ONLINE ROTOR RESISTANCE ESTIMATION FOR EFFICIENT SPEED CONTROL OF IVCIM DRIVE

A

DISSERTATION

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Candidate's Declaration

I, **Mandvi Singh**, Roll No. **2K16/C&I/11**, student of **M. Tech (Control & Instrumentation)**, herewith declare that the dissertation entitled "**Online Rotor Resistance Estimation for Efficient Speed Control of IVCIM Drive**", under the supervision of Dr. Mini Sreejeth, Associate Professor, Electrical Engineering Department, Delhi Technological University, in partial fulfilment of the need for the award of the degree of Master of Technology, has not been submitted elsewhere for the award of any degree.

I herewith solemnly and sincerely affirm that all the particulars declared above by me are true and correct to the best of my knowledge and belief.

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Certificate

This is to certify that the dissertation entitled **"Online Rotor Resistance Estimation for Efficient Speed Control of IVCIM Drive"** submitted by **Mandvi Singh** in completion of major project dissertation for the master of Technology degree in **Control & Instrumentation** at Delhi Technological University is an authentic work carried out by him underneath my superintendence and guidance.

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Speed control of drives are necessary in order to achieve variable speed, variable frequency operation. Earlier dc motor was mostly used for variable speed operation and ac motors for fixed speed because control of ac motor is complex than dc. Also ac motor as in this case induction motor is highly inductive and non-linear so speed control of induction motor is difficult. But by the invention of vector control method, it can be controlled like a separately excited dc motor. Also it is less bulky comparative to dc motor, can be used in dusty environment and under water also. So it has replaced dc motor at various industries. Indirect vector control is used mainly in industries because of its simplicity, less number of sensors are required than direct vector control. Scalar control method is easy to implement but it has inherent coupling effect which makes the performance sluggish and also good dynamic performance cannot be achieved. As in indirect vector control, both flux and torque currents are controlled separately so if torque control is required, it only affects torque and flux control is necessary only flux can be controlled. But as motor has resistance also which is temperature dependent so under running condition, motor's resistance can vary up to 100% which will result in coupling between torque and flux. So correct estimation of rotor-resistance is required to maintain the quality of indirect vector control.

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LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

Ɛ	Error
I_a, I_b, I_c	Three phase quantities
I_α, I_β	Stationary orthogonal reference frame quantities
i_{dr}, i_{qr}	Synchronously rotating d, q-axis rotor current
i_{ds}, i_{qs}	Synchronously rotating d, q-axis stator current
i_d^s, i_q^s	d, q-axis current in stationary frame
J, F	Moment of inertia and friction coefficient
K_1, K_2	Constant
L_{lr}, L_{ls}	Rotor and stator leakage inductance
L_m	Magnetizing inductance
L_r, L_s	Rotor and stator inductance
N_r, s	Rotor speed (rpm) and slip
p(P)	No. of poles
φ	Flux
R_r, R_s	Rotor and stator resistance
T_e, T_m	Developed and mechanical torque
THD	Total harmonic distortion

V_{dr}, V_{qr} Synchronously rotating d, q-axis rotor voltage

V_{ds}, V_{qs} Synchronously rotating d, q-axis stator voltage

θ_e Angel of synchronously rotating frame

θ_m Angular position of rotor

Ψ_{dr}, Ψ_{qr} Synchronously rotating d, q-axis rotor flux linkage

Ψ_{ds}, Ψ_{qs} Synchronously rotating d, q-axis stator flux linkage

Ψ_{dr}^{s} , Ψ_{qr}^{s} d, q-axis rotor flux in stationary reference frame

$\Psi_{dr}^{sv}, \Psi_{qr}^{sv}$ d, q-axis rotor flux in stationary reference frame for voltage model

$\Psi_{dr}^{sv}, \Psi_{qr}^{sv}$ d, q-axis stator flux in stationary reference frame for voltage model

$\Psi_{dr}^{si}, \Psi_{qr}^{si}$ d, q-axis rotor flux in stationary reference frame for current model

Ψ_r Rotor flux linkage

Ψ_r^* Reference rotor flux linkage

ω_e, ω_{sl} Stator or line and slip frequency (r/s)

ω_m, ω_r Rotor mechanical and electrical speed (r/s)

ω_r^* Reference rotor electrical speed

CHAPTER 1
INTRODUCTION

1.1 Introduction

Nowadays, highly used motor in industries is induction motor because it is robust, less costly and reliable [1]. It also exhibits good self-starting capability and high efficiency [10]. For adjustable speed applications in a wide-ranging power from fractional horsepower to multi-megawatts, Induction motor drives are the workhorses of the industry.

But the estimation and control of induction motor drives are much more complex than dc drives and increases essentially with high performance. The main reasons for complexity are machine parameter variations, complex dynamics of ac machines and the complications in the processing of feedback signals in the existence of harmonics.

The two main control strategies of induction motor drives are scalar control and vector control. Scalar control is simpler than vector control, but the internal coupling (i.e. flux and torque are dependent on voltage, frequency and current) effect makes the response sluggish and the system is easily disposed to to instability. Vector control can solve the above problem. By using Vector control technique, the induction motor can be controlled like a separately excited dc motor and it introduced a new start in the high performance of ac drives. It is an impressive control strategy for torque and speed control of induction motor. [13]

1.2 Scope of work

The dissertation deals with the speed control methods of induction motor. There are various speed control methods of induction motor like stator voltage control, rotor resistance control, pole changing method and stator frequency control (v/f control). Here open loop and closed loop scalar control (v/f control) method, and vector control method and rotor resistance estimation method have discussed.[31]

In scalar speed control method, as the name suggests only magnitude is varied of control variables and it ignores the effects of coupling. In this control method, ratio of voltage and frequency is constant. It is easy to implement. There are two types of scalar control – open loop and closed loop. In open loop as the name indicates there is no feedback loop. But in closed-loop control, there is speed is feedback to control the speed.

There are two types of vector control methods - direct vector control and indirect vector control. In direct vector control method, the unit vector is generated from flux vector signals. Flux vector can be estimated by voltage model and current model. In voltage model, fluxes are calculated from voltages and currents of stationary frame equivalent circuit. In current model, in the low speed region, the rotor flux can be computed with the help of speed and current signals. In indirect vector control, the unit vector is generated in feedforward manner with the help of rotor speed and slip speed.

In this work, indirect vector method is implemented for the speed control of IM drive as this method is best suited for high performance applications due to its good dynamic performance. But Indirect vector method is sensitive to variation in rotor resistance due to temperature effect. So estimation of rotor resistance is required for satisfactory performance of motor. In various types of rotor resistance estimation methods, Model Reference Adaptive Controller (MRAC) rotor resistance method is explained here. In this method, there are two models – one is reference model and other is estimated model. Reference model is independent of control parameter and other is dependent it. These two models are compared and error is processed to adaption mechanism which is mainly PI controller.[27]

1.3 History

Variable frequency drive is a combination of power electronics and machine. The history of variable frequency drive is not very old. Besides of it, its evolution was very fast and it has gained an important place in industry. The Very first variable frequency drive was based on mechanical principals because till that day, there is not big advancements in power electronics. Adjustable pitch diameter pulley was first VFD. In 1924, the first induction motor was designed and speed was frequency and pole dependent. After motor invention, it is required to vary the speed which is only possible at that time by varying the frequency. In early 60's in Finland, first PWM was put into effect. But first commercial achievement was made at Helsinki metro by Martti Harmoinen in 1972. Firstly variable frequency drive was based on 6 step voltage. But soon Philips presented sine coded PWM chipset. PWM based method does not require high torque and dynamic response. This method also has less cost associated with it because it has less losses, less maintenance cost and less installation cost.[34]

1.4 Organization of the dissertation:

The contents of the thesis have been divided into following chapters:

Chapter-1 Introduction

The first chapter is the introduction of variable frequency drive, its importance, development and history. Speed control methods and rotor resistance method are also discussed here.

Chapter-2 Literature Review

This chapter describes in details the literature survey of scalar control, vector control method of speed control and rotor resistance estimation method on running condition.

Chapter-3 Induction Motor

This chapter is the brief introduction to induction motor. Its equivalent circuit and stationary frame model are also explained here.

Chapter-4 Scalar Control of Induction Motor Drive

This chapter explains in details about the open loop and closed-loop scalar control method of speed control of induction motor drive with the help of Matlab/Simulink model.

Chapter-5 Indirect Vector Control of Induction Motor Drive

Indirect vector control method and Matlab/simulation result are explained in this chapter. Comparative dynamic performance for PI, IP and PR controller are also explained in this chapter. Transformations like Clark, Park are also discussed here.

Chapter-6 Online Rotor Resistance Estimation for IVCIM Drive

This chapter is about online rotor resistance estimation method and its Matlab/simulation result. Model Reference Adaptive Control (MRAC) method of rotor resistance estimation is explained here.

Chapter-7 Conclusion and Future Scope

In the seventh chapter the summary of the work carried out in this dissertation has been presented along with scope for extension of the work.

1.5 Conclusion

This chapter describes the importance and development of variable frequency drive with time. Scalar and vector control method of induction motor is also described. Necessity of online rotor resistance estimation is discussed. Chapter wise organization of thesis is summarized.

Chapter 2
LITERATURE REVIEW

2.1 Introduction

A brief introduction of speed control methods of induction motor drive and online rotor resistance estimation have been described in this chapter. Speed control of induction motor drive is necessary in terms of cost, energy savings and fewer losses. A lot of attention, focus and motivation are required to enhance the quality, performance and to achieve smoother operation. Vector control method of speed control of Induction motor drive is used everywhere in industry because of its robust performance, less operating cost and low losses.

Under running condition, machine parameters change effectively. So the estimation of these parameters is required for adequate performance of drives. Online rotor resistance estimation includes the effect of change in rotor resistance under working condition and its effect on machine performance. A method is required to neglect and reduce their effect on machine while working.

Variable speed operation is the key through by which the performance and efficiency of any system can be increased remarkably. Pulse width modulation is the best option by which by variable speed operation can be achieved with minimum cost and energy.

2.2 Literature Review

K. Anitha, G. Santosh, L. Suneel, K. Spandana, E. Raviteja [1] explains the v/f and rotor resistance speed control methods of induction motor. To maintain maximum torque constant, v/f ratio has to be fixed which in turn keeps the magnetizing flux fixed. At low speed, to maintain v/f constant, voltage decreases this reduces the torque because torque is proportional to square of voltage. To reduce jerk at starting and steady state time, rotor and stator inductance and stator resistance must be low. It also explains that high value of rotor resistance does not have any effect on steady state time while it leads to lesser jerks. But under running condition, the copper loss increases due to higher value of rotor resistance. This in turn decreases the motor efficiency.

Pabitra Kumar Behera, Manoj Kumar Behera, Amit Kumar Sahoo [2] explains that speed of induction motor can be varied by varying the frequency and stator voltage. The ratio of stator voltage and frequency is kept constant because of that it is called constant v/f method of speed control. A comparative study of open loop and closed loop is explained and closed-loop v/f control gives better result and response compared to open loop.

Ravi Prakash, Prof. Rishi Kumar Singh, Rajeev Ranjan Kumar [3] suggests that v/f method of speed control of induction motor is the most popular method of speed control. Parameters like voltage and current are analyzed and calculated at different stage of inverter. Performance analysis of induction motor is done under transient and steady state condition. Open loop control of induction motor is carried out and THD analysis of line current is also done.

Gaber El-Saady, El-Nobi A. Ibrahim, Mohamed Elbesealy [4] explains speed control method of induction motor using different pulse width modulation techniques by Matlab/Simulink. These are Third-harmonic pulse width modulation, Space vector pulse width modulation and Sine triangular pulse width modulation. By using these techniques, performance analysis of induction motor is done under full load condition for harmonic spectra, THD, motor speed and utilization of dc supply voltage. Under load variation and reference speed, dynamic performance of induction motor is analyzed by implementing space vector pulse width modulation. It is concluded that space vector pulse width modulation is the efficient one because it has better performance characteristic.

Mr. G. Pandian and Dr. S. Rama Reddy [5] present implementation and simulation of induction motor fed by multilevel inverter by using SVW strategy. Harmonic content reduces, power and voltage increases with increased level of inverter. Harmonic content can be reduced by properly selecting the switching angle so that higher torque and reduced total harmonic distortion can be achieved. Torque response is also improved because of elimination of fifth harmonic which develops torque in opposite direction.

M. S. Aspalli, Asha. R, P.V. Hunagund [6] represents analysis and design of induction motor drive in closed-loop using constant v/f technique with IGBT at inverter stage using 16 bit digital signal controller dsPIC30F2010. It is a single chip embedded controller that combines the controller capabilities of microcontroller with computational qualities of DSP in one core.

R. Dharmaprakash, Joseph Henry [7] describes comparative performance analysis of indirect vector and direct torque control of induction motor. These two methods provide good dynamic performance of induction motor. For step change in speed and constant full load torque, induction motor dynamic performance is analyzed using Matlab/Simulink. Comparative advantages and disadvantages are also showed like torque ripple is large in direct torque control which is because of hysteresis band controller. Also DTC is less parameter sensitive and its implementation is easy compared to indirect vector control. Indirect vector control uses more transformation and implementation is difficult.

Burak Ozpineci, Leon M. Tolbert [8] explains modular implementation in a step-by-step manner of induction motor model. In modular system, each block of induction motor is in the form of equation rather than black boxes used in Matlab/Simulink. In the form of equation, all the parameter are available for verification and control purpose. This modular model is further used in indirect vector control, open loop v/f and as an induction generator. This also explains that same model can be used as a motor and generator. There is no requirement of two different models.

K. Hemavathy, N. Pappa, S. Kumar [9] analyzes dynamic response of induction motor using indirect vector control and direct torque control for speed change and load disturbances and the results are compared. It explains that any one of method can be chosen depending upon the requirement of application. The dynamic response to speed changes and load variation is quick to direct torque control. Current and torque ripples are also high in direct torque control. Implementation of indirect vector control is difficult and has higher installation cost so direct torque control scheme can be used where fast dynamic response is required but neglecting the effect of torque and current ripples.

S. Riaz Ahamed, J. N. Chandra Sekhar, Dinakara Prasad Reddy P [10] explains comparative performance study of various speed control techniques of induction motor indirect vector control. Various techniques are like Genetic Algorithm (GA), Fuzzy PI hybrid controller and PI controller. It explains the decomposition on three phase stator current into flux and torque component. GA based PI controller is implemented and shows better results than PI-Fuzzy hybrid and PI controller for peak overshoot, rise time, settling time and speed regulation.

G. K. Singh, K. Nam, S.K. Lim [11] explains the advantages of multiphase over conventional three phase drives. In reduces amplitude and increases the frequency of torque pulsations, reduces harmonic currents of rotor, reduces current with reducing voltage per phase, lowers the dc-link current harmonics. For the same volume machine, by increasing the phases, torque/power per rms ampere can be increased. With a random displacement between the two three phase windings set, it develops six phase induction machine indirect vector control method. In this technique, two sets of three phase stator current are fed by two current controlled PWM three phase voltage source inverter. Two axis model of six phase induction motor is used which can further be increased to any multiples of three. The error between these two is eliminated automatically.

B. Venkata Ranganandh, A. Mallikarjuna Prasad, Madichetty Sreedhar [12] describes a hysteresis band current controller for a three level VSI. The Hysteresis Band PWM approach has the potential to deliver an upgraded way of deriving non-linear models. To check the legitimacy of this approach, HBPWM is used in indirect vector control and the results are compared with the traditional PWM current control technique. It provides better response in terms of switching losses, fault tolerance and total harmonic distortion. Hence it improves the overall performance of the drive.

Bimal K Bose [13] explains the important features of hysteresis band current controller like it is simple to implement, provides fast current control response and has natural peak current limiting ability. Though, a fixed band current controller has the drawback that modulation frequency diverges in a band and causes non optimum load current ripples. An adaptive hysteresis band current controller scheme is developed where the band follows the system parameter to keep the modulation frequency almost constant.

Ajay Tripathi and Paresh C. Sen [14] explain a sinusoidal band current controller over fixed band and performance evaluation is done with fixed band. For single and three phases, both controller has simulated. Finally it brings about that sinusoidal band control consequences in a reduced ripple and lesser harmonic content. Switching frequency is also greater with sinusoidal bands.

L. A. Serpa, S. D. Round and J. W. Kolar [15] explain decoupling hysteresis current controller and virtual flux concept. The virtual flux technique uses to abstract the mains voltage from line currents, dc voltage and switching state. By means of a decoupling hysteresis current controller, three phase currents are produced from the desired reactive and real powers. Switching interaction between the phases can be avoided by the decoupling hysteresis current controller. A nearly fixed switching frequency can be obtained when a variable hysteresis band controller is working.

Vinciane Chereau, Francois Auger, Luc Loron [16] explains that sometimes higher switching frequency can lead to devastation of inverter. In a single phase case, this frequency is limited and extends it to three phases. In a single phase case, inverter switching frequency is in limit through a simple hysteresis band control. But the switching frequency varies to some extent which in turn results in benefit of avoiding uncomfortable noises. This method is then converted to three phase in a easy manner with isolated neutral in a two single phase load application so that single phase control scheme can be implemented to three phase application.

Zen Guo, Jiasheng Zhang, Zhenchaun Sun, Changming Zheng [17] enlighten that current source inverter fed induction motor drives re mainly used in medium voltage application because of their simplicity, reliable short circuit protection and power reversal capability. Though there are some practical challenges like machine parameter dependency and poor dynamic response.

Ms. Rutuja S. Hiware, Prof. J.G. Chaudhari [18] states that indirect vector control is popular for extraordinary performance in induction motor. In it achieved by decoupling the torque and flux producing component of stator current. A new method of decoupling is familiarized here. Decoupling of rotor flux and torque component is obtained by magnetizing current component by integrating PI control system and space vector modulation technique.

Prof. Aziz Ahmed, Yogesh Mohan, Aasha Chauhan, Pradeep Sharma [19] proposes a new speed controller know as IP controller which was initially debated in 1978. As PI controller has some disadvantages like large starting overshoot, sluggish response and sensitivity to parameters. So to overcome these drawbacks IP controller is come into picture. IP controller demonstrates fewer oscillations around set point, overshoot in speed is restricted, offers good load recovery, adaptive in nature.

Pradeep K. Nandam, Paresh C. Sen [20] establishes comparative analysis of PI and IP controller. To demonstrate the benefits of IP controller over PI controller, speed response for change in speed and load torque is compared. IP controller indicates zero steady state error, eradicates overshoot glitches in current waveform.

Sreekumar T, Jiji K S [21] presents IP speed controlled technique for indirect vector control of induction motor to overcome the drawbacks obtainable by PI controller. As IP controller has no overshoot in speed, thus diminishing the overshoot in current at the time of staring. For a abrupt change in speed, IP controller improves speed sooner than PI controller.

Aamir Hasim Obeid Ahmed [22] pronounces that control of induction motor is tough pertaining to the fact that mathematical model of induction motor is extremely nonlinear. The frequently used PI speed controller also has some drawbacks associated with it so a new method is suggested named as IP controller. The main aim is to determine which offers better performance associated with induction motor.

Xiuqin Wang, Guoli Li, Maosong Zhang, Xing Qi, Qunjing Wang, Jiwen Zhao, Yuan fang [23] states that customary integration regulator yields phase and amplitude errors for ac input signals. So a new better observation method for rotor flux of induction motor based on proportional resonant regulator offered here. This system lessens steady state errors for rotor emf integration, advances the run characteristic and diminishes the amount of flux deviation. The method has verified by the simulation results for induction motor.

Andreas Upheus, Kilian Notzold, Ralf Wegener, Stefan Soter [24] advises that PR controller has better ability for reimbursing current harmonics. PR controller works on natural reference as compared to PI controller. So there is no need to transformation of one frame to another.

Scott Wade, Matthew W. Dunnigan and Barry W. Williams [25] advise a new way of rotor resistance estimation in vector controlled induction motor. In this method, short duration pulses added to fixed flux reference current and centered on resulting torque command current formed by a PI controller modifies the rotor resistance estimation. In properly tuned manner in closed loop, this self-tuned method of rotor time constant does not create torque pulsations. This does not need voltage sensors and is simple in calculation.

Saji Chacko, Chandrashekhar N. Bhende, Shailendra Jain, R.K. Nema [26] states that induction motor is sensitive to rotor time constant variation so its estimation is required. For online rotor resistance estimation, Model Reference Adaptive Controller has offered here which further improves the steady state performance of the drive. Rotor resistance estimation under transients and steady state situations for full load and full speed is done. Controllers used is Mamdani fuzzy and orthodox PI controller.

Suman Maiti, Chandan Chakraborty, Yoichi Hori, Minh C. Ta [27] presented a brief study of MRAC employing the reactive power for online estimation of rotor resistance to preserve the orientation of flux properly in indirect vector control. Selecting the reactive power as the serviceable parameter, the system is automatically immune to stator resistance. For rotor resistance estimation by MRAC, reference frame and estimated frame reactive power are compared so it eradicates the need of any flux estimation during computation. Also a speed sensor less technique is accomplished. To approve the usefulness of this scheme, simulation results have been offered.

Dong Qiang, Kan Jingbo, Zhang kai [28] states that for effective utilization of indirect vector control of induction motor drive, correct alignment of flux and torque component current are required. Rotor flux orientation is affected by the rotor resistance which varies significantly under running condition. So a new method of rotor resistance approximation is developed.

Huang Bin, QU Wenlong, LU Haifeng [29] enlightens the MRAS method of reactive power method for online rotor resistance approximation. The main benefit of this approach is that it does not have difficulties of initials condition and drift as there is no pure integration term. The soundness of this scheme is proved by simulation results. It also has lower computational necessity.

Baburaj Karanayil, Muhammed Fazlur Rahman, Colin Grantham [30] presents a new way of online estimate of both stator and rotor resistance for speed sensor less control of induction motor drive using artificial neural network. The difference between the rotor flux linkages relied on voltage model and neural network back promulgated to regulate the weight of neural network model for rotor resistance calculation. For stator current measurement, the error between the estimated stator current based on neural network and measured current is back broadcasted to adjust the weight of neural network.

2.3 Conclusion

This chapter describes an extensive literature analysis on speed control methods of Induction motor. It also discusses about rotor resistance estimate methods, different controllers like hysteresis band controller, integral proportional controller and proportional resonant controller.

CHAPTER 3
INDUCTION MOTOR

3.1 Introduction

Induction Motors account for over eighty fifth of all motors utilized in domestic applications and industry. In the past, these motors have been used as constant-speed motors as ancient speed management ways for ac motors are less economical than speed management ways for DC motors. Though, DC Motors need brushes and commutators that are risky and need maintenance. Therefore Induction Motor is the most popular and widely used motor for domestic and industrial applications.

3.2 Construction

Induction Motor incorporates a rotor and a stator. The stator of induction motor is wound for 3 phases and a set variety of poles. With evenly spaced slots, it has stampings to hold the three-phase windings. The speed of the rotor is reciprocally proportional to the number of poles. Once the stator is energized, a moving magnetic field is created and currents are formed within the rotor winding via electromagnetic induction. The main parts of induction motor are stator and rotor.

Stator

As the name specifies, it is the immobile part of induction motor. A three phase supply is given to the stator winding placed in the stator. The three main parts of induction motor are

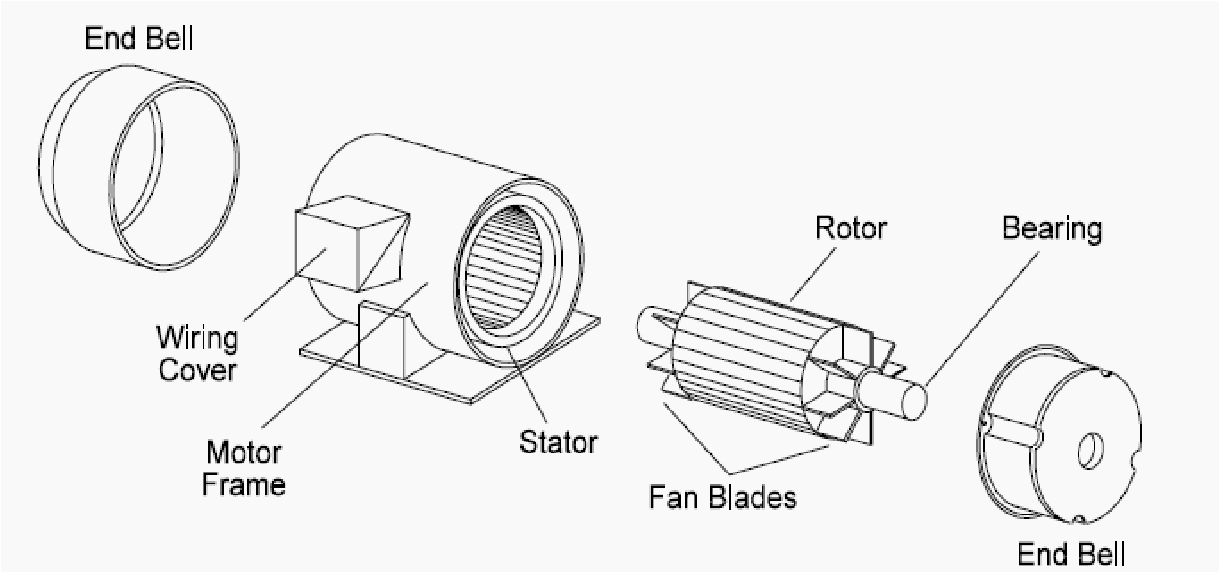


Fig. 3.1 Parts of induction motor

Stator frame

It is the outer part of induction motor which arrange for mechanical support to the stator core and filed winding. It is either prepared of fabricated steel or cast iron. It does not carry any stator flux. The frame must be firm and tough.

Fig. 3.2 Stator frame

Stator core

It mainly carries the alternating flux. To minimize the eddy current losses, the stator core is laminated. Laminations are made up of 0.4 to 0.5 mm thing stampings of silicon steel to diminish hysteresis losses. All the stamping are sealed along to make stator core, that is then housed in stator frame.

Fig. 3.3 Stator core

Stator winding

The three phase winding are housed inside the stator core which are supplied by three phase currents. Three phase winding can be connected in delta or star depending upon the starting method. The stator of the motor is wound for fixed number of poles.

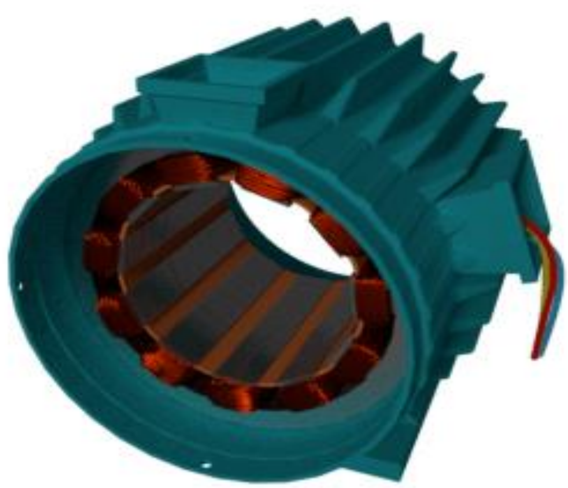


Fig. 3.4 Stator winding

Rotor

The rotor is constructed of thin laminations of similar material as stator. On the shaft, the laminated cylindrically core is placed and these laminations are slotted on the outward to take conductor. Based on the rotor construction, there are two sorts of induction motor

Squirrel cage induction motor

Laminated cylindrical core are enclosed in squirrel cage rotor. Semi closed slots are used at the outer periphery. Uninsulated copper and aluminium bar conductors lie in each slot. These bars are then shorted by heavy ring at the end connecting all the bars. This type of construction is more rough and a strong variant of the Induction Motor. The skewed rotor slots are used in place of parallel slots.

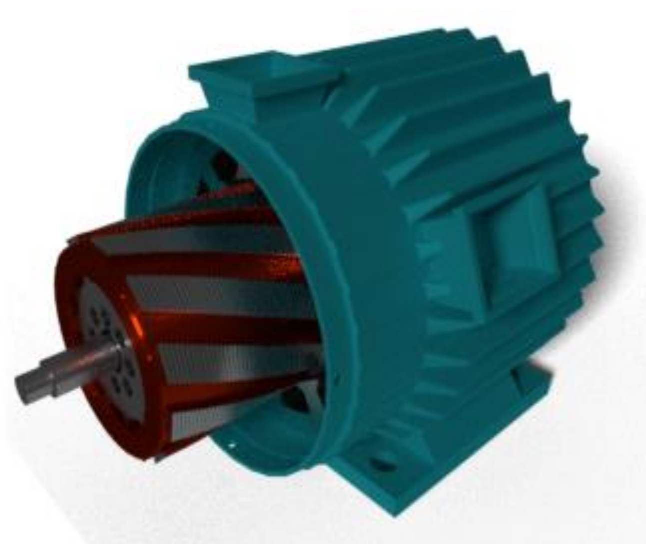


Fig. 3.5 Squirrel cage induction motor

Wound rotor induction motor

It is also known as slip ring rotor. In this type of construction of motor, the rotor ends are connected to end rings on which the three brushes make sliding contact. As the rotor rotates, the brushes slip over the rings and provide a connection with the external circuit. The semi closed slots lied on the outer periphery carries 3 phase insulated winding.

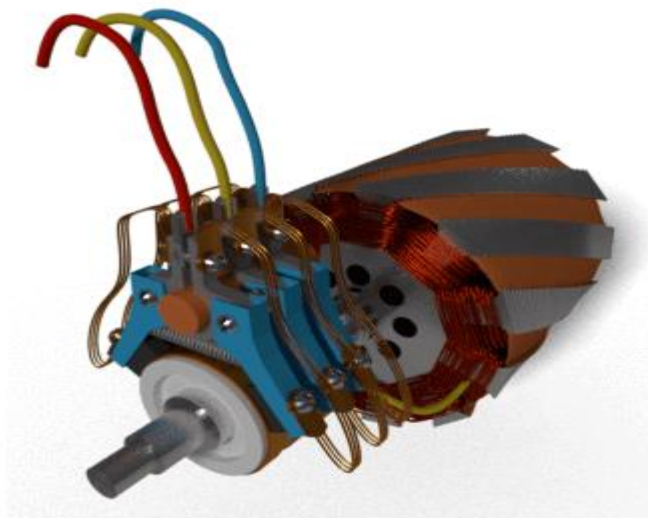


Fig. 3.6 Wound rotor induction motor

3.3 Working

When the stator winding is supplied by a three-phase supply, a rotating magnetic field is produced which rotates around the stator at synchronous speed *Ns.* This generated flux cuts the stationary rotor and induce an electromotive force in the rotor winding. As the rotor windings are short-circuited by end rings, a current starts to flow through them. As these conductors are situated in the stator's magnetic field so by Lenz's law this applies a mechanical force on them. According to Lenz's law, the direction of rotor currents will be such that they will try to oppose the cause producing them. Thus a torque is generated which tries to decrease the relative speed between the magnetic field and the rotor. Hence the rotor rotates in the direction of flux. Thus the relative speed between the rotor and the speed of the magnetic field is what drives the rotor. Hence the rotor speed *Nr* is always less than the synchronous speed *Ns.* Hence Induction Motor is also known as an asynchronous motor [35, 36].

Stator speed, slip and rotor speed are given by

Stator Speed

$$N_s = \frac{120f}{p} \tag{3.1}$$

Slip

$$s = \frac{N_s - N_r}{N_s} \qquad (3.2)$$

Rotor speed

$$N_r = \frac{120f}{p}(1 - s) \qquad (3.3)$$

3.4 Various speed control methods of Induction motor

There are various speed control methods of Induction motor. Speed can be controlled either from stator side or from rotor side.

