Induction Motor Operated In Vector Control Mode and Direct Torque Control Mode: A Comparative Study

A DISSERTATION

Submitted in partial fulfillment of the

requirements for the award of degree

of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(WITH SPECIALIZATION IN ELECTRIC DRIVES AND POWER ELECTRONICS)

BY

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May 2016

CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in this dissertation entitled "**Induction Motor Operated In Vector Control Mode and Direct Torque Control Mode: A Comparative Study**" in partial fulfilment of requirement for the award of degree of Master of technology in Electrical Engineering with specialization in Electric Drives & Power Electronics, and submitted in the Department of Electrical Engineering of Indian Institute of Technology Roorkee, India, is an authentic record of my own work carried out during the period from June 2015 to May 2016, under the supervision of Dr. Sumit Ghatak Choudhuri, Assistant Professor, Department of Electrical Engineering, of indian institute of technology Roorkee, India and Dr. S. P. Gupta, Professor, Department of Electrical Engineering, of Indian Institute of Technology Roorkee, India.

The matter embodied in this report has not been submitted by me for the award of any other degree of this or any other Institute/ University.

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CERTIFICATE

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ACKNOWLEDGEMENT

I wish to affirm my earnest acknowledgement to my respected guide **Dr. S. Ghatak Choudhuri**, **Assistant Professor,** Department of Electrical Engineering, Indian Institute of Technology Roorkee, for their intuitive and meticulous guidance and perpetual inspiration in completion of report. I want to express my profound gratitude for his co-operation in scrutinizing the manuscript and his valuable suggestions throughout the work.

I would also like to express my sincere gratitude to my co-guide, **Dr. S. P. Gupta, Professor**, Department of Electrical Engineering, Indian Institute of Technology Roorkee, for continuous support and evaluating my progress from time to time in completion of this work.

I would like to mention my parents for their endless support and encouragement and always believing and helping me to believe, that I can succeed at anything.

Acknowledgement would be incomplete without a word of gratitude to all my student friends for their timely help, encouragement and contribution in making it possible.

Dated: 24th May, 2016 ALOK NIRANJAN

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ABSTRACT

Variable speed operation of IM drives can be generally classified as scalar control and vector control. Scalar control is used for low performance drives where only the magnitude and frequency of stator voltage or current is regulated. The most commonly used scalar control technique is the constant volts/Hertz (V/f) control, which offers moderate dynamics performance and is therefore used in application where high speed precision is not required such as fans, pumps and elevators. These control methods results in poor torque and flux response. High performance induction motor drive can be implemented by using vector control or direct torque control.

For the induction motor controlling to achieve variable speed, Vector Control (VC) or Field Oriented Control (FOC) and Direct Torque Control (DTC) have become the industrial standard. The vector control technique decouples the two component of stator current: one is responsible for controlling torque and other is controlling flux independently as in the case of separately excited fully compensated DC motor.

Direct torque control technique also controlling torque and machine flux independently, but not same as DC motor or Vector control technique. In DTC, torque is controlled by controlling the angle between stator flux and rotor flux as torque is proportional to sine of that angle and flux is controlled by the stator voltage space vector.

The closed loop control of Vector control and Direct Torque Control of IM drives required accurate information of speed or rotor position. This information is provided by Techo-generator or encoder. However the use of speed sensors has many drawbacks such as, higher cost, lower reliability, increase in weight and size and difficulty to use in harsh environment. To overcome this difficulty, sensorless speed estimation algorithm for induction motor drive can be used to eliminate speed sensor for both the schemes.

This report work aimed to give a contribution for detailed comparison between the two control technique (FOC and DTC) based upon the various criteria including basic control strategy, steady state and dynamic performance and implementation complexity. Steady state and dynamic response of vector control and direct torque control under various operating condition such as starting, speed reversal, load application and load removal for both with and without speed sensor is simulated and examined in MATLAB environment using Simulink and Sim Power System toolboxes. The analysis has been carried out on the basis of result obtained by numerical simulations. The simulation and evaluation of both control technique are performed using voltage source inverter fed three phase squirrel cage induction motor for 30HP, 5HP and 2HP ratings.

List of Nomenclatures

OPERATOR	**NAME**
i_{as}, i_{bs}, i_{cs}	Three Phase Stator currents
i_{ar}, i_{br}, i_{cr}	Three Phase Rotor currents
$\bar{I}_s, \bar{I}_r$	Stator and rotor current vectors
$\bar{V}_s, \bar{V}_r$	Stator and rotor voltage vectors
$v_{as}, v_{bs}\ v_{cs}$	Stator voltages
i_{qs}, i_{ds}	Quadrature and direct axis stator current component
i_{qr}, i_{dr}	Quadrature and direct axis rotor current component
ω_r	Rotor speed (rad/sec)
ω_e	Synchronous speed (rad/sec)
ω_{sl}	Slip speed (rad/sec)
ω_{base}	Base speed of motor
ω_{er}	Speed error between reference and actual
i_{mr}	Excitation current
Ψ_s	Stator flux linkage
Ψ_{ds}, Ψ_{qs}	Direct and quadrature component of stator flux linkage
Ψ_r	Rotor flux linkage
Ψ_{dr}, Ψ_{qr}	Direct and quadrature component of rotor flux linkage
γ_{sr}	Angle between stator and rotor flux in space
Θ_{fs}, Θ_{fr}	Angle between stator flux and d-axis and angle between rotor flux and d-axis
L_{ls}, L_{lr}	Leakage inductance of stator and rotor
L_m	Mutual inductance
L_s, L_r	Stator and rotor self-inductance
R_s, R_s	Stator and rotor resistance
τ_s, τ_r	Stator and rotor time constant
$\sigma = 1 - \frac{L_m^2}{L_s L_r}$	Total leakage factor
T_{em}	Electromagnetic torque
Θ_e	Position angle of synchronously rotating frame
J	Moment of inertia
*	Indicate reference quantity
^	Indicate estimated state variable

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Mechanical energy is needed in the daily life use as well as in the industry. Induction motors play a very important role in both domains, for the reason that of low cost, consistent operation, robust operation and low maintenance. There are two main types of induction motors which are the wounded rotor and squirrel-cage design and both of them are in widespread use. Squirrel cage rotor design of induction motor is considered of the two more reliable and cheaper to make.

When induction motors are functioned without appropriate control, the motors are consuming large power and the functioning costs are high. In last few decades, power electronics has emerged, Digital signal Processing (DSP) and microcontrollers are now well established, allowing improved the performance. The contribution of power electronics in the area of driving the AC motors which is so called “adjustable speed drives or variable speed drive”, is characterized by the three phase mains voltages being converted to DC through conventional rectifier circuits to a DC bus.

Next to the DC bar is inverted to AC but with both a different voltage and different frequency, (V_{OUT} , f_{OUT}). Because the motor speed depends on the applied frequency, speed control is facilitated. DC to AC conversion totally depends on the control strategies and PWM techniques. DSP is reflected as a very significant component in recording and examining the PWM current and voltage data from speed and Hall Effect current and voltage sensors and to compare it with the desired conditions in the motor controller. Dynamic models are employed in to well understand the behaviour of induction motor in both transient and steady state. The dynamic modelling sets all the mechanical equations for the inertia, torque and speed versus time. It also models all the differential voltage, currents and flux linkages between the stationary stator as well as the moving rotor. In this dissertation, mathematical model will be done using MATLAB/Simulink which will characterise the three phase induction motor together with a three phase to d-q axis transformations.

Almost 40 years have passed, when the first paper on Field Oriented Control (FOC) or Vector Control (VC) for induction motor drive was introduce by F. Blaschke and 30 years have passed when the first paper on Direct Torque Control (DTC) and Direct Self Control (DSC) was introduce by I. Takahashi and M. Depenbroke respectively. Since that time, these techniques were completely developed and today is almost mature from the view of industrial application. Today DTCIMD and VCIMD both are industrial reality and are available in the market with different solutions and performance.

Three phase induction motor operated in VC and DTC mode have always been an interesting research area in electric drives field. Presence of drawback such as high initial cost, maintenance requirements for commutators, brushes and brush holders etc., in case of DC motors convey towards the use induction motor functioned in VC mode and DTC mode. These alternative methods leads to a robust, maintenance free and economic solution for variable speed operation. The objective of both (VCIMD and DTCIMD) are same, however the control strategies of both having different operating principles. Both are having aim to control effectively and efficiently the motor flux and torque in order to track the motor accurately on the command trajectory without any external disturbances or load parameter variation.

Indirect Vector Control method decoupled the flux and torque components, which are inherently coupled as both are the function of voltage and current. This control strategy is complex and more expensive to be implemented.

Unlike VC, DTC doesn’t require any PWM signal generator, current regulator and coordinate transformation. DTC is much simpler but also allows a good torque control in transient and steady-state operating condition. However, Conventional DTC present some disadvantages i.e. high current and torque ripples, lack of direct current control, difficulty control torque and flux at very low speed (in conventional DTC estimation of flux is done by integrating back emf) and variable switching frequency.

The closed loop control of Vector control and Direct Torque Control of IM drives required accurate information of speed or rotor position. This information is provided by Techo-generator or encoder. However, the use of speed sensors has many drawbacks such as, higher cost, poorer consistency, increase in weight and size and difficulty to use in harsh environment. To overcome this difficulty, sensorless speed estimation algorithm for induction motor drive can be used to eliminate the speed sensor. Numerous speed sensorless techniques are presented, among these schmes MRAS speed observers offer simple execution and require less computational effort matched to other methods. Numerous MRAS observers have been introduced based on speed tuning signal as the rotor flux, back emf and reactive power.

The integrator present in various estimations like stator flux, rotor flux and speed estimation methods may create the problem at the time of practical implementation because of inherent offset present in current sensors which can saturate the integrator. Various other methods have been proposed to overcome this drawback such as using low cutoff frequency LPF.

1.2 CONTROL TECHNIQUES OF INDUCTION MOTOR

Before the advent of vector control technique for induction motors, various control method ex: voltage control, frequency control, rotor resistance control, pole changing, Pole amplitude modulation technique, V/f control, flux control [2, 5] etc., have been used and named as scalar control. In scalar control particularly V/f control method, the motor is fed with variable frequency supply generated by an inverter controlled by Pulse Width Modulation (PWM) techniques. Here, the V/f ratio is maintained constant in order have constant torque throughout the operating range of the motor. Since only magnitudes of the input variable i.e. frequency and voltage are controlled, this is known as Scalar Control, such control techniques result in satisfactory response only in steady state conditions. The dynamic response of the drive from scalar control methods is observed to be sluggish. This is one of the major drawback of scalar control technique as applied to the induction motors. It had resulted in development of the variable voltage-variable frequency (VVVF) control technique, which could provide improved response of an induction motor drive in transient as well as in steady state operating conditions.

In general, this type of control drive are with no any feedback devices, that is open loop control. Hence, this type of control offer low cost, easy execution and less knowledge of motor is required for frequency control. But there are some demerits of this type of control scheme like, electromagnetic torque development is load dependent and is not controlled directly. Also, transient response of such a control is not fast due to the predefined switching pattern of inverter. Now variable speed application by IM came into existence with the arrival of solid-state power electronic devices like SCR, MOSFET and IGBT etc. these devices provide high performance control like torque control, flux control and speed control. Though IM using some scalar control can maintain a constant flux, their flux and torque dynamics performance is extremely poor. The advantage of IM are very high in term of robustness and cost, however as far as the speed controlling is concern, until the development and execution of Field oriented control (FOC) and Direct Torque Control (DTC), induction motor were not capable to compete with DC motor in high performance application.

1.3 CONCEPT OF VECTOR CONTROL

A control technique wherein two hypothetical, decoupled signals are produced, one responsible for the control of torque (i_{qs}^{*}) and the other for control of flux (i_{ds}^{*}) , so that the 3-ϕ Induction Motor behaves like a separately excited, fully compensated dc motor is referred as Vector Control (VC) or Field Oriented Control (FOC). This method gives an option to use induction motor in the industrial applications wherein four-quadrant operation with fast dynamics on a wide range of speed is required. The two decoupled signals of the stator current phasor are considered as control variables are expressed in d-q synchronously rotating reference current frame (SRRF). In this work rotor reference frame is considered, due to its simplicity, good dynamic performance and less implementation complexity. When the reference current signals generated by vector controller and the actual three phase current signals produced by induction motor (both in stationary reference frame) are identical to each other ,the vector control mode is said to be achieved.

The basic schematics of VCIMD shown in Fig.1.1. VCIMD system consist the synchronously rotating reference frame ($d^{*} – q^{*}$ axis) and the d^{e} axis is attached to the rotor flux vector ($\overline{\Psi}_{r}$) rotating at synchronous speed (ω_{e}). Consequent upon this, decoupling of the variables could be possible. So that, torque and flux can be separately controlled by two hypothetical current signal i.e. quadrature axis component (i_{q}^{*}) and direct axis component (i_{d}^{*}) respectively.

The feedback signals which is sensed from the machine is shaft speed (ω_{r}) and stator currents (i_{as} andi_{bs}). Reference speed (ω_{r}^{*}) and shaft speed (ω_{r}) is compared and error is computed, that error is passed through a suitable controller which will generate reference toque signal (T^*_{em}). Suitable value of excitation (i^*_{mr}) is generated by sensed shaft speed magnitude. T^*_{em} and i^*_{mr} act as two input which generate two hypothetical current signal (i^*_{qs} and i^*_{ds}), which independently responsible for controlling torque and flux of the drive.

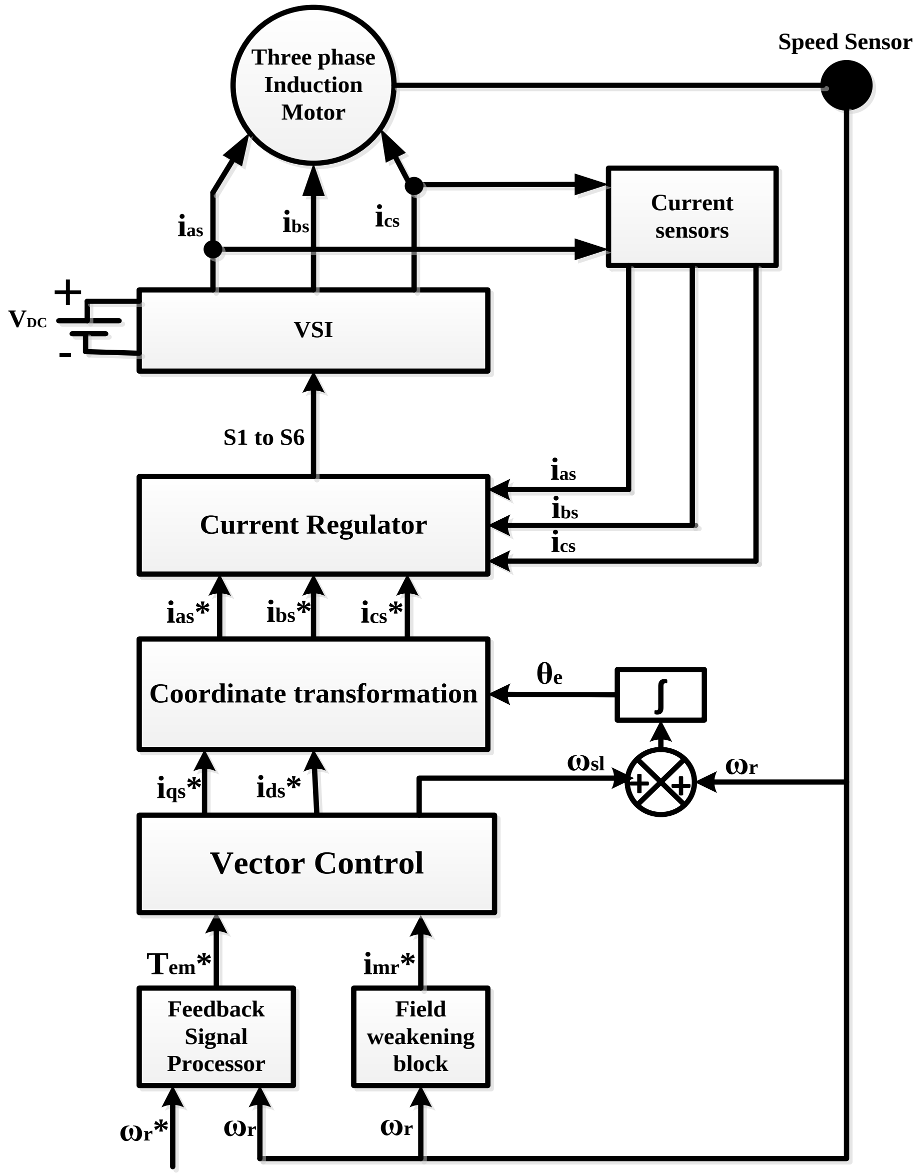


Fig.1.1 Basic block diagram of VCIMD

1.3.1 ANALOGY

The analogy between the induction motor operated in vector control mode and fully compensated, separately excited dc motor can be deal with the help of fig.1.2. The equation of electromechanical torque for the dc motor is give as:

$$T_{em} = K_t \times I_a \times I_f \tag{1.1}$$

Where,

K_t= the torque constant of dc motor.

I_a= Torque component of current.

I_f= Field component of current.

