CHAPTER TWO
BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

In this chapter available types of electrical motors suitable for high performance control are introduced and compared to the induction motor. Then the construction and principle operation of induction motors are briefly presented. Furthermore, modelling techniques for induction motor simulation and analysis are presented along with an analysis of the dynamic behaviour. Finally, the various induction motor control methods are briefly reviewed with particular focus given to vector control techniques.

2.2 Available Electrical Machine Types

Electrical machines have been playing an important role in industry progress during the last few decades. All kinds of electrical machine drives have been developed and applied, which serve to drive manufacturing facilities such as conveyor belts, robot arms, cranes, steel process lines, paper mills and so on. There are three main types of electric machines, the DC machines, the induction machines, and the synchronous machines. Any machine can work either as a motor or generator. If a generator, mechanical power is used to rotate the rotor and electrical energy can be extracted through the stator terminals. If a motor, electrical power is supplied through the stator terminal and mechanical power is performed by the rotor's shaft. Both DC and synchronous machines are called double fed, but the induction machines are called single fed [1, 2]. In this section each of these machine types are discussed and their relative advantages and disadvantages examined.

The DC machines have been used widely during the last century in applications where variable speed operation was needed. The reason is that its construction allows simple methods for the control of generated torque. The

DC machine consists of a field winding or permanent magnet on the stator which provide a magnetic field and armature winding on the rotor. In the DC machines the fields are stationary and rotor winding is connected with a commutator and brushes which ensures correct displacement between the stator and rotor fields. The control of the DC machine is therefore straightforward, because its flux and torque can be controlled easily by means of changing the field and the armature currents respectively. However, in comparison with their counterparts, the induction machine drives, DC drives result more expensive and less robust devices, not to mention the periodic maintenance they require due to the commutator [1, 2].

The induction motor has historically been utilised for undemanding fixed speed applications and is often referred to as the work horse of industry, undertaking an estimated 70-80% of electro-mechanical conversion. For reasons of simplicity, cost, efficiency, and ease of manufacture, the induction machine is the most widely used machine in fixed speed applications [3]. Although it is possible to use induction machine as either a motor or generator, it has many disadvantages as generator and so is rarely used in that manner. For this reason, induction machines are usually referred to as induction motors. An induction motor has the same physical stator as a synchronous machine, with different rotor construction.

There are two types of induction motor rotors, which can be placed inside the stator. One is called a squirrel-cage rotor (or cage rotor), and the other is called a wound rotor. Wound rotor induction motors are more expensive than squirrel cage, and they require much more maintenance because of the wear associated with their brushes and slip rings. As result, wound rotor induction machines are rarely used [1, 2]. The operation of the induction motor is such that the rotating field of the stator induces a current to flow in the rotor, this in turn generates the rotor field and the interaction of the stator and rotor fields produces torque. Thus there must be a difference in speed, known as slip speed, between the stator field and the rotor in order to induce a current to flow in the rotor. The induction motor exhibits highly non-linear behaviour and as such requires complex control technique to achieve high performance torque regulation. Recently as a consequence of the important progress achieved in power electronics and with advance of microelectronics and computer technologies made induction machine displacing the DC machine in many high performance torque and speed controlled applications.

Synchronous machines have the same stator construction as the induction machine; however the rotor is constructed with either permanent magnets or as a wound rotor with and external DC supply to provide the rotor field. As induction is no longer required to produce the rotor field there is no slip between the stator field and the rotor, and the rotor will run at synchronous frequency, effectively locked into the rotating field of the stator. A sub-class of the synchronous machine are the so called brushless DC and brushless AC machines which are typically used for servo applications. The brushless AC machine is effectively a synchronous machine as it has a sinusoidal back emf and utilises a sinusoidal supply [1, 2].

The brushless DC machine however has a trapezoidal back emf, which uses a square wave supply i.e. each of the phases is fed with a DC current to produce torque. The brushless machines are popular for servo applications due to their relative ease of control with torque proportional to current, high efficiency and high dynamic response. One further sub-class which has recently gained popularity is the synchronous reluctance machine. This also has a similar stator construction to the induction machine but utilises a salient pole rotor to produce reluctance torque. The reluctance machine has advantages of low cost, simplicity of control, absence of rotor losses, and field weakening capability. This has led to an increase in research activity in this area with commercial applications of synchronous reluctance drives now appearing [1, 2].

