ANALYSIS AND COMPARISON OF SCALAR AND VECTOR CONTROL FOR ADJUSTABLE SPEED AC DRIVES

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In

POWER SYSTEMS & ELECTRIC DRIVES

Submitted By:

Kulraj Kaur

800941016

Under the Supervision of:

Mr. Shakti Singh

Assistant Professor, EIED

&

Mr. S.S.S.R. Sarathbabu Duvvuri

Lecturer, EIED

DEPARTMENT OF ELECTRICAL AND INSTRUMENTATION ENGINEERING

THAPAR UNIVERSITY PATIALA, PUNJAB-147004

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CERTIFICATE

I hereby declare that the work which is presented in the thesis report, entitled, "**Analysis and Comparison of Scalar and Vector Control for Adjustable Speed AC Drives** ", in partial fulfilment of the requirements for the award of the Master's degree in Power Systems & Electric Drives, submitted in Electrical and Instrumentation Engineering Department, Thapar University, Patiala, is an authentic record of initial work carried out under the supervision of Mr. Shakti Singh, EIED and Mr. SSSR Sarathbabu Duvvuri, EIED, THAPAR UNIVERSITY,PATIALA.

Kulraj Kaur

Dated 11/7/2011 **Kulraj Kaur**

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

Shakti Singh 11/7

D. Sarathbabu

Shakti Singh
Assistant Professor, EIED
Thapar University, Patiala

SSSR Sarathbabu Duvvuri
Lecturer, EIED
Thapar University, Patiala

Countersigned by

S. Ghosh 11/7/11

Dr. Smarajit Ghosh
Professor & Head, EIED
Thapar University, Patiala

Dr.S.K.Mohapatra
Dean (Academic Affairs)
Thapar University, Patiala

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ABSTRACT

The control and estimation of induction motor drives constitutes a vast subject and the technology has been advanced in recent years. The control and estimation of AC drives in general are considerably more complex than those of DC drives and this complexity increase substantially if high performances are demanded. The main reason for this complexity are the need of variable-frequency, harmonically optimum converter power supplies, the complex dynamics of AC machines ,machine parameter variations, and the difficulties of processing feedback signals in the presence of harmonics.

The scalar V/f method is able to provide speed variation, but this method cannot provide real-time control. In other words, the system response is only satisfactory at steady state and not during transient conditions. The indirect field oriented controls, or vector control, for speed and torque controlled AC drives are becoming the industry standard in order to obtain high dynamic motor performance. The vector control of induction motor is used instead of conventional scalar control aims at decoupling the torque and flux producing components of the stator current under all operating speed and load conditions. Consequently, the drive can be tuned for quasi – instantaneous tracking of load and reference changes.

Here in this thesis, several fundamental methods for speed control and efficiency enhancement are discussed. The complete proposed system is simulated in MATLAB/Simulink. Simulation studies on induction motor using different techniques are carried out which is tested and recorded for its performance under various conditions and the result is compared with hardware.

CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

DC	Direct Current
AC	Alternating Current
V/f	Voltage/frequency
IM	Induction Motor
LQ	Linear Quadratic
DSP	Digital Signal Processor
PWMVSI	Pulse Width Modulation Variable Source Inverter
VFD	Variable Frequency Drive
VSD	Variable Speed Drive
VVVF	Variable Voltage Variable Frequency
PI	Proportional Integral

LIST OF SYMBOLS

Symbol	**Description**
a	120° operator.
$\bar{i}_r$	Space phasor of the rotor current expressed in the rotor reference frame
$\bar{i}_r'$	Space phasor of the rotor current expressed in the stator reference frame.
$i_{ri}(t)$	Rotor current per phase
$i_{si}(t)$	Stator current per phase
$\bar{i}_s$	Space phasor of the stator current expressed in the stator reference frame
$\bar{i}_s'$	Space phasor of the stator current expressed in the rotor reference frame
L_m	Three phase magnetizing inductance
L_r	Total three phase rotor inductance
$\bar{L}_r$	Rotor self-inductance
L_{r1}	Leakage rotor inductance
L_{rm}	Rotor magnetising inductance
L_s	Total three phase stator inductance
$\bar{L}_s$	Stator self-inductance
L_{sm}	Stator magnetising inductance
L_{s1}	Leakage stator inductance
$\bar{M}_r$	Mutual inductance between rotor windings
$\bar{M}_s$	Mutual inductance between stator windings
$\bar{M}_{sr}$	Maximal value of the stator- rotor mutual inductance
p	Derivation operator
P	Pair of poles
R_r	Rotor Resistance
R_s	Stator Resistance
s	Slip
α,β	Stator orthogonal coordinate system
$u_{s\alpha\beta}$	Stator voltages [V]

$i_{s\alpha\beta}$	Stator currents [A]
$u_{r\alpha\beta}$	Rotor voltages [V]
$i_{r\alpha\beta}$	Rotor currents [A]
$\psi_{s\alpha\beta}$	Stator magnetic fluxes
$\psi_{r\alpha\beta}$	Rotor magnetic fluxes
R_s	Stator phase resistance [Ohm]
R_r	Rotor phase resistance [Ohm]
L_s	Stator phase inductance [H]
L_r	Rotor phase inductance [H]
L_m	Mutual (stator to rotor) inductance [H]
ω / ω_s	Electrical rotor speed / synchronous speed [rad/s]
p_p	Number of pole pairs
t_e	Electromagnetic torque [Nm]
1/s	Integration operator
T_e	Instantaneous value of the electromagnetic torque
$\bar{U}_r$	Space phasor of the rotor voltage expressed in the rotor reference frame
$\bar{U}_r'$	Space phasor of the rotor voltage expressed in the stator reference frame
θ_m	Stator to rotor angle
θ_r	Rotor angle
θ_s	Stator angle
$\psi_{ri}(t)$	Flux linkage per rotor winding
$\bar{\psi}_r'$	Space phasor of the rotor flux linkage expressed in the rotor reference Frame
$\psi_{si}(t)$	Flux linkage per stator winding

Chapter 1
INTRODUCTION

1.1 Historical Review

The history of electrical motors goes back as far as 1820, when Hans Christian Oersted discovered the magnetic effect of an electric current. One year later, Michael Faraday discovered the electromagnetic rotation and built the first primitive D.C. motor. Faraday went on to discover electromagnetic induction in 1831, but it was not until 1883 that Tesla invented the A.C asynchronous motor. Currently, the main types of electric motors are still the same, DC, AC asynchronous and synchronous, all based on Oersted, Faraday and Tesla's theories developed and discovered more than a hundred years ago.

Since its invention, the AC asynchronous motor, also named induction motor, has become the most widespread electrical motor in use today. At present, 67% of all the electrical energy generated in the UK is converted to mechanical energy for utilization. In Europe the electrical drives business is worth approximately $1.0 Billion/ Annum. These facts are due to the induction motors advantages over the rest of motors. The main advantage is that induction motors do not require an electrical connection between stationary and rotating parts of the motor. Therefore, they do not need any mechanical commutator (brushes), leading to the fact that they are maintenance free motors. Induction motors also have low weight and inertia, high efficiency and a high overload capability. Therefore, they are cheaper and more robust, and less prone to any failure at high speeds. Furthermore, the motor can work in explosive environments because no sparks are produced.

Taking into account all the advantages outlined above, induction motors must be considered the perfect electrical to mechanical energy converter. However, mechanical energy is more than often required at variable speeds, where the speed control system is not a trivial matter.

The only effective way of producing an infinitely variable induction motor speed drive is to supply the induction motor with three phase voltages of variable frequency and variable amplitude. A variable frequency is required because the rotor speed depends on the speed of the rotating magnetic field provided by the stator. A variable voltage is required because the motor impedance reduces at low frequencies and consequently the current has to be limited by means of reducing the supply voltages [2] [1].

Before the days of power electronics, a limited speed control of induction motor was achieved by switching the three-stator windings from delta connection to star connection, allowing the voltage at the motor windings to be reduced. Induction motors are also available with more than three stator windings to allow a change of the number of pole pairs. However, a motor with several windings is more expensive because more than three connections to the motor are needed and only certain discrete speeds are available. Another alternative method of speed control can be realized by means of a wound rotor induction motor, where the rotor winding ends are brought out to slip rings. However, this method obviously removes most of the advantages of induction motors and it also introduces additional losses. By connecting resistors or reactance's in series with the stator windings of the induction motors, poor performance is achieved.

At that time the above described methods were the only ones available to control the speed of induction motors, whereas infinitely variable speed drives with good performances for DC motors already existed. These drives not only permitted the operation in four quadrants but also covered a wide power range. Moreover, they had a good efficiency, and with a suitable control even a good dynamic response. However, its main drawback was the compulsory requirement of brushes [1].

With the enormous advances made in semiconductor technology during the last 20 years, the required conditions for developing a proper induction motor drive are present. These conditions can be divided mainly in two groups:

- The decreasing cost and improved performance in power electronic switching devices.
- The possibility of implementing complex algorithms in the new microprocessors.

However, one precondition had to be made, which was the development of suitable methods to control the speed of induction motors, because in contrast to its mechanical simplicity their complexity regarding their mathematical structure (multivariable and non-linear) is not a trivial matter. It is in this field, that considerable research effort is devoted. The aim being to find even simpler methods of speed control for induction machines. One method which is popular at the moment is Vector Control [5].

1.2 Literature Review

Implementation of a Scalar Controlled Induction Motor Drives, this paper presents design and implementation of a V/F control of induction motor. This scheme leads to be able to adjust the speed of the motor by control the frequency and amplitude of the stator voltage, the ratio of stator voltage to frequency should be kept constant, which is known as V/F or scalar control. The PI controller is applied to speed signal model of the inverter and is then downloaded to dSPACE through Simulink.[33]

Improvement of the stability of the V/f controlled Induction motor drive systems; this paper presents a new approach of V/f control, which is based on current feedback to improve the stability of the conventional V/f control. The proposed approach is based on the stator current derivatives. This new method has successfully damped the torque and speed oscillations in V/f control for low power IM drive system. However, applying this method for high voltage IM resulted in more oscillations and lead to a highly unstable drive system. This paper analyzes the causes of this instability and proposes a damper to suppress the undesirable oscillations. The proposed damper is easy to implement and helps eliminate the oscillations which caused the instability of V/f for high voltage IM. [34]

A Novel V/f Scalar Controlled Induction Motor Drives with Compensation Based on Decoupled Stator Current, The control scheme is based on the popular constant volts per hertz (V/f) only using the current sensors. Based on the angles per second mathematical model of the induction motor, the rotor flux vector is estimated to decouple the stator current. The slip frequency and the current-resistant stator voltage drop are and compensated based on flux and torque component of the stator current in the rotor-flux oriented reference frame. It shows that, by using the proposed method, the speed can be controlled down to l Hz with full load torques.[32]

Vector or Field-Oriented Control: Ideally a vector-controlled induction motor drive behaves like a separately excited dc motor drive. The vector control is also known as decoupling, orthogonal, or trans-vector control. It is a revolutionary invention in ac drives Technology. The higher order and coupling model of the machine that gives complex stability and sluggish response problems in a scalar controlled drive tend to vanish with vector control. Vector control techniques can be classified as indirect or feed forward method and direct or feedback method depending on the method of unit vector generation for vector rotation. There is also classification of control based on orientation with air gap flux, rotor flux, stator flux. [2]

Induction motor space vector control using adaptive reference model Direct and Indirect methods, presents the simulation results of vector speed control of an induction motor. In this paper, both the direct and indirect methods were simulated using MATLAB (SIMULINK). A squirrel cage induction motor model was used, taking the reference coordinates as the rotor magnetic field.[28]

Design, Modelling, Simulation and Implementation of Vector Controlled Induction Motor Drive, uses the principle of vector control of AC machine which enables the dynamic control of AC motors, and induction motors in particular to a performance level comparable to that of a DC machine. The basic equations describing the dynamic behaviour of an induction machine in a rotating reference frame are listed. Based on these equations the structure of the vector controlled induction motor drive is obtained. A design procedure is developed for systematic design of the gain and time constant of various controllers. The procedure is evaluated through extensive computer simulation.[27]

Optimal and robust digital current controller synthesis for vector-controlled induction motor drive systems, describes that the vector-controlled induction-motor drive is a multi-input multi-output system. By using modern control techniques, all feedback loops can be closed simultaneously, in addition to obtaining optimal gains for the controllers. A systematic approach to the design of the digital current controllers is proposed. A vector controlled Induction motor drive system is usually viewed as a full-state feedback problem, where the non-measurable states are estimated using suitable reduced-order observers. Here, the induction-motor-drive system is viewed as a linear quadratic (LQ) tracker problem with output feedback, as this approach uses only the measurable states of the system and provides flexibility in choosing the control structure. The current controllers are designed for the torque dynamics of the induction motor. The controller should also be so designed that the whole drive system is stable for a class of induction motors, i.e. the whole drive system should be stable in the face of uncertainties in the parameters of the induction motor. Therefore, it becomes essential to build stability robustness into the controller design. The concepts are illustrated by simulation.[26]

Indirect Vector Control of Induction Motor, this paper emphasis a solution for induction motor speed control. It presents a vector control model of induction machine with four parameters only. The indirect vector control structure was reformulated according to this model, simulated with MATLAB, and implemented with a floating-point DSP processor. The experimental results show good transient and steady-state performances. The accuracy of the results is given by the precision of the motor model used.[25]

From scalar control to space vector control: functions and limitations of the different elements, this paper begins with the description of a rotary flux scalar scheme and studies the influence of the parameter uncertainties on the flux orientation and on the current values. Then it builds step by step a feed-forward based vector control scheme, explaining the role and the limits of each control blocks.[30]

1.3 Research Methodology

The control scheme used has been done in MATLAB. Then accordingly the results have been obtained after simulation. Suitable development environments are very important in simulation. MATLAB 7.10 has been used for this work.

