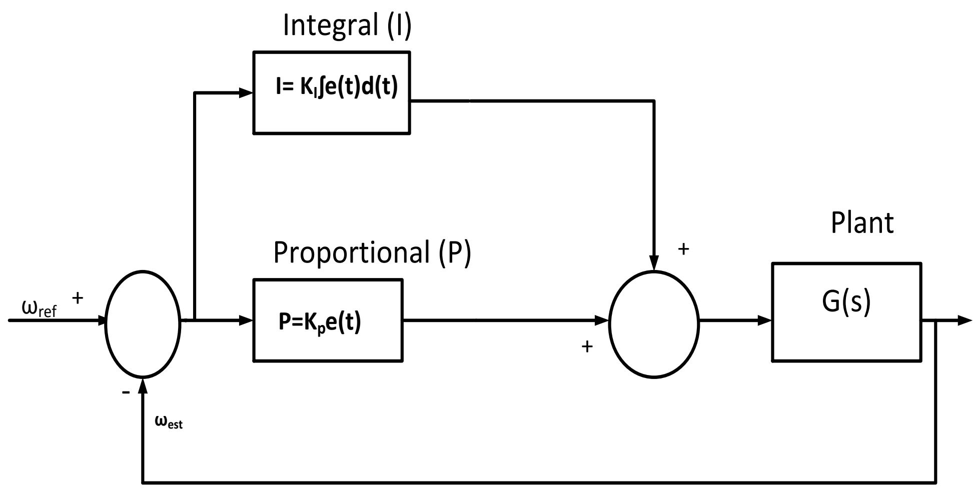


Figure 4.7 Proportional and integral controller

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

K_P= Proportional control gain

K_P= Integral control gain

ω_{ref}= Reference speed

ω_{est}= Estimated speed

In most practical applications the continuous-time PI controller is implemented as a corresponding discrete-time algorithm based on a numerical approximation of the integral term. Typically, the sampling time of the discrete-time controller is so small – compared to the dynamics (response-time or time-constant) of the control system [49].

Proportional and integral controller is also knows as feedback controller. Proportional controller has a major drawback it produces offset and to eliminate that integral controller has implemented but it makes the response sluggish. The PI speed controller output gives the electromagnetic torque which is then used for evaluating the stator current i_{qs}^*. For the constant torque and rotor flux values the stator quadrature current i_{qs}^* is constant. Also the stator direct current i_{ds}^*component should be constant and consequently 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].

4.7 Conclusion

This chapter classifies controlling techniques of induction machine and different methods for rotor resistance estimation. It concludes that vector control provides the good dynamic performance in comparison to scalar control. PWM control using SVPWM (Space Vector PWM) is discussed. This technique is implemented in the MATLAB simulation.

Chapter V

SIMULATION RESULTS & DISCUSSION

5.1 GENERAL

Simulation of indirect vector controlled induction motor drive in MATLAB/Simulink for the analysis of motor dynamics is presented in this chapter. Complete mathematical model of the indirect vector controlled induction motor and rotor resistance estimation using model reference adaptive controller is described and analysed in detail. The MATLAB model using the library of Simulink blocks is developed and analyzed. The developed block diagram can be simulated with the help of different solvers. These solvers can solve the internal variables with the help of ordinary differential equations. By choosing the suitable solver, it can decrease the computational time and improves the accuracy of the simulation.

The controller can be implemented in continuous time using the Laplace variable and in discrete time while using the z variables. The difference between the continuous model and the discrete model is in discrete blocks they responds to change in inputs with a constant period and they 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 can follow the behavior of the dynamic model, to implement this it requires a variable step solver which not only do the calculations but also estimates the step size which decides the occurrence of the steps. The step size improves the speed by avoiding the unnecessary calculations. A system with both continuous and discrete time blocks can solve with the solver Runge-kutta (ODE23 or ODE45 solvers).

5.2 Simulink Model of Indirect Vector Controlled Drive with Rotor Resistance estimation block

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 SVPWM controller for 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 5.2 shows the MATLAB model of vector control drive with rotor resistance estimation block.

