CHAPTER 1

INTRODUCTION

1.1 GENERAL

Drives today have become an indispensable part of the industrial applications requiring high performance. Electric motors have their impact on almost every sphere of modern life. Electric motors convert electrical energy into useful mechanical energy. Refrigerators, vacuum cleaners, Air conditioners, computer hard drives, automatic car windows, and a number of other appliances and devices use different types of electric motors. Electric motors are also responsible for a very large portion of industrial processes. There are over 700 million motors of various sizes in operation across the world owing to the unlimited number of applications. These can be utilised in applications, where power requirement varies from few watts to many thousands of kilowatts. Besides these, applications range from very accurate, high-performance position-controlled drives in robotics to variable-speed drives for adjusting flow rates in pumps, blowers and fans. In these applications speed and position control is of great significance, hence, the drives are controlled via a power electronic converter which acts as an interface between the input power and the motor.

Squirrel-cage induction motors are widely used in industrial drives because they are rugged, reliable, and economical and require less maintenance. These are least expensive motors. Induction motor is a complex higher-order, nonlinear, strongly coupled, and multi-variable system. When operated directly from the line voltages, an induction motor operates at a almost constant speed. By the use of power electronic converters, it is now possible to vary the speed of an induction motor. Due to a wide range of applications of the induction motor torque and speed control have remained the focus of study. Its main speed-controller patterns include: slip power consumer, slip power feeder and fixed slip power. In applications where dynamic control is not in issue, the control requirement of the AC machine drive has been done using constant '*voltshertz (V/f)'* technique.

With the advancement in the field of high performance AC drives, the application of in induction motor has increased tremendously. The advance features of control in IM are being invaded through advance in modelling, control algorithm and development of lower loss switching, power electronic devices and microprocessors/digital signal processing.

High performance AC drives can be classified as, field oriented and direct torque control (DTC) drives. These drives have various applications that were previously dominated by and reserved for DC motors and drive systems. Vector control belongs to the fixed slip power pattern. It is the typical representative method for high efficiency. The stator current of induction motor has two components: field current and torque current component. The two components can be controlled independently to achieve good dynamic response, which is similar to the control pattern of the DC motor.

The improvement in control techniques, in addition to the advent of power electronic converters has resulted in better dynamic response of the motor characteristics. Intelligent Control techniques like Fuzzy, Neural Network etc are now replacing P, PI, PID speed controllers. This has led to an improvement in the dynamic performance of drive system.

In the present work, fuzzy logic speed controller, ANFIS controller has been applied on a vector controlled induction motor drive. The performance of the drive with and without intelligent controller has been analysed in real time and compared with the performance obtained through simulation in MATLAB/Simulink.

1.2 LITERATURE REVIEW

Vector control or the field oriented control (FOC) technique has widespread use in high performance induction motor drives, where the motor speed should closely follow a specified reference trajectory irrespective of the disturbances. In vector control, the principle of field orientation of an AC induction or synchronous motor helps in controlling the motor like a separately excited DC motor. The decoupled control of torque and flux is used in this method. The AC motor behaves like a DC motor in which the field flux linkage and armature flux linkage created by the respective field and armature (or torque component) currents are orthogonally aligned in such a way that, when torque is changed, the field flux linkage is not changed, hence providing dynamic torque response. By using coordinate transformation, Vector control of induction motor allows us to decouple the electromagnetic torque control from the rotor flux, and hence induction motor acts as a DC motor. In this technique, the variables are transformed into a reference frame in which the dynamic variables are like DC quantities. The decoupling control between the flux and torque results induction motor in achievement of fast transient response. Therefore, it is preferably used in high performance motor applications. Various emerging intelligent control techniques and methods of speed/torque control of three phase Induction motor have been discussed below:

1.2.1 Indirect Vector Control

The two general methods of vector control are the direct or feed- back method and the other one, which is known as feed forward control or indirect method. The direct or feed-back method was invented by **Blaschke** [1] and the indirect or feed forward method was invented by **Hasse** [2].The method of rotor angle determination distinguishes the two methods . In direct FOC the angle is obtained by the terminal voltages and currents, whereas in indirect FOC, the angle is obtained by using rotor position measurement and machine parameter's estimation.

The dynamic performance of inverters supplied induction motors or inverter supplied synchronous motors is comparable to that of a converter fed four quadrant dc drives. Field orientation is an important and powerful tool for controlling such ac machines. Intelligent controllers such as microcontrollers or digital signal processors (DSP) can execute the complex functions required by FOC. It results in great deal of reduction in necessary control hardware [3, 6].

By making the motor parameters in the field-oriented controller coincide with the actual parameters of the motor, good control performance can be achieved. A new identification technique utilizing injected negative sequence components was described by **Takayoshi** [4]. The stator as well as rotor resistance and leakage inductance can be determined on line while the motor is driving the load. A full-scale hybrid computer simulation of a field-oriented controlled PWM inverter based induction motor drive verified this theory. The performance of induction motor drive is mainly determined by the gating pulses feeding the inverter and hence the output current generated by the inverter. For determining the pulse pattern, a **current control technique using hysteresis** [5, 9] can be applied.

Fast response current loop can be obtained by this method and knowledge of load parameter is not required. Variable switching frequency of inverter and undesirable harmonic generation may be obtained by this method. **Ting–Yu et.al**.[16], proposed a new Space vector current control technique, for induction motor drive, which shows better performance. Time-varying coordinate transformation and complicated calculation are eliminated. Even a simple 8751 microcomputer can be used to implement a high-performance drive system. The proposed space vector-based current controller also uses the extra information of error derivative and manages to reduce the switching frequency. Conventional PI control technique is widely used for speed controllers. Advancement in control strategies has resulted in a number of efficient controllers over the years. **Yau-Tze et.al** [13] proposed the use of H2 and H∞ control technique for implementation in vector control scheme. This scheme has shown better disturbance rejection capability than a PI controller and, in particular, H∞ controller shows the best performance. Fixed gain controllers are very sensitive to parameter variations, load disturbances etc. Other techniques involving the use of soft computing techniques like fuzzy logic controllers are also available. Fuzzy logic controller is more advantageous as compared to conventional PI, PID and adaptive controller. No mathematical model is required and it is based on linguistic rules within IF-THEN general structure, which is the basic of the human logic. Fuzzy Logic Controller has its application in vector controlled induction motor drive and it is replacing PI controllers. A fuzzy logic based on-line efficiency optimization control for an indirect vector controlled drive system was proposed by **Gilberto et.al** [20]. A fuzzy controller is used to adjust adaptively the magnetizing current based on the drive measured input power. It gives true optimum efficiency operation and fast convergence. By using adaptive step size of the excitation current fast convergence is achieved. By a feed forward compensation algorithm the low-frequency pulsating torque generated by the efficiency controller has been suppressed. **Emanuele** [29] proposed a fuzzy adaptive control scheme for vector controlled induction motor drive. A semiautomatic procedure to optimize adaptive fuzzy laws is developed by using the neuro fuzzy approach. Based on some linguistic rules that describe the expected behaviour of the adapting process, the design of the adaptive fuzzy laws is presented. Results showed much better performance than the conventional methods.

The results in real time for rapid control prototyping (RCP) were obtained from D-space implementation of the vector control scheme for induction motor drive. The real time hardware, based on a Power PC microprocessor and its I/O interfaces make the board ideally suited for developing controllers in various fields, in both industry and research organisation.

M.Nasir-uddin [40] presented a new Fuzzy Logic Controller design. The fuzzy logic speed controller is employed in the outer loop. Using a digital signal processor board DS-1102 for the laboratory 1-hp squirrel-cage IM, the complete vector control scheme of the IM drive incorporating the FLC is experimentally implemented. In order to minimize the real-time computational burden, simple membership functions and rules have been used. The proposed FLC shows superior performances over the PI controller.

A space-vector-based current-regulated PWM inverter with new switching tables was designed and implemented by **Yi-Hwa Liu et.al** [30]. Due to full utilization of all available voltage vectors, current harmonic contents have been improved by the proposed switching table in the angular coordinate. New Optimisation techniques are proposed in [42, 45]. Such hybrid techniques ensure high performance drives.

1.2.2 Direct Vector Control

Direct vector control was first proposed by **Blaschke** [1]. The direct vector control is also known as feedback vector control scheme. In direct vector control method rotor angle or control vector is obtained by the terminal voltages and currents directly with the help of flux estimators. Various controllers have been designed and implemented on direct vector controlled induction motor drives for improving the drive performance.

Though this method is the most desirable control scheme, it suffers from drawbacks like high cost and unreliability of the flux measurement. The indirect method can approach the performance of the direct measurement scheme, but the major weakness of this approach is based upon the accuracy of the control gains which, in turn, depend heavily on the motor parameters assumed in the feed forward control algorithm [4].

Neural networks can be used effectively for various applications in power electronics and motion control systems. **M. Godoy et.al** [21] proposed a feed forward neural network technique for estimation of feedback signals of a direct vector-controlled (DVC) induction motor drive. The neural network estimator showed the advantages of faster convergence, immunity to the ripples due to various harmonics, and fault tolerance characteristics compared to DSP-based estimator.

Susumu [25] et.al proposed a combined feed forward and feedback (FF/FB) control for improving the robustness of vector controlled induction motors. This system maintains the quick response of the slip-frequency-type and is insensitive to parameter variation in cooperation with field-orientation control. A neural network controller has also been proposed for controlling the dynamics of the drive. The neural network based technologies help in providing an adjustment-free and maintenance-free vector-controlled induction motor for industrial applications.

Bimal.K.Bose et.al [26] controlled a stator flux-oriented direct vector-controlled electric vehicle (EV) induction motor drive of 100-kW power by extending the fuzzy efficiency optimization. The fuzzy controller input– output transfer characteristics are then used to train a feed forward neural network with delayed feedback, which then replaces the fuzzy controller in the drive system. Such a control combines the advantages of fuzzy and neural controls. The control attains fast convergence with inherent adaptive step size signals of fuzzy control. The implementation of neural network based system allows fast computation and can be implemented by a dedicated hardware chip or by DSP-based software. According to simulation study results, the performance of such a controller is found to be excellent.

1.2.3 Direct Torque Control

In this method an estimate of the motor's magnetic flux and torque is calculated based on measured voltage and current of the motor. It is used to control the speed of the motor. **Isao Takahashi and Toshihiko Noguchi** described a control technique termed DTC in an IEEE paper presented in September 1984 and in an IEEE paper published in late 1986 [7].

By using optimum PWM output voltage, limit cycle control of both flux and torque is achieved; a switching table is employed for selecting the optimum inverter output voltage vectors which helps in attaining a fast torque response, a low inverter switching frequency, and low harmonic losses. The efficiency optimization in the steady-state operation is also considered which can be achieved by controlling the amplitude of the flux in accordance with the torque command.

Isao Takahashi in 1989 [8] proposed another DTC control scheme, which has better performance. New control schemes have been proposed in this paper based on the principle of the disk of Arago, which can be considered a basic law of torque generation in the induction motor. It allows the achievement of fast torque response as well as high-efficiency control at the same time. In the system, instantaneous values of the flux and the torque are calculated from primary variables and controlled independently by using an optimum switching table. Therefore, it can achieve not only the fastest torque response but also the lowest harmonic losses and acoustic noise.

In 1995 **Marian** [22] showed that by the introduction of an additional carrier signal to the torque controller input, improved performance at starting and robust operation at low speed region can be achieved. No separate voltage modulation block and no current regulation loops are required. There is no coordinate transformation. Voltage decoupling network is also not required.

A torque control scheme, based on a direct torque control (DTC) algorithm using a 12-sided polygonal voltage space vector, was proposed for a variable speed control of an open-end induction motor drive, by **Chintan et.al** [64]. The proposed DTC scheme selects eight switching vectors based on the sector information of the estimated fundamental stator voltage vector and its relative position with respect to the stator flux vector. The proposed DTC scheme utilizes the exact positions of the fundamental stator voltage vector and stator flux vector to select the optimal switching vector for fast control of torque with small variation of stator flux within the hysteresis b and . The present DTC scheme enables full load torque control with fast transient response to very low speeds of operation; the switching frequency variation has also decreased.

1.2.4 Sensor less Vector Control

Speed Sensors are not used in sensor less vector control. A Speed encoder increases the cost and reliability problems. Speed can be estimated from machine terminal voltages and currents. The sensor less vector control method adds to complexity, but with the help of various estimation algorithms available reliability can be achieved.