2.3 Comparison of DC and AC Machine Types

The induction machine, especially a squirrel-cage rotor, is the most commonly used electrical machine in industry. Its advantages and disadvantages, compared to other types of electrical machines, are given below [1, 2].

(1) The DC machine is not suitable for use in environments containing explosive gasses, because the arcing produced by the mechanical commutator and brushes arrangement used in the DC machine. But the other two types of machines can be used in this environment.

(2) The main advantage of any AC machine is the simplicity of controlling its output. The DC machine is the simplest machine to control, but the two other types are more difficultly control specially induction machine.

(3) The induction machine is lower in cost than other electrical machines, because the induction machine offers the simplest mechanical construction.

(4) The synchronous machine has the highest power to volume ratio of the three types of machines, because the other two types require current in the rotor circuit to produce torque, these current produces rotor losses, this usually means a cooling fan has to be fitted.

(5) An essential part of any economic comparison is the cost of keeping spares as well as the frequency of maintenance. A supply of brushes and brush holders are necessary stock items for DC machines. A DC machine must be regularly taken out of service to check or replace brushes and at less frequent intervals to resurface the commutator. Maintenance of these brushes is particularly burdensome in harsh environmental conditions. Expect for the bearings, an induction machine is essentially maintenance free.

(6) All three-machine types can offer high dynamic performance with suitable control techniques. Its commutator and brushes limit the DC machine speed range and peak torque. The speed range of the synchronous machine is limited to base speed and is generally unsuitable for field weakening operation. The induction machine is capable of a fast torque response, peak

torque of several times the rated torque, and operating in the field-weakening region.

2.4 Construction of the Induction Motor

The stator of a three phase induction motor is the stationary part corresponding to the yoke of a DC machine. It's wound to give a 2-pole, 4-pole, 6-pole, rating magnetic field , depending on the rotor speed required the rotor, corresponding to armature of a DC machine is built up of laminated iron, to reduce eddy currents. In the type most widely used, known as squirrel cage rotor, copper or aluminium bars are placed in slots cut in the laminated ring. A cross-sectional view of three- phase induction motor. The conductors are placed in slots is the laminated iron rotor core. If the slots are skewed, better starting and quieter running is achieved. This type of rotor has no external connections which mean that slip ring and brushes are not needed. The squirrel-cage motor is cheap, reliable and efficient [1, 2].

2.5 Principle Operation of Induction Motor

When a three-phase supply is connected to the stator windings, a rotating field magnetic field is produced as the magnetic flux cuts a bar on the rotor, an e.m.f is induced in it and since it is joined, via the end conducting rings, to another bar on pole pitch away a current flow in the bars. The magnetic field associated with current in the bars interacts with rotating magnetic field and a force is produced tending to turn the rotor in the same direction as the rotating magnetic field. Similar forces are applied to all conductors on the rotor, so that a torque is produced causing the rotor to rotate [1, 2].

2.6 Induction Motor Modelling

In this section, various induction machine models are introduced. First, the concepts of coordinate transformations and inverse transformations are introduced. A state-space model which is required by the rotor flux based model reference adaptive system.

2.6.1 Three and two phase transformations

A dynamic model for the three-phase induction machine can be derived from the two-phase machine if the equivalence between three and two phases is established. The equivalence is based on the equality of the mmf produced in the two-phase and three-phase windings and equal current magnitudes. Assuming that each of the three-phase windings has *N* turns per phase and equal current magnitudes, the two-phase winding will have 1.5*N* turns per phase for mmf equality. Let us consider the stator supply voltages only and derive transformation relations between a_s, b_s and c_s stator axes and d_s-q_s axes, where both are in the stationary reference frame shown in Figure 2.1 [3, 4].