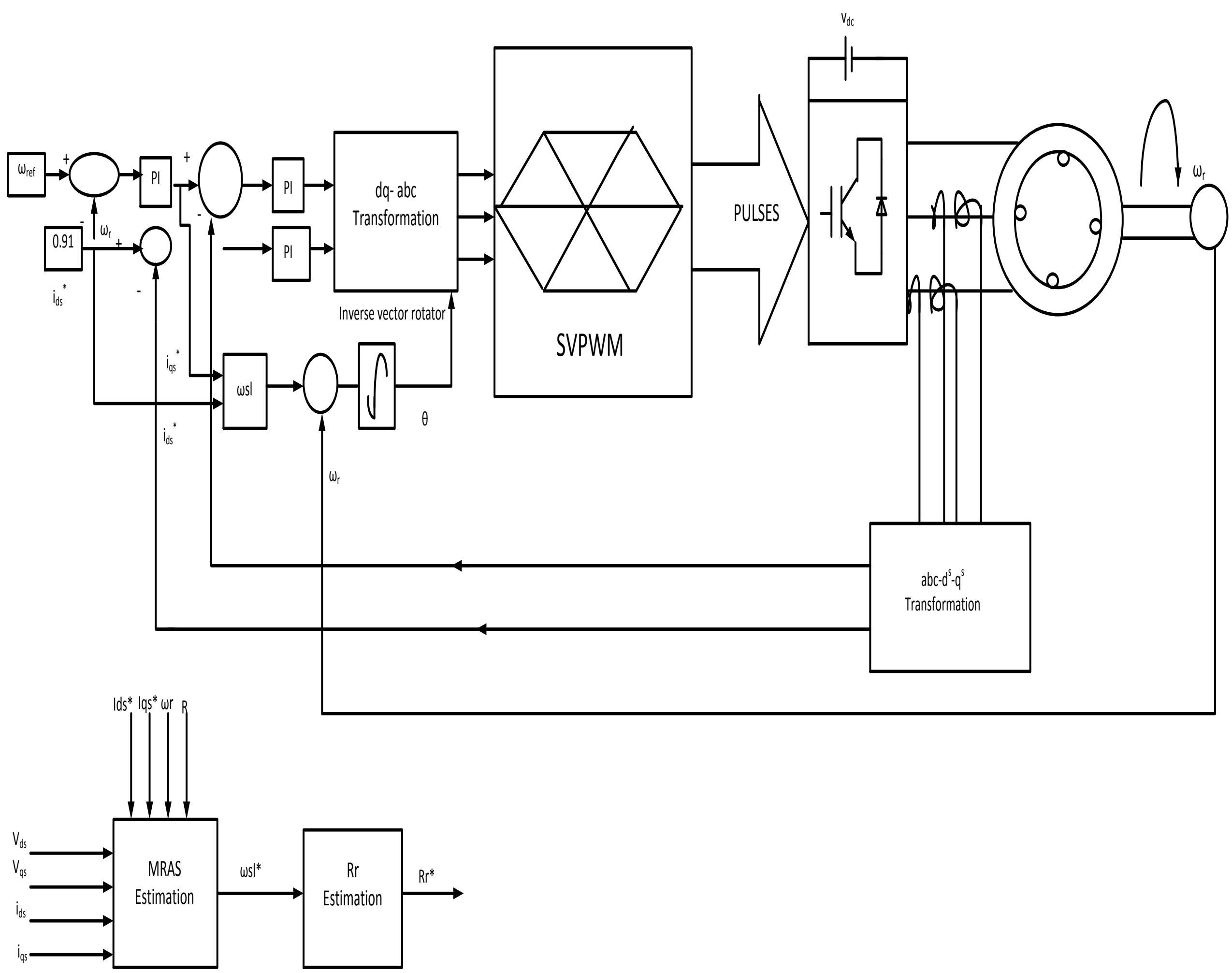


Figure 5.1 Block diagram of rotor resistance estimation of Induction motor

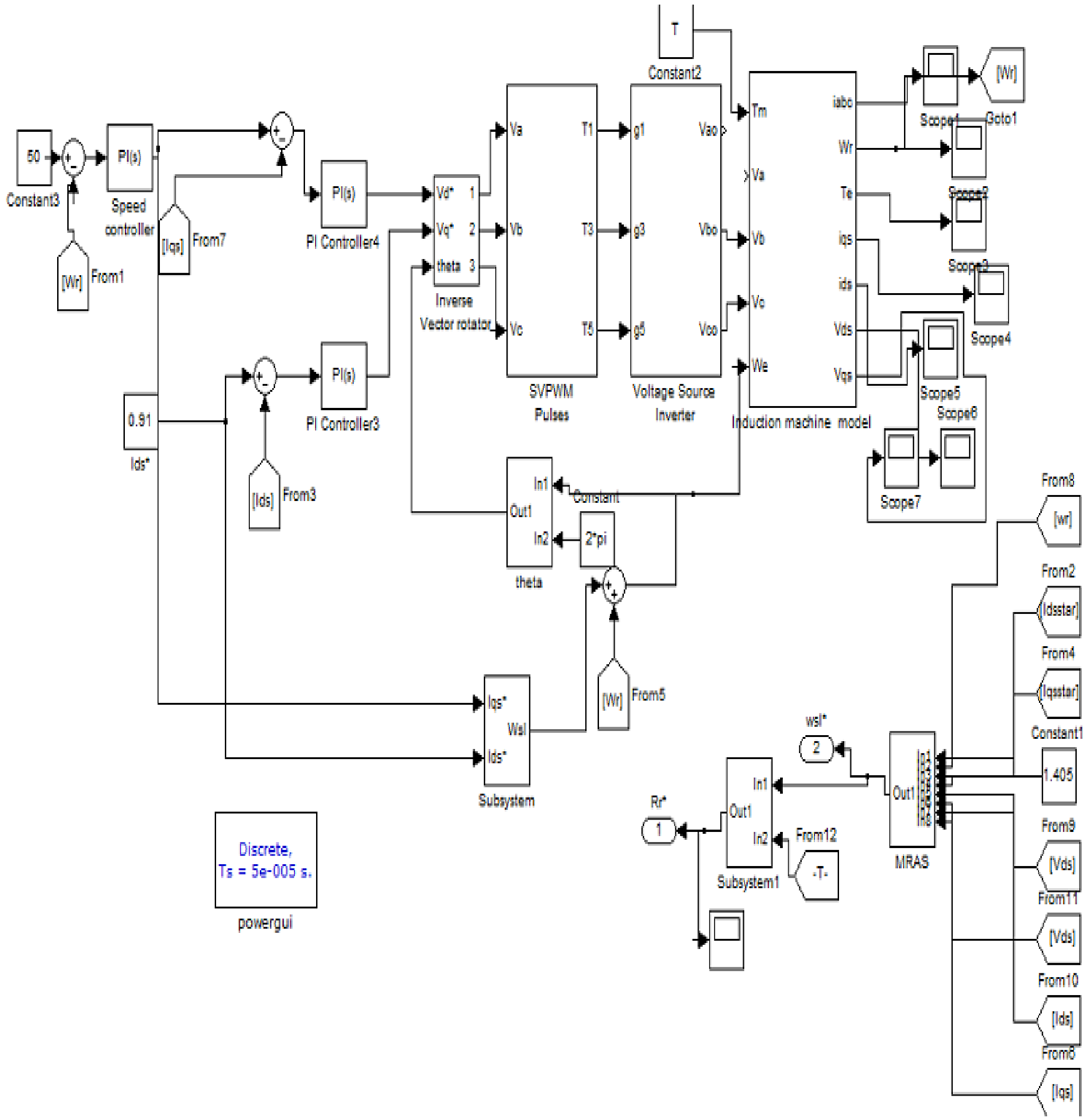


Figure 5.2 shows the MATLAB model of rotor resistance estimation of Induction motor

5.3 Simulation Results

A 3 phase induction motor 5.4 HP, 400V, 50Hz, 1430rpm is being considered for simulation study and rotor resistance estimation under different conditions.

The MRAC 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 MRAC tracks the actual rotor resistance of the machine.

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

A. Trapezoidal profile of change in rotor resistance is used in this thesis for the study of machine tracking performance of the above. The resistance increases linearly and decreases linearly in trapezoidal change form as shown in figure 5.3.