A vector-control scheme based on a rotor-flux speed control was proposed by **Tsugutoshi** [12]. It involves torque-producing current and rotor flux, calculated from the stator current and voltage. In the proposed rotor-flux estimator, a lag circuit is employed, to which both the motor-induced voltage and the rotor-flux command are imposed, and therefore it is possible to calculate even a low frequency down to stand still. Selecting the rotor-flux estimator parameter to set the same time constant to the lag circuit as that of the rotor circuit is considered to reduce the influence of stator resistance. This system can be controlled precisely over a wide speed and load range.

Joachim [39] et.al proposed an approach for speed estimation through stator flux integration. High estimation bandwidth is permitted by employing a pure integrator for stator flux estimation. Offset identification enables compensation of the drift components. A self-adjusting inverter is employed to correct the no-linear voltage distortions model. A further improvement is a novel method for online adaptation of the stator resistance. Smooth steady-state operation and high dynamic performance is achievable at extremely low speed.

Colin [14] proposed a development of Model Reference Adaptive System (MRAS) for the estimation of induction motor speed from measured terminal voltages and currents. The new MRAS scheme is less complex and more effective. **Fang-Zheng** [19] described a new approach to estimate induction motor speed from measured terminal voltages and currents for speed-sensor less vector control. The instantaneous reactive power of the motor is observed. The estimated speed is used as feedback in an indirect vector control system. This approach is independent of the knowledge of the value of the stator resistance. It is also unaffected by stator resistance variations due to temperature change. Furthermore, mathematical computation like integration of measured variables, in principle, is not required at all. This new method can thus achieve much wider b and width speed control than previous tacho less drives.

A new simple algorithm capable of running in a low cost microcontroller was proposed by **Epaminondas et.al** [37]. This algorithm is derived from the dynamic model of the induction machine. If it is assumed that flux calculation errors are due to stator change in stator resistance, the algorithm used for estimation automatically corrects the stator resistance value in order to eliminate the error. With the proposed method it is proved that an accurate estimation of the stator flux can be achieved. Hence, precise torque control is obtained even in the low-speed range, and the dynamic performance of the asynchronous machine is improved.

1.3 OBJECTIVES OF PRESENT WORK

Implementation of an intelligent control scheme for a three phase vector controlled induction motor is the main objective of this work. The speed control of the motor is achieved under different operating conditions.

The simulation model of the IVCIM is developed and performance of intelligent controllers is compared with the conventional PI controller. The various control schemes used in the present work are:

A. PI Controller

PI controller is most widely used controller structure used in the control applications and various industrial controls. The main advantage associated with the PI controller is its simplicity and simple relationship that exist between various parameters. The hardware prototype of Vector control of Induction motor is implemented with PI controller.

B. Fuzzy Logic Controller

Fuzzy logic controller is based on the converting variables into the crisp values. The advantage of FLC is that its performance is better when system uncertainties are considered. Generally all physical processes are time variant and complex with non linear characteristics. In such conditions, performance of FLC is better.

C. ANFIS controller

The concept of intelligent controllers has become very popular these days because of their performance. Fuzzy logic controller and Artificial Neural network are famous because of their better response when used to control the non linear system. ANFIS controller eliminates the need of knowledge about the system as rule base is designed automatically and this aspect of the ANFIS control scheme makes it unique.

The indirect vector control strategy has been completely implemented in hardware by using DS 1104. The results obtained through simulation in MATLAB/Simulink validate the results obtained from the hardware.

1.4 OUTLINE OF THE PROJECT

The vector control scheme for induction motor control has been greatly improved over the years. The advent of control techniques like Fuzzy and Neural network, has led to more efficient and effective control of motor speed. The use of microprocessors for controlling the speed or the use of the motor dynamics can be controlled in real time by using Digital Signal Processing Kits. The dynamic modelling of induction motor and the vector control scheme is described in Chapter 2. In Chapter 3, control schemes are discussed in detail which basically contains the details of various controllers used. In chapter 4, the simulation model of indirect vector control is presented. Chapter 5 presents the hardware description of the IVCIM. The results are presented in chapter 6. The main conclusion and the future scope of the present work are discussed in the chapter 7.

CHAPTER 2
DYNAMICS OF VECTOR CONTROL OF INDUCTION MOTOR

2.1 GENERAL

Dynamic mathematical modeling of 3 phase IM is necessary for realizing vector control of the motor. The internal structure of three phase induction motor is shown in figure 2.1. The three phase induction motor has a stator and a rotor. The stator has slots on its inner periphery on which distributed field winding is placed. The rotor of three phase induction motor is either wound type, which consist three phase winding in which end terminals aren’t short circuited or squirrel cage type in which winding’s end terminals are short circuited by end rings. There is small air gap between stator and rotor which is provided for giving the mechanical clearance between stator and rotor. The size of the air gap depends on the power rating of the motor. The rotor of induction motor rotates at speed slightly less than synchronous speed and because of this reason; induction motor is also called Asynchronous motor. The operating speed of the motor depends on the slip which comes from the rotational speed of stator field and therefore speed is somewhat lower than the synchronous speed.

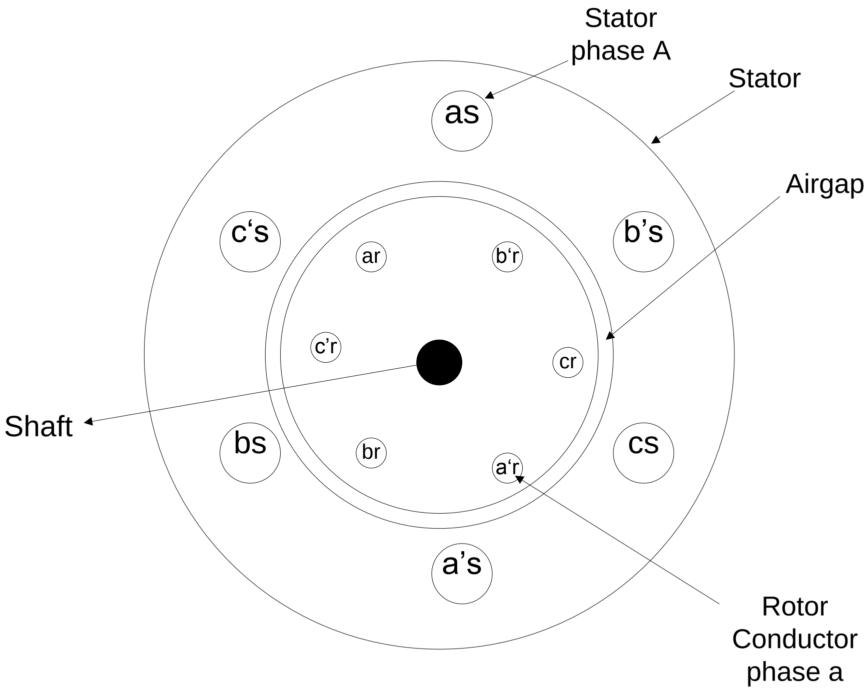


Figure 2.1 Internal structure of three phase induction motor.

A sinusoidal three-phase balanced power supply in the three-phase stator winding creates a synchronously rotating magnetic field. Each phase winding will independently produce a sinusoidal distributed MMF (magneto-motive force) wave, which pulsates along the respective axes. Consider the superposition of three coplanar magnetic field intensities, at a point in space where three field intensities are displaced 120 degree in space and 120 degree in time. Each of the three components of magnetic fields is uniform with respect to the space coordinates.

When rotor conductors are subjected to this sinusoidal rotating magnetic field, emf is induced the rotor conductors. As rotor conductors are short circuited by end rings (in case of squirrel cage rotor), a current starts to flow in the rotor circuit which causes a MMF to develop in the rotor. This rotor mmf and synchronously rotating field interacts with each other and therefore a steady state torque is developed in the motor which makes rotor to rotate in the direction of rotating field. At synchronous speed of the machine, the rotor cannot have any flux cutting action and therefore no torque would be developed, hence an induction motor can never run at synchronous speed. The rotor moves in the same direction as that of the rotating magnetic field to reduce the induced current. Basic to the operation of induction motor is the control of speed or torque by controlling the slip and control of flux by controlling voltage or current.

In this chapter, different methods of speed control of Induction motor, including scalar control, vector control have been discussed.

2.2 VARIOUS METHODS OF SPEED CONTROL OF INDUCTION MOTOR

On the basis of rotor construction, induction motor can be classified into two types, i.e. Squirrel cage motors and wound rotor motors. As per the construction point of view, squirrel cage motors are simple and rugged. They are considered as the workhouse of the modern industry. Due to various advantages associated with the induction motor drives, they dominate the world market. However, the designs of control structure used for induction motor drive are usually complex due to the revolving nature of stator field. Moreover, in squirrel cage rotor, the current in the rotor circuit cannot be measured directly. It adds to the complexity of the control structure.

The control and analysis of Induction motor drives in general are considerably more complex as compared to the DC drives and this complexity is multiplexed substantially if high performances are demanded [67]. The reason behind this complexity is requirement of variable frequency, harmonically optimum convertors, power supplies and the complex dynamics of Induction motor drives. Machine parameter variations and difficulties that arise in the processing of feedback signals in presence of harmonics add to the difficulty. However, by using fundamental laws of physics or space vector theory, it is easy to depict that, instantaneous electromagnetic torque of an induction motor can be expressed in the same way as of separately excited DC motor, as product of a flux producing current and a torque producing current, if a special flux oriented frame is considered for the calculations.

The control strategies of Induction motor have been broadly classified into two main groups.

A. Scalar Control
B. Vector Control

2.2.1 Scalar Control

As compared to other control strategies, scalar control stands on a bit easy and less complex methods. It basically involves the change in the magnitude of the control variable. This method involves the variation of flux and torque. Flux of the motor can be controlled by controlling the stator voltage of the machine. Also, by controlling the frequency of the supply, control of torque can be achieved. However, the variation of torque or flux is not independent of each other. Controlling one parameter affects the other. Change in control parameter of either voltage or frequency also leads to change in torque and flux respectively, which in turn degrades the performance of the drive. This is termed as coupling effect. Scalar control is in contrast to vector or field oriented control (will be discussed in the later) where both magnitude an space alignment of the control variable are controlled independently. In terms of performance, Scalar controlled drives are somewhat inferior as compared to the vector or field oriented controlled drives. Moreover the importance of scalar controlled drives has been diminished recently because of the superior performance of vector controlled drives which is in demand in the present industrial applications.

Various types of scalar control techniques are available in the literature. The variation in speed and torque can be achieved by using one of the following means:

A. Stator Voltage Control
B. Rotor Voltage Control
C. Frequency Control
D. Stator Voltage and Frequency control
E. Stator Current Control
F. Voltage, Current and frequency control

Out of all of these control methods, stator voltage and frequency control methods are most widely used and most acceptable methods. The stator voltage and frequency control is to control the induction motor speed and torque by altering the ratio of voltage to frequency that is used to supply the stator. As air gap flux depends on the ratio of voltage to frequency, so if V/f is kept constant, torque does not alter. This will also prevent the saturation of the motor core due to increase in flux. By keeping V/f constant, this method allows induction motor drive to deliver rated torque at all speeds up to rated speed. The difficulty associated with this method is that it needs voltage boost when operated at low frequency. This is because; the air gap flux is reduced due to drop in the stator impedance when motor operates at low frequency.

2.2.2 Vector Control

Scalar techniques are well popular and easy to implement when comparison is made with the vector control but they have inherent coupling effect (i.e. both torque and flux are functions of voltage or current and frequency, which basically account for the sluggish response of the drive and the system is easily prone to instability due to presence of higher order harmonics that are present [67]. For example, if torque is increased by incrementing the slip, the speed tends to decrease. The variation of flux is a sluggish affair. The flux variation is then compensated by the sluggish flux control loop feeding in additional voltage. This momentary dip in the flux reduces the sensitivity of torque with slip and lengthens the system response time.

The various problems associated with the scalar control were eliminated by the invention of the vector control method for controlling induction motor drive. In 1970's, **Blaschke** [1] and **Hasse** [2], developed the concept of field oriented control or more popularly known as Vector control which brought revolution in the field of induction motor drives. The field oriented control can be implemented in two fashions, the Direct FOC and the Indirect FOC. The idea behind the Vector Control is to control the Induction motor in the same manner as that of separately excited DC motor. Because of DC machine like performance, vector control is also known as decoupling, orthogonal or Trans vector control [67]. However, designing and processing vector control is highly complex and requires the use of high speed microcontrollers, Digital Signal Processors (DSP), D space controllers etc.

The detailed description of the Vector control is discussed later in this chapter.

