Nonlinear Control for Induction motor and comparison with vector control techniques

By

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Approval

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Abstract

Induction motor is a complex nonlinear structure where strong coupling exists between rotor flux and produced electromagnetic torque.So, different decoupling techniques are applied to decouple the system which make the control design easy.Moreover, the proposed model of the motor has nonlinearities and parametric uncertainties which make control more difficult.In the thesis Multi-scalar variable model is used to decouple the complex motor structure,which transform the system in two subsystems namely mechanical and electromagnetic.As the presented system is nonlinear so a nonlinear control scheme is better choice to control such system.In this research work Backstepping controller of the system is proposed which gives better performance than conventional techniques. All the simulations are done in the MATLAB/SIMULINK. For mathematical analysis Laypunov theory is used to prove the stability of the proposed control.Comparison of proposed controller and conventional control techniques from literature is also done to show the robustness of controller.

Dedication

I dedicate my work to my family, in-laws, friends and my esteemed teachers.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

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Thesis Acceptance Certificate

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Chapter 1

Introduction

Motor works on the concept of electro-magnetic induction. when we put a electric conductor into a rotating magnetic field electromotive forces are induced across it, this phenomenon is known as electromagnetic induction.

Induction motor (IM), are being used in various industrial application and domestic applications for decades. The reason for its extended use is robustness, low cost and less maintenance. To meet different process needs induction motor are used in many different configurations e.g. fixed speed applications and variable speed applications.

Traditionally, DC motors were used for variable-speed applications as linear relationship exist between current and produced torque. However, DC motor have disadvantages such as they are expensive and require high maintenance because of brushes and commutators moreover they cannot operate in rough, grimy and explosive environment. AC motors don not have these disadvantages. Therefore, in past few decade DC motors are being replaced by AC motor.

Control of speed of induction motor is much more complicated than that of a DC motor, as model dynamics are nonlinear multi-variable and strong coupling exists between rotor flux and produced electromagnetic torque, Moreover the states cannot be measured easily and can get affected by parameter variations and parametric uncertainties.

Most fundamental technique is called Field-oriented control (FOC) which was initially given by F. Blaschke(1971-1973) [1] and K. Hasse(indirect FOC) [2] these methods were appreciated for its simplicity and efficiency. In this method motor coordinated are transformed in ti rotating coordinated which are synchronized with rotor flux which fully decouple the model only for constant flux, motor model is still non linear. FOC use classical PI control scheme to control motor speed.

In the middle of 1980's induction motor torque control strategies were introduced by T. Noguchi and I. Takahashi which are called Direct-Torque Control scheme (DTC) and Direct-self control scheme (DSC) [3], [4], [5], these methods are alternative to classical vector control FOC. Since 1985 these methods are continuously improved and developed . In these method the Linearization and decoupling of motor parameters is replaced by hysteresis controllers, which work by invert er ON-OFF operation. DTC main features are good dynamic behavior and simplicity, but its has disadvantage of variable switching frequency.

As induction motor is a nonlinear system so a nonlinear control must be designed to improve the performance of controller in steady state as well as during transients.In few decades, control innovation are being applied to the system to improve its performance. One of those methods is Feedback-Linearization Control scheme (FLC) which apply a nonlinear transformation on motor state variables, in such a way that speed and produced flux by motor are decoupled by the feedback application. [6] , [7].

Recently, Passivity based control method had been developed which is based on energy shaping and variation theory [8].In the passivity based method the induction motor is expressed in the generalized coordinated in the form of Euler-Lagrange equations.

The Fuzzy control technique can fairly regulate the speed at transients and has advantage over conventional PI controller, but its not robust to parametric variations [9] [10]. Recently the nonlinear optimal control technique has also been applied with success for motor control. [11]

For the control of speed of motor, sliding mode control scheme has gained alot of popularity. It has the properties of quick dynamic response and robustness to load disturbances. [12], [13] However, all these control strategies has advantage over classical FOC technique but are not robust to model uncertainties. In most of the scenario the exact model of the drive is not available i.e. in large volume serial production, where the parameters of motor can vary, or retrofits, where the equivalent motor circuit parameters are unknown and cannot be measured.

Adaptive sliding mode control can only insure robustness within certain bounds of uncertainties and also have the chattering problem. [14]

An alternative method for the control of speed of motor has been proposed which is known as neural networks. [15], [16] It have the property to approximate uncertainty and non-linearity by using training laws. It has the the drawback that, long computations increase the complexity of the algorithm, which limit the implementation of this technique in the industrial applications. In addition to that the load torque is assumed to be zero in this technique which lower its reliability. [17]

At the end of 1970's control theory of predictive control was developed, recently this technique has been introduce as an alternative of the speed control of IM. The uncertain parameters can be estimated using observer.

However, the stability of this scheme is cannot be guaranteed. [18], [19]

Recently the Backstepping control technique became very popular for wide range of classes of nonlinear systems. Reason for its huge popularity is its quality to ensure the global stability, also even when the parametric uncertainties are present. The design scheme of the control depend on the construction of Lyapnuov function, which make sure the stability of system. [20], [21]

1.1 Background and Motivation

Speed control of induction motor is complex problem, as model dynamics are nonlinear multi-variable and strong coupling exists between rotor flux and produced electromagnetic torque, Moreover the states cannot be measured easily and can get affected by parameter variations and parametric uncertainties.

As induction motor is a nonlinear system so a nonlinear control must be designed to improve the performance of controller in steady state and also in transients. In general vector control scheme is applied to formulate a suitable control scheme and it combined with advance nonlinear control techniques, But there are some vector control inconvenience in the resulting global performance, moreover it makes the control law design much more complex.

Backstepping control is an efficient nonlinear controller which can deal effectively with parametric uncertainties and variations,external disturbances ,as well as misalignment of the flux vector, Moreover it can ensure global stabilization of the system.

The Multi-scalar induction motor model is used in the place of conventional Vector control method, as its is an ideal way to reduce the mathematical complexity. By this the initial model of induction is transformed in to two fully decoupled linear systems(mechanical system and electromagnetic system). After that Backstepping controller can easily be applied.

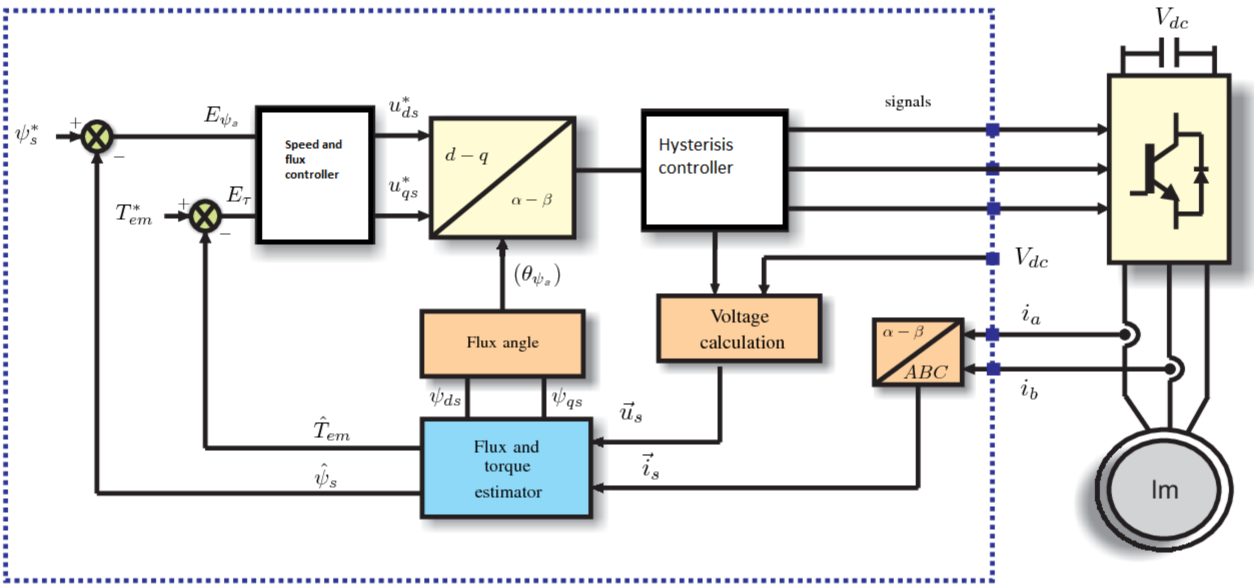

Figure 1.1: Control overview

The main idea of this work is to show that backstepping nonlinear controller for speed and produced rotor flux ,based on Multiscalar model, provide an ideal way to reduce mathematical complexity of induction motor model and can perfectly track the reference trajectory ,in addition to fully decoupling of the system, even at transients.

1.2 Composition of Research Work

Research work of this thesis is formulated as follows:

2nd Chapter: is Motor structure and operation.

3rd Chapter: is about induction motor dynamic model

4th Chapter: Decoupling techniques.

5th Chapter: is about conventional control schemes.

6th Chapter: gives idea about proposed control scheme

7th Chapter: conclude the control concept and gives an idea about future aspect of the work.

Chapter 2

Motor structure and operation

2.1 Structure:

An electric motor where the magnetic field produced on stator winding, produce the current in the rotor,required to produce required torque, by phenomena of electromagnetic induction, is called an induction motor. Therefore, no electrical connections are required between rotor and stator.Rotor of motor can be of two types depending on it contraction, namely squirrel cage or wounded. Induction motor usually run on 1-phase or 3-phase depending on application but 2-phase motors can also exist. However, electric motors may have various number of phases.

Just like other electric motor the IM also has two main parts namely stator and rotor.Which are described as follows:

Stator: As appears from its name stationary part of IM is known as stator. Stator wingdings are present on the stator which are supplied by 3-phase voltage connect in delta or Wei connection.Winding is present in slots through out stator,where magnetic field of stator have equal number of south and north poles, this evenly distribute the field around the stator.

Rotor: It is the rotating part of the motor.Rotor is connected to the mechanical load through a shaft.

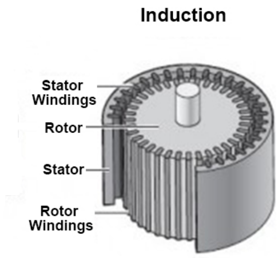

Figure 2.1: Induction Motor

Other important parts in addition to stator and rotor are:

1.Shaft of the motor is made up of steel, it is used to transfer produced torque to the connected load.

2. Bearings provide support to the shaft.

3. A fan is needed for cooling in the motor, as heat produce during the rotation, and can cause serious problem.

4. Terminal box is used to make external electric connections

5.Small distance, usually varies from 0.4mm to 4mm , is present between rotor and stator, which is call air gap.

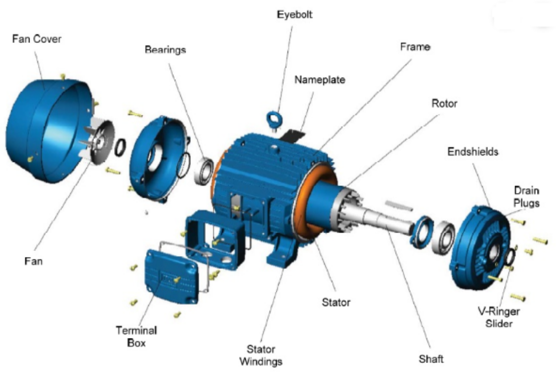

Figure 2.2: A typical structure of induction motor

2.2 Operation

The stator of the IM has evenly spaced stamping for poles. Number of poles can vary, as poles increase the motor speed become less and vice-versa. When the voltage is supplied to the stator winding, a variable rotating magnetic field is produced, because the poles keep shifting surrounding the stator.

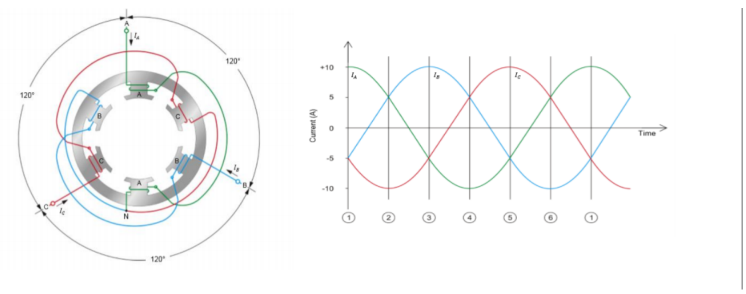

Figure 2.3: Stator currents

The field produced by stator pass through the air-gap and thus from the current in the stationary conductor of the rotor. By the principle of electromagnetic induction, when we place a electric conductor in a rotating magnetic field electromotive forces are induced across it, so forces are induced in the rotor conductor. As conductors are present in the stator magnetic filed, this generates a mechanical push which acts on the rotor conductor.Torque produced tries to bend the rotor in the direction of rotating field. As by Lenz's law produced currents tries to oppose the cause. As the relative speed between stator magnetic filed and stationary conductor of rotor is causing the currents, thus the currents cause the rotor to run in the same direction as filed to reduce the relative speed.