From stator side, the control techniques are further categorized as

- Frequency control or v/f control
- By changing the number of poles of stator
- By varying the supply voltage
- By adding resistance in stator circuit

From rotor side, speed can be varied by the given below methods

- By adding additional resistance in the rotor circuit
- By Cascade control method
- By addition slip frequency emf into rotor side

3.5 Dynamic model of induction motor

The Squirrel Cage Induction Motor using the concept of direct and quadrature axis (d-q) concept in the stationary reference frame requires less variables and analysis becomes somewhat easy, as shown in the figures below [10]

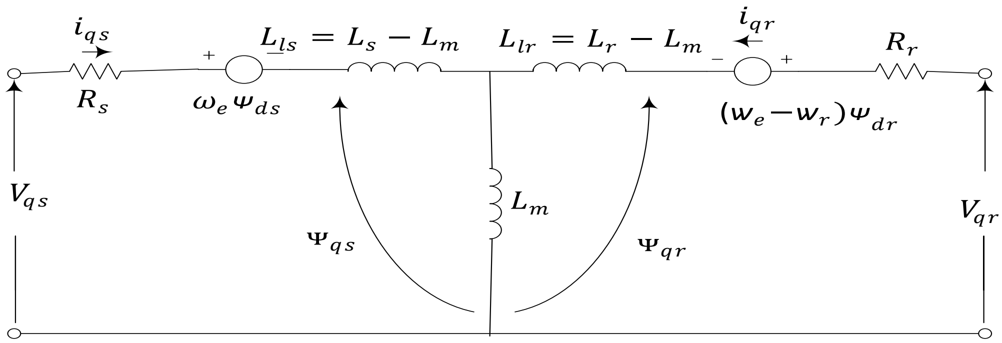


Fig. 3.7 Rotor and stator axis in q-axis reference frame

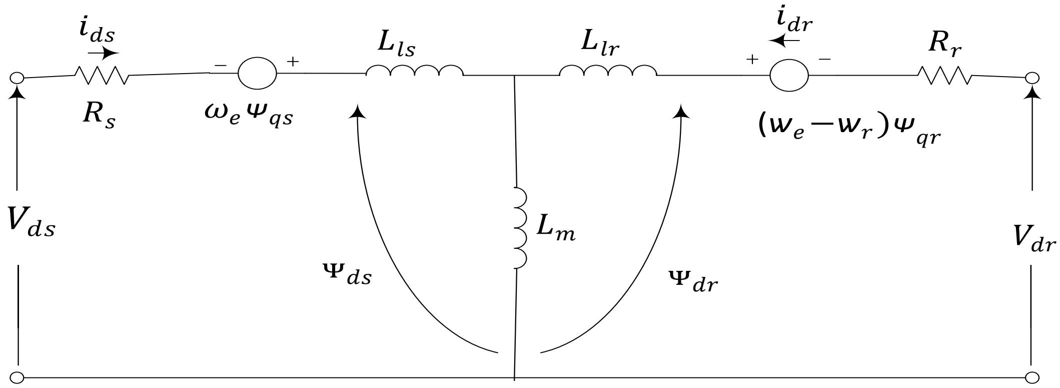


Fig. 3.8 Rotor and stator axis in d-axis reference frame

The d-q axis voltage equations are as follows

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + sL_s & \omega_e L_s & sL_m & \omega_e L_m \\ -\omega_e L_s & R_s + sL_s & -\omega_e L_m & sL_m \\ sL_m & (\omega_e - \omega_r)L_m & R_r + sL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & sL_m & -(\omega_e - \omega_r)L_r & R_r + sL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{3.4}$$

where s is Laplace operator. To a singly-fed machine, $V_{dr} = V_{qr=}0$ [13].

The d-q stator and rotor flux linkages are given by

$$\Psi_{qs} = L_s i_{qs} + L_m i_{qr} \tag{3.5}$$

$$\Psi_{ds} = L_s i_{ds} + L_m i_{dr} \tag{3.6}$$

$$\Psi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{3.7}$$

$$\Psi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{3.8}$$

where, $$L_s = L_{ls} + L_m \tag{3.9}$$

$$L_r = L_{lr} + L_m \tag{3.10}$$

The torque equation is

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \tag{3.11}$$

$$\frac{d}{dt}\omega_m = \frac{1}{2J}(T_e - F\omega_m - T_m) \tag{3.12}$$

$$\frac{d}{dt}\theta_m = \omega_m \tag{3.13}$$

3.6 Conclusion

In this chapter, a brief study of induction motor is done. Here induction motor, its construction, working principle, speed control methods, dynamic model and few important equations are discussed.

CHAPTER 4

SCALAR CONTROL OF INDUCTION MOTOR DRIVE

4.1 Introduction

Scalar control is due to magnitude variation of control variables as it name indicates and it does take into account of the coupling effect of the machine. Scalar controlled drives have been broadly used in industry. It is easy to implement but it gives low-grade performance. In this method, the ratio of v/f is kept constant so keep magnetizing flux constant thus torque will be independent of supply voltage and frequency. The stator voltage is adjusted according to supply frequency, apart from low and above base speeds. Above base speed, v/f is not applicable because of insulation break down. At low frequency, there is voltage drop across stator resistance which is sufficient to take into account. To compensate this effect, boost stator voltage is used which has its effect at only low speed. At high speed, its effect is neglected. To reduce jerks and steady state time constant at starting, motor inductance both rotor and stator and stator resistance must be low. While high rotor resistance will lead to lesser jerk but will result in higher copper losses [1, 13].

$$\phi = \frac{V}{4.44KTf} \tag{4.1}$$

Therefore,

$$\phi \alpha \frac{V}{f} \tag{4.2}$$

Where, V is stator voltage, f is stator frequency, ϕ is flux and K is proportional constant.

There are two types of scalar control techniques. These are

- Open loop scalar control
- Closed-loop scalar control

But before discussing open loop and closed loop scalar control, PWM is discussed here which is used in both open and closed loop simulation.

4.2 Pulse width modulation

Pulse-width modulation (PWM) is a scheme where one waveform controls the duty ratio of other waveform. The opening and closing time for the switches is obtained by the intersections between the carrier waveform and the reference voltage waveform. By PWM technique, total power supplied to a load reduces without any losses. It is used to regulate the applied voltage to the motor. The speed of motor changes by changing the duty ratio. The higher power can be delivered to the load if the closed period is high than the opened period. Due to rapid change of state between closing and opening, the average power dissipation is very less compared to the power being delivered. PWM amplifiers are compact and more proficient than linear power amplifiers. There are many PWM techniques but here only sine PWM technique is discussed.

In sine PWM, a low-frequency sinusoidal modulating waveform is compared with high frequency carrier waveform. The switching state changes based on the intersection of sine waveform and carrier waveform. The desired output voltage is accomplished by changing the amplitude and frequency of modulating voltage.

4.3 Open loop scalar control

By far the most common method of speed control is v/f because of its ease and these types are of most extensively used motor in industry. Conventionally, for fixed speed applications, induction motors have been used with open loop 50 Hz power supplies. Frequency control is common for variable speed uses**.** To fulfill the above requirement, voltage is required to be proportional to frequency to keep the flux constant, but by overlooking the stator resistance drop. Diode rectifier with a single phase or three phase supply, PWM voltage served inverter and filter will form power supply. As the name indicates, no feedback signal is required for this technique [3, 4].

PWM inverter is combined in inverter block itself. There are few complications in the operation of open loop drive which are as below

- The motor speed cannot control exactly, as the speed of rotor is marginally less than the synchronous speed which is the stator frequency in this scheme and hence the synchronous speed is the single control parameter.
    - The slip speed which is the difference of the electrical rotor speed and synchronous speed cannot be kept constant in this scheme.

In this technique, the supply voltage is produced directly from the supply frequency command by a gain factor G (V_s/ω_e) therefore the flux will be constant. By neglecting the stator leakage inductance and resistance, the flux corresponds to air gap flux Ψ_m or rotor fluxΨ_r. The stator resistance absorbs the major part of stator voltage. To maintain the flux and full torque constant at low speed, boost voltage is added. Effect of boost voltage is neglected at higher frequencies. To generate the angle signal, the speed signal is integrated. By the angle signal and voltage obtained by gain block G, corresponding phase voltages will be generated.

Below is the block diagram of open loop v/f control

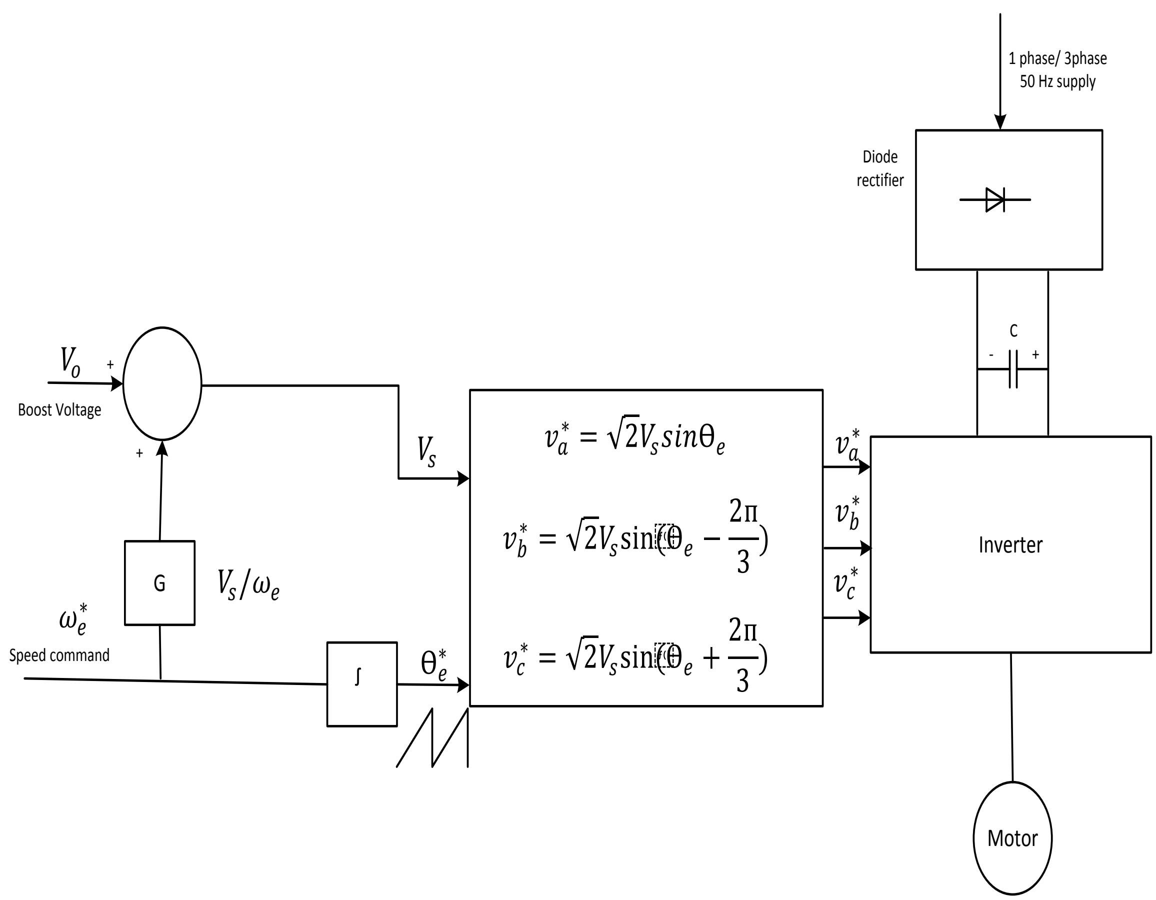


Fig. 4.1 Block diagram of open loop volts/Hz speed control

4.4 Closed loop scalar control

The basis of fixed v/f speed control of induction motor is to supply a flexible magnitude and adjustable frequency voltage to the motor. Both the current source inverter and voltage source inverter can be implemented in variable frequency ac drives. To sense the speed in feedback loop, a shaft position encoder or speed sensor is used. Then the actual speed is compared with the reference speed. The difference between these two is known as error signal which is then processed with speed controller mainly PI controller. The output of speed controller and actual speed will produce the inverter frequency.

Block diagram of closed loop scalar control

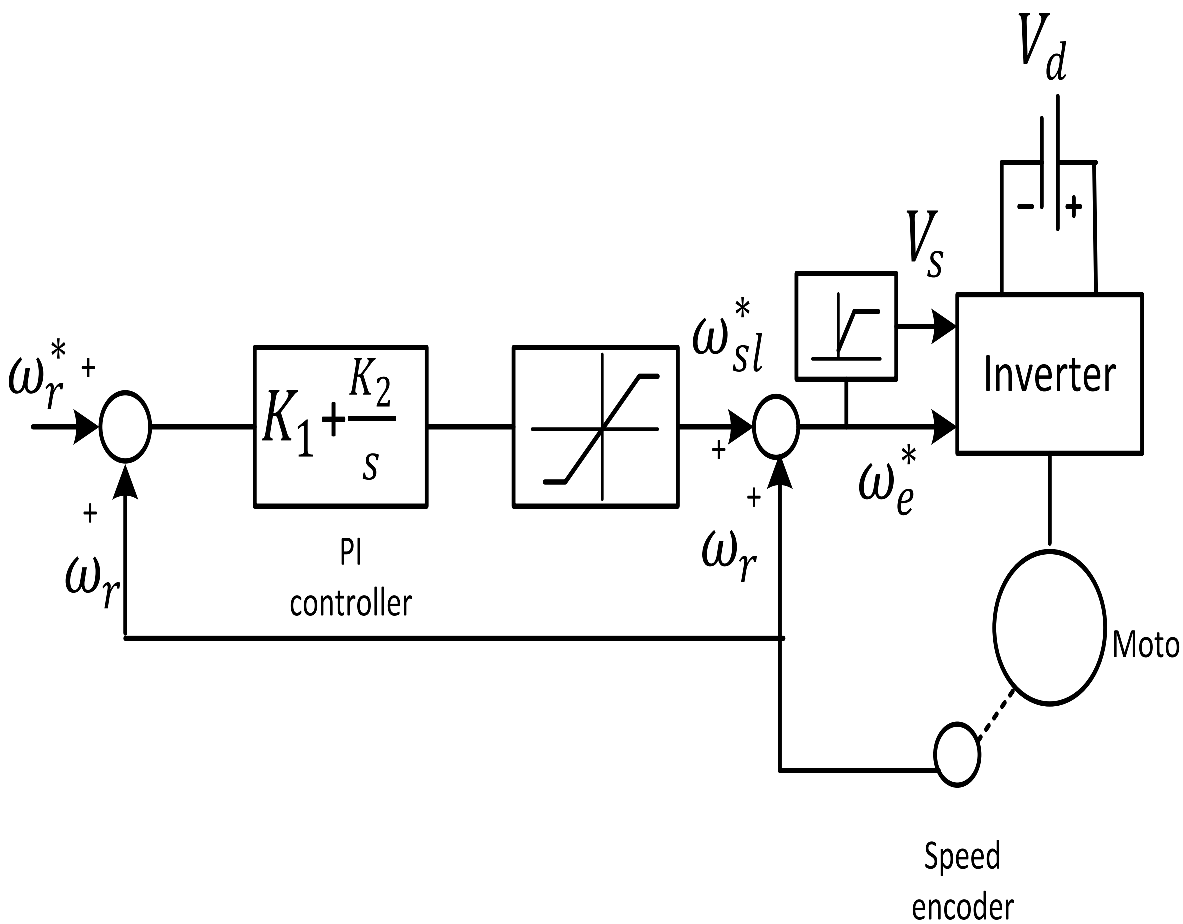


Fig. 4.2 Block diagram of closed loop v/f control of induction motor drive

4.5 Result and discussion

Modelling and simulation of open loop and closed loop scalar control of induction motor drive is carried out using an induction motor with functional specification given in table 4.1.

Table 4.1 Machine Parameters and specifications

Rated Power (kW)	4
Rated Line voltage (V)	400
Pole pairs	2
Frequency (Hz)	50
Stator resistance (Ω)	1.405
Rotor resistance (Ω)	1.395
Stator leakage inductance (mH)	5.839
Rotor leakage inductance (mH)	5.839
Magnetizing inductance (mH)	172.2
Moment of Inertia(kg-m^2)	0.0131

4.5.1 Performance analysis of open loop scalar control

Open loop v/f control under different operating conditions is carried on a 3 phase induction motor as per technical specifications given in table 4.1.

Below is the Matlab/Simulink diagram of open loop v/f scalar control.

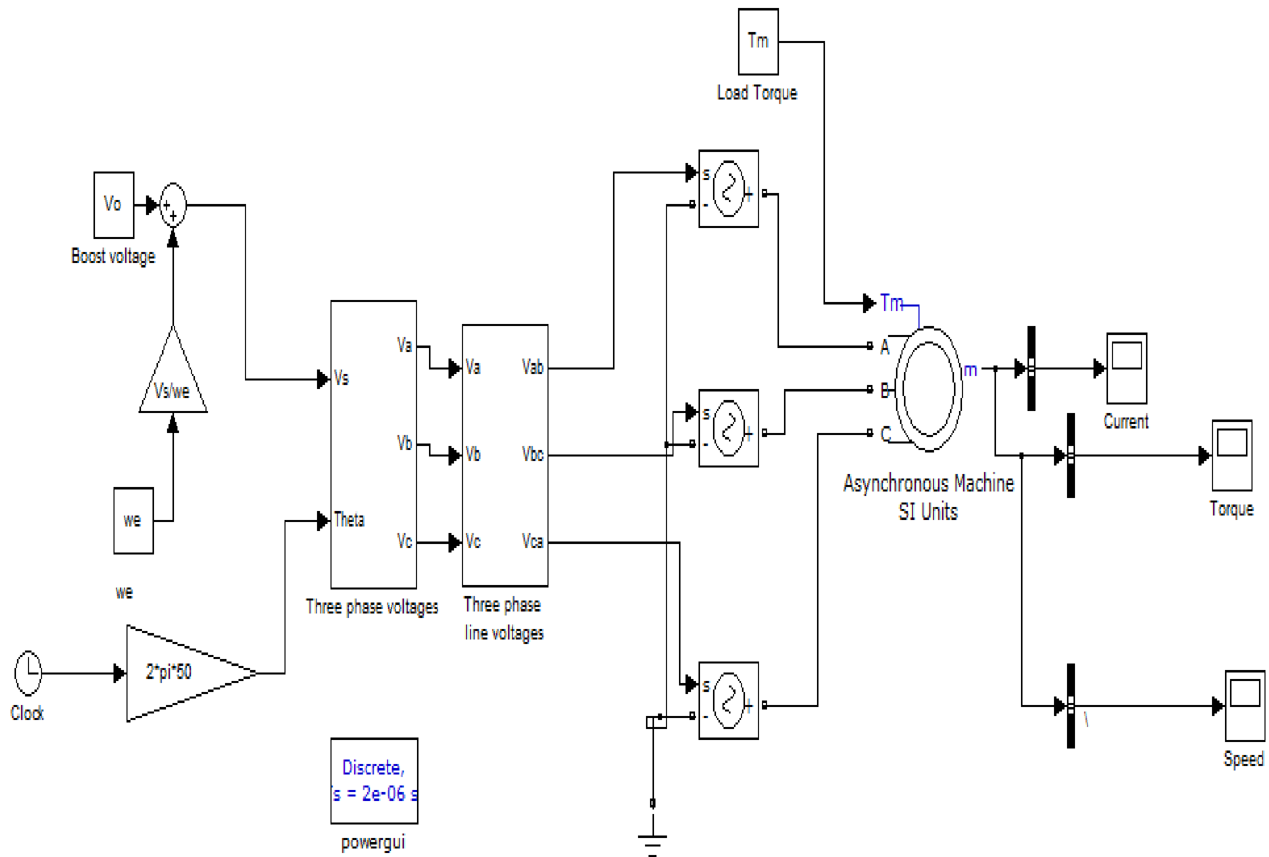


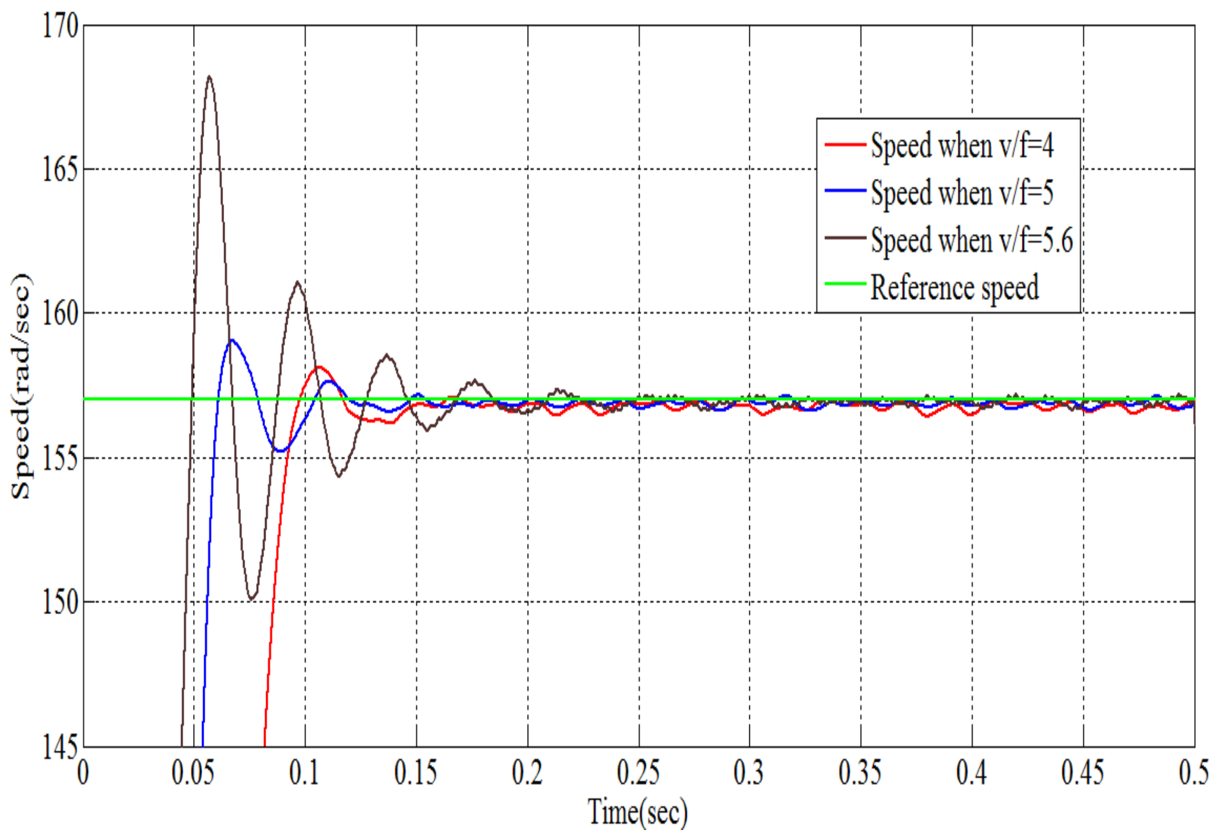
Fig. 4.3 Matlab/Simulink diagram of open loop v/f control of three phase induction motor

Simulation results for different values of v/f gain

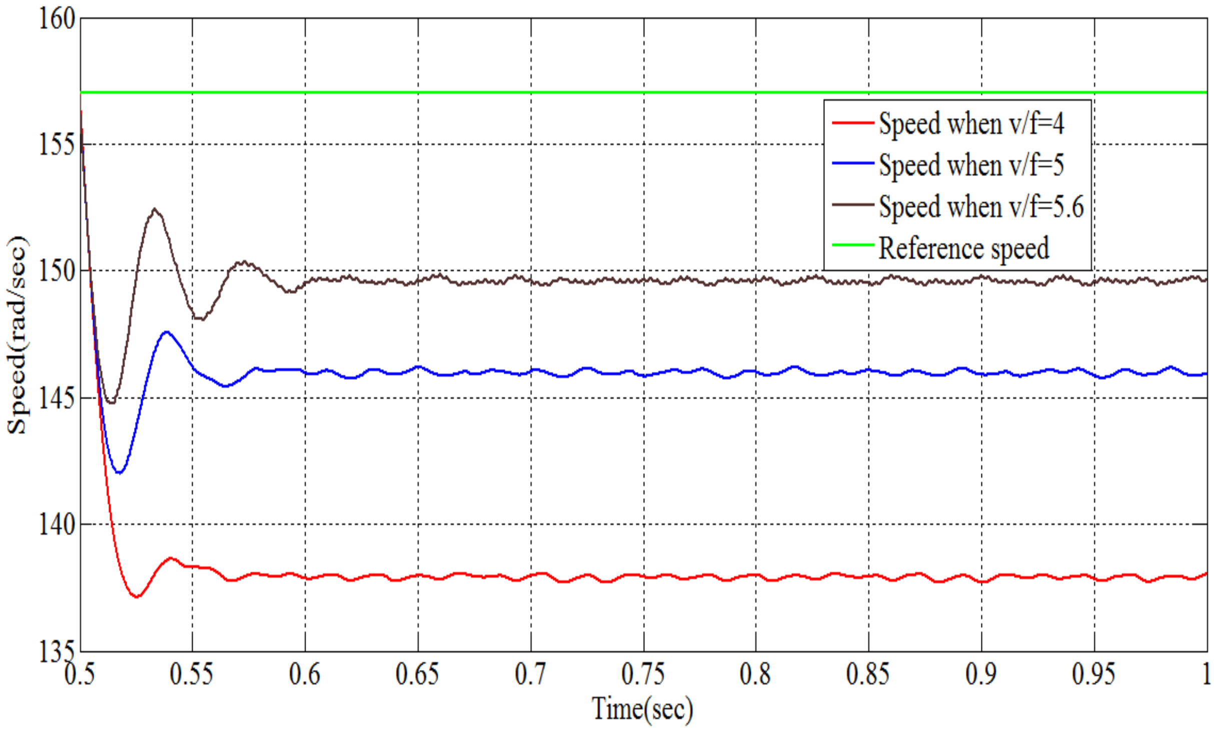
The performance for open loop scalar control is analyzed for different v/f gain at full speed and on load torque. Initially motor is running at 157 rad/sec and load is given at 0.5 sec. Three gain values used for v/f are 4, 5 and 5.6. It is witnessed that for low values of v/f, overshoot in speed is less compared to high values of v/f. As gain value increases, overshoot in speed rises. For high gain values, maximum values of torque and current are also high.

At 0.5 sec, load of 20 N-m is applied. It is observed that for low gain value, there is large steady state error in speed as compared to high value of gain. Speed, torque and current waveforms are shown below. A three phase current waveform for gain value of 4 is also presented.

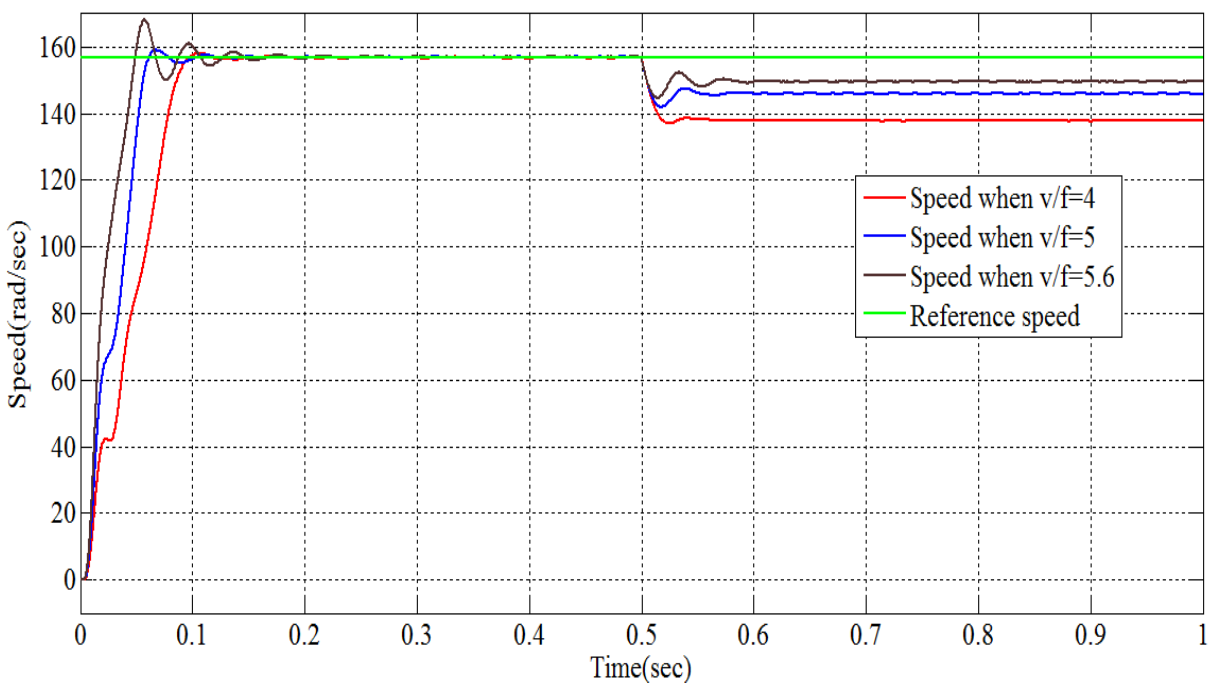
After the application of load, the speed does not follow the reference speed resulting in a steady state error in output. This is the main reason of replacement of open loop scalar control in industry. It does not provide the required output because there is no feedback loop and also there are oscillations in the output waveform. The output waveform is not very smooth. In table 4.2, comparison is done based on peak overshoot without load, with load and steady state error.