As shown in fig.1.2, the two control signals of induction motors in SRRF (i_{qs}^* and i_{ds}^*) are analogous to field and armature component of current i.e. i_f and i_a respectively of DC motor. Therefore, the torque equation of an induction motor is expressed as:

$$T_{em}^* = K_{t1} \times i_{qs}^* \times i_{ds}^* \tag{1.2}$$

Where,

K_{t1}= the torque constant of VCIMD.

i_{qs}^*= Torque component of current.

i_{ds}^*= Field component of current.

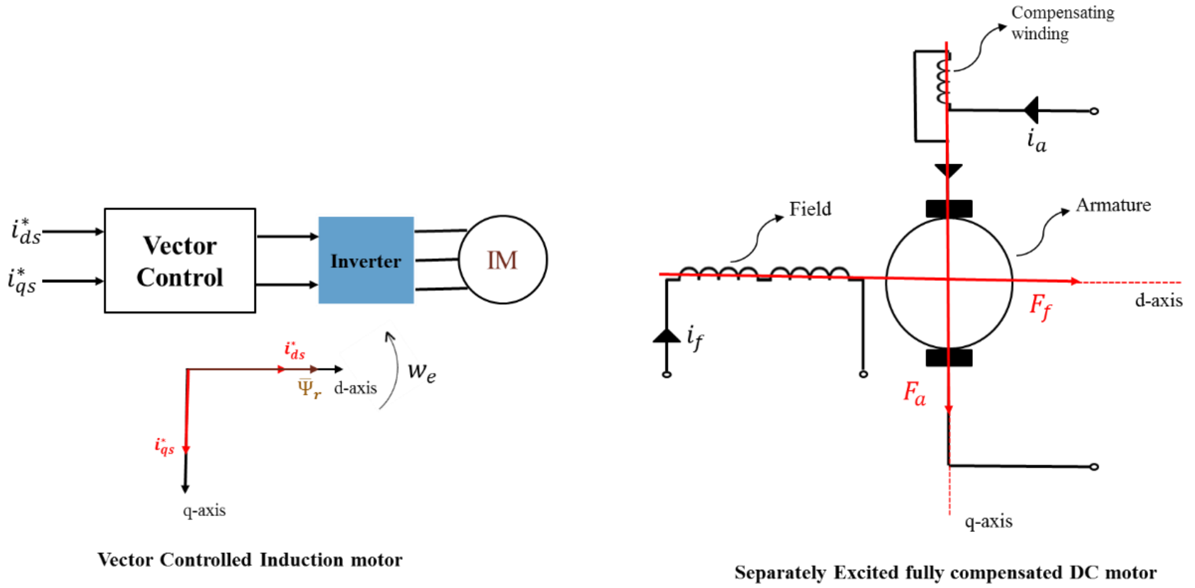


Fig.1.2 VCIMD Analogy with DC Motor

Two torque equations 1.1 and 1.2, conclude that the Torque expressions are identical to each other. This shows that independent control can be achieve in case of induction motor by controlling it in SRRF. Therefore, the method known as Field Oriented Control (FOC) or Vector Control (VC) gives the induction motor control as separately excited, fully compensated DC motor.

The detailed discussion on VCIMD will on Chapter 2.

1.4 CONCEPT OF DIRECT TORQUE CONTROL

Like VCIMD, Direct Torque Control (DTC) of induction motor drive also control the torque and flux of the induction machine independently. As seen in previous discussion of vector control that it has very complexity in algorithm and not so easy to implement, infect VCIMD need the transformation from synchronously rotating d-q frame component to stationary a, b and c component. This transformation need lot of computational power in every sampling cycle and make algorithm complex. On the other hand, DTC does not required any such transformation and also it can be seen in future chapter that the algorithm require in DTC is much simpler.

The schematic block diagram of Direct Torque Control of Induction Motor Drive (DTCIMD) is shown in fig.1.3. The feedback signal processor takes the rotor speed (ω_r) as input along with the set reference speed (ω_r^*) which generated the command values of torque (T_{em}^*). And flux reference (Ψ_s^*) is set. The estimated values of torque and flux of running induction motor drive T_{em} and Ψ_s respectively and reference value of torque and flux T_{em}^* and Ψ_s^* respectively will go to the flux and torque comparator, that will provide the position of torque and flux by d_T and d_Ψ respectively. These command combination with sector, which is calculated by sector estimator go to the switching look-up table box and then generate the gate pulse signal for switching action of VSI.

All the blocks which are used in the block diagram Fig.1.3, have been explained explicitly in later chapter.

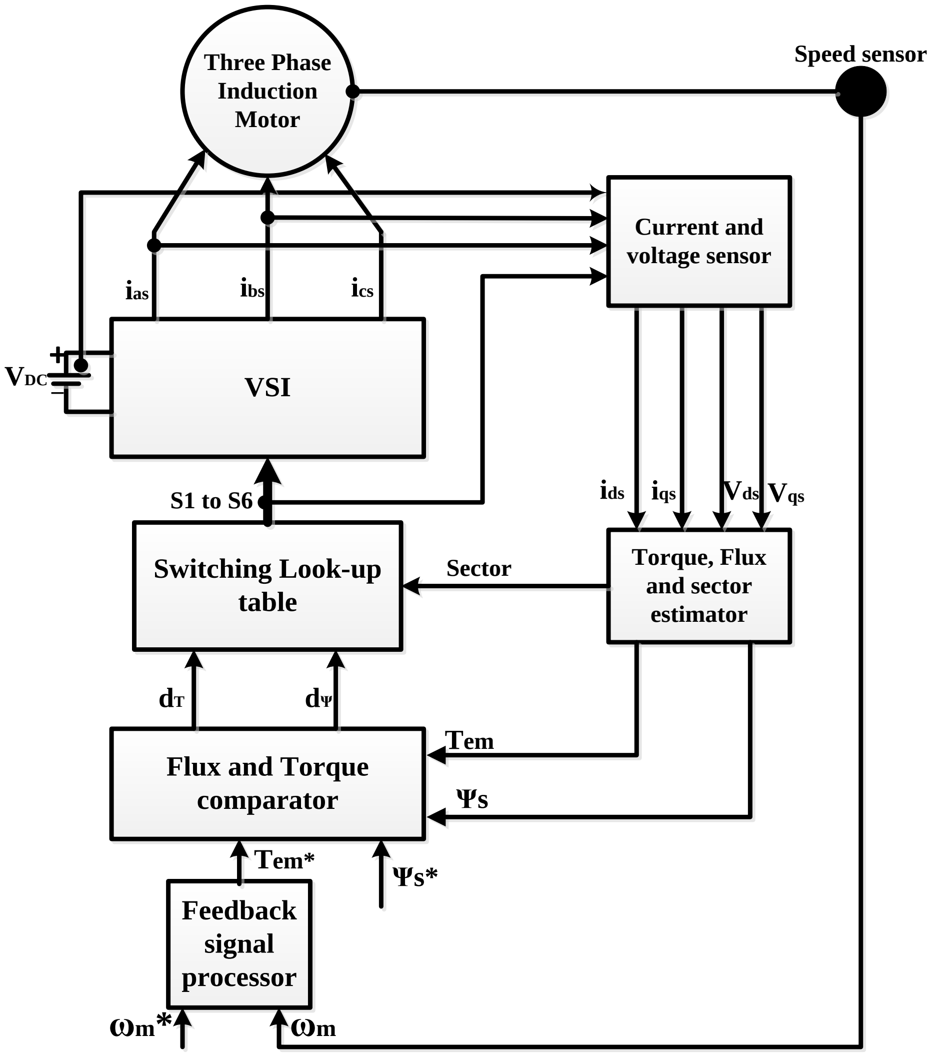


Fig.1.3 Block diagram of Direct Torque Control of Induction Motor Drive

1.5 LITERATURE REVIEW

Vector control (VC) was first introduced by F. Blaschke [12] in 1972. This method comes with the revolution for controlling the speed of Induction motor drive in field of variable frequency variable speed drive which gives the excellent dynamic as well as steady state performance similar to a separately excited fully compensated dc motor. Before the concept of VC or Field Oriented Control (FOC), scalar control techniques of induction motor [1]-[6], [12], and [30] were being used. The transient response obtain from these techniques were far from satisfaction [1]-[4] Due to this, necessity was of having such methodology that can give better response of IM in various operating condition.

The main objective of FOC method is to get advantage of both the machine i.e. constructional feature of IM and controlling feature of separately excited fully compensated DC motor [This methodology gives independent control between flux and torque, and convert the non-linear control system into linear one [5-10],[29].

In 1986, I. Takahashi, N. Noguchi, came with new methodology [17] that is known as Direct Torque Control of induction motor drive. The proposed scheme was “A new quick response and high efficiency control strategy of an induction motor”. In this technique also, independent control of torque and flux is possible [10] and even with the less complexity and faster torque response [26]-[29], [34].

The Mathematical modelling of IM is completed by on the foundation of many developed theory [11]. The expansion in Power Electronics area [15], [26], [28], [50] has surfaced the way of real time execution of both the technique FOC [13]-[14], [20]-[22], [49] and DTC [21]-[22], [35], [47], [50] of induction motor drive. The use of digital signal processors (DSPs) [14]-[16], [34], [36], Microprocessors have made it promising to implement complex algorithm like FOC and DTC at a sensible cost. MATLAB with its toolboxes and Simulink have made the simulation of FOC and DTC much easier and modest.

After the fully implementation of both the technique i.e. Vector Control and Direct Torque control, researchers found the great interest in this area. But each method having some drawback, like complexity, switching behaviour [9]-[11], [26], [36], current and torque ripples [25], [33], [40]-[41]. However, many researchers came forward to improve all the demerits of individual methodology [25], [28], [33], [37], [40] but nevertheless with improvement, complexity of techniques have also increased.

Several papers have been published on VC and DTC in the last 40 years, but only rare of them was intended to highlight dissimilarities, advantages and disadvantages [11], [39]-[40], [42]. The name Direct Torque Control is consequent by the fact that, on the base of the errors between the reference and the estimated values of flux and torque, it is likely to directly control the Inverter states in order to reduce the torque and flux errors within the prefixed band limits [29], [35], [41], [46]. Unlike Vector Control, DTC does not require any current regulator [37], [34], [36], [46], co-ordinate transformation and PWM signals generator (as a con-sequence timers are not required). In spite of its easiness, DTC permits a decent torque control in steady-state and transient operating situations. The problem is to measure how decent the torque control is with respect to FOC [42]. In addition, this controller is very little functional to the parameters detuning in contrast with FOC [40], [42].

As far as the controlling of Voltage Source Inverter is concern for both the technique, that handled quit different. In FOC, popularly Current Control VSI (CCVSI) is used with diverse current regulating techniques [46], like Sinusoidal PWM, synchronous dq frame PI regulator, stationary frame PR, stationary frame PI and hysteresis current regulators etc. In all of those regulators Hysteresis Current control method of VSI offers an matchless transient response in contrast with other analog and digital method, which makes it suitable to accept this method in all cases where high accuracy, wide bandwidth, and robustness are essential [25], [34], [37].

Hysteresis control technique is fundamentally an analogic technique. In spite of the merits given by digital controllers, in term of flexibility, maintenance integration interfacing, their correctness and response speed are often insufficient for current control in highly challenging applications, such as active filters and high- precision drives [26], [35], [41], [44]. In these applications, reference current waveform categorised by high harmonic content and fast transient must followed by good accuracy. In these belongings, the hysteresis technique can be a fine solution [25], [33], provided some improvement are introduced to overcome its main limitations, which are sensitivity to phase commutation interference and switching frequency. In this scenario, a variety of provisions both digital and analog, have been proposed [37], [39], [49].

In Direct Torque Control of induction motor drive, there have been some strategies, e.g., voltage vector selection using switching table [28], direct self-control, and space-vector modulation [22]. Among them, voltage vector selection using switching table is widely researched and commercialised [28] because of its conceptual simplicity and implementation ease without using complicated over-modulation technique, which is unavoidable in Space Vector Pulse Width Modulation (SVPWM) [26]-[29]. However strategy using switching table for DTC has some drawbacks. First, variation in switching frequency according to hysteresis band of flux and torque and to the motor speed. Second, high torque and flux ripple is generated, in particular, in low range of speed because of small back EMF of an IM, and requirement of very less control sampling time to achieve better performance [37], [41], [45]-[47]. However Constant Switching Frequency concept has been achieved to the several extent [46]. Some of study shows their concentration only for constant switching frequency regulation and some of them consider the effect of torque ripples [29], [40], [47], and [49].

Many authors try to merge both FOC and DTC as hybrid control technique to combine the fine response of FOC and simplicity of DTC, but this concept also not come as satisfactory as it has to be.

In DTC, the estimation of flux can be done on the base of voltage model or current model or a combination of both [53]. When the low frequency operation of drive is required then current estimation technique is useful, for this, stator current and rotor speed is require. This technique can remove stator parameter sensitivity but introduce rotor parameters in the estimation which will create problem especially in high speed [26]. On the other hand, voltage model is preferred for high speed operation [36], because it create some problem for low speed operation due to small back emf [36], [51].

1.6 CONCLUSION

From the above discussion it can be concluded that the controlling of induction motor is very essential as it is very common part of any industry as well as home appliances. Hence, the well implemented induction motor drive which is modest, low cost, rugged and low maintenance can serve the required purpose. At the same situation it is also needed to control the inverter output voltage used in the drive implementation. The modelling and simulation of both the technique (FOC and DTC) will be explained in further chapters with the great extent and also the comparison will done by considering dynamic performance and implementation issues based on the MATLAB simulation. After the comparison of both techniques, main discussion will be concentrated on DTCIMD. Some new technique like constant frequency operation, ripple free DTC and sensor less DTC also will be discuss in later chapters.

CHAPTER 2

VECTOR CONTROL INDUCTION MOTOR DRIVE

2.1 INTRODUCTION

Vector control technique has significantly broadened the choice of application of cage induction motor. Now, this motor can be used even in those applications which were considered to be limited domain of DC motors [3]. The separately excited dc motor has a linear control plant with decoupled control structure which enable the independent control of flux and torque, Unlike, the induction motor has a non-linear and highly interacting multivariable control plant. The method of vector control helps in transporting its dynamics structure in such a way that it behave like a separately excited fully compensated dc motor.

The basic objective of the Vector control or field oriented control is “control of the induction motor just like a separately excited fully compensated dc motor”. In another words vector control does the mixture of constructional feature of induction motor and controlling feature of separately excited fully compensated dc motor.

2.2 CLASSIFICATION OF VECTOR CONTROL SCHEMES

In the broader sense there are two criteria which can be used for classifying the vector control of induction motor drive. The first depends upon the method used in determining the rotor flux vector and its position. The second one depends on the selection of reference frame for assisting the control of the motor. There are two methods of determining the rotor flux vector which are known as direct and indirect methods of vector control. Similarly, the vector can also be classified depending upon fixation of reference frame. Thus one can have stator flux orientation or rotor flux orientation or air gap flux orientation control [3]. Generally in induction motors, the rotor flux orientation is preferred due to its simplicity, better dynamics [2] and also inherent decoupling of its current components. Vector control technique can be classified in to (a) Direct Vector Control and (b) Indirect Vector control.

2.2.1 DIRECT VECTOR CONTROL METHOD

Direct vector control, determines the magnitudes and position of rotor flux vector by direct flux measurement or by a computation based on terminal condition [4], [7]. Direct vector control also called as flux feedback control, is a method in which the required information regarding the rotor flux magnitude and its position is obtained by means of direct flux measurement or estimation. Direct flux measurement is achieved by Hall Effect sensors, search coils, tapped stator winding of machine etc. Alternatively, rotor flux can also be achieve by use of flux model, which is based on the motor parameters and electrical input variables.

The major disadvantages of this method is the need of number of sensors. This drawback add motor cost and less reliability to the motor drives. Moreover, fixing up of flux sensors becomes more tedious job. Problem such as drift because of temperature, poor flux sensing at low speed also continue.

2.2.2 INDIRECT VECTOR CONTROL METHOD

Existence of related problem in case of direct vector control leads to use of indirect vector control. In indirect vector control technique, the rotor flux vector position is computed from the speed feedback signal of motor [2]-[6]. The indirect method eliminates the need of using flux sensors or flux model. However, it require an accurate measurement of shaft position in order to determine the precise position of rotor vector.

Mathematical modelling of vector control of induction motor drive consisting the various blocks modelling, as seen in the basic block diagram of VCIMD in Chapter 1 (Fig.1.1). So, the mathematical modelling of blocks basically consisting the derivation of the final equations, which can be easily simulate or written in the form of code in discrete form for hardware implementation. The feedback signals which is sensed from the machine is shaft speed (ω_r)

and stator currents (i_{as} andi_{bs}). Reference speed (ω_r^*) and shaft speed (ω_r) is compared and error is computed, that error is passed through a suitable controller which will generate reference toque signal (T_{em}^*). Suitable value of excitation (i_{mr}^*) is generated by sensed shaft speed magnitude. T_{em}^* and i_{mr}^* act as two input which generate two hypothetical current signal (i_{qs}^* and i_{ds}^*), which independently responsible for controlling torque and flux of the drive.

Therefore, method adopt in this work is indirect vector control or indirect rotor flux oriented control.

2.3 MATHEMATICAL MODELLING

2.3.1 SPEED CONTROLLER

The work of speed controller is to generate suitable reference torque signal from the speed error (difference between actual speed and the reference speed). There are many speed controller techniques are available like PI controller, Fuzzy Logic base controller, Intelligent Speed controller (Fuzzy + PI) etc. from all of the above, I have used PI controller to compelete this simulation.