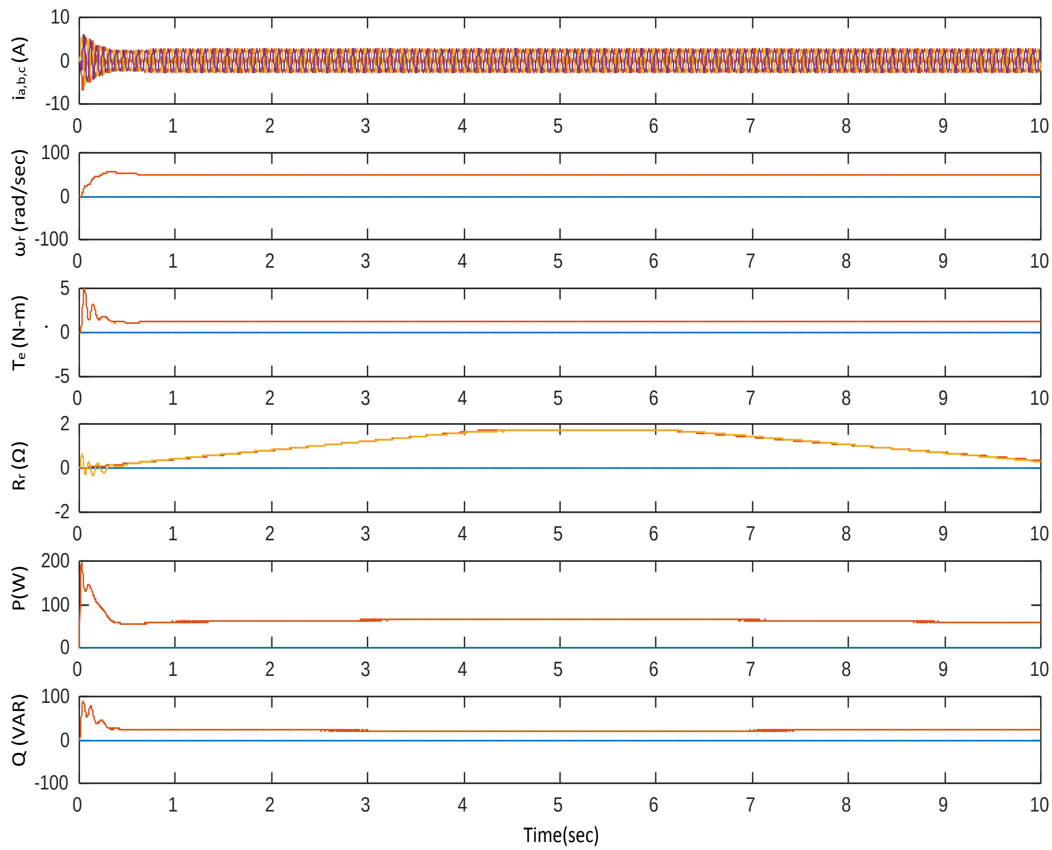


Figure 5.3 Dynamic response of Indirect vector control of induction motor on trapezoidal change in rotor resistance (a)Stator current I_{abc} [A],(b) Rotor Speed ω_r [rad/s] (c)Torque [N/m] (d) Rotor Resistance [ohm] (e)Active Power [P] (f) Reactive Power [Q]

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=0.5sec 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 attains the steady state stator current. Due to high starting current the initial torque of the motor has some transients from t=0sec to t=0.6 sec after that t=0.6 to t=10sec the torque attains the steady state condition. The initial current drawn by motor is high so the active power (W) consumed by the motor is also high. With the trapezoidal change in rotor resistance it affects the active power and reactive power with the small linear change.

B. Estimation of Rotor Resistance for Indirect Vector Controlled Induction Motor (IVCIM)

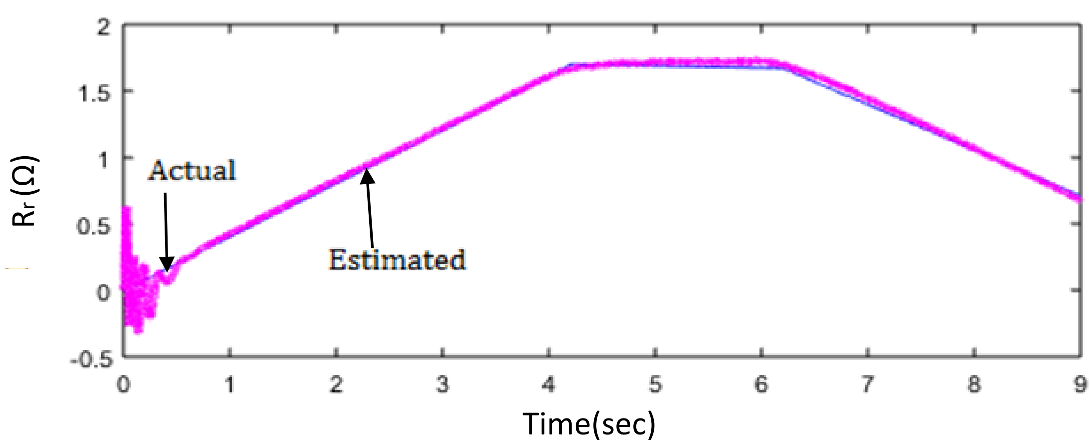


Figure 5.4 Trapezoidal Change in the Rotor Resistance of Induction motor

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 1.6ohm resistance after that at t=6 sec 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 controlled induction motor under the speed reversal operation.