2.3 Axes Transformation The soul of Field oriented control lies in the transformation of three phase quantities into equivalent two phase quantities, which is more commonly known as *abc-dq* transformation. The *abc-dq* transformation is an essential part of this control strategy. The direct-quadrature-zero (or dq0) transformation or zero-direct-quadrature (or 0dq) transformation is a mathematical tool *(*Transformation) which is used to simplify the calculation and analysis of three-phase circuits.

The transformation of three phase quantities into equivalent two phase quantities involves the decoupling of the variables which have time varying coefficients and then referring all these decoupled variables into a common reference frame. This transformation reduces the three phase stator line current into equivalent two DC quantities in dq reference frame. The two DC quantities are orthogonal or in quadrature to each other hence they do not affect the magnitude relationship of each other. This basically allows the control of two orthogonal quantities independently and in this way, induction motor is controlled same as separately excited DC motor.

Various methods and transformation techniques were depicted. Some of the popular methods are Stanley's transformation, Park's transformation etc. These techniques involve mathematical relations which show how to calculate the equivalent values of the three phase quantities when referred to equivalent two phase system.

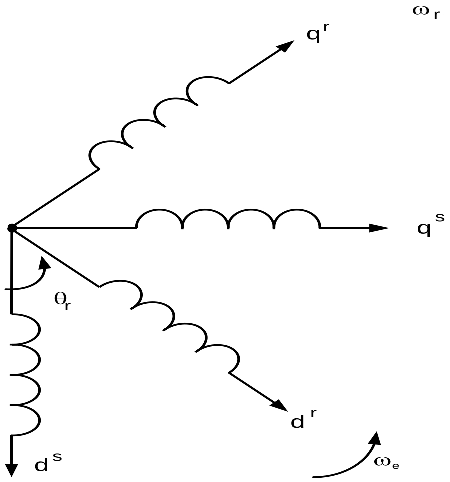


Figure 2.2 Equivalent two phase machine

Park’s transformation applied to three phase current is shown below in matrix form:

$$i_{dq0} = \frac{2}{3}\begin{bmatrix} Cos\theta & Cos\,(\theta - \frac{2\pi}{3}) & Cos\,(\theta + \frac{2\pi}{3}) \\ -Sin\theta & -Sin\,(\theta - \frac{2\pi}{3}) & -Sin\,(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2.1}$$

The inverse transform is:

$$i_{abc} = \begin{bmatrix} Cos\theta & -Sin\theta & 1 \\ Cos\,(\theta - \frac{2\pi}{3}) & -Sin\,(\theta - \frac{2\pi}{3}) & 1 \\ Cos\,(\theta + \frac{2\pi}{3}) & -Sin\,(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} \tag{2.2}$$

A simple *abc-dq* representation in a synchronously rotating reference frame is shown in Figure 2.3. It is shown that three phase stator voltages V_{as},V_{bs} and V_{cs} are displaced 120 degree in space and also the two resolved voltagesV_{qs} and V_{ds} are orthogonal to each other. In this frame of reference, the reference frame is rotating at angular speed ω_s .

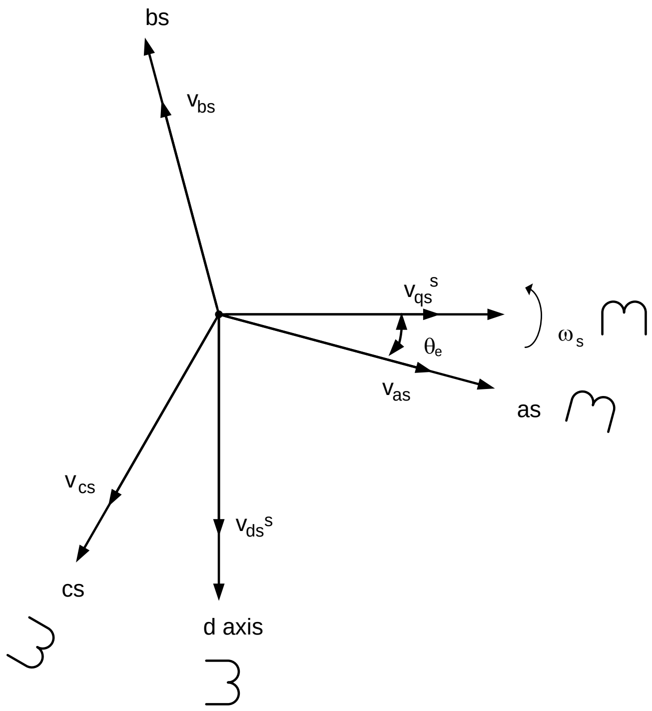


Figure 2.3 abc-dq axes transformation in synchronously rotating frame of reference

2.4 DYNAMICS OF INDUCTION MOTOR CONTROL

The steady state behavior of Induction motor can be studied by steady state model of induction motor which is represented by equivalent circuit of induction motor which is shown as in Figure 2.2. It is used when steady state performance analysis or steady state calculations such as efficiency, losses, steady state torque, current and fluxes are to be evaluated. If steady state model of the machine is used for designing an Induction motor drive, it will only result in the production of a drive that normally has poor transient response. When drive for high performance application is required, a model that can describe transient as well as steady state performance is needed. Therefore, by using the dynamic model, the transient behavior of Induction motor, which cannot be analyzed using steady state model, can be predicted and studied. The dynamic model of induction motor involves the transformation of axis from *abc* frame into *d-q* frame. This transformation is the basic of the Vector or Field oriented control strategy of Induction motor drive.

The Dynamic model of three phase induction motor in synchronously rotating reference frame is shown in figure 2.4. This model shows the direct and quadrature axis components of current flowing through stator and rotor of the induction motor.

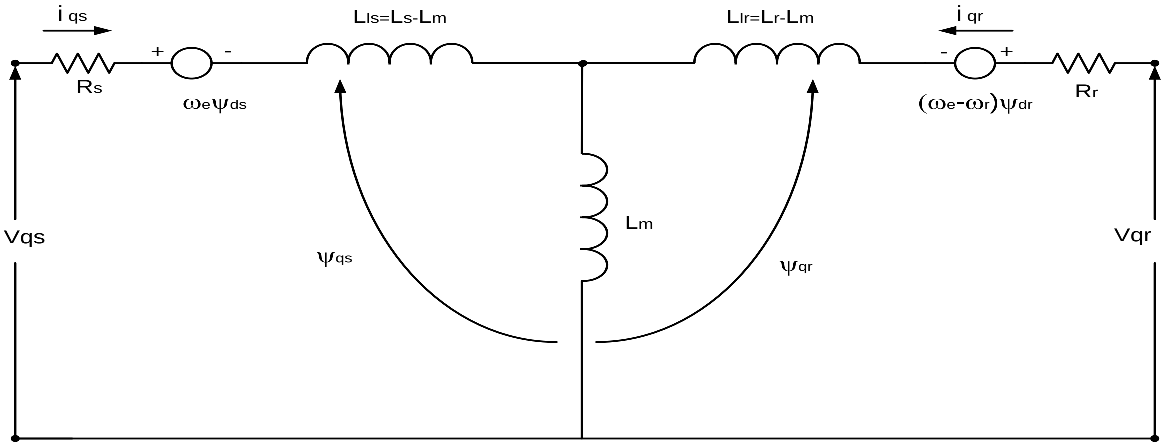


Figure 2.4(a) Equivalent circuit of induction motor in a synchronously rotating frame, quadrature axes circuit

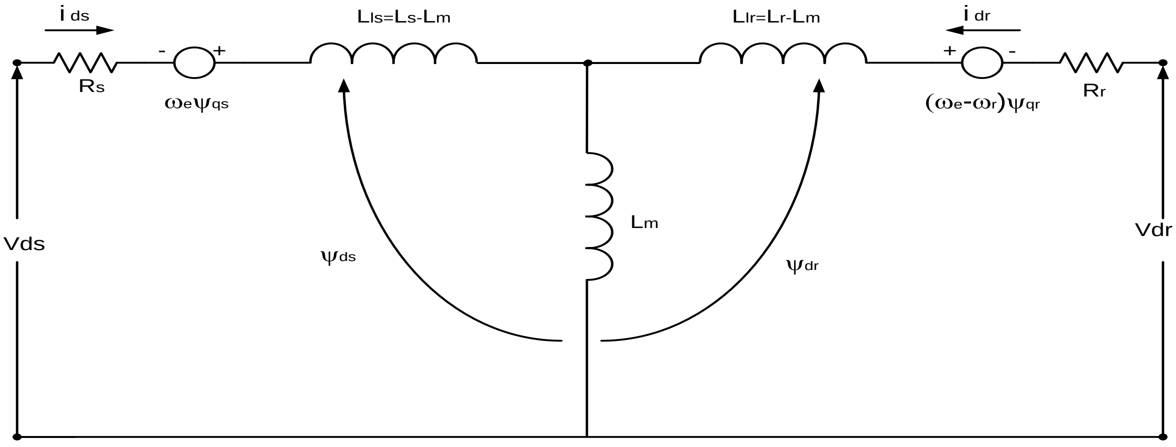


Figure 2.4 (b) Equivalent circuit of induction motor in a synchronously rotating frame, direct axes circuit

Voltage equations are, calculated as per equivalent circuit in stationary frame which is fixed at rotor as shown in Figure 2.4(a) and 2.4 (b).

$$v_{qs} = R_s * i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_e \psi_{ds} \tag{2.3}$$

$$v_{ds} = R_s * i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_e \psi_{qs} \tag{2.4}$$

$$v_{qr} = R_r * i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_e - \omega_r)\psi_{dr} \tag{2.5}$$

$$v_{dr} = R_r * i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_e - \omega_r)\psi_{qr} \tag{2.6}$$

Squirrel cage induction motor has short circuited rotor, so the equations gets modified as

$$0 = R_r * i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_e - \omega_r)\psi_{dr} \tag{2.7}$$

$$0 = R_r * i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_e - \omega_r)\psi_{qr} \tag{2.8}$$

Calculation of flux using transient equivalent circuit

$$\psi_{qs} = L_{ls} * i_{qs} + \left(i_{qs} + i_{qr}\right)L_m \tag{2.9}$$

$$\psi_{qr} = L_{lr} * i_{qr} + \left(i_{qs} + i_{qr}\right)L_m \tag{2.10}$$

$$\psi_{ds} = L_{ls} * i_{ds} + (i_{ds} + i_{dr})L_m \tag{2.11}$$

$$\psi_{dr} = L_{lr} * i_{dr} + (i_{ds} + i_{dr})L_m \tag{2.12}$$

Where v_{qs} and v_{ds} are the applied voltages to the stator; i_{qs} , i_{ds} ,i_{dr} and i_{qr} are the corresponding q-axes and d-axes currents. ψ_{qs},ψ_{qr} , ψ_{ds} and ψ_{dr} are rotor and stator flux components; R_s and R_r are the stator and rotor resistances; L_{ls} and L_{lr} denotes the stator and rotor leakage inductances, whereas L_m is the mutual inductance.

To obtain the dynamic model of induction motor so that performance of the induction motor during transients can be analyzed, we need to convert three phase voltage and current into equivalent two phase quantities as proposed by Park in early 1920’s. Park formulated a change in variables, by which voltage, current and flux variables, associated with the stator winding, are replaced with fictitious variable of a winding rotating with the rotor at synchronous speed. Park transferred or referred the stator variable into a synchronously rotating reference frame, fixed in the rotor. With such a transformation, (which is known as Park’s transformation), he depicted that all time varying inductances that occur in the steady state equivalent circuit model of the induction motor can be eliminated and hence effect of varying reluctances and relative motion can be accounted with less complexity in the electrical circuits involving complex calculations. Few years later, in 1930’s, **H.C.Stanley** [67] another way of eliminating time varying inductances and effect of variable reluctances which arise in the electric circuits due to relative motion. He depicted that these time varying reluctances can be eliminated by transforming the rotor variable to variables to a fictitious stationary winding. In this case rotor variables are transformed to a '*stationary reference frame*' fixed on the stator. Later, **G. Kron** [67] proposed a transformation of both stator and rotor variables to a '*rotating reference frame'*, which is fixed on the rotor. In fact, It was shown later by Krause and Thomas [67] that time varying inductances can be eliminated by referring the stator and rotor variables to a common reference frame which may rotate at any speed *'arbitrary reference frame'*.