With the MATLAB language, one can program and develop algorithms faster than with traditional languages because it is not needed to perform low-level administrative tasks, such as declaring variables, specifying data types, and allocating memory. The need for ‘for’ loops is also eliminated most of the times in MATLAB. As a result, one line of

MATLAB code can often replace several lines of C or C++ code. Its simple syntax makes it easy to learn and use. It makes debugging faster than any of the programming languages and developing environments. It can also be used as a numerical and symbolic calculator, visualization system, a programming language, modeling and data analysis environment and many more. It allows one to perform numerical calculations, and visualize the results without the need for complicated and time consuming programming. Toolboxes available can replace or enhance the usage of traditional simulation tools for advanced engineering applications.

MATLAB was developed in the 1970s by Cleve Moler. MATLAB was written in C and MathWorks was founded in 1984 to continue its further development. These rewritten libraries were called as JACKPAC. A newer set of libraries for matrix manipulation was again added in 2000 called LAPACK. An additional package, Simulink, adds graphical multi-domain simulation and provides model-based designs for dynamic and embedded systems [16].

The MATLAB application is built around the MATLAB language. The simplest way to execute MATLAB code is to type the code in the Command Window, which is one of the elements of the Desktop of MATLAB. Once code is entered in the Command Window, MATLAB can be used as an interactive mathematical shell. Sequences of commands can be saved in a text file, using the MATLAB Editor or encapsulated into a function, extending the commands available. For general-purpose scalar computations, MATLAB generates machine-code instructions using its JIT (Just-In-Time) compilation technology.

MATLAB is a proprietary product of MathWorks, so users are subject to vendor lock-in. Although MATLAB Builder can deploy MATLAB functions as library files which can be used with .NET or Java application building environment, future development will still be tied to the MATLAB language. In 2004, MATLAB had around one million users across industry and academia MATLAB users come from various backgrounds of engineering, science, and economics. It is widely used in academic and research institutions as well as industrial enterprises.

1.4 Scope and objectives of the Research

The research will be carried out keeping in view the following main objectives:

1. The present thesis deals with the development of a High Precision Control of Induction Motor Drive using different techniques so that the overall performance of the drive system is excellent.

2. To theoretically analyze the cause of the instability of the V/f based drive system, and to propose a method to eliminate the errors and

3. To carry out simulation study to verify the effectiveness of the proposed approach.

1.5 Layout of the dissertation

Defining the outline of this work, Chapter 2 starts with a detailed theoretical analysis of induction motor like popularity and advantages of stationary reference frame theory in induction motor. And also gives the details of modeling of the Induction Motor. It introduces a mathematical model of cage rotor induction motors. Different ways of implementing these models are presented.

Chapter 3 entitled “Induction motor Control”. In this chapter types of induction motor controls are discussed briefly and the scalar and vector control in depth. The system block diagrams for both methods are given and discussed based upon which the simulation in MATLAB is done.

Chapter 4 “Simulink model and experimental results” elaborates the simulation results for the control techniques and the comparative analysis is made between them.

Finally, the conclusions and recommendations along with the future scope according to work done in the field are summarized in Chapter 5.

Chapter 2

MODELLING OF INDUCTION MOTOR

2.1. Introduction

A dynamic model of the machine subjected to control must be known in order to understand and design vector controlled drives. Due to the fact that every good control has to face any possible change of the plant, it could be said that the dynamic model of the machine could be just a good approximation of the real plant. Nevertheless, the model should incorporate all the important dynamic effects occurring during both steady-state and transient operations. Furthermore, it should be valid for any changes in the inverter's supply such as voltages or currents.

Such a model can be obtained by means of either the space vector phasor theory or two-axis theory of electrical machines. Despite the compactness and the simplicity of the space phasor theory, both methods are actually close and both methods will be explained. For simplicity, the induction motor considered will have the following assumptions:

- Symmetrical two-pole, three phase windings.
- The slotting effects are neglected.
- The permeability of the iron parts is infinite.
- The flux density is radial in the air gap.
- Iron losses are neglected.
- The stator and the rotor windings are simplified as a single, multi-turn full pitch coil situated on the two sides of the air gap.

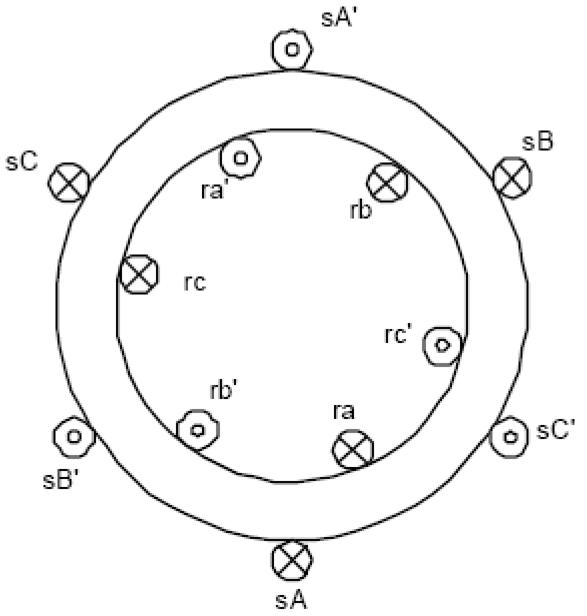


Figure 2.1 Cross-section of an elementary symmetrical three-phase machine

2.2 Mathematical Description of AC Induction Motors

There are a number of AC induction motor models. The model used for vector control design can be obtained by using the space vector theory. The 3-phase motor quantities (such as voltages, currents, magnetic flux, etc.) are expressed in terms of complex space vectors. Such a model is valid for any instantaneous variation of voltage and current and adequately describes the performance of the machine under both steady-state and transient operation. Complex space vectors can be described using only two orthogonal axes. The motor can be considered a 2-phase machine. The utilization of the 2-phase motor model reduces the number of equations and simplifies the control design.[4]

2.2.1 Space Vector Definition

Assume that i_{sa} , i_{sb} , and i_{sc} are the instantaneous balanced 3-phase stator currents:

$$i_{sa} + i_{sb} + i_{sc} = 0 \tag{2.1}$$

The stator current space vector can then be defined as follows:

$$\bar{i}_s = k(i_{sa} + ai_{sb} + a^2 i_{sc}) \tag{2.2}$$

The space vector defined by equation (2.1) can be expressed utilizing the two-axis theory. The real part of the space vector is equal to the instantaneous value of the direct-axis stator current component, $i_{s\alpha}$, and whose imaginary part is equal to the quadrature-axis stator current component, $i_{s\beta}$. Thus, the stator current space vector in the stationary reference frame attached to the stator can be expressed as:

$$\bar{i}_s = i_{s\alpha} + ji_{s\beta} \tag{2.3}$$

In symmetrical 3-phase machines, the direct and quadrature axis stator currents $i_{s\alpha}$, $i_{s\beta}$ are fictitious quadrature-phase (2-phase) current components, which are related to the actual 3-phase stator currents as follows:

$$i_{s\alpha} = k(i_{sa} - \frac{1}{2}i_{sb} + \frac{1}{2}i_{sc}) \tag{2.4}$$

$$i_{s\beta} = k\frac{\sqrt{3}}{2}(i_{sb} - i_{sc}) \tag{2.5}$$

Where:

$k=2/3$ is a transformation constant

The space vectors of other motor quantities (voltages, currents, magnetic fluxes, etc.) can be defined in the same way as the stator current space vector.

2.2.2 Voltage equations

The AC induction motor model is given by the space vector form of the voltage equations. The system model defined in the stationary α,β-coordinate system attached to the stator is expressed by the following equations. Ideally, the motor model is symmetrical, with a linear magnetic circuit characteristic. The stator voltages will be formulated in this section from the motor natural frame, which is the stationary reference frame fixed to the stator. In a similar way, the rotor voltages will be formulated to the rotating frame fixed to the rotor. In the stationary reference frame, the equations can be expressed as follows:

(a) The stator voltage differential equations:

$$u_{SA}(t) = R_s i_{SA}(t) + \frac{d\psi_{SA}(t)}{dt} \tag{2.6}$$

$$u_{SB}(t) = R_s i_{SB}(t) + \frac{d\psi_{SB}(t)}{dt} \tag{2.7}$$

$$u_{SC}(t) = R_s i_{SC}(t) + \frac{d\psi_{SC}(t)}{dt} \tag{2.8}$$

(b) The rotor voltage differential equations:

$$u_{RA}(t) = R_R i_{RA}(t) + \frac{d\psi_{RA}(t)}{dt} \tag{2.9}$$

$$u_{RB}(t) = R_R i_{RB}(t) + \frac{d\psi_{RB}(t)}{dt} \tag{2.10}$$

$$u_{RC}(t) = R_R i_{RC}(t) + \frac{d\psi_{RC}(t)}{dt} \tag{2.11}$$

(c) The stator and rotor flux linkages expressed in terms of the stator and rotor current space vectors:

$$\psi_{SA} = \bar{L}_S i_{sA} + \bar{M}_S i_{sB} + \bar{M}_S i_{sC} + \bar{M}_{sr} \cos\theta_m i_{ra} + \bar{M}_{sr} \cos(\theta_m + \frac{2\pi}{3}) i_{rb} + \bar{M}_{sr} \cos(\theta_m + \frac{4\pi}{3}) i_{rc} \tag{2.12}$$

$$\psi_{SB} = \bar{L}_S i_{sA} + \bar{M}_S i_{sB} + \bar{M}_S i_{sC} + \bar{M}_{sr} \cos(\theta_m + \frac{4\pi}{3}) i_{ra} + \bar{M}_{sr} \cos\theta_m i_{rb} + \bar{M}_{sr} \cos(\theta_m + \frac{2\pi}{3}) i_{rc} \tag{2.13}$$

$$\psi_{SC} = \bar{L}_S i_{sA} + \bar{M}_S i_{sB} + \bar{M}_S i_{sC} + \bar{M}_{sr} \cos(\theta_m + \frac{2\pi}{3}) i_{ra} + \bar{M}_{sr} \cos(\theta_m + \frac{4\pi}{3}) i_{rb} + \bar{M}_{sr} \cos\theta_m i_{rc} \tag{2.14}$$

In a similar way, the rotor flux linkages can be expressed as follows:

$$\psi_{ra} = \bar{L}_r i_{rA} + \bar{M}_r i_{rB} + \bar{M}_r i_{rC} + \bar{M}_{sr} \cos(-\theta_m) i_{sa} + \bar{M}_{sr} \cos(-\theta_m + \frac{2\pi}{3}) i_{sb} + \bar{M}_{sr} \cos(-\theta_m + \frac{4\pi}{3}) i_{sc} \tag{2.15}$$

$$\psi_{rb} = \bar{M}_r i_{rA} + \bar{L}_r i_{rB} + \bar{M}_r i_{rC} + \bar{M}_{sr} \cos(-\theta_m + \frac{4\pi}{3}) i_{sa} + \bar{M}_{sr} \cos(-\theta_m) i_{sb} + \bar{M}_{sr} \cos(-\theta_m + \frac{2\pi}{3}) i_{sc} \tag{2.16}$$

$$\psi_{rc} = \bar{M}_r i_{rA} + \bar{L}_r i_{rB} + \bar{M}_r i_{rC} + \bar{M}_{sr} \cos(-\theta_m + \frac{2\pi}{3}) i_{sa} + \bar{M}_{sr} \cos(-\theta_m + \frac{4\pi}{3}) i_{sb} + \bar{M}_{sr} \cos(-\theta_m) i_{sc} \tag{2.17}$$

Taking into account all the previous equations, and using the matrix notation in order to compact all the expressions, the following expression is obtained:

$$\begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \\ u_{ra} \\ u_{rb} \\ u_{rc} \end{bmatrix} = \begin{bmatrix} R_s + p\bar{L}_S & p\bar{M}_S & p\bar{M}_s & p\bar{M}_{sr}\cos\theta_m & p\bar{M}_{sr}\cos\theta_{m1} & p\bar{M}_{sr}\cos\theta_{m2} \\ p\bar{M}_S & R_s + p\bar{L}_S & p\bar{M}_s & p\bar{M}_{sr}\cos\theta_{m2} & p\bar{M}_{sr}\cos\theta_m & p\bar{M}_{sr}\cos\theta_{m1} \\ p\bar{M}_s & p\bar{M}_S & R_s + p\bar{L}_S & p\bar{M}_{sr}\cos\theta_{m1} & p\bar{M}_{sr}\cos\theta_{m2} & p\bar{M}_{sr}\cos\theta_m \\ p\bar{M}_{sr}\cos\theta_m & p\bar{M}_{sr}\cos\theta_{m1} & p\bar{M}_{sr}\cos\theta_{m2} & R_s + p\bar{L}_S & p\bar{M}_r & p\bar{M}_r \\ p\bar{M}_{sr}\cos\theta_{m2} & p\bar{M}_{sr}\cos\theta_m & p\bar{M}_{sr}\cos\theta_{m1} & p\bar{M}_r & R_r + p\bar{L}_r & p\bar{M}_r \\ p\bar{M}_{sr}\cos\theta_{m1} & p\bar{M}_{sr}\cos\theta_{m2} & p\bar{M}_{sr}\cos\theta_m & p\bar{M}_r & p\bar{M}_r & R_r + p\bar{L}_r \end{bmatrix} . \begin{bmatrix} i_{sA} \\ i_{sB} \\ i_{sC} \\ i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} \tag{2.18}$$