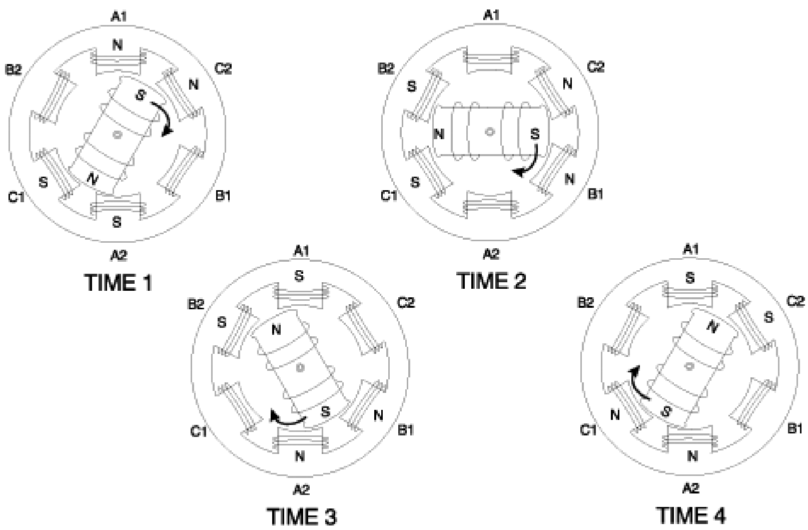

Figure 2.4: Rotor rotation

2.3 Speed control to control the process:

For variable speed operation of induction motor different logarithms can be applied but we require an algorithm with better settling time and stability. To understand this lets consider the driving of car as a process. Driving at constantly fast speed can be dangerous and can cause accident. On the other other hand driving at the slow speed will take more time to reach the destination. So, by adjusting the speed according to the route will make system reliable and will minimize the time to reach the location.

Adjustable speed provide benefits as follows.

1.Variable speed according to operation.

2.Accurate positioning made possible.

3.Torque control.

4.Compensate the process fluctuations.

5.Smooth operation.

2.4 Speed control techniques

The speed of motor and synchronous speed has the following mathematical relation.

$$n = (1 - s) * n_s \tag{2.1}$$

Also,

$$n_s = 120f/p \tag{2.2}$$

This shows that there are two ways to control the speed, given as follows.

1.Synchronous speed control.

2.Slip control.

A detailed analysis suggests the following methods,

1. Changing the number of poles.
2. Voltage control of stator.
3. Frequency control of supply.
4. Eddy currents coupling.

5. Resistance control of rotor.

6. Recovery of slip power.

2.5 Variable speed control

Motor speed can be controlled by controlling synchronous speed, which can be done by varying supply frequency. Induced voltage in the stator $E1 \propto \psi f$,where ψ is the flux and f is the frequency of supply.

Terminal voltage $V \propto \psi f$, neglecting the voltage drop of stator.

As it is obvious that reducing the supply frequency , keeping the terminal voltage constant, will cause an increase in the flux.This increase has following disadvantages:

1. Evident increase in magnetizing current.

2. Line current and voltage distortion.

3. Stator copper loss and core loss increase.

4. Acoustic noise introduction.

So, The variable frequency control is carried out below the rated frequency and at rated flux,by changing the terminal voltage in such a way that a constant V/f ratio is maintained at rated value. In this manner the above disadvantages can be avoided.

Chapter 3

Induction motor dynamic model

3.1 Introduction

Induction motor mathematical model will be presented in this chapter. This model is based on space vector notation.

This mathematical of 3-phase motor is described [22] by making the following simplifying assumptions:

• 3-phase motor is considered to symmetrical.

• The higher harmonics of magnetomotive force (M.M.F) in the air gap and spatial field distribution are disregarded, only fundamental harmonic is considered.

• A concentrated coil replaces the spatially distributed rotor and stator wingdings.

• Magnetic saturation, iron losses, eddy currents and the anisotropy effects are neglected.

• The reactance and resistance of the coil are taken constant.

• In most of the cases the current and voltages are considered to be sinusoidal, especially while considering the steady state.

3.2 Mathematical Model

Taking in to consideration the previously described assumptions the instantaneous stator phase voltages can be written by following equations:

$$U_A = I_A R_S + \frac{d\psi_A}{dt} \tag{3.1}$$

$$U_B = I_B R_S + \frac{d\psi_B}{dt} \tag{3.2}$$

$$U_C = I_C R_S + \frac{d\psi_C}{dt} \tag{3.3}$$

Generally, the space vector method is used to describe the induction motor model, which have following advantages:

1. The number of dynamic equations are reduced.
2. Analysis at any supply voltage become possible.
3. Various rectangular coordinate system representation of system equation can be obtained.

A symmetric three-phase system represented by phase quantities, such as currents, voltages and flux linkages, in a neutral coordinate system can be replaced by the currents, voltages and flux linkages resulting space vector respectively. A space vector can be defined as:

$$\vec{k} = 2/3[\vec{1}.k_A(t) + \vec{a}.k_B(t) + \vec{a^2}.k_C(t)] \tag{3.4}$$

where:

$k_A(t)$,$k_B(t)$,$k_C(t)$ are random phase quantities in natural coordinates system, which satisfies the condition $(k_A(t) + k_B(t) + k_C(t) = 0)$.

$\vec{1}, \vec{a}, \vec{a^2}$ are phase shifted complex unit vectors.

2/3 is normalization factor.

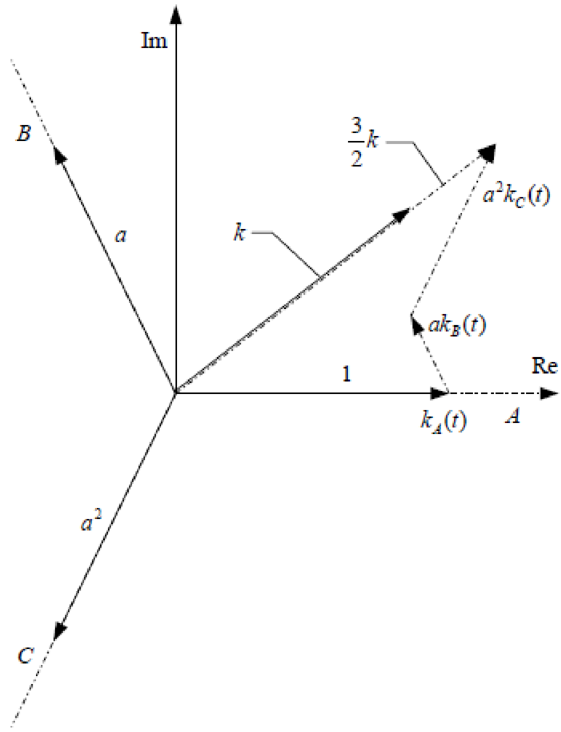

Figure 3.1: Space vector representation

Using the above space vector method motor equations can be written as:

Voltages equations:

$$\vec{U_s} = \vec{I_s}R_s + \frac{d\vec{\psi_s}}{dt} \tag{3.5}$$

$$\vec{U_r} = \vec{I_r}R_r + \frac{d\vec{\psi_r}}{dt} \tag{3.6}$$

Flux-current equations:

$$\vec{\psi_s} = L_s\vec{I_s} + Me^{j\gamma_m}\vec{I_r} \tag{3.7}$$

$$\vec{\psi_r} = L_r\vec{I_r} + Me^{j\gamma_m}\vec{I_s} \tag{3.8}$$

Few steps must be followed to obtain the complete set of electric motor equations.First of all transform the equations (3.5-3.8) in to common rotating coordinate system, then transform the rotor value in to stator side.

$$\vec{U_{sK}} = \vec{I_{sK}} R_s + \frac{d\vec{\psi_{sK}}}{dt} + j\Omega_K \vec{\psi_{sK}} \tag{3.9}$$

$$\vec{U_{rK}} = \vec{I_{rK}} R_s + \frac{d\vec{\psi_{rK}}}{dt} + j(\Omega_K - p_b\Omega_m)\vec{\psi_{rK}} \tag{3.10}$$

$$\vec{\psi_{sK}} = L_s \vec{I_{sK}} + L_M \vec{I_{rK}} \tag{3.11}$$

$$\vec{\psi_{rK}} = L_r \vec{I_{rK}} + L_M \vec{I_{sK}} \tag{3.12}$$

These above equations are represented in the coordinate system K which is rotating with angular speed Ω_K.The dynamic rotor rotation can be expressed in equation as:

$$\frac{d\Omega_m}{dt} = \frac{1}{J}[M_e - M_L - B\Omega_m] \tag{3.13}$$

where,
M_e is electromagnetic torque.
M_L is load torque.
B is viscous constant.
(B=0),By neglecting the friction factor.
Electromagnetic torque M_e can be expressed in the form of mathematical equation as follows:

$$M_e = -p_b \frac{m_s}{2} L_M Im(\vec{I_s^*}\vec{I_r}) \tag{3.14}$$

$$M_e = p_b \frac{m_s}{2} Im(\vec{\Psi_s^*}\vec{I_s}) \tag{3.15}$$

Considering the above electromagnetic torque equation and by applying the fact that rotor voltage of a cage motor is equals to zero, the complete set of motor equation are:

$$\vec{U_{sK}} = \vec{I_{sK}} R_s + \frac{d\vec{\psi_{sK}}}{dt} + j\Omega_K \vec{\psi_{sK}} \tag{3.16}$$

$$0 = \vec{I_{rK}} R_s + \frac{d\vec{\psi_{rK}}}{dt} + j(\Omega_K - p_b\Omega_m)\vec{\psi_{rK}} \tag{3.17}$$

$$\vec{\psi_{sK}} = L_s \vec{I_{sK}} + L_M \vec{I_{rK}} \tag{3.18}$$

$$\vec{\psi_{rK}} = L_r \vec{I_{rK}} + L_M \vec{I_{sK}} \tag{3.19}$$

$$\frac{d\Omega_m}{dt} = \frac{1}{J}[p_b \frac{m_s}{2} Im(\vec{\Psi_s^*}\vec{I_s}) - M_L] \tag{3.20}$$

3.3 Clark transformation

Clark Transformation is also known as the alpha-beta (α, β, γ) transformation , in electrical engineering. This transformation simplifies the analysis of three-phase systems as it convert it in to stationary coordinate system. One of very important application of this transformation is the generation reference signal for space vector modulation which control the three-phase inverters.