2.5 INSIGHTS OF VECTOR CONTROL

2.5.1 Principle of operation of Vector Control

The idea behind the Vector Control is to develop a control strategy which can control the induction motor in the same fashion as a separately excited DC motor is controlled. The main attraction of this type of control is that torque and flux are decoupled and hence they can be controlled independently without disturbing one another. The DC motor has an inherent decoupling present between flux and torque. This inherent decoupling allows to control DC motor in more efficient and simply way and it can produce rated torque at all speeds up to its rated speed. The torque and flux, in case of DC motor are controlled by armature and field current respectively. By using Field oriented control, similar control strategy can be applied on the Induction motor drive. Speed and Torque of Induction motor can be controlled by controlling direct axes and quadrature axes components of stator current respectively, which are obtained from three phase stator current by Park's transformation.

A separately excited DC motor is shown as in Figure 2.5. If we neglect the effect of armature reaction and field saturation then, developed electromagnetic torque is given by

$$T_e = K_t \psi_f \psi_a = K'_t I_f I_a \tag{2.13}$$

Where,

I_f = Field current

I_a= Armature current

T_e = Electromagnetic torque

ψ_f= Field flux

ψ_a= Armature flux

K_t= Constant

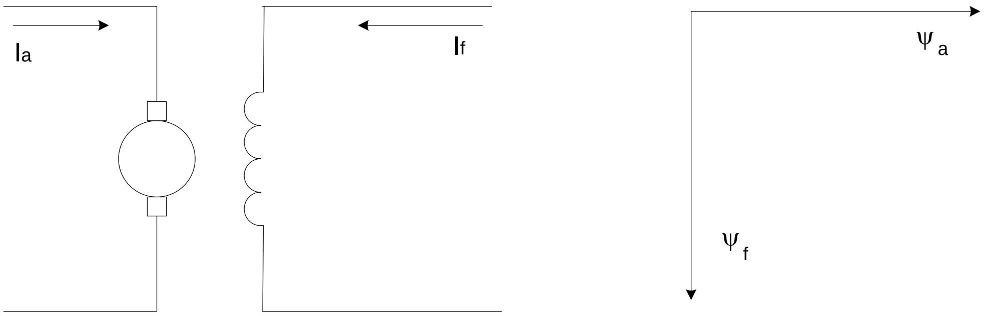


Figure 2.5 Separately Excited DC motor

In a DC machine, the field flux is produced by field current which is denoted by I_f, and armature flux is produced by armature current I_a. The physical structure of machine is such that these two flux vectors are orthogonal to each other. Due to this perpendicular nature of two currents, these two fluxes are independent of each other and variation in one does not affects the other one. This allows the control of torque by controlling the armature current and the flux by controlling the field current without affecting each other.

Theoretically, a field oriented control or Vector Controlled drive can be controlled in the same manner as a separately excited DC motor. This is done by transforming the three phase stator current into two equivalent orthogonal DC quantities.

Applying Park's transformation to three phase stator current provides two currents (i_{ds} and i_{qs}) which are equivalent to field current and armature current (I_f and I_q) respectively. Therefore, the developed electromagnetic torque is given by

$$T_e = K_t \psi_r \psi_a = K'_t i_{ds} i_{qs} \tag{2.14}$$

The prerequisite of this type of control is that i_d must be oriented in the direction of ψ_r and i_q must be in space quadrature with it. This means when one of these are controlled, variation in it does not affect the other one.

In 'dq' reference frame, the electromagnetic torque is given by

$$T_e = \frac{3\ P\ L_m}{4\ L_r}\left(\psi_{dr}\, i_{qs} - \psi_{qr}\, i_{ds}\right) \tag{2.15}$$

Where P=Number of poles of machine

2.5.2 Synchronously Rotating Reference Frame

In field oriented control, or more precisely Vector control scheme, the d-q frame rotates along with the rotor flux (which is maintained at its rated value). The direct axis or d axis is aligned in the direction of rotor flux. Therefore, the direct axes or d-axes component of rotor flux is none as it is in quadrature direction to it. The expression of electromagnetic torque is

$$T_e = \frac{3\ P\ L_m}{4\ L_r}\left(\psi_{dr}\, i_{qs}\right) \tag{2.16}$$

In this way, the developed electromagnetic torque is controlled by quadrature axis current only.

The conversion of a stationary frame into synchronously rotating frame is shown in figure 2.6.

Thus the *d*-axis stator current (i_{ds}) is controlled to maintain the flux at its rated value where as the *q*-axis stator current (i_{qs}) is varied to achieve the desired electromagnetic torque. Therefore, the IM can be controlled just like a separately excited dc motor drive because the *d*- and *q*-axes are orthogonal

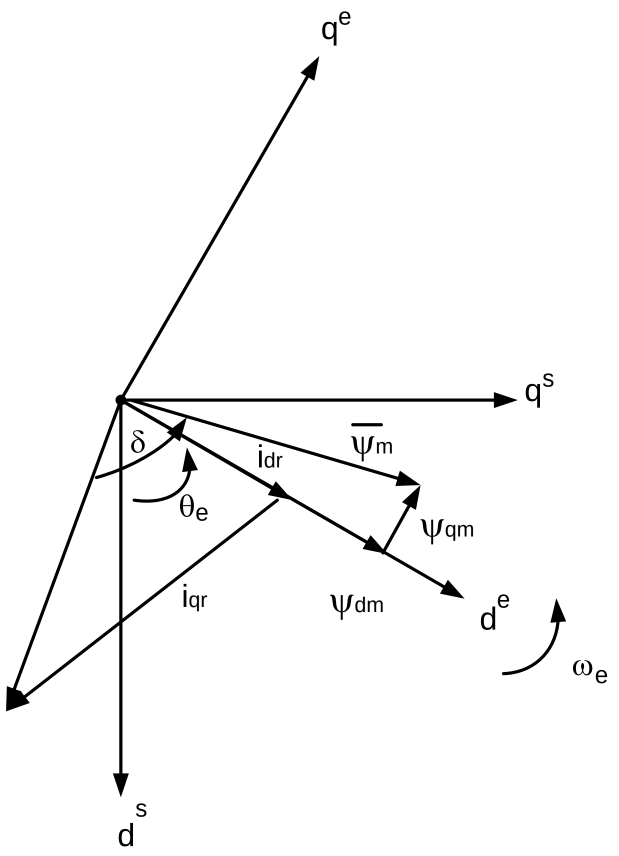


Figure 2.6 Stationary frame to synchronously rotating frame transformation

2.6 TYPES OF VECTOR CONTROL

There are various methods of vector control of induction motor. Two methods are relatively more popular and widely used namely Direct Vector Control and Indirect Vector Control. The two methods are differentiated on the basis of method of calculation of rotor angular position "theta (ϴ)". It should be mentioned here that the orientation of 'i_{ds}' with rotor flux, air gap flux, or stator flux is possible in vector control. However, rotor flux orientation gives natural decoupling control, whereas air gap or stator flux orientation gives a coupling effect which has to be compensated by a decoupling compensation current [67].

2.6.1 Direct Vector Control

In direct vector control, first flux vector is calculated, or measured or estimated with the help of available variables, and angle obtained is used for the coordinate transformation of three phase to two phase conversion of stator quantities and with this flux vector, electromagnetic torque can be calculated. The current and voltage of stator side is measured using various methods/algorithms, and with the help of this current/voltage, control vector is estimated or measured directly. Rotor flux phasor position θ_e is to be calculated as per the equation given

$\theta_e = \int \omega_s \, dt$ (2.17)

The direct vector control scheme is depicted with the help of the block diagram as shown in figure 2.7.

The direct vector control scheme is much complex and accuracy and reliability depends considerably on the motor parameters. In direct vector control method, as the name suggest, air gap flux is directly measured with the help of sensors such as hall probes, search coils or tapped stator windings or estimated/observed from machine terminal variables such as

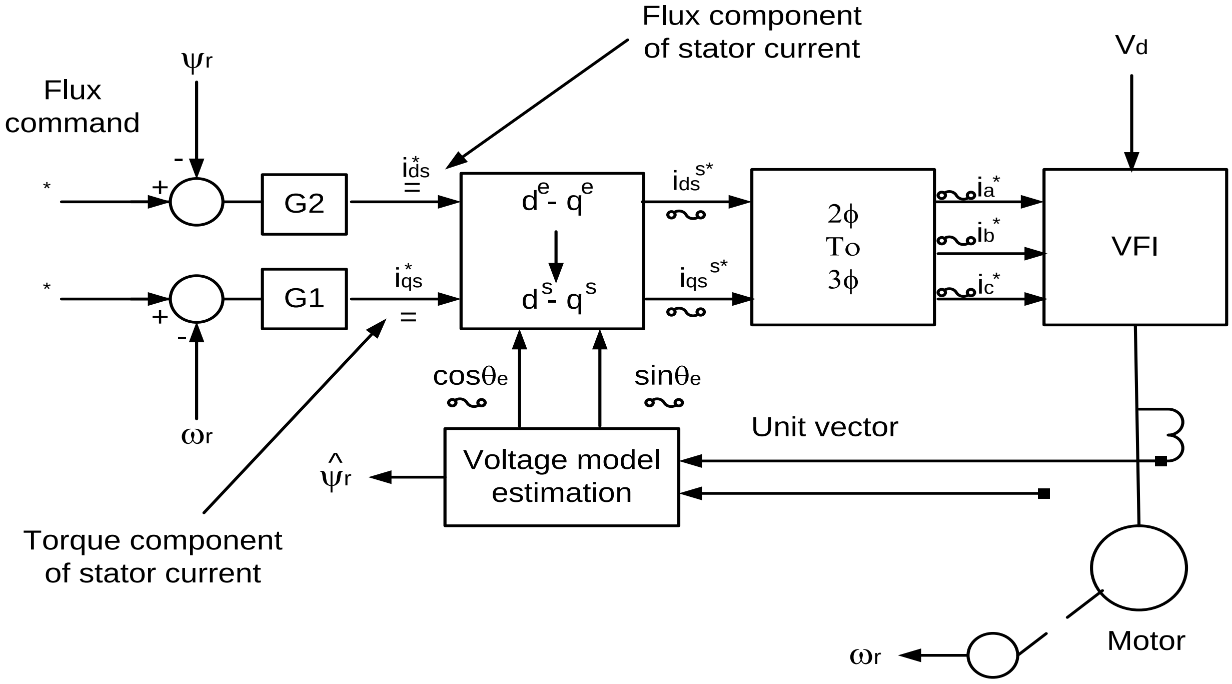


Figure 2.7 Block diagram representing direct vector control scheme

stator voltage, stator current and speed.

This method suffers from the drawback that at low speeds, the voltage drop in the resistance of the motor circuit is more and it dominates which requires integration of the signal to measure the air gap flux is difficult.

There are various authors who have proposed different ways of estimation of flux vector for induction motor, but there are essentially two main methods of flux estimation [67].

A. **Voltage Model**: In voltage model of flux vector estimation, machine terminal voltage and current are estimated and flux is computed using these values and stationary equivalent frame circuit. This model is generally more suitable for high speed region only as accuracy degrades considerably in low speed region.

B. **Current Model**: This method is more suitable for low speed region, the rotor flux components can be computed more easily with the help of speed and current signals.

2.6.2 Indirect Vector Control

In this control scheme, slip speed and actual speed is measured and with the help of these two speed signals, rotor angle θ_e is calculated using the expression shown below:

$$\theta_e = \int \omega_e \, dt = \int (\omega_r + \omega_{sl})dt = \theta_e + \theta_{sl} \qquad (2.18)$$

The torque controlling current component i_{qs}^{*} of stator current is calculated by comparing the reference speed and actual speed and giving the error signal to PI controller or any other intelligent control scheme which depends on the requirement. This component of current is basically used to control or regulate the torque with the slip speed, i.e. it helps to keep torque to the rated values at various speeds up to rated speed.