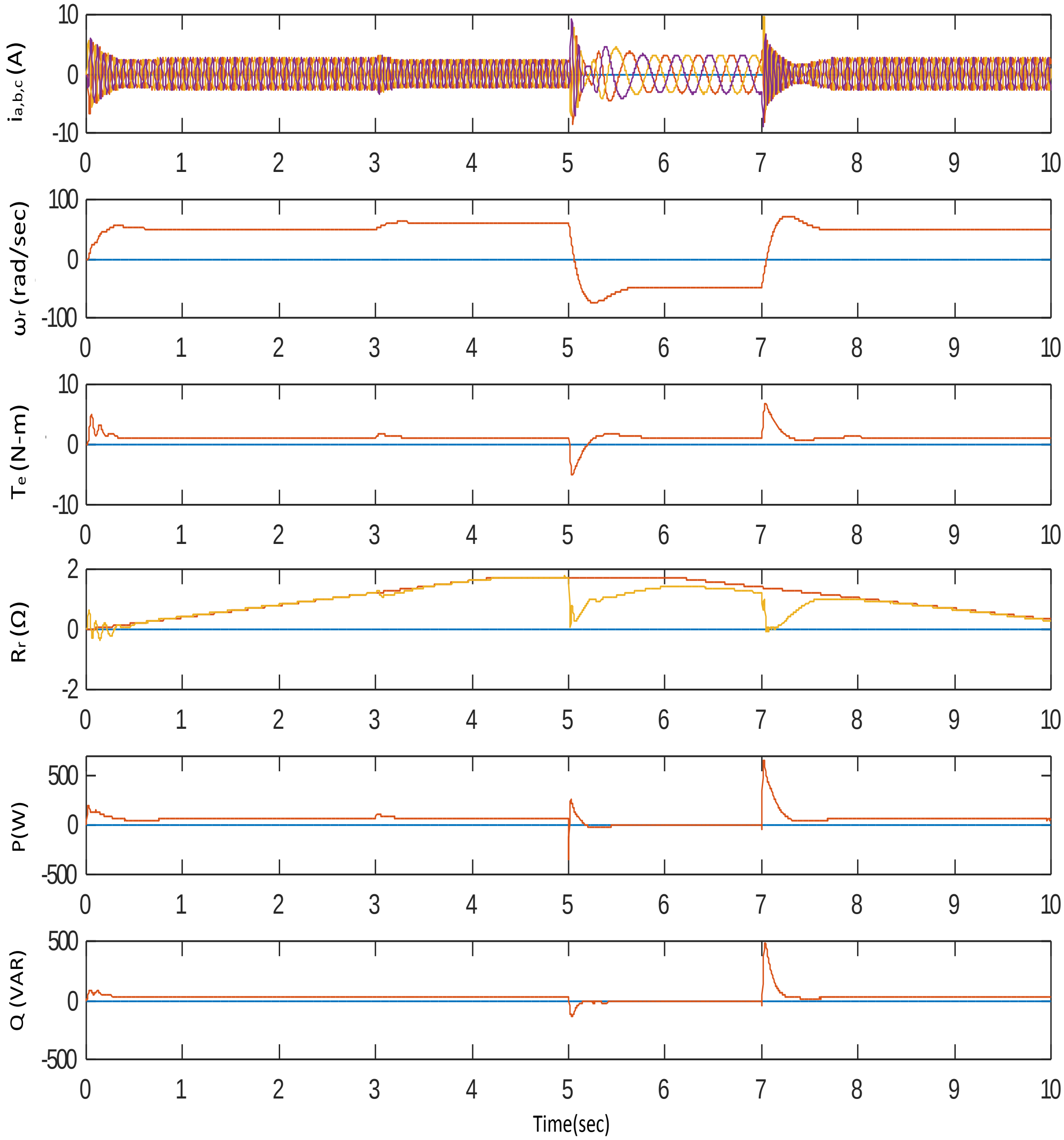


Figure 5.5 Dynamic response of Induction motor on trapezoidal change in rotor resistance for speed reversal (a)Stator current I_{abc} [A],(b) Rotor Speed ω_r [rad/s] (c)Torque [N/m] (d) Rotor Resistance [ohm] (e)Active Power [P] (f) Reactive Power [Q]

Initially the induction motor speed is set at 50 rad/sec, In 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. The initial current drawn by motor is high so the active power (W) consumed by the motor is also high. With the change in speed it affects the active power and reactive power with the small change.

D. Response of linear change in rotor resistance under the speed reversal operation

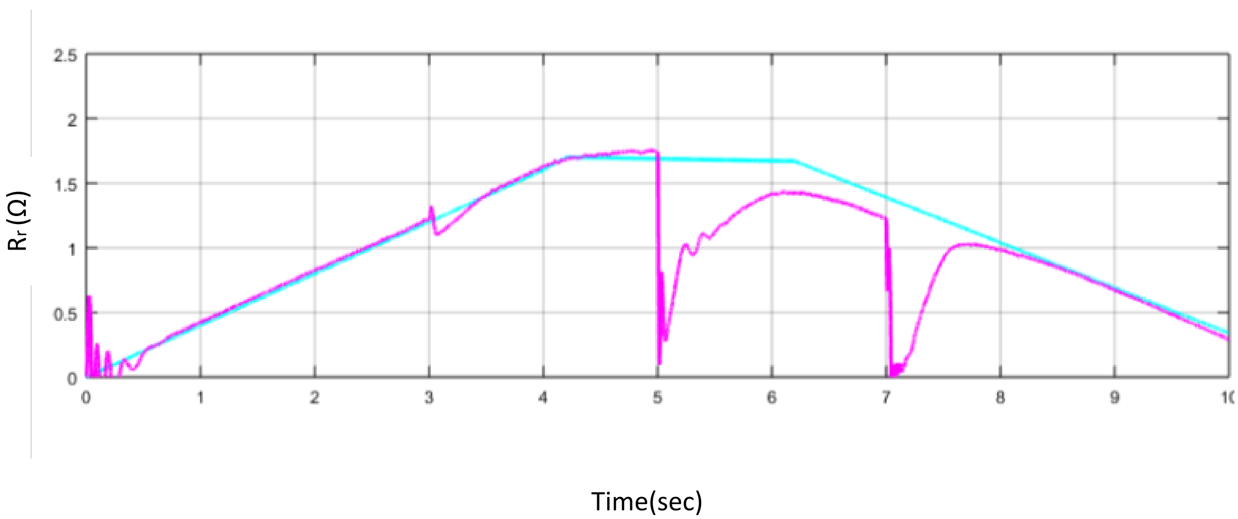


Figure 5.6 Effect of speed reversal on trapezoidal change of rotor resistance

As shown in figure 5.6 estimated rotor resistance tracks the actual rotor resistance with the minimum error. From t=0sec to t=0.4sec estimated rotor resistance has transients and after that t=0.4sec to t=3sec estimated rotor resistance tracks the actual rotor resistance. At t=5sec due to reversal in speed of motor from +50 rad/sec to -50rad/sec the rotor resistance decreases, again at t= 7 sec the speed of the motor is changed to -50rad/sec to +50 rad/sec and the rotor resistance tracks the actual resistance of the machine.