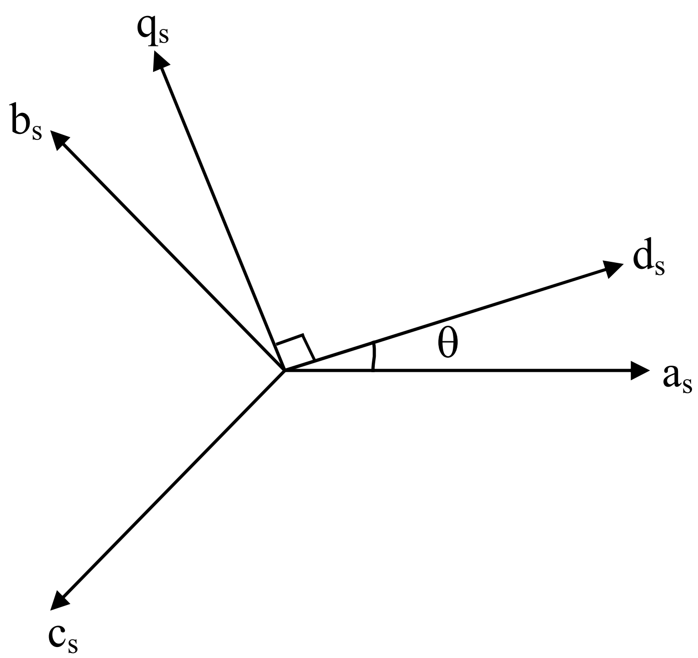

Figure 2.1: Presents the two and three phase stator windings

The other quantities such as current and flux can be transformed in a similar manner. The d_s-axis is assumed to be lagging the a_s-axis by angle θ. The relationship between three-phase and two-phase can be written in matrix form as [3, 4]:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{0s} \end{bmatrix} = K \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{2.1}$$

Where the coefficient K depends on the convention used. For the power invariant form K=$\sqrt{\frac{2}{3}}$, and for the non-power invariant form K=$\frac{2}{3}$.The inverse transformation for above transformation is given as:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{0s} \end{bmatrix} \tag{2.2}$$

The v_{os} represents the imbalances in the three-phase voltages and can be recognised as the zero-sequence component of the voltage. In practical applications, the machine is connected either in Delta or in Wye without a neutral return path. Thus, the three-stator voltages sum to zero. As a result, the other significant three phase variables such as stator currents, the stator flux linkages and rotor currents also sum to zero. It is usual to align the d_s-axis with the phase a_s-axis; this implies that the d_s-q_s frames are fixed to the stator. The model is known as Stanley's model or the stator reference frames model. In that case $\theta = 0$, the transformation relations can be simplified as [3]:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{0s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{2.3}$$

And the inverse transformation for above transformation is given as:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -0.5 & \frac{-\sqrt{3}}{2} & 1 \\ -0.5 & \frac{\sqrt{3}}{2} & 1 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{0s} \end{bmatrix} \tag{2.4}$$

2.6.2 Transformations between different reference frames

The conversion from the (*a, b, c*) frame to the (*d, q*) frame gives values in a stationary reference frame fixed to the stator. Another useful coordinate transformation is between the two-phase stationary plane and two-phase rotating plane. In practice, the rotating d_e-q_e plane is always chosen to rotate at synchronous speed (ω_e). Referring to Figure 2.2 the transform from the stationary frame to any arbitrary rotating reference frame is given as [3, 4]:

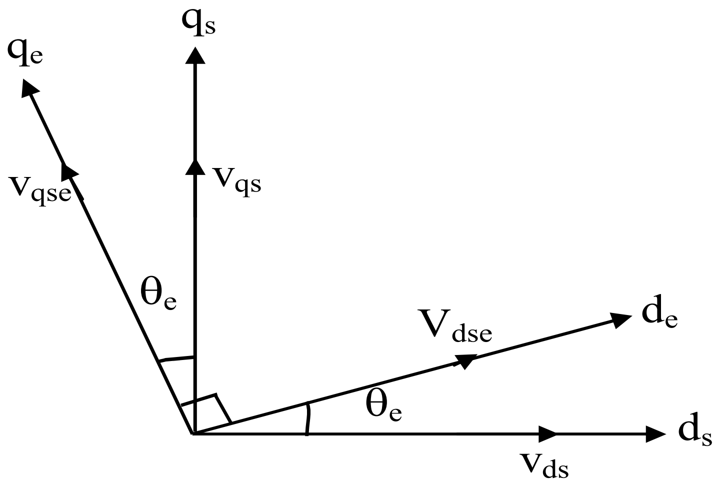

Figure 2.2: The d_s-q_s axes to d_e-q_e axes transformation

$$\begin{bmatrix} v_{dse} \\ v_{qse} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \tag{2.5}$$

Where, θ_e is the angle between the arbitrary synchronously rotating reference frame *d*-axis and the stationary frame *d*-axis. The reverse transformation from the synchronous frame to the stationary frame is given by:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v_{dse} \\ v_{qse} \end{bmatrix} \tag{2.6}$$