Besides the stationary reference frame attached to the stator, motor model voltage space vector equations can be formulated in a general reference frame, which rotates at a general speed, ω_g. [6]

The motor model voltage equations in the general reference frame can be expressed by using the transformations of the motor quantities from one reference frame to the general reference frame introduced. The AC induction motor model is often used in vector control algorithms. The aim of vector control is to implement control schemes which produce high-dynamic performance and are similar to those used to control DC machines. To achieve this, the reference frames may be aligned with the stator flux-linkage space vector, the rotor flux-linkage space vector or the magnetizing space vector. The most popular reference frame is the reference frame attached to the rotor flux linkage space vector with direct axis (*d*) and quadrature axis (*q*). After transformation into d-q coordinates the motor model follows:

2.2.3 Park’s transform

In order to reduce the expressions of the Induction motor equation voltages given in equation 2.1 to equation 2.6 and obtain constant coefficients in the differential equations, the

Park’s transform will be applied. Physically, it can be understood as transforming the three windings of the induction motor to just two windings.[6]

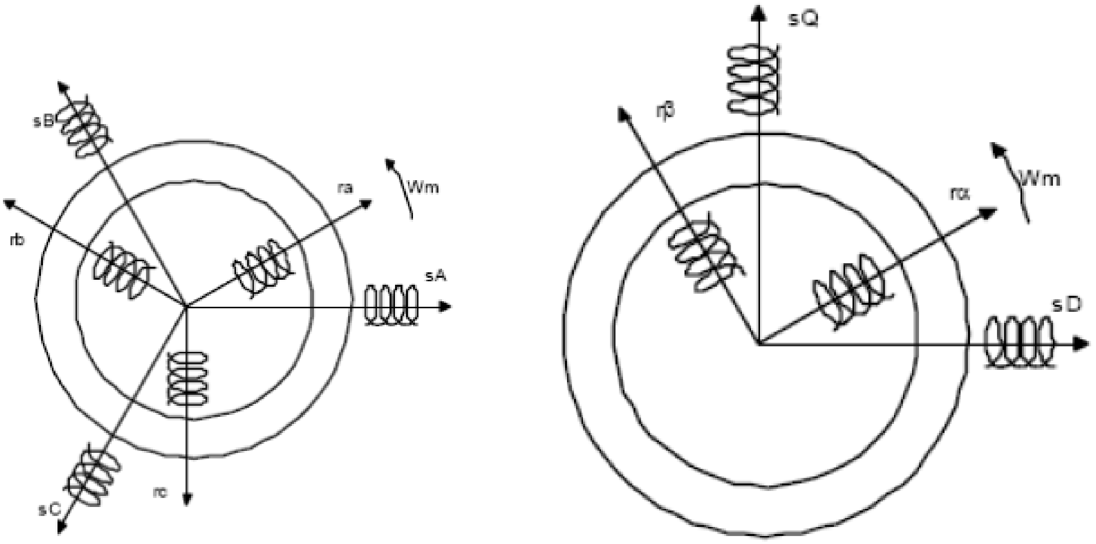


Figure 2.2 Schematic of the transformation

In the symmetrical three-phase machine, the direct and the quadrature-axis stator magnitudes are fictitious. The equivalencies for these direct (D) and quadrature (Q) magnitudes with the magnitudes per phase are as follows:

$$\begin{bmatrix} u_{sA} \\ u_{sB} \\ u_{sC} \end{bmatrix} = c \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & \cos\theta & -\sin\theta \\ \frac{1}{\sqrt{2}} & \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \cdot \begin{bmatrix} u_{so} \\ u_{sD} \\ u_{sQ} \end{bmatrix} \tag{2.19}$$

$$\begin{bmatrix} u_{sA} \\ u_{sB} \\ u_{sC} \end{bmatrix} = c_1 \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & \cos\theta & -\sin\theta \\ \frac{1}{\sqrt{2}} & \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \cdot \begin{bmatrix} u_{so} \\ u_{sD} \\ u_{sQ} \end{bmatrix} \tag{2.20}$$

Where c, c_1 are the constants with the values 2/3 or 1 for the so-called non-power invariant form or the value 2/3 for the power-invariant form. These previous equations can be applied as well for any other magnitudes such as currents and fluxes.

Notice how the expression (2.18) can be simplified into a much smaller expression in (2.21) by means of applying the mentioned Park's transform.

$$\begin{bmatrix} u_{sD} \\ u_{sQ} \\ u_{r\alpha} \\ u_{r\beta} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -L_s p\theta_s & pL_m & L_m(P \cdot w_m + p \cdot \theta_r) \\ L_s p\theta_s & R_s + pL_s & L_m(P \cdot w_m + p \cdot \theta_r) & pL_m \\ pL_m & -L_m(p\theta_s - P \cdot w_m) & R_r + pL_r & -L_r p\theta_r \\ L_m(p\theta_s - P \cdot w_m) & pL_m & L_r p\theta_r & R_r + pL_r \end{bmatrix} \cdot \begin{bmatrix} i_{sD} \\ i_{sQ} \\ i_{r\alpha} \\ i_{r\beta} \end{bmatrix} \tag{2.21}$$

2.3 Space phasor notation

Space phasor notation allows the transformation of the natural instantaneous values of a three phase system onto a complex plane located in the cross section of the motor. In this plane, the space phasor rotate with an angular speed equal to the angular frequency of the three phase supply system. A space phasor rotating with the same angular speed, for example, can describe the rotating magnetic field. Moreover, in the special case of the steady state, where the supply voltage is sinusoidal and symmetric, the space phasor become equal to three-phase voltage phasors, allowing the analysis in terms of complex algebra. It is shown in figure 2.3 the equivalent schematic for this new model.[6]

In order to transform the induction motor model, in natural co-ordinates, into its equivalent space phasor form, the 120º operator is introduced:

$$a = e^{j2\pi/3} \tag{2.22}$$

$$a^2 = e^{j4\pi/3} \tag{2.23}$$

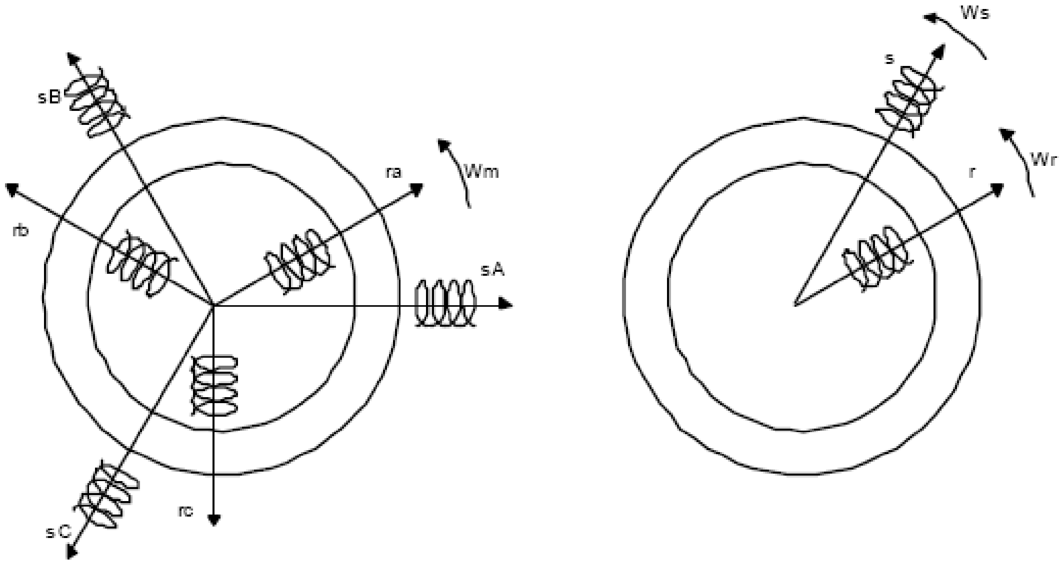


Figure 2.3 The equivalent two rotating windings of induction motor

2.4 Torque expressions

Electromagnetic torque expressed by utilizing space vector quantities:

$$T_e = \frac{3}{2} p_p (\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \tag{2.24}$$

The mechanical Torque equation is given by:

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \tag{2.25}$$

2.5 SUMMARY

This chapter deals with the detailed modeling of induction motor and derives equivalent two phase mathematical model of the induction motor which can be easily implemented in MATLAB/Simulink. The model is developed in the stator reference frame, and the torque expressions have also been derived.

Chapter 3
INDUCTION MOTOR CONTROL

3.1 Introduction

Asynchronous motor is a type of alternating current motor where power is supplied to the rotor by means of electromagnetic induction. An electric motor turns because of magnetic force exerted between a stationary electromagnet called the stator and a rotating electromagnet called the rotor. Different types of electric motors are distinguished by how electric current is supplied to the moving rotor. In a DC motor and a slip-ring AC motor, current is provided to the rotor directly through sliding electrical contacts called commutators and slip rings. In an induction motor, by contrast, the current is induced in the rotor without contacts by the magnetic field of the stator, through electromagnetic induction. An induction motor is sometimes called a rotating transformer because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Unlike the normal transformer which changes the current by using time varying flux, induction motors use rotating magnetic fields to transform the voltage. The current in the primary side creates an electromagnetic field which interacts with the electromagnetic field of the secondary side to produce a resultant torque, thereby transforming the electrical energy into mechanical energy. Induction motors are widely used, especially polyphase induction motors, which are frequently used in industrial drives.

Induction motors are now the preferred choice for industrial motors due to their rugged construction, absence of brushes (which are required in most DC motors) and thanks to modern power electronics—the ability to control the speed of the motor. The idea of the rotating magnetic field was developed by Francois Arago (1824) and implemented first by Walter Baily. The practical induction motors were independently realized by Galileo Ferraris, in Italy, and Nikola Tesla, in the United States. According to his 1915 autobiography Tesla had conceived the rotating magnetic field principle in 1882 and used it to invent the first brushless AC motor or induction motor in 1883. Ferraris developed the idea in 1885. In 1888, Ferraris published his research in a paper to the Royal Academy of Sciences in Turin where he detailed the theoretical foundations for understanding the way the motor operates.

Separately, in the same year, Tesla gained U.S. Patent 381,968. The induction motor with a cage was invented by Mikhail Dolivo-Dobrovolsky about a year later.[1]

The control and estimation of induction motor drives constitute a vast subject, and the technology has further advanced in recent years. Induction motor drives with cage type machines have been the work horses in the industry for the variable speed applications in a wide power range that covers from fractional horse power to multi megawatts. These applications include pumps and fans, paper and textile mills, subway and locomotive propulsions, electric and hybrid vehicles, machine tools and robotics, home appliances, heat pumps and air conditioners rolling mills, wind generation systems, etc. in addition to process control, the energy saving accept of variable frequency drives is getting a lot of attention now a days.

The control and estimation of ac drives in general is considerable more complex than those of dc drives, and this complexity increases substantially if high performances are demanded. The main reasons for this complexity are the need of variable frequency, machine parameter variation, and the difficulties of processing feedback signals in the presence of harmonics. While considering drive applications, we need to address the following questions:

- One, two or four quadrant drive?
- Torque, speed, or position control in the primary or outer loop?
- Single or multi motor drive?
- Range of speed control? Does it include zero speed and field-weakening regions?
- Accuracy and response time?
- Robustness with load torque and parameter variations?
- Control with speed sensor and senseless control?

To control the induction motor there are different types of control are there they are scalar control, vector control, direct torque control and flux control.

3.2 Basic Principles of Speed Control

The speed control of an induction motor requires more elaborate techniques than the speed control of DC machines. First, we will analyze the basic relationship for the speed-torque characteristics of an induction motor:

$$T_d = \frac{P_d}{\omega} = \frac{V^2 R_2'}{s\omega_s[\left(R_1 + \frac{R_2'}{s}\right)^2 + X_{eq}^2]} \tag{3.1}$$

By examining this equation, one can conclude that the speed ω [or slip s] can be controlled if at least one of the following parameters is altered:

1. Armature or rotor resistance
2. Armature or rotor inductance
3. Magnitude of terminal voltage
4. Frequency of terminal voltage

Each of the techniques by itself is not sufficient. However when more than one are combined, the control of the induction motor becomes more effective. Although it is not evident by examining equation 3.1, there are other useful and effective techniques for speed control. Among them are:

1. Rotor voltage injection
2. Slip energy recovery
3. Voltage/frequency control
4. Vector control

3.3 Scalar control

Scalar control as the name indicates, is due to magnitude variation of the control variables only and disregards the coupling effects in the machine. For example, voltage of a machine can be controlled to control the flux, and the frequency or the slip can be controlled to control the torque. However, flux and torque are also functions of frequency and voltage respectively. In Scalar control both the magnitude and phase alignment of vector variables are controlled. Scalar controlled drives give somewhat inferior performance, but they are easy to implement. Scalar controlled drives have been widely used in industry. However, their importance has diminished recently because of the superior performance of vector-controlled drives which is demanded in many applications.