(a)

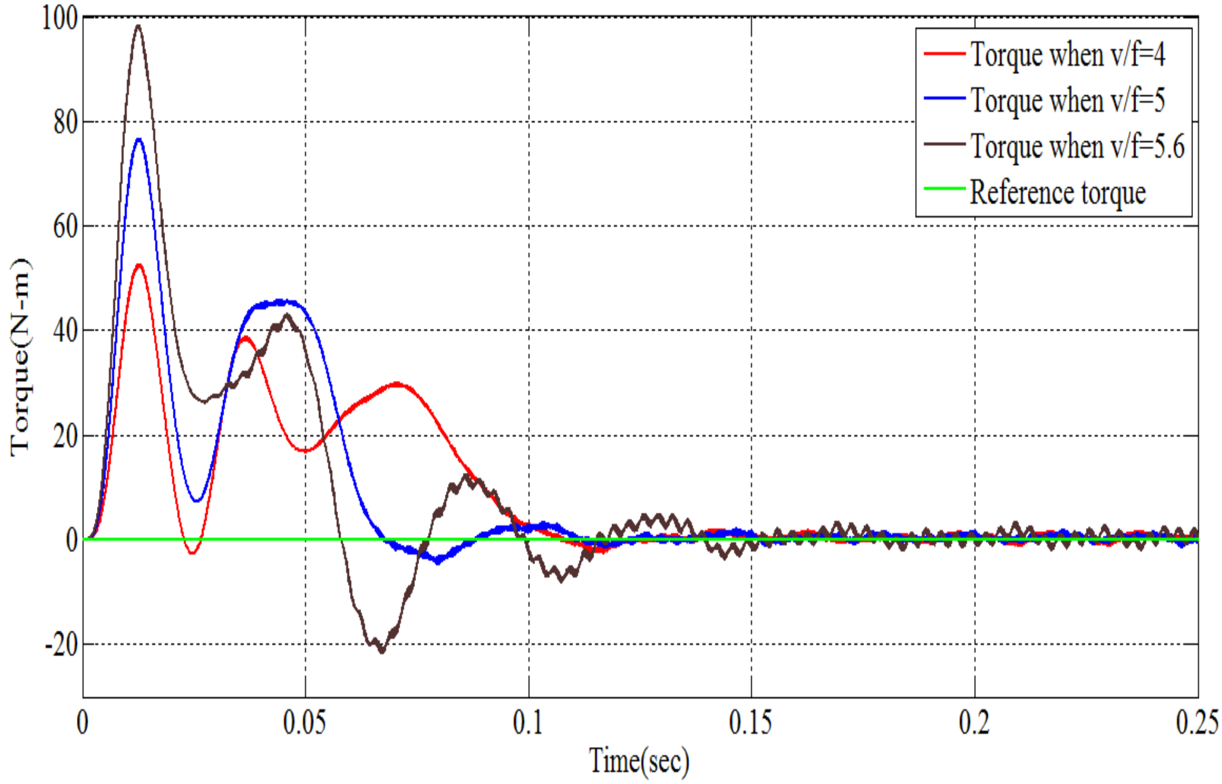


(b)

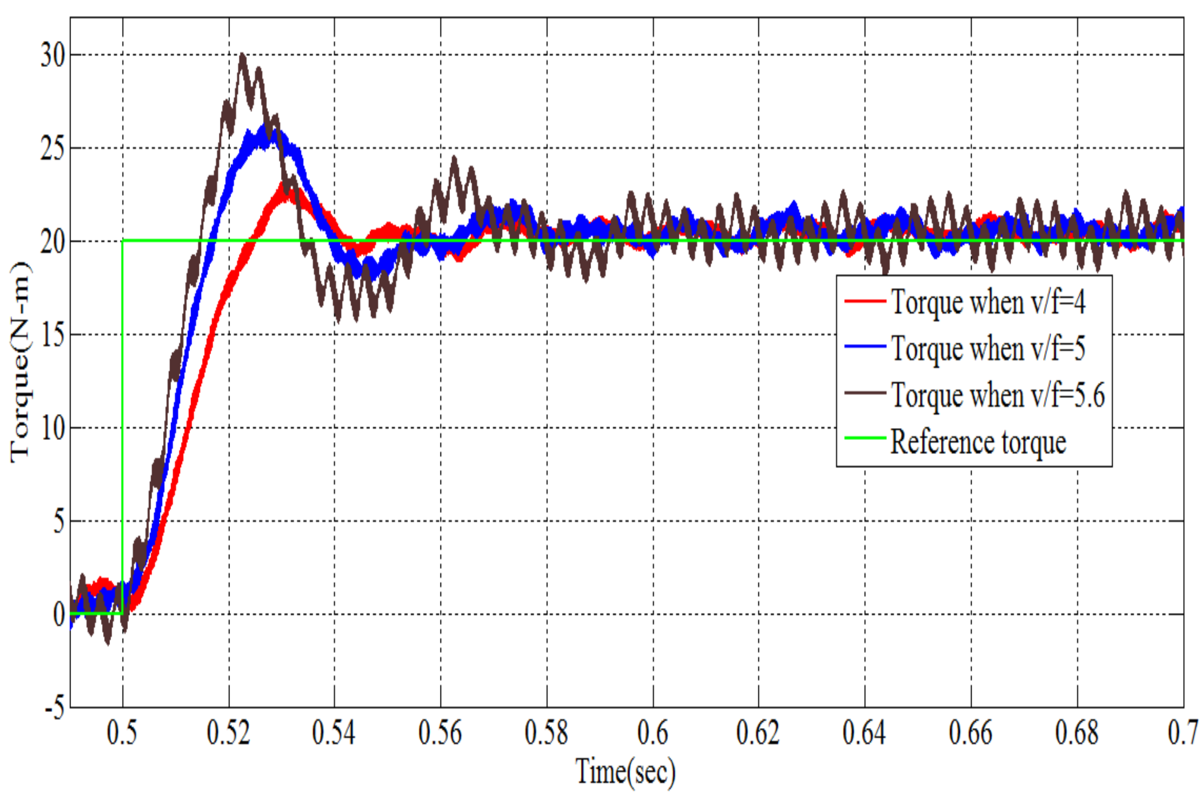


(c)

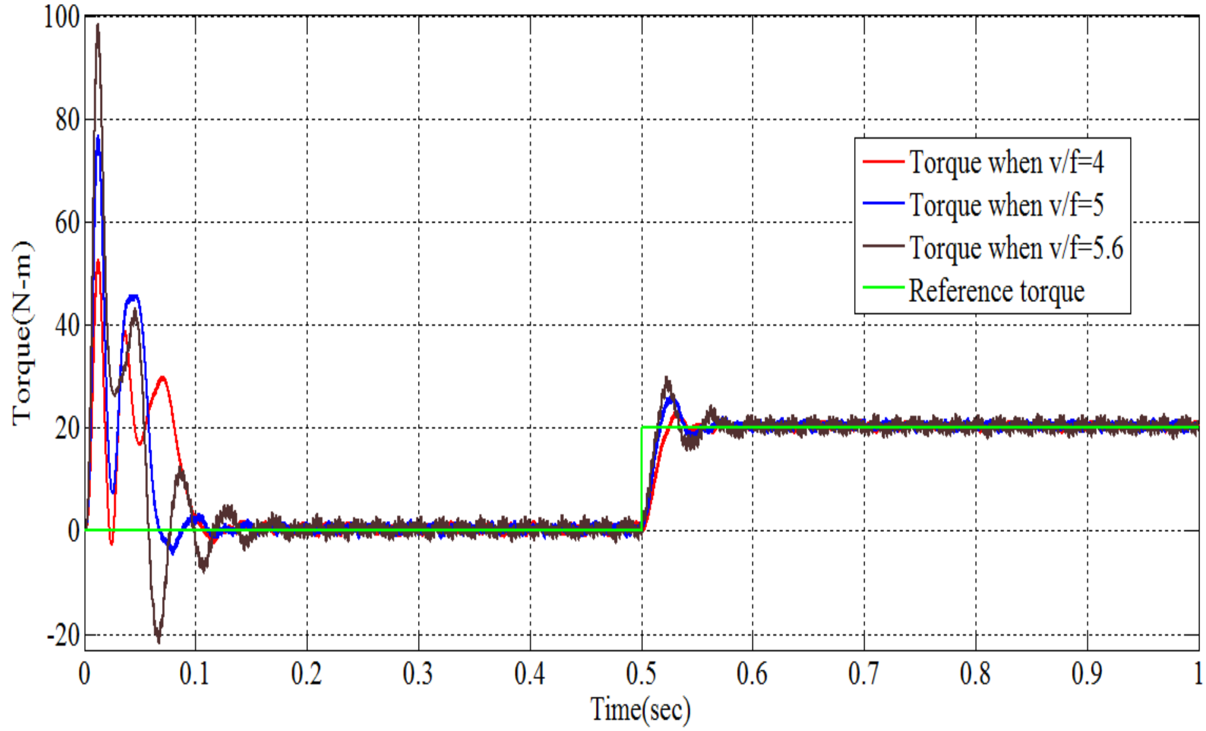
Fig. 4.4 Speed waveform of induction motor drive for varying values of v/f gain (a) without load, (b) with load, (c) waveform without load and with load at 0.5 sec


Torque when v/f=4
Torque when v/f=5
Torque when v/f=5.6
Reference torque
Torque(N-m)
Time(sec)
100
80
60
40
20
0
-20
0
0.05
0.1
0.15
0.2
0.25

(a)

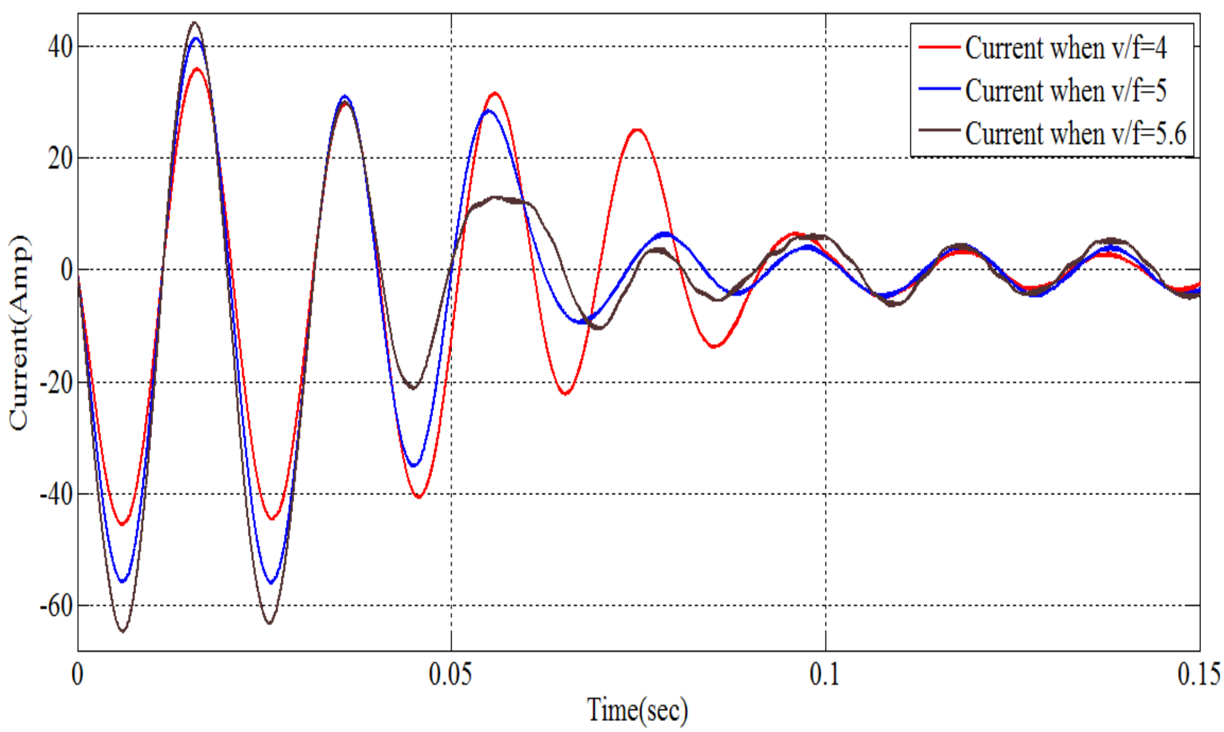

Torque when v/f=4
Torque when v/f=5
Torque when v/f=5.6
Reference torque
Torque(N-m)
Time(sec)
30
25
20
15
10
5
0
-5
0.5
0.52
0.54
0.56
0.58
0.6
0.62
0.64
0.66
0.68
0.7

(b)

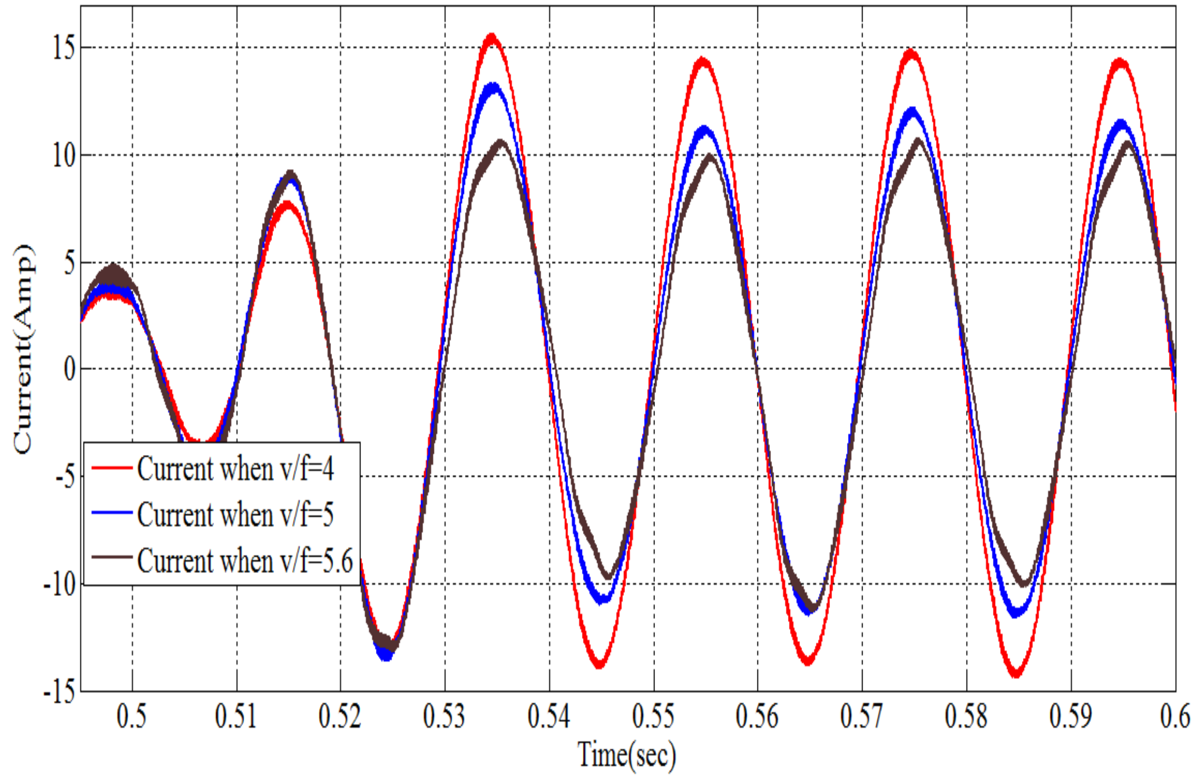


(c)

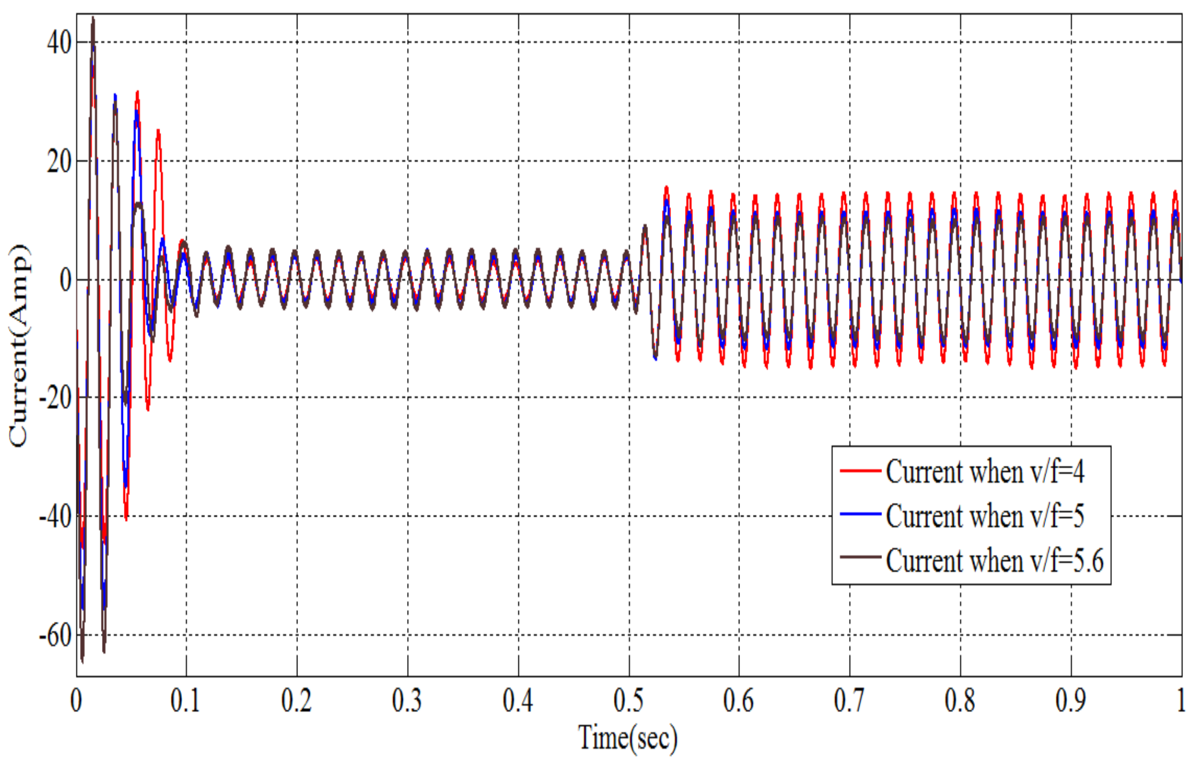
Fig. 4.5 Torque waveform of induction motor drive for varying values of v/f gain (a) without load, (b) with load, (c) waveform without load and with load at 0.5 sec



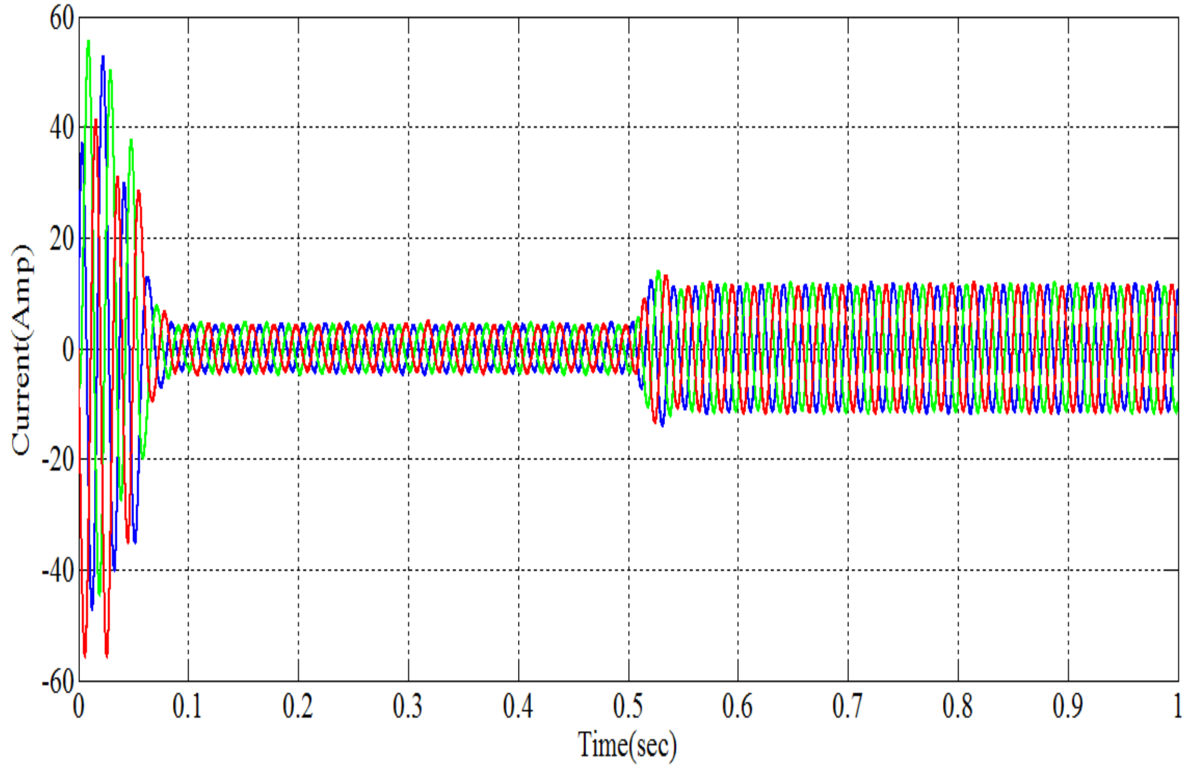
(a)


Current(Amp)
Time(sec)
Current when v/f=4
Current when v/f=5
Current when v/f=5.6

(b)


Current(Amp)
Time(sec)
Current when v/f=4
Current when v/f=5
Current when v/f=5.6

(c)



(d)

Fig. 4.6 Current waveform of induction motor drive for varying values of v/f gain (a) without load, (b) with load, (c) single phase waveform, (d) three phase current waveform

Table 4.2 Peak overshoot without load, with load and steady state error with load for varying values of v/f gain

Parameters / v/f Gain	Peak overshoot(rad/sec) without load	Peak overshoot(rad/sec) with load	Steady state error(rad/sec)
4	1.095	19.87	19.1
5	2.025	15	11
5.6	12.24	12.67	7.9

4.5.2 Performance analysis of closed loop scalar control

Closed loop v/f control under different operating conditions is carried on a 3 phase induction motor where technical specification is given at table 4.1.

Below is the Matlab/Simulink diagram of closed loop v/f scalar control.

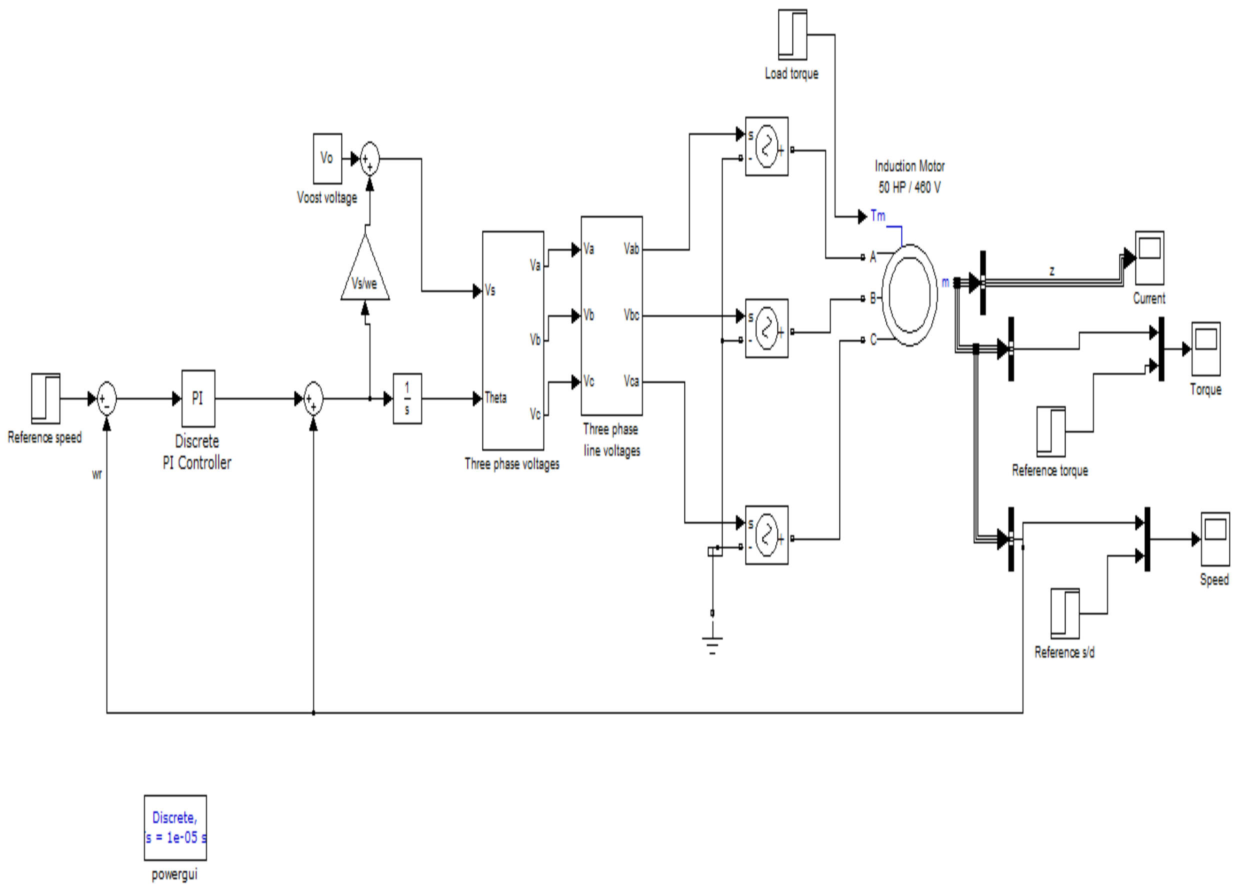
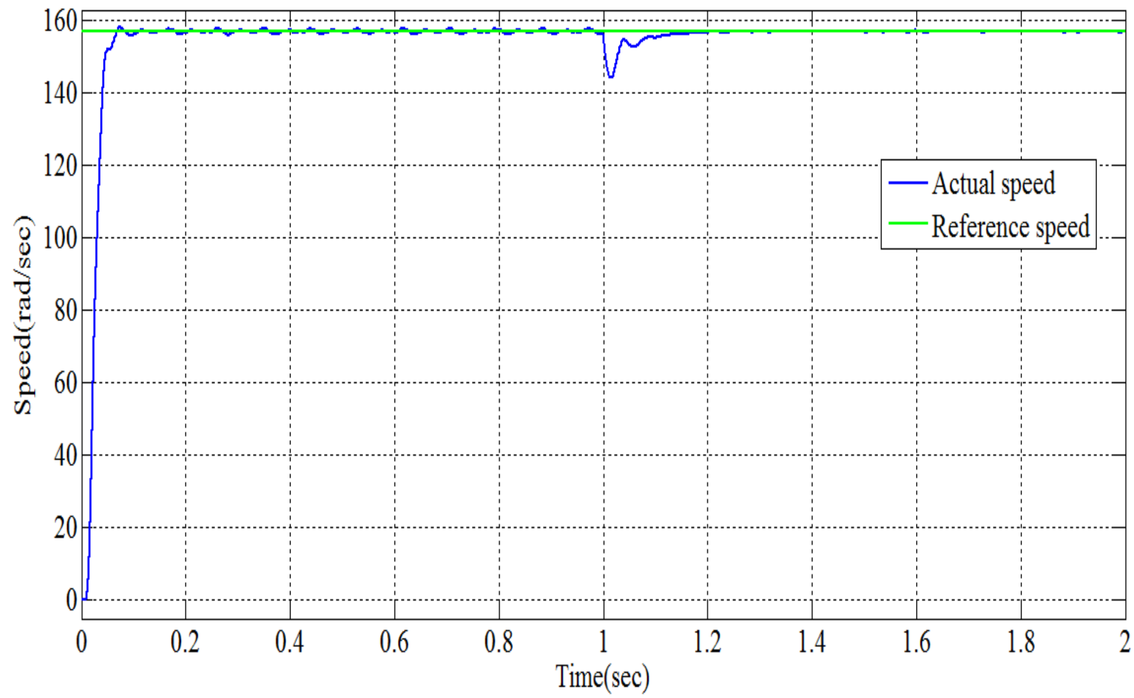


Fig. 4.7 Matlab/Simulink diagram of closed loop v/f control of three phase induction motor

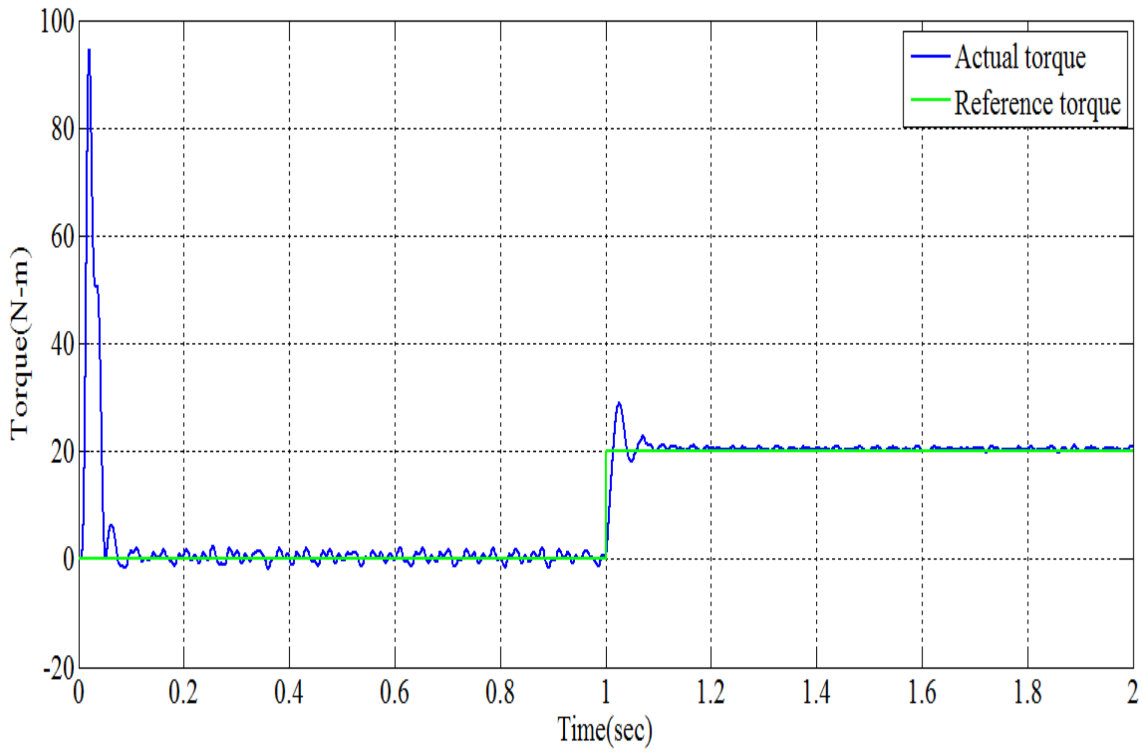
Simulation results of closed loop scalar control

Initially motor is running at 157 rad/sec. It takes around 0.8 sec to settle down to reference speed. There is a very small overshoot in speed. The waveform is presented for 4.5 v/f gain. Current and torque waveform is also shown. The waveform is not smooth at low speed around 32 rad/sec it is because at low speed, stator-resistance absorbs major amount of voltage. Boost voltage is provided but still there is dip in at low speed.

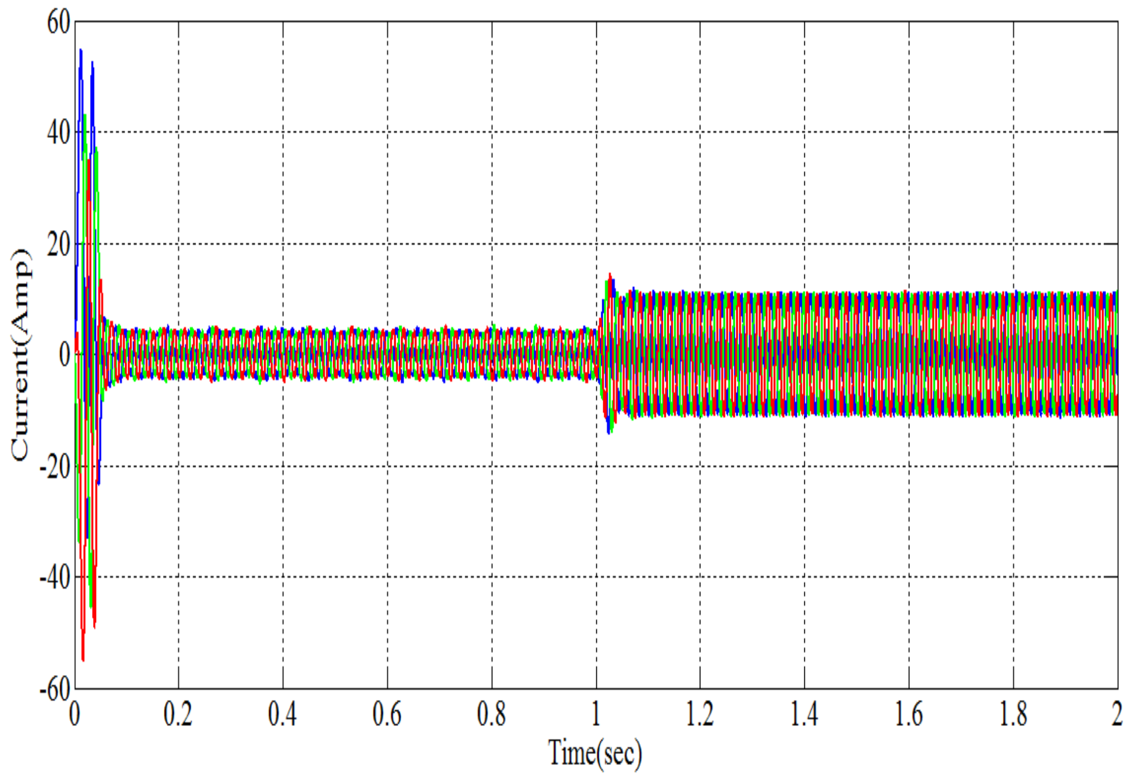
At 1 sec, torque of 150 N-m is applied to the motor. On application of torque, speed takes a small drop and settles to base speed in0.7 sec.



(a)



(b)



(c)

Fig. 4.8 Induction motor dynamic performance for closed loop scalar control (a) speed, (b) torque, (c) current

4.6 Conclusion

Matlab simulation of open loop and closed loop of induction motor is carried out. For open loop, it is carried out for different value of v/f gain. For lowest value of v/f gain, peak overshoot is minimum, undershoot is maximum and steady state error is also minimum. For increasing value of v/f ratio, overshoot increases, undershoot decreases and steady state error decreases. This is the reason to prefer vector control in industrial application. But it is simple to implement so it is in use where simple v/f control is required such as mines, chemical industries, mill run out of tables, steel mills, pumps, fans, blowers, conveyers, machine tools etc.

CHAPTER 5

INDIRECT VECTOR CONTROL OF INDUCTION MOTOR DRIVE

5.1 Introduction

Induction motor drives are the workhorses of the industry for variable speed applications in a wide-ranging power from fractional horsepower to multi-megawatts. But the estimation and control of induction motor drives are much more complex than dc drives and rises essentially with high performance. The main complexity reasons are machine parameter variations, complex dynamics of ac machines and the difficulties in processing of feedback signals in the existence of harmonics. Two main control strategies of induction motor drives are there named as scalar control and vector control. Scalar control is much simpler compared to vector control, but the internal coupling (i.e. flux and torque are dependent on voltage, frequency and current) effect makes the response sluggish and the system is easily disposed to instability. Vector control can solve the above problem. By vector control technique, the induction motor can be operated like a separately excited dc motor and introduced a new start in the high performance of ac drives. It is an outstanding control strategy for speed and torque control of induction motor [13].

5.2 Vector control

The development of vector control in the start of 1970s, and the demo that an induction motor can be controlled like a separately excited dc motor, transported a new start in the high performance control of ac drives. Because of similar performance to dc machine, vector control is also known as decoupling, transvector or orthogonal control. Vector control is valid for both induction motor and synchronous motor drives. Undoubtedly, vector control and the corresponding feedback signal processing, mainly for modern sensor less vector control, are difficult and use of powerful microprocessor or DSP is mandatory.

Vector Control describes the way in which the control of torque and speed are directly based on the electromagnetic state of the motor, similar to a DC motor. Vector control is the first technology to control the “real” motor control variables of torque and flux. With decoupling between the stator current components (magnetizing flux and torque), the torque producing component of the stator flux can be controlled independently. Decoupled control, at low speeds, the magnetization state of motor can be maintained at the appropriate level, and the torque can be controlled to regulate the speed. Indirect vector control has been solely developed for high-performance motor applications which can operate smoothly over the wide speed range, can produce full torque at zero speed, and is capable of quick acceleration and deceleration.

There are essentially two common methods of vector control. One, known as direct or feed-back method, was invented by Blaschke and other, identified as the feed forward or indirect method was invented by Hasse. The two methods differ in the way the rotor angle is determined. Indirect vector control is the most popular control method in induction motor due to its better dynamic performance.

In Direct vector control strategy rotor flux vector is either measured by means of a flux sensor mounted in the air-gap or by using the voltage equations starting from the electrical machine parameters. But in case of Indirect vector control rotor flux vector is estimated using the field oriented control equations (current model) requiring a rotor speed measurement. Among both schemes, Indirect vector control is more commonly used because in closed-loop mode it can easily operate throughout the speed range from zero speed to high-speed field-weakening.