2.6.3 State space model of induction motor

Under the assumptions of linearity of the magnetic circuit, equal mutual inductances, and neglecting iron losses, a three-phase IM model in the fixed stator d-q reference frame can be described as a fifth order nonlinear differential equations with four electrical variables (stator currents (i_{ds}, i_{qs}) and rotor fluxes (ψ_{dr}, ψ_{qr})), and one mechanical variable (rotor speed ω_r) [7].

$$\begin{bmatrix} \frac{di_{ds}}{dt} \\ \frac{di_{qs}}{dt} \\ \frac{d\psi_{dr}}{dt} \\ \frac{d\psi_{qr}}{dt} \\ \frac{d\omega_r}{dt} \end{bmatrix} = \begin{bmatrix} -\alpha\ \mathrm{i}_{ds} + \beta\ \psi_{dr} + \omega_r\ \gamma\ \psi_{qr} \\ -\alpha\ \mathrm{i}_{qs} + \beta\ \psi_{qr} - \omega_r\ \gamma\ \psi_{dr} \\ \frac{\mathrm{L}_m}{\mathrm{T}_r}\ \mathrm{i}_{ds} - \frac{1}{T_r}\ \psi_{dr} - \omega_r\ \psi_{qr} \\ \frac{\mathrm{L}_m}{\mathrm{T}_r}\ \mathrm{i}_{qs} - \frac{1}{T_r}\ \psi_{qr} + \omega_r\ \psi_{dr} \\ \frac{\mathrm{P}}{2}\left(\frac{3PL_m\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right)}{4L_r J} - \frac{T_L}{J} \right) \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & \frac{1}{L_a} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \tag{2.7}$$

Where:

$$\begin{aligned} \alpha &= \frac{R_s}{L_a} + \frac{R_r L_m^2}{L_r^2 L_a} \\ \beta &= \frac{\mathrm{R}_r L_m}{L_r^2 L_a} \\ \gamma &= \frac{\mathrm{L}_m}{\mathrm{L}_r L_a} \\ \mathrm{L}_a &= L_s - \frac{L_m^2}{L_r} \\ \mathrm{T}_r &= \frac{L_r}{R_r} \end{aligned} \tag{2.8}$$

Where L_s is the stator inductance, L_r is the rotor inductance, L_m is the mutual inductance, L_a is the redefined leakage inductance. R_s and R_r are stator and rotor inductance resistances, respectively. J is the moment of inertia of the motor, T_L is the torque of external load disturbance, P is the number of pole, and T_r is the time constant of the rotor dynamics.

2.7 Induction Motor Control Techniques

There are many different ways to drive an induction motor. The main differences between them are the motor's performance and the viability and cost in its real implementation. In the past, simple control techniques had been applied, including the star-delta starter to limit starting current for fixed speed drives and pole changers and stator-tap changers for multi-speed drives. The introduction of static power converters has allowed the use of more sophisticated control techniques, which allow the induction machine to operate as wide speed range, four quadrant drives. There are a number of significant control methods available for induction machines, the most popular control methods are presented below [2, 3]:

(1) Voltage control.

(2) Scalar control.

(3) Direct torque control.

(4) Vector control.

(5) Sliding mode control.

Out of various control techniques, vector control the most popular strategies employed.

2.8 Vector Control

Variable speed drive systems are essential in many industrial applications. For over fifty years, DC machines have been used extensively in the field of variable speed applications mainly because of the simple control techniques required to achieve good performance in speed or position control applications. In a separately excited DC machine the axes of the armature current (I_a) and field current (I_f) are orthogonal to one anther. This means that the armature flux (φ_a) produced by the armature current is also orthogonal to the field flux (φ_f) produced by the field current. Therefore there is no magnetic coupling between the field circuit and the armature circuit, which mean that field current and armature current can be adjusted independently without interference. The basic structure is schematically illustrated in Figure 2.3 [3, 4].