For improvement of quality many industrial applications require variable speed and constant speed. Several techniques have been developed to control Alternating Current (AC) power. The operation of induction motors in the constant volts per hertz (V/f) mode has been known for many decades, and its principle is well understood. With the introduction of solid-state inverters, the constant V/f control became popular. Since the introduction of vector control theory almost all research has been concentrated in this area, and little has been published about constant V/f operation. Its practical application at low frequency is still challenging, due to the influence of the stator resistance and the necessary rotor slip to produce torque. In addition, the nonlinear behavior of the modern pulse width modulated voltage-source inverter (PWMVSI) in the low voltage range makes it difficult to use constant V/f drives at frequencies below 3 Hz.[36]

With the advancement in the semiconductor fabrication technology, both the size and the price of semiconductors have gone down drastically. This means that the motor user can replace an energy inefficient mechanical motor drive and control system with a Variable Frequency Drive (VFD). The VFD not only controls the motor speed, but can improve the motor’s dynamic and steady state characteristics as well. In addition, the VFD can reduce the system’s average energy consumption. V/f control caters to a large number of applications where the basic need is to vary the motor speed and control the motor efficiently. It is also simple to implement and cost effective.

A variable-frequency drive (VFD**)** is a system for controlling the rotational speed of an alternating current (AC) electric motor by controlling the frequency of the electrical power supplied to the motor. A variable frequency drive is a specific type of adjustable-speed drive. Variable-frequency drives are also known as adjustable-frequency drives (AFD), variable-speed drives (VSD), AC drives, micro drives or inverter drives. Since the voltage is varied along with frequency, these are sometimes also called VVVF (variable voltage variable frequency) drives. The most common type of packaged VF drive is the constant-voltage type, using pulse width modulation to control both the frequency and effective voltage applied to the motor load.[2]

3.3.1 V/f Control Principle

The base speed of the induction motor is directly proportional to the supply frequency and the number of poles of the motor. Since the number of poles is fixed by design, the best way to vary the speed of the induction motor is by varying the supply frequency. The torque developed by the induction motor is directly proportional to the ratio of the applied voltage and the frequency of supply. By varying the voltage and the frequency, but keeping their ratio constant, the torque developed can be kept constant throughout the speed range. This is exactly what V/f control tries to achieve.[34]

Other than the variation in speed, the torque-speed characteristics of the V/f control reveal the following:

- The starting current requirement is lower.

- The stable operating region of the motor is increased. Instead of simply running at its base rated speed (N_B), the motor can be run typically from 5% of the synchronous speed (N_S) up to the base speed. The torque generated by the motor can be kept constant throughout this region.

- At base speed, the voltage and frequency reach the rated values. We can drive the motor beyond the base speed by increasing the frequency further. However, the applied voltage cannot be increased beyond the rated voltage. Therefore, only the frequency can be increased, which results in the reduction of torque. Above the base speed, the factors governing torque become complex.

- The acceleration and deceleration of the motor can be controlled by controlling the change of the supply frequency to the motor with respect to time.

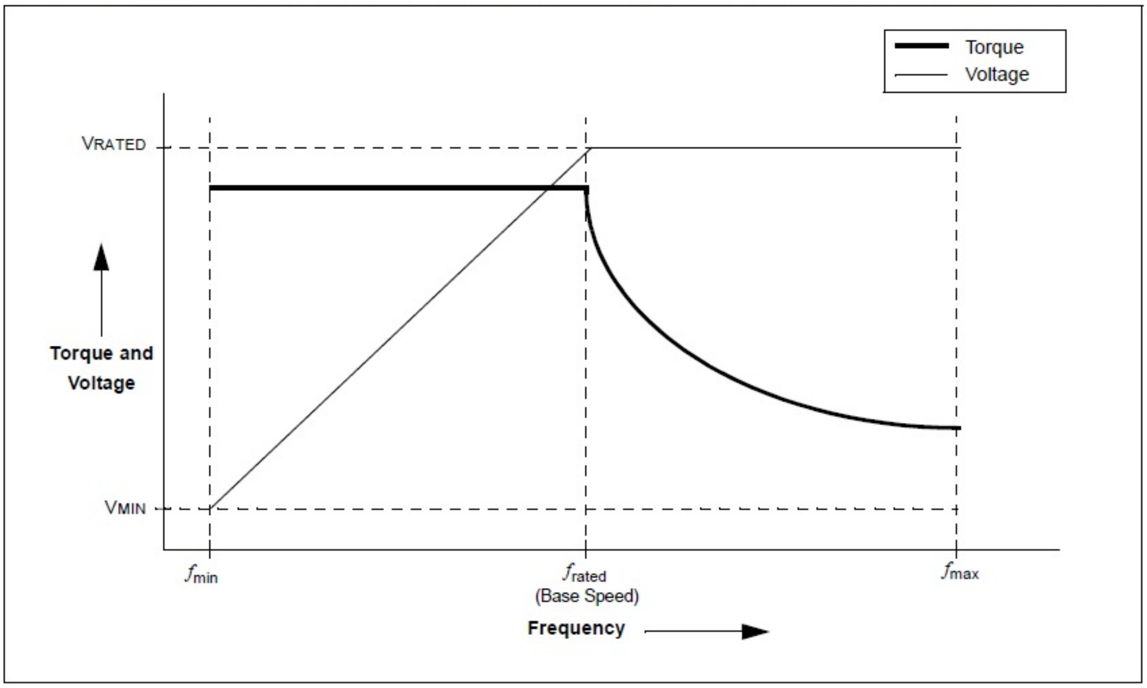


Figure 3.1 Torque Speed Characteristics of Induction Motor

The constant Volts per Hertz principle is today the most common control principle used in adjust-able-speed drives of induction machines. Hence, many real-life motor control applications do not need a high dynamic performance, as long as the speed can be efficiently varied in the full range. This allows to use a sinusoidal steady state model of the induction motor, in which the magnitude of the stator flux is proportional to the ratio between the magnitude and the frequency of the stator voltage. If this ratio is kept constant, the stator flux will remain constant, and so the motor torque will only depend on the slip frequency.

Roughly speaking, the scalar V/f control principle consists in feeding the motor windings with a 3-phase sinusoidal voltage whose amplitude is proportional to the frequency, except below the boost frequency and over the rated frequency. In practice, the slope that defines the relation between the voltage magnitude and the voltage frequency is deduced from the rated terminal supply voltage and the rated supply frequency written on the motor name plate, and the boost frequency is chosen equal to a percentage (say 5%) of the rated frequency. This principle can be used to build a speed control loop (in which the difference between the desired speed and the measured speed feeds a PI controller that determines the stator voltage frequency. To decrease the complexity of the controller, the input of the V/f law and of the space vector PWM algorithm is the absolute value of the stator voltage frequency. If the output of the PI controller is a negative number, two of the switching variables driving the power transistors of the inverter are interchanged.

The general control block diagram for variable frequency speed control of an induction motor drive is shown below. It consists of converter machine system with hierarchy of control loops added to it. The converter machine is shown with voltage V and frequency as control inputs. Instead of voltage control loop, the converter may be current controlled with direct and indirect voltage control in the inner loop.[35]

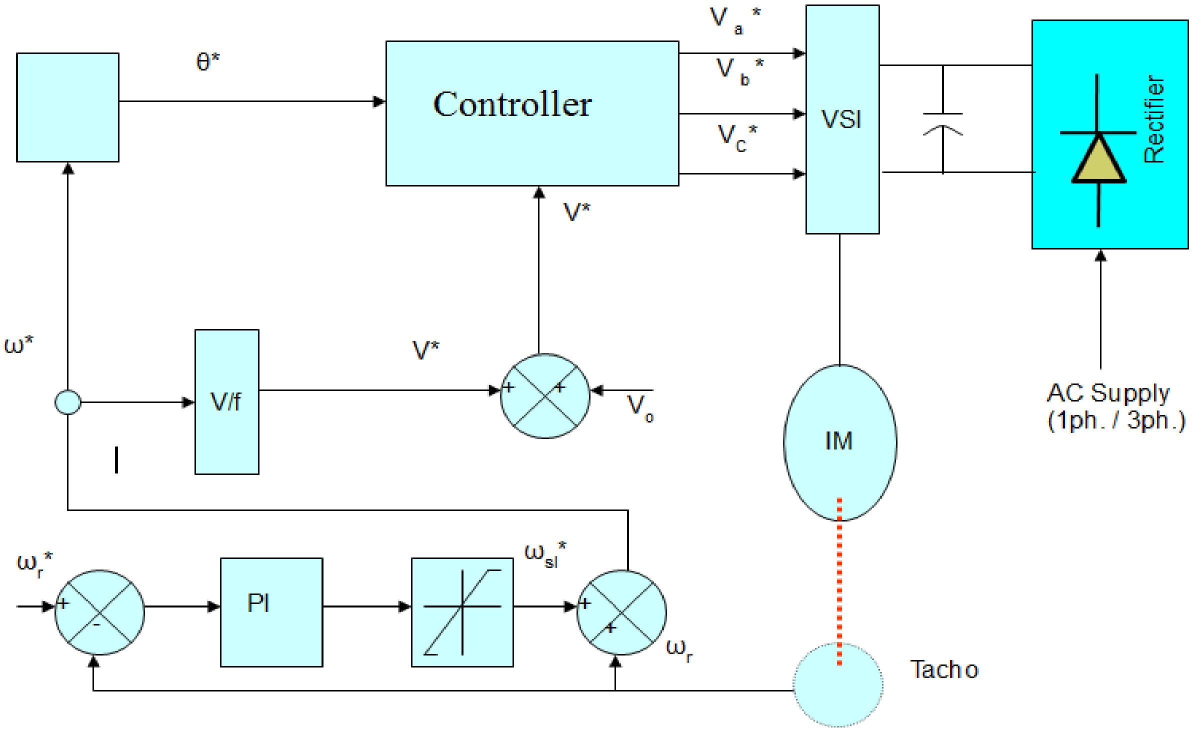


Figure 3.2 Block Diagram of V/f control of Induction Motor

The speed control is shown with an inner torque control loop, which may be optional. Adding a higher gain inner loop control provides the advantage of linearization, improved bandwidth and the ability to control the signals with in safe limits, like a dc machine, the flux of an AC machine is normally controlled to be constant at a rated value because it gives the faster response and high developed torque per ampere of current. In fact the flux under consideration may be stator flux), rotor flux or the air gap flux. However, the rotor flux control is considered in the present case. The inner control loops have faster response (i.e., higher bandwidth) than the outer loop. Since an AC drive system is a multivariable, nonlinear with internal coupling effect, and discrete time in nature, its stability analysis is very complex.

3.4 Vector or Field oriented control

The scalar control is somewhat easier to implement, but the inherent coupling effect (i.e. both torque flux are functions of voltage or current and frequency) gives sluggish response and the system is easily prone to instability because of higher order system effect. To make it more clear, if, for example, if the torque is increased by incrementing the slip (i.e. the frequency), the flux tends to decrease. Note the flux variation is always sluggish. The decrease is then compensated by the sluggish flux loop by feeding in additional voltage. This temporary dip in flux reduces the torque sensitivity with slip and lengthens the response time. This explanation is also valid for current fed inverter drives.

The foregoing problems can be solved by vector control or field – oriented control. The invention of vector control is in the beginning of 1970s, and the demonstration that the induction motor can be controlled like a separately excited dc motor, brought a renaissance in high performance control of ac drives. Because of dc machine like performance, vector control is also known as decoupling, orthogonal or trans vector control. Vector control is applicable to both induction and synchronous motor drives. Undoubtedly, vector control and the corresponding feedback signal processing, particularly for modern sensor less vector control, are complex and the use of powerful microcomputer or DSP is mandatory. It appears that eventually, vector control will oust scalar control, and will be accepted as industry standard control for ac drives.

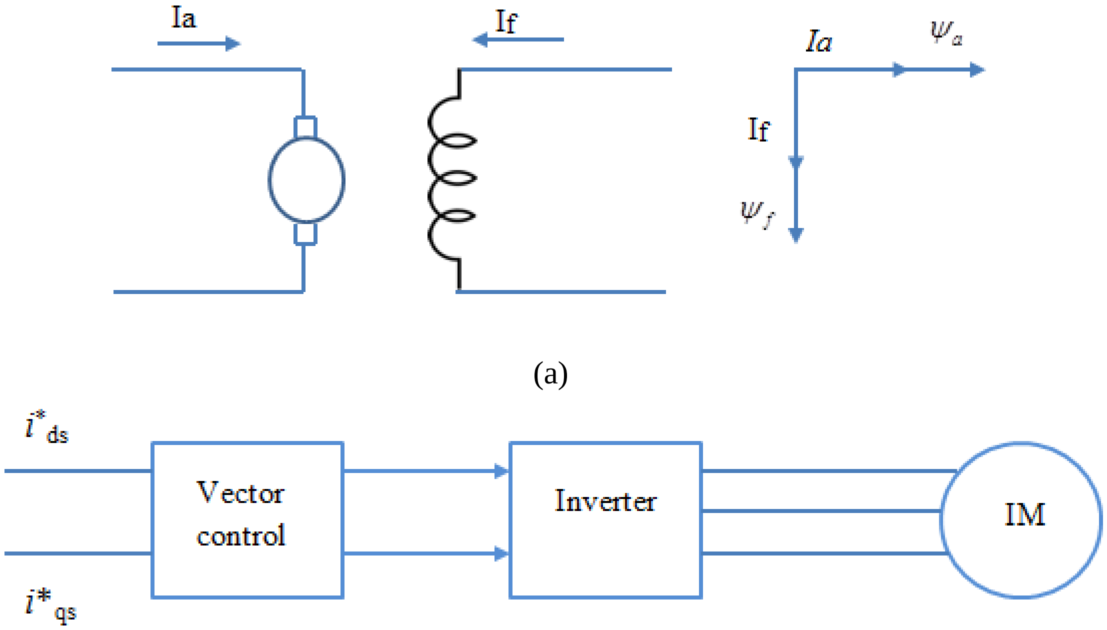
3.4.1 DC drive analogy

Ideally, a vector-controlled induction motor drive operates like a separately excited DC motor drive, as mentioned above; Figure 3.3 explains this analogy [2]. In a DC machine, neglecting the armature reaction effect and field saturation, the developed torque is given by

$$T_e = K^{'} I_a I_f \tag{3.2}$$

Where i_a = armature current and i_f= field current, the construction of a DC machine is such that the field flux ψ_f produced by the current I_f is perpendicular to the armature flux ψ_a, which is produced by the armature current I_a. These space vectors which are stationary in space are orthogonal or decoupled in nature. This means that when torque is controlled by controlling the current I_a, the flux ψ_f is not affected and we get the fast transient response and high torque/ampere ratio with rated ψ_f. Because of decoupling when the field current if is controlled, it affects the field flux ψ_f only, but not ψ_a flux. Because of the inherent coupling problem, an induction motor cannot generally give such fast response.