With consideration of the $d^e - q^e$ equivalent circuits, we can make the following derivation of equations to carry out the indirect Vector Control

$$\frac{d\psi_{dr}}{dt} + R_r i_{dr} - (\omega_e - \omega_r)\psi_{qr} = 0 \qquad (2.19)$$

$$\frac{d\psi_{qr}}{dt} + R_r i_{qr} - (\omega_e - \omega_r)\psi_{dr} = 0 \qquad (2.20)$$

The rotor flux linkage expressions can be given as

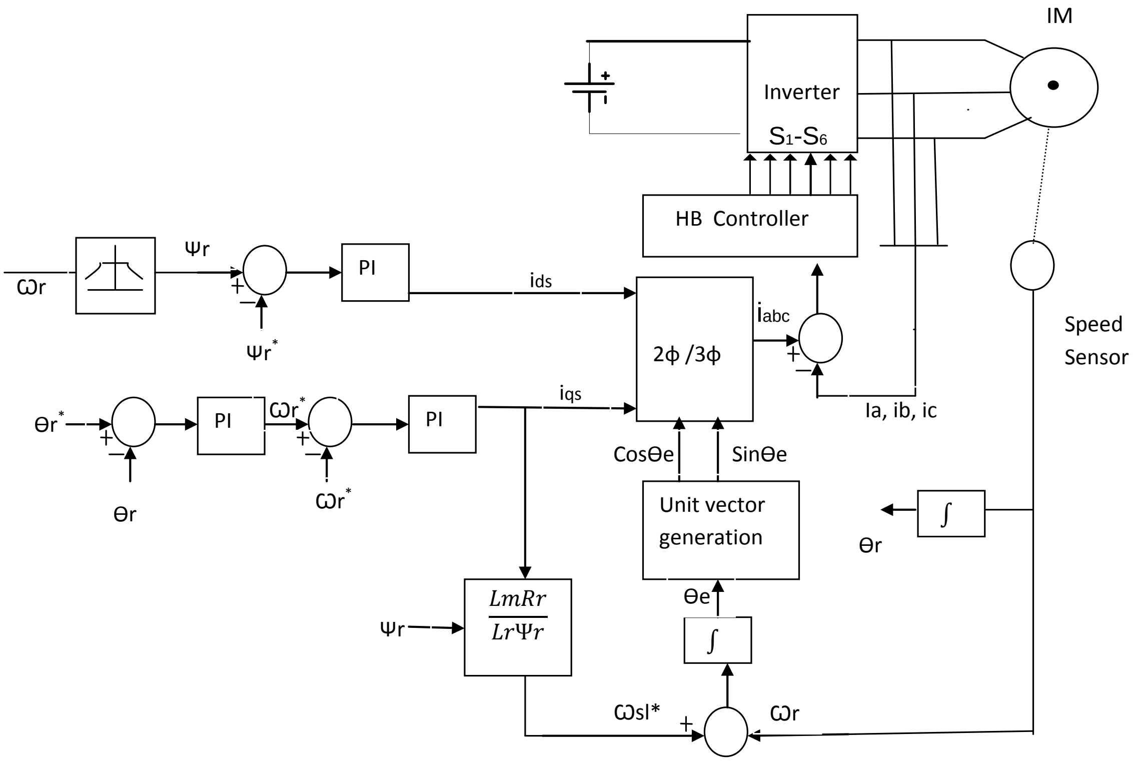


Figure 2.8 Block Diagram showing PWM generation in indirect vector control scheme

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{2.21}$$

$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{2.22}$$

From the above equations, we can derive

$$i_{dr} = \frac{1}{L_r}\psi_{dr} - \frac{L_m}{L_r} i_{ds} \tag{2.23}$$

$$i_{qr} = \frac{1}{L_r}\psi_{qr} - \frac{L_m}{L_r} i_{qs} \tag{2.24}$$

The rotor current equations (2.12) and (2.20) are observed inaccessible, can be eliminated using the equation (2.23) and (2.24) as considered

$$\frac{d\psi_{dr}}{dt} + \frac{R_r}{L_r}\psi_{dr} - \frac{L_m}{L_r} R_r i_{ds} - \omega_{sl}\psi_{qr} = 0 \tag{2.25}$$

$$\frac{d\psi_{qr}}{dt} + \frac{R_r}{L_r}\psi_{qr} - \frac{L_m}{L_r}R_r i_{qs} - \omega_{sl}\psi_{dr} = 0 \tag{2.26}$$

Where $\omega_{sl} = \omega_e - \omega_r$ has been substituted.

To observe the decoupling control, it is obvious that

$$\psi_{qr} = 0 \tag{2.27}$$

$$\frac{d\psi_{qr}}{dt} = 0 \tag{2.28}$$

So that the total rotor flux $\hat{\psi}_r$ is directed on the d^e axis. Substituting the above conditions in equations (2.25) and (2.26), we obtain

$$\frac{L_r}{R_r}\frac{d\hat{\psi}_r}{dt} + \hat{\psi}_r = L_m i_{ds} \tag{2.29}$$

$$\omega_{sl} = \frac{L_m R_r}{\hat{\psi}_r L_r}\, i_{qs} \tag{2.30}$$

$$\cos\theta_e = \frac{\psi_{ds}^s}{\sqrt{\psi_{ds} + \psi_{qs}}} = \frac{\psi_{ds}^s}{\psi_s} \tag{2.31}$$

A general block diagram representing the IVCIM motor is shown in Figure 2.8. Speed sensed using techogenerator is integrated to get the θ_r. Difference between slip speed and actual speed is used to generate the unit vector which is utilized to perform two phase to three phase conversion of stator current. Difference between actual stator current and current obtained using park's transformation is processed by hysteresis controller to produce the triggering pulses for VSI.

2.7 CONCLUSION

In this chapter, a brief description of the dynamics of d-q model of three phase induction motor in synchronously rotating reference frame and stationary frame have been presented. The various state space equations in terms of flux linkage were derived. The performance of vector controlled drive is different from scalar controlled drive in terms of the variable frequency operation of drive also. In vector control, the frequency of the drive is not controlled as in Scalar control. The machine is essentially "self-controlled", where phase as well as frequency is controlled indirectly with the help of unit vector. The mechanism of production of unit vector is different in direct and indirect control. The main advantage of vector control of induction motor drive is that its transient state performance is enhanced and torque and speed can be controlled independently as in case of separately excited DC motor. In addition to this, four quadrant operations is also possible same as that of separately excited DC motor. In the forward motoring condition, if the torque becomes negative, the drive initially goes into regenerative braking mode, which causes speed to slow down. In both direct and indirect vector control schemes, inverter is controlled using instantaneous current control scheme.

CHAPTER 3

CONTROL SCHEMES FOR INDIRECT VECTOR CONTROL OF INDUCTION MOTOR

3.1 GENERAL

This chapter presents a brief theoretical overview of various control schemes used in the present work. The conventional PI controller is among the most common control schemes used in the industrial electrical drive control because of its simplicity and the relationship that exists between error and controller output. The tuning parameters of PI controllers are fixed to a value but this may not perform well when system uncertainties and non linearities are taken into the consideration. In order to eliminate such problems associated with the conventional PI controller, intelligent control schemes are used. The performance of IVCIM is analysed with Fuzzy Logic controller and Adaptive neuro fuzzy inference system control schemes which are discussed in detail in the chapter.

3.2 PROPORTIONAL PLUS INTEGRAL CONTROLLR (PI)

PI controller is the most widely used controller structure used in the control applications and various industrial controls. The hardware prototype of vector control of Induction motor is implemented with PI controller. The input to PI controller is the difference between reference speed ω^* and actual measured speed ω_r. The output of PI controller has following relationship with its input signal,

If e(t)=ω^*-ω_r, then output of controller would be

$$e_o = K_p\, e(t) + K_i \int e(t)dt \tag{3.1}$$

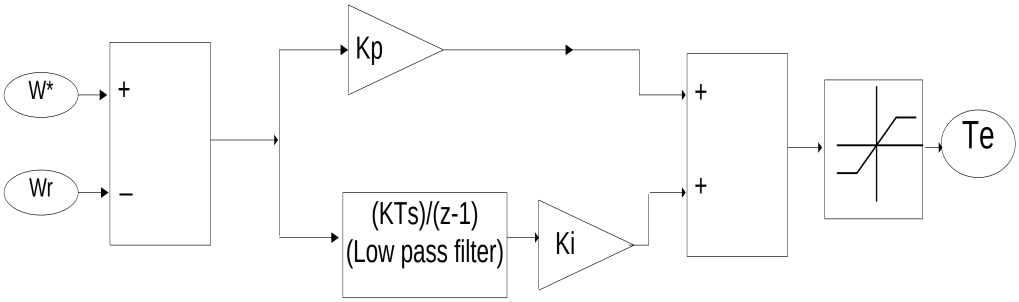


Figure 3.1 Proportional plus Integral Controller block diagram

The PI controller which is used is shown in Figure 3.1

Where K_p = 1.8 and K_i= 0.8. Discrete low pass filter has $T_s = 3\ ms$ and filter gain K=1.

There are various methods of tuning PI controller. Tuning means finding out values of the K_p and K_i for the optimum performance of the drive. There are tuning methods like Ziegler-Nichols method, Cohen-Coon method etc. used for tuning of PI controller. The Optimum values of the parameters K_p and K_i decides the performance of the PI speed controller. **Hit and trial method** is used to tune the PI controller.

3.3 FUZZY LOGIC CONTROLLER

Fuzzy logic is a branch of artificial intelligence that deals with reasoning algorithms used to emulate human thinking and decision making process in machines. The fuzzy logic algorithms are used at the places where process data cannot be represented in binary form. Fuzzy logic requires prior knowledge in order to reason. This knowledge is provided by a person who knows the process or machine (the expert). This knowledge is stored in the fuzzy system. The FLC general scheme is shown in Figure 3.2 in which the error and rate of change of error is fed to FLC to control the speed of induction motor. The error is the difference of actual speed from the reference speed. The control of torque is done by controlling the I_q component of stator current. From the FLC we get a controlled output of currentI_q, which is then fed to the Hysteresis current controller to generate gating pulses for the voltage source inverter.

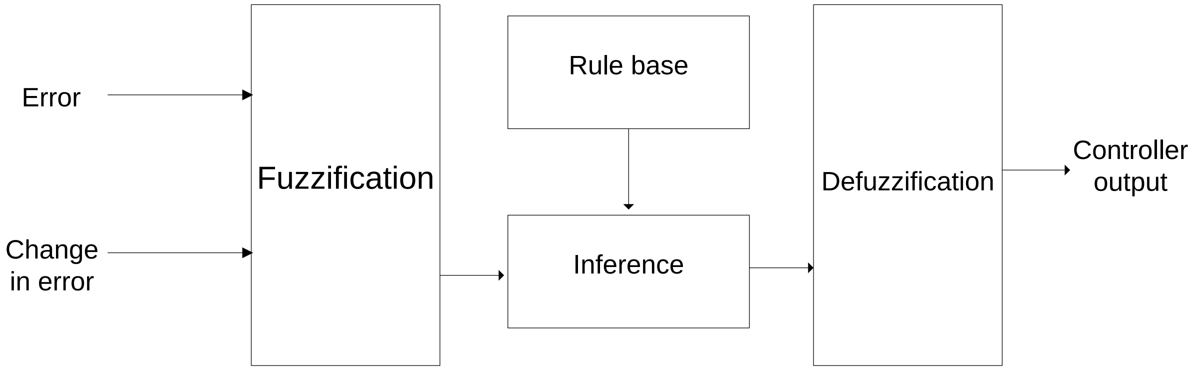


Figure 3.2 Block diagram of fuzzy logic controller

Here the first input is the speed error 'e' and second is the change in speed error '*ce'* at sampling time 't_s'. The two input variables $e(t_s)$ and $ce\ (t_s)$ are calculated at every sampling time as

$$e(t_s)=\omega_r^*(t_s)-\omega_r(t_s) \quad (3.2)$$

$$ce(t_s)=e(t_s)-e(t_s-1) \quad (3.3)$$

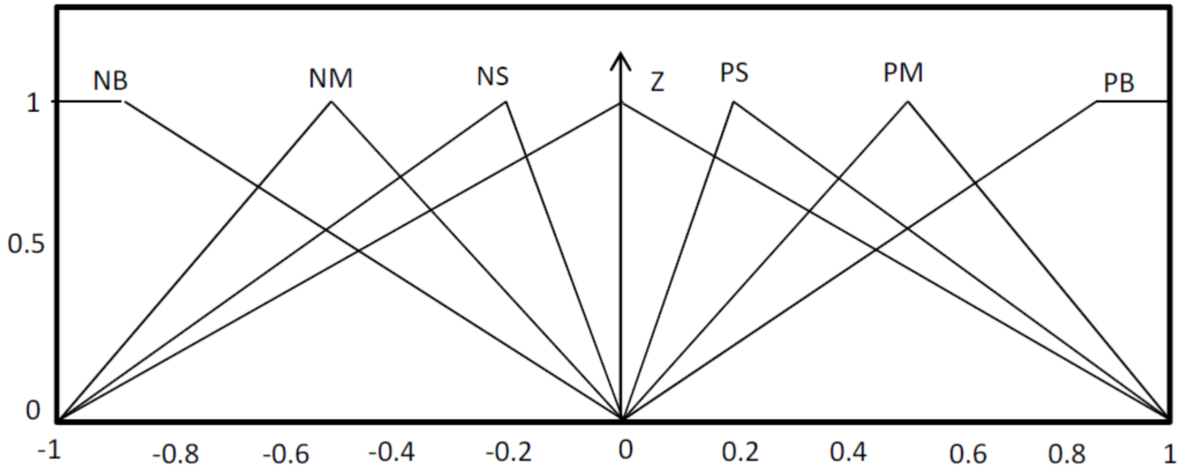
Where,

"e" denotes error, "ce" denotes change in error.