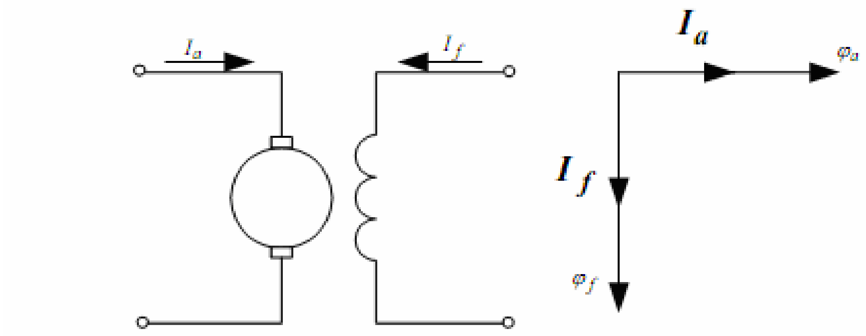

Figure 2.3: Separately excited DC machine & space vector representation

If neglecting the armature reaction effect and field saturation, the developed electromagnetic torque (T_e) is given by:

$$T_e = KI_f\ I_a \tag{2.9}$$

Where: K constant. Obviously, the electromagnetic torque is proportional to the product of the armature current and the as shown in Equation (2.9). If the flux current is fixed then the torque is varied directly by the armature current. It is for this reason that DC machines are said to have decoupled or independent control over torque and flux. DC motors have certain disadvantages, which are due to the existence of the commutator and the brushes. That is, they require periodic maintenance; they cannot be used in explosive or corrosive environments and they have limited commutator capability under high speed, high voltage operational conditions. These problems can be overcome by the application of alternating current motors, which can have simple and rugged structure, high maintainability and economy; they are also robust and immune to heavy overloading. These advantages have recently made induction machines widely used in industrial applications [3, 4].

However, the speed or torque control of induction motors is more difficult than DC motors due to their coupled, nonlinear, multivariable systems whose stator and rotor fields are not held orthogonal to one anther. In order to achieve decoupled control over the torque and flux producing components of the stator currents a technique known as vector control or field oriented control is used. In vector control, decoupled control of flux and torque is achieved by splitting the current into two dc components rotating in synchronous reference frame aligned with the selected flux. The direct axis current acts to control the flux magnitude and the quadrature axis current control the torque magnitude. Thus, the control of flux and torque is similar to that of a separately excited DC machine. The synchronously rotating reference frame can be aligned with the stator flux, the air-gap flux or the rotor flux. The rotor flux oriented scheme has become the most commonly implemented scheme because of simpler control dynamics including less complex coupling between flux and torque producing currents and the possibility of instability in the stator flux orientation scheme [3, 4].

2.8.1 Types of vector control

There are essentially two varieties of vector control. The first variety proposed by Blaschke is the direct vector control or feedback method. In the second variety, developed by Hasse and called indirect vector control or feed forward method. The two methods are different essentially by how the unit vector ($\cos\theta_{e,}$ $\sin\theta_e$) is generated for the control. Because of its simplicity and more practical to fit speed/position sensor than flux sensor, the indirect vector control is more popular than the direct vector control technique [3-9].

(1) Direct vector control

In the direct vector control usually indicates that the rotor flux position is directly evaluated, either by using direct flux measurement with Hall Effect sensors or search coils installed in the machine, calculated using a flux model of the machine, or estimated using a flux observer. Direct vector control method, in which direct measurement of flux is performed using flux sensing coils or Hall Effect devices installed in the machine, proved to be impractical for general use. Also it is costly and reduces reliability. There is also a problem of signal distortion at lower speeds. However, direct measurement of flux is robust to parameter variations. Calculation of the flux vector using a flux model requires the measurement of the stator currents and rotor speed sensor. The flux vector is then calculated using these measurements with an accurate model of the induction machine. The accuracy of the estimated flux signals is dependent on the machine parameters, and in particular the rotor resistance. The parameter variation effect is most significant at low speeds. Using a state observer such as the Kalman filter or Luenberger observer to estimate the flux requires stator voltage and current measurement, and rotor speed sensor if the speed is not estimated. Parameter variation reduces the accuracy of the estimated flux [3-9].

(2) Indirect vector control

The indirect vector control method is essentially the same as direct vector control, except the flux position θ_e generated in the feed forward manner. Indirect vector control is very popular in industrial applications because of the various advantages such as no required flux sensor and higher reliability. The rotor position θ_r is either measured using a shaft position encoder, or calculated by integrating the measured rotor speed. The rotor angle is added to the slip angle to give the position of the flux relative to the stator [3]. The flux angle is used to perform the transformation and inverse transformation between stationary and synchronous reference frames. The accuracy of the indirect vector control method depends on how accurately the slip speed can be calculated. The slip speed calculation contains the rotor time constant, and it is a well known fact that this parameter is temperature and frequency dependent. To implement the indirect vector control method, sensors are used to measure the stator currents, and rotor speed. A shaft encoder can be used instead of speed sensor. Figure 2.4 shows a block diagram of the complete indirect vector control technique [3-9].