DC machine like performance can also be extended to an induction motor if the machine control is considered in a synchronously rotating reference frame [d^e-q^e], where the sinusoidal variables appear as DC quantities in steady state. In figure, the induction motor with the inverter and vector control in the front end is shown with two control inputs i_{ds} and i_{qs}. [2]



(a)

(b)

Figure 3.3 (a) Separately excited DC motor, (b) Vector controlled Induction motor

The current is divided into two components. These currents are the direct axis component and quadrature axis component of the stator axis component, respectively, in a synchronously rotating reference frame. With vector control, i_{ds} is analogous to field current i_f and i_{qs} is analogous to armature current i_a of a dc machine. Therefore the torque can be expressed as

$$T_e = K_t \hat{\psi}_r i_{qs}$$

Or

$$T_e = K_t^{'} i_r i_{qs} \tag{3.3}$$

Where $\hat{\psi}_r$ =absolute $\bar{\psi}_r$ is the peak value of the sinusoidal space vector. This DC machine like performance is only possible if ids is oriented [or aligned] in the direction of flux $\hat{\psi}_r$ and i_{qs} is established perpendicular to it, as shown by the space vector diagram. This means when i_{qs}^* is controlled, it effects the actual i_{qs} current only and does not affect the flux $\hat{\psi}_r$. Similarly when i_{ds}^* is controlled, it controls the flux only and does not affect the i_{qs} component of current.

This vector or field orientation of currents is essential under all operating conditions in a vector-controlled drives. Note that when compared to dc machine space vectors, induction machine space vectors rotate synchronously at a frequency ω_e, as indicated in the figure. In summary, vector control should assure the correct orientation and equality of command and actual currents. The developed torque may be expressed as

$$T_{em} = k_a \phi(I_f) I_a \tag{3.4}$$

Where k_a is the constant coefficient, $\phi(I_f)$ the field flux, and I_a , the armature current. Here, the torque angle is naturally 90 degrees, flux may be controlled by adjusting the field current, I_f and torque can be controlled independently of flux by adjusting the armature current, I_a since the time constant of the armature circuit is much smaller than that of field winding, controlling torque by changing armature current is quicker than changing I_f , or both.

3.4.2 Principles of Vector Control

The fundamentals of vector control implementation can be explained with the help of figure 3.4 where the machine model is represented in a synchronously rotating reference frame. The inverter is omitted from the figure, assuming that it has unity current gain, that is, it generates currents i_a, i_b and i_c as dictated by the corresponding command currents i_a^*, i_b^* and i_c^* from the controller. A machine model with internal conversions is shown on the right. The machine terminal phase currents i_a, i_b and i_c are converted to i_{ds}^s and i_{qs}^s components by 3-phase and 2-phase transformation. These are then converted to synchronously rotating frame by the unit vector components $\cos\theta_e$ and $\sin\theta_e$ before applying them to the d^e-q^e machine model as shown. The controller makes two stages of inverse transformation, as shown, so that the control currents i_{ds}^* and i_{qs}^* correspond to the machine currents i_{ds} and i_{qs} respectively. In addition unit vector assures correct alignment of i_{ds} current with the flux vector $\bar{\psi}_r$ and i_{qs} perpendicular to it, as shown. Note that the transformation and inverse transformation including the inverter ideally do not Incorporate any dynamics and therefore the response to i_{ds} and i_{qs} is instantaneous.[2]

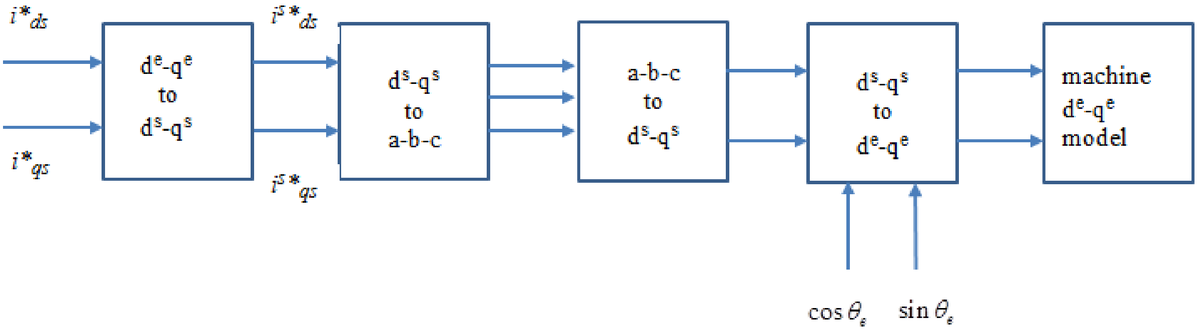


Figure 3.4 Vector Control Implementation Principle with Machine d^e-q^e Model

There are essentially two general methods of vector control:

1. Direct or Feedback method
2. Indirect or Feed-forward method

These methods are different essentially by how the unit vector ($\cos\theta_e$ and $\sin\theta_e$) is generated for the control. It should be mentioned here that the orientation of i_{ds} with rotor flux ψ_r, air gap flux ψ_m, or stator flux(ψ_s) 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. Vector control methods based in the orientation of the machine's magnetic field along one of the rotating reference axis makes it possible to uncouple the rotor magnetic field from the electromagnetic torque. The equations obtained within the reference framework selected permit the implementation of a control scheme for the induction motor, thus achieving dynamic response similar to that given by a separately excited dc motor.

The possibility to use the squirrel cage motor in high performance control systems in which a dynamic response similar to that given by dc motor opens up new applications in industry for this type of motors. In both methods, it is necessary to determine correctly the orientation of the rotor flux vector, lack of which leads to degradation in the speed control of the motor.

Vector control is the most popular control technique of AC induction motors. In special reference frames, the expression for the electromagnetic torque of the smooth-air-gap machine is similar to the expression for the torque of the separately excited DC machine. In the case of induction machines, the control is usually performed in the reference frame (d-q) attached to the rotor flux space vector. That's why the implementation of vector control requires information on the modulus and the space angle (position) of the rotor flux space vector. The stator currents of the induction machine are separated into flux- and torque-producing components by utilizing transformation to the d-q coordinate system, whose direct axis (*d*) is aligned with the rotor flux space vector. That means that the *q*-axis component of the rotor flux space vector is always zero:

$$\psi_{rq} = 0 \quad \text{and} \quad \frac{d}{dt}\psi_{rq} = 0 \tag{3.5}$$

The rotor flux space vector calculation and transformation to the d-q coordinate system require the high computational power of a microcontroller; a digital signal processor is suitable for this task. This section deals with the software implementation of the vector control of induction motor drive.[6]

3.4.3.1 Block Diagram of the Vector Control

Figure 3.5 shows the basic structure of the vector control of the AC induction motor. To perform vector control, follow these steps [6]:

- Measure the motor quantities (phase voltages and currents)
- Transform them to the 2-phase system (α,β) using a Clarke transformation
- Calculate the rotor flux space vector magnitude and position angle
- Transform stator currents to the d-q coordinate system using a Park transformation
- The stator current torque- (i_{sq}) and flux- (i_{sd}) producing components are separately controlled
- The output stator voltage space vector is calculated using the decoupling block
- An inverse Park transformation transforms the stator voltage space vector back from the d-q coordinate system to the 2-phase system fixed with the stator
- Using the space vector modulation, the output 3-phase voltage is generated

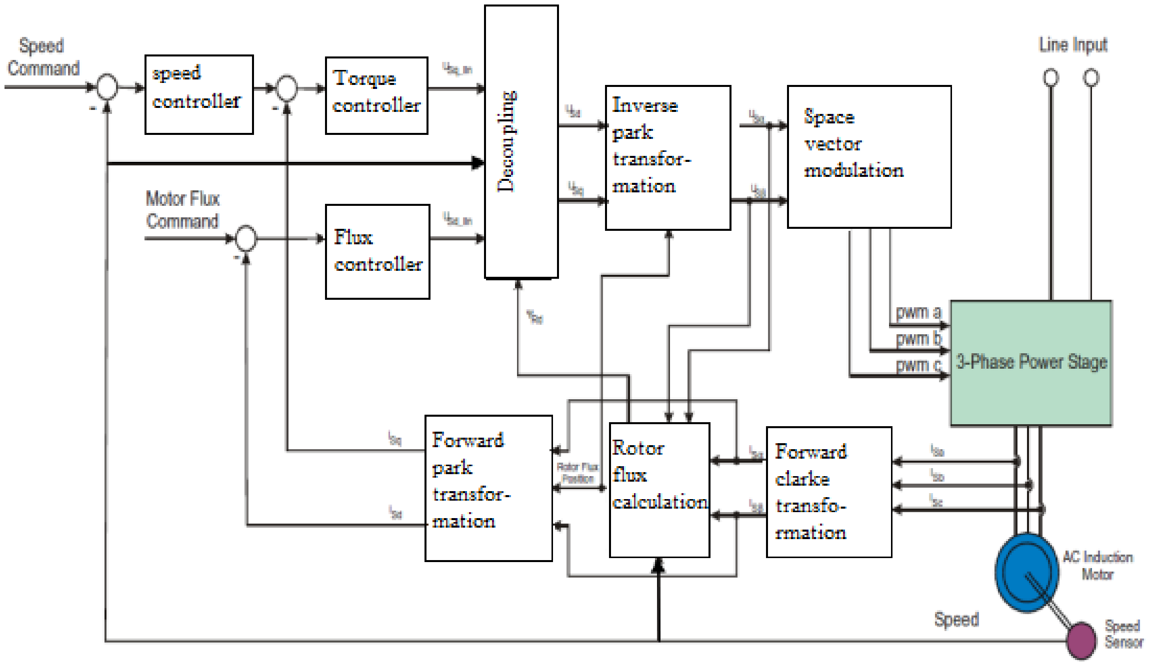


Figure 3.5 Block Diagram of AC Induction Motor Vector Control

3.4.3.2 Forward and Inverse Clarke Transformation (a,b,c to α,β and backwards)

The forward Clarke transformation converts a 3-phase system (a, b, c) to a 2-phase coordinate system (α, β). Figure 3.6 shows graphical construction of the space vector and projection of the space vector to the quadrature-phase components α, β.[6]

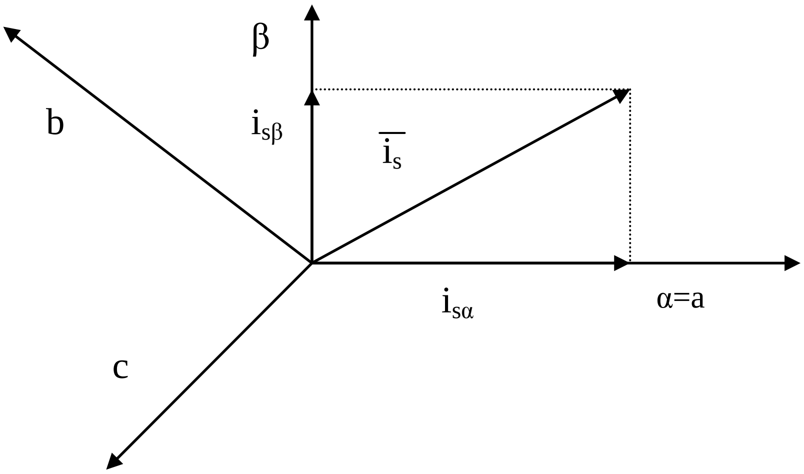


Figure 3.6 Stator current space vector and its components in (α,β)

3.4.3.3 Forward and Inverse Park Transformation (α,β to d-q and backwards)

The components $i_{s\alpha}$ and $i_{s\beta}$, calculated with a Clarke transformation, are attached to the stator reference frame α, β. In vector control, all quantities must be expressed in the same reference frame. The stator reference frame is not suitable for the control process. The space vector $\overline{i_s}$ is rotating at a rate equal to the angular frequency of the phase currents. The components $i_{s\alpha}$ and $i_{s\beta}$ depend on time and speed. These components can be transformed from the stator reference frame to the d-q reference frame rotating at the same speed as the angular frequency of the phase currents. The i_{sd} and i_{sq} components do not then depend on time and speed. If the *d*-axis is aligned with the rotor flux, the transformation is illustrated in Figure 3.7, where θ is the rotor flux position.[6]