5.2.1 Direct Vector control

In direct vector control the rotor angle or control vector is obtained by the terminal voltages & currents directly by using flux estimators. The direct vector control is also known as feedback vector control scheme. Similar to Indirect Vector Control, various controllers have been implemented on direct vector controlled induction motor drives also to improve the performance of the drive. While the direct method is inherently the most desirable control scheme, it suffers from high cost and the unreliability of the flux measurement. Although the indirect method can approach the performance of the direct measurement scheme, the major weakness of this approach is centered upon the accuracy of the control gains which, in turn, depend heavily on the motor parameters assumed in the feed forward control algorithm.

The direct vector control determines the orientation of the air-gap flux by use of a hall-effect sensor, search coil or other measurement techniques. However, using sensors is expensive because special modifications of the motor are required for placing the flux sensors. Furthermore, it is not possible to directly sense the rotor flux. Calculating the rotor flux from a directly sensed signal may result in inaccuracies at low speed due to the dominance of stator resistance voltage drop in the stator voltage equation and inaccuracies due to variations on flux level and temperature. In vector control, to perform the frame transformation, accurate rotor flux position is needed. Because with inaccurate rotor flux position torque and flux components are not be completely decoupled, as a result of which dynamic response become poor . So, knowledge of rotor flux position is the core of the vector control. The measurement of the rotor flux position is different if we consider synchronous or induction motor. In synchronous machine the rotor speed and rotor flux speed are equal. Then rotor flux position is directly measured by position sensor or by integration of rotor speed. In the induction machine the rotor speed is not equal to the rotor flux speed, then it needs a particular method to calculate field angle.

The main disadvantages of direct vector control are

1. Fixing of number of sensors is a tedious job.
2. The sensors increase the cost of the machine.
3. Drift problem exist because of temperature.
4. Poor flux sensing at lower temperatures.

5.2.2 Indirect Vector control

In indirect vector control, the angle is obtained by using rotor position measurement and machine parameter’s estimation. Field orientation has emerged as a powerful tool for controlling ac machines such as inverter -supplied induction rotors/synchronous motors.

The complex functions required by field oriented control are executed by intelligent controllers using microcontrollers or digital signal processors (DSP), thus greatly reducing the necessary control hardware. An important requirement to obtain good control performance is to make the motor parameters in the Field -oriented controller coincide with the actual parameters of the motor. The ability to inject currents into the motor with a current source opened up new possibilities for parameter determination. It was Takayoshi who described a new identification technique utilizing injected negative sequence components. It is shown that the stator as well as rotor resistance and leakage inductance can be determined on line while the motor is driving the load.

The main advantages of indirect vector control method are

1. The sensors are eliminated.
2. The dynamic performance of the indirect vector control is better than the direct vector control.
3. The cost factor is decreased.
4. There is no drift problem as in direct vector control.

Comparison between Direct and Indirect vector control

The major disadvantage of direct vector method is the need of so many sensors. Fixing so many sensors in a machine is a tedious work as well as costlier. Due to this the scheme is prevented from being used. Several other problems like drift because of temperature, poor flux sensing at lower speeds also persists. Due to these disadvantages and some more related ones, indirect vector control is used. In indirect vector control technique, the rotor position is calculated from the speed feedback signal of the motor. This technique eliminates most of the problems, which are associated with the flux sensors as they are absent. Here the in phase component of stator current space vector n the SRRF is aligned with the rotor mmf vector. This component of the vector is responsible for the production of flux. In the similar fashion the quadrature component is responsible for the production of the torque. Hence such a control technique provides a substitute of a separately excited dc motor using a three -phase squirrel cage induction motor in variable speed application.

5.3 Matlab/Simulink Implementation of Indirect Vector Control

Indirect vector control block diagram is shown in Fig. 5.2. There are two control loops namely hysteresis current control loop and another external speed control loop.

The indirect vector control is basically same as direct vector control, apart from the fact that the unit vector signal are achieved in feed forward manner with the help of measured rotor speed ω_r and slip speed ω_{sl} . In industrial application, IVC is very common. Current controlled PWM inverter provides three phase sinusoidal current source to Induction motor. The error between reference speed and speed signal is given to speed controller which gives the command Torque T_e^* [11].

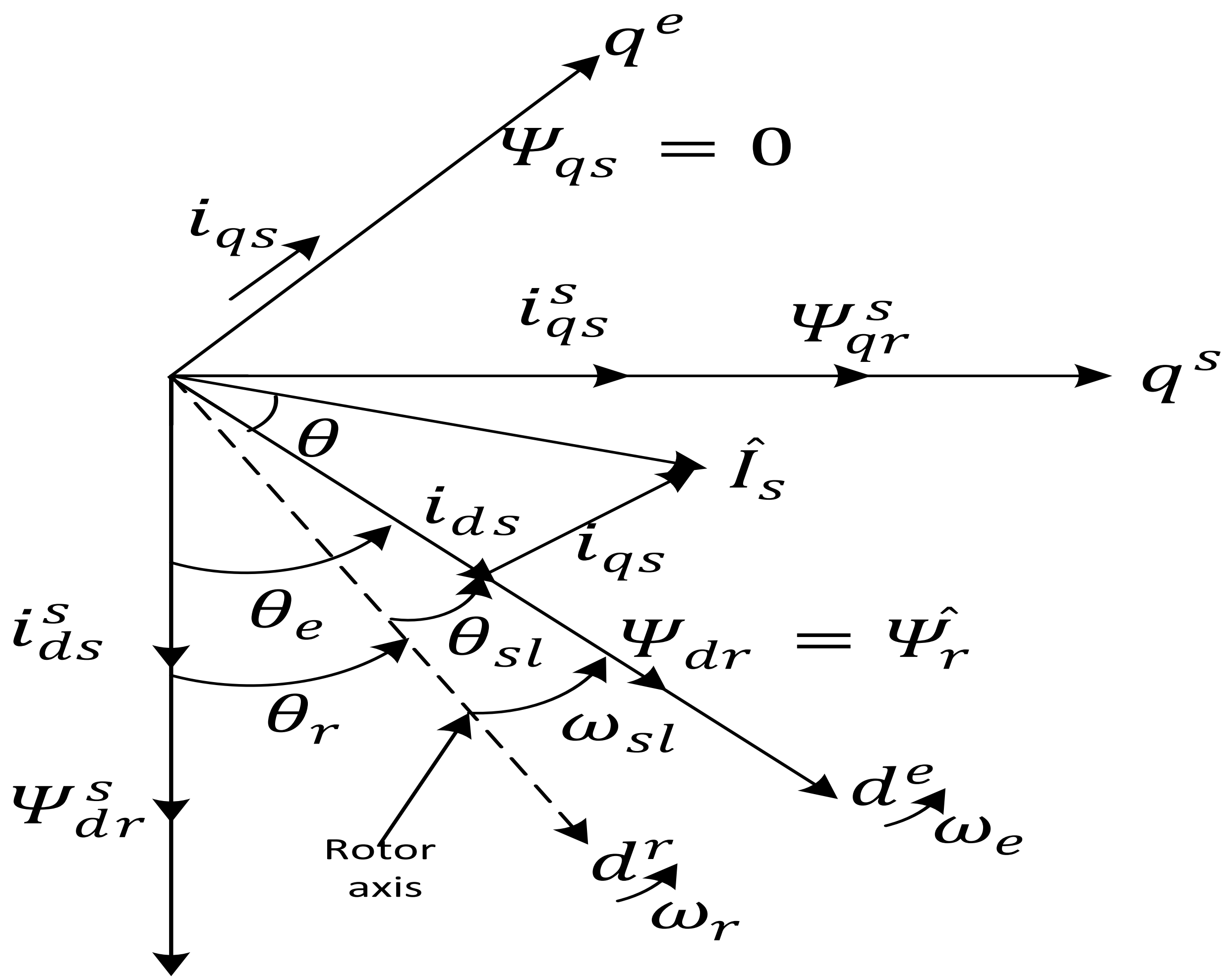


Fig. 5.1 Phasor diagram of indirect vector control

From command torque signal T_e^*, the q-axis stator reference current i_{qs}^* is calculated as

$$i_{qs}^* = \frac{2}{3}\frac{2}{P}\frac{L_r}{L_m}\frac{T_e}{|\Psi_r|} \tag{5.1}$$

$|\Psi_r|$ is the estimated rotor flux linkage and can be computed using

$$|\Psi_r| = \frac{L_m i_{ds}}{1+\tau_r s} \tag{5.2}$$

where $\tau_r = \frac{L_r}{R_r}$ is the time constant of rotor.

The d-axis stator reference current i_{ds}^* is calculated from rotor flux reference input $|\Psi_r|^*$as shown below.

$$i_{ds}^* = \frac{|\Psi_r|^*}{L_m} \tag{5.3}$$

Flux and torque can be controlled by d-axis and q-axis current respectively.

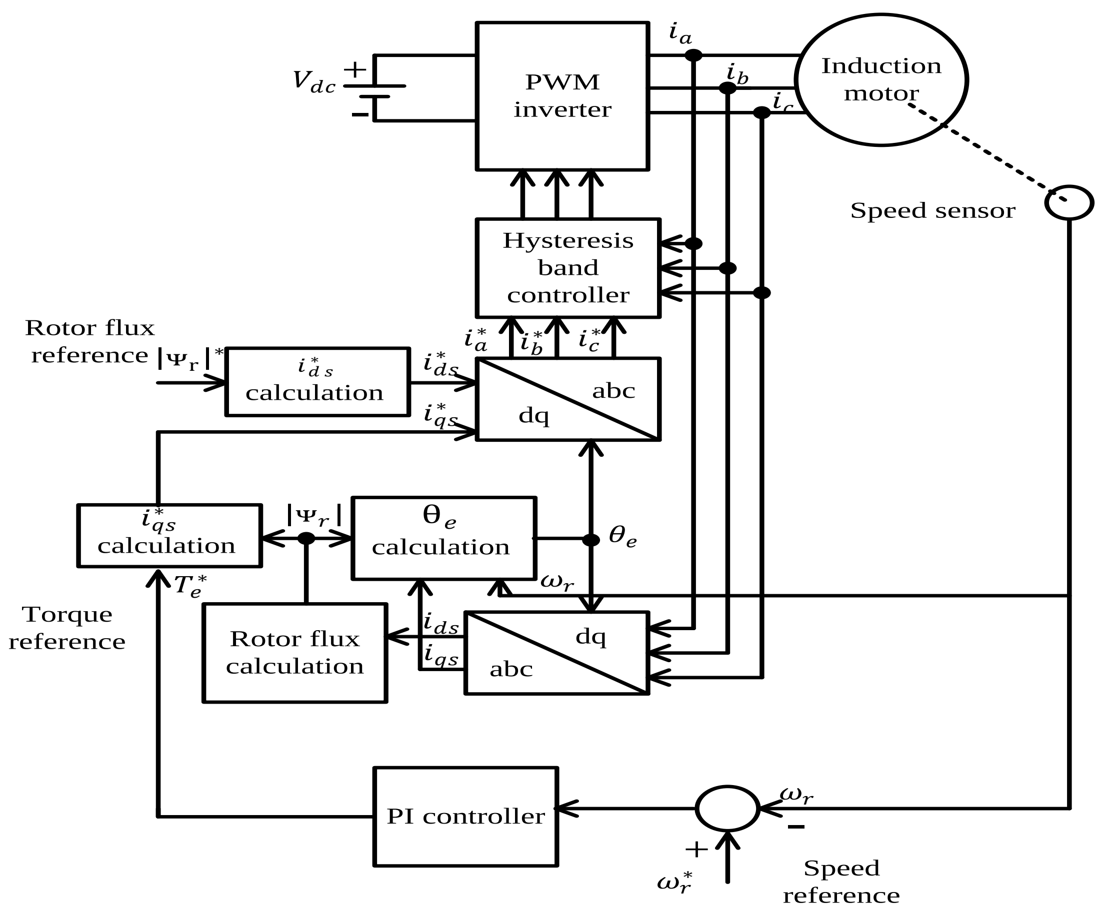


Fig. 5.2 Indirect Vector control block diagram

The rotor flux position θ_e needed for coordinate transformation is calculated from slip frequency ω_{sl} and rotor speed ω_r as shown below.

$$\theta_e = \int (\omega_{sl} + \omega_r)\, dt \tag{5.4}$$

The slip frequency ω_{sl} is computed as below from motor parameters and stator current reference i_{qs}^*.

$$\omega_{sl} = \frac{L_m}{|\Psi_r|} \frac{L_r}{R_r} i_{qs}^* \tag{5.5}$$

The current references i_{qs}^* and i_{ds}^* are transformed into three phase currents i_a^*, i_b^* , i_c^* with the help of inverse Park and inverse Clarke transformation for the current regulators. The current regulators compare the reference currents and the measured currents for inverter gating signals. For good dynamic response during transient condition, the motor speed must be equal to reference speed.

5.3.1 a, b, c/d-q Transformation

a, b, c to d-q transformation is done with the help of Clarke and Park, and d-q to a, b, c with the help of inverse Clarke and inverse Park transformation.

a, b, c to d-q transformation

First convert three phase stationary a, b, c quantities into two phase stationary *α, β* quantities and then two phase rotatory d-q quantities.

a, b, c to α, β transformation (Clarke transformation)

Clarke transformation alters balanced three phase quantities into two-axis orthogonal stationary reference frame measures. The Clarke transformation is expressed by following equations

$$I_\alpha = \frac{2}{3}(I_a) - \frac{1}{3}(I_b - I_c) \tag{5.6}$$

$$I_\beta = \frac{2}{\sqrt{3}}(I_b - I_c) \tag{5.7}$$

Where I_α is superposed with I_a and $I_a + I_b + I_c$ is zero. I_α and I_β can be written as follows

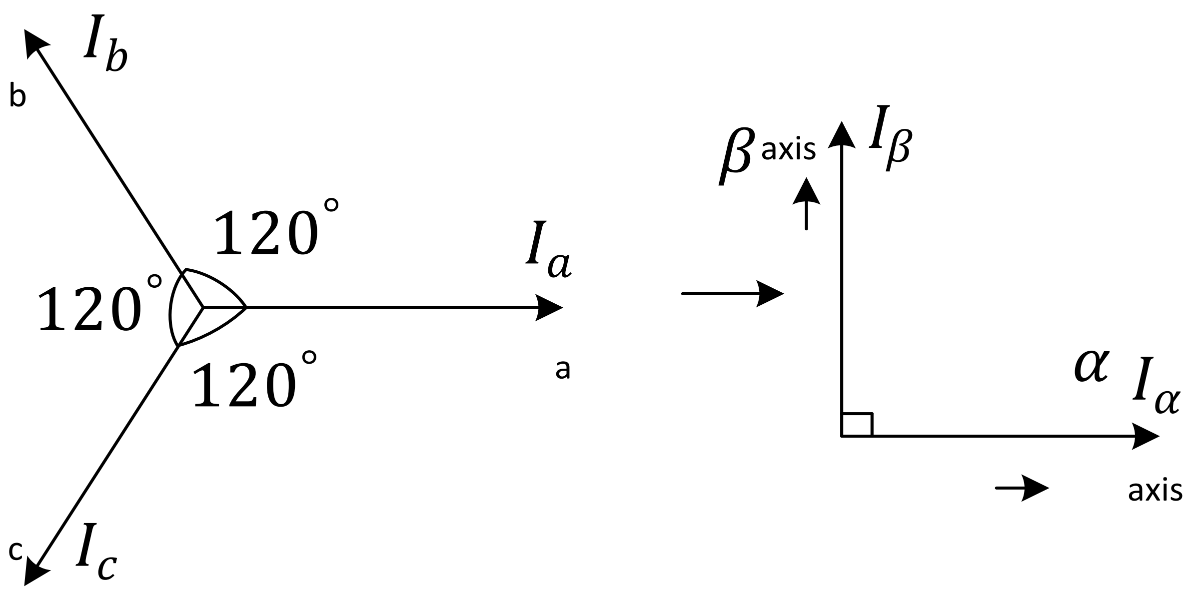


Fig. 5.3 Clarke Transformation

$$I_\alpha = I_a \tag{5.8}$$

$$I_\beta = \frac{2}{\sqrt{3}}(I_b - I_c) \tag{5.9}$$

where $I_a + I_b + I_c = 0$.

α, β to d-q transformation (Park transformation)

The two orthogonal stationary reference frame quantities are transformed into rotating reference frame quantities using Park transformation. The Park transformation is expressed by the following equations

$$I_d = I_\alpha * \cos(\theta) + I_\beta * sin(\theta) \tag{5.10}$$

$$I_q = I_\beta * \cos(\theta) - I_\alpha * sin(\theta) \tag{5.11}$$

where I_d, I_q are rotating reference frame quantities

I_α and I_β are stationary orthogonal reference frame quantities

$\boldsymbol{\theta}$ is the rotation angel

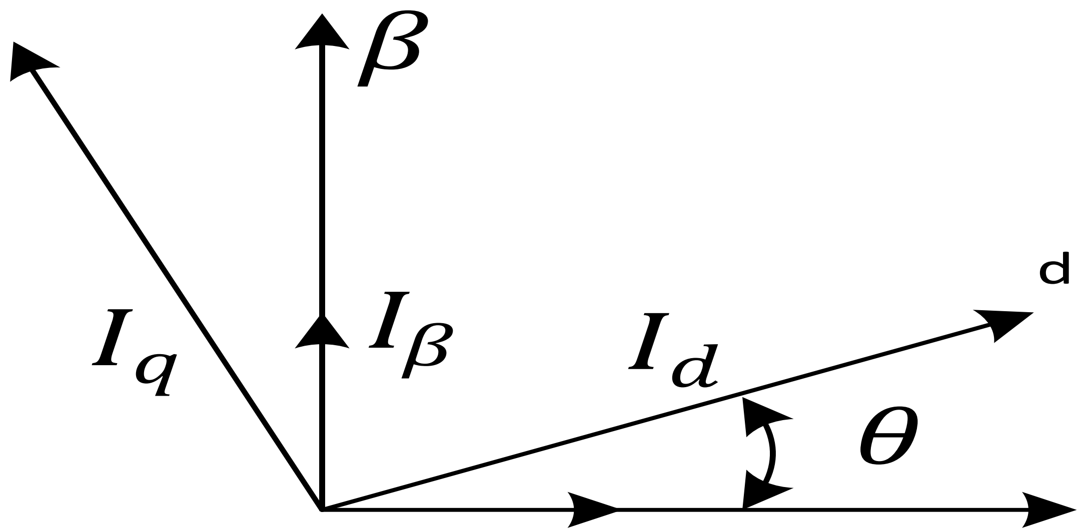


Fig. 5.4 Park transformation

d-q to a, b, c transformation

First convert two phase rotatory d-q quantities into two phase stationary *α, β* quantities and then three phase stationary a, b, c quantities.

d-q to α, β transformation (Inverse Park transformation)

The quantities in rotating reference frame are transformed to two-axis orthogonal stationary reference using Inverse Park transformation. The equations are as follows

$$I_\alpha = I_d * \cos(\theta) - I_q * sin(\theta) \tag{5.12}$$

$$I_\beta = I_q * \cos(\theta) + I_d * sin(\theta) \tag{5.13}$$

α, β to a, b, c transformation (Inverse Clarke transformation)

The transformation from a two-axis orthogonal stationary reference frame to a three-phase stationary frame is accomplished using Inverse Clarke transformation. The Inverse Clarke transformation is expressed by the following equations

$$I_a = I_\alpha \tag{5.14}$$

$$I_b = \frac{-I_\alpha + \sqrt{3} * I_\beta}{2} \tag{5.15}$$

$$I_c = \frac{-I_\alpha - \sqrt{3} * I_\beta}{2} \tag{5.16}$$

5.3.2 Implementation of different controllers

For optimum performance of any system, controllers are used to maintain the error as low as possible. In IVC, PI controller is operated as speed controller and hysteresis band controller as current controller.

A speed controller is the one which processes speed error as an input and deliver controlled output. They are used to reduce steady maximum overshoot, state error and settling time. We are here presenting few controllers based on our requirement. Traditionally PI controller is used for speed control of induction motor drive. But it has some disadvantages associated with it like high overshoot, slow response due to abrupt response, sensitive to controller gains so new controller are introduced here to compare the performance of induction motor based on different controlled techniques. Here PI, IP and PR controller are introduced to study the comparative dynamic performance of induction motor drive. The function of current controller is to maintain minimum ripple currents and switching losses.

Proportional integral controller

In order to get variable speed operation, conventional PI controller have mainly used because of its simplicity in the outer loop. In this control scheme, the accuracy relies on the mathematical model of the system and the desired performance response is not achieved due to load disturbances. However the transient response under model uncertainty downgrades because of integral action, leading to loss of nominal performance. Moreover, the dynamic response may exhibit large settling time and overshoot and prone to oscillation when the input control saturates. A part of PI controller acts like a disturbance observer that takes the speed tracking error in evaluating the offset representing external disturbance and model uncertainty to take care of their effects. The PI controller keeps the expected transient performance under unknown disturbance and model uncertainty [19, 20]

To keep the motor speed at required set point, controllers are used. PI controller exhibits a property of zero steady state error because of integral action. The two speeds are compared and the error is minimized by using the PI controller.

$$\frac{T_e}{E(t)} = K_p e(t) + K_i \int e(t)dt \tag{5.17}$$

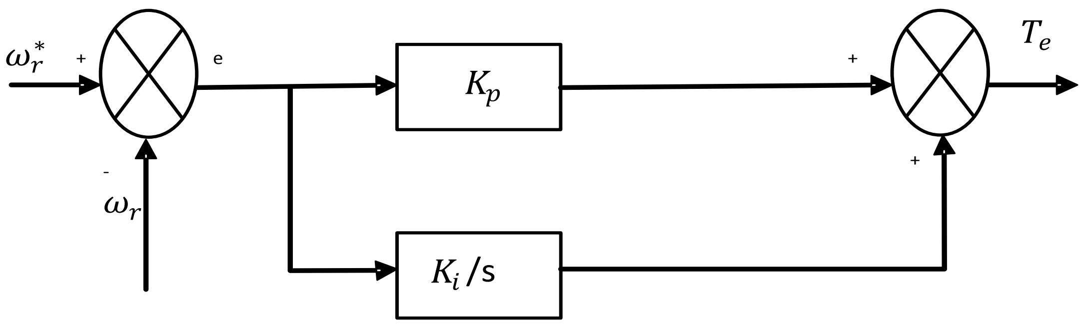


Fig. 5.5 Block diagram of PI controller

To limit the gain of controller from exceeding certain point, a limiter ahead of PI controller is used to maintain the stability of system.

$$T_e = \begin{cases} T_{emax} & \rightarrow T_e \geq T_{emax} \\ -T_{emax} & \rightarrow T_e \leq T_{emax} \end{cases} \tag{5.18}$$

Integral proportional controller

Harashima, Takahashi and Kondo proposed a new method of speed control known as integral proportional controller to resolve the main drawbacks of PI controller. The new introduced IP controller is an amalgamation of integral and proportional controller. In IP controller, the overshoot in speed is reduced because PI controller introduces zero which is absent in IP controller. Also IP controller offers good load recovery characteristic. In IP controller, the proportional term is shifted to feedback path and acts like a feedback compensation.

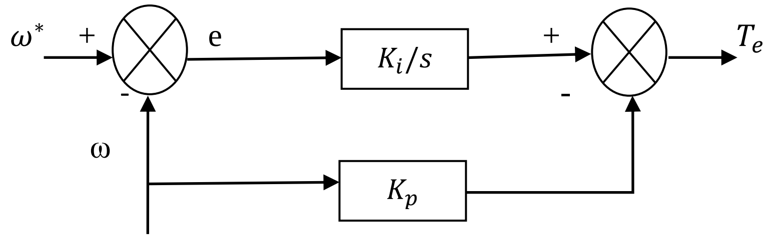


Fig. 5.6 Block diagram of IP controller

The transfer function of IP controller is as below

$$\frac{T_e}{E(t)} = K_i \int e(t)dt - K_p e(t) \tag{5.19}$$

Proportional resonant controller

A proportional–resonant (PR) controller announces an infinite gain at a certain resonant frequency to eradicate current harmonic or steady-state error at that frequency. When the compensated frequency is not within the bandwidth of the system, the harmonic compensators of the PR controller are restricted to numerous low-order harmonics due to system unpredictability. To keep system stability, passive damping is frequently used but then again it is restricted by losses, deprivation of the filter performance and cost. The usage of active damping by means of control may seem smart, but it is frequently restricted by a compound tuning process of the controllers. This controller provides a benefit in performance at the fundamental frequency and disregards other frequency [23, 24]

The transfer function of PR controller is as follows

$$G(s) = K_p + \frac{K_i s}{s^2 + {\omega_0}^2} \tag{5.20}$$

Where $\omega_0(2\pi f)$ is the fundamental frequency and K_p and K_i indicates proportional and resonant gains correspondingly. PI control for the dc quantity in the synchronous frame is same as PR control for the ac quantity in the stationary frame. Intended controller is divided into three main parts which is input, controller contains of proportional gain(K_p) and resonant gain(K_i), transfer function and at last output. It is used to lessen steady state error. Resonant controller will further support to discard sine wave turbulences with a smaller amount of steady state error. It has improved disturbance rejection ability. When there is a harmonic at or near a certain frequency in the controlled signal produced by the harmonic disorders, the resonant frequency of the controller must be at harmonic frequency which is thought to be abolished.

Hysteresis band controller

In various available current control techniques, the hysteresis current control is widely used due to its robustness, fast dynamic response and inherent peak current limiting. But the major drawback of this technique is that high switching frequency can occur at lower hysteresis band so the switching loss of the inverter, limit cycle oscillations and non-optimum current ripples increases. The current ripple can exceed twice the hysteresis band. The hysteresis band of the current controller is deciding factor of switching losses in the inverter circuit. The current ripple and torque ripple of the induction motor drive are also affected by hysteresis band [16, 17].

The hysteresis band current controller is the simplest and mostly used controller due to its fast transient response and simple implementation. A fixed hysteresis band is used in this technique. It is basically a feedback of current control based on PWM technique. In this technique, actual current i is compared with reference current i^* and then error between these two waveform is passed through comparator to confine the current as close as possible to the actual current value. The value of hysteresis band will decide the switching frequency and peak to peak current ripples. When current exceeds the mentioned HB value, the upper switch turns off and lower switch turns on. Thus the actual current waveform is forced to follow the reference current in the hysteresis band through the inverter switching. This process is applicable to all the phases and each phase reference currents i^*_{abc} is compared with actual supply current i_{abc} for generating six gate pulses .

The switching conditions for hysteresis band current controller are as follows:

When $(i^* - i\,) > HB$: Upper switch will turn on

When $(i^* - i\,) < HB$: Lower switch will turn on

Upper hysteresis band current $i_u = i^* + \Delta\, i$

Lower hysteresis band current $i_l = i^* - \Delta\, i$

For optimum performance, balance must have to be kept between the current ripples and switching frequency e.g. for small values of hysteresis band, current ripples are low and switching frequency is high and for high value of hysteresis band , current ripples are high and switching frequency is less.

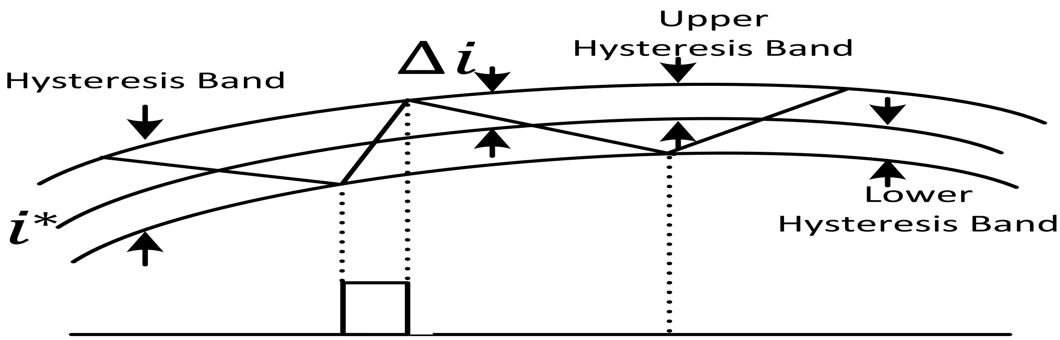


Fig. 5.7 Hysteresis band controller

5.3.3 Result and discussion

Modeling and simulation of indirect vector controlled IM drive is carried out on an induction motor with functional specifications given at Table 5.1. The performance of IM drive is analyzed under different operating conditions.

Table 5.1 Machine Parameters and specifications

Rated Power (kW)	2.2
Rated Line voltage (V)	380
Pole pairs	2
Frequency (Hz)	50
Stator resistance (Ω)	3.3
Rotor resistance (Ω)	2.2
Stator leakage inductance (mH)	13.6
Rotor leakage inductance (mH)	13.6

Magnetizing inductance (mH)	286.4
Moment of Inertia(kg-m^2)	0.05

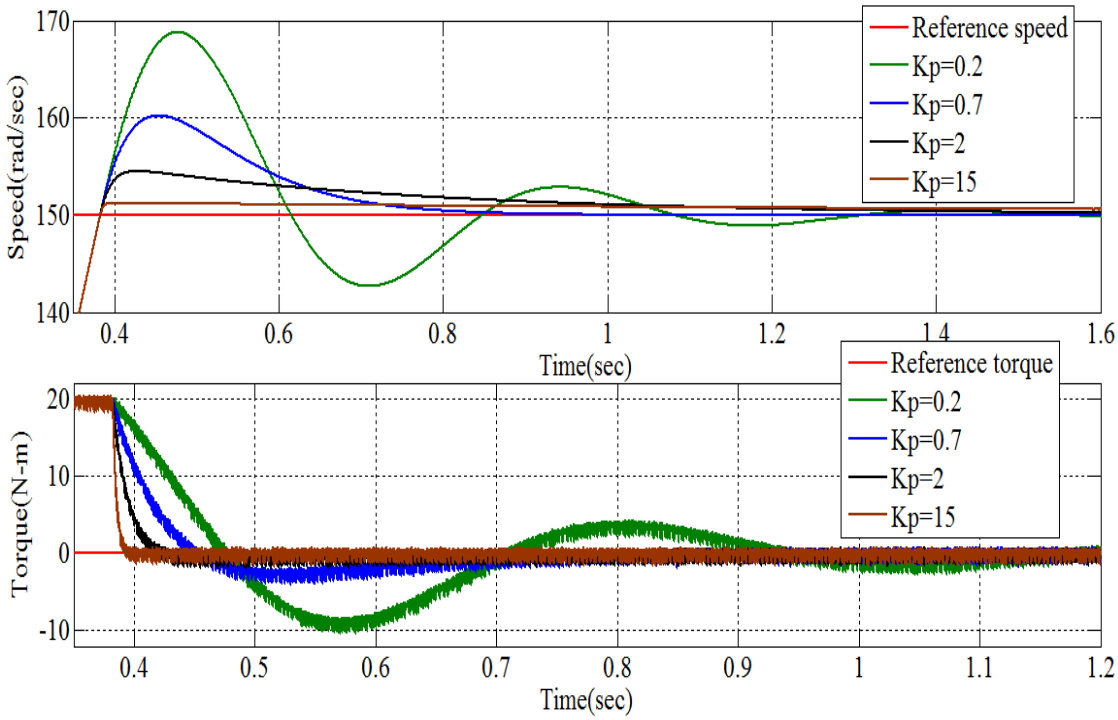
5.3.3.1 Dynamic Performance of IM Drive for PI Controller with different Operating conditions

A comparative study is carried out on the performance of the IM drive with different values of K_p, K_i of PI controller and band values of hysteresis band controller. The IVC performance is analyzed and shown in Fig. 5.8 for different K_p values and by keeping K_i constant at 5. In Fig. 5.9, the performance is analyzed by keeping K_p constant at 0.7, HB at 0.001and by varying K_i values. By maintaining K_p, K_i constant, THD analysis is carried out by varying hysteresis band and results are shown in Fig. 5.10. Fig. 5.11 shows the speed, torque and current performance for best suited values of K_p, K_i and HB to this particular indirect vector control model of induction motor. Comparison of rise time, settling time, peak overshoot for Fig. 5.8(a) and 5.9(a) are observed in table 5.2 and 5.4. Comparison of peak undershoot, settling time for full load application of Fig. 5.8(b) and 5.9(b) are mentioned in table 5.3 and 5.5. THD analysis comparison for Fig. 5.10 is done in table 5.6.