E. Dynamic response of indirect vector control of induction motor under sudden change in torque

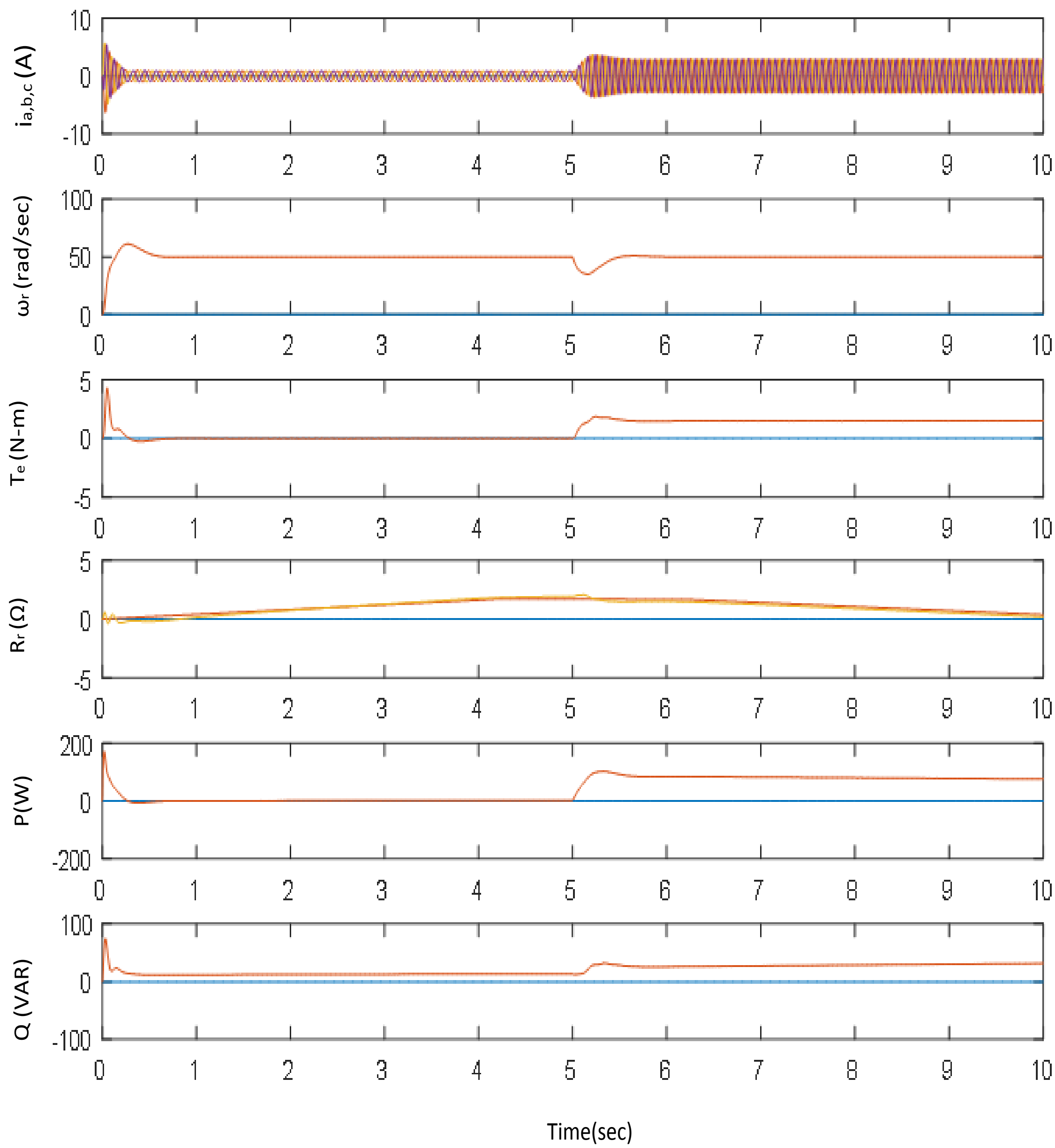


Figure 5.7 Dynamic response of Indirect vector control of Induction motor for step change in torque(a) Stator current I_{abc} [A],(b) Rotor Speed ω_r [rad/s] (c)Torque [N/m] (d) Rotor Resistance [ohm] (e)Active Power [P] (f) Reactive Power [Q]

Initially the induction motor is started with reference speed set point 50 rad/sec, In figure 5.7 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. The initial current drawn by motor is high so the active power (W) consumed by the motor is also high. With the change in torque it affects the active power and reactive power with the small change. At t=5sec due to step change in torque the active power and reactive power increase and attains the steady state. Due to increase in torque the rotor resistance decreases from its actual value because torque is indirectly proportional to the rotor resistance.

F. Response of rotor resistance under sudden change in torque

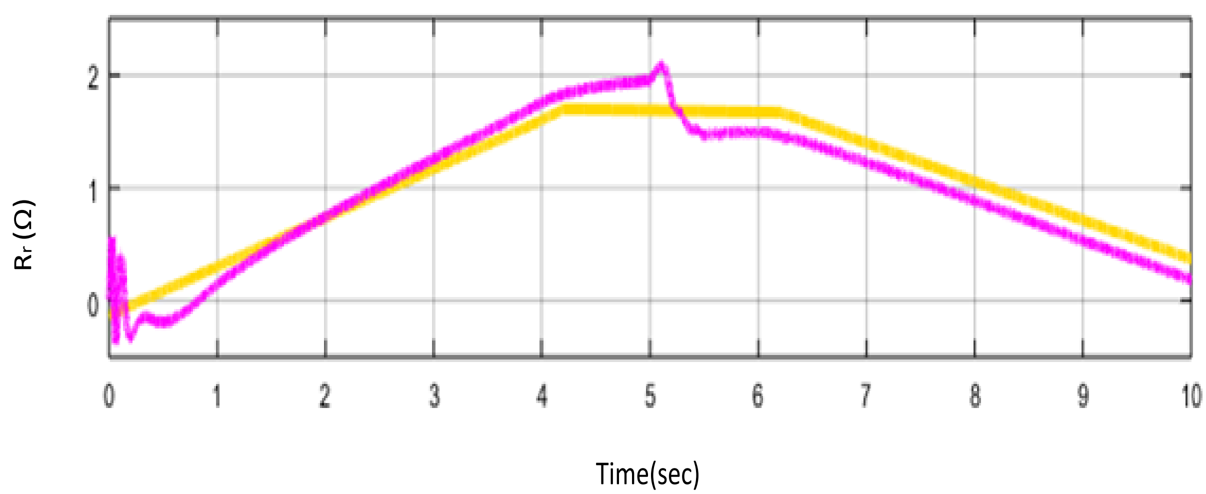


Figure 5.8 Effect of torque variation in rotor resistance

Trapezoidal reference resistance is used here for the estimation of rotor resistance in this at t=5sec the load torque of the induction motor is increased from 0 N-m to 1.25 N-m, due to that the rotor resistance of induction machine decreases because torque is inversely proportional to the rotor resistance is shown in figure 5.8.

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.