PI controller

In the continuous time frame, the proportional integral controller can be represent as,

$$T_{em} = K_p(\omega_r^* - \omega_r) + K_I \int(\omega_r^* - \omega_r)\,dt \qquad (2.1)$$

But simulation model is in the discreet time frame, so the above equation can be converted in DTF as below,

$$\mathbf{T_{em\,(N)} = T^*_{em(N\text{-}1)} + K_p\,\{\omega_{er(N)} - \omega_{e(N\text{-}1)}\} + K_I\,\omega_{er(N)}} \qquad (2.2)$$

The equation (2.2) shows the basic PI controller in DTF and basic block diagram is shown in the Fig.2.1. The electromagnetic torque of N^{th} sample will be pass through the Limiter, so that the reference value of torque will in certain liming band. The simulation block of PI is shown in Fig.2.2.

Where K_p and K_I are proportional and integral gain parameter of PI controller. The gain parameters are judicially selected by observing their effects on the drive response. Numerical values of the controller gains are given in Appendix-II for motor drives used in this work.

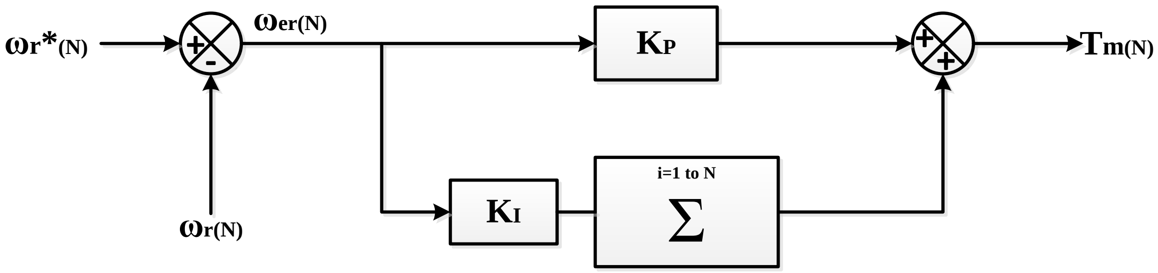


Fig.2.1 Block diagram of PI controller

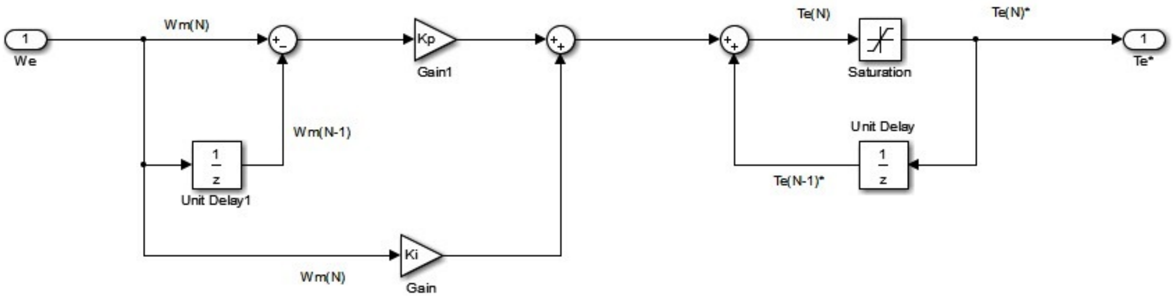


Fig.2.2 MATLAB block showing Speed controller using PI controller logic

2.3.2 FIELD WEAKENING

Field weakening (FW) operation is considered when reference speed (ω_r^*) is more than the base speed (ω_{base}). After all the vector control technique make induction motor operation as dc motor and in dc motor, Field weakening method is used to operate it for greater than base speed. Here also the same method has been consider to reduce the flux in proportional to the speed when speed is greater than base speed [40].

$i_{mr}^* = i_m$; When $\omega_r < \omega_{base}$

$i_{mr}^* = K_f \frac{i_m}{\omega_r}$ When $\omega_r \geq \omega_{base}$

Where i_{mr} refers to rms value of magnetizing current, and K_f refers to flux constant.

MATLAB code for this block in simulation can be shown as follows:

```
function imr = fcn(wm,im)
 wb= 314.16
if wm<wb
    imr=im;
else
    imr=(wb)*im/wm;
end

## where, imr= i*mr, wm = speed and wb = base speed
```

2.3.3 VECTOR CONTROLLER

The vector term in the vector control comes due the controlling of both magnitude as well as phase angle (stator mmf) in this methodology. Vector control is also known as Field Oriented Control (FOC) because by the orientation of stator flux or rotor flux or mutual (air gap) flux with synchronously rotating reference frame (d-q frame).

The vector control consist of three stage as sated by the following mathematical equations.

$$i_{ds}^{*} = i_{mr}^{*} + \tau_r di_{mr}^{*}/dt \tag{2.3}$$

$$i_{qs}^{*} = T_{em}^{*}/(k\, i_{ds}^{*}) \tag{2.4}$$

$$\omega_{sl} = \frac{1}{\tau_r}\frac{i_{qs}^{*}}{i_{ds}^{*}} \tag{2.5}$$

$$k = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r} \tag{2.6}$$

Where, i_{ds}^{*} , i_{qs}^{*} is d-q axis current components of synchronously rotating reference frame and ω_{sl} is slip speed.

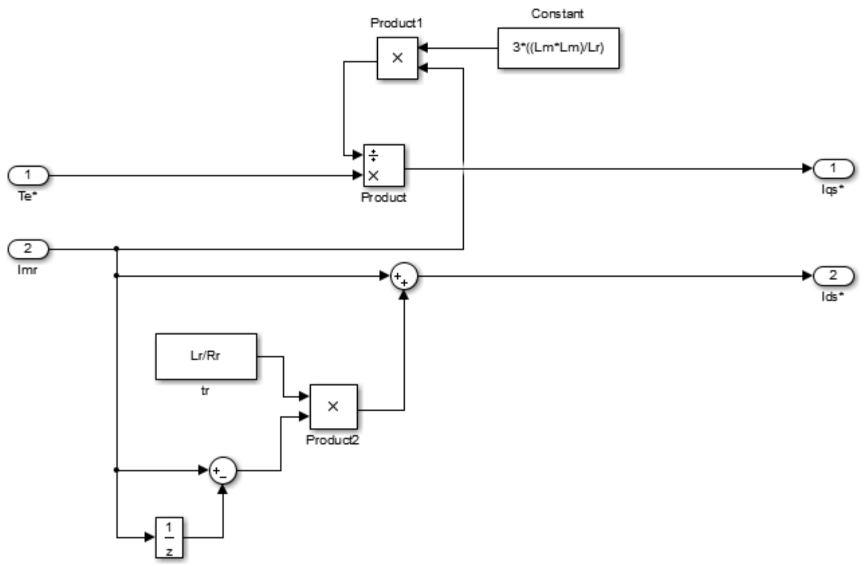
Position of rotor flux can be estimated by adding then integrating the slip speed and feedback rotor speed. The equation can be written as,

$$\Theta_e = \int \omega_e \, dt = \int (\omega_r + \omega_{sl})\, dt \tag{2.7}$$

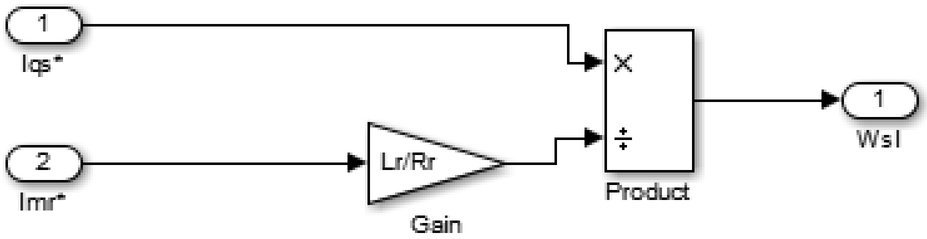
And in discrete frame can be expressed as,

$$\Theta_{e(N)} = \left(\omega_{e(N)} + \omega_{sl(N)}\right) \times \Delta T + \Theta_{e(N-1)} \tag{2.8}$$

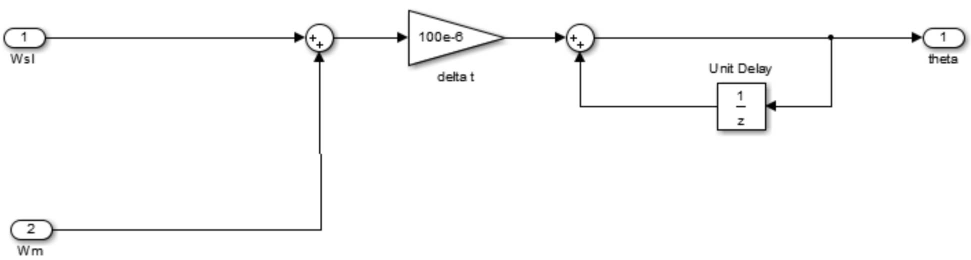
Blocks in the simulation modelling like Direct and Quadrature axis (synchronously rotating ref. frame) component of stator current Calculation, Slip speed calculation and rotor flux position ($\theta_{e_{(N)}}$)etc. can be easy modelled by equations (2.3) to (2.8) as shown below Fig.2.2.



(a)



(b)



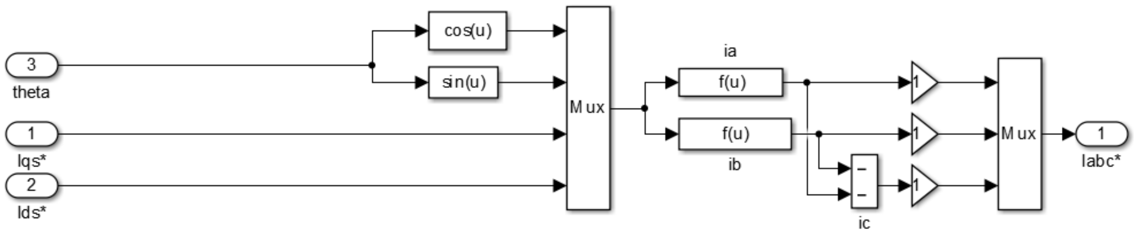
(c)

Fig.2.3 MATLAB block showing (a) Estimation of i_{qs}* and i_{ds}*. (b) Estimation of slip speed and (c) Estimation of Θ_e

2.3.4 TRANSFORMATION OF i^e_{qs} and i^e_{ds} into i_{as} , i_{bs} and i_{cs}

$$\begin{bmatrix} i^*_{as} \\ i^*_{bs} \\ i^*_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta e & -\sin\theta e \\ \cos(\theta e - 120) & -\sin(\theta e - 120) \\ \cos(\theta e + 120) & -\sin(\theta e + 120) \end{bmatrix} \begin{bmatrix} i^*_{ds} \\ i^*_{qs} \end{bmatrix} \tag{2.9}$$

The evaluation of Θ_e will lead us to go for direct evaluation and indirect evaluation knows Direct Vector Control and Indirect Vector Control respectively.in this report concentration will on only Indirect Vector control because of its simplicity in algorithm of finding the position and less sensitive to the parameter variation. The Matlab block showing coordinate transformation is shown in Fig.2.4.



(d)

Fig.2.4 MATLAB block showing Coordinate Transformation

2.3.5 SPEED SENSOR

It sense the speed of rotating machine it can either be a speed encoder or Tacho-generator with Voltage sensor. Here, for the hardware purpose Tacho-generator (mounted on the same shaft with induction motor) with Voltage sensor (which is calibrated in terms of rpm output) have used.

2.3.6 CURRENT REGULATORS

Diverse current regulating techniques like, Sinusoidal PWM, synchronous dq frame PI regulator, stationary frame PR, stationary frame PI and hysteresis current regulator etc. In all of those regulators Hysteresis Current control method of VSI offers an matchless transient response in contrast with other analog and digital method, which makes it suitable to accept this method in all cases where high accuracy, wide bandwidth, and robustness are essential.

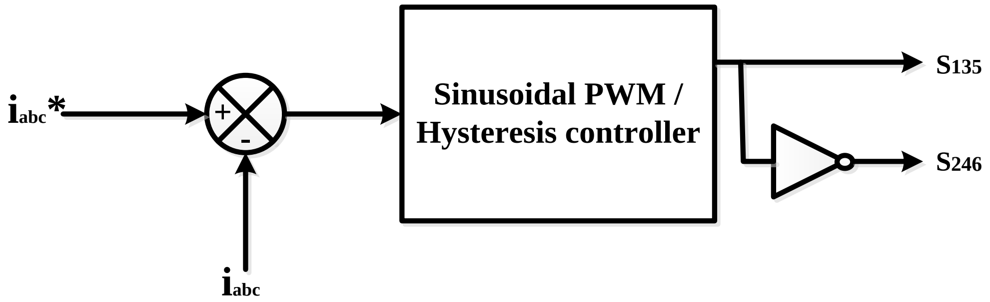


Fig.2.5 Block Diagram of Current Regulator using SPWM and Hysteresis Controller

Sinusoidal PWM

Here, depending upon the frequency of carrier, the switching device will operated by comparing the reference current and actual current, the error signal will generate then it will pass through PI controller to give the Modulation Index (MI). MI signal will pass through Limiter then multiply with sine wave having unity peak value, after that it compare with carrier wave to generate Gate Pulse signal. Modelling of this technique is shown in Fig 2.6.

Hysteresis Current Regulator

Hysteresis control technique is fundamentally an analogic technique. In spite of the merits given by digital controllers, in term of flexibility, maintenance integration interfacing, their correctness and response speed are often insufficient for current control in highly challenging applications, such as active filters and high- precision drives. In these applications, reference current waveform categorised by high harmonic content and fast transient must followed by good accuracy. In these belongings, the hysteresis technique can be a fine solution, provided some improvement are introduced to overcome its main limitations, which are sensitivity to phase commutation interference and switching frequency. The modelling of this technique is shown in Fig. 2.7.

2.3.7 THREE PHASE VSI

Two hypothetical signals i.e. i^*_{qs} and i^*_{ds} are converted in to the three phase reference currents i.e. i^*_{as}, i^*_{bs} and i^*_{cs} for current regulators. Regulator process take sensed actual three phase current and the reference three phase currents to produce the inverter getting signals SF_a, SF_b and SF_c. The output PWM voltage from VSI is as follows [6],

$$V_{as} = \frac{V_{DC}}{3}[2SF_a - SF_b - SF_c] \quad (2.10)$$

$$V_{bs} = \frac{V_{DC}}{3} [- SF_a + 2SF_b - SF_c] \quad (2.11)$$

$$V_{cs} = \frac{V_{DC}}{3} [- SF_a - SF_b + 2SF_c] \quad (2.12)$$

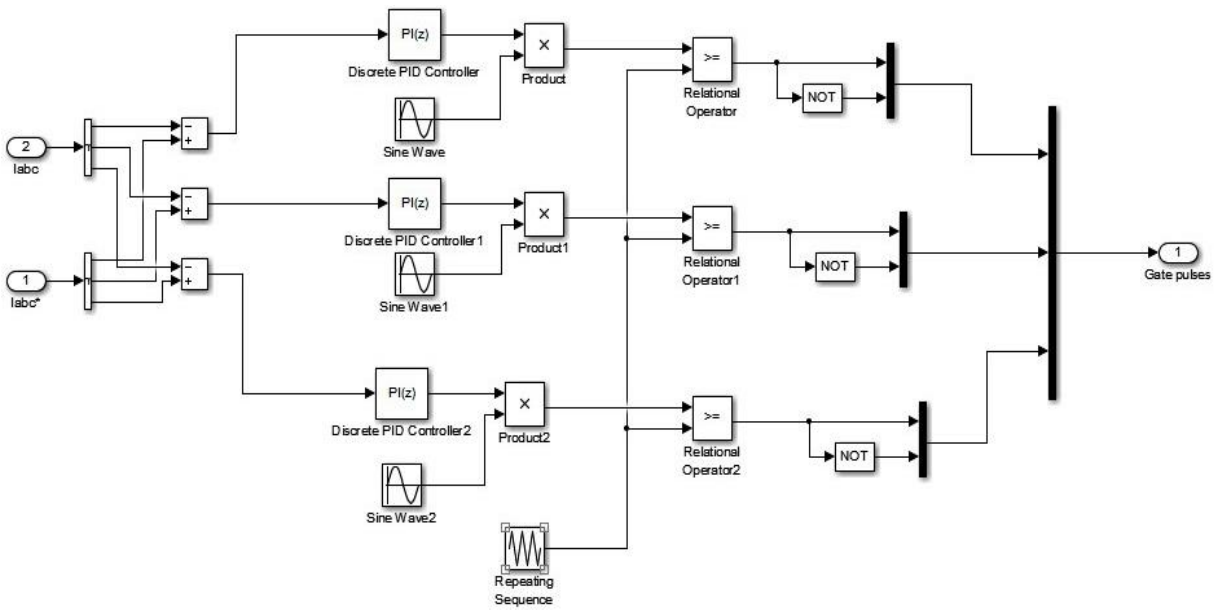


Fig.2.6 Sinusoidal PWM method to generate gate pulse for two level Inverter

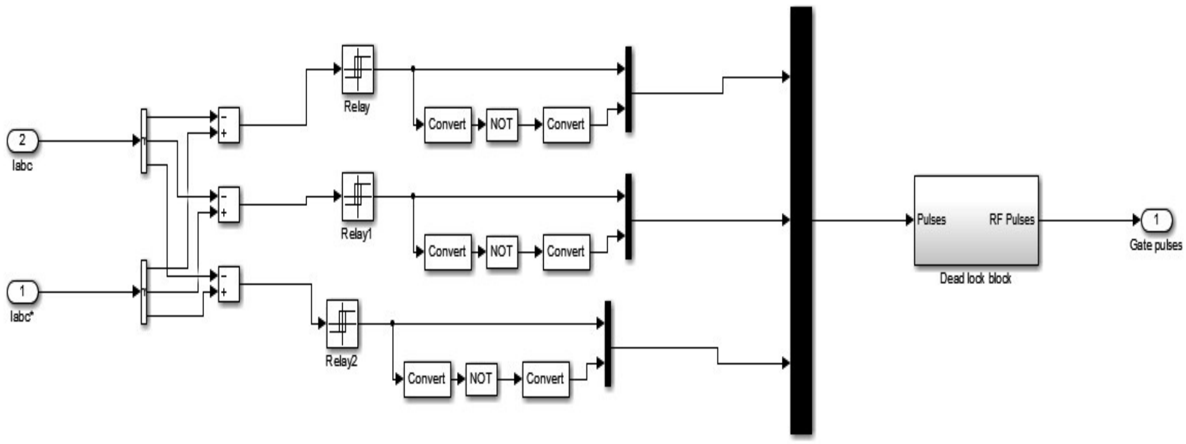


Fig. 2.7 Hysteresis current regulator to generate gate pule for inverter

The complete block diagram of Indirect Vector Control Induction Motor Drive is shown in Fig.2.8.