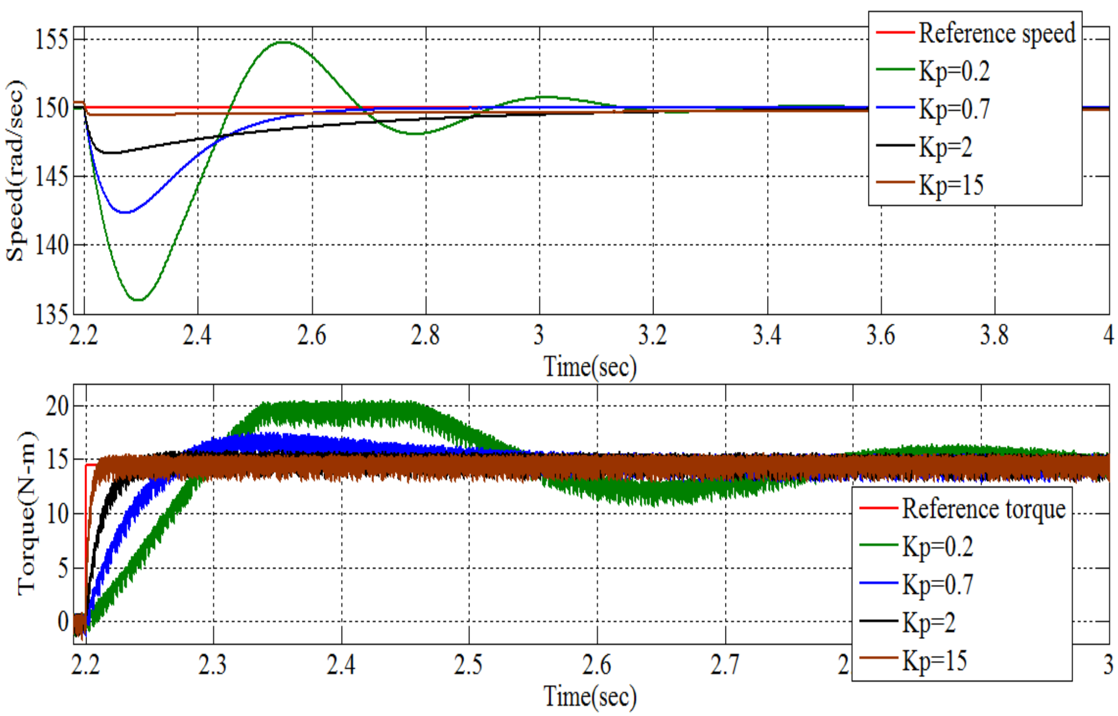
By varying K_p values and keeping K_i and HB constant

Initially motor is running at 150 rad/sec speed. K_i is constant at 5. It is observed that when proportional gain is 0.2 then there is maximum overshoot and also there is 2 cycle oscillations. As proportional gain increases to 0.7, overshoot decreases as compared to 0.2 value. It is observed that when value of proportional gain increases, overshoot decreases but the settling time increases. The maximum settling time is for highest proportional gain. 0.2 proportional gain, settling time is more than 0.7 proportional gain

Full load torque of 14.5 N-m is provided at 2.2 sec. For low proportional gain values, there is largest undershoot in speed and torque on application of load torque and after 2 cycles of oscillation, the speed settles down to reference speed. As proportional gain increases, value of undershoot decreases.



(a)



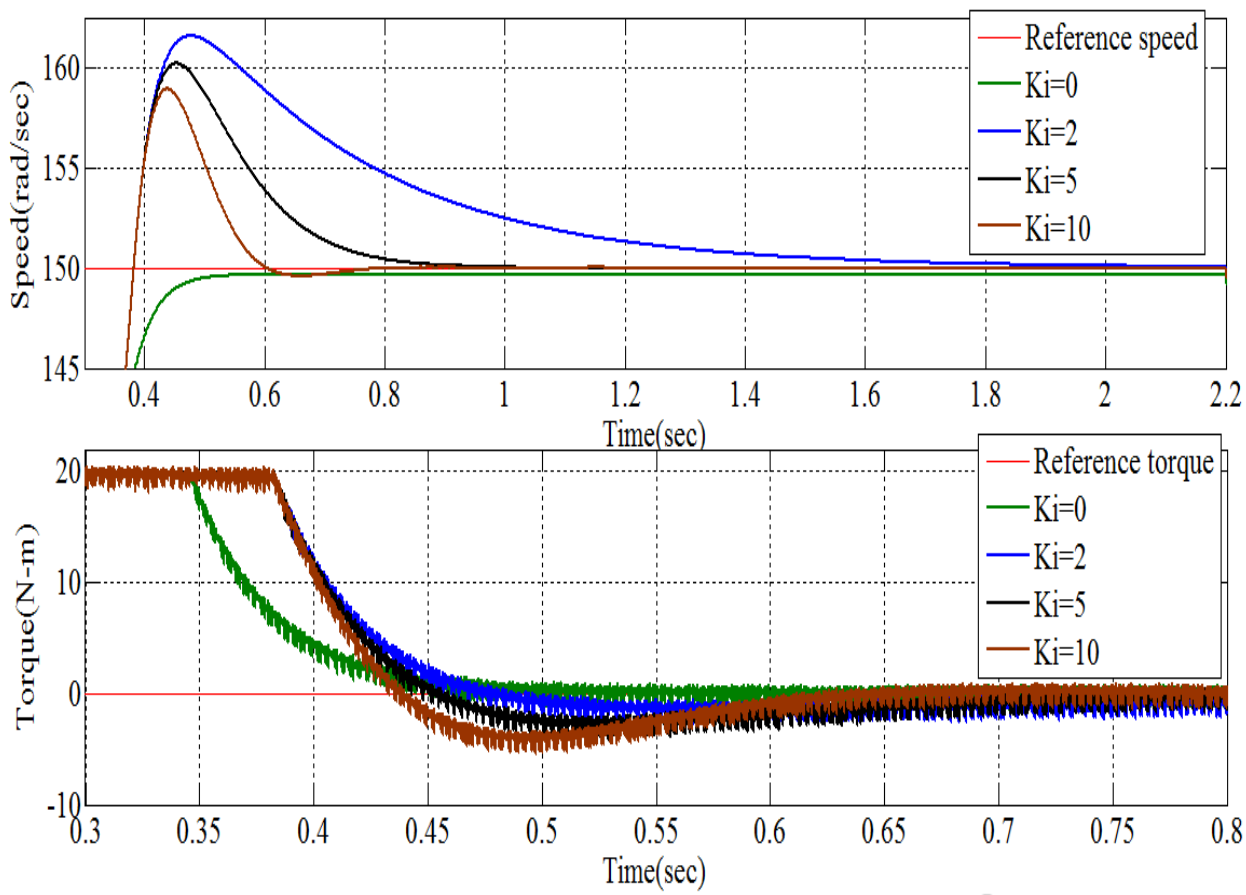
(b)

Fig. 5.8 Starting speed and torque dynamics for IVC of IM drive with varying values of K_p, fixed values of K_i = 5 and HB = 0.001 (a) without load, (b) with full load

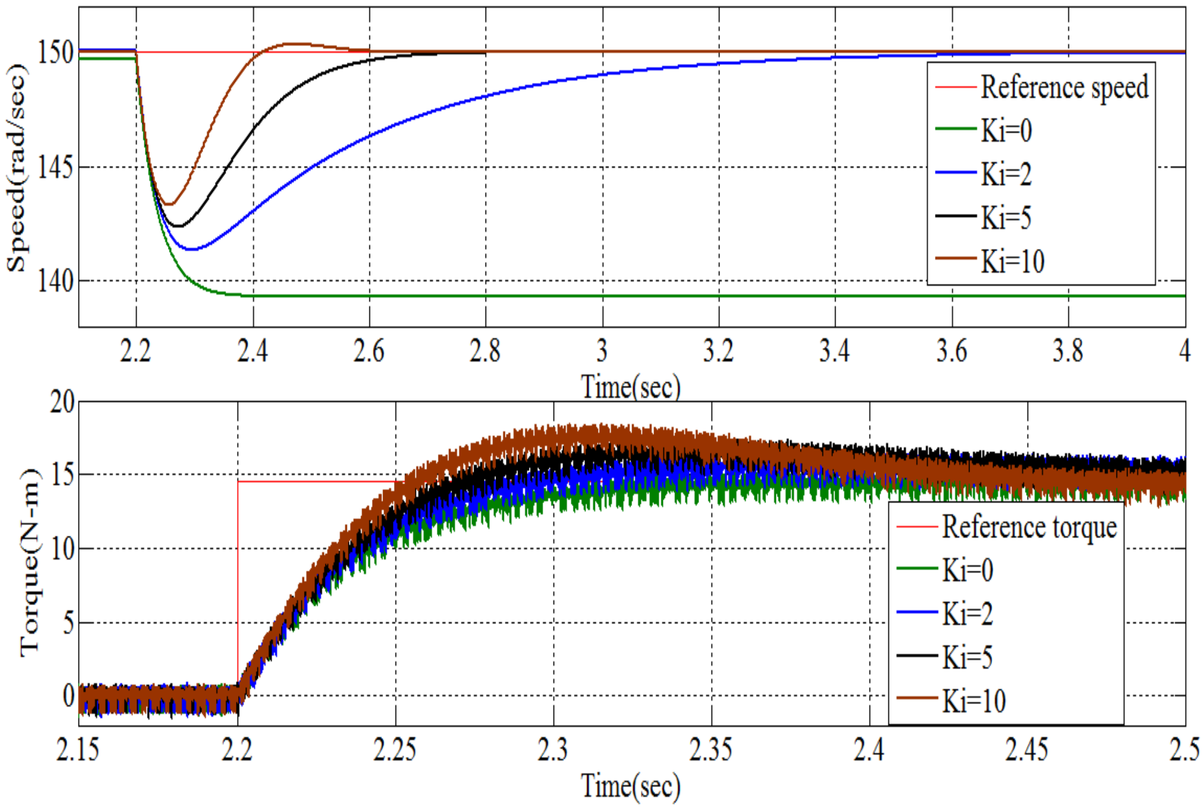
By varying K_i values and keeping K_p and HB constant

Initially motor is running at 150 rad/sec speed. K_p is constant at 0.7. It is observed that when integral gain is 0, there is no overshoot. As proportional gain increases to 2, overshoot increases to its maximum value for this particular model compared to other three cases. Further increasing the value of integral gain, the overshoot and settling time both decreases.

Full load torque of 14.5 N-m is provided at 2.2 sec. With 0 integral gain, Speed is not following reference speed after application of load. As simulation is performed for 4 sec, it is observed that actual speed is lower than reference speed. With increasing value of integral gain, the speed and torque response settle down rapidly. So integral gain is used to reduce final steady state error as early as possible.



(a)

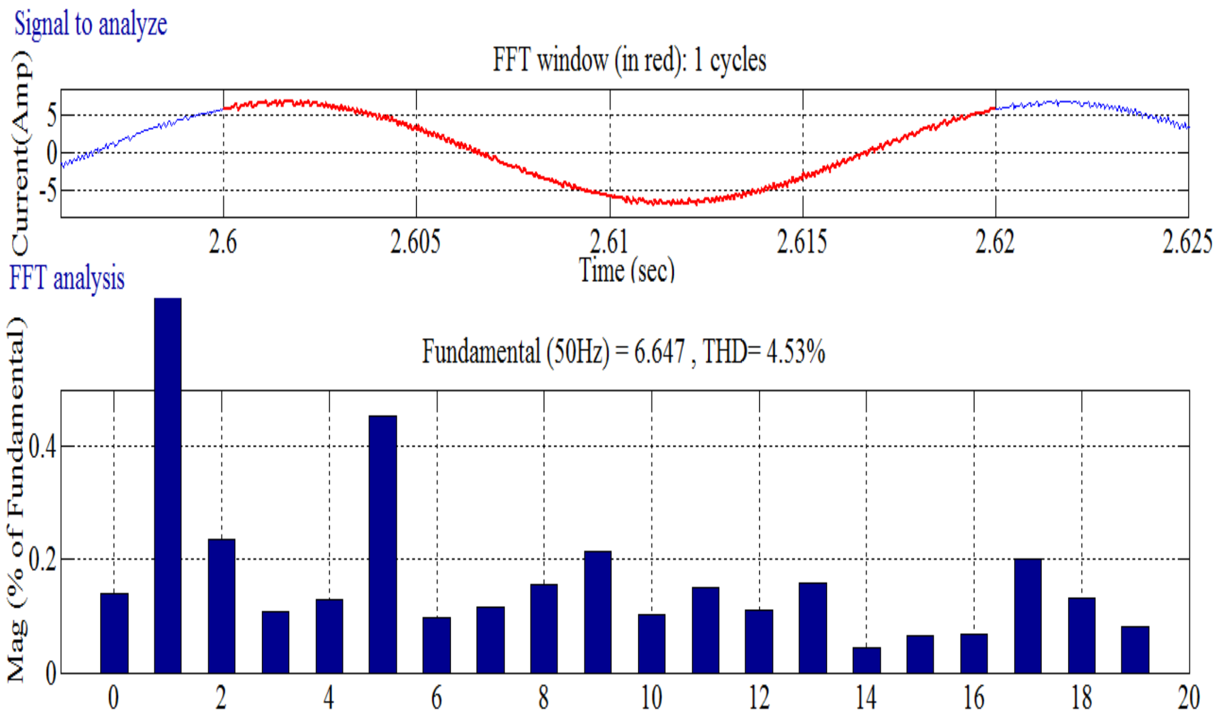


(b)

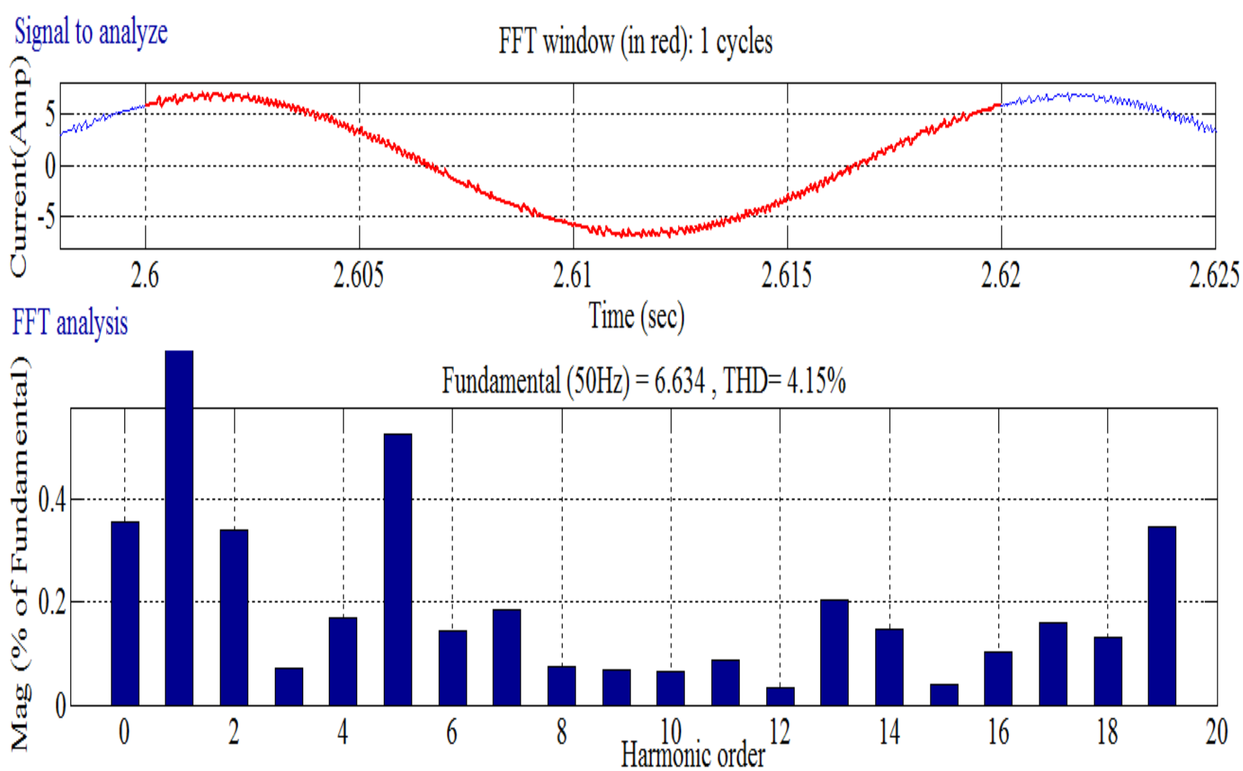
Fig. 5.9 Starting speed and torque dynamics for IVC of IM drive with varying values of K_i, fixed values of K_p = 0.7 and HB = 0.001 (a) without load, (b) with full load

By keeping K_p and K_i values constant and varying HB

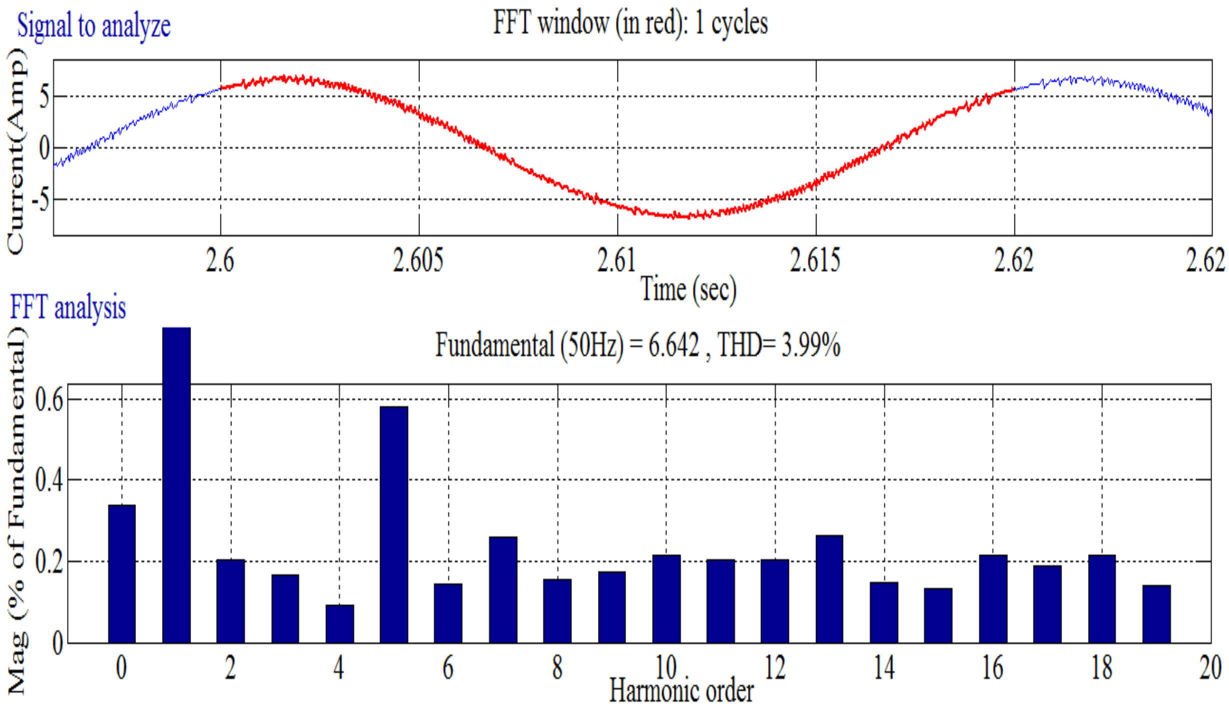
THD analysis is carried out for 1 cycle with full load torque of 14.5 N-m. For higher value of HB, switching frequency is less, so THD content is higher and current quality is low. With decreasing size of HB, switching frequency keeps on increasing resulting in better current quality and improved THD. For small value of HB, switching of devices increases in hysteresis band controller which increases the switching losses. From Fig. 5.11, it is observed that THD content improves with decreasing value of HB. THD content is minimum for HB=0.003.


Signal to analyze
FFT window (in red): 1 cycles
Current(Amp)
Time (sec)
FFT analysis
Fundamental (50Hz) = 6.647 , THD= 4.53%
Mag (% of Fundamental)

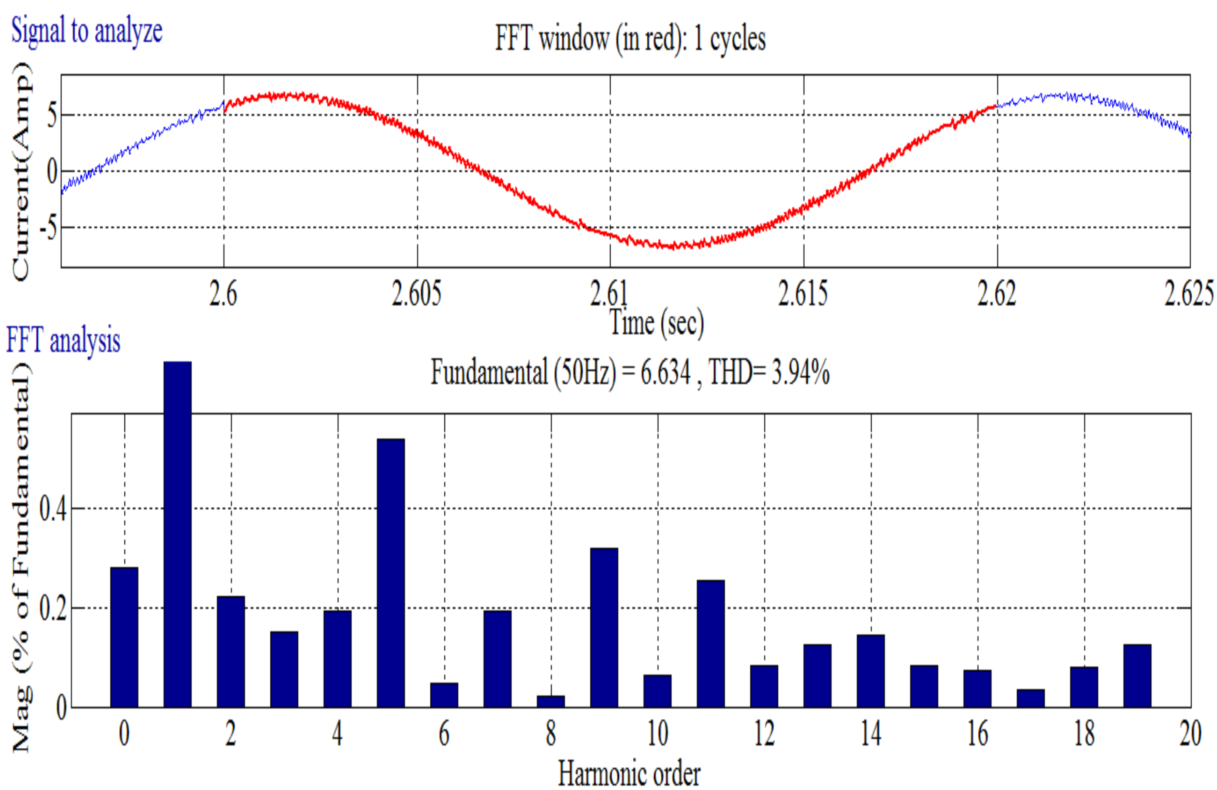
(a)


Signal to analyze
FFT window (in red): 1 cycles
Current(Amp)
Time (sec)
FFT analysis
Fundamental (50Hz) = 6.634 , THD= 4.15%
Mag (% of Fundamental)
Harmonic order

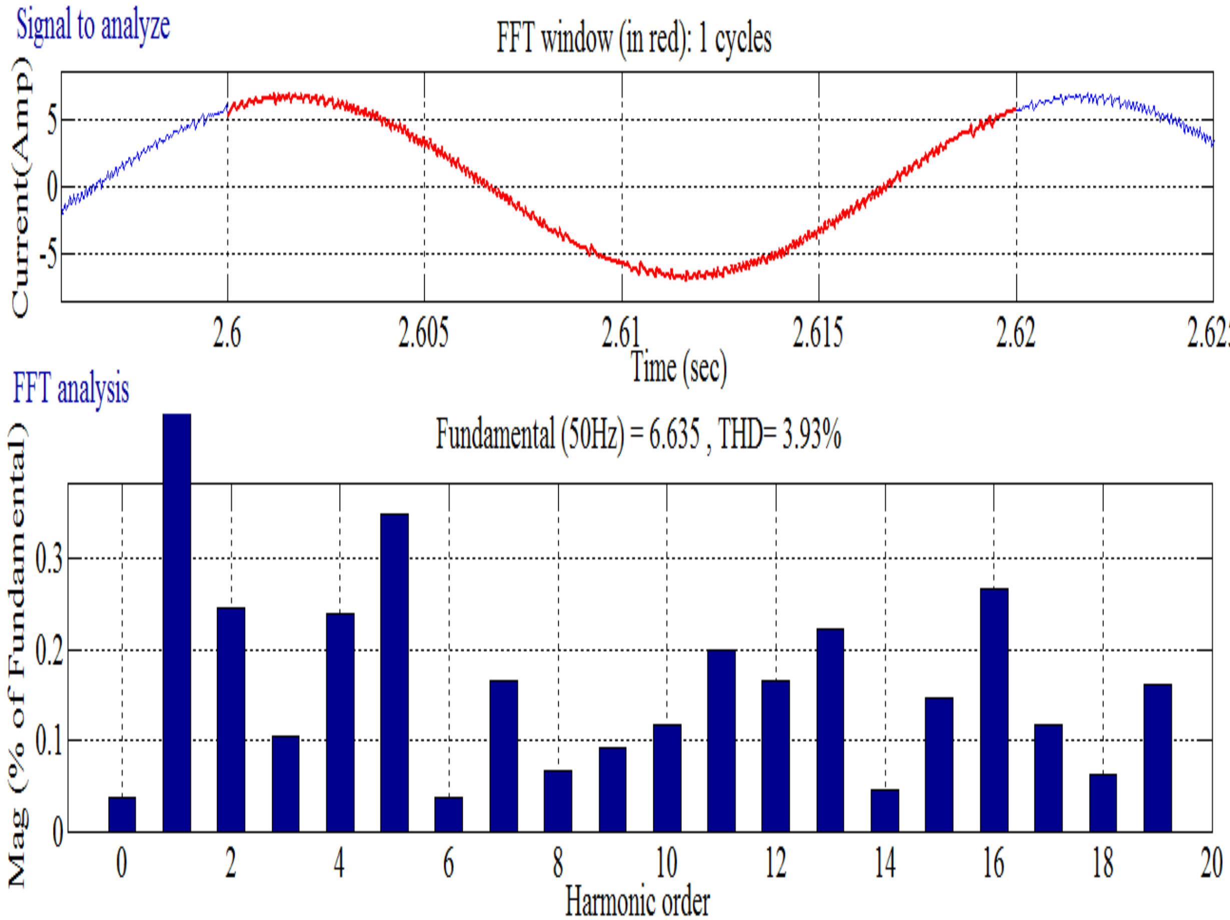
(b)


Signal to analyze
FFT window (in red): 1 cycles
Current(Amp)
5
0
-5
2.6
2.605
2.61
2.615
2.62
2.62
Time (sec)
FFT analysis
Fundamental (50Hz) = 6.642 , THD= 3.99%
Mag (% of Fundamental)
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20
Harmonic order

(c)


Signal to analyze
FFT window (in red): 1 cycles
Current(Amp)
5
0
-5
2.6
2.605
2.61
2.615
2.62
2.625
Time (sec)
FFT analysis
Fundamental (50Hz) = 6.634 , THD= 3.94%
Mag (% of Fundamental)
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20
Harmonic order

(d)



(e)

Fig. 5.10 THD analysis with full load for different values of HB and keeping K_p = 0.7 and K_i =5 (a) HB = 0.09, (b) HB = 0.05, (c) HB = 0.006, (d) HB = 0.005, (e) HB = 0.003

With K_p=0.7, K_i =5 and HB=0.003

Fig. 5.12 shows the dynamic performance of the drive when started with a reference speed of 150 rad/sec and the above parameter values. From the figure, it is observed that the maximum rise time is 0.3343 sec, settling time is 0.7741 sec and overshoot is 10.2 rad/sec.

Full load torque of 14.5 N-m is applied at 0.9 sec and observed that the settling time is 0.5332 sec and maximum undershoot is 7.6 rad/sec.

At 1.5 sec, speed change of -150 rad/sec is applied. Here maximum overshoot is 17.78 with settling time 0.8731sec. With speed reversal also, the device performance is tracking the reference speed.

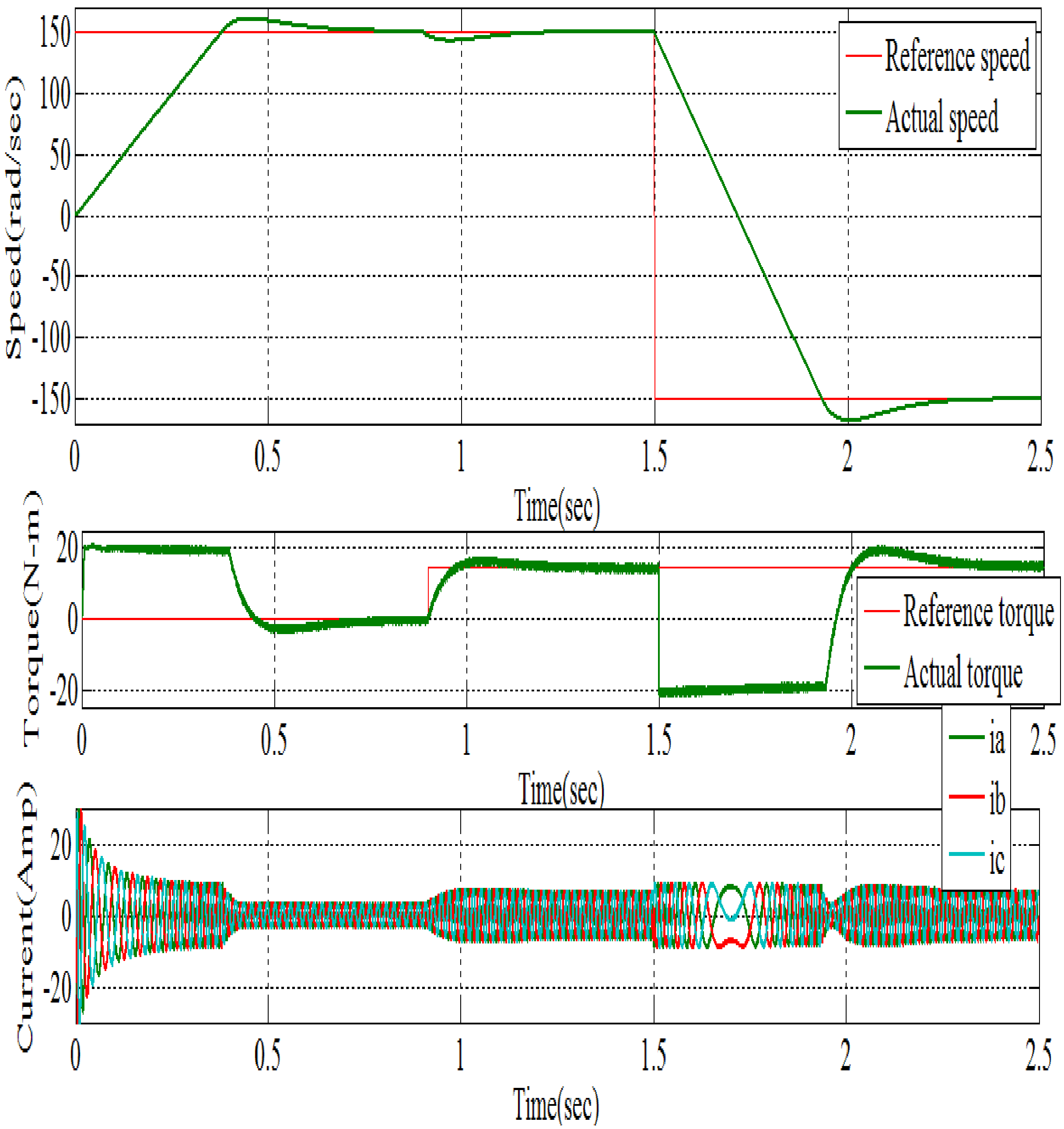


Fig. 5.11 Starting and speed reversal dynamic performance of IVCIM drive for K_p = 0.7, K_i = 5 and HB = 0.003 without load and with full load

Table 5.2 Rise time, settling time and peak overshoot with varying values of K_p, fixed value of K_i = 5 and HB = 0 without load

Parameters / Proportional Gain	Rise time(sec)	Settling time(sec)	Peak overshoot(rad/sec)
0.2	0.3443	1.7577	18.8
0.7	0.3443	0.8338	10.2
2	0.3443	2.0091	4.484
15	0.3443	More than 2.2 sec	0.65

Table 5.3Settling time and peak undershoot with varying values of K_p, fixed value of K_i = 5 and HB = 0 with load

Parameters / Proportional gain	Settling time(sec)	Peak undershoot(rad/sec)
0.2	1.5034	14.066
0.7	0.572	7.66
2	1.1214	3.332
15	More than 4 sec	0.14

Table 5.4 Rise time, settling time and peak overshoot with varying values of K_i, fixed value of K_p = 0.7 and HB = 0 without load

Parameters / Proportional gain	Rise time(sec)	Settling time(sec)	Peak overshoot(rad/sec)
0	0.3442	More than 2.2	0
2	0.3442	1.675	11.58
5	0.3442	0.8338	10.2
10	0.3442	0.7513	8.938

Table 5.5 Settling time and peak undershoot with varying values of K_i, fixed value of K_p = 0.7 and HB = 0 with load

Parameters / Proportional gain	Settling time(sec)	Peak undershoot(rad/sec)
0	More than 4 sec	10.7
2	1.74	8.65
5	0.572	7.66
10	0.3706	6.7

Table 5.6 THD analysis for full load with $K_p = 0.7$ and $K_i = 5$ and varying size of HB

HB size	THD content
0.09	4.53
0.05	4.15
0.006	3.99
0.005	3.94
0.003	3.93

5.3.3.2 Performance analysis of different speed controllers under different operating conditions

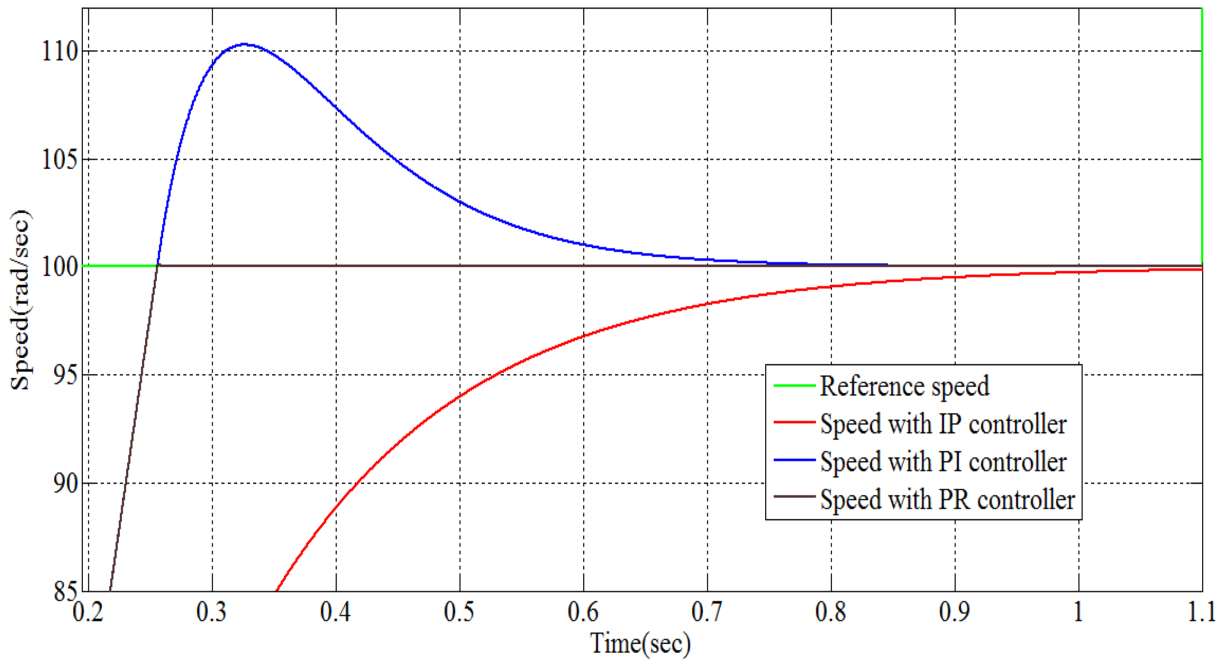
A comparative study is carried out on the performance of the induction motor drive with different speed controllers. PI, IP and PR speed controllers are used for this purpose. THD analysis is also carried out. Performance is also verified for different integral term in IP controller.