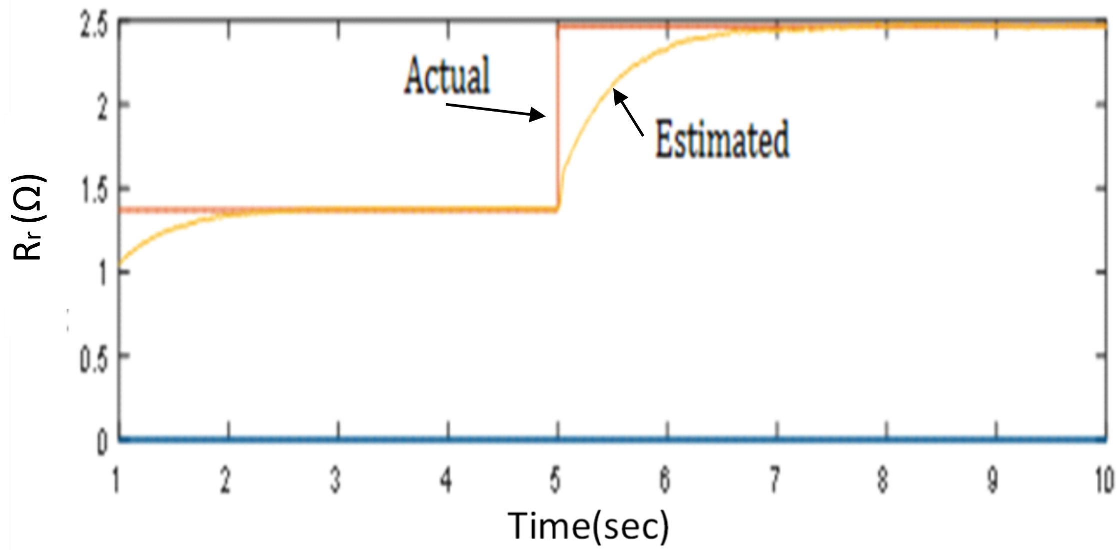


Figure 5.9 Step change in Rotor resistance of Induction motor

As shown in Figure 5.9 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

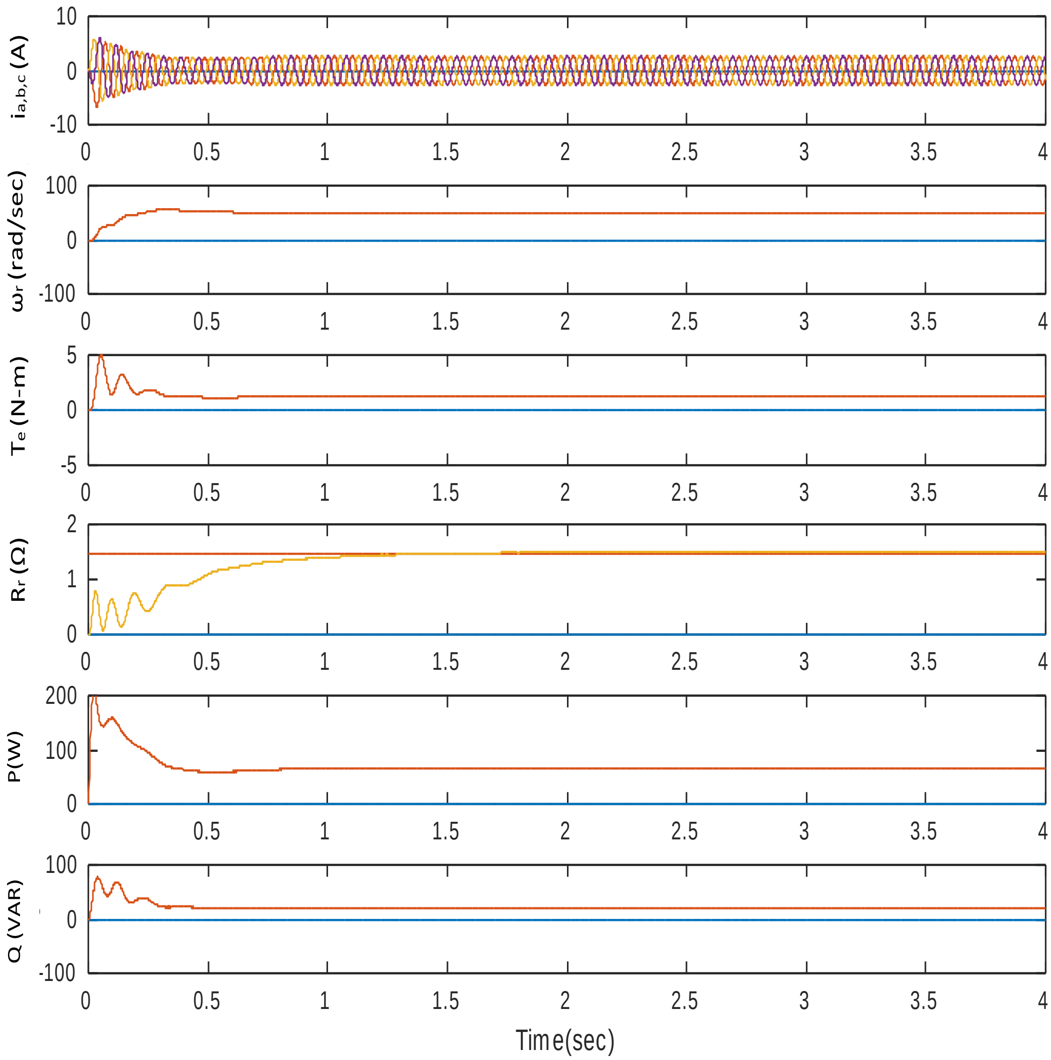


Figure 5.10: Dynamic response of Indirect vector control of Induction motor and estimation of rotor resistance (a)Stator current I_{abc} [A],(b) Rotor Speed ω_r [rad/s] (c)Torque [N/m] (d) Rotor Resistance [ohm] (e)Active Power [P] (f) Reactive Power [Q]

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 5.10. The initial current of induction motor is high with that the initial torque becomes high. When motor reached 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 under the speed reversal operator