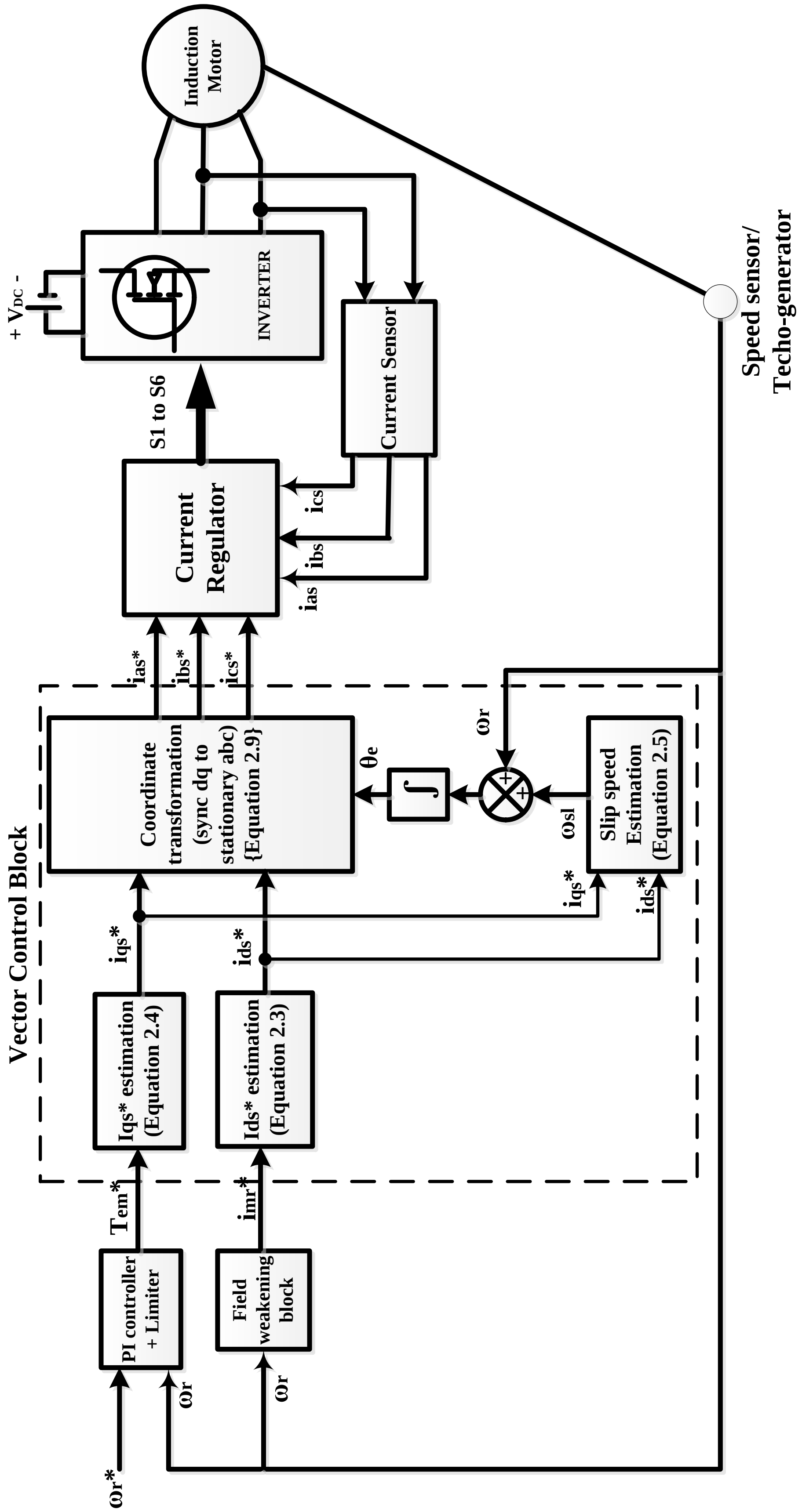


Fig.2.8 Block diagram of Indirect Vector Control of Induction Motor Drive

All three machines are simulated under indirect vector control strategy of MATLAB platform using SPS toolbox in the Discrete Time Frame (DTF). The Simulink model is shown in Fig. 2.9.

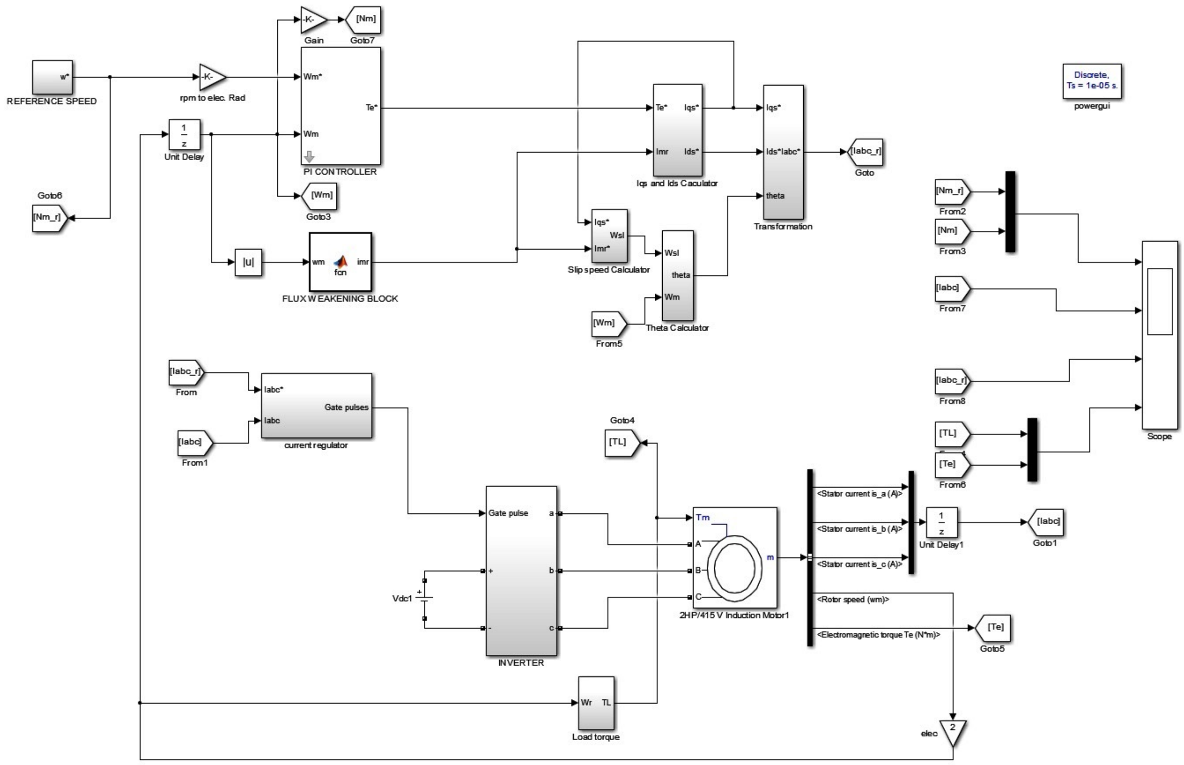


Fig. 2.9 Basic simualtion model of indirect vector control of IM drive

CHAPTER 3

DIRECT TORQUE CONTROL INDUCTION MOTOR DRIVE

3.1 INTRODUCTION

The history and literature survey about the direct torque control of induction motor drive has been given in chapter 1. The basic objective of the Direct Torque Control (DTC) is "control of the induction motor Torque and flux independently" (same as the FOC). However, the DTC will provide less complex, less parameter sensitive and faster dynamics algorithm if compare to FOC. This chapter deals with concept of DTC, its modelling and simulation.

As in the last chapter simulation of Vector Control Induction Motor Drive (Art. 2.2) have been discussed, Where some blocks already been explain like PI controller (Art 2.2.1), Field Weakening (Art.2.2.3), Speed sensor (Art 2.2.4) etc. these block are not going to be re-discussed here.

All three machines are simulated under Direct Torque Control strategy of MATLAB platform using SPS toolbox in the Discrete Time Frame (DTF). The Simulink model is shown in Fig. 3.8.

3.2 MATHEMATICAL MODELLING

3.2.1 SPEED CONTROLLE

In the Direct Torque Control Induction Motor Drive, to generate the reference torque from speed error, a speed controller is needed as in case of VCIMD. The same mathematical modelling is applied here too. (Refer Art. 2.2.1).

3.2.2 DIRECT TORQUE CONTROLLER

In DTC Electromagnetic Torque and Flux can also controlled independently. Of course, it has discussed, in the vector control drive the torque and flux controlled independently. But a vector controlled drive is sophisticated drive where Processor need lots of signal processing. In fact it need the transformation of synchronously rotating d-q frame to stationary abc frame in space, takes lots of computation power with complex algorithm. DTC doesn't require any such transformation.

In the stationary reference, the electromagnetic torque can be written as,

$$T_{em} = \frac{3}{2}\frac{P}{2}\left(\Psi_{ds}\, i_{qs} - \Psi_{qs}\, i_{ds} \right) \tag{3.1}$$

Derivation:

Based on the energy conservation principle

$$P_{mech} = \frac{dW_{mech}}{dt} = T_{em}\omega_r \tag{3.2}$$

For every machine, input electrical energy (W_e) has to cover the energies related to stator and rotor losses (W_{loss}), the magnetic energy stored in the field (W_{field}) and mechanical output energy (W_{mech}) [2],[4].

$$W_e = W_{loss} + W_{field} + W_{mech} \tag{3.3}$$

$$\frac{dW_{mech}}{dt} = \frac{dW_e}{dt} - \frac{dW_{loss}}{dt} + \frac{dW_{field}}{dt} \tag{3.4}$$

$$P_e = \frac{dW_e}{dt} = \frac{3}{2}\,\mathrm{Re}\{\bar{v}_s \bar{i}_s^* + \bar{v}_r \bar{i}_r^*\} \tag{3.5}$$

$$P_{loss} = \frac{dW_{loss}}{dt} = \frac{3}{2}\{R_s|i_s|^2 + R_r|i_r|^2\} \tag{3.6}$$

$$\frac{dW_{field}}{dt} = \frac{3}{2}\,\mathrm{Re}\{\bar{v}_{si}\bar{i}_s^* + \bar{v}_{ri}\bar{i}_r^*\} \tag{3.7}$$

Where $\bar{v}_{si}$ and $\bar{v}_{ri}$ are space phasors of induced stator and rotor transformed emfs respectively in stationary reference frame, can be written as:

$$\bar{v}_{si} = \frac{d\bar{\Psi}_s}{dt} \tag{3.8}$$

$$\bar{v}_{ri} = \frac{d\bar{\Psi}_r}{dt} \tag{3.9}$$

By taking equation 3.7 to 3.9,

$$\frac{dW_{field}}{dt} = \frac{3}{2}\ \mathrm{Re}\{\frac{d\overline{\Psi}_s}{dt}\overline{i}_s^* + \frac{d\overline{\Psi}_r}{dt}\overline{i}_r^*\} \tag{3.10}$$

$$\text{Or, } W_{field} = \frac{3}{2}\ \mathrm{Re}\{\ \overline{\Psi}_s\overline{i}_s^* + \overline{\Psi}_r\overline{i}_r^*\ \} \tag{3.11}$$

By putting equations 3.5, 3.6 and 3.10 in to equation 3.4,

$$\frac{dW_{mech}}{dt} = \frac{3}{2}\ \mathrm{Re}\{\overline{v}_s\overline{i}_s^* + \overline{v}_r\overline{i}_r^*\} - \frac{3}{2}\ \{R_s|i_s|^2 + R_r|i_r|^2\} + \frac{3}{2}\ \mathrm{Re}\{\frac{d\overline{\Psi}_s}{dt}\overline{i}_s^* + \frac{d\overline{\Psi}_r}{dt}\overline{i}_r^*\} \tag{3.12}$$

Total mechanical work done (W_{mech}) is the combination of mechanical work done by stator (W_{mechS}) and mechanical work done by rotor (W_{mechR}).

$$\frac{dW_{mech}}{dt} = \frac{dW_{mechS}}{dt} + \frac{dW_{mechR}}{dt}$$

Equation 3.12 can be divided in to stator and rotor form, as shown below

$$\frac{dW_{mechS}}{dt} = \frac{3}{2}\ \mathrm{Re}\{\overline{v}_s\overline{i}_s^*\} - \frac{3}{2}\ \{R_s|i_s|^2\} + \frac{3}{2}\ \mathrm{Re}\{\frac{d\overline{\Psi}_s}{dt}\overline{i}_s^*\} \tag{3.13}$$

$$\frac{dW_{mechR}}{dt} = \frac{3}{2}\ \mathrm{Re}\{\overline{v}_r\overline{i}_r^*\} - \frac{3}{2}\ \{R_r|i_r|^2\} + \frac{3}{2}\ \mathrm{Re}\{\frac{d\overline{\Psi}_r}{dt}\overline{i}_r^*\} \tag{3.14}$$

Since, in the stationary ref. frame, the stator voltage space phasor ($\overline{v}_s$) can only be poised by the stator ohmic drop ($R_s\overline{i}_s$) plus the rate of change of stator flux linkages ($\frac{d\overline{\Psi}_s}{dt}$), it followed from equation 3.13 that dW_{mechS} must be equal to zero.

The rotor voltage phasor ($\overline{v}_r$) must be balanced by the sum of rotor ohmic voltage drop ($R_r\overline{i}_r$) plus the rate of change of rotor flux linkages ($\frac{d\overline{\Psi}_r}{dt}$) and a rotational voltage ($-j\omega_r\overline{\Psi}_r$).

$$\overline{v}_r = R_r\overline{i}_r + \frac{d\overline{\Psi}_r}{dt} - j\omega_r\overline{\Psi}_r$$

$$\text{Or, } \overline{v}_r\overline{i}_r^* - R_r|i_r|^2 - \overline{i}_r^*\frac{d\overline{\Psi}_r}{dt} = -j\omega_r\overline{i}_r^*\overline{\Psi}_r \tag{3.15}$$

From equation 4.14 and 4.15,

$$P_{mech} = \frac{dW_{mech}}{dt} = \frac{3}{2}\ \mathrm{Re}(-j\omega_r\overline{i}_r^*\overline{\Psi}_r) = \frac{3}{2}\ \omega_r\mathrm{Re}(-j\overline{i}_r^*\overline{\Psi}_r)$$

$$\text{Or, } P_{mech} = -\frac{3}{2}\ \omega_r(\overline{\Psi}_r * \overline{i}_r) \tag{3.16}$$

$$T_{em} = -\frac{3}{2}\frac{P}{2}\ (\overline{\Psi}_r * \overline{i}_r) \tag{3.17}$$

Above torque expression also in force when rotor flux linkage and rotor current in rotating reference frame, as the electromagnetic torque is invariant to change of reference frames. To produce equation 3.17 in the form of stator parameter, need to follow some step as,

From the fig.3.1,

$$\bar{\Psi}_s = L_s\,\bar{i}_s + L_m\,\bar{i}_r \tag{3.18}$$

$$\bar{\Psi}_r = L_r\,\bar{i}_r + L_m\,\bar{i}_s \tag{3.19}$$

Putting the expression of $\bar{\Psi}_r$ and $\bar{i}_r$ in term of $\bar{\Psi}_s$ and $\bar{i}_s$ using equation 3.18 and 3.19, one will easily get the torque expression in term of stator parameter as shown below,

$$T_{em} = \frac{3}{2}\frac{P}{2}\left(\bar{\Psi}_s \times \bar{i}_s\right) \tag{3.20}$$

Where, $\bar{\Psi}_s = \Psi_{ds} + j\Psi_{qs}$ and $\bar{i}_s = i_{ds} + ji_{qs}$

Fig.3.1 Equivalent circuit of Induction Motor in stationary reference frame

Now, in the extended form,

$$\mathbf{T_{em} = \frac{3}{2}\,\frac{P}{2}\,(\,\Psi_{ds}\,i_{qs} - \Psi_{qs}\,i_{ds}\,)} \tag{3.21}$$

Equation 3.21 is exact same as equation 3.1. So, here the derivation has completed for the expression of electromagnetic torque. However, derivation of this expression in terms rotor parameter, rotor and stator flux and rotor and stator currents can also be done.