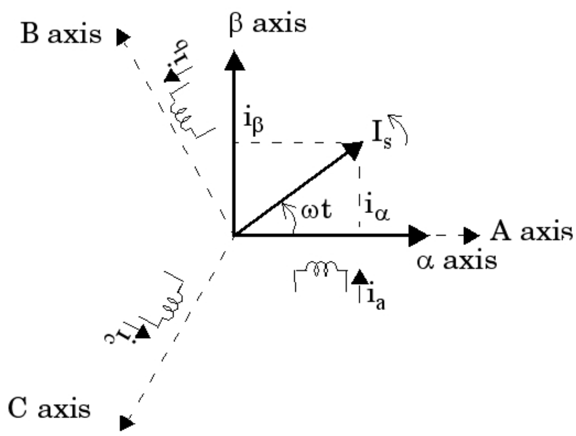

Figure 3.2: Clark Transformation

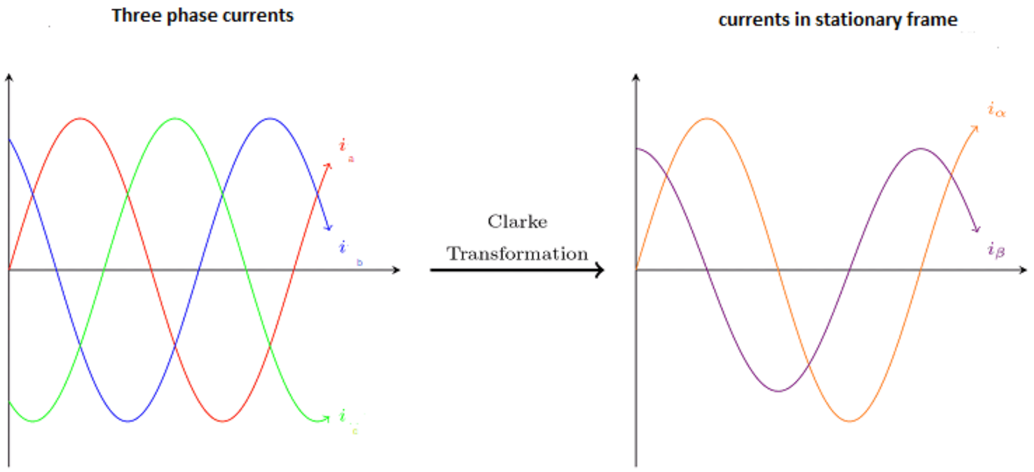

Figure 3.3: Visual description of Clark transformation

By space vector method motor equations can be represented in any coordinate system for the purpose of analysis. Stationary coordinate α, β which has zero angular speed ($\Omega_k = 0$) ,is aligned with stator. The space vectors can be resolved in to its respectiveα and β components.

$$\vec{U_{sK}} = U_{s\alpha} + jU_{s\beta} \tag{3.21}$$

$$\vec{I_{sK}} = I_{s\alpha} + jI_{s\beta} \tag{3.22}$$

$$\vec{I_{rK}} = I_{r\alpha} + jI_{r\beta} \tag{3.23}$$

$$\vec{\psi_{sK}} = \psi_{s\alpha} + j\psi_{s\beta} \tag{3.24}$$

$$\vec{\psi_{rK}} = \psi_{r\alpha} + j\psi_{r\beta} \tag{3.25}$$

So, the motor equations in α, β coordinates are:

$$U_{s\alpha} = I_{s\alpha}R_s + \frac{d\psi_{s\alpha}}{dt} \tag{3.26}$$

$$U_{s\beta} = I_{s\beta}R_s + \frac{d\psi_{s\beta}}{dt} \tag{3.27}$$

$$0 = I_{r\alpha}R_s + \frac{d\psi_{r\alpha}}{dt} + p_b\Omega_m\psi_{r\beta} \tag{3.28}$$

$$0 = I_{r\beta}R_s + \frac{d\psi_{r\beta}}{dt} - p_b\Omega_m\psi_{r\alpha} \tag{3.29}$$

$$\psi_{s\alpha} = L_sI_{s\alpha} + L_MI_{r\alpha} \tag{3.30}$$

$$\psi_{s\beta} = L_sI_{s\beta} + L_MI_{r\beta} \tag{3.31}$$

$$\psi_{r\alpha} = L_rI_{r\alpha} + L_MI_{s\alpha} \tag{3.32}$$

$$\psi_{r\beta} = L_rI_{r\beta} + L_MI_{s\beta} \tag{3.33}$$

$$\frac{d\Omega_m}{dt} = \frac{1}{J}[p_b\frac{m_s}{2}(\Psi_{s\alpha}I_{s\beta} - \Psi_{s\beta}I_{s\alpha}) - M_L] \tag{3.34}$$

The relationships between equations can be represented in the form of block diagram. There is not just single block diagram representation of induction motor, the block diagram vary depending upon the different coordinate systems and input signal. for instance let us consider the block diagram of motor in $\alpha - \beta$(stationary coordinate) and the input of the system are stator voltages, the above equation can be mold like the following form:

$$\frac{d\psi_{s\alpha}}{dt} = U_{s\alpha} - I_{s\alpha}R_s \tag{3.35}$$

$$\frac{d\psi_{s\beta}}{dt} = U_{s\beta} - I_{s\beta}R_s \tag{3.36}$$

$$\frac{d\psi_{r\alpha}}{dt} = -I_{r\alpha}R_s - p_b\Omega_m\psi_{r\beta} \tag{3.37}$$

$$\frac{d\psi_{r\beta}}{dt} = -I_{r\beta}R_s + p_b\Omega_m\psi_{r\alpha} \tag{3.38}$$

$$I_{s\alpha} = \frac{1}{\sigma L_s}\psi_{s\alpha} - \frac{L_M}{\sigma L_sL_r}\psi_{r\alpha} \tag{3.39}$$

$$I_{s\beta} = \frac{1}{\sigma L_s}\psi_{s\beta} - \frac{L_M}{\sigma L_sL_r}\psi_{r\beta} \tag{3.40}$$

$$I_{r\alpha} = \frac{1}{\sigma L_r}\psi_{r\alpha} - \frac{L_M}{\sigma L_sL_r}\psi_{s\alpha} \tag{3.41}$$

$$I_{r\beta} = \frac{1}{\sigma L_r}\psi_{r\beta} - \frac{L_M}{\sigma L_s L_r}\psi_{s\beta} \tag{3.42}$$

$$\frac{d\Omega_m}{dt} = \frac{1}{J}[p_b \frac{m_s}{2}(\Psi_{s\alpha} I_{s\beta} - \Psi_{s\beta} I_{s\alpha}) - M_L] \tag{3.43}$$

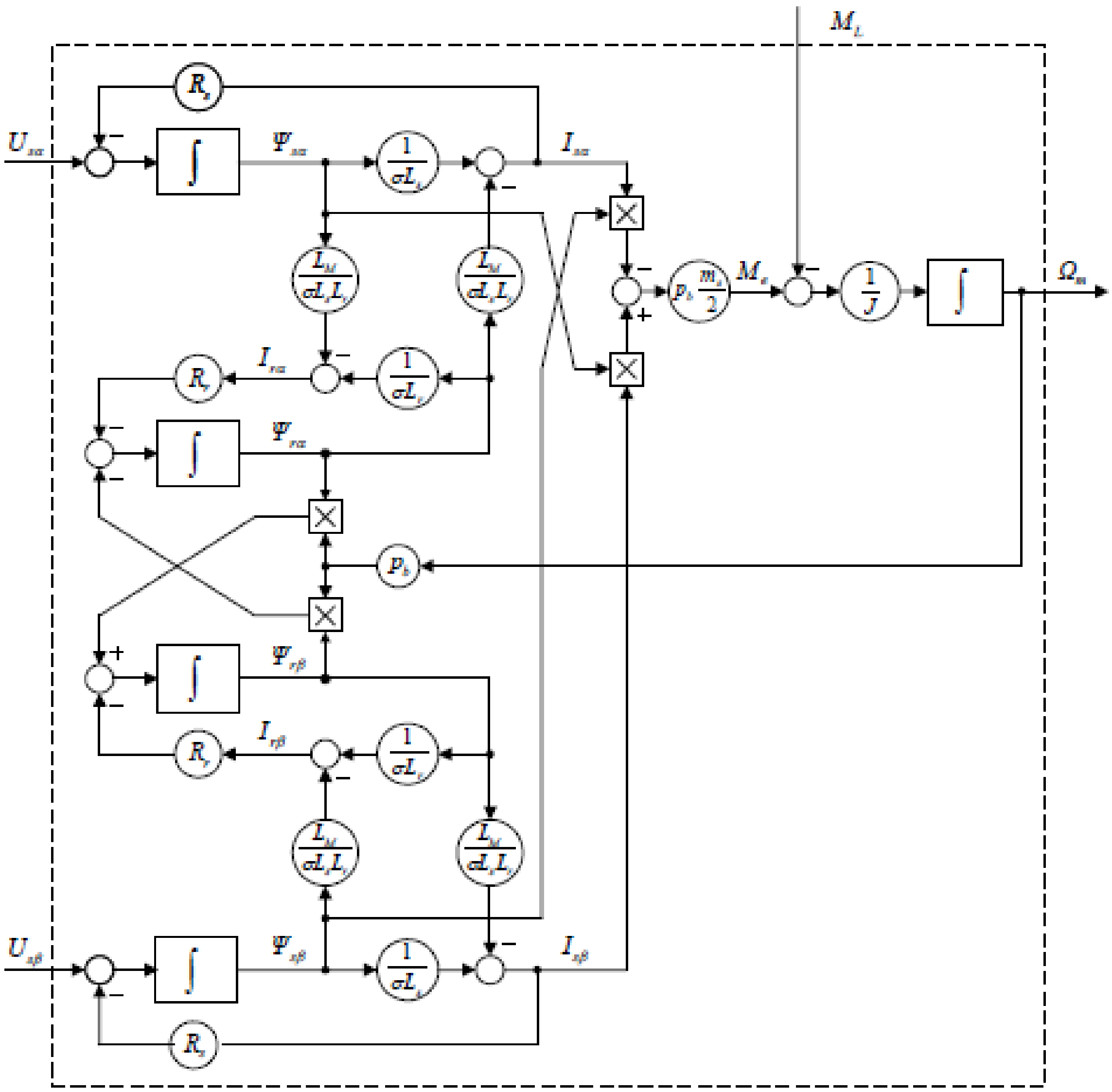

Figure 3.4: Induction motor block diagram representation in $\alpha - \beta$ coordinates

As obvious from the above representation of induction motor that the output signal flux, speed and torque depend upon both inputs so this representation is not good enough to design the control structure, as system is complicated from control point of view. Due to this reason different decoupling methods have be presented which decouple both torque and flux. This is done by aligning the coordinates system stator or rotor flux vectors.

Chapter 4

Decoupling

4.1 Transformation in D-Q coordinates

To control the induction motor easily and to reduce the complexity of control, independent control of flux and torque should be implemented. This is possible when the coordinated transformation is applied. A coordinate system which is connected with rotor flux vector is called d-q system. It angular speed is equal to rotor flux vector speed($\Omega_k = \Omega_{sr}$). Which can be calculated by formula:

$$\Omega_{sr} = \frac{d\gamma_{sr}}{dt} \tag{4.1}$$

Voltage,flux and current vectors can be transformed in to rotating d-q coordinates:

$$\vec{U_{sK}} = U_{s_d} + jU_{s_q} \tag{4.2}$$

$$\vec{I_{sK}} = I_{s_d} + jI_{s_q} \tag{4.3}$$

$$\vec{I_{rK}} = I_{r_d} + jI_{r_q} \tag{4.4}$$

$$\vec{\psi_{sK}} = I_{s_d} + j\psi_{s_q} \tag{4.5}$$

$$\vec{\psi_{rK}} = I_{r_d} + j\psi_{r_q} \tag{4.6}$$

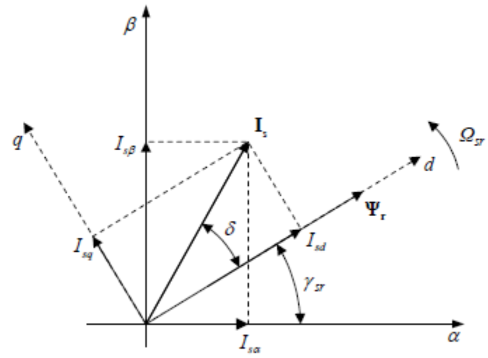

Figure 4.1: Induction motor's vector diagram in stationary ($\alpha - \beta$) and rotating (d-q) coordinates

$$U_{sd} = I_{sd}R_s + \frac{d\psi_{sd}}{dt} - \Omega_{sr}\Psi_{sq} \tag{4.7}$$

$$U_{sq} = I_{sq}R_s + \frac{d\psi_{sq}}{dt} + \Omega_{sr}\Psi_{sd} \tag{4.8}$$

$$0 = I_{rd}R_s + \frac{d\psi_r}{dt} \tag{4.9}$$

$$0 = I_{rq}R_s + (\Omega_{sr} - p_b\Omega_m)\psi_r \tag{4.10}$$

$$\psi_{sd} = L_sI_{sd} + L_MI_{rd} \tag{4.11}$$

$$\psi_{sq} = L_sI_{sq} + L_MI_{rq} \tag{4.12}$$

$$\psi_{rd} = L_rI_{rd} + L_MI_{sd} \tag{4.13}$$

$$\psi_{rq} = L_rI_{rq} + L_MI_{sq} \tag{4.14}$$

$$\frac{d\Omega_m}{dt} = \frac{1}{J}[p_b\frac{m_s}{2}\frac{L_m}{L_r}\Psi_rI_{sq} - M_L] \tag{4.15}$$