Speed waveform for different speed controllers with different operating conditions

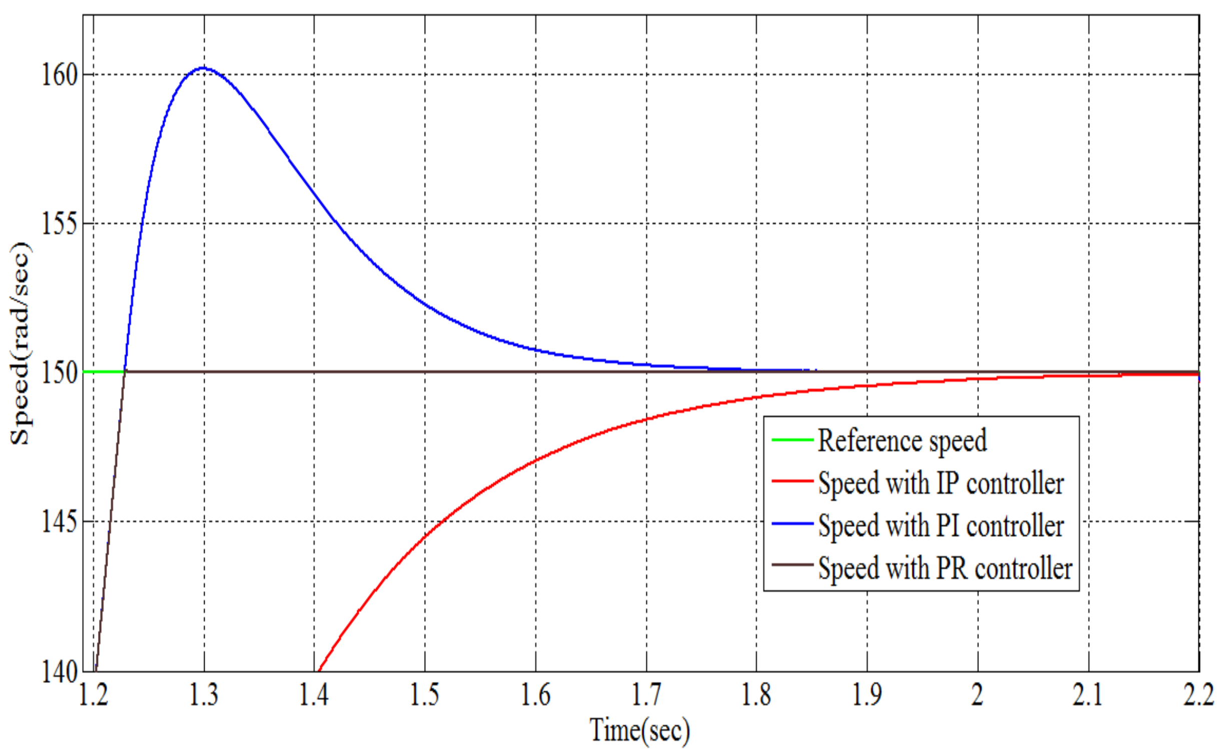
Initially motor is running at 100 rad/sec with machine specification in table 5.1. From speed waveform, it is observed that for PI controller has the maximum overshoot, PR and IP controller has zero overshoot. Settling time for PR controller is less than any other controller. Even it is settling in no time or zero time. Settling time for PI controller is less that IP controller.

At 1.1 sec, a sudden change in speed is applied. Again there is no overshoot in speed waveform for PR controller and minimum settling time. PI controller has once again maximum overshoot and less settling time than IP controller.

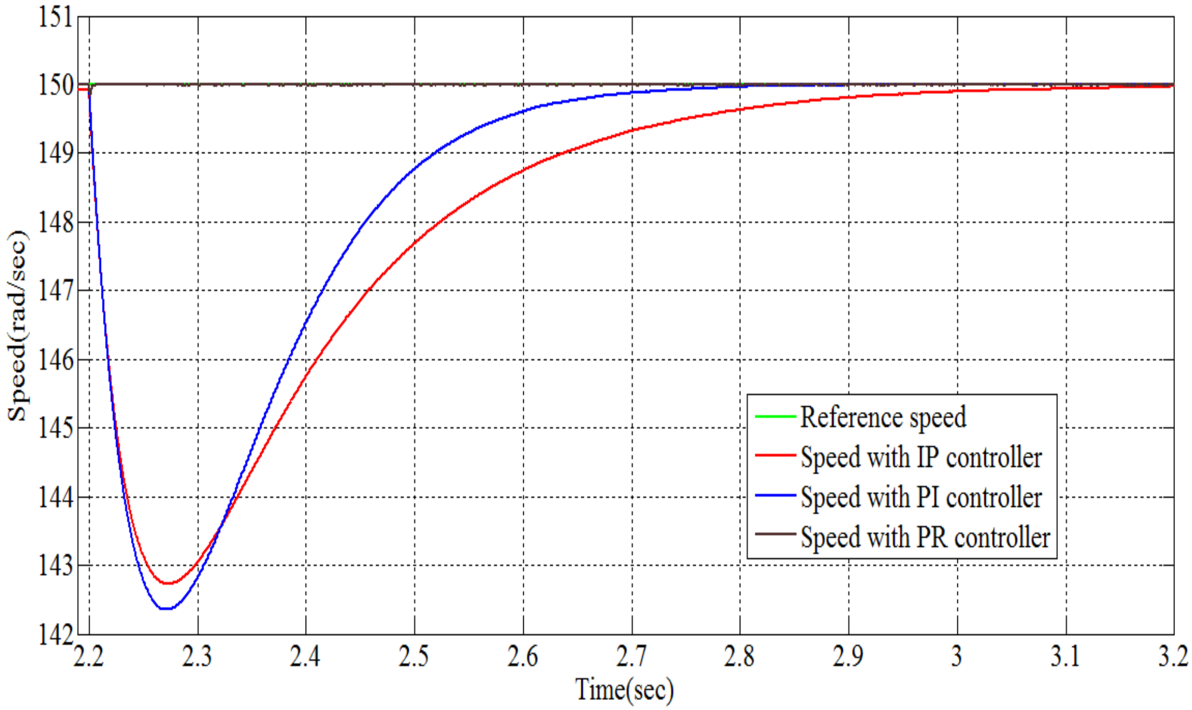
A load of 14.5 N-m is applied at 2.2 sec and speed waveform is observed. PR controller takes minimum undershoot and yet again around zero settling time. IP controller has less undershoot than PI controller but more settling time. As there is very minor drop in speed for PR controller on full load application so separate speed waveform for PR controller is shown.



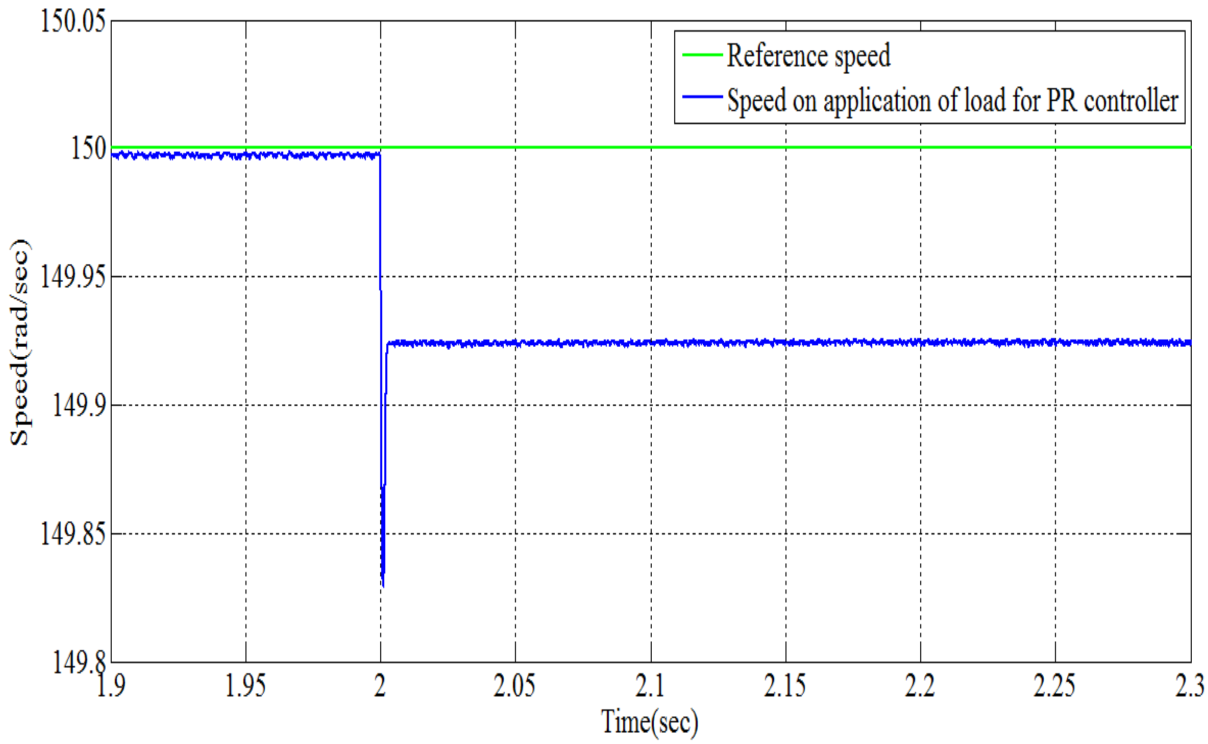
(a)



(b)



(c)



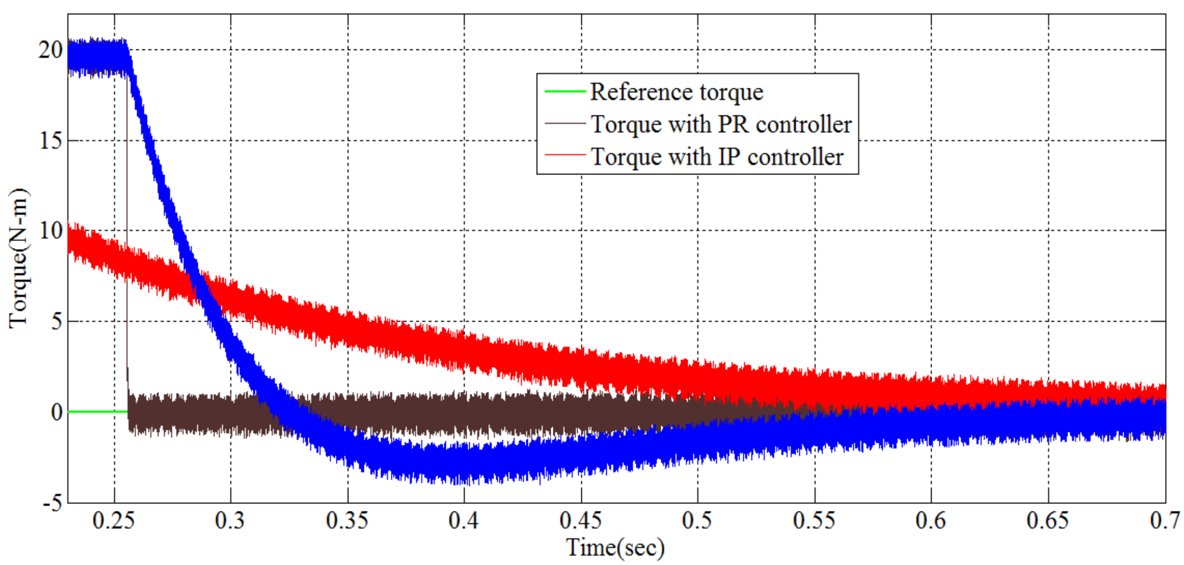
(d)

Fig. 5.12 Speed waveform for PI, IP and PR controller (a) 100 rad/sec, (b) 150 rad/sec, (c) with full load, (d) drop in speed for PR at full load

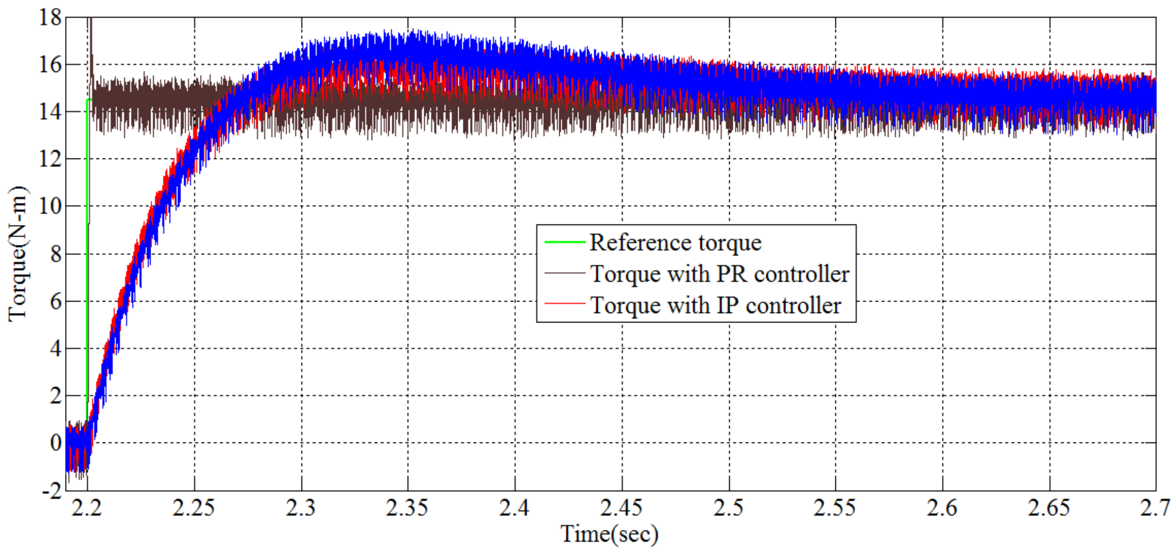
Torque waveform for different speed controllers with different operating conditions

Under no load, torque for PR controller settles with in no time. Torque for PI controller takes some small dip than 0 and settles to zero in time less than IP controller. IP takes more time than any other controller.

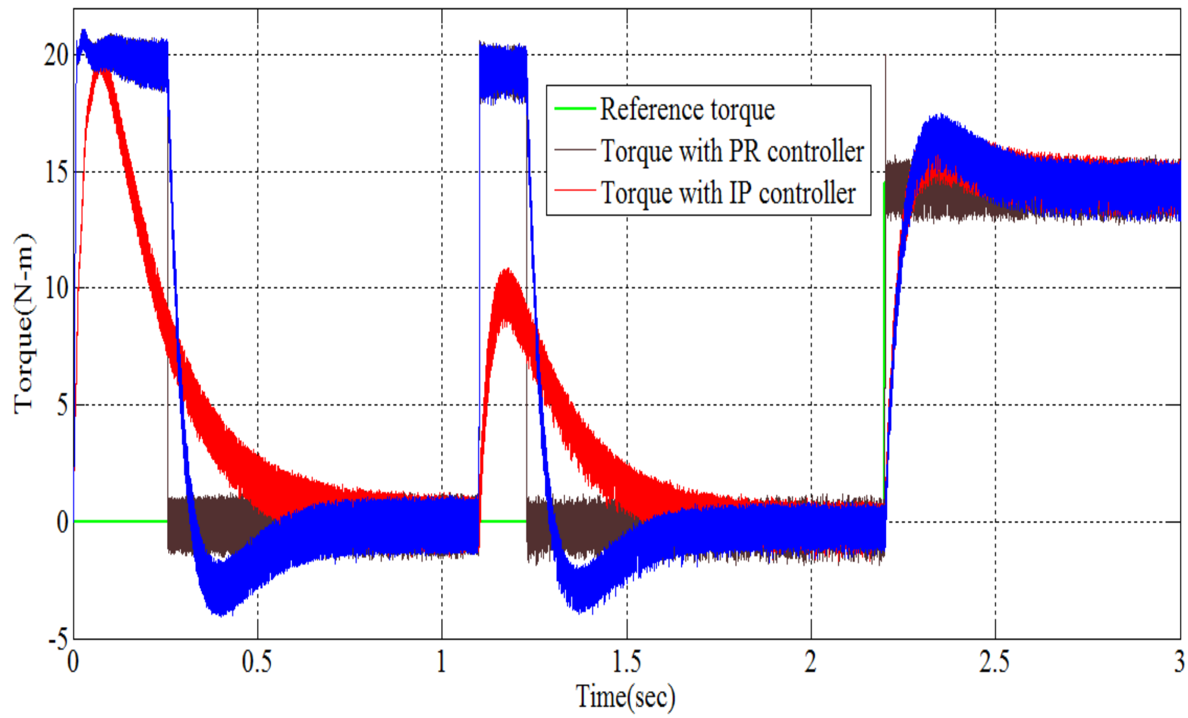
On application of load once again PR controller takes no time and settles to full load. PI controller takes a little bit more overshot than IP and settles in less time than IP. In Fig. 5.14 (c), torque waveform for complete 3 sec is shown.



(a)



(b)

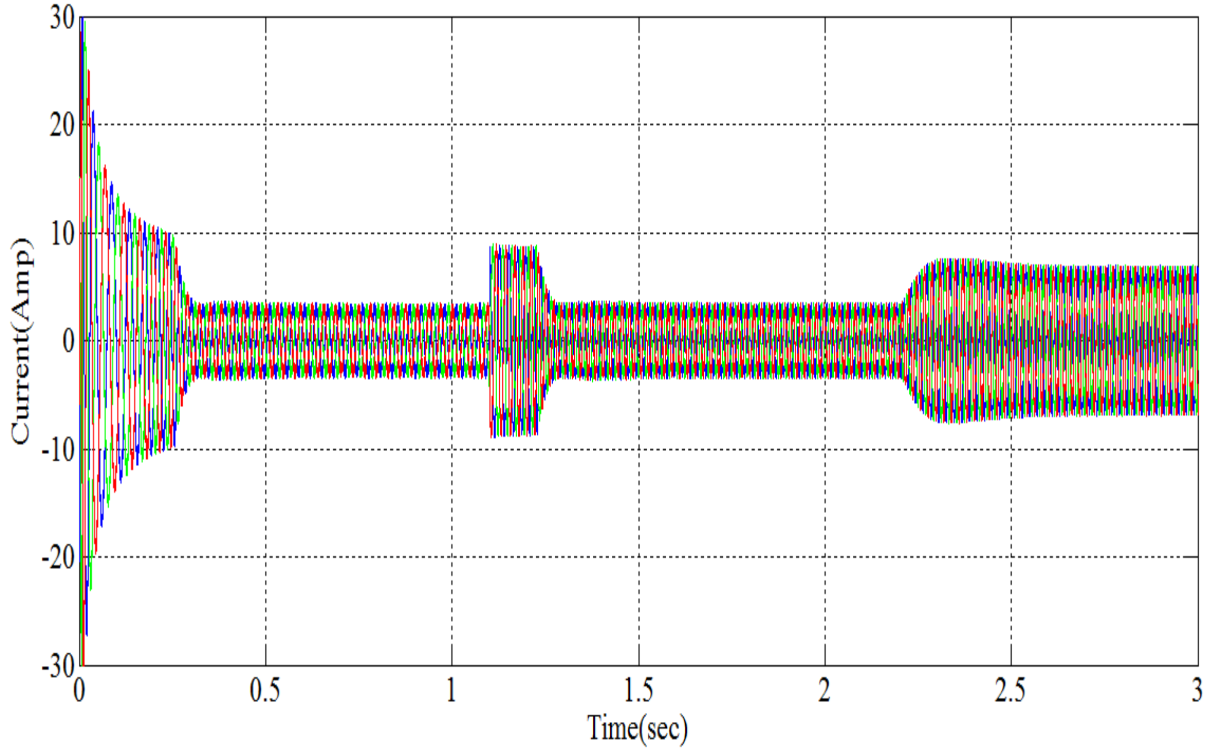


(c)

Fig. 5.13 Torque waveform for PI, IP and PR controller (a) without load, (b) with load, (c) waveform without load and with load at 2.2 sec

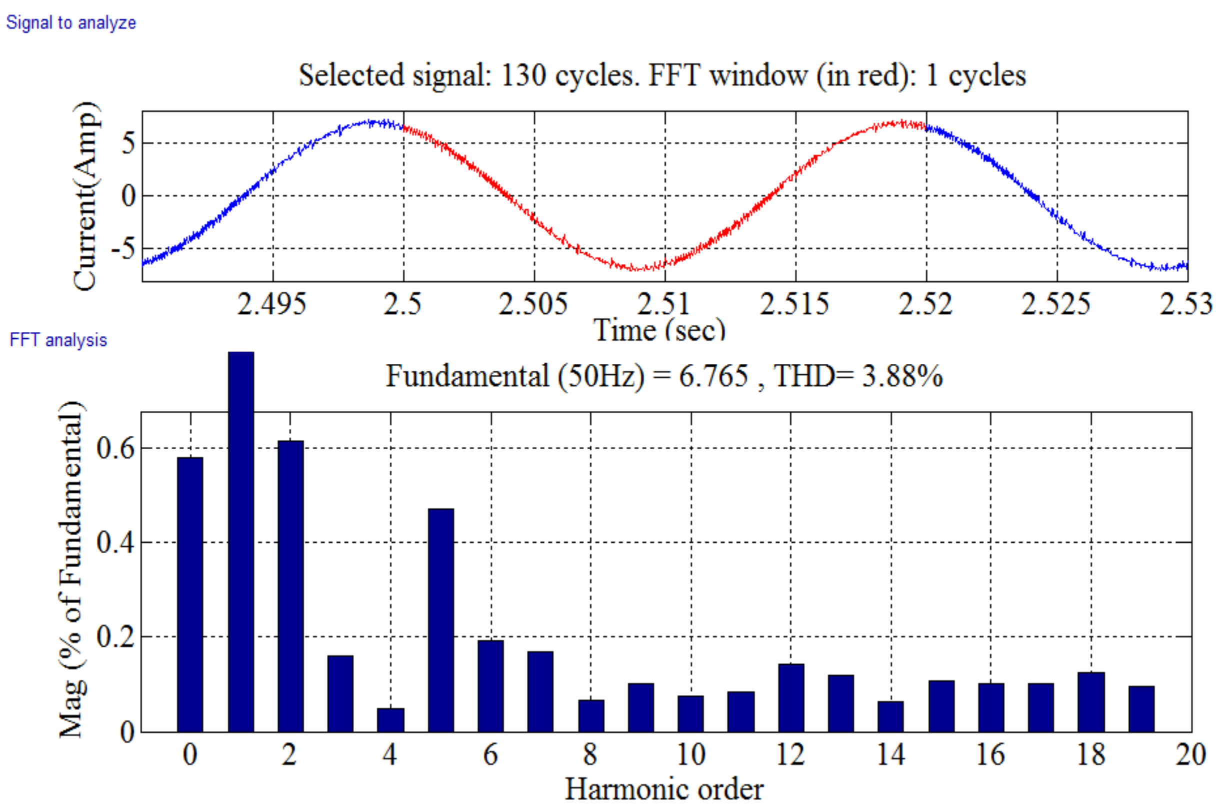
Current waveform and THD analysis for PI, IP and PR controller

Current waveform for PI, IP and PR are shown for complete 3 seconds in Fig. 5.15 (a), (c) and (e) respectively. THD analysis is carried out for 1 cycle with full load torque of 14.5 N-m. For PI controller, THD analysis is carried out for hysteresis band value of 0.003. For IP, hysteresis band value is 0.0001 and for PR it is 0.0003. In Fig. 5.15 (b), (d) and (f) THD waveform for PI, IP and PR controllers are shown respectively. There is maximum THD for IP controller.



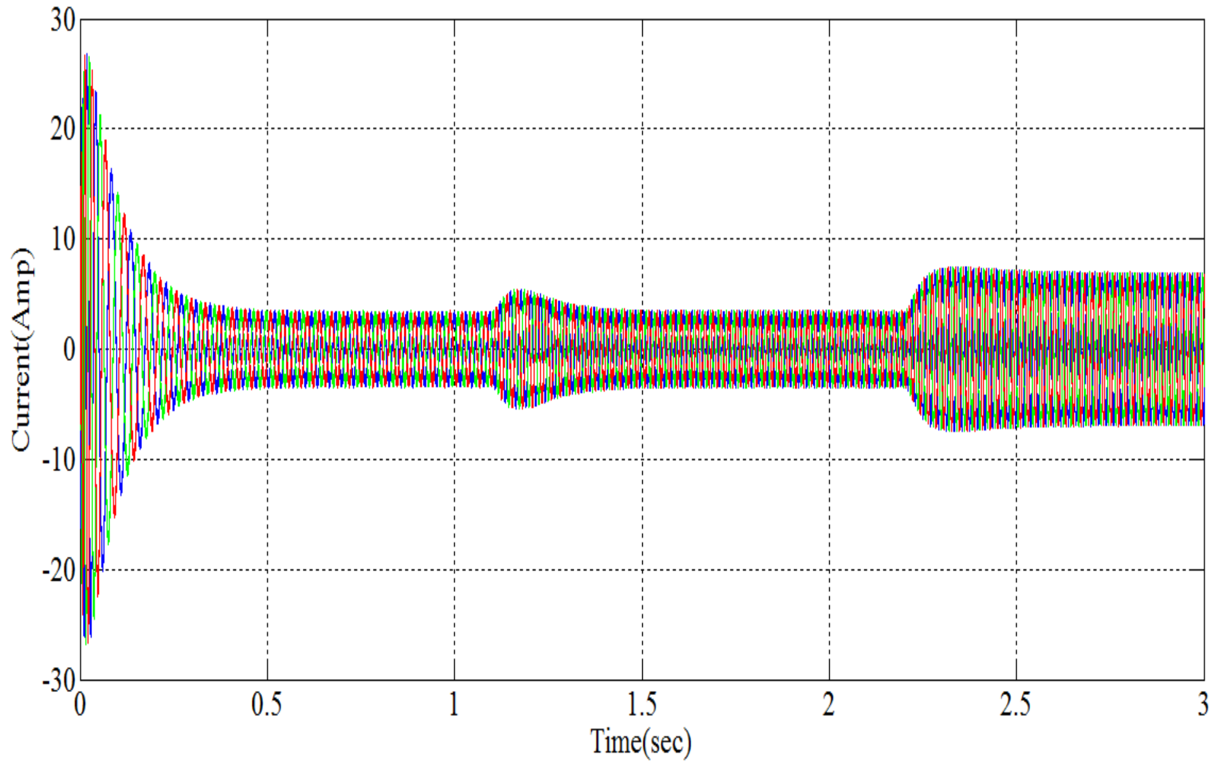
30
20
10
0
-10
-20
-30
Current(Amp)
0
0.5
1
1.5
2
2.5
3
Time(sec)

(a)



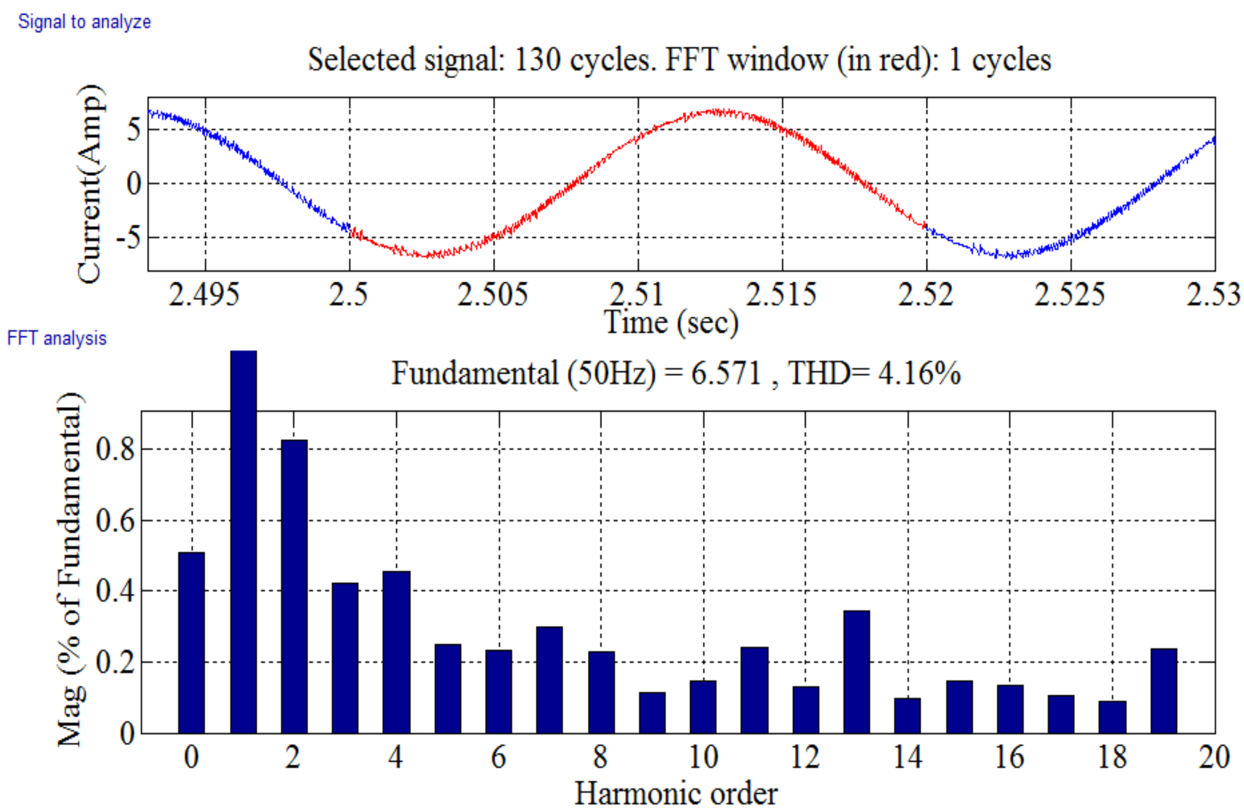
Signal to analyze
Selected signal: 130 cycles. FFT window (in red): 1 cycles
Current(Amp)
5
0
-5
2.495
2.5
2.505
2.51
2.515
2.52
2.525
2.53
Time (sec)
FFT analysis
Fundamental (50Hz) = 6.765 , THD= 3.88%
Mag (% of Fundamental)
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20
Harmonic order