Above equation is having two variables, it is better to reduce it to one variable form.

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

$$\text{Or, } \Psi_{ds} = L_s\,i_{ds} + L_m\left(\frac{\Psi_{dr} - L_m i_{ds}}{L_r}\right)$$

$$= L_s\,i_{ds} + \frac{L_m}{L_r}\Psi_{dr} - \frac{L_m^2}{L_r}\,i_{ds}$$

$$= L_s\left(1 - \frac{L_m^2}{L_s L_r}\right) i_{ds} + \frac{L_m}{L_r}\,i_{ds}$$

$$\text{Or, } \Psi_{ds} = \sigma L_s\,i_{ds} + \frac{L_m}{L_r}\,\Psi_{dr}$$

By rearranging the above equation

$$i_{ds} = \frac{1}{\sigma L_s}\left(\Psi_{ds} - \frac{L_m}{L_r}\Psi_{dr}\right) \tag{3.22}$$

Similarly

$$i_{qs} = \frac{1}{\sigma L_s}\left(\Psi_{qs} - \frac{L_m}{L_r}\Psi_{qs}\right) \tag{3.23}$$

Put equation (3.2) and (3.3) in the equation (3.1),

$$T_{em} = \frac{3}{2}\frac{P}{2}\left[\frac{L_m}{\sigma L_s L_r}\right][\Psi_{qs}\Psi_{dr} - \Psi_{ds}\Psi_{qr}] \tag{3.24}$$

From the Fig. 3.2, rotor and stator flux vector in the form of d and q- axis component can be written as,

$$\Psi_{qs} = \Psi_s \sin\Theta_{fs}$$

$$\Psi_{ds} = \Psi_s \cos\Theta_{fs}$$

$$\Psi_{qr} = \Psi_r \sin\Theta_{fr}$$

$$\Psi_{dr} = \Psi_r \cos\Theta_{fr}$$

Put all four relation in the equation (3.24),

$$\mathbf{T_{em}} = \frac{\mathbf{3}}{\mathbf{2}}\frac{\mathbf{P}}{\mathbf{2}}\left[\frac{\mathbf{L_m}}{\boldsymbol{\sigma}\mathbf{L_s L_r}}\right]\boldsymbol{\Psi_s}\boldsymbol{\Psi_r}\,\mathbf{sin}(\boldsymbol{\Theta_{fs}} - \boldsymbol{\Theta_{fr}}) \tag{3.25}$$

Or, $\mathbf{T_{em}} = \mathbf{K}\,\boldsymbol{\Psi_s}\,\boldsymbol{\Psi_r}\,\mathbf{sin}(\boldsymbol{\gamma_{sr}})$ (3.26)

From looking at equation (3.26), it can conclude that torque can be control either by stator flux (as rotor flux cannot be directly accessible) or angle between rotor flux and stator flux.

For the independent control of flux and torque, if it is manage to control the angle (γ_{sr}) by keeping the flux constant or with in the certain band than, purpose will be solved. To do so, Voltage Space Vector selection method can be used.

Voltage space vector and the sector division diagram is shown in the Fig. 4.2. In the figure voltage space vector shown as V_0, V_1 ……, V_7. In these vectors 6 vectors are non-zero (V_1 to V_6) and two vectors are zero or null vectors (V_0 and V_7) and there are six sectors 1, 2… 6. Now, switching of these all voltage vector will depends on the flux position, torque and flux requirement.

As,

$$\frac{d\overline{\Psi}_s}{dt} = \overline{V}_s - \overline{I}_s R_s$$

$$\overline{\Psi}_s = \int(\overline{V}_s - \overline{I}_s R_s)dt + (\overline{\Psi}_s)_{\text{Initial}}$$

$$\overline{\Psi}_s = \int \overline{V}_s\, dt - R_s \int \overline{I}_s\, dt + (\overline{\Psi}_s)_{\text{Initial}} \tag{3.27}$$

In the equation (3.27), $\overline{V}_s$ is one of the eight voltage vectors (V_0 to V_7). For the simplicity resistive drop ($R_s \int \overline{I}_s\, dt$) can be neglected.

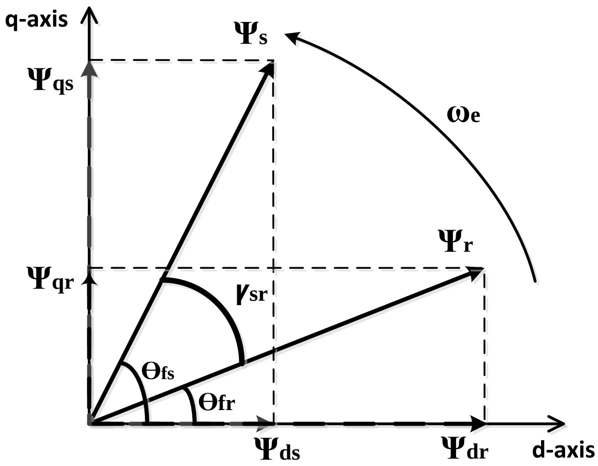


Fig. 3.2 Rotor and Stator flux vector and their component in the space.

Assuming the voltage vector will remains same for time Δt, then the equation would become,

$$\overline{\Psi}_s = \overline{V}_s\, \Delta t + (\overline{\Psi}_s)_{\text{Initial}} \tag{3.28}$$

The above equation (3.28) shows control over the stator flux, so ultimately control over the angle between stator flux and rotor flux (γ_{sr}) have been achived. It can be easily shown in Fig. 3.3. Now by having control over the angle and the flux, torque can be controlled. But the final objective is to control torque without affecting Flux. So, two type of hysteresis controller have been taken to keep flux and torque with in certain band limit.

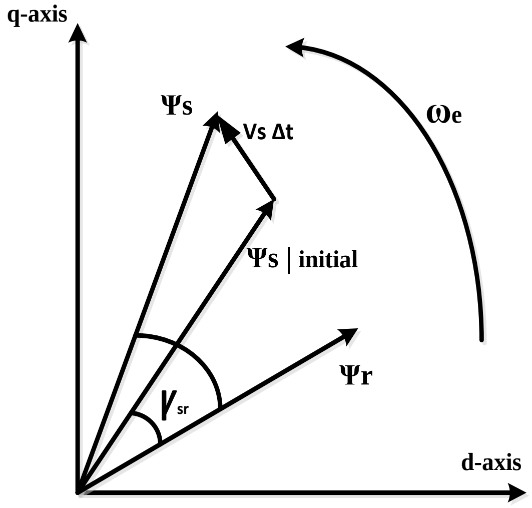


Fig. 3.3 Space phasor of Equation (3.8)

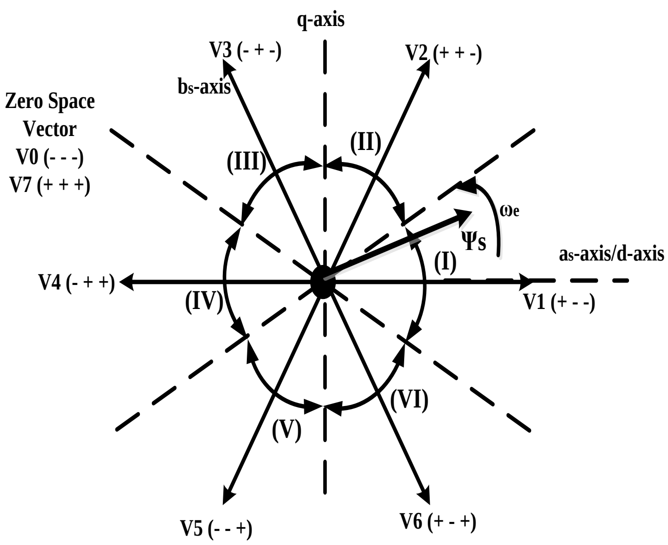


Fig. 3.4 Voltage Space Vectors and Sector division.

3.2.2.1 Flux Comparator

It is a two level hysteresis controller which will give the output according to the error between the reference flux (mostly constant for speed below base speed) and actual machine flux as shown in Fig. 3.5(a). The logic of this comparator will be as follows,

If $\Psi_s \leq \Psi_s^* - \Delta\Psi_s$ then $d_\Psi = 1$;

If $\Psi_s \geq \Psi_s^* + \Delta\Psi_s$ then $d_\Psi = 0$;

Where, $2\Delta\Psi_s$ are the band width of flux hysteresis comparator.

3.2.2.2 Torque Comparator

It is a three level hysteresis controller which will give the output according to the error between the reference Torque (depends upon the speed error) and actual machine electromagnetic torque as shown in Fig. 3.5 (b). The logic of this comparator will be as follows,

If $T_{em} \leq T^*_{em} - \Delta T_{em}$ then $d_T = 1$;

If $T_{em} \geq T^*_{em}$ then $d_T = 0$;

If $T_{em} \geq T^*_{em} + \Delta T_{em}$ then $d_T = -1$;

If $T_{em} \leq T^*_{em}$ then $d_T = 0$;

Where, $2\Delta T_{em}$ are the band width of torque hysteresis comparator.

MATLAB Code

```
function d_si = fcn(si_r,si,h_si)
d_si=0;
if (si_r-si)>h_si
    d_si=1;
elseif (( (si_r-si)>-h_si) && ((si_r-si)<h_si) && d_si==1)
    d_si=1;
elseif  ((si_r-si)<-h_si)
    d_si=2;
elseif ( ((si_r-si)>-h_si) && ((si_r-si)<h_si) && d_si==2)
    d_si=2;
end
```

Where, d_si= d_Ψ , si_r= Ψ^*_s, si= Ψ_s and h_si= $\Delta\Psi_s$.

MATLAB Code

```
function dT = fcn( Ter,Te,Hm )
dT=0;
if ((Ter-Te)> Hm)
    dT=1;
elseif ((Ter-Te)>0 && (Ter-Te)<Hm && dT==1)
    dT=1;
elseif ((Ter-Te)<-Hm)
    dT=3;
elseif ((Ter-Te)>-Hm && (Ter-Te)<0 && dT==3)
    dT=3;
elseif ((Ter-Te)>0 && (Ter-Te)<Hm && dT==3)
    dT=0;
elseif ((Ter-Te)>-Hm && (Ter-Te)<0 && dT==1)
    dT=0;
end
```

Where, dT= d_T , Ter= T^*_{em}, Te= T_{em} and Hm= ΔT_{em}.

Up to now, flux status (d_Ψ) and torque status (d_T) have achieved. But one another information require which is Flux position. Flux position gives the idea about the sector (see Fig. 3.6).

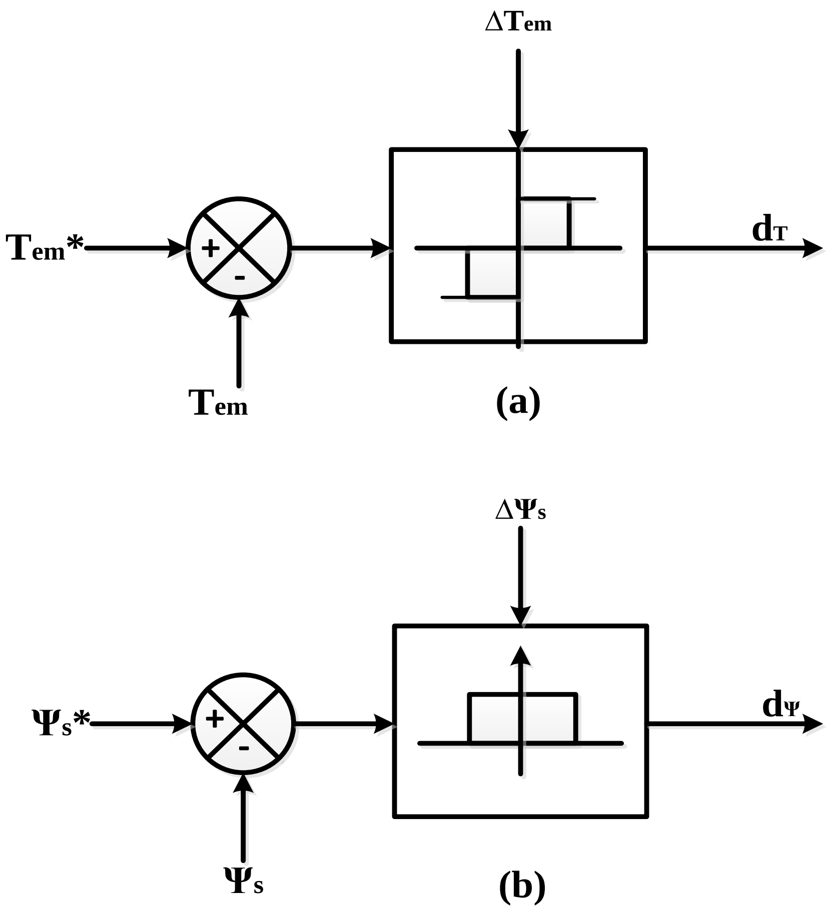


Fig. 3.5 (a) Two level flux comparator and (b) Three level Torque comparator

3.2.2.3 TORQUE (T_{em}), FLUX (Ψ_s) AND SECTOR ESTIMATION

$$\overline{\Psi}_{ds} = \int(\overline{V}_{ds} - \bar{i}_{ds} R_s)dt \tag{3.29}$$

$$\overline{\Psi}_{qs} = \int(\overline{V}_{qs} - \bar{i}_{qs} R_s)dt \tag{3.30}$$

$$\Psi_s = \sqrt{\Psi_{ds}^2 + \Psi_{qs}^2} \tag{3.31}$$

$$\Theta_\Psi = \tan^{-1}\left(\frac{\Psi_{qs}}{\Psi_{ds}}\right) \tag{3.32}$$

$$T_{em} = \frac{3}{2}\frac{P}{2}(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \tag{3.33}$$

Sector Estimation

Generally, sector estimation is done by algorithm which use trigonometric calculation to find the angle of position of stator flux vector (equation 3.32). But in this simulation one modification is carried out to remove this trigonometrical calculation. See Fig.3.7. , Three axis has been shown, i.e. a or d axis, q axis and b axis. Now, the sign change of stator flux vector components Ψ_{ds} and Ψ_{qs} from one sector to another sector is being evaluated according to d and q axis and tabulated in Table 3.1.

Table 3.1 Sign of Ψ_{ds} and Ψ_{qs} in all sectors

Sectors	1	2	3	4	5	6
Ψ_{ds}	+	+	-	-	-	+
Ψ_{ds}	-,0,+	+	+	+,0,-	-	-

From the Table 3.1, sign of Ψ_{ds} and Ψ_{qs} in different sectors are not clarifying the logic because in sectors 1 and 4, q-axis component of flux having three different sign. To overcome this difficulty instead of q-axis, b-axis can be considered. The b-axis component of stator flux can be formulated as:

If non-power-invariant form of the space vectors are used, then

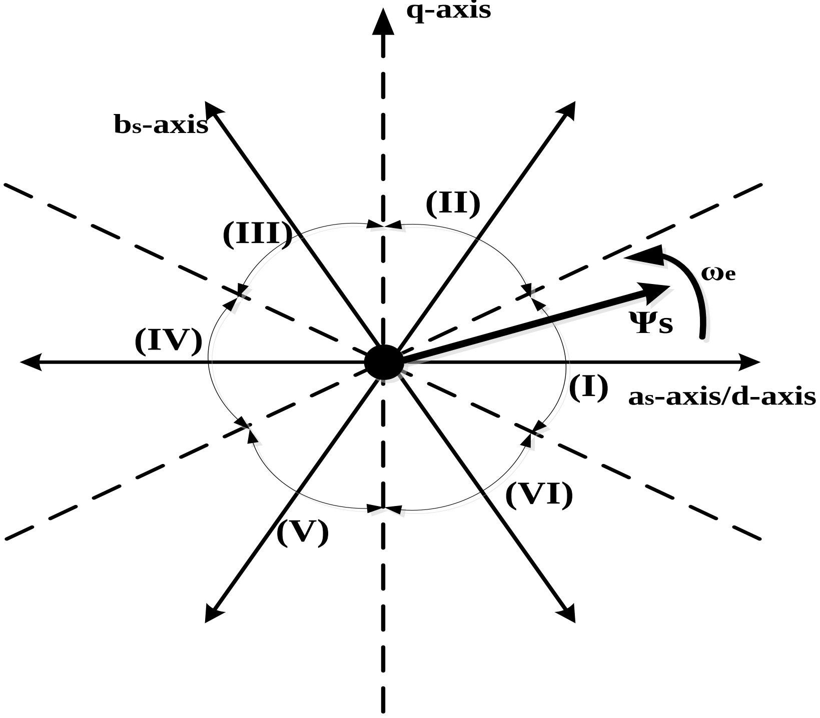


Fig. 3.6 Sector division diagram.

$$\overline{\Psi}_s = \frac{3}{2}\left(\Psi_{as} + a\Psi_{bs} + a^2\Psi_{cs}\right) = \Psi_{ds} + j\Psi_{qs} \quad (3.34)$$

$$\Psi_{as} = \Psi_{ds} = \int (\, v_{ds} - \, i_{ds}\, R_s \,)dt \quad (3.35)$$

Where $v_{ds} = v_{as}$ and $i_{ds} = i_{as}$. Furthermore,

$$\Psi_{qs} = \frac{\Psi_{bs} - \Psi_{cs}}{\sqrt{3}} = \int (\, v_{qs} - \, i_{qs}\, R_s \,)dt \quad (3.36)$$

Where,

$$v_{qs} = \frac{v_{bs} - v_{cs}}{\sqrt{3}}$$

$$i_{qs} = \frac{i_{bs} - i_{cs}}{\sqrt{3}}$$

By solving above equation, the expression for b-axis component of stator flux vector can written as:

$$\boldsymbol{\Psi_{bs} = \frac{\sqrt{3}\Psi_{qs} - \Psi_{ds}}{2}} \quad \textbf{(3.37)}$$

Table 3.2 Sign of Ψ_{ds} and Ψ_{bs} in all sectors

Sectors	1	2	3	4	5	6
Ψ_{ds}	+	+	-	-	-	+
Ψ_{bs}	-	+	+	+	-	-

So, now the algorithm to find out the sector from the sign of d and b axis components of stator flux vector magnitude is as follows;

1. Find quadrant of stator flux:

MATLAB Code

```
if si_d>=0 && si_q>=0
    Qd=1;
elseif si_d<0 && si_q>0
    Qd=2;
elseif si_d<0 && si_q<0
    Qd=3;
elseif si_d>0 && si_q<0
    Qd=4;
```

Where, si_d = Ψ_{ds}, si_q= Ψ_{qs} and Qd= quadrant.