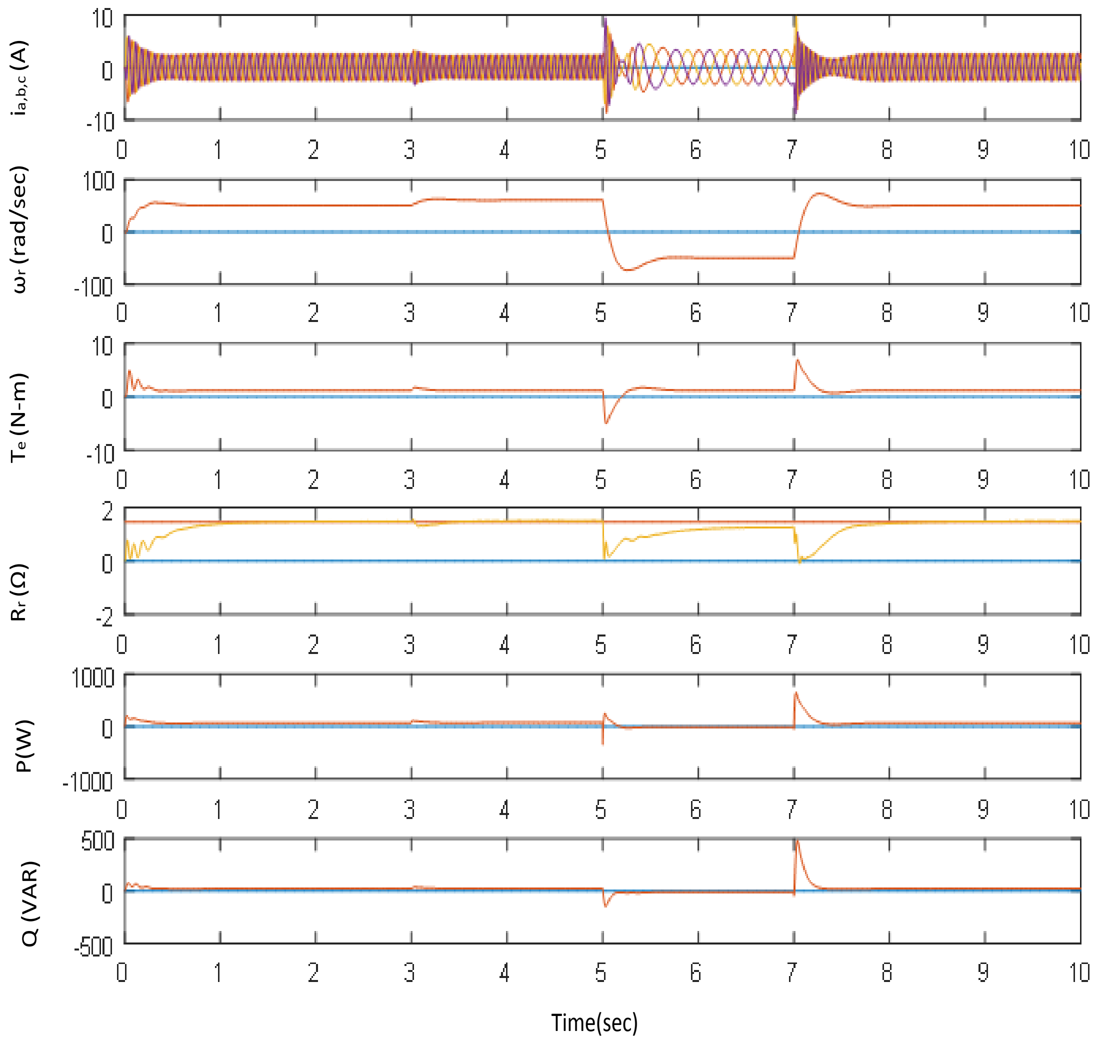


Figure 5.11: Dynamic response of Indirect vector control of Induction motor for speed reversal (a)Stator current I_{abc} [A],(b) Rotor Speed ω_r [rad/s] (c)Torque [N/m] (d) Rotor Resistance [ohm] (e)Active Power [P] (f) Reactive Power [Q]

Induction motor is started with the set speed of 50 rad/sec, In figure 5.11 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. The initial current drawn by motor is high so the active power (W) consumed by the motor is also high. With the change in speed it affects the active power and reactive power with the small change.

D. Response of sudden change in rotor resistance under the speed reversal operation

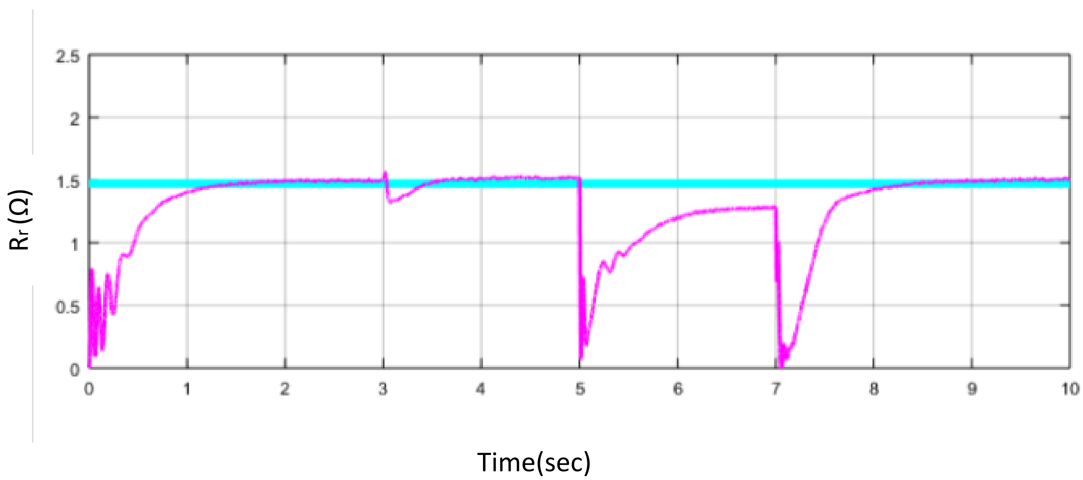


Figure 5.12 Effect of speed reversal on rotor resistance

Estimated rotor resistance tracks the actual rotor resistance of the machine, at t=3sec the speed of the motor is changed to +60rad/sec from +50 rad/sec and with that dynamic change in rotor resistance is observed. After that at t=5sec the speed of the motor is changed from t=+60 rad/sec to -50 rad/sec and the response is observed in figure 5.12, and again at t=7sec the speed of the motor is changed from -50 rad/sec to +50 rad/sec and with that estimated rotor resistance tracks the actual rotor resistance of the machine.