Motor flux can be expressed in rotor flux and stator current q component.Equations 4.9 and 4.13 can be transformed in to the following form:

$$\frac{d\Omega_m}{dt} = p_b\frac{m_s}{2}\frac{L_m}{L_r}\Psi_rI_{sq} \tag{4.16}$$

$$\frac{\psi_r}{dt} = \frac{L_m R_r}{L_r} I_{sd} - \frac{R_r}{L_r}\psi_r \tag{4.17}$$

By using equation 4.16 and 4.17 the block diagram of motor in rotating D-Q coordinates can be expressed as:

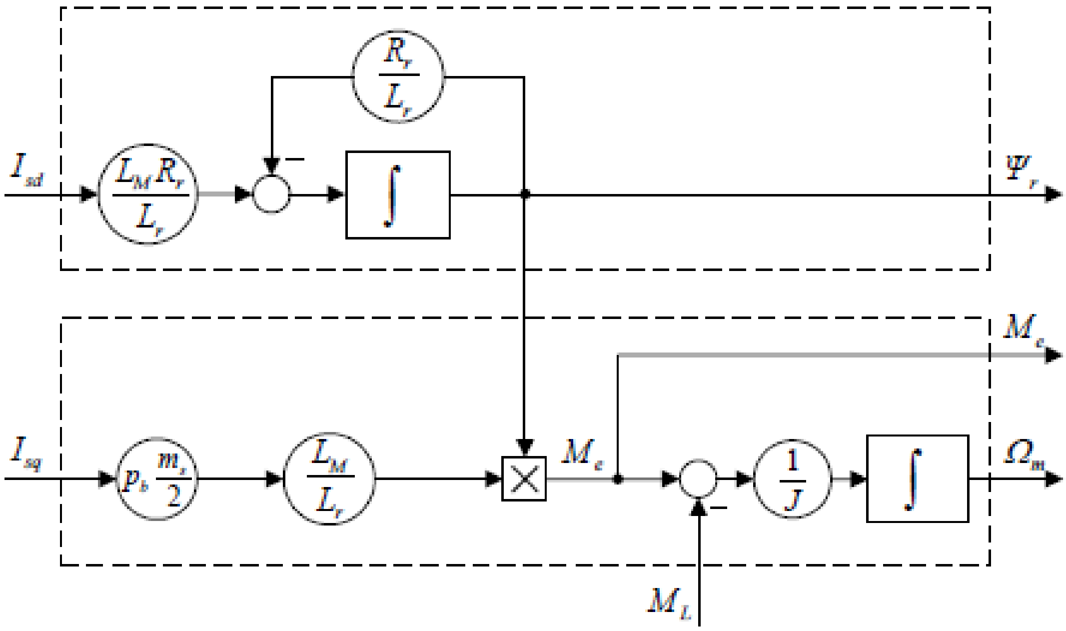

Figure 4.2: Induction motor block diagram in d-q coordinates

The above block diagram shows that the rotor flux and torque can be separately controlled by $I_{sd} and I_{sq}$ respectively. The currents vectors from motor are measured in stationary coordinates$\alpha - \beta$,so they must be transformed in to d-q coordinates and then the flux and torque control will be applied. Similarly, the reference voltages which are provided by will be in d-q coordinates so they must be converted in to stationary $\alpha - \beta$ coordinates before giving it to the motor. The transformations are carried out with the help of rotor flux angle γ_{sr}. This decoupling technique is used in FOC. Depending on the calculation of angle two different types of FOC can be implemented.

Which are Direct-field-oriented control(D.F.O.C) and Indirect field oriented control(I.F.O.C).

4.2 Transformation in X-Y coordinates

X-Y coordinate is quite similar to d-q coordinate except the fact that is not alligened with rotor flux, it rotates with arbitrary angular speed Ω_s and angle of rotation can be calculated as:

$$\theta_s = \int \Omega_s \tag{4.18}$$

Voltage,flux and current vectors can be transformed in to rotating x-y coordinates:

$$\vec{U_{sK}} = U_{s_x} + jU_{s_y} \tag{4.19}$$

$$\vec{I_{sK}} = I_{s_x} + jI_{s_y} \tag{4.20}$$

$$\vec{I_{rK}} = I_{r_x} + jI_{r_y} \tag{4.21}$$

$$\vec{\psi_{sK}} = I_{s_x} + j\psi_{s_y} \tag{4.22}$$

$$\vec{\psi_{rK}} = I_{r_x} + j\psi_{r_y} \tag{4.23}$$

So, the equation of induction motor can be written as:

$$U_{sx} = I_{sx}R_s + \frac{d\psi_{sx}}{dt} - \Omega_s\psi_{sy} \tag{4.24}$$

$$U_{sy} = I_{sy}R_s + \frac{d\psi_{sy}}{dt} + \Omega_K\psi_{sx} \tag{4.25}$$

$$0 = I_{rx}R_s + \frac{d\psi_{rx}}{dt} - (\Omega_s - \Omega_m)\psi_{ry} \tag{4.26}$$

$$0 = I_{ry}R_s + \frac{d\psi_{ry}}{dt} + (\Omega_s - \Omega_m)\psi_{rx} \tag{4.27}$$

$$\psi_{sx} = L_sI_{sx} + L_MI_{rx} \tag{4.28}$$

$$\psi_{sy} = L_s I_{sy} + L_M I_{ry} \tag{4.29}$$

$$\psi_{rx} = L_r I_{rx} + L_M I_{sx} \tag{4.30}$$

$$\psi_{ry} = L_r I_{ry} + L_M I_{sy} \tag{4.31}$$

$$\frac{d\Omega_m}{dt} = \frac{1}{J}[p_b \frac{m_s}{2} \frac{L_m}{L_r}(\psi_{rx} I_{sy} - \psi_{ry} I_{sx}) - M_L] \tag{4.32}$$

The above model equations can be represented as differential equations of rotor currents and stator flux in the x-y coordinate system which is rotating with the angular speed of Ω_s, these differential equations can be represented as following:

$$\frac{d\psi_{rx}}{dt} = -\frac{R_r \psi_{rx}}{L_r} + \frac{R_r L_m i_{sx}}{L_r} + (\Omega_s - \Omega_m)\psi_{ry} \tag{4.33}$$

$$\frac{d\psi_{ry}}{dt} = -\frac{R_r \psi_{ry}}{L_r} + \frac{R_r L_m i_{sy}}{L_r} - (\Omega_s - \Omega_m)\psi_{rx} \tag{4.34}$$

$$\frac{di_{sx}}{dt} = -\frac{1}{T_d} i_{sx} + \frac{R_r L_m}{L_r \omega_\delta}\psi_{rx} + \Omega_s i_{sy} + \frac{L_m \Omega_m}{\omega_\delta}\psi_{ry} + \frac{L_r}{\omega_\delta} u_{sx} \tag{4.35}$$

$$\frac{di_{sy}}{dt} = -\frac{1}{T_d} i_{sy} + \frac{R_r L_m}{L_s \omega_\delta}\psi_{sy} - \Omega_s i_{sx} - \frac{L_m \Omega_m}{\omega_\delta}\psi_{rx} + \frac{L_r}{\omega_\delta} u_{sy} \tag{4.36}$$

$$\frac{d\Omega_m}{dt} = \frac{1}{J} p_b \frac{L_m}{L_r}(\psi_{rx} i_{sy} - \psi_{ry} i_{sx}) - \frac{p_b T_l}{J} \tag{4.37}$$

From the above model it is clear that the model is multi-variable nonlinear system where coupling exists between x-y axis. It is very difficult to use this complex model directly for the control design, therefore some transformation is required to control such system.

4.2.1 Multi-scalar Induction motor model:

For the purpose of simplicity machine model can be described by four state variables.These four multi-scalar variables in the terms of motor parameters can be described as: Rotor angular speed, scalar and vector product of rotor flux vectors and stator currents and square of rotor flux. [20]- [22]

$$x_{11} = \omega_m \tag{4.38}$$

$$x_{12} = \psi_{rx} i_{sy} - \psi_{ry} i_{sx} \tag{4.39}$$

$$x_{21} = \psi_{rx}^2 + \psi_{ry}^2 \tag{4.40}$$

$$x_{22} = \psi_{rx} i_{sx} + \psi_{ry} i_{sy} \tag{4.41}$$

In the coordinate system, which is aligned with the stator current vector in x-axis y-component ($i_{sy} = 0$). A first order delay is introduced in the stator current value channel which has time constant T_d, the differential equations of the system changes to:

$$\frac{di_{sx}}{dt} = \frac{1}{T_d}(i_{sx} - I_s*) \tag{4.42}$$

$$\frac{d\psi_{rx}}{dt} = -\frac{R_r \psi_{rx}}{L_r} + \frac{R_r L_m i_{sx}}{L_r} + (\Omega_s - \Omega_m)\psi_{ry} \tag{4.43}$$

$$\frac{d\psi_{ry}}{dt} = -\frac{R_r \psi_{ry}}{L_r} - (\Omega_s - \Omega_m)\psi_{rx} \tag{4.44}$$

$$\frac{d\Omega_m}{dt} = \frac{1}{J} p \frac{L_m}{L_r}(-\psi_{ry} i_{sx}) - \frac{pT_l}{J} \tag{4.45}$$

According to the method proposed by Z. Krzeminski, the multi-scalar model of the induction motor can be find out by taking the derivative of new multi-scalar variables and incorporating the above mentioned differential equations.

$$\frac{dx_{11}}{dt} = \frac{pL_m}{JL_r} x_{12} - \frac{p}{J} T_l \tag{4.46}$$

$$\frac{dx_{12}}{dt} = \frac{1}{T} x_{12} + v_1 \tag{4.47}$$

$$\frac{dx_{21}}{dt} = -\frac{2R_r}{L_r} x_{21} + \frac{2R_r L_m}{L_r} x_{22} \tag{4.48}$$

$$\frac{dx_{22}}{dt} = -\frac{1}{T}x_{22} + \frac{R_r L_m}{L_r} i_{sx}^2 + v_2` \quad (4.49)$$

where;

$$\frac{1}{T} = \frac{R_r}{L_r} + \frac{1}{T_d} \quad (4.50)$$

$$v_1 = (\Omega_s - \Omega_m)x_{22} - \frac{1}{T_d}\psi_{ry} I_s* \quad (4.51)$$

$$v_2` = (\Omega_s - \Omega_m)x_{12} + \frac{1}{T_d}\psi_{rx} I_s* \quad (4.52)$$

$v_1 and v_2`$ are the input of the system and machine controlling quantities $\Omega_s * and I_s*$ can be computed using these inputs. Now, the new model, contain relatively simple non-linear differential equations.Using nonlinear feedback the nonlinear term in the equation(4.49) can be compensated, which gives the following expression:

$$v_2 = v_2` - \frac{R_r L_m}{L_r} i_{sx}^2 \quad (4.53)$$

From the above system the stator current magnitude and slip frequency can be represented as follows:

$$I_s* = T_d \frac{\psi_{rx} v_2 - \psi_{ry} v_1}{\psi_r^2} \quad (4.54)$$

$$(\Omega_s - \Omega_m) = \frac{\psi_{rx} v_2 + \psi_{ry} v_1}{i_{sx}^2 \psi_r^2} \quad (4.55)$$

Also;

$$I_s* = \frac{x_{12}^2 + x22^2}{x_{21}} \quad (4.56)$$

These above transformations of the system convert the system in to two fully decoupled linear subsystems namely mechanical and electromagnetic.Now the control scheme can easily be applied on these subsystems.

Mechanical subsystem:

$$\frac{dx_{11}}{dt} = \frac{pL_m}{JL_r}x_{12} - \frac{p}{J}T_l \quad (4.57)$$

$$\frac{dx_{12}}{dt} = \frac{1}{T}x_{12} + v_1 \quad (4.58)$$

Electromagnetic subsystem:

$$\frac{dx_{21}}{dt} = -\frac{2R_r}{L_r}x_{21} + \frac{2R_r L_m}{L_r}x_{22} \tag{4.59}$$

$$\frac{dx_{22}}{dt} = -\frac{1}{T}x_{22} + v_2 \tag{4.60}$$

Chapter 5

Conventional Techniques

5.1 Vector Control

Vector control of induction motor entirely depend on frequency orientation. This approach can simply implemented when the rotor flux is in direct-axes. [23] This is carried out by transforming the current in to different axes. The system can be transformed from rotating d-q axes to stationary axes using the following equations,

$$i_{s\alpha} = i_{sd}cos(\theta) - i_{qs}sin(\theta) \tag{5.1}$$

$$i_{s\beta} = i_{sd}sin(\theta) + i_{qs}cos(\theta) \tag{5.2}$$

where the $i_{s\alpha}andi_{s\beta}$ are the currents in stationary $\alpha - beta$axes. $i_{ds}andi_{qs}$ are currents in rotating d-q axes, and θ is the rotor flux angle. To achieve the good dynamic performance like that of separately excited DC motor the flux is usually kept constant and torque is varied according to the speed.