2. Find the sector in which stator flux existing.

MATLAB Code

```
if Qd == 1 && si_d>0 && si_B<=0
    sector = 1;
elseif Qd == 1 && si_d>=0 && si_B>0
    sector = 2;
elseif Qd == 2 && (abs(si_q/si_d)>=0.5774) && si_d<0 && si_B>0
    sector = 3;
elseif Qd == 2 && (abs(si_q/si_d)<0.5774) && si_d<0 && si_B>0
    sector = 4;
elseif Qd == 3 && si_d<0 && si_B>=0
    sector = 4;
elseif Qd == 3 && si_d<=0 && si_B<0
    sector = 5;
elseif Qd == 4 && (abs(si_q/si_d)>=0.5774) && si_d>0 && si_B<0
    sector = 6;
elseif Qd == 4 && (abs(si_q/si_d)<0.5774) && si_d>0 && si_B<0
    sector = 1;
```

Where, si_d = Ψ_{ds}, si_q= Ψ_{qs}, si_B = Ψ_{bs} and Qd= quadrant.

After estimating flux position, sector information can easily estimate. Now with help of three quantity flux status, torque status and sector will lead us to make switching logic according to the Switching Look-up Table shown in Table 3.3.

Table 3.3 Switching Look-Up logic Table

Status \ Sectors		θ(1)	θ(2)	θ(3)	θ(4)	θ(5)	θ(6)
d_Ψ=1	d_T=+1	V_2	V_3	V_4	V_5	V_6	V_1
	d_T=0	V_7	V_0	V_7	V_0	V_7	V_0
	d_T=-1	V_6	V_1	V_2	V_3	V_4	V_5
d_Ψ=0	d_T=+1	V_3	V_4	V_5	V_6	V_1	V_6
	d_T=0	V_0	V_7	V_0	V_7	V_0	V_7
	d_T=-1	V_5	V_6	V_1	V_2	V_3	V_4

3.2.3 GATE PULSE GENERATION

To generate the gate pulse Sector information, flux status, torque status and Switching look-up table (see art 3.2.2 and Table 3.3) are requred. Implementation logic in MATLAB Simulink is shown in Fig 3.7.

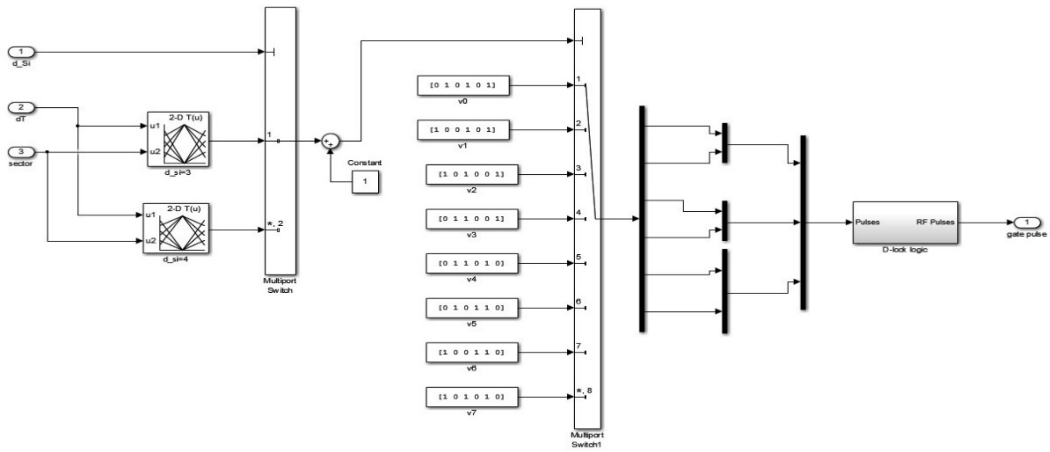


Fig. 3.7 Gate Pulse Generation logic in MATLAB Simulation

The block diagram and simulation model of DTC is shown in Fig.3.8 and Fig.3.9 respectively.

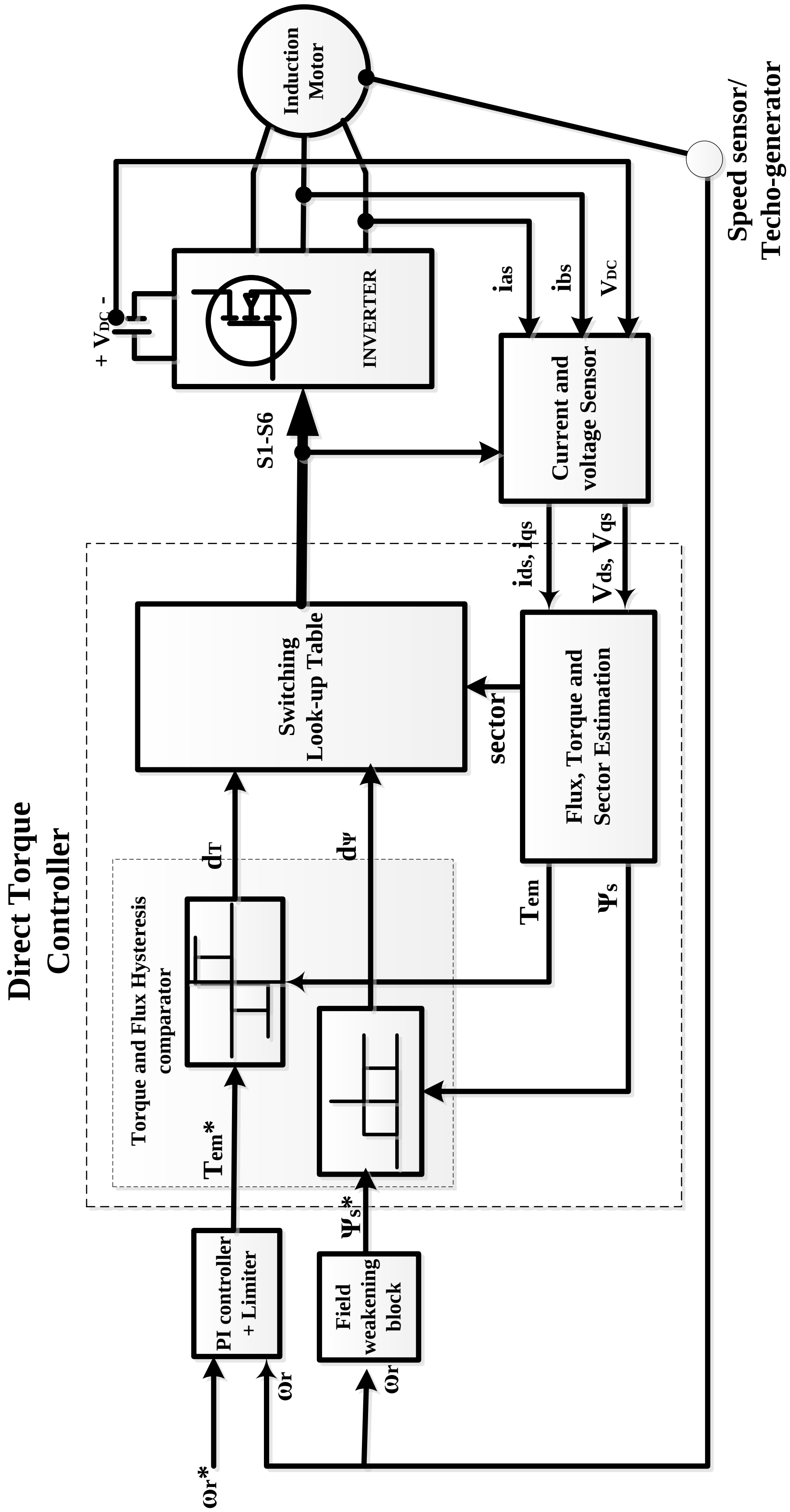


Fig. 3.8 Block diagram of Direct Torque Control of Induction Motor Drive

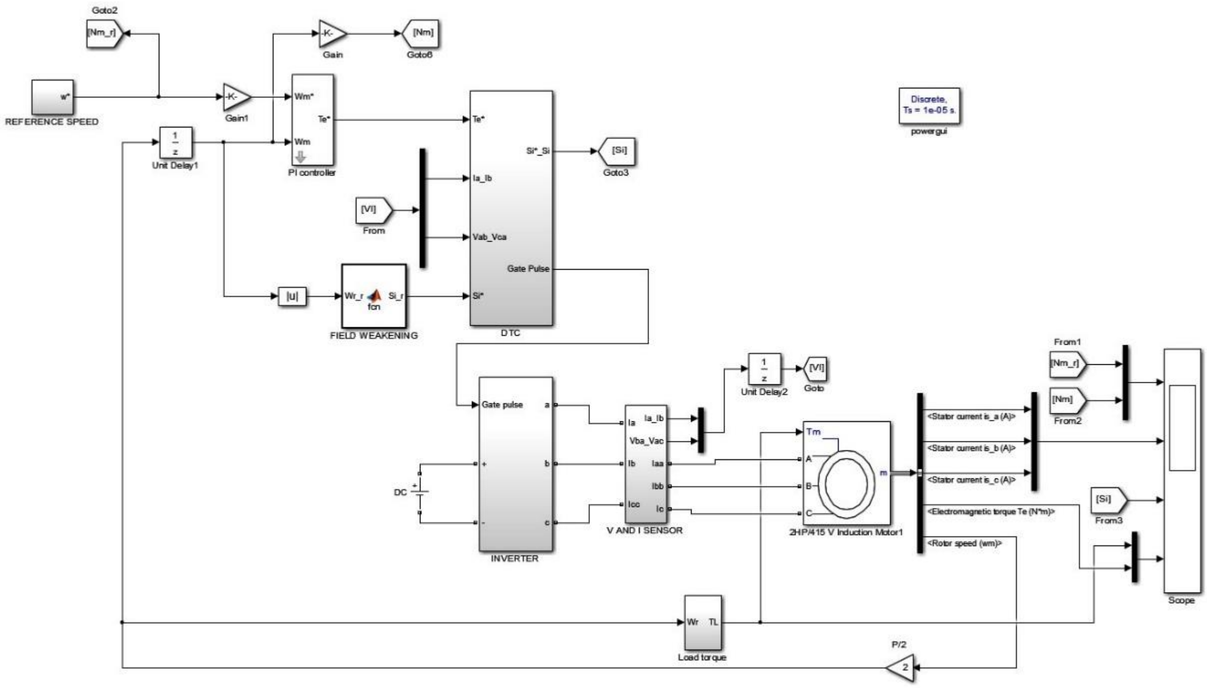


Fig. 3.9 Basic simualtion model of direct torque control of IM drive

CHAPTER 4

COMPARISON BETWEEN DIRECT TORQUE CONTROL AND VECTOR CONTROL INDUCTION MOTOR DRIVE

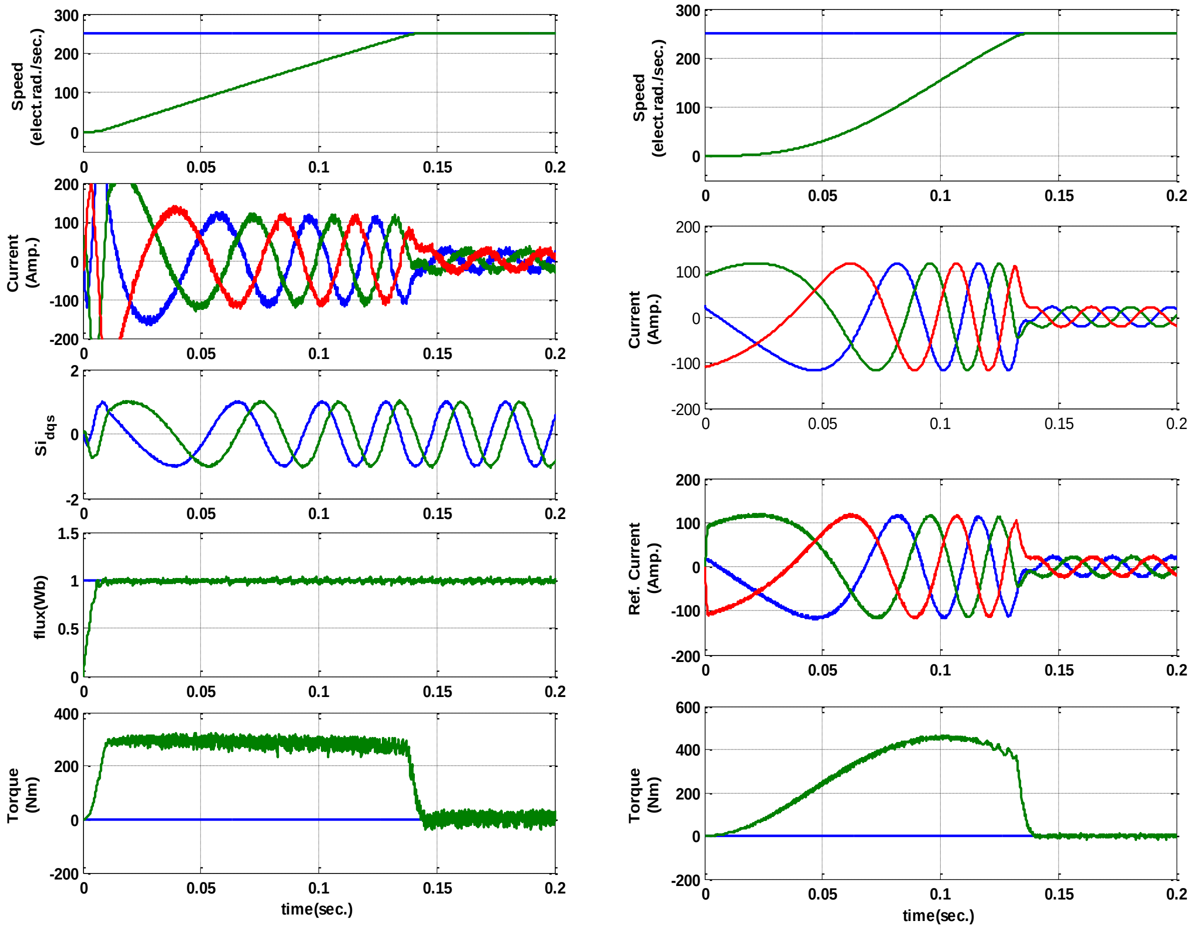
Simulation of Vector Controlled IM drive and Direct Torque Controlled IM drive have been discussed in chapter 4. Simulation results of those simulations for 30HP, 5HP and 2HP is discussed in this chapter. The comparative analysis for both the considered schemes is based on their dynamic performance and implementation complexity. The dynamic performance of the drive is analysed in various operating modes such starting, speed reversal and load perturbation.

4.1 ON THE BASIS OF DYNAMIC PERFORMANCE

In this section, VCIMD and DTCIMD schemes are compared on the basis of results, which are obtained by simulation in MATLAB environment using Simulink and SPS Toolboxes. These tools allows the control system and power circuits representation in the same diagram. These simulations is done in Discrete Time Frame. Since the aim is compare both methods on the basis of dynamics, so here starting, reversal and load perturbation dynamics for three different rated three phase induction motor (30HP/415V, 5HP/415V and 2HP/415V) is considered and machines parameters are listed in Appendix I.