3.3.1 Fuzzification

In this stage the crisp variables of input $e(t_s)$ and ce(t_s) are converted into fuzzy variables. The fuzzification maps the error and change in error to linguistic labels of fuzzy sets. Membership function is associated to each label with triangular shape which consists of two inputs and one output. The proposed controller uses following linguistic labels *NB, NM, NS, Z, PS, PM, PB*. Each of the inputs and output contain membership function with all these seven linguistics. The proposed membership function has been tested through simulation in MATLAB.

A Sugeno type Fuzzy Logic Controller has been designed for the control system. The inputs i.e. the error, *e* and change in error, *ce* follow the membership function plot as shown in Figure 3.3.



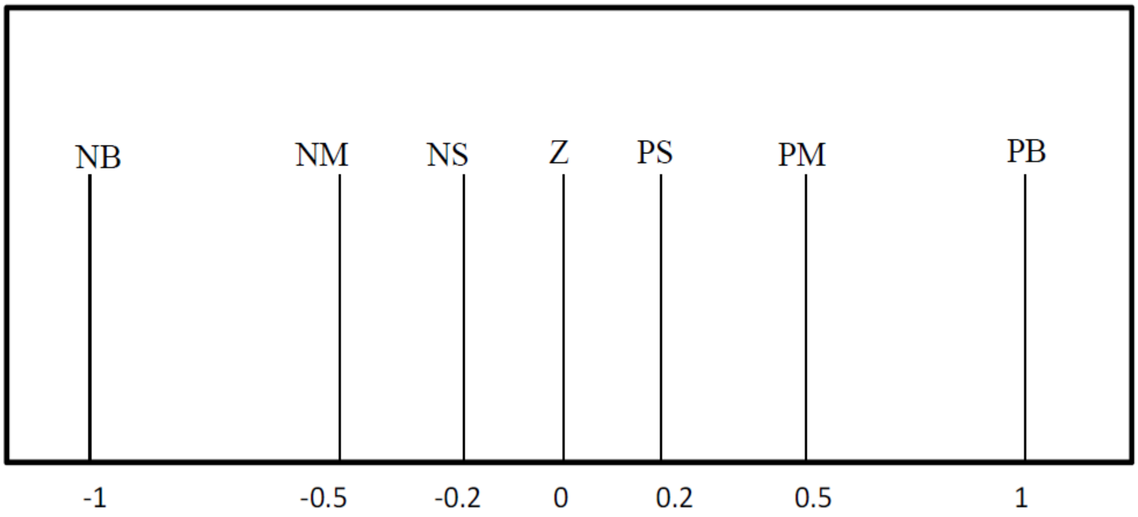


Figure 3.3 Input and Output membership function representation

3.3.2 Rule base and Inference

Knowledge base involves defining the rules represented as *IF-THEN* rules statements governing the relationship between input and output variables in terms of membership function. In this stage the input variables e(t_s) and ce(t_s) are processed by the inference mechanism that executes *7*7* rules represented in rule base shown as follows

E **CE**	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Table 1 : Fuzzy Rule Base

Where various linguistic variables are:

NB	Negative Big
NM	Negative Medium
NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big

"IF 'e' is NB, AND 'ce' is NB, THEN controller output is NB", i.e. once the error between the reference speed and measured speed is large, and change in error is also large, then the controller also has to act accordingly, i.e. the control output should also be large enough to quickly reduce the error and change in error. This control action will take place initially when the motor has just started. It can also be observed from the rule base table, that ***"IF 'e' is Z, AND 'ce' is Z, THEN output is Z"***, i.e. since error is zero and is not changing, the controller need not to act and hence the controller output is also zero. This control action can be seen once steady state has been achieved and the speed has set to reference speed.

3.3.3 Defuzzification

This stage introduces different methods that can be used to produce fuzzy set value for the output fuzzy variable. Here the centre of gravity or centroids method is used to calculate the final fuzzy value.

3.3.4 Tuning Fuzzy Logic Controller

Tuning FLC is most important part of the process. Proper values of gains need to be chosen so that the FLC membership values are properly selected so as to ensure proper functioning of the controller. The FLC shown in Figure 3.4 can be tuned in a similar way of PI controller where we can find K_p and K_i as follows.

$$\text{GCE} * \text{GCU} = K_p \tag{3.4}$$

$$\frac{\text{GE}}{\text{GCE}} = \frac{1}{\tau_i} \tag{3.5}$$

So the Fuzzy logic controller can be tuned in the same way as that of PI controller.

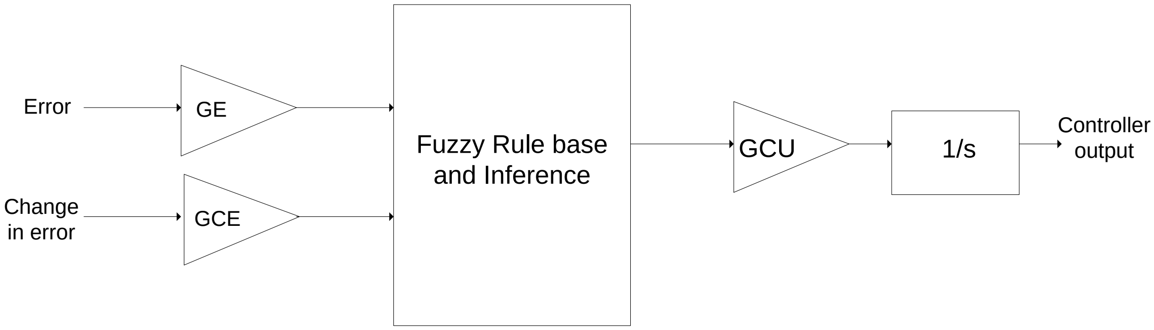


Figure 3.4 Block diagram of Fuzzy logic controller

Where GE, GCE and GCU are constants which are given as:

GE = 0.05

GCE = 0.0007

GCU = 3300.

3.4 ADAPTIVE NEURO FUZZY INFERENCE SYSTEM (ANFIS)

The concept of intelligent controllers has become very popular these days because of their performance. Fuzzy logic controller and Artificial Neural network are popular because of their better response when used to control the non linear system. The conventional PID controller, which is used in many configurations depending on the system and performance requirements, have a limitation due to difficulty that arise in tuning the controllers when they are subjected to transfer function variations and non linearities of the actual systems. Making the rule base for Fuzzy logic controller is a difficult task and it needs in depth knowledge of the system parameters and other attributes. ANFIS controller provides an easier way to overcome the above stated difficulties. The fuzzy logic controllers and the neural networks (both static and dynamic) are two modern system analyses which had been applied successfully in many practical applications. These two techniques are very useful when the system under study is partially unknown and previously assumed to be nonlinear. The combination between the two methods (Neuro-fuzzy control systems) is a powerful identification and control technique. In recent years, Fuzzy Inference Systems (FISs) and Artificial Neural Networks (ANNs) have attracted considerable attention as candidates for novel computational systems because of the variety of the advantages that they offer over conventional computational systems. In ANFIS controller, we don’t need to design the rule base and it is automatically generated based on the test data provided to the ANFIS controller toolbox.

3.4.1 Structure of Adaptive Neuro-Fuzzy controller

An ANFIS controller use both fuzzy and neural network, which leads to neuro-fuzzy controller. The basic concept of neuro-fuzzy control models is first to use structure-learning algorithms to find the appropriate fuzzy rules and then use parameters learning algorithms to fine the membership functions and other parameters.

In the hybrid structure ,the input and output nodes represents the input states and output control or decision signal respectively and in hidden layer there are nodes functioning as membership functions and fuzzy logic rules. The basic structure of the utilized neuro-fuzzy controller takes the form of fuzzy controller, and separate elements are composed of a neural network. The structure of this controller contains the parts of fuzzification, inference engine and the part of defuzzification.

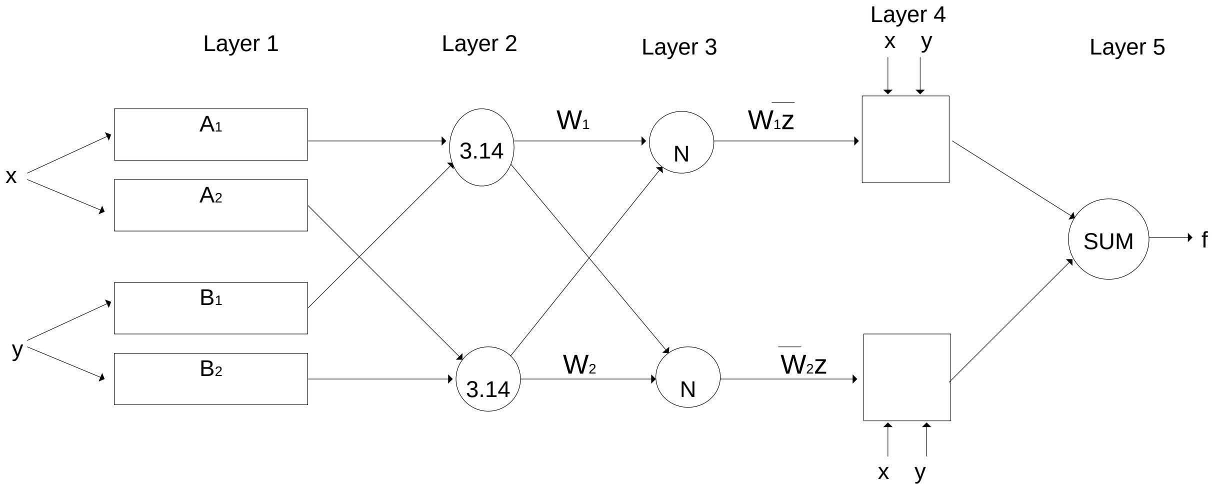


Figure 3.5 Basic structure of ANFIS controller

Figure 3.5 shows five layer architecture of ANFIS controller in which weights are adjusted the same way as in neural network. Where x and y are the input variables, f denotes the output of controller, W_1, W_2, $\overline{W_1 z}$ and $\overline{W_2 z}$ are initial weights of layer 2 and layer 3 respectively.

ANFIS is equipped with the advantages of both neural network as well as FLC. The weights are updated according to following equations:

$$\overline{W_1} = A_1P_1 + B_1Q_1 \tag{3.6}$$

$$\overline{W_2} = A_2P_2 + B_2Q_2 \tag{3.7}$$

$$f = \frac{\overline{W_1}\ Z_1 + \overline{W_2}\, Z_2}{W_1 + W_2} \tag{3.8}$$

Where$\mathbf{P_1}$, $\mathbf{P_2}$, $\mathbf{Q_1}$ and $\mathbf{Q_2}$ are constants which depends on the weight updation algorithm.

3.4.2 Training Adaptive Neuro Fuzzy Inference Systems

Sugeno-type fuzzy systems can be generated using the ANFIS GUI Editor. To start the GUI, type the following command the MATLAB prompt:

“anfisedit”

The ANFIS Editor GUI window includes four distinct areas to support a typical workflow. The GUI performs the following tasks:

A. Loading, Plotting, and Clearing the Data
B. Generating or Loading the Initial FIS Structure
C. Training the FIS

3.4.3 Loading, Plotting and Clearing the Data

To train a FIS, we begin by loading a Training data set that contains the desired input/output data of the system to be modeled. Any data set we load must be an array with the data arranged as column vectors, and the output data in the last column. To load a data set using the Load data portion of the GUI:

A. Specify the data Type.
B. Select the data from a file or the MATLAB workspace.
C. Click Load Data.

3.4.4 Generating or Loading the Initial FIS Structure

Before start the FIS training, initial FIS model structure must be specified. To specify the model structure, perform one of the following tasks:

I. Load a previously saved Sugeno-type FIS structure from a file or the MATLAB workspace.
II. Generate the initial FIS model by choosing one of the following partitioning techniques:

A. Grid partition Generates a single-output Sugeno-type FIS by using grid partitioning on the data.
B. Sub. Clustering Generates an initial model for ANFIS training by first applying subtractive clustering on the data.