(b)



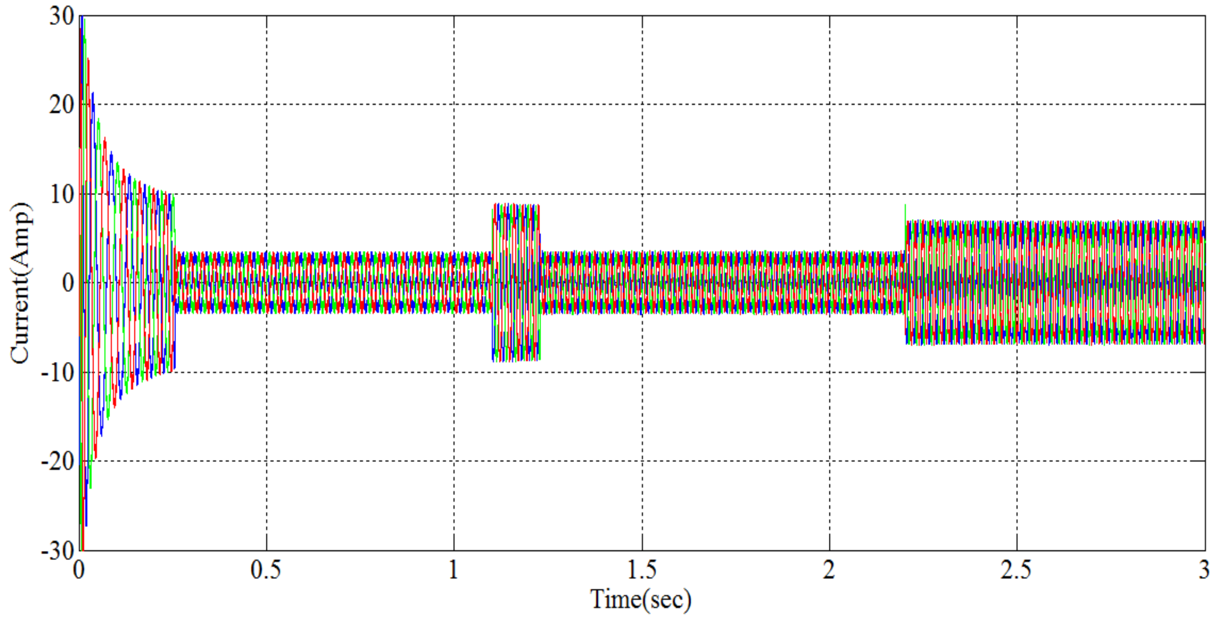
30
20
10
0
-10
-20
-30
Current(Amp)
0
0.5
1
1.5
2
2.5
3
Time(sec)

(c)

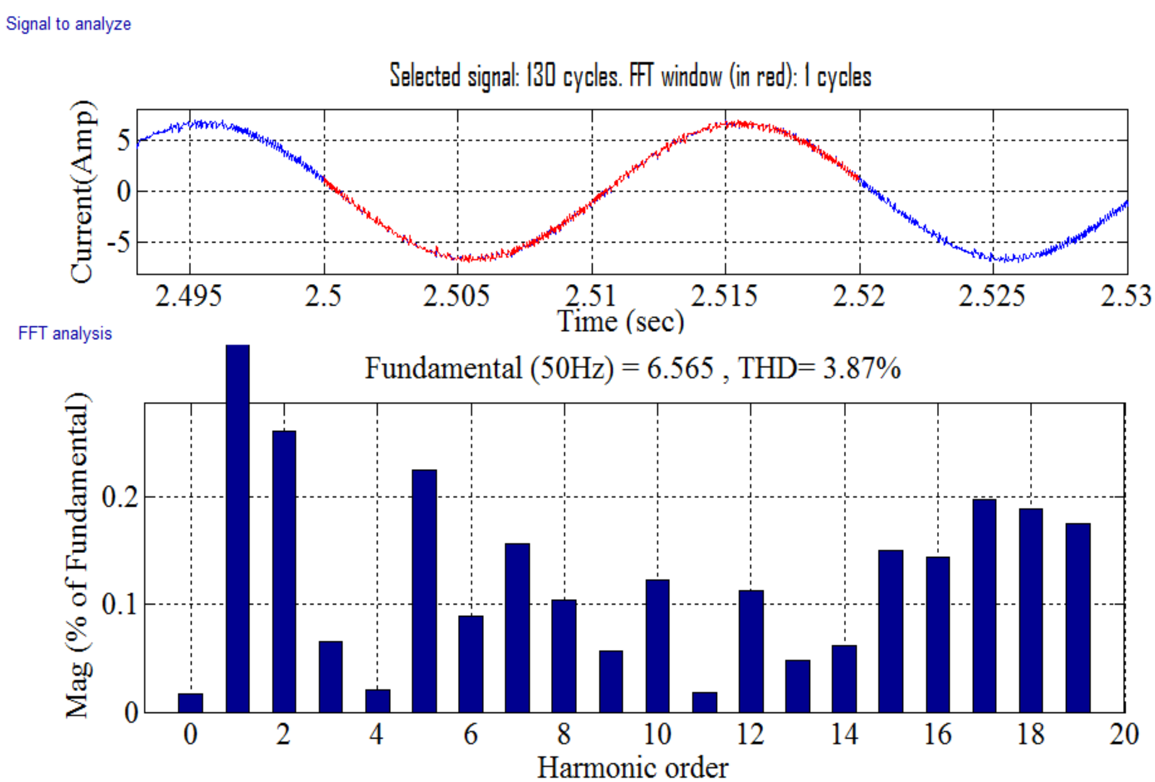


Signal to analyze
Selected signal: 130 cycles. FFT window (in red): 1 cycles
Current(Amp)
5
0
-5
2.495
2.5
2.505
2.51
2.515
2.52
2.525
2.53
Time (sec)
FFT analysis
Fundamental (50Hz) = 6.571 , THD= 4.16%
Mag (% of Fundamental)
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20
Harmonic order

(d)



(e)

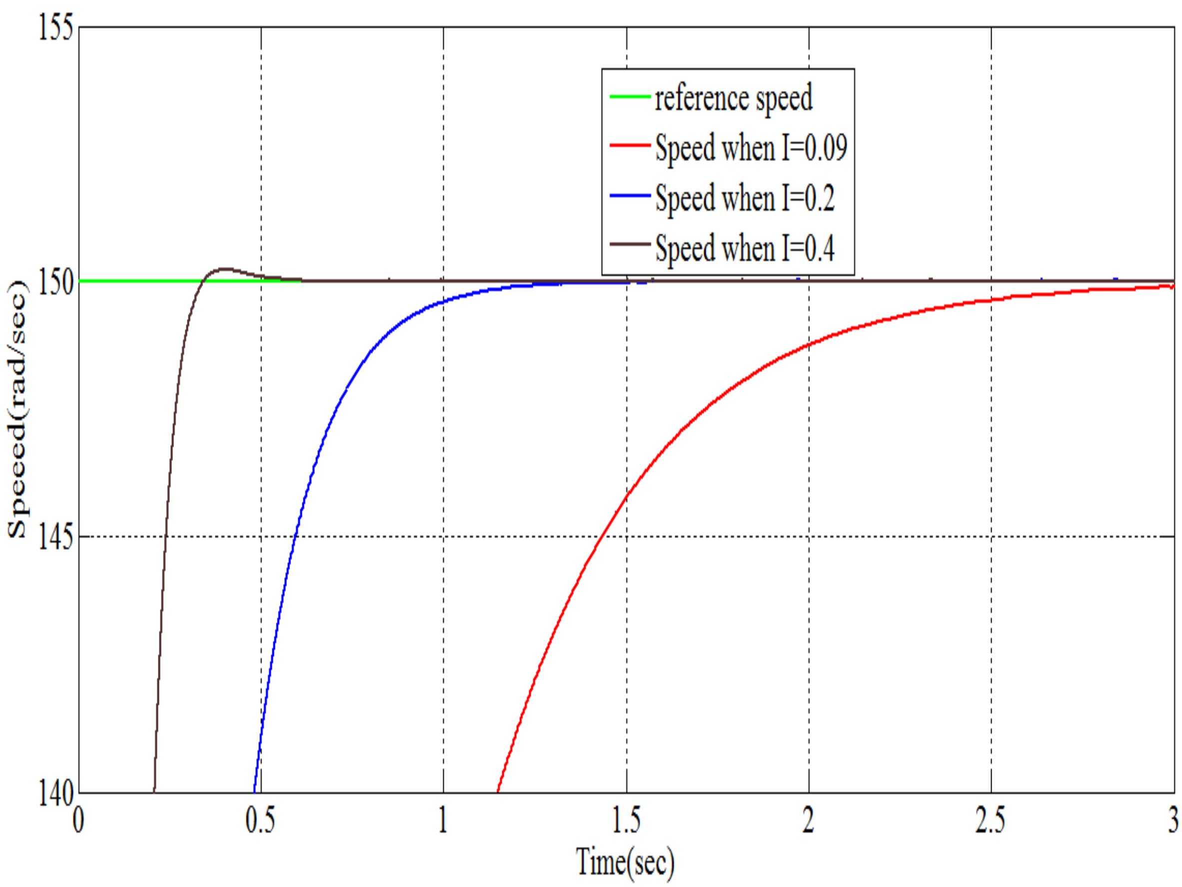


(f)

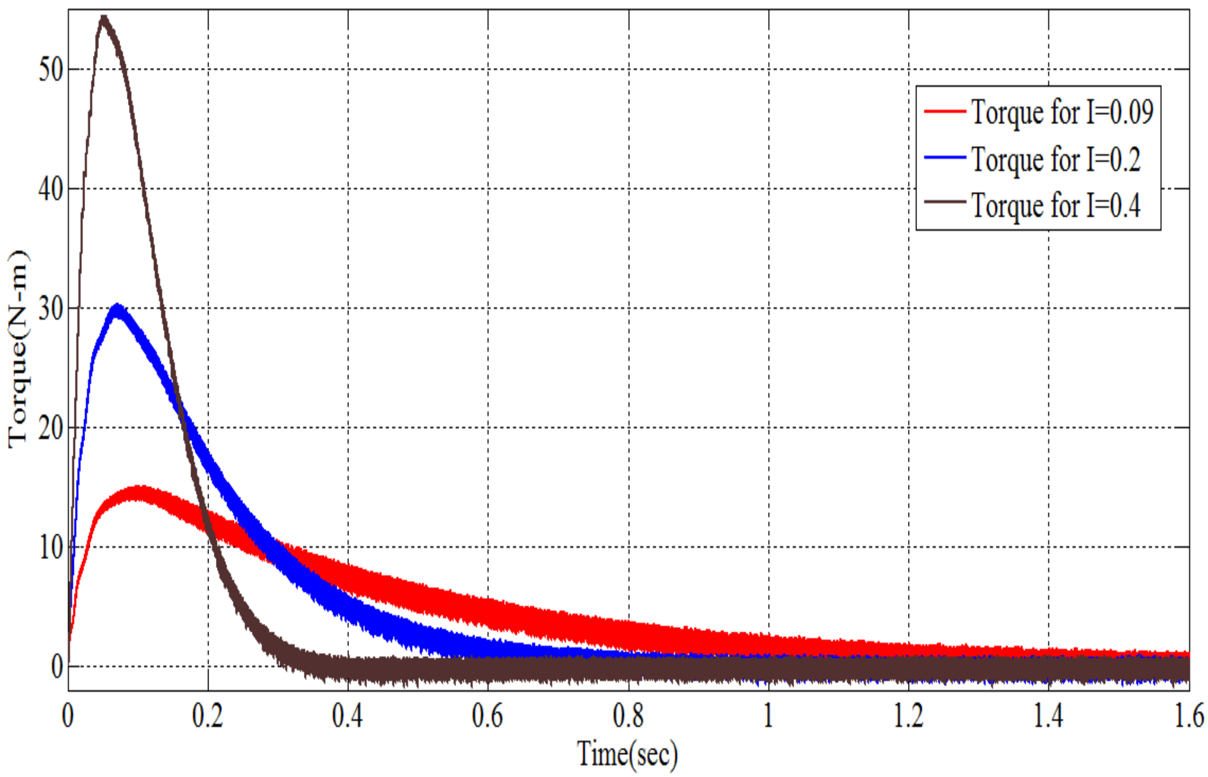
Fig. 5.14 Current waveform and THD analysis for PI, IP and PR controller respectively (a) current waveform, (b) THD analysis, (c) current waveform, (d) THD analysis, (e)current waveform, (f) THD analysis

Speed and torque waveform for varying value of integral term in IP controller

Earlier in outputs of Fig. 5.12, IP controller takes highest settling time so again it is required to analyze it separately for varying integral gain values of IP controller. Motor is running at 150 rad/sec. For integral value of 0.09, IP controller takes maximum time to settle down. But on increasing the value of integral term further to 0.2 and 0.4, settling decreases which can be seen in Fig. 5.16 (a). But at what cost, settling time of IP controller decreases. As value of integral term increases, the highest value of torque at stating increases which is clear by Fig. 5.16 (b). So an optimum value is have to be chosen for dynamic performance. In Fig. 5.12, 0.2 value of integral term is chosen.



(a)



(b)

Fig. 5.15 Waveform for varying value of integral term in IP controller (a) speed, (b) torque

Speed waveform for different speed controllers and operating conditions

Initially motor is started at 150 rad/sec and full load torque is applied at 2 sec and speed reversal at 3 sec. Waveforms are compared on the basis of rise time, peak overshoot and settling time for 150 rad/sec in table 5.7 without load. For full load, settling time and undershoot is calculated and compared in table 5.8 and for speed reversal in table 5.9. As already these waveforms are mentioned above so the motive here to mention them again is to compare them on the basis of settling time, overshot, undershoot, rise time and absorb the waveform for speed reversal.

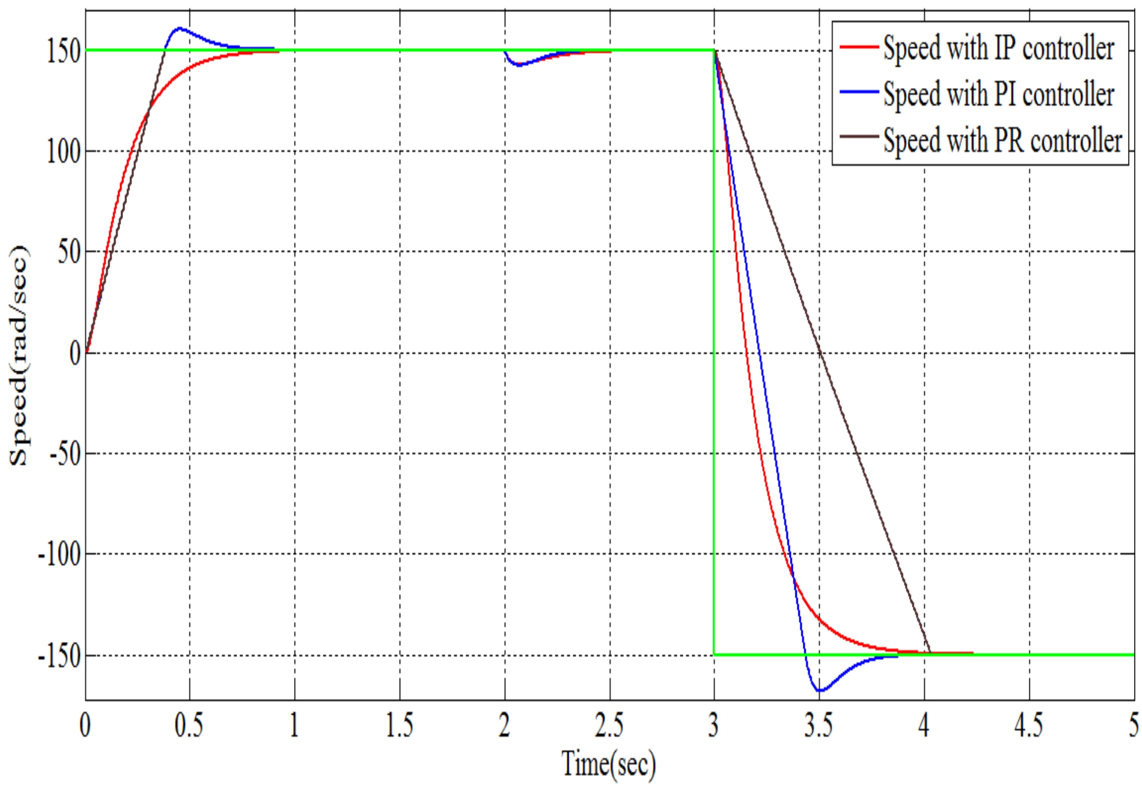


Fig. 5.16 Speed waveform for PI, IP and PR controller without load, with load at 2 sec and with speed reversal at 3 sec

Table 5.7 Rise time, settling time and peak undershoot for PI, IP and PR controller without load

Parameters / Controller	Rise time(sec)	Settling time(sec)	Peak overshoot(rad/sec)
PI	0.3443	1.06	10.21
IP	0.417	1.5	0
PR	0.3442	0.39	0

Table 5.8 Rise time, settling time and peak undershoot for PI, IP and PR controller with load

Parameters / Controller	Settling time(sec)	Peak undershoot(rad/sec)
PI	0.533	7.6
IP	0.8	7.21
PR	0.003	0.17

Table 5.9 Rise time, settling time and peak undershoot for PI, IP and PR controller with load and speed reversal

Parameters / Controller	Settling time(sec)	Peak overshoot(rad/sec)
PI	0.873	17.75
IP	1.372	0
PR	1.034	0

5.4 Conclusion

The performance comparison of IVC motor drive is presented here for different values of K_p, K_i of PI controller and HB of hysteresis band controller. For all gain values of PI and band values of hysteresis band controller, the performance is satisfactory for wide range of speed for both full load and no load. It is observed from simulation results that for increased value of proportional gain, the overshoot decreased but the settling time increases. Integral term improves steady state response. With increased value of integral gain, first overshoot increases but further increasing the integral gain, it starts decreasing. It is observed that HB size affects the current quality. With high value of HB, the switching frequency is less resulting in high THD content. Smaller HB resulting in higher switching frequency, producing lesser current ripple, attains smaller THD content. But smaller HB affects the switching of devices and switching loses increases so it is required to obtain the optimum value of HB to ensure good quality of current response.

The performance comparison of IVC motor drive is presented here for PI, IP and PR speed controllers. For IP and PR controller, there is no overshoot in output as present in PI controller. But in IP controller, the integral term makes it slow and it takes more time to settle than PI and PR controller. For increasing value of Integral term, IP controller takes less time to settle but there is a small amount of overshot in speed and maximum torque value at starting also increases. So IP controller shows no overshot but takes time to settle and takes small hysteresis band than PI controller. PR controller also has no overshoot in speed and there is not much drop in speed on application of load but it takes a small hysteresis band value for optimum THD performance than PI. PI controller has overshoot in speed but takes more time than PR controller but it takes the smallest hysteresis band than other two. So according to the required dynamic performance, any of the three controllers can be chosen.

CHAPTER 6
ONLINE ROTOR RESISTANCE ESTIMATION FOR IVCIM DRIVE

6.1 Introduction

For high performance torque control of indirect vector control of induction motor drive, it is necessary to estimate the rotor resistance. In indirect vector control, for correct decoupling of flux and torque, correct rotor flux position is required. In indirect vector control, the rotor flux position is mainly affected by rotor resistance. So the online estimation of rotor resistance is required for optimum performance of induction motor drive. There are various methods of online estimating rotor resistance but here Model Reference Adaptive Controller is discussed in brief and simulation is carried out on the basis of it.

6.2 Online rotor resistance estimation

The extensively employed drive in extraordinary performance industrial application is indirect vector controlled induction motor drive for its fast dynamic response and simplicity. Though the slip calculation which require rotor resistance, creates the technique to depend on machine parameters. Among all the parameters, rotor resistance experiences a considerable variation and if attention is not given to compensate for the variation, it will result in coupling between d-axis and q-axis parameters. As it is well known that the beauty of indirect vector control is the decoupling between the d-axis and q-axis and coupling makes the dive sluggish and performance deteriorate. The main reasons affecting rotor resistance can be observed as ambient temp, running time, rotor current, skin effect and frequency. Rotor resistance may diverge up to 100 percent. A disparity between the estimated rotor flux and actual rotor flux which results because of rotor resistance discrepancy will result in error between the estimated torque and actual torque and hence to deprived dynamic performance [25, 26, 28].

As there are various online parameter estimation techniques available; few of them are as below

6.2.1 Signal injection based method

In this technique, short duration pulses added to the fixed reference current and based on PI controller produced resulting torque command, rotor resistance estimates.

6.2.2 Observer based Method

Extended Kalman filter (EKF), adaptive observer and Extended Luenberger Observer(ELO) are mostly fall under this category. Here the additional variable is rotor time constant along with rotor speed. These methods are mainly efficient for parameter estimation and joint speed operation but the problem with them is that they require large memory, constraint like all inductances are constant in machine model and computational intricacy.

6.2.3 Model reference adaptive system (MRAS) based Technique

Rotor resistance estimation technique based on model reference adaptive controller, a single quantity is formulated by two different ways. One is independent of R_r and one is dependent on rotor resistance. These two quantities are compared and generate error signal. The error signal is then processed to adaption mechanism which is mostly the PI controller and in this way we will get the estimated quantity which is the output of PI controller. Various types of MRAC techniques are available which depends on the quantity used for the generation of error signal, examples are, rotor flux based, electromagnetic torque based, reactive power based and outer product of stator current and back emf based etc. The reactive power based method is most popular because it is intendent of stator resistance.

6.2.4 Other methods

There are a number of other techniques for rotor resistance online estimation such as spectral analysis method, recursive least square method and criterion function based method. Fuzzy logic and Artificial Neural Network (ANN) based methods are also available [27].

Here for online estimation of rotor resistance, the performance of a rotor flux based Model Reference Adaptive Controller (MRAC) is analyzed**.** The exceptionality of the MRAC under study is that steady state reactive power is used in adaptable model and instantaneous reactive power is used in the adjustable model.

6.3 Proposed technique

The Model Reference Adaptive Systems technique is the utmost used scheme for rotor resistance estimation because it is easy to implement and fewer computational efforts required compared to other methods. In this method, the proposed parameter is calculated by the two different methods. In one method, calculated parameters is independent of estimated parameter and in other method, calculated parameter is dependent on estimated parameter. The independent model is called reference model and the dependent model is adjustable model

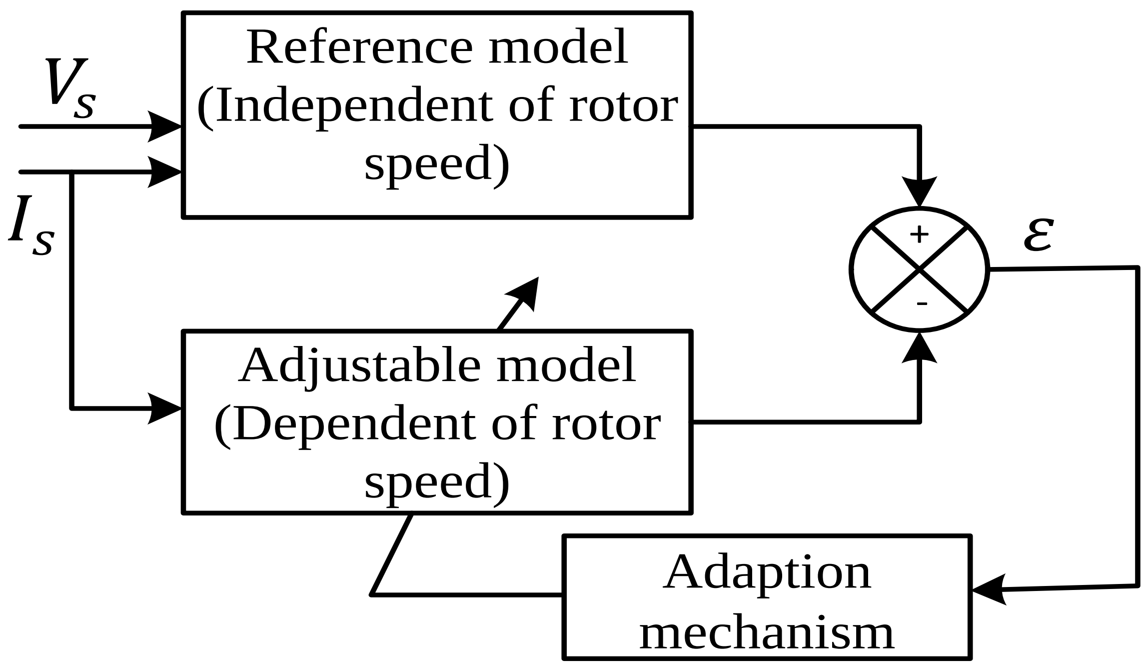


Fig. 6.1 Block diagram of MRAC

. The accuracy of this scheme is greatly reliant on the machine model. The difference between the reference and adjustable model forms the error signal which is further processed to adaption mechanism. Adaption mechanism is mainly PI controller. As here the estimated parameter is rotor resistance so the PI controller generates the changes in rotor resistance ΔR.

The block diagram of indirect vector control of induction motor for online rotor resistance estimation is shown in Fig. 6.2. In this technique, current control loops are within the speed control loops. PI controllers are used in current control loops too.

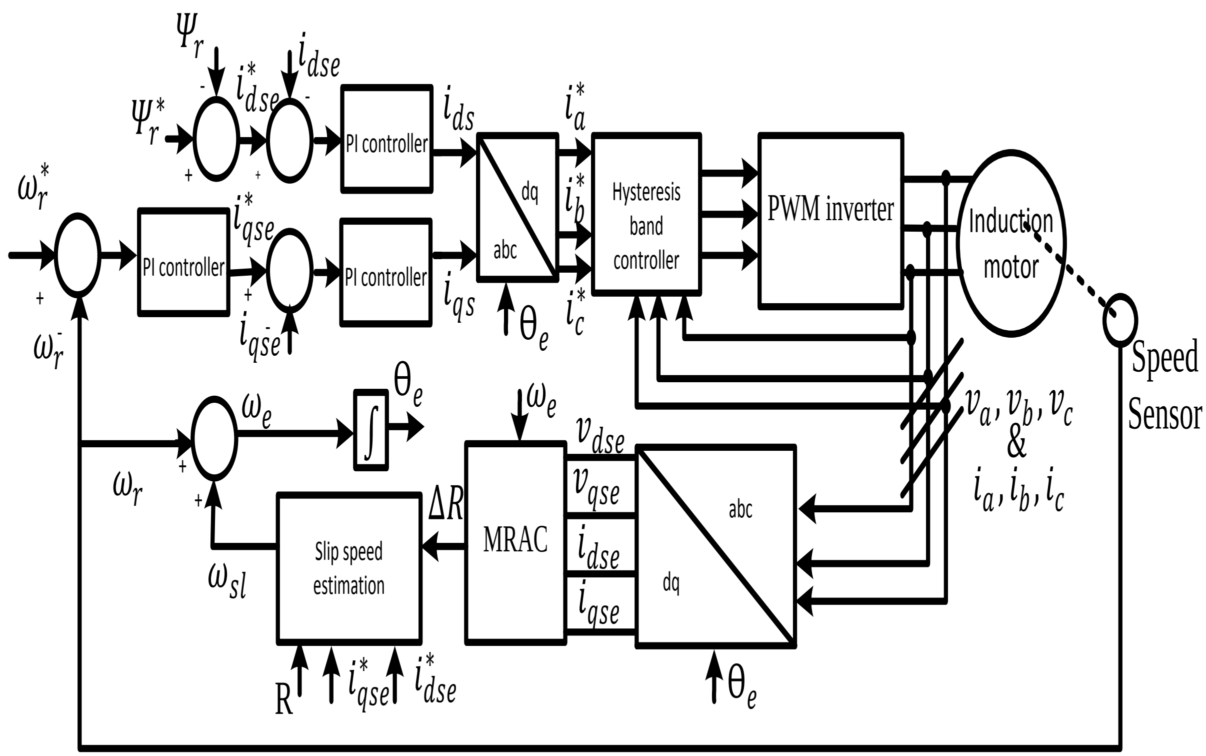


Fig. 6.2 Block diagram of indirect vector control for online rotor resistance estimation technique

Rotor resistance estimation by means of rotor flux

The block diagram for MRAC based rotor flux estimation is shown in Fig. 6.3. Here the flux calculated by voltage model used as reference model and flux calculated by current model is used as adjustable model. Flux calculated by current model is dependent on rotor speed which is dependent on rotor resistance. So the current model is dependent on rotor resistance and voltage model is independent of rotor resistance. The three phase quantities are measured and transformed to stationary quantities which are then further used in current and voltage model for flux calculation [25, 30].

The rotor flux $\Psi_r^v = \sqrt{(\Psi_{dr}^{sv^2} + \Psi_{qr}^{sv^2})}$ where Ψ_{dr}^{sv} and Ψ_{qr}^{sv} are the d-axis and q-axis rotor flux in the stationary reference frame are derived as follows

$$\Psi_{dr}^{sv} = \frac{L_r}{L_m}(\Psi_{ds}^{sv} - \sigma L_s id^s) \tag{6.1}$$

and

$$\Psi_{qr}^{sv} = \frac{L_r}{L_m}(\Psi_{qs}^{sv} - \sigma L_s iq^s) \tag{6.2}$$

Where Ψ_{ds}^{sv} and Ψ_{qs}^{sv} can be calculated as

$$\Psi_{ds}^{sv} = \int (v_{ds}^s - R_s id^s)\, dt \tag{6.3}$$

$$\Psi_{qs}^{sv} = \int (v_{qs}^s - R_s iq^s)\, dt \tag{6.4}$$

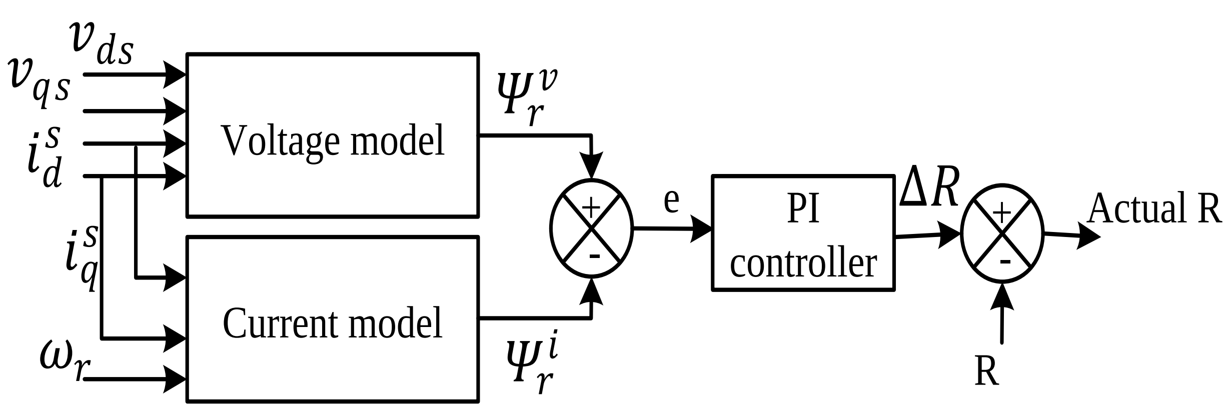


Fig. 6.3 Proposed rotor flux based MRAC for rotor resistance estimation

Likewise current model based flux output $\Psi_r^i = \sqrt{(\Psi_{dr}^{si^2} + \Psi_{qr}^{si^2})}$ is obtained by measuring the current and rotor speed ω_r where

$$\Psi_{dr}^{si} = \int (\frac{L_m}{T_r} id^s - \omega_r \Psi_{qr}^s - \frac{1}{T_r} \Psi_{dr}^s)\, dt \tag{6.5}$$

$$\Psi_{qr}^{si} = \int (\frac{L_m}{T_r} iq^s + \omega_r \Psi_{dr}^s - \frac{1}{T_r} \Psi_{qr}^s)\, dt \tag{6.6}$$

The difference between Ψ_r^v and Ψ_r^i generates error signal for adaption mechanism which is PI controller whose output further directs the change in rotor resistance ΔR which is then added with the rotor resistance to attain the actual rotor resistance R_r. This new value of rotor resistance is then used to calculate slip speed ω_{sl} which is then added with rotor speed to generate synchronous speedω_e. ω_e is used in generation of unit vector which is employed for decoupling.