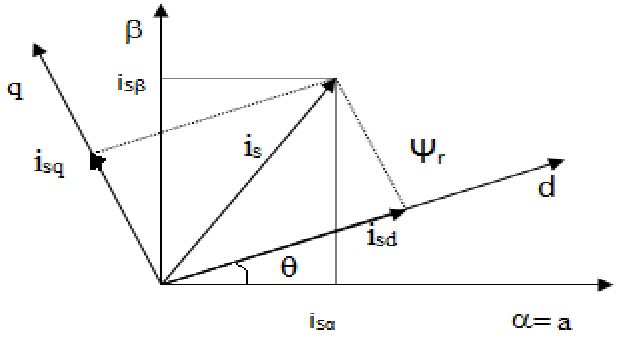


Figure 3.7 Stator current space vector and its component in (α,β) and in the d,q rotating reference frame

The components i_{sd} and i_{sq} of the current space vector in the d-q reference frame are determined by the following equations:

$$i_{s\beta} = i_{sd} \sin\theta + i_{sq} \cos\theta \tag{3.6}$$

$$i_{sq} = -i_{s\alpha} \sin\theta + i_{s\beta} \cos\theta \tag{3.7}$$

The component i_{sd} is called the direct axis component (the flux-producing component) and i_{sq} is called the quadrature axis component (the torque-producing component). They are time invariant; flux and torque control with them is easy. To avoid using trigonometric functions on the hybrid controller, directly calculate sinθ and cosθ using division, defined by the following equations:

$$\psi_{rd} = \sqrt{\psi_{r\alpha}^2 + \psi_{r\beta}^2} \tag{3.8}$$

$$\sin\theta = \frac{\psi_{r\beta}}{\psi_{rd}} \tag{3.9}$$

$$\cos\theta = \frac{\psi_{r\alpha}}{\psi_{rd}} \tag{3.10}$$

The inverse Park transformation from the d-q to α, β coordinate system is found by the following equations:

$$i_{s\alpha} = i_{sd} \cos\theta - i_{sq} \sin\theta \tag{3.11}$$

$$i_{s\beta} = i_{sd} \sin\theta + i_{sq} \cos\theta \tag{3.12}$$

3.5 Indirect or feed forward Vector control

The indirect vector control method is essentially the same as direct vector control, except the unit vector signals [$\cos\theta_e$ and $\sin\theta_e$] are generated in feed-forward manner. Indirect vector control is very popular in industrial applications. Figure 3.8 explains the fundamental principle of indirect vector control with the help of diagram.[37] The d^s- q^s axis are fixed on the stator, but the d^r-q^r axes, which are fixed on the rotor, are moving at speed ω_r. Synchronously rotating axes d^e-q^e are rotating ahead of the d^r-q^r axes by the positive slip angle θ_{sl} corresponding to slip frequency ω_{sl}. Since the rotor pole is directed on the d^e axis and $\omega_e = \omega_r + \omega_{sl}$, we can write

$$\theta_e = \int \omega_e dt = \int (\omega_r + \omega_{sl}) dt = \theta_r + \theta_{sl} \tag{3.13}$$

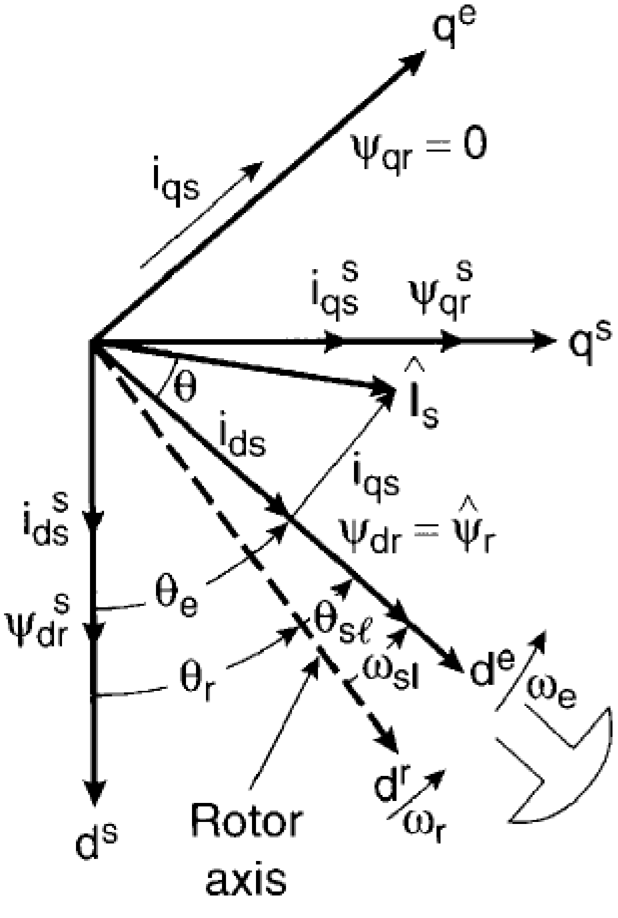


Figure 3.8 Phasor diagram explaining indirect vector control

Note that the rotor pole position is not absolute, but is slipping with respect to the rotor at frequency ω_{sl} . The phasor diagram suggests that for decoupling control, the stator flux component of current i_{qs} should be on the q^e axis as shown.[2]

For decoupling control we can now make a derivation of control equations of indirect vector control with the help of de-qe equivalent circuits. The rotor equations can also be written as:

$$\frac{d\psi_{dr}}{dt} + R_r i_{dr} - (\omega_e - \omega_r)\psi_{qr} = 0 \tag{3.14}$$

$$\frac{d\psi_{qr}}{dt} + R_r i_{qr} - (\omega_e - \omega_r)\psi_{dr} = 0 \tag{3.15}$$

The rotor flux linkage expressions can be given as

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{3.16}$$

$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{3.17}$$

From the above equations we can write

$$i_{dr} = \frac{1}{L_r}\psi_{dr} - \frac{L_m}{L_r} i_{ds} \tag{3.18}$$

$$i_{qr} = \frac{1}{L_r}\psi_{qr} - \frac{L_m}{L_r} i_{qs} \tag{3.19}$$

The rotor currents in equation (3.14) and (3.15), which are inaccessible, can be eliminated with the help of equations (3.18) and (3.19) as

$$\frac{d\psi_{dr}}{dt} + \frac{R_r}{L_r}\psi_{dr} - \frac{L_m}{L_r} R_r i_{ds} - \omega_{sl}\psi_{qr} = 0 \tag{3.20}$$

$$\frac{d\psi_{qr}}{dt} + \frac{R_r}{L_r}\psi_{qr} - \frac{L_m}{L_r} R_r i_{qs} - \omega_{sl}\psi_{qr} = 0 \tag{3.21}$$

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

For decoupling control, it is desirable that

$$\psi_{qr} = 0 \tag{3.22}$$

That is,

$$\frac{d\psi_{qr}}{dt} = 0 \tag{3.23}$$

so that the total flux $\hat{\psi}_r$ is directed on the d^e axis.

Substituting the above conditions in equations (3.20) and (3.21), we get

$$\frac{L_r}{R_r}\frac{d\hat{\psi}_r}{dt} + \hat{\psi}_r = L_m i_{ds} \tag{3.24}$$

$$\omega_{sl} = \frac{L_m R_r}{\hat{\omega}_r L_r} i_{qs} \tag{3.25}$$

Where $\hat{\psi}_r = \psi_{dr}$ has been substituted.

If rotor flux $\hat{\psi}_r =$ constant, which is usually the case, then from equation (3.24),

$$\hat{\psi}_r = L_m i_{ds}$$

In other words, the rotor flux is directly proportional to current i_{ds} in steady state.

In both the direct and indirect vector control methods discussed so far, instantaneous current control of the inverter is necessary. Hysteresis- band PWM current control can be used, but its harmonic content is not optimum. [6][39]

3.6 Conclusion

In this chapter the types of control of induction motors have been explained. The scalar control, vector control of induction motor and indirect vector control of induction motor is dealt in depth. Let us now summarize a few salient features of vector control:

- The frequency of the drive is not directly controlled as in a scalar control. The machine is essentially “self-controlled” where the frequency as well as the phase are controlled indirectly with the help of unit vector.

- There is no fear of an in stability problem by crossing the operating point beyond the breakdown torque T_{em} as in a scalar control. Limiting the total $\hat{I}_s\left(\sqrt{i_{ds}^2+i_{qs}^2}\right)$ within the safe limit automatically limits operation within the stable region.
- The transient response will be fast and dc machine like because torque control by i_{qs} does not affect the flux. However, note that ideal vector control is impossible in practice because of delay in converter and signal processing and the parameter variation effect.
- $\hat{\psi}_r = L_m i_{ds}$ Like a dc machine speed control is possible in four quadrants without any additional control elements. In forward motoring, if the torque T_e is negative, the drive initially goes into regenerative braking mode, which slows down the speed. At zero speed, the phase sequence of the unit vector automatically reverses, giving reverse motoring operation.

Chapter 4
SIMULINK MODEL AND EXPERIMENTAL RESULT

4.1 Introduction

This section summarizes the results of the research work done on the existing and proposed algorithms. The work demonstrates the speed control of Vector Controlled Induction motor and the V/f (scalar) control and the proposed design is tested by MATLAB/simulink. Computer modelling and simulation is widely used to study the behaviour of various complex systems. With proper simulation techniques, a significant amount of experimental cost could be saved in the prototype development. Among several simulation software packages, SIMULINK is one of the most powerful techniques for simulating dynamic systems due to its graphical interface and hierarchical structure and in addition SIMULINK uses MATLAB as a Tool for mathematical purposes which further enhance the modelling process. This software permits the design of special user blocks, which can be added to the main library. Firstly, the simulation and its results for scalar technique are described, after that vector control is presented.

4.2 Scalar Control

4.2.1 Machine parameters

In order to start simulating the system, the parameters must be known. They can be either calculated or measured as in this investigation. The parameters of the motor, used for simulation are given as follows:

Stator resistance(ohm) = 0.087

Stator leakage inductance[H]= 0.8e-3

Rotor resistance(ohm)= 0.228

Rotor leakage inductance[H]= 0.8e-3

Magnetizing inductance[H]= 0.8e-3

Magnetizing inductance[H]= 0.8e-3

Number of poles=4

Proportional gain (Kp)= 100

Integral gain (Ki)=5200

Torque limit (Nm)=300

4.2.2 Description of Simulation (Simulation model)

The drive system shown in Figure 3.5 with the proposed control strategy has been simulated. For simulation purposes, software packages such as Matlab/Simulink and Advanced Continuous Simulation Language (ACSL) can be used. In this section, Simulink has been used to model the induction motor. The induction motor has been simulated with the dynamic q-d-0 model using the nominal parameters as given in. The dc link voltage in the simulation is equal to 100V. Maximum phase current has been limited to the rated value. Initially, the magnetizing current is set at 60% of the rated current. The Simulink model is shown in the figure below.

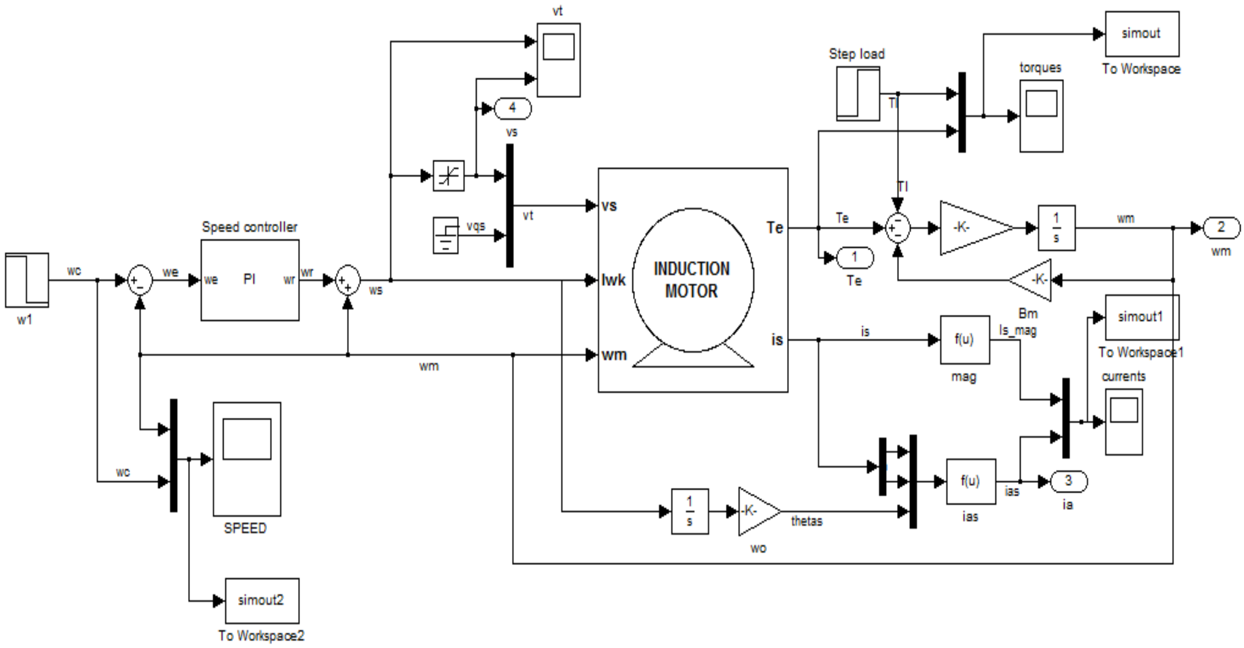


Figure 4.1 Simulation Model of V/f control

4.2.3 Results

Figure 4.3 shows the results obtained from the above control scheme.