The three phase currents can be calculated using following equations:

$$i_a = i_{s\beta}; \tag{5.3}$$

$$i_b = i_{s\alpha} sin(-120) + i_{s\beta} cos(-120); \tag{5.4}$$

$$i_c = i_{s\alpha} sin(120) + i_{s\beta} cos(120); \tag{5.5}$$

The relationship between abc and d-q axes is shown below:

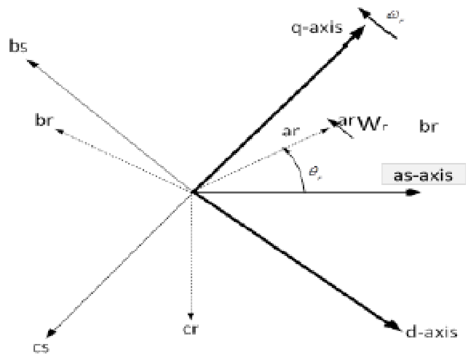

Figure 5.1: Relationship between abc and d-q axes

Decoupling between rotor flux and torque is shown below:

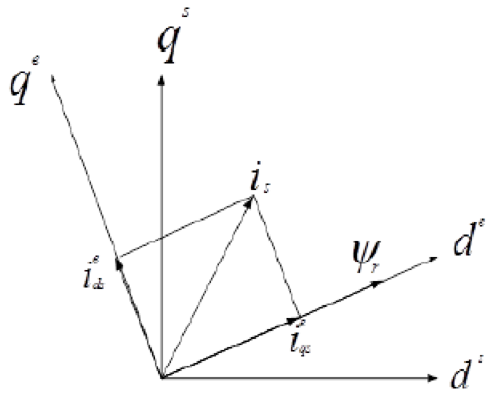

Figure 5.2: Decoupling between rotor flux and torque

5.2 Field Oriented control (FOC)

5.2.1 FOC Algorithm

The basic steps of FOC can be described by the following points:

1. Measure the stator currents ia,ib and ic form the motor. These currents follow the equation $(i_a + i_b + i_c = 0)$

2.Transform these three-phase currents in to two-axes$\alpha - \beta$ stationary coordinate system. This transformation is known as Clark Transformation

3.Measure or estimate rotor flux vector.

4.Rotate $\alpha - \beta$ coordinate system in such a way that is align with rotor flux vector.

5.Calculate angle of rotation on each iteration.

6.This rotation gives us the $i_d and i_q$ currents this transformation is known as Park transformation.

7.Error is calculated using reference flux and estimated flux.

8.PI controller is applied on the error to generate the control current signal i_d*.

9.These $i_d * and i_q *$ are transformed in to three phase $i_a *, i_b * and i_c *$ currents.

10.Hysteresis competitor is used to compare $i_a, i_b, i_c with i_a *, i_b *, i_c *$ which generate the gate signal for the inverter. [24]

5.2.2 Flux Estimator

Flux is estimated using motor equations

$$\psi_r = \frac{L_m i_{ds}}{1 + T_r} \tag{5.6}$$

where ,T_r is the time constant.

5.2.3 System overview

The motor we want to control is connected with FOC block in a closed loop. The currents from the motor goes to FOC block which generate gate pulses for the inverter which control the motor

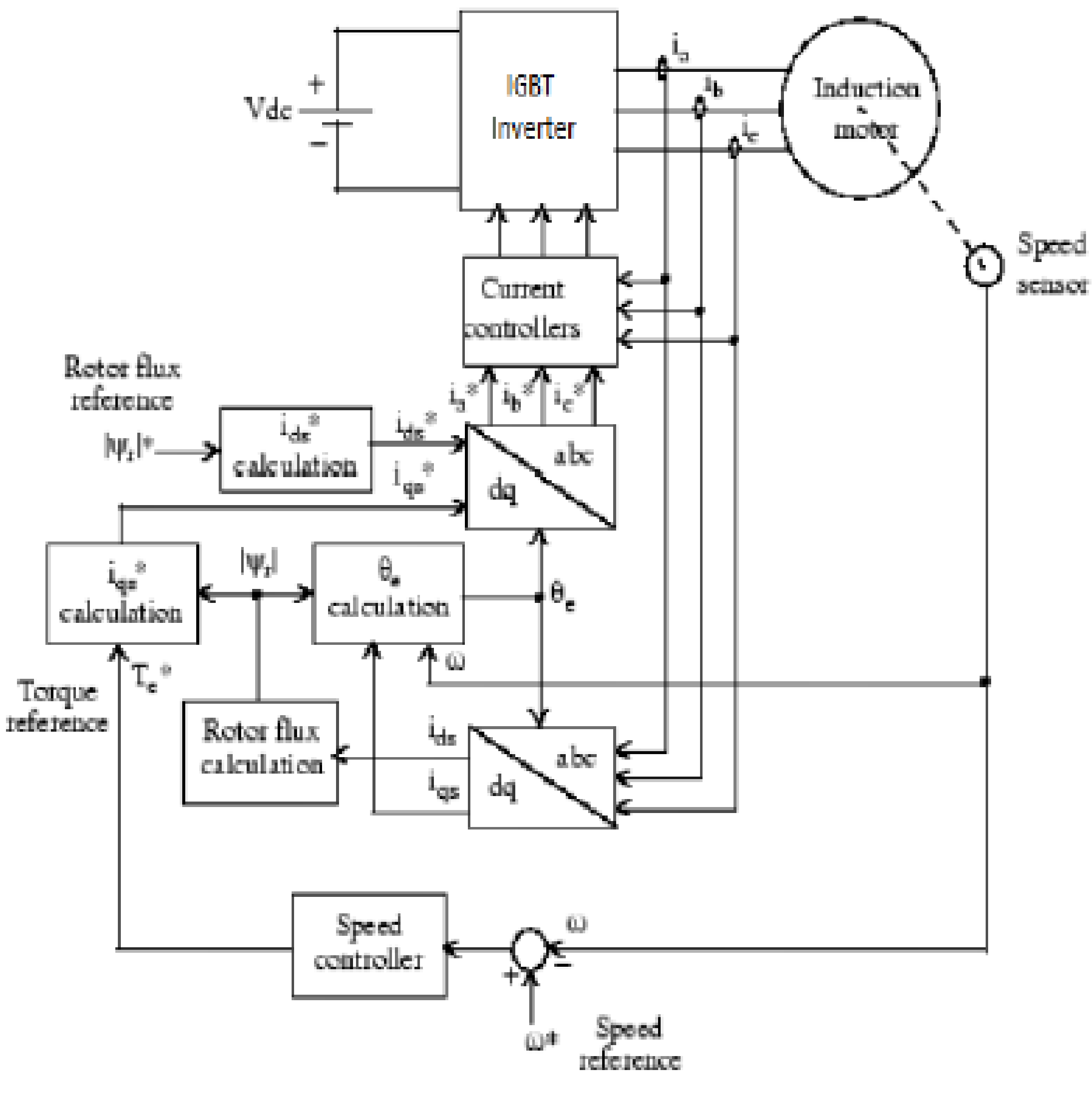

Figure 5.3: Block diagram representation of FOC [25]

5.2.4 Simulink model of FOC

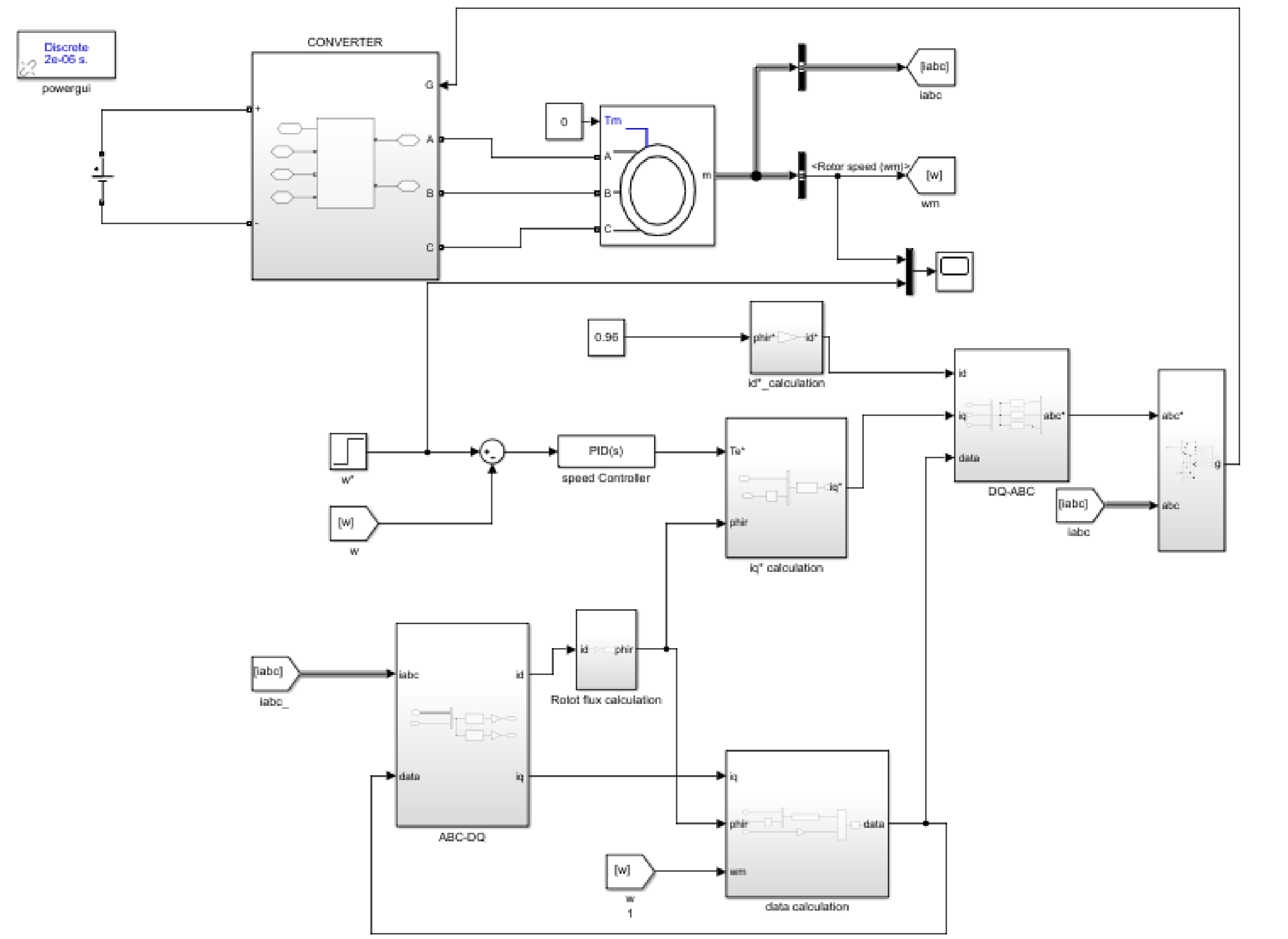

Figure 5.4: Simulink Diagram of FOC

5.3 Direct-Torque control (DTC)

As discussed above in the FOC for the fixed flux the torque can be controlled by stator current component i_{sq} as presented by following equation:

$$M_e = p_b \frac{m_s}{2} \frac{L - M}{L_r} \psi_r I_s sin(\delta) \qquad (5.7)$$

where: δ- is angle between stator current and rotor flux.

The above equation can be transformed in to the following form:

$$M_e = p_b \frac{m_s}{2} \frac{L_m}{L_r L_s - L_m^2} \psi_s \psi_r sin(\delta_\psi) \tag{5.8}$$

where; δ_ψ is the angle between rotor and stator fluxes. It can be seen from the formula that not only the magnitude of rotor and stator flux is important but also the angle between these fluxes is very important. Angle δ is important in FOC where as δ_ψ is important in DTC.