E. Dynamic response of indirect vector control of induction motor under sudden change in torque

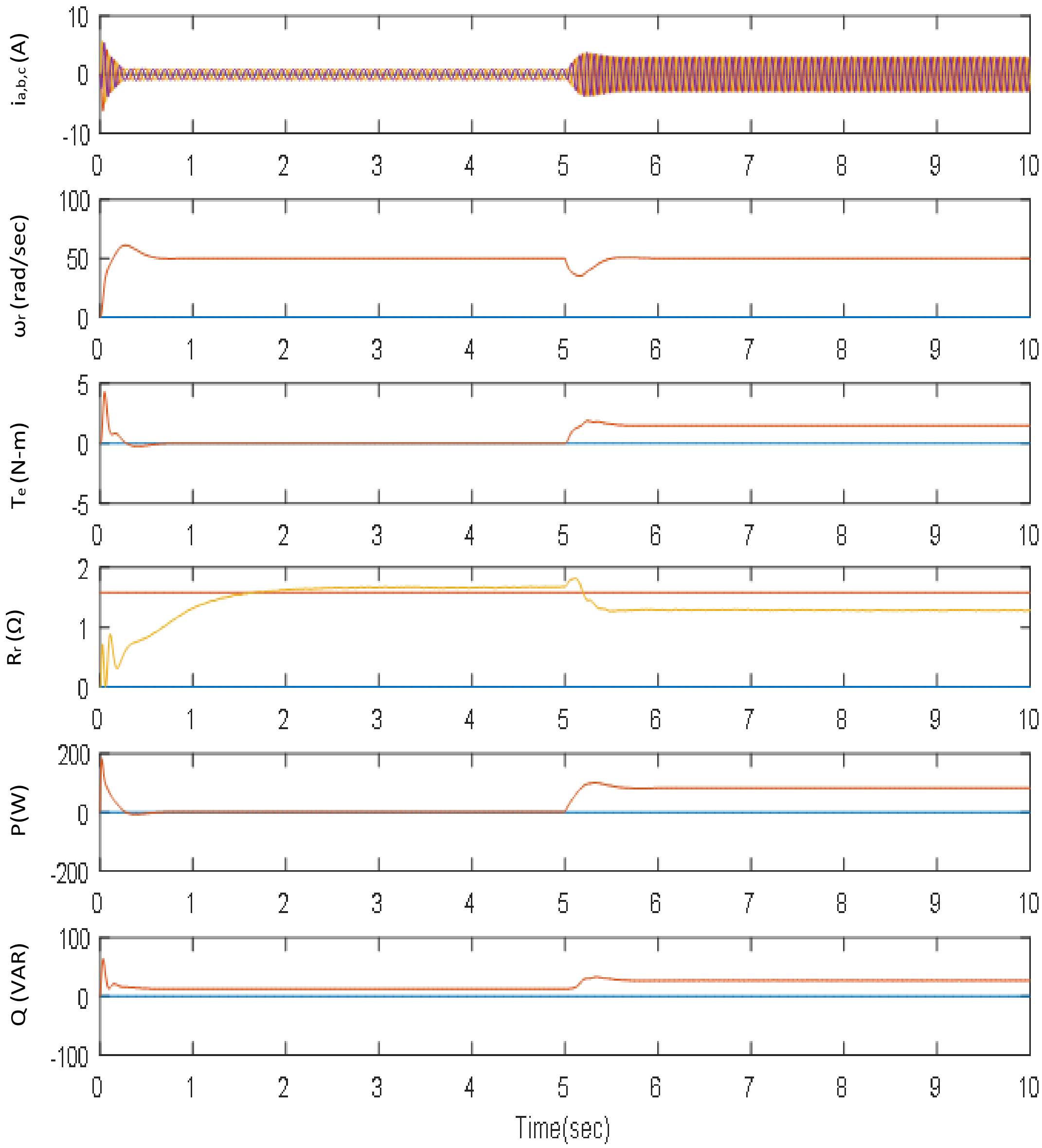


Figure 5.13: Dynamic response of Indirect vector control of Induction motor on step change in rotor resistance (a)Stator current I_{abc} [A],(b) Rotor Speed ω_r [rad/s] (c)Torque [N/m] (d) Rotor Resistance [ohm] (e)Active Power [P] (f) Reactive Power [Q]

The induction motor is started with the speed set at 50 rad/sec, In figure 5.13 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. With the change in torque it affects the active power and reactive power with the small change. At t=5sec due to step change in torque the active power and reactive power increase and attains the steady state.

F. Response of sudden change in rotor resistance under sudden change in torque

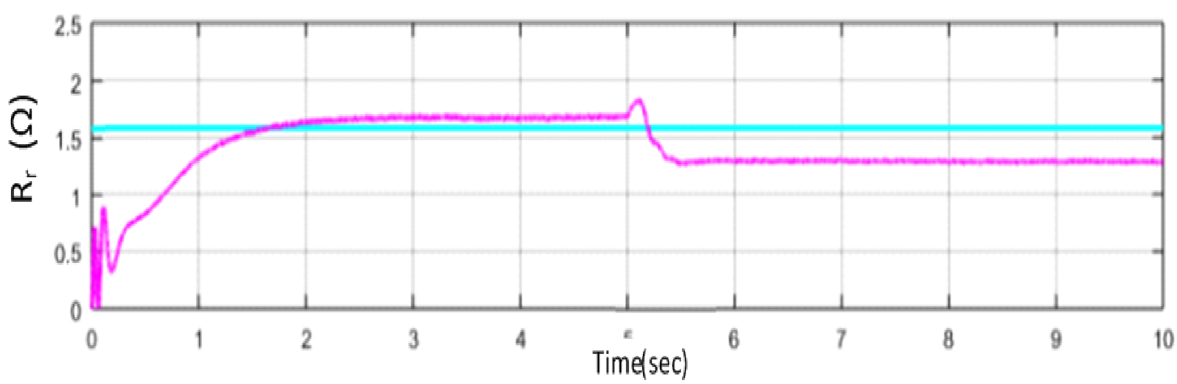


Figure5.14 Effect of rotor resistance for step change in torque

Estimated rotor resistance tracks the actual resistance of the machine, at t=5 sec the load torque of the induction motor is increased from 0 N-m to 1.25 N-m, due to that the rotor resistance of induction machine decreases because torque is inversely proportional to the rotor resistance as shown in figure 5.14

Table 5.1 Variation of rotor resistance and estimation error

Change in Rr %	Actual Rr	Estimated Rr	Error
10	1.545	1.69	0.0857
25	1.756	1.88	0.065
55	2.177	2.30	0.056
85	2.39	2.50	0.460
100	2.81	2.9	0.391

5.4 CONCLUSION

In this chapter estimates the rotor resistance for two variations in trapezoidal change and step change in rotor resistance using the SVPWM modulation techniques to generate the gate pulse for the voltage source inverter (VSI). In this chapter different variations with speed and torque are calculated and corresponding results are calculated. SVPWM is one of the best among all the PWM techniques. This technique is complex in comparison to the other techniques but they have very less chattering effect.

CHAPTER VI

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

The main objective of the thesis was to estimate the rotor resistance of the Induction motor drive using MRAS controller in MATLAB/Simulink. In the present work necessary MATLAB model developed for estimator and drive to simulate the sudden and linear change in the rotor resistance in the induction motor drive. The dynamic performance of the induction motor and the direct indirect and sensorless control of induction motor is discussed. The indirect vector control model of induction motor based on hysteresis current controller and SVPWM controller in simulated in MATLAB/Simulink and the speed, torque, current curves with respect to time are studied. Hysteresis current controller has fast response in comparison to SVPWM controller but they have high chattering in torque as compared to SVPWM.

6.2 Future scope of work

In future scope of work, the controller can be applied to other machine model with the higher rating and where the parameter variations are large. Intelligent controller such as Fuzzy logic, Genetic Algorithm, and Neural Network Controller can be incorporated to this controlling technique instead of proportional and integral controller to make it efficient and more robust controller. Sliding mode controller can be implemented for the speed control of Induction motor

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Appendix

Table A.1 System Parameters

Rated Power	5.4 hp
Rated Voltage	400 V
Stator Resistance	1.405 Ω
Stator Inductance	0.17803 H
Rotor Resistance	1.395 Ω
Rotor Inductance	0.17803 H
Mutual Inductance	0.1722 H
Frequency	50 Hz
Rotor friction co-efficient	0.002985 N.m.s
Rotor Inertia	0.0131 kg.m^2
Pole pairs	2
Rated Torque	26.88 N-m
Rated Speed	149.74 rad/s

Proportional and Integral Controller	
k_p	0.160
k_I	1

Proportional and Integral Controller	
k_p	0.2
k_I	2.5