3.4.5 Training the FIS

After loading the training data and generating the initial FIS structure, we start training the FIS.

The following steps show how to train the FIS:

A. In Optimum Method, choose hybrid or back propagation as the optimization method.
B. Enter the number of training Epochs and the training Error Tolerance to set the stopping criteria for training. The training process stops whenever the maximum epoch number is reached or the training error goal is achieved.
C. Click Train Now to train the FIS.

3.5 CONCLUSION

In this chapter, basic structure of all three controllers which are being used in the present work is discussed with a brief information that how to use these controllers in the Matlab /SIMULINK. The intelligent controllers like Fuzzy logic controller and ANFIS controller have gained lot of popularity because of their better response to the non linear and time variant systems.

CHAPTER 4

PERFORMANCE OF IVCIM USING PI, FUZZY AND ANFIS CONTROLLERS

4.1 GENERAL

This chapter presents a detailed simulation study of an Indirect Vector Control of Induction Motor Drive in MATLAB/Simulation. Simulations are generally performed to understand the dynamics of the actual system under worst working conditions and based on the results, enhancement of performance is done. The simulation was done with PI, Fuzzy Logic Controller and (Adaptive Neuro Fuzzy Inference system) ANFIS control schemes. The performance of indirect Vector Control under different working conditions such as forward motoring, forward braking, reverse braking conditions were observed and analysed through simulation and variation of various associated parameters was observed.

4.2 MATLAB MODEL

The MATLAB/Simulation model which is developed for the performance analysis of three phase Induction Motor drive is shown in figure 4.1. It is based on the current control model of vector control. It consists of following main parts:

A. Three phase VSI inverter
B. Three phase 3HP, 1440 rpm Induction motor
C. Hysteresis current controller
D. abc-dq transformation block
E. Flux estimator block
F. Torque control element

In the simulation, current sensed from stator terminals measured and is decoupled into two independent components i_d and i_q using Park’s transformation method. The torque is controlled by controlling i_q component which is in space quadrature to i_d. The hysteresis controller is used to generate PWM pulses for the three phase VSI. The hysteresis band determines the switching frequency of the PWM pulses.

The parameters of the actual machines were determined by performing block rotor and no load test on the machine several times and average values of all the tests were used in the control scheme. Skin effect is also taken into account for determining stator and rotor resistance by multiplying the values calculated by a factor 1.2 (numerical value).

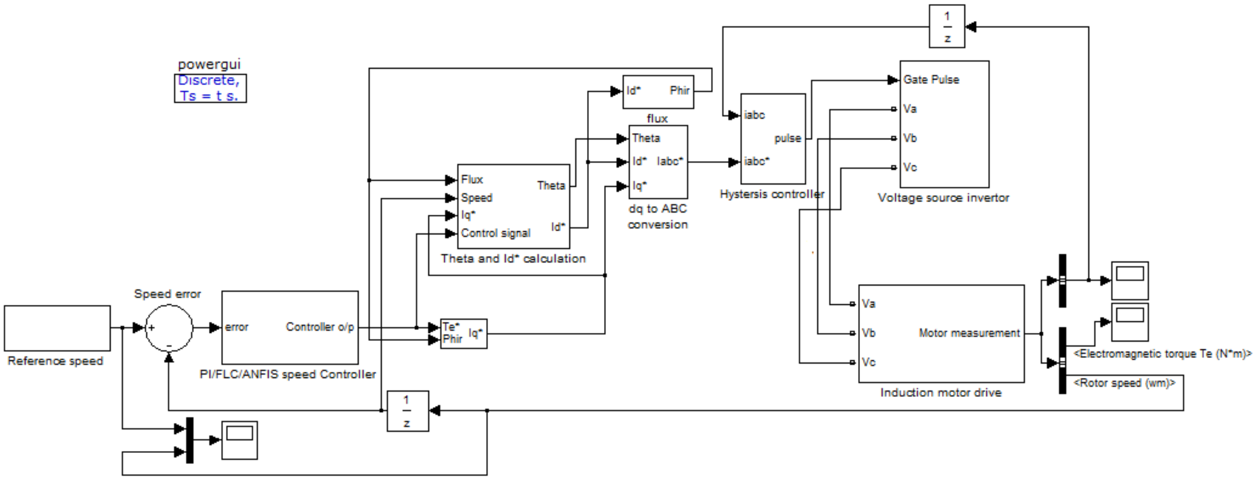


Figure 4.1 Simulink model of indirect vector control of induction motor

Figure 4.1 shows a MATLAB model of indirect vector controlled induction motor in Simulink. It comprises of a three-phase Voltage Source Inverter (VSI), a three-phase 3HP, 415V, 1440 rpm Induction Motor, Hysteresis Current Controller, *abc* – *dq* conversion block, *dq* – *abc* conversion block, flux control element and a torque control element which in turn results in the control of current and speed respectively. The speed controller used in the simulation as shown in Figure 4.1 (a) is a conventional PI controller. Another control scheme like Fuzzy Logic Controller and ANFIS controller are also used to analyze the performance of IVCIM. The FLC is based on the rules described in the previous chapter. The results obtained through simulation are presented in the upcoming chapter for PI, FLC and ANFIS control schemes.

The hysteresis controller is used to generate the pulses for triggering the three phase voltage source inverter. The block diagram of hysteresis controller is shown in figure 4.2. Hysteresis controller compares the actual three phase (i_{abc}) current with the reference current (i^*_{abc}) and on the basis of value of actual current, it provides the gating pulse to the inverter.

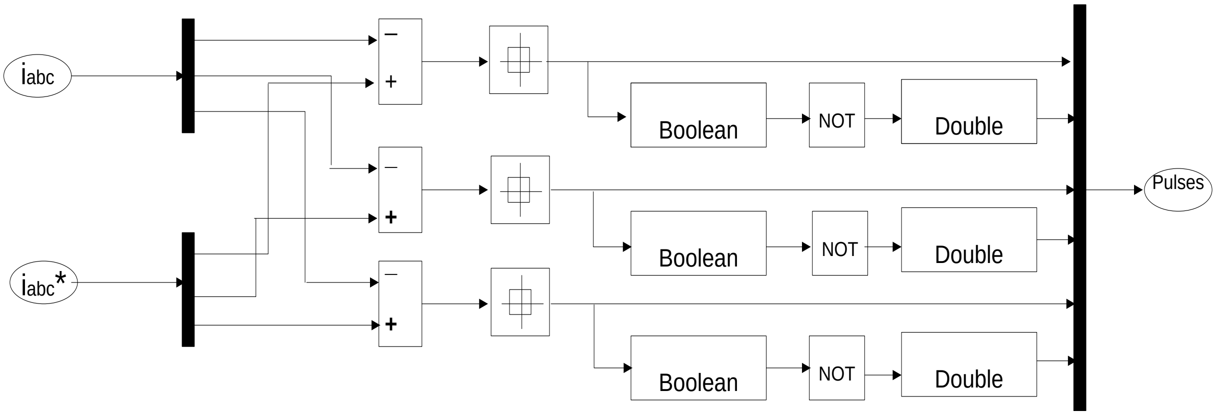


Figure 4.2 Block diagram of hysteresis PWM controller

4.3 HARDWARE DESCRIPTION OF IVCIM

As shown in Figure 4.3, the main components used in the hardware schemes are:

A. Three phase IGBT inverter (VSI)
B. Hall effect Current sensors
C. Hall effect voltage sensors
D. Optical Isolator and gain circuit
E. DS-1104 R and D controller board

4.3.1 Three Phase IGBT inverter (VSI)

Three phase IGBT based convertor, which basically have a three phase diode bridge which converts applied three phase AC voltage into equivalent DC voltage, and a 3 phase IGBT base VSI which convert this into controlled PWM, and this PWM is used to supply the stator of three phase motor. The first stage in convertor is a rectifier bridge which converts AC into DC while second stage converts this DC into controlled AC.

A three phase voltage source inverter (VSI) is used in the development of the hardware prototype of indirect vector control of induction motor, manufactured by *Semikron* industries. This voltage source inverter has a three phase diode bridge in its first stage which converts AC into DC voltage which is maintained as DC link voltage. Capacitors are used to filter this DC link voltage. Second stage of convertor is a three phase IGBT bridge which convert DC link voltage into regulated (controlled by Gating pulse logic) AC voltage which is used to feed the three phase induction motor.

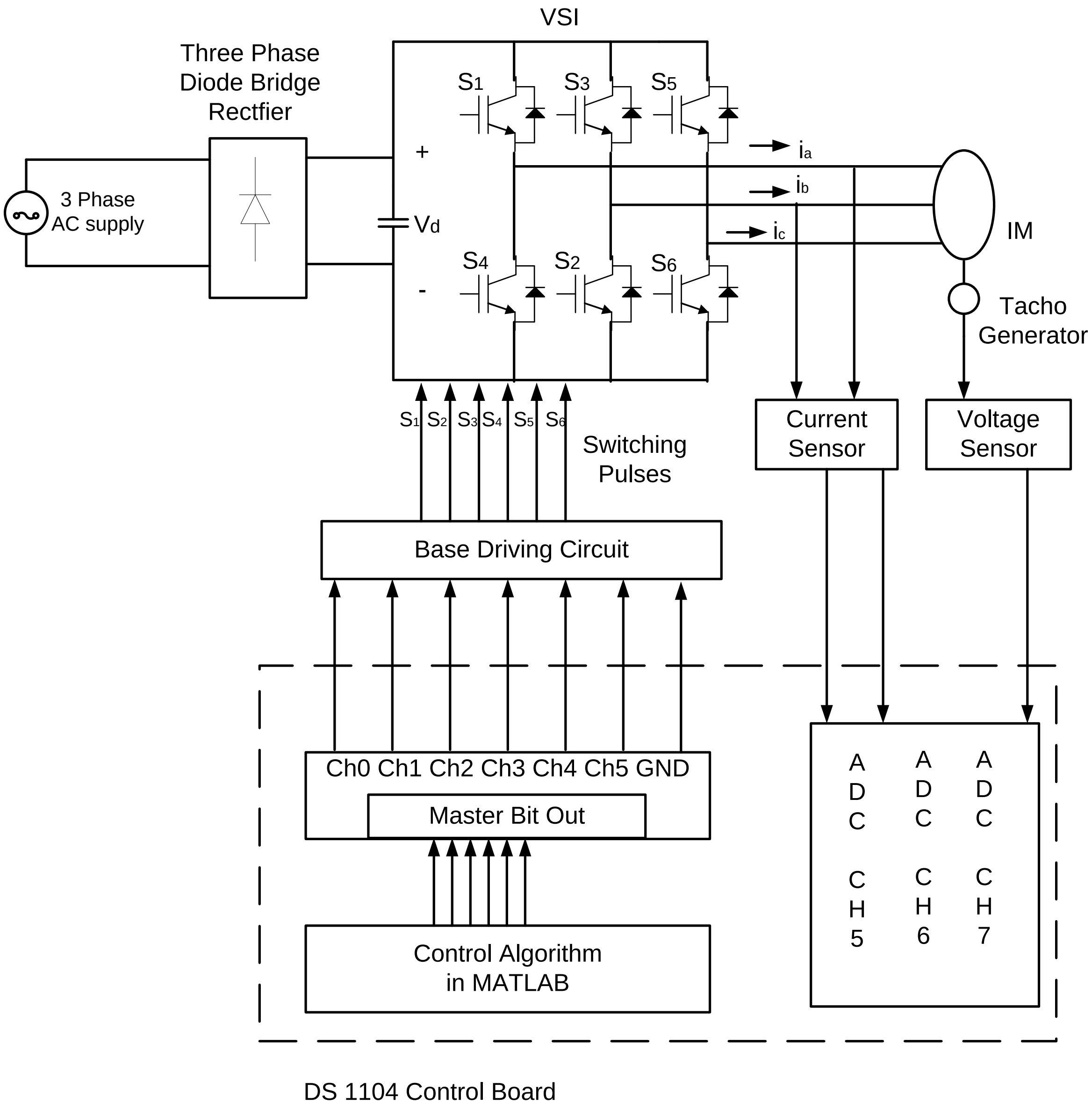


Figure 4.3 Block diagram representing the Implementation of Indirect vector control scheme

In the VSI, IGBT semiconductor switches are used because of various advantages associated with the IGBT switches. The IGBT has a upper hand in the power electronic applications where PWM (Pulse width modulation), servo and other applications where high performance is required with less noisy operation of the drive. IBGT also accounts for less audio noise production in drive and also improves the dynamic performance. IGBT's are available in the market for low switching as well as low conduction losses. It has very low on stage voltage drop which enhances the efficiency of overall drive. It can be easily controlled by using low voltage GATE pulse for high power application.