By omitting motor voltage drop on stator resistance, equations for the motor flux are:

$$\frac{\vec{\psi_s}}{dt} = \vec{U_s} \tag{5.9}$$

also;

$$\vec{\psi_s} = \int_t^0 \vec{U_s} dt \tag{5.10}$$

where;

$$\vec{U_v} = \begin{cases} \frac{2}{3} U_{dc} e^{j(v-1)\frac{\pi}{3}}, & \text{v=1...6.} \\ 0, & \text{v=0,7.} \end{cases} \tag{5.11}$$

Possible inverter states can be represented by above eight voltage vectors, there are six active vectors and two zero vectors as presented by below diagram,

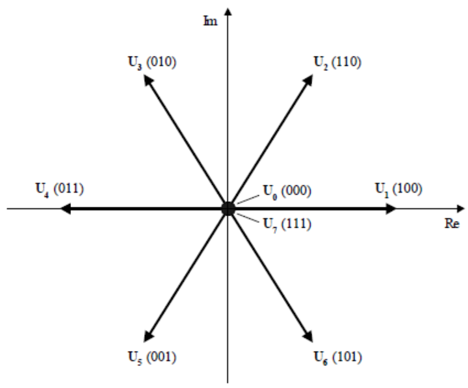

Figure 5.5: Space vectors representation of inverter output voltage

In induction motor the stator flux can easily be changed immediately but on the contrary the rotor flux moves slowly. In the Direct torque control the angle between rotor and stator flux δ_ψ is very important as it can be used for variable torque operation.Also, the stator voltage can easily control the stator flux. This shows that the by appropriate selection of voltage vectors flux angle and torque can be changed.

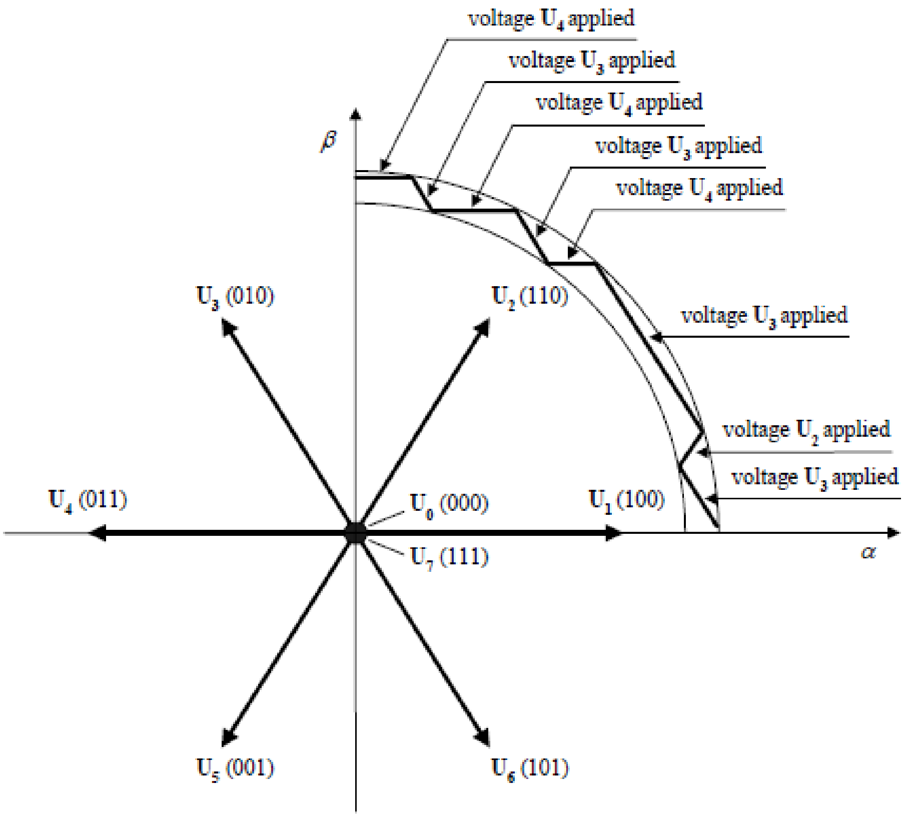

Figure 5.6: Stator flux trajectory formation by appropriate selection of voltage vectors

5.3.1 DTC overview

Take electromagnetic torque $M_c$and stator flux amplitude ψ_{sc} as reference signals to the system. These references are compared with estimated values of these two quantities. Errors are then fed to the hysteresis controller. Digitized output with the position sector select the appropriate voltage vector from the switching table. Pulses S_A, S_B, S_C) are generated by the table to control the inverter switching.

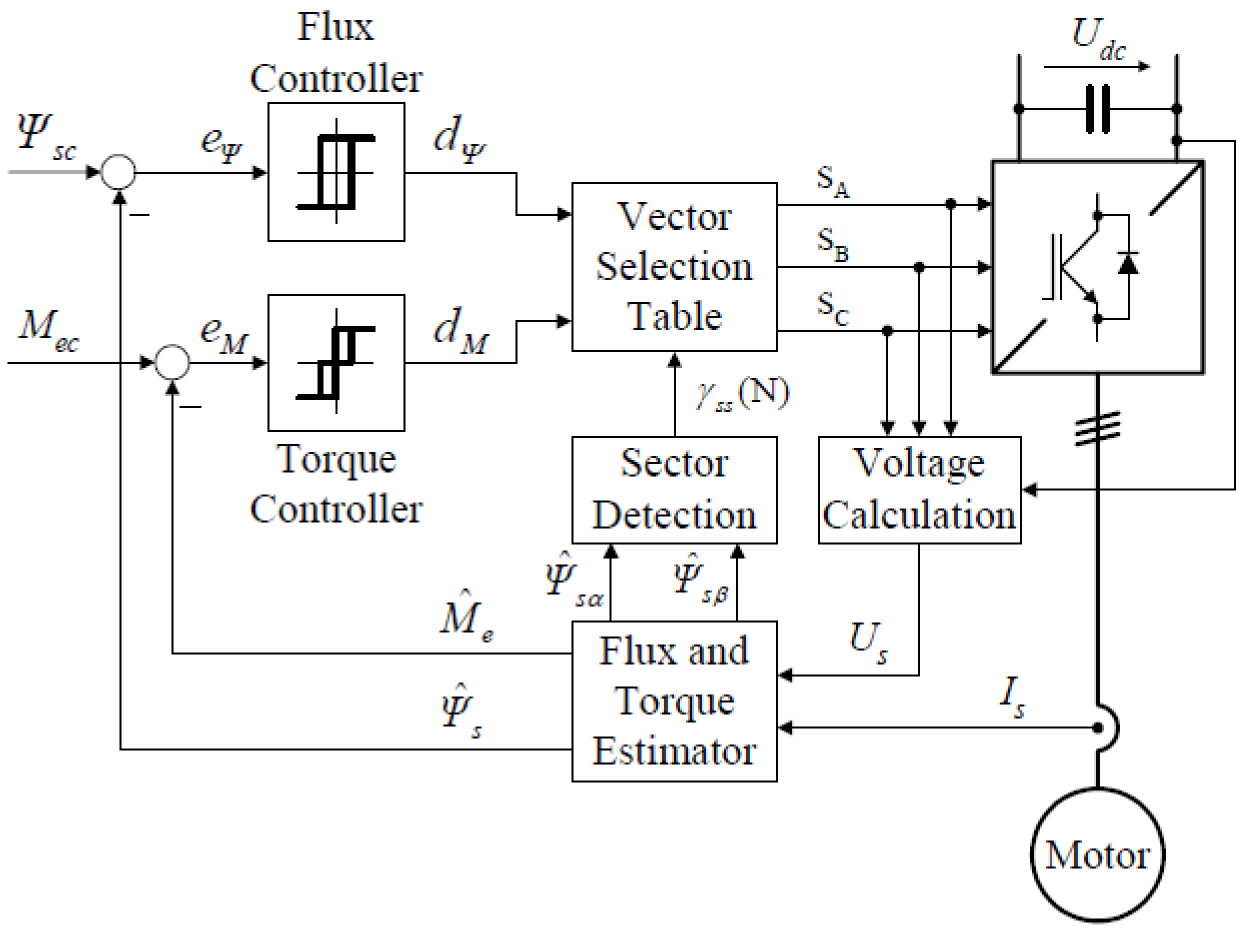

Figure 5.7: Block diagram of Direct torque control

5.3.2 Simulink model of DTC

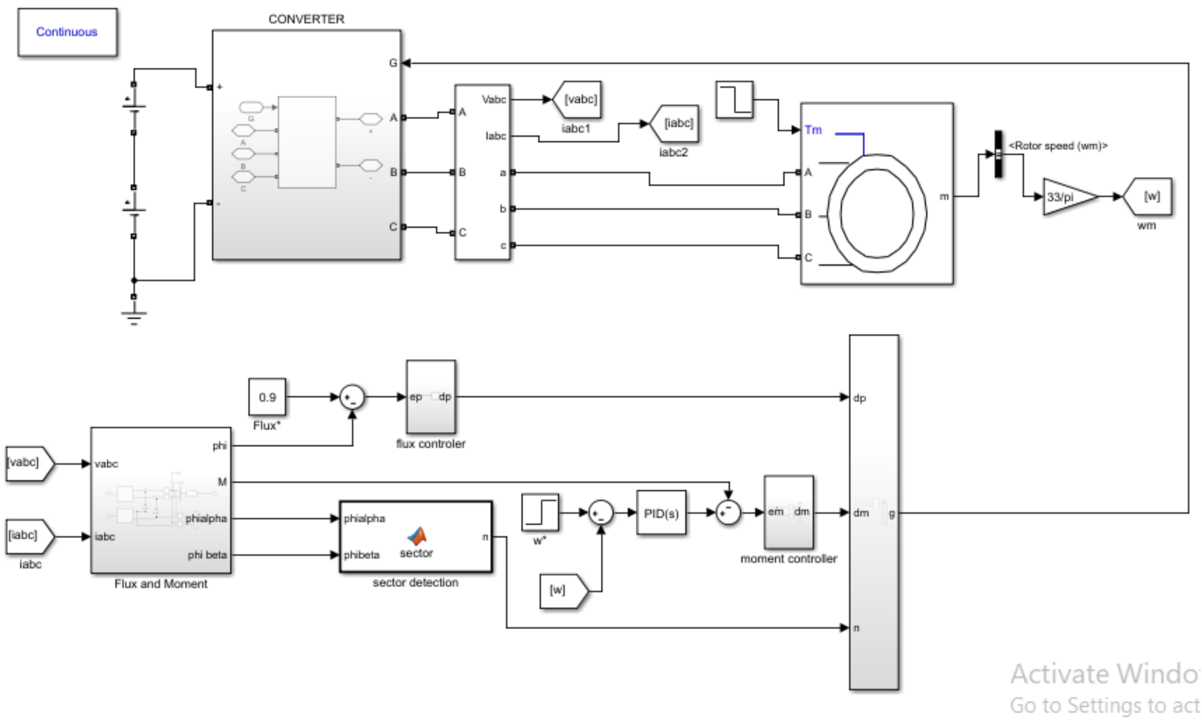

Figure 5.8: Simulink diagram of Direct torque control

Chapter 6

Proposed control scheme

6.1 Back Stepping Control

6.1.1 Motor model

The Induction motor model with uncertainties and inaccuracies from paper "Adaptive Speed Control of Induction Motor Drive With Inaccurate Model" [26]. This motor model in $x - y$ coordinate system rotating with angular speed ω_s is given by following equations:

$$\frac{d\psi_{rx}}{dt} = l_5 i_{sx} - l_4 \psi_{rx} + (\omega_s - \omega_m)\psi_{ry} + \varepsilon_{\psi x} \tag{6.1}$$

$$\frac{d\psi_{ry}}{dt} = l_5 i_{sy} - l_4 \psi_{ry} - (\omega_s - \omega_m)\psi_{rx} + \varepsilon_{\psi y} \tag{6.2}$$

$$\frac{di_{sx}}{dt} = -l_7 i_{sx} + l_4 l_6 \psi_{rx} + \omega_s i_{sy} + l_6 \omega_m \psi_{ry} + l_8 v_{sx} + \varepsilon_x \tag{6.3}$$

$$\frac{di_{sy}}{dt} = -l_7 i_{sy} + l_4 l_6 \psi_{ry} - \omega_s i_{sx} - l_6 \omega_m \psi_{rx} + l_8 v_{sy} + \varepsilon_y \tag{6.4}$$

$$\frac{d\omega_m}{dt} = l_3(\psi_{rx} i_{sy} - \psi_{ry} i_{sx}) - l_1 T_l + \varepsilon_\omega \tag{6.5}$$

where;