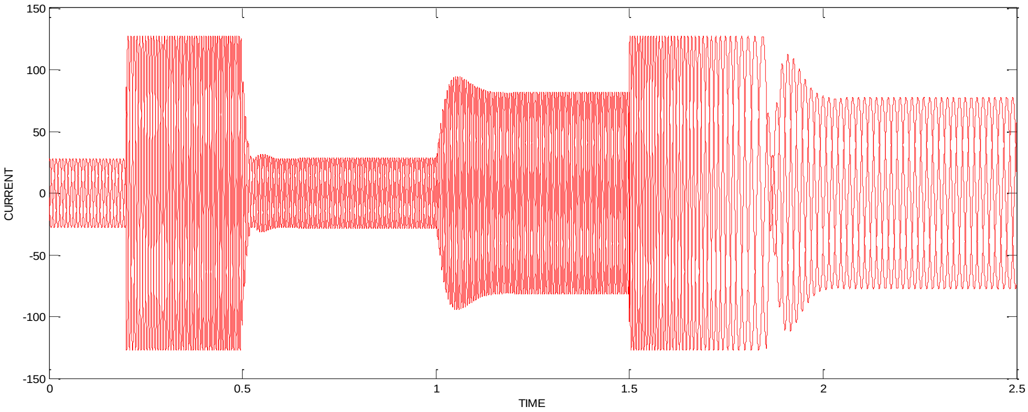


Figure 4.2 Current Response of V/f control of IM

It is noted that with increase in load the speed decreases and current increases.

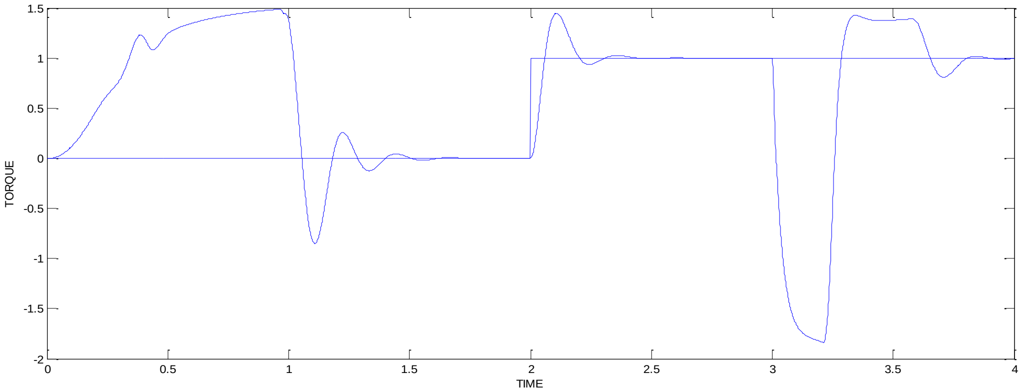


Figure 4.3 Torque Response of V/f control of IM

It is shown that large torques are obtainable even in low speed ranges, with almost no steady-state error in speed.

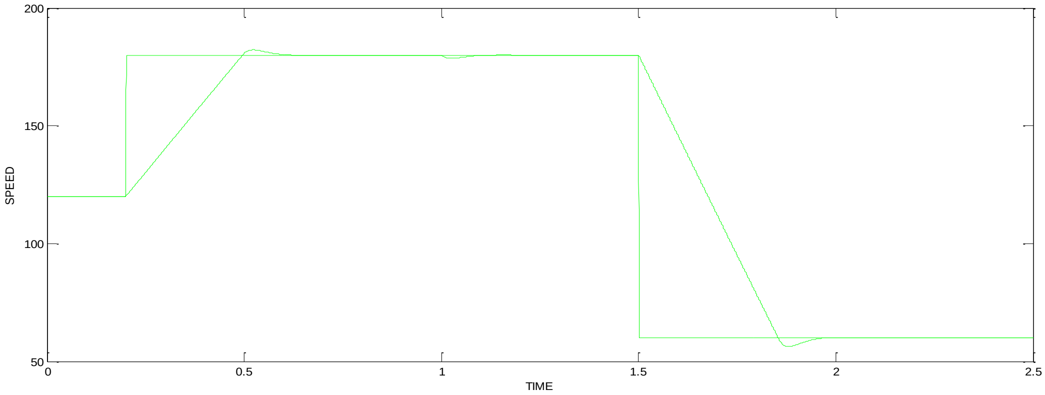


Figure 4.4 Speed Response of V/f control of IM

The results show that with increase in voltage the speed varies in all load conditions at all frequencies.

4.3 Vector control

4.3.1 Machine parameters

The parameters of the motor, used for simulation are as shown in Table.

Voltage (V) = 220

Frequency (Hz) =60

Inertia =0.089

Proportional gain (Kp) = 0.5

Integral gain (Ki) = 30

Derivative gain (Kd) =0

4.3.2 Simulation model

Vector controlled motor (kW) has been simulated and the dynamic responses have been obtained. The simulation results for speed-time, torque-time and current-time are as shown in figures 3-5 respectively.

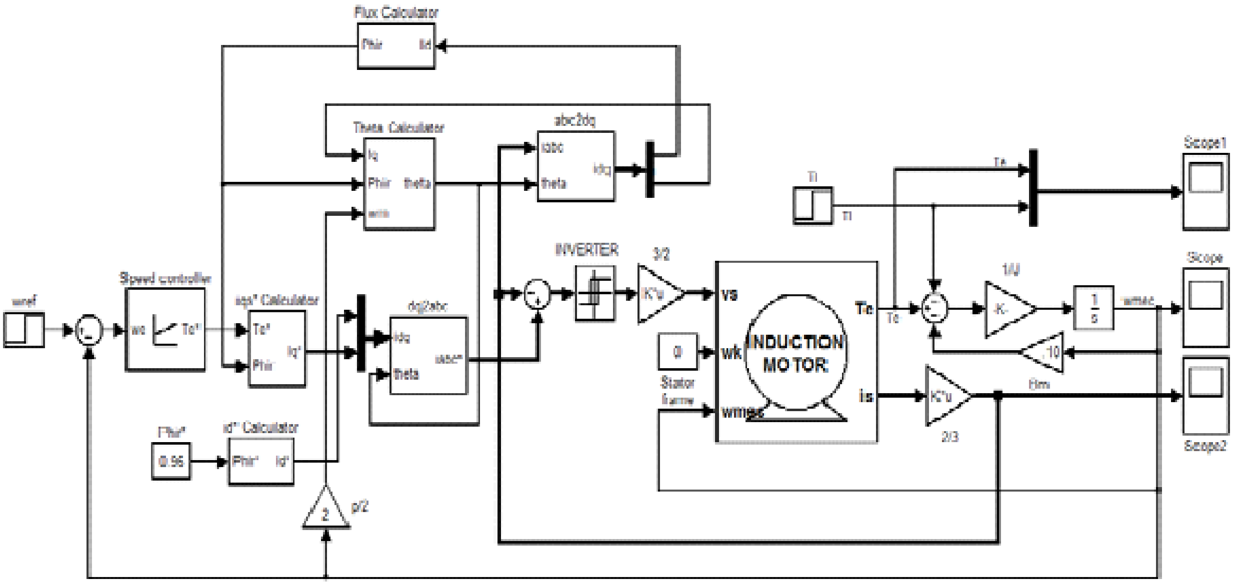


Figure 4.5 Simulink model of vector control of IM

4.3.3 Results

In this section, the concept of vector control has been presented and the induction motor drive is simulated using vector control. For evaluation of implemented drive, different responses of drive are presented. Starting response of for the source current, generated torque and rotor speed of the vector controlled Induction motor drive is presented. The results for the above control scheme are given below:

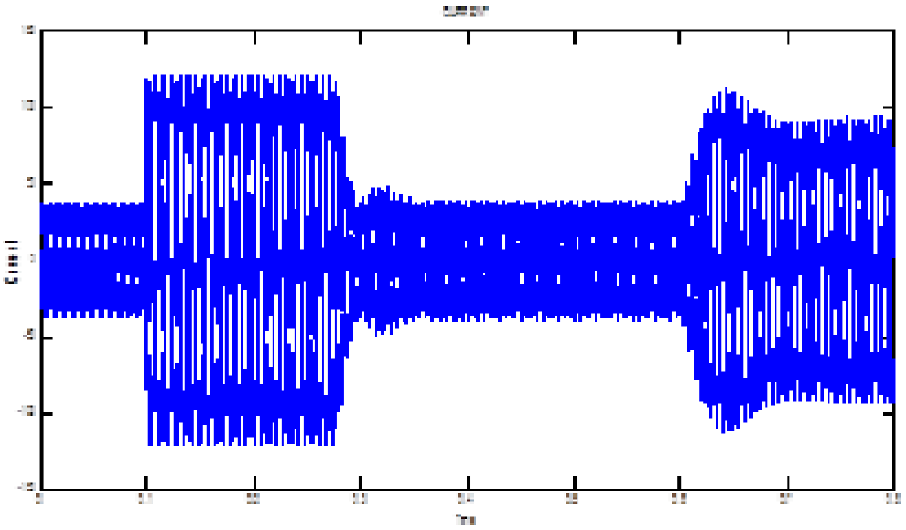


Figure 4.6 Current Response of VCIM

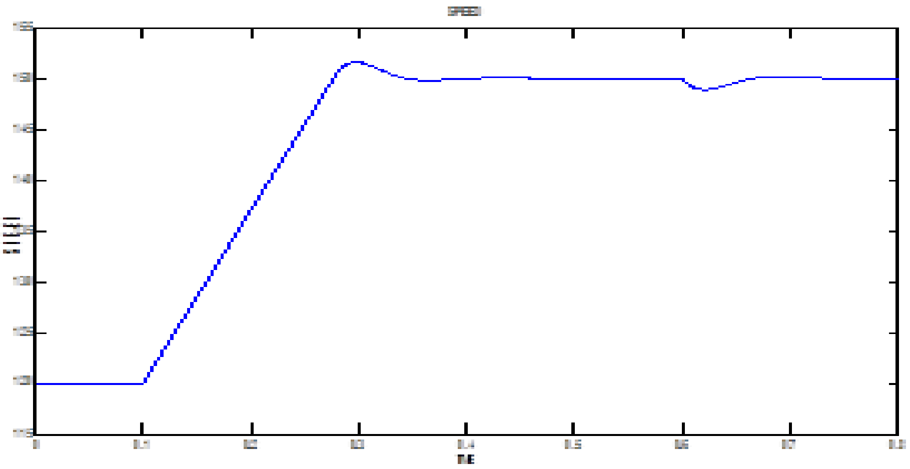


Figure 4.7 Speed Response of VCIM

Above figure shows the speed response for the motor with different load torque *(T,)* when the reference speed is 200 (rad sec) while keeping the voltage-frequency ratio (V/f) constant.

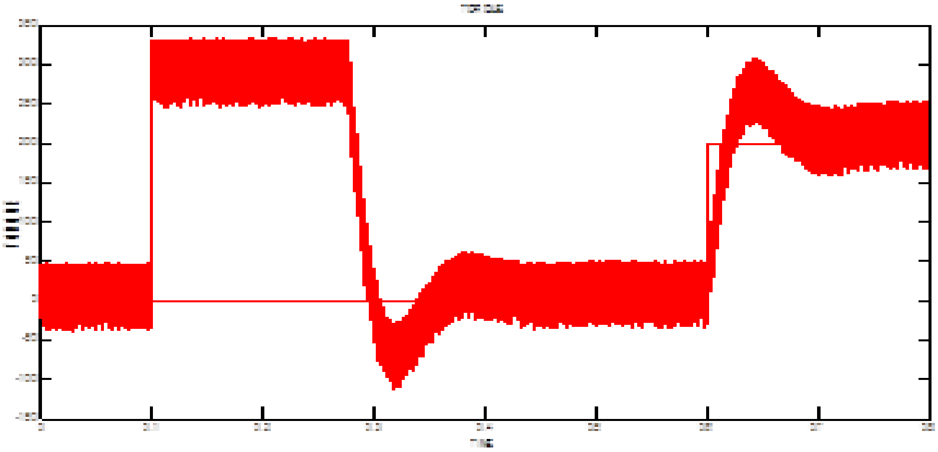


Figure 4.8 Torque Response of VCIM

This figure shows the starting torque produced by the motor when the motor started from rest. This torque response reflects the ripples are less.