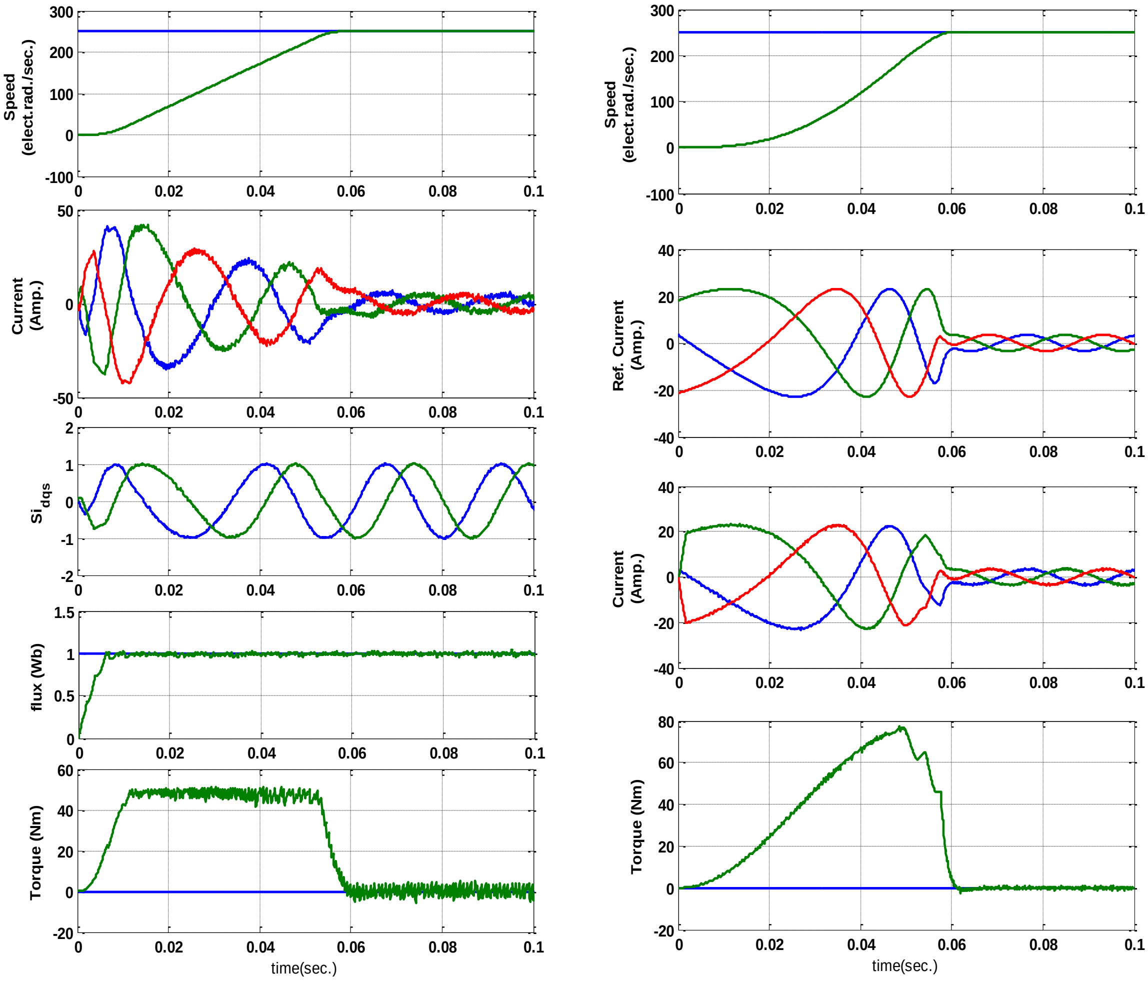
4.1.1 STARTING DYNAMICS

The induction motor is fed from a controlled voltage and frequency source. Initially, drive starts at low frequency controlled by controller and finally reaches at set steady- state speed (here taken as 250 electrical rad/sec). Due to appropriate torque limit in speed controller, starting current of induction motor also remain in safe limits. The comparison results of the starting dynamics for 30HP, 5HP and 2HP separately for both (VCIMD and DTCIMD) are shown in Fig.4.1, 4.2 and 4.3.



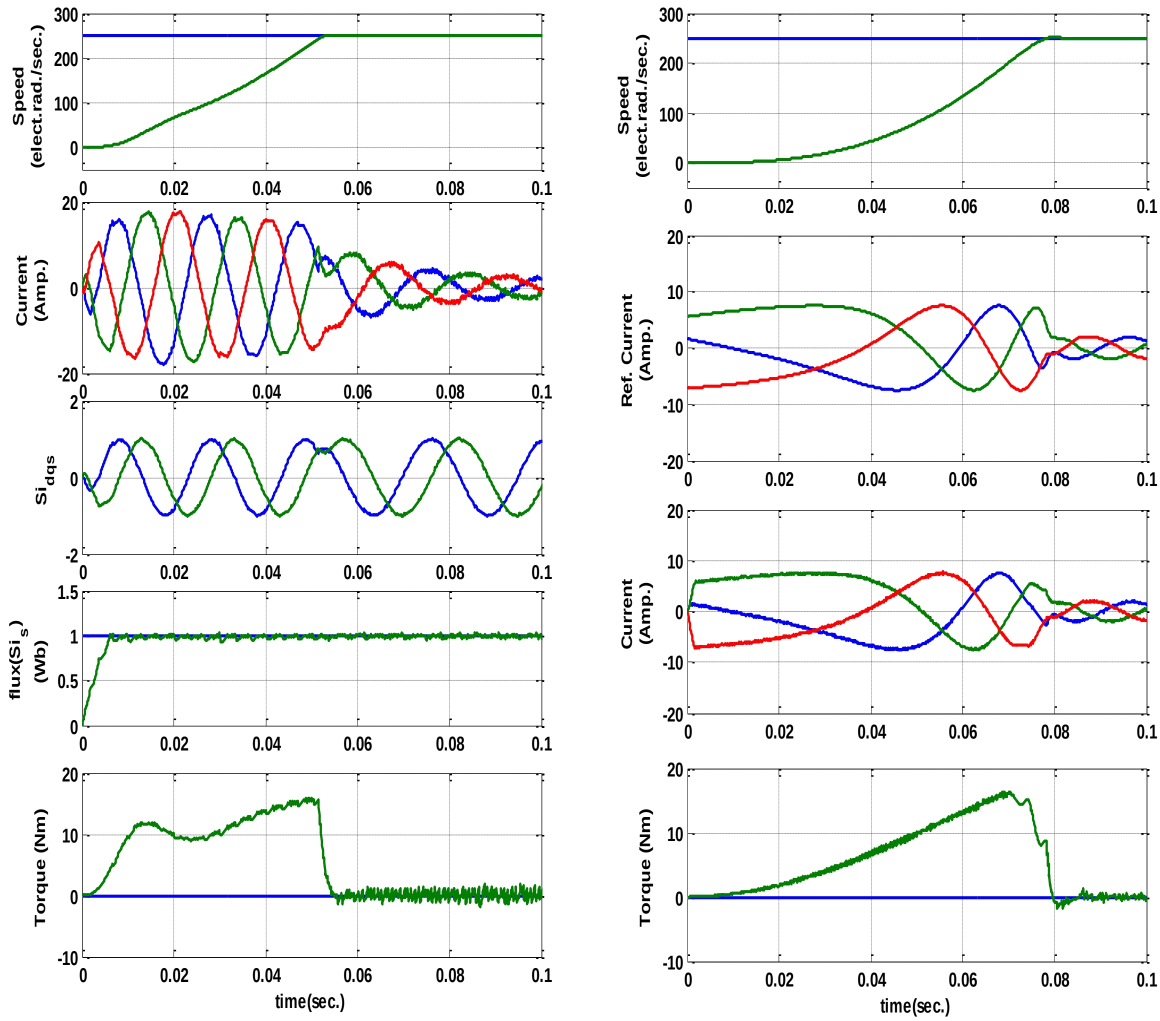
(a) (b)

Fig.4.1 Starting Dynamics of 30HP Induction motor drive operated under (a) DTCIMD and (b) VCIMD



(a) (b)

Fig.4.2 Starting Dynamics of 5HP Induction motor drive operated under (a) DTCIMD and (b) VCIMD

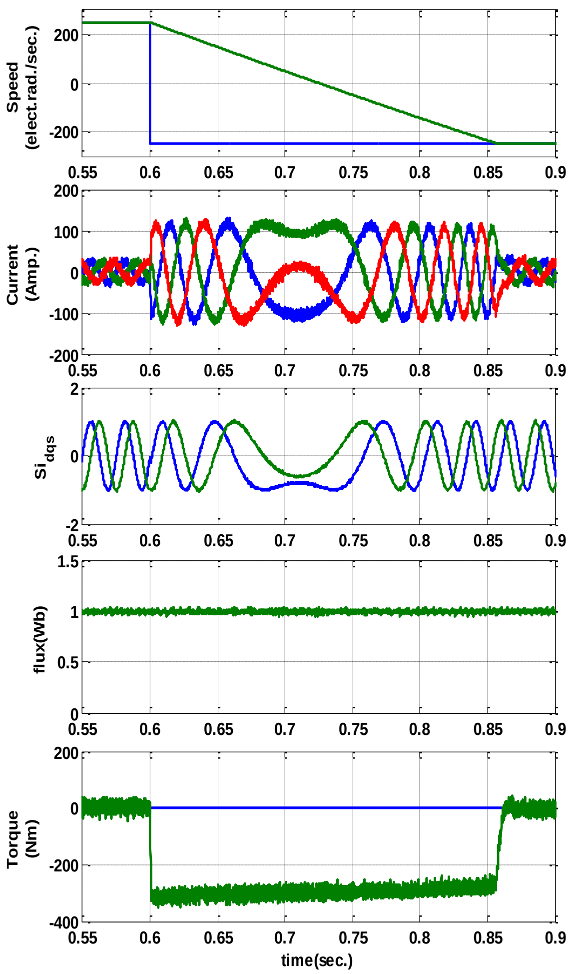


(a) (b)

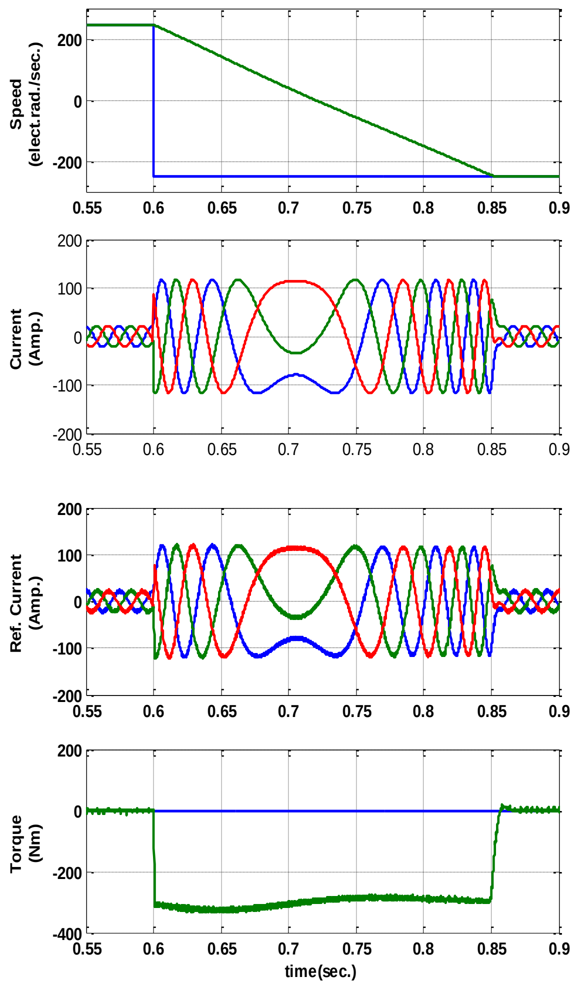
Fig.4.3 Starting Dynamics of 2HP Induction motor drive operated under (a) DTCIMD and (b) VCIMD

4.1.2 SPEED REVERSAL DYNAMICS

When the reference speed change from +250 electrical rad/sec to -250 electrical rad/sec, controller initially reduces frequency of stator current followed by the phase reversal to get the motor shaft rotation in the reverse direction. As the load condition is same, so stator current will get settled in the same magnitude as it was before reversal, however the phase sequence will change to get rotating magnetic field in reverse direction. The comparison results of the speed reversal dynamics for 30HP, 5HP and 2HP separately for both (VCIMD and DTCIMD) are shown in Fig.4.4, 4.5 and 4.6.

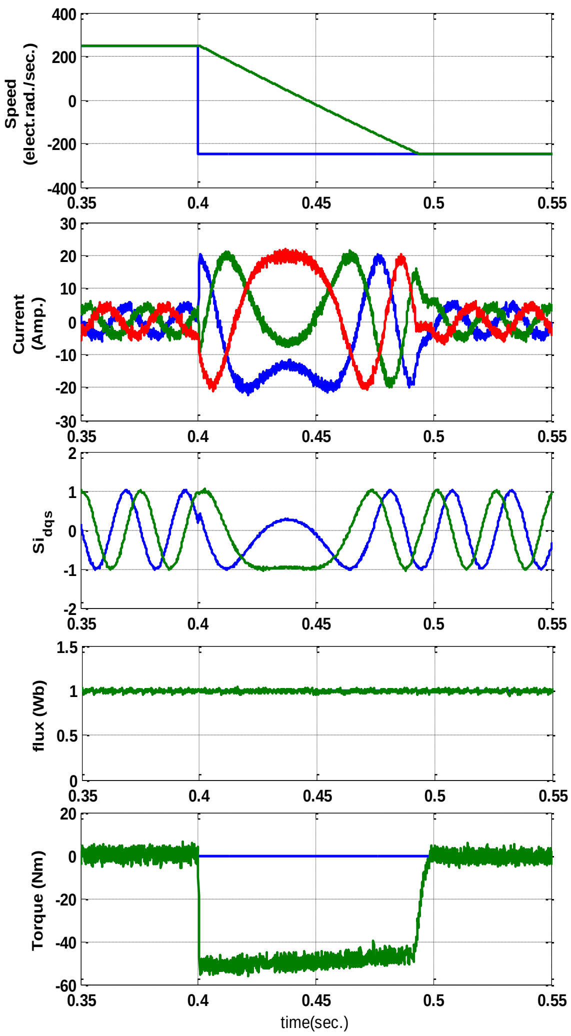


(a)

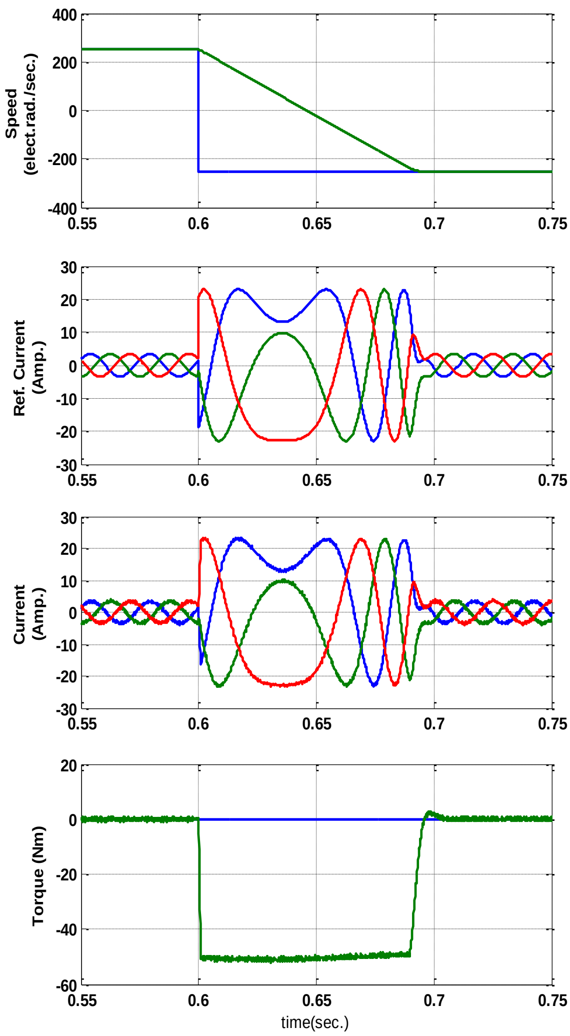


(b)

Fig.4.4 Reversal Dynamics of 30HP Induction motor drive operated under (a) DTCIMD and (b) VCIMD