$l_4 = \frac{R_r}{L_r}, l_5 = R_r\frac{L_m}{L_r}, l_8 = \frac{L_r}{\omega_\delta}, l_7 = \frac{1}{T_d}, l_6 = \frac{L_m}{\omega_\delta}, l_3 = \frac{L_m p}{JL_r}, l_1 = \frac{p}{J}$, $\omega_\delta = L_s L_r -$

L_m^2 Here, T_d is stator delay, p is number of poles, J is rotor inertia , R_r, R_s are rotor and stator resistances, L_r, L_s are rotor and stator inductance's ,L_m is mutual inductance,T_l is load torque, and $\varepsilon_x, \varepsilon_y, \varepsilon_\psi, \varepsilon_\omega$ there are the uncertainties in the parameters which includes flux vectors misalignment and external non-linearities

6.1.2 Multi-scalar Model

As explained earlier in the section(4.2.1), multi-scalar model of the motor is given by equations(4.38-4.41) by aligning the system with x-component of stator current the y-component becomes zero, so equation take the following form:

$$x_{11} = \omega_m \tag{6.6}$$

$$x_{12} = -\psi_{ry} i_{sx} \tag{6.7}$$

$$x_{21} = \psi_{rx}^2 + \psi_{ry}^2 \tag{6.8}$$

$$x_{22} = \psi_{rx} i_{sx} \tag{6.9}$$

The first order delay in the stator current channel is represented as:

$$\frac{di_{sx}}{dt} = l_7(i_{sx} - I_s*) \tag{6.10}$$

According to Z. Krzeminski the new model can be expressed by taking derivatives of aboves multi-saclar states and putting the differential equations of the system in it.So, equations formed by this technique are;

$$\frac{dx_{11}}{dt} = l_3 x_{12} - l_1 T_l + \varepsilon_\omega \tag{6.11}$$

$$\frac{dx_{12}}{dt} = -(l_7 - l_4) x_{12} + v_1 \tag{6.12}$$

$$\frac{dx_{21}}{dt} = -2l_4 x_{21} + 2l_5 x_{22} + 2\psi_{rx}\varepsilon_{\omega x} + 2\psi_{ry}\varepsilon_{\omega y} \tag{6.13}$$

$$\frac{dx_{22}}{dt} = -(l_4 - L_7) + l_5 i_{sx}^2 + v_2` \tag{6.14}$$

where;

$$v_1 = l_7 \psi_{ry} I_s * + (\omega_s - \omega_m) x_{22} - i_{sx} \varepsilon_{\omega y} \tag{6.15}$$

$$v_2` = -l_7 \psi_{rx} I_s * + (\omega_s - \omega_m) x_{12} + i_{sx} \varepsilon_{\omega x} \tag{6.16}$$

The non-linearities present in the equation(6.14) can be removed by applying feedback control such that;

$$v_2 = v_2` - l_5 isx^2 \tag{6.17}$$

The system can now be written as the combination of two subsystems namely electromagnetic subsystem and mechanical subsystem;

Electromagnetic subsystem

$$\frac{dx_{11}}{dt} = l_3 x_{12} - l_1 T_l + \varepsilon_\omega \tag{6.18}$$

$$\frac{dx_{12}}{dt} = -(l_7 - l_4) x_{12} + v_1 \tag{6.19}$$

Mechanical subsystem

$$\frac{dx_{21}}{dt} = -2 l_4 x_{21} + 2 l_5 x_{22} + 2 \psi_{rx} \varepsilon_{\omega x} + 2 \psi_{ry} \varepsilon_{\omega y} \tag{6.20}$$

$$\frac{dx_{22}}{dt} = -(l_4 - L_7) + v_2` \tag{6.21}$$

6.1.3 Backstepping control

From this simplified decoupled structure the traditional control scheme of cascade PI controllers can be replaced by the backstepping control approach, to control the angular speed and rotor flux. Reference signals of angular speed and flux are considered to be smooth and they have bounded continuous second order derivatives.

In the backstepping control we use the idea of the virtual control which decompose the complex system in to relatively smaller and simpler systems.In backstepping scheme we divide the system in to single input-single output problem which gives the reference signal for next step, at each step we have a reference signal for the next step. Lyapnuov function ensures the stability of the overall system.

Step 1

First of all we define the tracking errors for angular speed$x_{11} = \omega_m$ and rotor flux$x_{21} = \psi_r^2$ as;

$$e_1 = x_{11}^* - x_{11} \tag{6.22}$$

$$e_3 = x_{21}^* - x_{21} \tag{6.23}$$

Equations for error dynamics can be written as:

$$\dot{e_1} = \dot{x_{11}^*} - l_3 x_{12} + l_1 T_l - \varepsilon_\omega \tag{6.24}$$

$$\dot{e_3} = \dot{x_{21}^*} + 2l_4 x_{21} - 2l_5 x_{22} - 2\psi_{rx}\varepsilon_{\psi x} - 2\psi_{ry}\varepsilon_{\psi y} \tag{6.25}$$

step 2

We want these errors to converge to zero, this can be done by taking x_{12}andx_{22} as virtual control and control errors e_1, e_3 by them. Take Layunov function:

$$V = \frac{1}{2}e_1^2 + \frac{1}{2}e_3^2 \tag{6.26}$$

For stable system its derivative should be less than or equal to zero;

$$\dot{V} = e_1\dot{e_1} + e_3\dot{e_3} \tag{6.27}$$

$$\dot{V} = e_1(\dot{x}^*_{11} - l_3x_{12} + l_1T_l - \varepsilon_\omega) + e_3(\dot{x}^*_{21} + 2l_4x_{21} - 2l_5x_{22} - 2\psi_{rx}\varepsilon_{\psi x} - 2\psi_{ry}\varepsilon_{\omega y}) \tag{6.28}$$

$$\begin{aligned} \dot{V} &= -K_1e_1^2 - K_3e_3^2 + e_1(K_1e_1 + \dot{x}^*_{11} - l_3x_{12} + l_1T_l - \varepsilon_\omega) \\ &+ e_3(K_3e_3 + \dot{x}^*_{21} + 2l_4x_{21} - 2l_5x_{22} - 2\psi_{rx}\varepsilon_{\psi x} - 2\psi_{ry}\varepsilon_{\omega y}) \end{aligned}$$

Here; K_1, K_3 are positive constants, closed loop dynamics are defined by them. From above equation virtual control to stabilize the system can be chosen as;

$$x^*_{12} = \frac{1}{l_3}(K_1e_1 + \dot{x}^*_{11} + l_1T_l - \varepsilon_\omega) \tag{6.29}$$

$$x^*_{22} = \frac{1}{2l_5}(K_3e_3 + \dot{x}^*_{21} + 2l_4x_{21} - 2\psi_{rx}\varepsilon_{\psi x} - 2\psi_{ry}\varepsilon_{\psi y}) \tag{6.30}$$

so our laypnuov function becomes;

$$\dot{V} = -K_1e_1^2 - K_3e_3^2 \leq 0$$

The above defined virtual controls at as the reference signals for the next step. now we want to control $x_{12} and x_{22}$ so for that define errorse_2, e_4;

step 3

$$\begin{aligned} e_2 &= x^*_{12} - x_{12} \\ &= \frac{1}{l_3}(K_1e_1 + \dot{x}^*_{11} + l_1T_l - \varepsilon_\omega) - x_{12} \\ e_4 &= x^*_{12} - x_{12} \\ &= \frac{1}{2l_5}(K_3e_3 + \dot{x}^*_{21} + 2l_4x_{21} - 2\psi_{rx}\varepsilon_{\psi x} - 2\psi_{ry}\varepsilon_{\psi y}) - x_{22} \end{aligned} \tag{6.31}$$

the error dynamics equation of e_1, e_3 can also be expressed as;

$$\begin{aligned} \dot{e_1} &= e_2l_3 - K_1e_1 \\ \dot{e_3} &= 2l_5e_4 - K3e_3 \end{aligned} \tag{6.32}$$

Error dynamics of e_2 and e_4 can be computed by;

$$\begin{aligned} \dot{e_2} &= \phi_1 - v_1 \\ \dot{e_4} &= \phi_2 - v_2 \end{aligned} \tag{6.33}$$

ϕ_1, ϕ_2 are known signals and can be expressed as follows;

$$\begin{aligned} \phi_1 &= \frac{1}{l_3}(K_1(-K_1 e_1 + e_2 l_3)) + \frac{1}{l_3} l_1 \dot{T}_l + (l_7 - l_4) x_{12} \\ \phi_2 &= \frac{K_3}{2l_5}(-K_3 e_3 + 2l_5 e_4) - \frac{2l_4^2}{l_5} x_{21} + (3l_4 - l_7) x_{22} \\ &+ \frac{3l_4}{l_5}\psi_{rx}\varepsilon_{\psi x} + \frac{3l_4}{l_5}\psi_{ry}\varepsilon_{\psi y} - i_{sx}\varepsilon_{\psi x} - i_{sy}\varepsilon_{\psi y} \\ &- \frac{(\omega_s - \omega_m)}{l_5}\psi_{ry}\varepsilon_{\psi x} + \frac{(\omega_s - \omega_m)}{l_5}\psi_{rx}\varepsilon_{\psi y} - \frac{\varepsilon_{\psi x}^2}{l_5} - \frac{\varepsilon_{\psi y}^2}{l_5} \end{aligned} \tag{6.34}$$

step 4

Now consider the extended lypnuov function for the whole system ;

$$V_e = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 + \frac{1}{2}e_3^2 + \frac{1}{2}e_4^2 \tag{6.35}$$

By taking derivative of the function;

$$\begin{aligned} \dot{V_e} &= e_1\dot{e_1} + e_2\dot{e_2} + e_3\dot{e_3} + e_4\dot{e_4} \\ &= e_1(-K_1 + e_2 l_3) + e_2(\phi_1 - v_1) + \\ & e_3(-K_3 e_3 + 2l_5 e_4) + e_4(\phi_2 - v_2) \\ &= -K_1 e_1^2 - K_2 e_2^2 - K_3 e_3^2 - K_4 e_4^2 + \\ & e_2(K_2 e_2 + e_1 l_3 + \phi_1 - v_1) + e_4(2l_5 e_3 + \phi_2 - v_2 + K_4 e_4) \end{aligned} \tag{6.36}$$

For negative laypnuov function control input can be given as;

$$\begin{aligned} v_1 &= K_2 e_2 + e_1 l_3 + \phi_1 \\ v_2 &= K_4 e_4 + 2e_1 l_5 + \phi_2 \end{aligned} \tag{6.37}$$

This implies;

$$\dot{V_e} = -K_1 e_1^2 - K_2 e_2^2 - K_3 e_3^2 - K_4 e_4^2 \leq 0 \tag{6.38}$$

6.1.4 Flux estimation

Implementation of this multi scalar model require the fluxes ψ_{rx}, ψ_{ry} which makes this complex. Different methods can be used to find state variables. Observer of the system based on current or voltage model can be used with simple power measurements estimation. Stator fluxes can be represented i stationary frame as follows;

$$\begin{aligned} \psi_{s\alpha} &= \int (u_\alpha - R_s i s\alpha) dt \\ \psi_{s\beta} &= \int (u_{s\beta} - R_s i s\beta) dt \end{aligned} \tag{6.39}$$

Rotor fluxes can be given as;

$$\begin{aligned} \psi_{r\alpha} &= \frac{L_r}{L_m}(\psi_{s\alpha} - \sigma L_s i_{s\alpha}) \\ \psi_{r\beta} &= \frac{L_r}{L_m}(\psi_{s\beta} - \sigma L_s i_{s\beta}) \end{aligned} \tag{6.40}$$