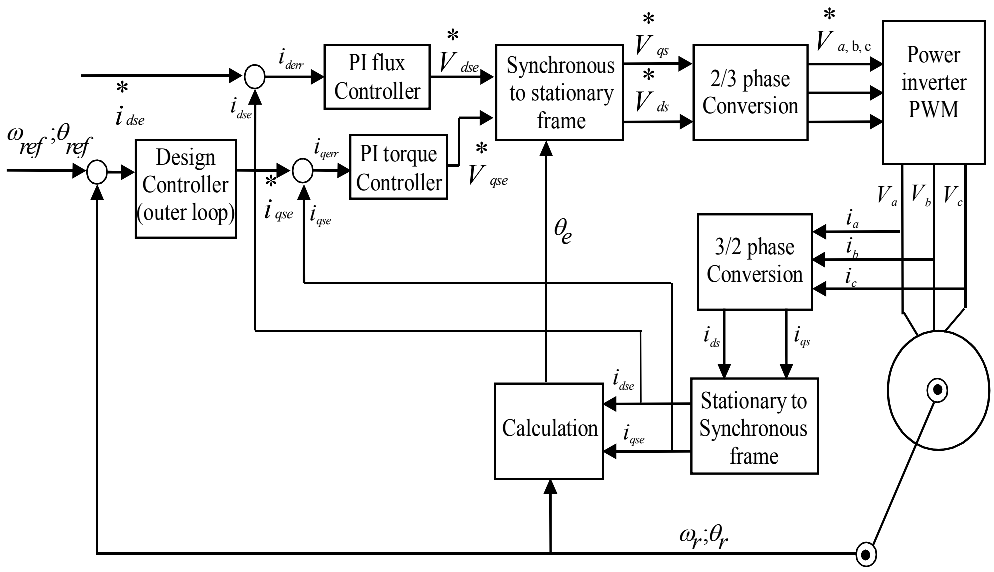

Figure 2.4: Indirect vector control scheme

Two feedback loops are considered in the control scheme. An inner loop having, generally, a Proportional plus Integral (PI) form is used for current regulation and an outer loop where many controllers can be adopted for the speed/position control. Traditionally, because of its simplicity and inexpensive cost, a PI controller is used for outer loop. However, it is well known that the performance obtained by proportional plus integral controller is sensitive to machine parameter variations [3-9].

2.8.2 Advantages of vector control

Vector control has several advantages over other control techniques for induction machine drives. The decoupled torque and flux producing commands allow easy control, similar to that of a separately excited DC machine. The fast torque response allows accurate torque, speed or position control. One further advantage of decoupled flux and torque control is operating the induction machine with a low load torque. By reducing the field command current to an appropriate level, depending on the load torque, and increasing the torque command current to compensate for the reduced flux, more efficient operation of the induction machine is possible. This is only possible where the load torque is small and significant power would otherwise be lost in maintaining the rated flux [3-9].

2.8.3 Limitations of vector control

Vector control in induction motor is sensitive to deviation in estimated motor parameters values used in the control algorithm from their actual values. In addition, the parameters values may need to be updated while the motor is running, if there are large changes in the operating temperature and flux magnitude because resistances values depend on the temperature and inductances values changes due to flux saturation. Direct vector control requires values of the rotor leakage inductance, and the ratio of the rotor inductance to the mutual inductance while the first parameter has a constant value independent of temperature and flux, the second parameter is moderately affected by the saturation of the main flux path in the motor. In addition, there is the need for the special flux sensors, which need frequent maintenance and impose limitation in the motor mounting. If the sensorless form of direct method is implemented, the value of the stator resistance is sensitive to temperature changes. Indirect vector control is more sensitive to parameters values inaccuracy than direct vector control. The value of the rotor time constant (L_r/R_r) is used in the slip speed calculation this parameter is sensitive to temperature, skin effect and flux level. Errors in the slip speed calculation produce coupling between the flux and torque producing currents and result in a torque response with possible overshoot/undershoot and a steady state error. The need of special position incremental encoder is another disadvantage of the method. Beside the above limitations, vector control is complex and need fast speed microcontrollers [3-9].