The rectified circuit has a voltage gain of 1.35. For example, for a input AC voltage of 100 volt (Line to Line voltage V_L) , the DC link voltage would be 135 volts. The PWM output which it produces is controlled via six gating Pulses which are generated from the MATLAB using hysteresis current controller are fed to the inverter through DS-1104 Controller board using an optical isolator circuit.

4.3.2 Hall Effect Current Sensor

A sensor is a convertor that measures a physical quantity and converts it into an equivalent signal which can be measured/ observed by an observed or electronic circuit.

Hall Effect Current sensors manufactured by ABB Electricals are being used in the project. ABB current sensors are based on Hall Effect technology. They allow measurement of direct, alternating and impulse currents, with galvanic insulation between primary and secondary circuits. A Hall Effect current sensor is a device that detects current flowing in its primary, and a signal proportional to it is produced in the secondary circuit of the sensor. The generated signal is current which is made to flow into a resistance and voltage developed across the sensor is used as an equivalent quantity of current input to the MATLAB model using DS-1104. The output signal of the sensor can also be used to display the measured current in the ammeter or even the output can be stored in a data acquisition system or can be utilised for various control applications.

4.3.3 Voltage Sensors

The voltage sensor is used in the hardware implementation to sense the voltage from the techogenerator (speed sensor) which produces equivalent DC voltage of speed of the motor. The voltage generated by the speed sensor is used for the calibration and hence actual speed is estimated.

4.3.4 Optical Isolator and Gain circuit

Optical isolator is an element which isolates two electrical circuits. It contains a photodiode, one LED and two transistors. The convertor circuit is high power circuit and interfacing board (DS-1104) operates at 5 Volt, so it is needed to isolate both the circuits.

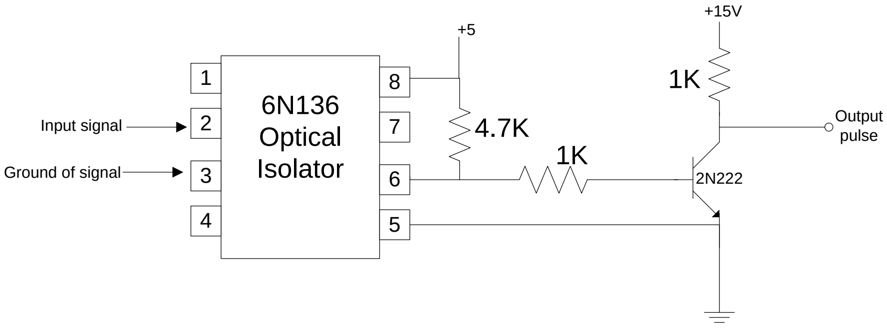


Figure 4.4 Optical isolator and gain circuit

Optical isolator circuit is used to complete the above said requirement. The gating pulse which are generated using Hysteresis controller in MATLAB are feed from DS-1104 board which gives pulses of 5 volt magnitude through DS-1104. To trigger the IGBT Bridge, pulses of magnitude 15Volts are needed.

4.3.5 DS1104 Controller Board

The DS1104 R and D Controller Board upgrade the PC to a development system for rapid control prototyping (RCP) [69]. The real-time hardware, based on a PowerPC microprocessor and its I/O interfaces make the board ideally suited for developing controllers in various fields, in both industry and academics. The DS1104 is specifically designed for the Development of high-speed multivariable digital controllers and real-time simulations in various fields. It is a complete real-time control system based on a 603 PowerPC floating point processor running at 250 MHz for advanced I/O purposes, the board includes a slave-DSP subsystem based on the TMS320F240 DSP microcontroller [70, 71]

Interfacing of DS1104 and PC- MATLAB is done in order to ease the operation of control. The three-phase current and speed once sensed are fed to the ADC port of DS1104 by means of BNC cable. DS1104 interfaces with the MATLAB, where the control circuit is designed. The gate pulses are determined through the control circuitry. These gate pulses are then fed to the inverter through the Digital I/O connector port of DS1104 separated by the isolating circuit in order to prevent the gate from being shorted. The pulses determine the speed of the induction motor.

The DS1104 contains two different types of analog/digital converters (ADCs) for the analog input channels:

A. One 16-bit ADC with four multiplexed input signals: the channels, ADCH1 ... ADCH4

B. Four 12-bit parallel ADCs with one input signal each: the channels, ADCH5 ...ADCH8

The digital I/O connector (CP17) is a 37-pin; male Sub-D connector located on the front of the connector panel [70]. The important thing to note is that the ADC input to the DS-1104 should be between ±10V. In order to make this possible, the gain of current sensor and voltage sensor are accordingly set in the circuit.

The technical details of DS-1104 are given in Appendix C.

4.4 EXPERIMENTAL SETUP

The hardware prototype developed is shown in Figure 4.5. The feedback signals from the actual machine are stator side current, voltage and output of the techo generator. The stator current of two phases is sensed using current sensors (i_a and i_b) and voltage generated by techogenerator is sensed using a voltage sensor. The current of third phase is calculated using the condition of three phase balanced load, i.e.

$$i_a + i_b + i_c = 0 \tag{4.1}$$

The current equivalent of i_a and i_b, so

$$i_c = -(i_a + i_b) \tag{4.2}$$

The voltage sensed by voltage sensor is electrical signal which represents the actual speed of the motor. These sensed current and voltage signals are fed to the ADC terminals of the D-Space controller board, from where it goes to MATLAB/Control desk. The DS-1104 board, by default multiplies every incoming signal by a factor of 0.1. To get the actual signal, we need to multiply the signal by 10 in the MATLAB model. The interfacing of the MATLAB model with the hardware using DS-1104 controller is done by using RTI library of the DS-1104 Board (Control desk). It is important to note that proper gain values and gain adjustment need to be done for each sensor to avoid malfunctioning of the control scheme. On the basis of the current and speed signal, Pulses are generated in the MATLAB/Simulink model, which are fed to the three phase IGBT inverter through digital I/O connector ports of DS-1104 controller board. The software

Platform of DS-1104, i.e. Control desk, is used to tune the PI controller for the actual plant (Motor) and to provide the reference speed during running conditions.

The actual controller station of the hardware prototype is MATLAB/Simulation model interfaced using RTI blocks. The principle of operation is indirect vector control scheme. The Proportional plus Integral controller (PI) is used to implement the scheme on Hardware. The experimental results obtained are compared with the simulation results to analyse the performance of the drive.

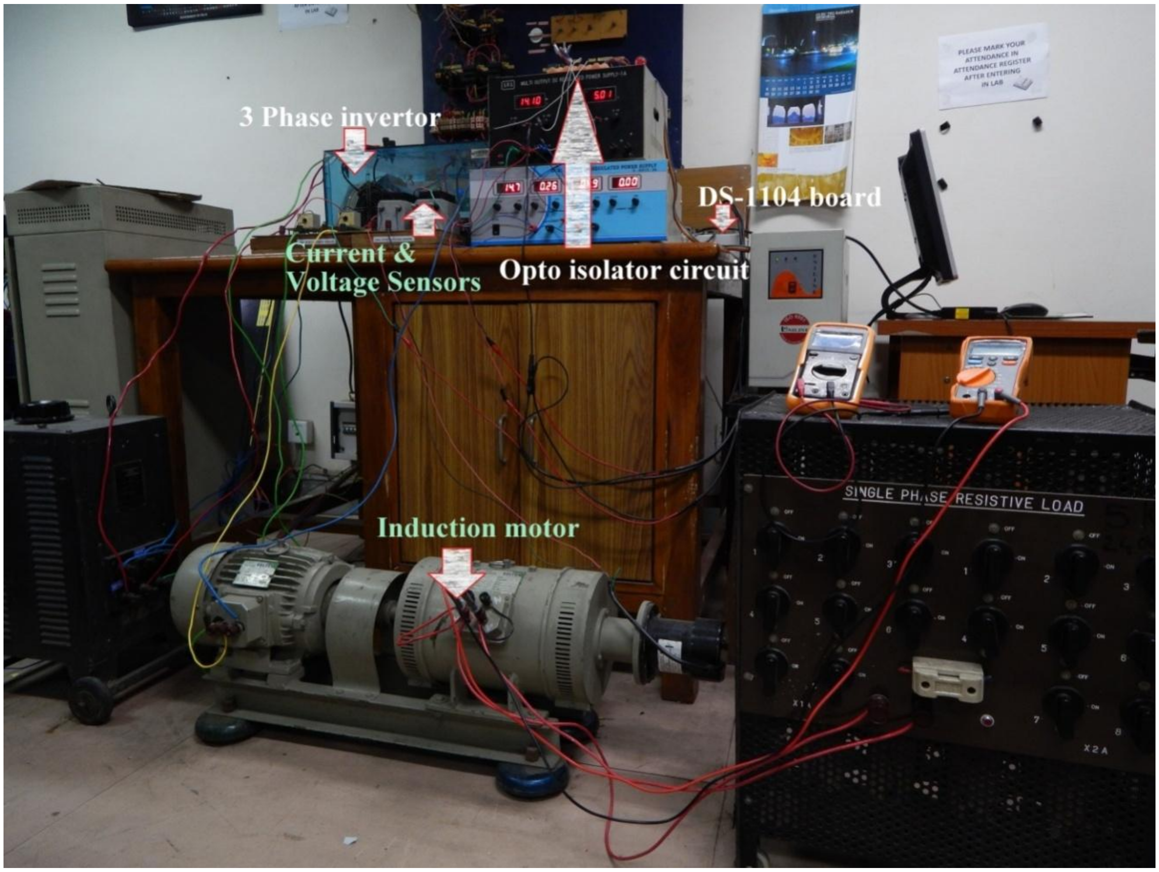


Figure 4.5 Picture of original hardware setup

4.4.1 Operation with PI (Proportional plus Integral) controller

PI controller is most widely used controller structure used in the control applications and various industrial controls. The hardware prototype of Vector control of Induction motor is implemented with PI controller. The input to PI controller is the difference between reference speed ω^* and actual measured speed ω_r. The output of PI controller has following relationship with its input signal,

If e(t)=ω^*-ω_r, then output of controller would be

$$e_o = K_p\, e(t) + K_i \int e(t)dt \tag{4.3}$$

The PI controller which is used is shown in figure 4.6

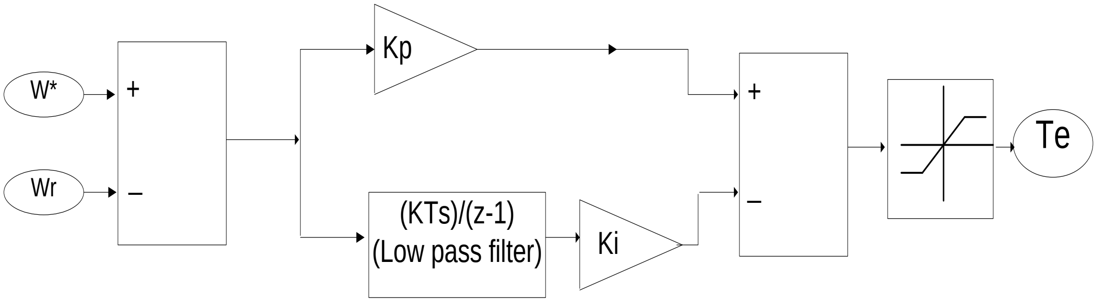


Figure 4.6 Proportional Integral Controller block diagram

Where K_p = 1.8 and K_i= 0.8. Discreet low pass filter has $T_s = 3\ ms$ and filter gain K=1.

There are various methods of tuning PI controller. Tuning means finding out values of the K_p and K_i for the optimum performance of the drive. There are tuning methods like Ziegler-Nichols method, Cohen-Coon method etc. used for tuning of PI controller. In the present work, Hit and trial method is used to tune the PI controller as transfer function of the hardware setup was unknown. The Optimum values of the parameters K_p and K_i decides the performance of the PI speed controller.

4.5 CONCLUSION

In this chapter, the simulation along with hardware scheme of indirect vector control of induction motor with PI, Fuzzy and ANFIS Controller has been discussed. In IVCIM, hysteresis PWM controller have been used which compares i_{abc} and i_{abc}^* and on the basis of the comparison, triggering pulse for IGBT inverter are generated. Intelligent control schemes are implemented because of their popularity to handle non linear systems.