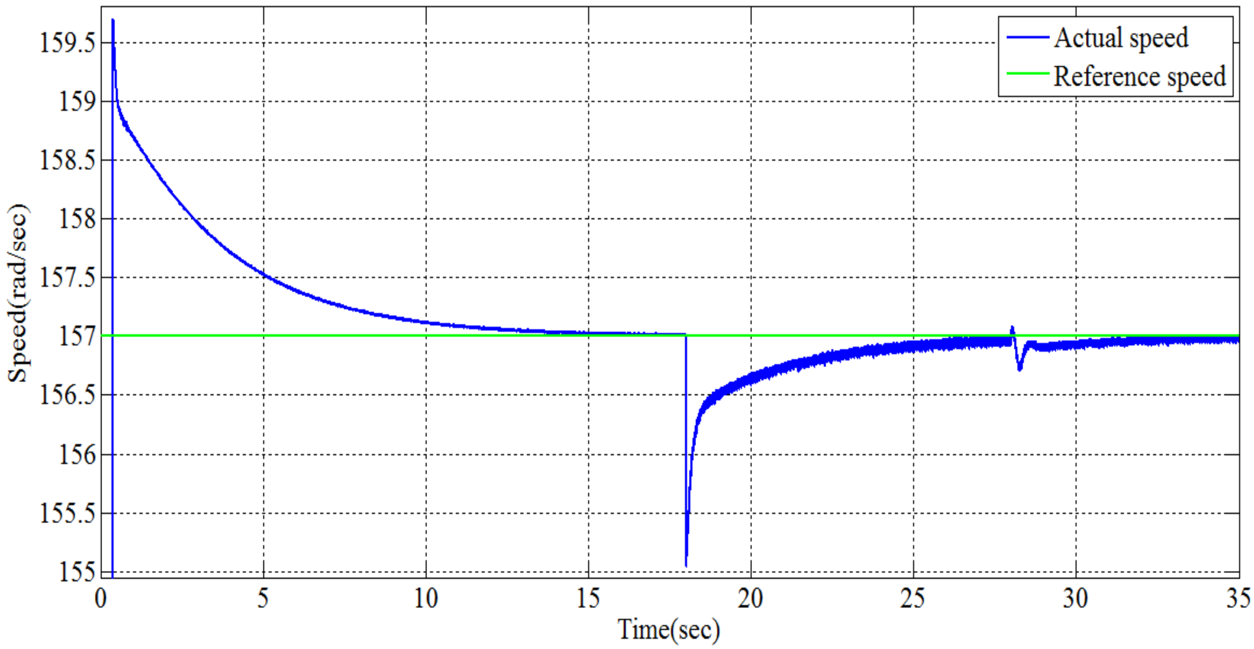
6.4 Result and discussion

Modelling and simulation of indirect vector control of induction motor is carried with functional specification listed in table 5.1 to find out the effectiveness of proposed scheme. The SPWM based indirect vector control for online rotor resistance is verified for step change in rotor resistance. In real world, of course, abrupt change in resistance is not possible. Rotor resistance undergoes gradual variation because of large thermal time constant so this is an extreme case to check the robustness of the developed scheme.

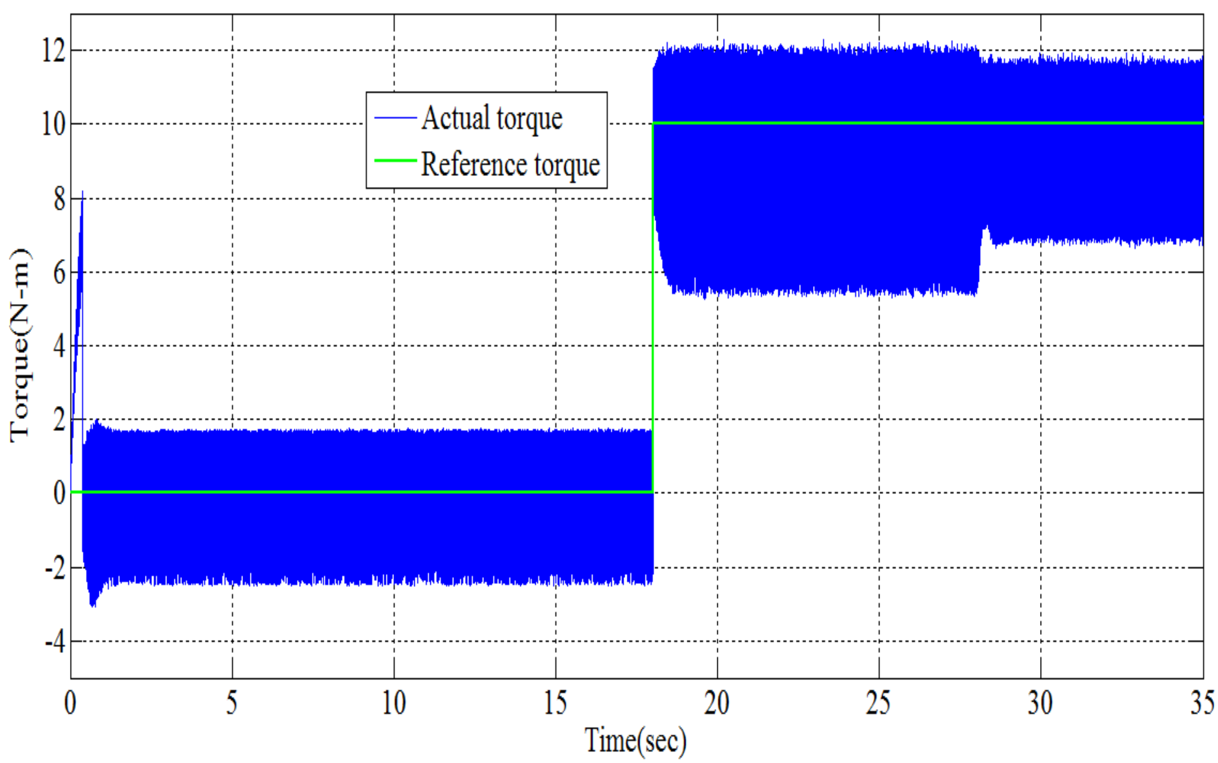
At starting machine is running at 157 rad/sec speed. It takes around 15sec to settle down to reference speed due to large thermal time constant and due to complex estimation technique. Current, torque, rotor-resistance and rotor-flux waveform is also shown. Estimated rotor –resistance is almost equal to actual rotor-resistance.

At 18 sec, 10 N-m torque is applied to the motor. There is small dip in speed and it settles to reference speed 8 sec. There is small undershoot in rotor-flux but finally settles to 0.5weber.

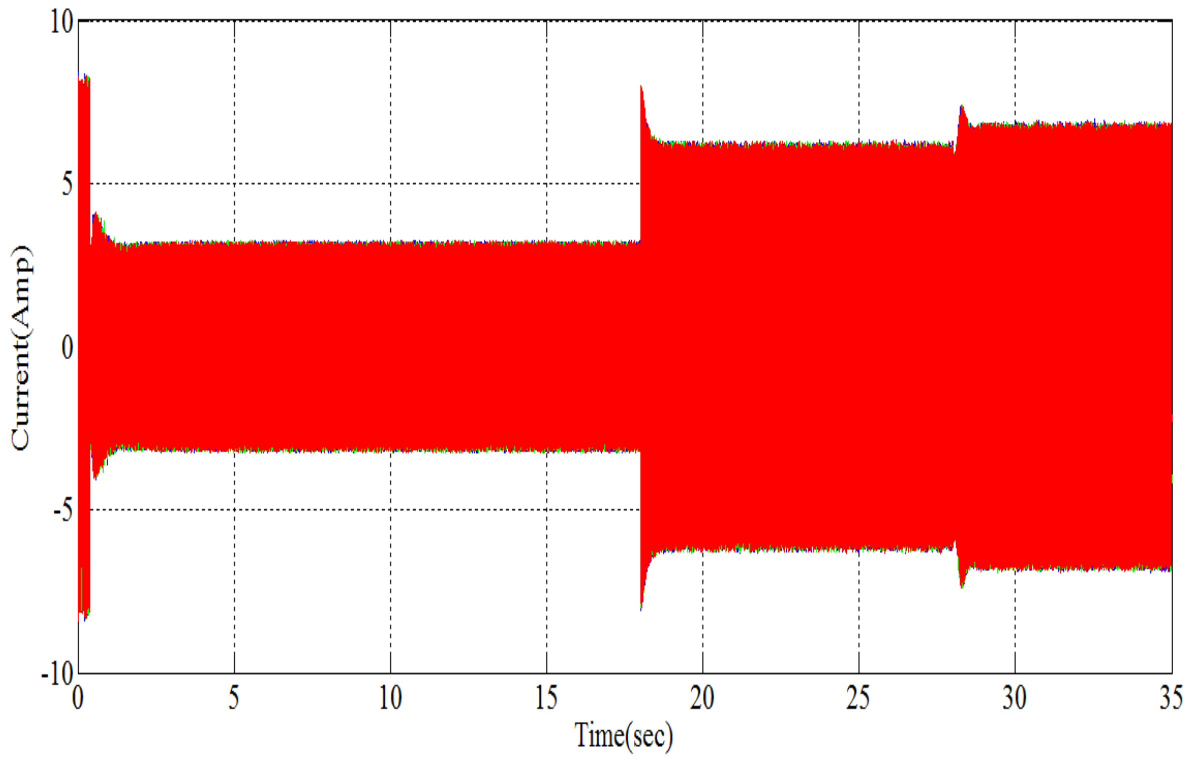
As the main objective is to check the robustness of the developed model under the variation of rotor-resistance so it is varied to 1.5 times to its actual value at 28 sec. Under this variation, the machine speed shows a little variation from its reference speed but it settles to final speed within no time. As rotor-resistance increases, the machine draws more current. Actual rotor-resistance is again nearly equal to reference rotor-resistance. In rotor-flux, there is a small overshoot but finally settling to 0.5 wb. As motor is presenting good dynamic performance under the step change in rotor change, it is surely will display better performance for gradual variation change in rotor-resistance.



(a)

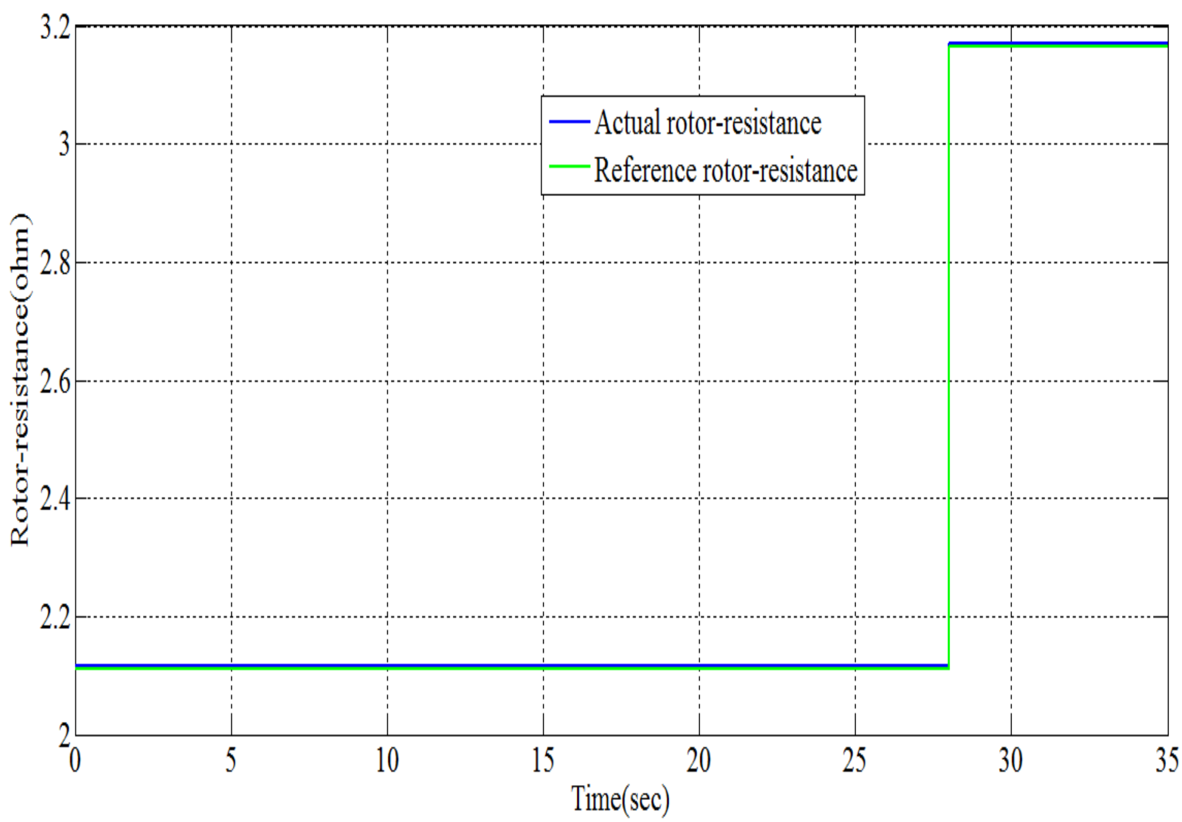


(b)



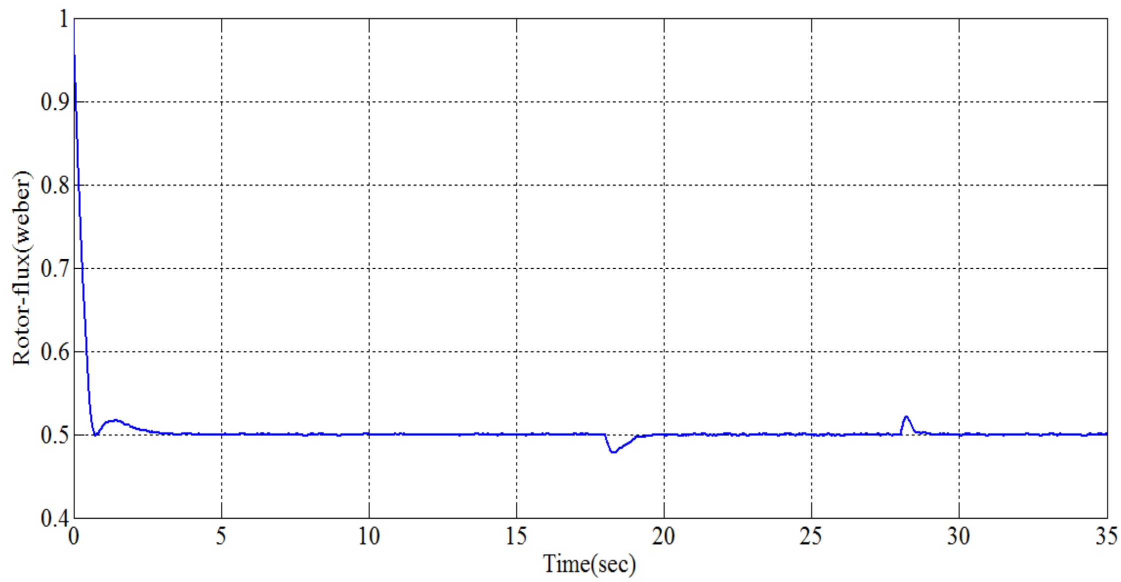
Current(Amp)
Time(sec)

(c)



Actual rotor-resistance
Reference rotor-resistance
Rotor-resistance(ohm)
Time(sec)

(d)

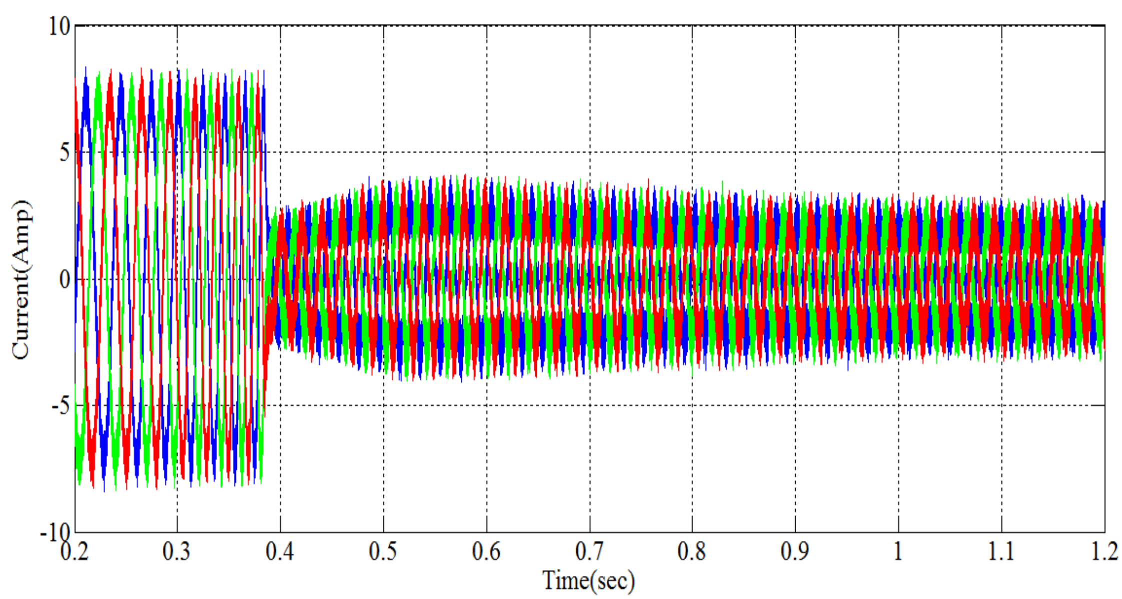


(e)

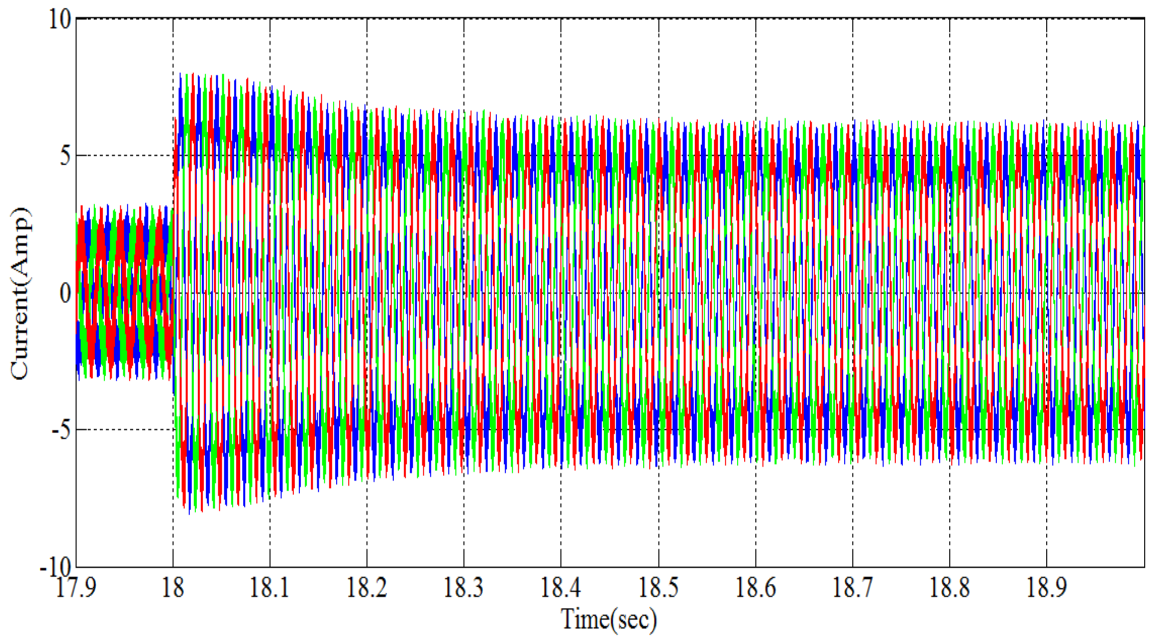
Fig. 6.4 Online rotor -resistance estimation technique's dynamic response without load, with load at 1.8 sec and with 1.5 times rotor resistance at 2.8 sec (a) speed, (b) torque, (c) current, (d) rotor resistance, (e) rotor flux

Current waveform

As in Fig. 6.4(c), current is not clear and understandable. So the current waveform is presented here with zoom in view so that all the three phase waveforms are visible.



(a)



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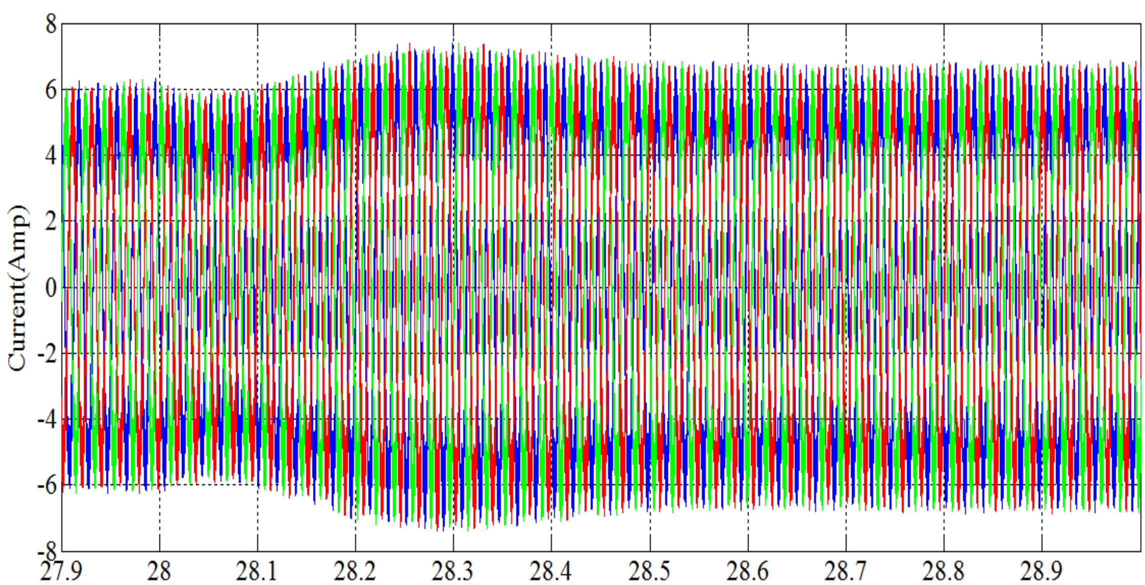

(c)

Fig. 6.5 Current waveform (a)with 157 rad/sec speed, (b) with load applied at 18 sec, (c) with 1.5 times rotor resistance at 28 sec.

6.5 Conclusion

The dynamic performance of induction motor is carried out for step change in rotor-resistance to observe the effect of rotor-resistance variation on the performance of machine. Machine shows satisfactory dynamic performance under abrupt change in rotor-resistance so it can also display good dynamic performance for steady variation in rotor-resistance. Machine performance for load torque of 10 N-m at 18 sec and step change in rotor-resistance at 28 sec is observed. Speed takes time to settle to reference speed under load condition because of complexity of technique. Actual rotor-resistance is approximately equal to reference rotor-resistance. There is not large variation in speed upon application of step change in rotor-resistance. But overall performance is good.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

In this project, scalar and vector control of induction motor have been achieved using Matlab/Simulink. Open loop scalar control performance is carried out for different gain values of v/f to check how these affect overshot, undershoot and steady state error in speed. Indirect vector control of Induction motor for different values of proportional, integral and hysteresis band is carried out to analyze the effect of these parameters on the dynamic performance of drive. Comparison is done on the basis peak overshoot, undershoot in speed and rise time, peak time and settling time. Dynamic performance is also compared for different speed controllers like PI, IP and PR. Based on the required performance, any one of these can be preferred. Even though indirect vector control method results in excellent dynamic performance, its performance is subjected to parameter variation especially rotor resistance. Therefore MRAC based online rotor resistance estimation is also carried out. Online rotor resistance estimation is useful for effective performance of induction motor drive. Under running condition, motor resistance changes which will further affect the rotor flux and the decoupling between rotor flux and torque will lost.

7.2 Scope for future work

As the future of the project, following work can be carried out

1. The developed scheme is easy to implement in real time application using d-Space controller.
2. Develop robust controllers which would give high performance control even if subjected to machine parameter variation.

3. Develop algorithm for accurate estimation of rotor resistances for perfection in flux estimation.

References

[1] K. Anitha, G. Santosh, L. Suneel, K. Spandana, E. Raviteja, “Simulation and speed control of 3-phase induction motor drives”, International Journal of Engineering Science and Computing, Vol. 6, Issue no. 4, April 2016, pp. 4478-4481.

[2] Pabitra Kumar Behera, Manoj Kumar Behera, Amit Kumar Sahoo, “Speed control of induction motor using scalar control technique”, International Journal of Computer application(0975-8887), International Conference on Emergent Trends in Computing and Communication (ETCC-2014).

[3] Ravi Prakash, Prof. Rishi Kumar Singh, Rajeev Ranjan Kumar, “Variable voltage variable frequency speed control of induction motor using FPGA-Xilinx”, IRJET, e-ISSN: 2395-0056, p-ISSN:2395-0072, Vol. 2, issue 03, July 2015.

[4] Gaber El-Saady, El-Nobi A. Ibrahim, Mohamed Elbesealy, “ V/F control of three phase induction motor drive with different PWM techniques”, Innovative Systems Design and Engineering, ISSN 2222-1727(Paper) ISSN 2222- 2871(Online), Vol. 4, No.14, 2013.

[5] Mr. G. Pandian and Dr. S. Rama Reddy, “Implementation of multilevel inverter-fed induction motor drive”, Journal of Industrial Technology, Vol. 24, No. 2, April 20008 through June 2008.

[6] M. S. Aspalli, Asha. R, P.V. Hunagund, “ Three phase induction motor drive using IGBTs and constant v/f method”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, ISSN ONLINE(2278-8875) PRINT (2320-3765).

[7] R. Dharmaprakash, Joseph Henry, “Comparative study of Indirect vector control and direct torque control of induction motor”, IJTES, Vol. 1(6), pp:1014-1020, ISSN: 2320-8007, Sept 2013.

[8] B. Ozpineci and L. M. Tolbert, "Simulink implementation of induction machine model - a modular approach," Electric Machines and Drives Conference, 2003. IEMDC'03. IEEE International, 2003, pp. 728-734 vol.2.

[9] K. Hemavathy, N. Pappa and S. Kumar, "Comparison of indirect vector control and direct torque control applied to Induction Motor drive," 2014 IEEE International Conference on Advanced Communications, Control and Computing Technologies, Ramanathapuram, 2014, pp. 192-197.

[10] S. Riaz Ahamed, J. N. Chandra Sekhar, Dinakara Prasad Reddy P, “Speed control of Induction Motor by using intelligence techniques,” Int. Journal of Engineering Research and Applications, ISSN: 2248-9622, Vol. 5, Issue 1(Part 5), pp. 130-135, Jan 2015.

[11] G. K. Singh, K. Nam and S. K. Lim, "A simple indirect field-oriented control scheme for multiphase induction machine," in IEEE Transactions on Industrial Electronics, vol. 52, no. 4, pp. 1177-1184, Aug. 2005.

[12] B. Venkata Ranganandh, A. Mallikarjuna Prasad, Madichetty Sreedha, “Modelling and simulation of a hysteresis band pulse width modulated current controller applied to a three phase voltage source inverter by using Matlab”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (An ISO 3297:2007 Certified Organization), Vol. 2, Issue 9, September 2013, ISSN(Print): 2320-3765, ISSN(Online): 2278-8875.

[13] Bose, B. K., “Power Electronics and AC Drives”, New Jersey, Prentice-Hall, N.J, 2006.

[14] A. Tripathi and P. C. Sen, "Comparative analysis of fixed and sinusoidal band hysteresis current controllers for voltage source inverters," in IEEE Transactions on Industrial Electronics, vol. 39, no. 1, pp. 63-73, Feb 1992.

[15] L. A. Serpa, S. D. Round and J. W. Kolar, "A virtual-flux decoupling hysteresis current controller for mains connected inverter systems," 2006 37th IEEE Power Electronics Specialists Conference, Jeju, 2006, pp. 1-7.

[16] V. Chereau, F. Auger and L. Loron, "A new three-phase varying-band hysteresis current controller for voltage-source inverters," 2007 7th International Conference on Power Electronics and Drive Systems, Bangkok, 2007, pp. 1179-1186.

[17] Zen Guo, Jiasheng Zhang, Zhenchaun Sun, Changming Zheng, “Indirect field oriented control of three-phase induction motor based on current-source inverter ”, ELSEVIER, 13th Global Congress on Manufacturing and Management, GCMM 2016, Procedia Engineering 174(2017) 588-594.

[18] R. S. Hiware and J. G. Chaudhari, "Indirect Field Oriented Control for Induction Motor," 2011 Fourth International Conference on Emerging Trends in Engineering & Technology, Port Louis, 2011, pp. 191-194.

[19] Prof. Aziz Ahmed, Yogesh Mohan, Aasha Chauhan, Pradeep Sharma, “Comparative study of speed control of D.C. motor using PI, IP and fuzzy controller”, International Journal of Advanced Research In Computer and Communication Engineering, Vol. 2, Issue 7, July 2013.

[20] P. K. Nandam and P. C. Sen, "Analog and Digital Speed Control of DC Drives Using Proportional-Integral and Integral-Proportional Control Techniques," in IEEE Transactions on Industrial Electronics, vol. IE-34, no. 2, pp. 227-233, May 1987.

[21] T. Sreekumar and K. S. Jiji, "Comparison of Proportional-Integral (P-I) and Integral-Proportional (I-P) controllers for speed control in vector controlled induction Motor drive," 2012 2nd International Conference on Power, Control and Embedded Systems, Allahabad, 2012, pp. 1-6.

[22] Aamir Hasim Obeid Ahmed, “Speed control of vector controlled induction motors using integral-proportional controller”, SUST Journal of Engineering and Computer Science (JECS), Vol. 15, No. 2, 2014.

[23] Xiuqin Wang, Guoli Li, Maosong Zhang, Xing Qi, Qunjing Wang, Jiwen Zhao, Yuan fang, “Research on asynchronous motor rotor flux model based on PR controller”, 2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA), Auckland, 2015, pp. 1857-1861.

[24] A. Uphues, K. Nötzold, R. Wegener and S. Soter, "Frequency adaptive PR-controller for compensation of current harmonics," IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, Dallas, TX, 2014, pp. 2103-2108.

[25] Scott Wade, Matthew W. Dunnigan and Barry W. Williams, “A new method of rotor resistance estimation for vector-controlled induction machines”, IEEE Transaction on Industrial Electronics, Vol. 44, No. 2, pp. 247-257, April 1997.

[26] Saji Chacko, Chandrashekhar N. Bhende, Shailendra Jain, R.K. Nema, “A Novel rotor resistance estimation technique for vector controlled induction motor drive using TS fuzzy”, IJPEDS, Vol. 6, No. 3, September 2015, pp. 538-553, ISSN: 2088-8694.

[27] Suman Maiti, C. Chakraborty, Y. Hori and M. C. Ta, "Model Reference Adaptive Controller-Based Rotor Resistance and Speed Estimation Techniques for Vector Controlled Induction Motor Drive Utilizing Reactive Power," in IEEE Transactions on Industrial Electronics, vol. 55, no. 2, pp. 594-601, Feb. 2008.

[28] D. Qiang, K. Jingbo and Z. Kai, "Research on rotor resistance adaptation algorithm for indirect vector control of induction machines," 2015 IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), Chongqing, 2015, pp. 831-836.

[29] Huang Bin, Qu Wenlong and Lu Haifeng, "A novel on-line rotor resistance estimation method for vector controlled induction motor drive," The 4th International Power Electronics and Motion Control Conference, 2004. IPEMC 2004., Xi'an, 2004, pp. 655-660 Vol.2.

[30] B. Karanayil, M. F. Rahman and C. Grantham, "Online Stator and Rotor Resistance Estimation Scheme Using Artificial Neural Networks for Vector Controlled Speed Sensorless Induction Motor Drive," in IEEE Transactions on Industrial Electronics, vol. 54, no. 1, pp. 167-176, Feb. 2007.

[31] Prof. Krishna Vasudev, Prof. G. Sridhara Rao, Prof. P. Sasidhara Rao, “Speed Control of Induction Machines” Electrical Machines II, Indian Institute of Technology Madras.

[32] Bo Fan, Zhixin Yang, Wei Xu, Xianbo wang, “Rotor resistance online identification of vector controlled induction motor based on neural network”, Hindawi Publishing Corporation, Mathematical problems in Engineering, Vol. 2014, Article ID 831839, 10 pages, http://dx.doi.org/10.1155/2014/831839.

[33] Jitendra Kr. Jain, Sandip Ghosh, Somnath Maity and Pawel Dowark, “PI controller design for indirect vector controlled Induction motor: A decoupling approach”, *ISA Trans.*, vol. 70, pp. 378-388, 2017.

[34] Syed Usama Hassan, Hafiz Bilal Akram, “Speed and frequency control of ac induction motor using variable frequency drive”, Student Research Paper Conference Vol-2, No-56, July 2015.

[35] https://circuitglobe.com/construction-of-induction-motor.html.

[36] https://www.electrical4u.com/construction-of-three-phase-induction-motor/.

List of publications

[1] Mandvi Singh, Dr Mini Sreejeth, Ambrish devanshu, “Comparative Performance Analysis of IVCIM Drive using different Gain values of PI and Band values of Hysteresis Band Controller” published in 2018 1st IEEE International Conference on Power Energy, Environment & Intelligent Control (PEEIC2018) held in G L Bajaj Noida