To validate the simulation results, the prototype of the proposed scheme is worked upon in the laboratory and tests are conducted on it. The motor is run at speed of 1425 rpm in both simulations as well as in experimentation. It can be observed that the simulation results match reasonably with the experimental results. It has been observed that the design of proposed method is flexible for making it suitable for retrofit applications. The experimental set up is shown as under:

Figure 4.9 AC Vector Control Drive

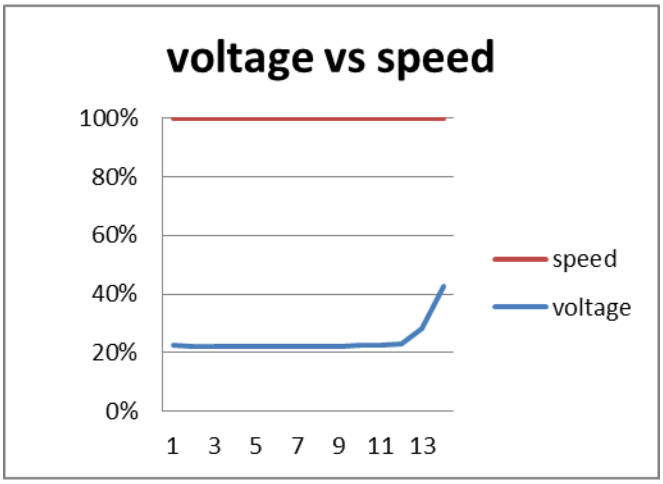


Figure 4.10 Voltage Vs Speed

Hardware setup for control drive consists of:

Induction motor = 3Hp, 3Φ,400V

Voltmeter = 500V ac

Tachometer → Non-contact type

AC VC DRIVE- Siemens

Table 4.1 Hardware Vector Control Motor Drive

Applied Voltage(V)	Speed (r.p.m)
413.5	1478
400.28	1428
380.00	1354
360.00	1280
340.00	1200
320.00	1126
300.00	1062
280.00	992.8
260.00	910.6
240.00	827
220.00	756
200.00	665
160.00	505
100.00	267.7

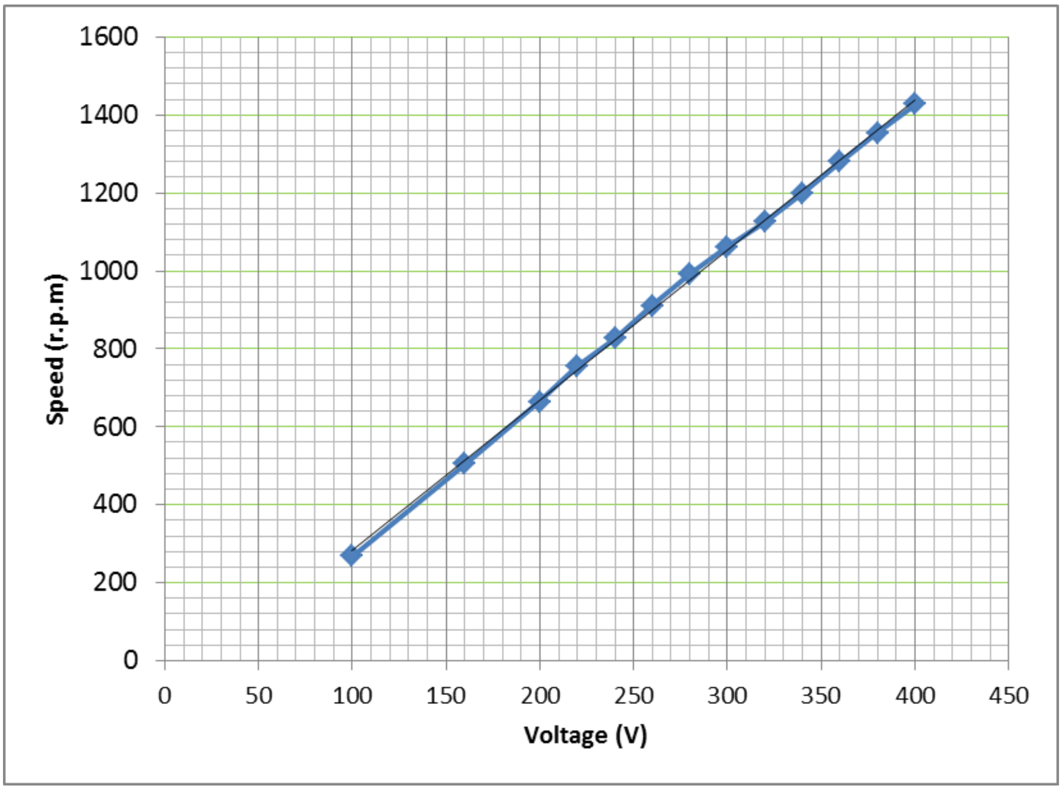


Figure 4.11 Graph Speed Vs Voltage

4.4 Indirect Vector control of Induction motor

4.4.1 Induction machine parameters

Stator resistance (ohm) = 0.087

Stator leakage inductance [H] = 0.8e-3

Rotor resistance (ohm) = 0.228

Rotor leakage inductance [H] = 0.8e-3

Magnetizing inductance [H] = 34.7 -3

Number of poles = 4

Proportional gain (Kp) = 100

Integral gain (Ki) = 2500

Torque limit (Ki) = 350

4.4.2 Simulink model

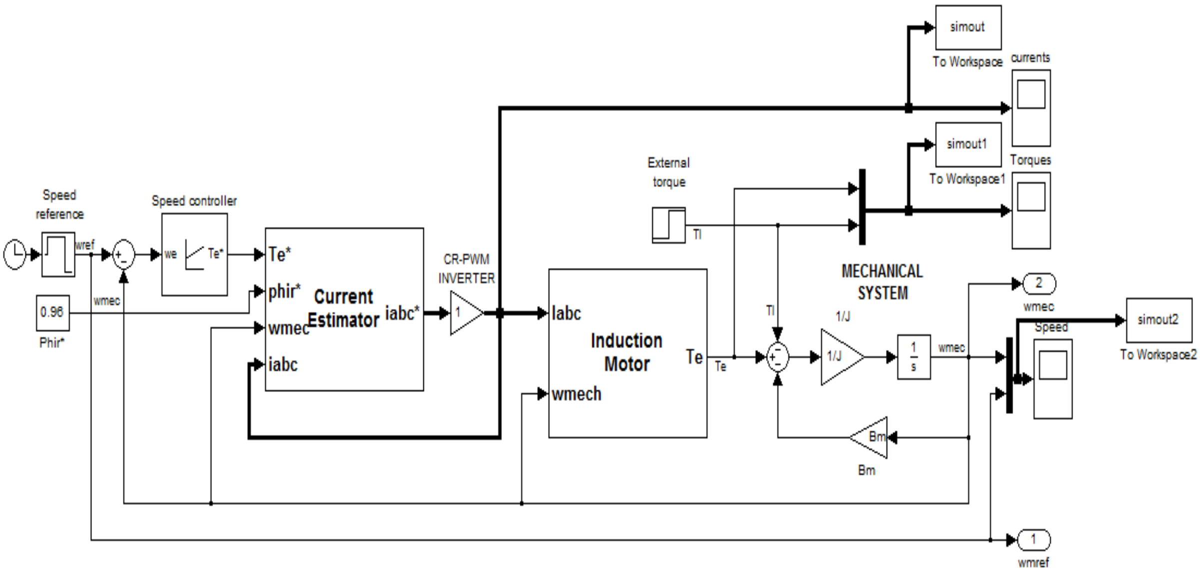


Figure 4.12 Simulink model of Indirect VCIM

4.4.3 Results

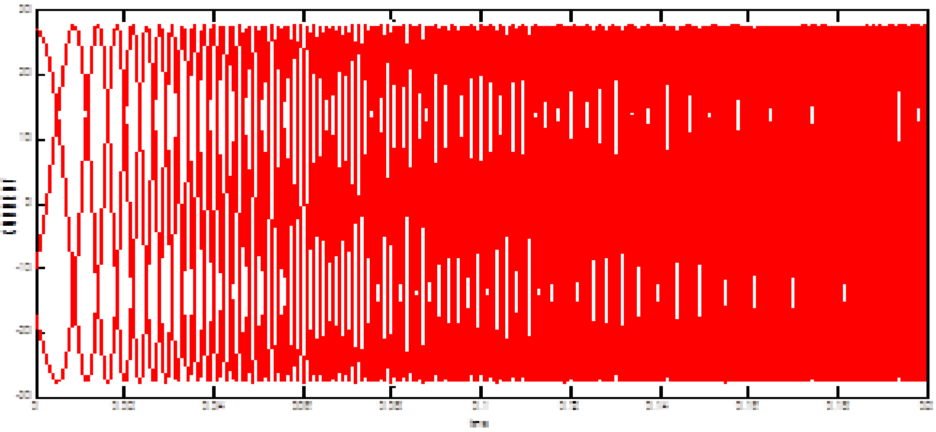


Figure 4.13 Current response of Indirect Vector Control

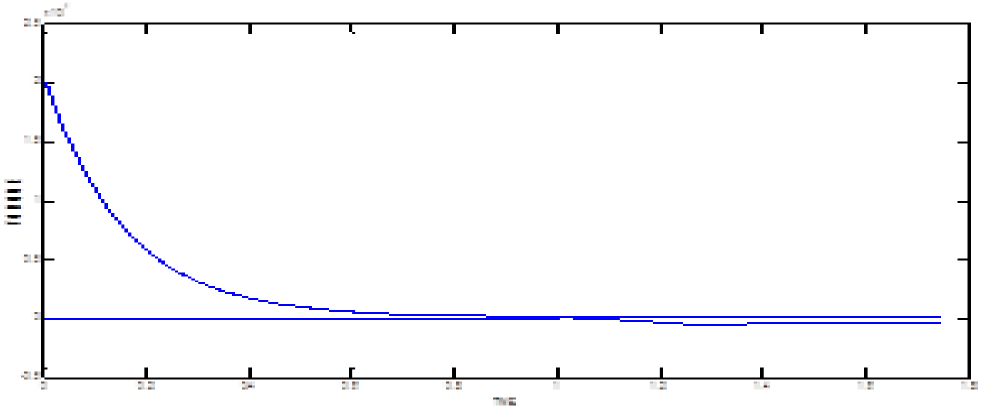


Figure 4.14 Torque response of Indirect Vector Control

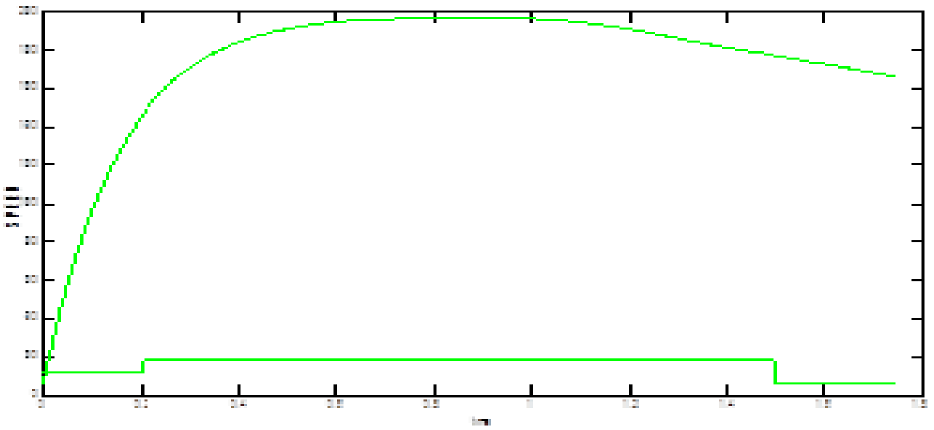


Figure 4.15 Speed response of Indirect Vector Control

4.5 Conclusion

In this chapter the Simulink model of induction motor of variable speed control of induction motor is realized through the Scalar control, Vector control, Indirect Vector control using Simulink and Sim Power System blocks. The Vector control has been performed using current estimator and current controller. The results of torque estimation, voltage and speed estimation is given. By performing the experiment using Vector Controlled Induction Motor Drive available in our Power Electronics and Drives lab the above results are obtained. It is realized that the Vector control provides fast torque response, better speed accuracy and steady state torque ripples are considerably reduced.

Chapter 5
CONCLUSION AND FUTURE SCOPE

The work presented in this dissertation is a comparative study of different control strategies of induction motor drive based on their simulation results. Scalar control technique is compared with the vector control scheme. For evaluation of implemented drive, different responses of drive are presented. To verify the proposed Converter-Drive system MATLAB has been chosen in this work due to its versatility. Simulation results are presented for different operating conditions. All the conclusions drawn are obtained by analyzing the simulations done in MATLAB. Following conclusions have been drawn from the work accomplished.

5.1 Conclusion and Recommendations

1. V/f control provides a simple and cost efficient method for close-loop speed control of 3-phase induction motors. Simultaneously it is noted that with increase in load the speed decreases and current increases. These results are shown in Fig.4.2, Fig.4.3, Fig.4.4. It is shown that large torques is obtainable even in low speed ranges, with almost no steady-state error in speed. The results show that with increase in voltage the speed varies in all load conditions at all frequencies.

2. The torque response, shown in the figure 4.8 reflects the ripples are less and response in the load condition is quick for the vector controlled drive compared with scalar technique. One main advantage is high, controlled transient torque production and therefore fast response to load or demanded speed changes.

3. The main weakness of the scalar control strategies stems from their philosophical base. Either broad assumptions are made about drive and load characteristics, or crude attempts are made to measure the controlled variable. Using this control strategy the steady-state torque can be controlled accurately, but the transient torque response is unsatisfactory.

4. The simulation result support that the vector method settles quickly and has better performance. Experimental and simulation results validate the effectiveness of the method and show that good close-loop speed regulation can be achieved. It is concluded from these

results that V/f controlled induction motor drive cannot meet the requirement of wide speed-control range and individual torque control.

5.2 Future Scope

1. In order to harness all aspects of Induction motor control and new applications demanding further refinement, further research needs to be done. The control structure can be formulated and implemented with a floating-point DSP processor.
2. A large number of artificial intelligence techniques have been employed in modern power system, fuzzy logic is a powerful tool in meeting challenging problems in modern power systems. This is so because fuzzy logic is the only technique that can handle imprecise, vague of fuzzy information. Therefore, the control problem can also be realized using fuzzy logic.

To conclude, it is safe and sound to say that vector and scalar control will remain a hot research and development topic for years to come and future components based on this technology will continue to impress the scientific community with a steadily increasing performance and flexibility of the resulting smart structures.

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