Rotor fluxes in stationary coordinate system can be easily estimated by using stator currents;

$$\begin{aligned} \frac{\tilde{\psi_{r\alpha}}}{dt} &= \frac{R_r}{L_r}\tilde{\psi_{r\alpha}} - \omega_m \tilde{\psi_{r\beta}} + \frac{R_r L_m}{L_r} i_{s\alpha} \\ \frac{\tilde{\psi_{r\beta}}}{dt} &= \frac{R_r}{L_r}\tilde{\psi_{r\beta}} - \omega_m \tilde{\psi_{r\alpha}} + \frac{R_r L_m}{L_r} i_{s\beta} \end{aligned} \tag{6.41}$$

Fluxes in stationary and rotating frames can be linked as;

$$\begin{bmatrix} \tilde{\psi_{rx}} \\ \tilde{\psi_{ry}} \end{bmatrix} = \begin{bmatrix} cos(\theta_s^*) & sin(\theta_s^*) \\ -sin(\theta_s^*) & cos(\theta_s^*) \end{bmatrix} \begin{bmatrix} \tilde{\psi_{r\alpha}} \\ \tilde{\psi_{r\beta}} \end{bmatrix} \tag{6.42}$$

where;

$$\theta_s^* = \int \omega_s^* dt \tag{6.43}$$

6.1.5 System parameters

Table 6.1: Parameters and Their Values

Parameters	**Discription**	**Values**
P_rated	Rated Power	700 W
P_c	Number of pole	2
R_s	Stator resistance	0.6837 Ω
R_r	Rotor resistance	0.451 Ω
L_s	Stator inductance	4.128 mH
L_r	Rotor inductance	4.125 mH
L_m	Mutual inductance	145.6 mH
J	Rotor inertia	0.11 kgm^2
vdc	DC-link voltage	460 $volts$

6.1.6 Results:

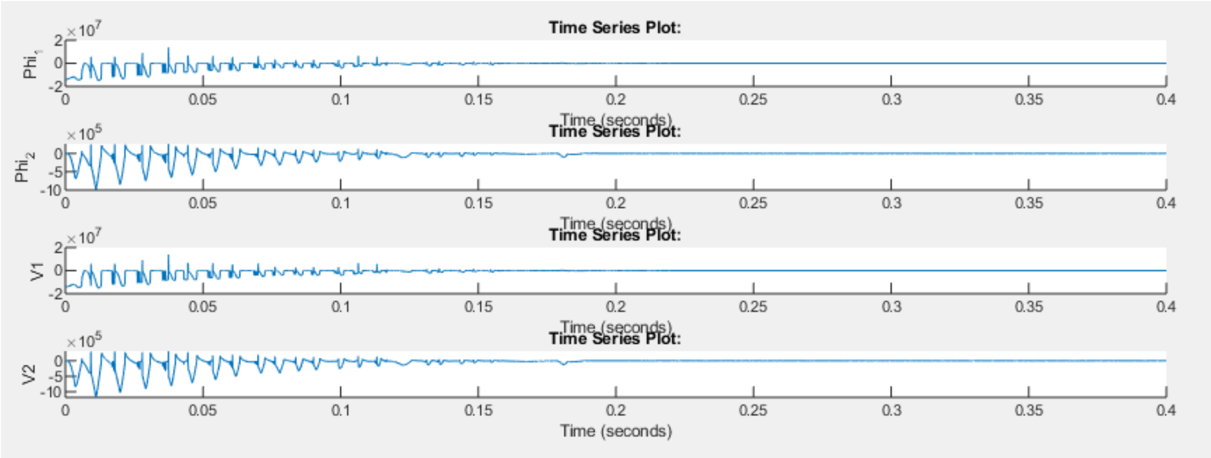

Figure 6.1: Flux and voltage functions

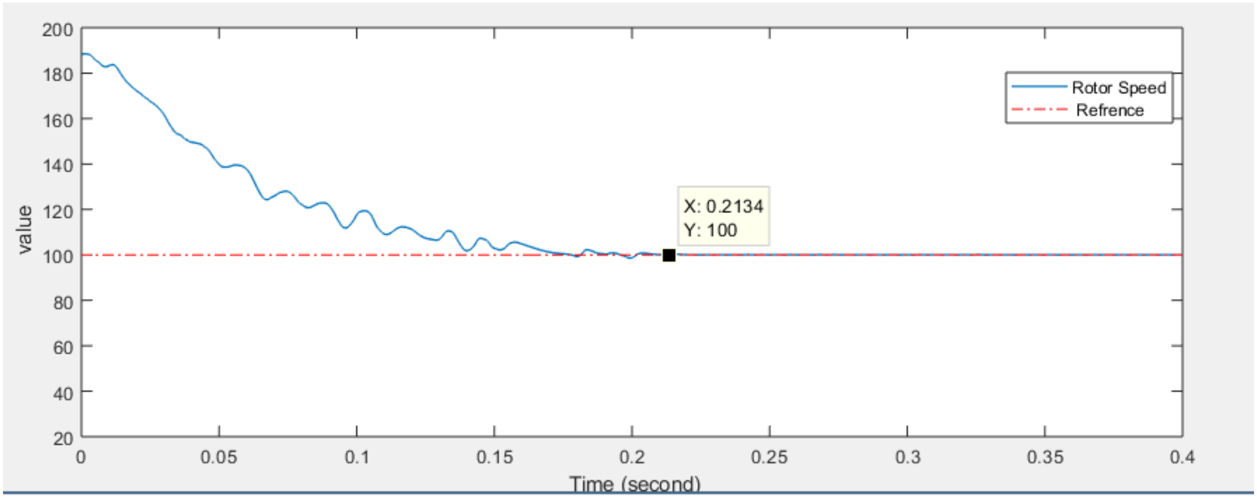

Figure 6.2: Speed control of motor

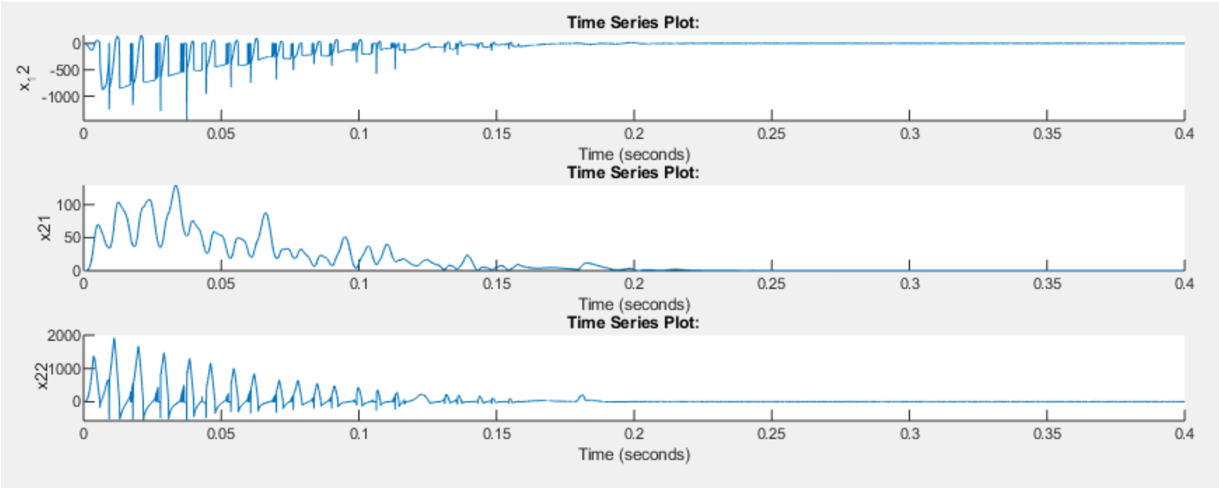

Figure 6.3: Four states of motor

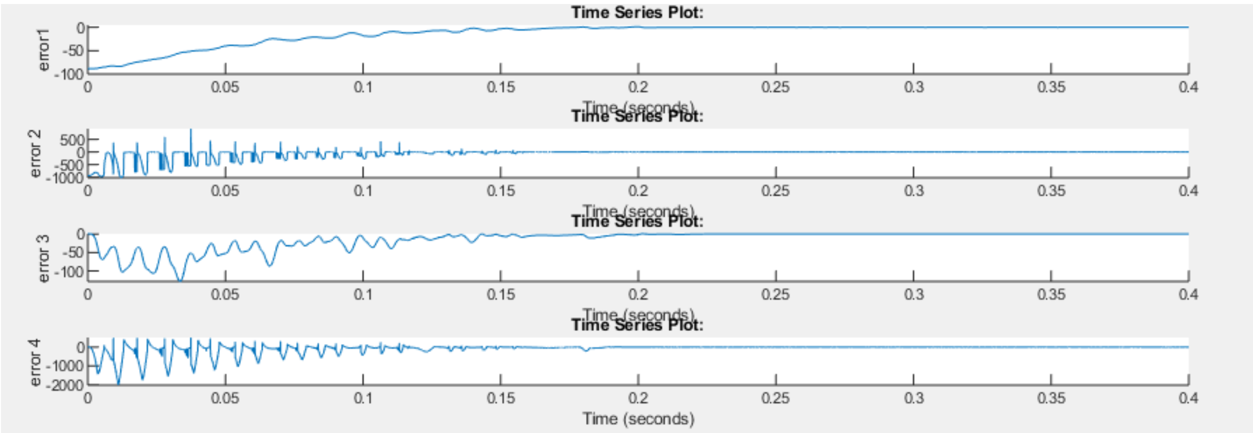

Figure 6.4: Error in states

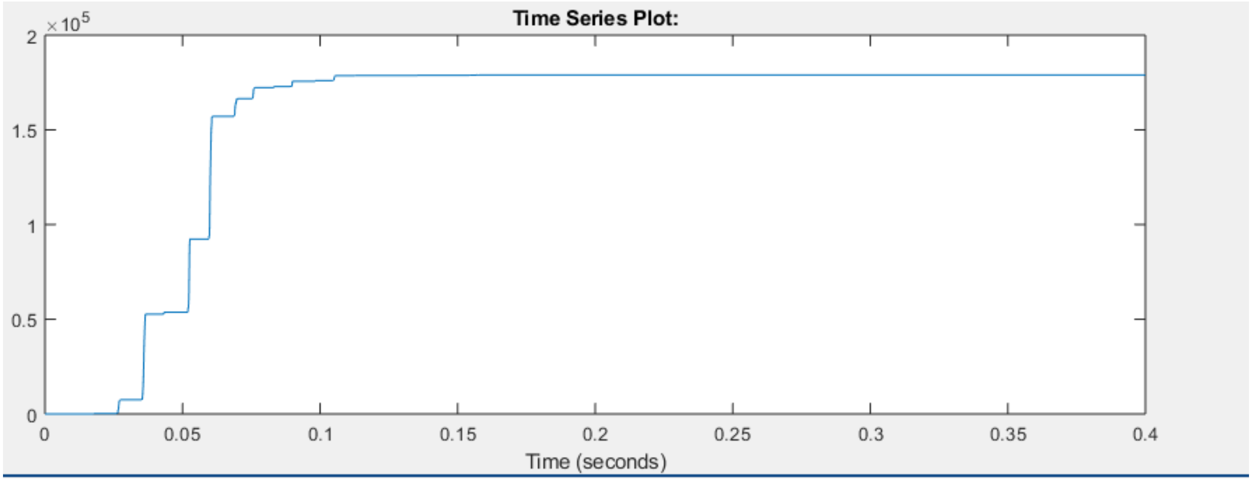

Figure 6.5: Rotating frame angle

Chapter 7

Conclusions

In the thesis above we are presenting the nonlinear Backstepping control of 4-states non-linear induction motor model, which can deal with the external disturbances and model parametric uncertainty. Lyapunov function theory knowledge provides us with mathematical analysis of this control and it shows the global asymptotic stability of the system. Comparing the results with classical techniques like Field oriented control and Direct torque control shows that Backstepping controller gives much better tracking and stability performance. All the above simulation's analysis are done using MATLAB. Numerical comparison of the performances of controllers are given in the Table II . This table gives the overall view of performance of proposed and classical techniques. It shows that the proposed controller has overall better performance than other control techniques. Further more this can also be seen in the graphical results.

7.1 Future Work

In the above research work is can be seen that the proposed control scheme for motor control gives much better results than classical one. Computational cost is very important factor in control scheme practical implementation, so keeping that in view our proposed scheme might be computationally costly. So, in the future Backstepping and Sliding mode control combined can be applied to the system which might give more better and computationally effective results.

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