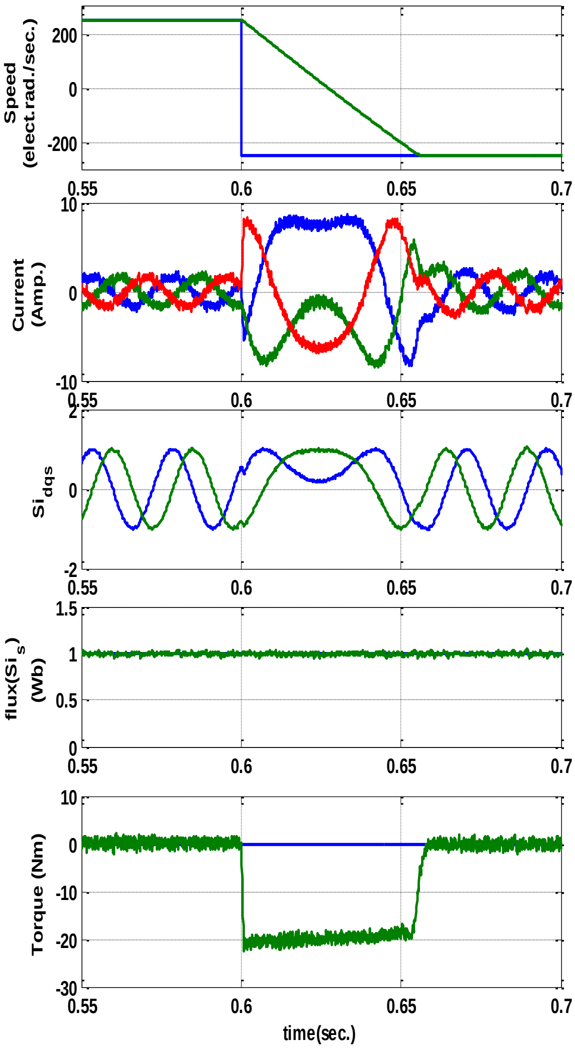


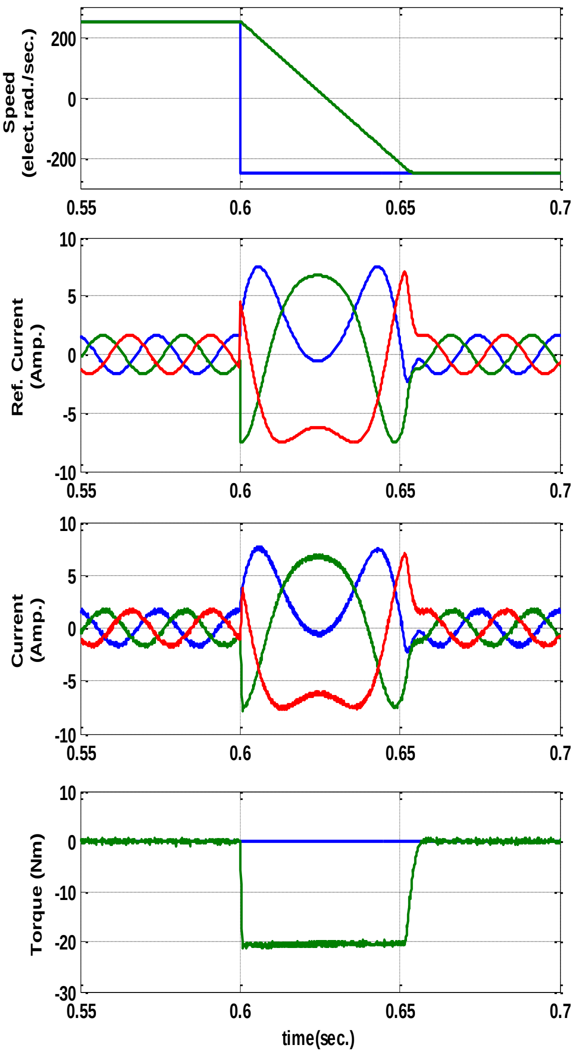
(a)



(b)

Fig.4.5 Reversal Dynamics of 5HP Induction motor drive operated under (a) DTCIMD and (b) VCIMD





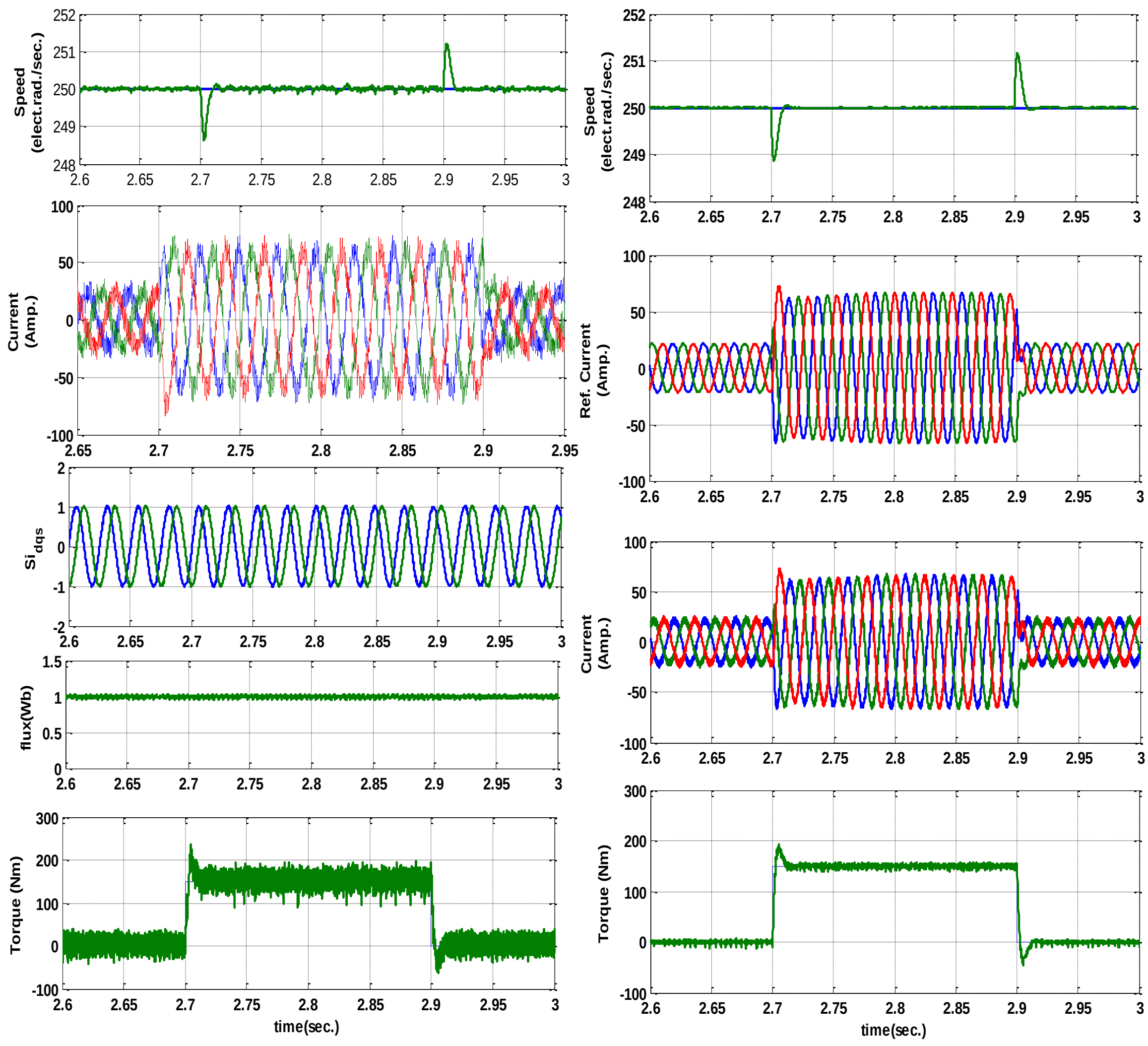
(a)

(b)

Fig.4.6 Reversal Dynamics of 2HP Induction motor drive operated under (a) DTCIMD and (b) VCIMD

4.1.3 LOAD PERTURBATION DYNAMICS

This dynamic study is very significant because drive should not differ from operating set speed for any load disturbances. To get this dynamics of drive, sudden load torque equal to rated torque on motor applied when motor operating in 250 elect. rad/sec. Sudden application of load causes an instantaneous drop in speed. In response of this drop, speed controller increases the reference torque (T_{em}^{*}) value. Therefore, the developed electromagnetic torque (T_{em}) of motor drive increases followed by motor speed to get settled at set value with increase stator winding currents.

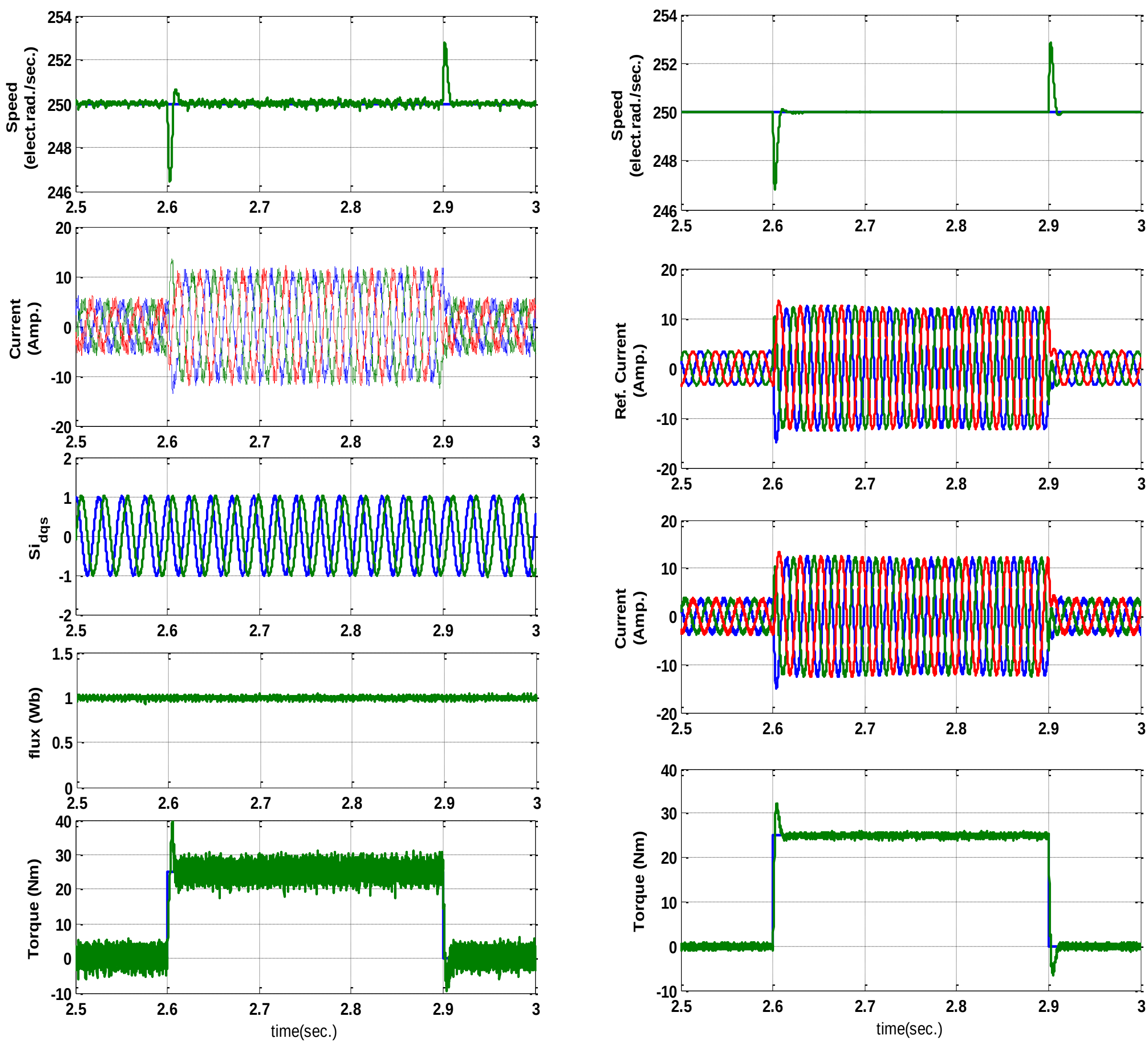


(a) (b)

Fig.4.7 Load Perturbation Dynamics of 30HP Induction motor drive operated under

(a) DTCIMD and (b) VCIMD

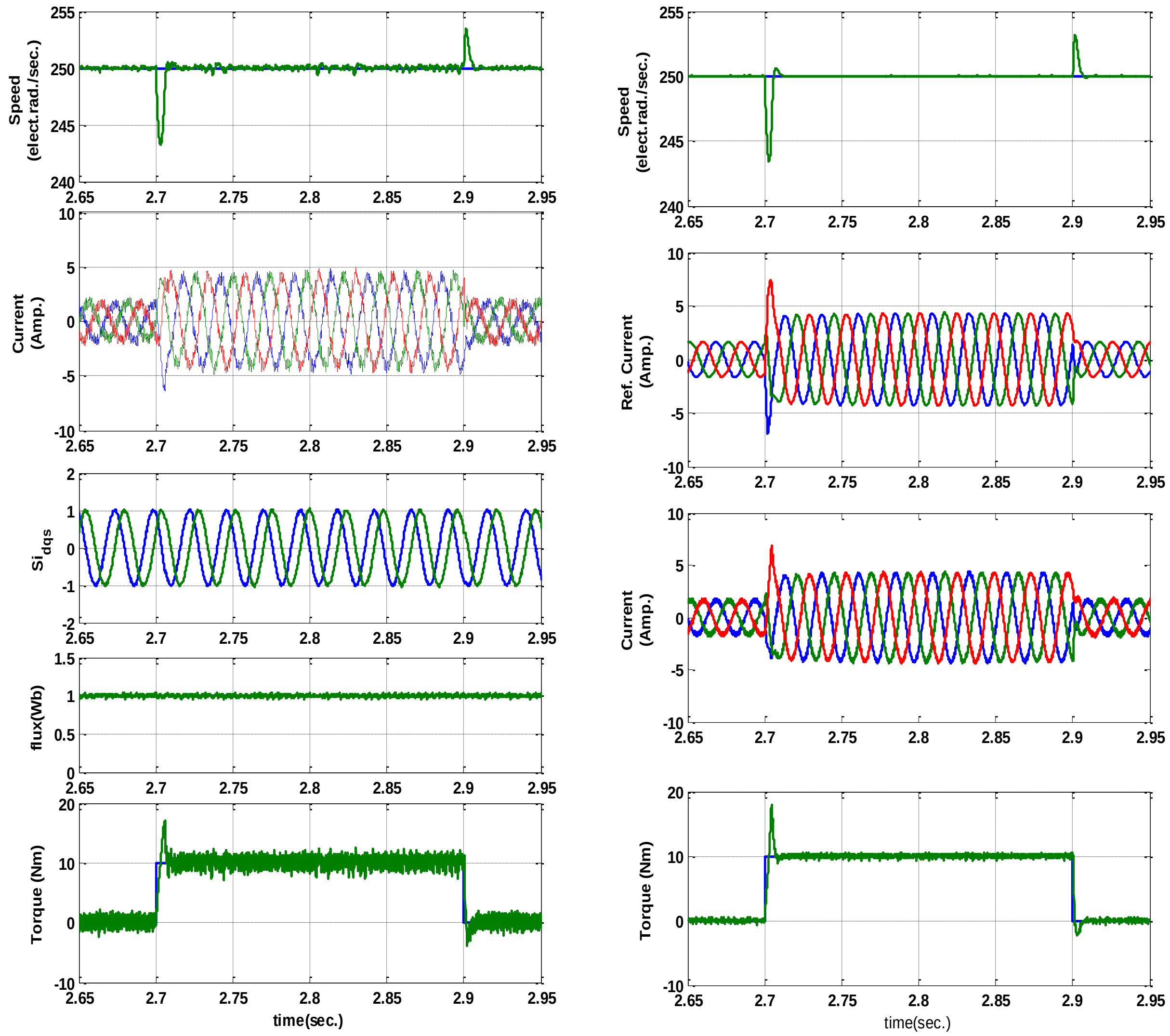
Similarly, on sudden removal of load causes a small overshoot in motor speed. Because of this the input of speed controller will become negative. Consequently, the output of speed controller i.e. reference torque (T^*_{em}) reduced. Therefore, the developed electromagnetic torque (T_{em}) of motor drive decreases followed by motor speed to get settled at set value with no load stator winding currents. The comparison results of the load perturbation dynamics for 30HP, 5HP and 2HP separately for both (VCIMD and DTCIMD) are shown in Fig.4.7, 4.8 and 4.9.



(a) (b)

Fig.4.8 Load Perturbation Dynamics of 5HP Induction motor drive operated under

(a) DTCIMD and (b) VCIMD



(a) (b)

Fig.4.9 Load Perturbation Dynamics of 2HP Induction motor drive operated under

(a) DTCIMD and (b) VCIMD

Table 4.1 comparison results for 30hp induction motor drive for constant load application

Technique	Starting Time(ms)	Speed Reversal (ms)	%speed Dip at Load Application	%speed rise at Load Removal
DTC	138.2	256.3	0.70	0.45
Vector control	149	286	0.55	0.34

Table 4.2 comparison results for 5hp induction motor drive for constant load application

Technique	Starting Time(ms)	Speed Reversal (ms)	%speed Dip at Load Application	%speed rise at Load Removal
DTC	58	97.2	1.432	1.118
Vector control	69.8	102.5	1.256	1.146

Table 4.3 comparison results for 2hp induction motor drive for constant load application

Technique	Starting Time(ms)	Speed Reversal (ms)	%speed Dip at Load Application	%speed rise at Load Removal
DTC	53.9	63.9	2.84	1.26
Vector control	67.5	74	2.62	1.23

4.2 ON THE BASIS OF IMPLEMANTATION COMPLEXITY

The comparison for implementation of both considered schemes can't be perfectly done because of many issue that can impact the software and hardware configuration [17],[38],[43]. Still, study of the complexity of considered schemes can be done in general manner in order to predict the implementation concern.

Computational task of Indirect VCIMD algorithm is listed below:

- Estimation of i_{qs}^*
- Estimation of i_{mr}^*
- Estimation of i_{ds}^*
- Estimation of ω_{sl}
- Estimation of Θ_e
- Coordinate Transformation from synchronously rotating (d-q) reference frame to stationary (abc) reference frame.
- Current Regulator

The estimation of variables in VCIMD strategy are done in synchronously rotating (d-q) reference frame. So that Coordinate Transformation involving Trigonometric function which is time consuming task.

On the other hand, in DTCIMD all estimations are done in stationary (d-q) reference frame, therefore no Trigonometric function require.

Computational task of DTCIMD algorithm is listed below:

- Stationary (abc) reference frame to stationary (d-q) reference frame transformation.
- Estimation of T_{em}
- Estimation of $|\Psi_s|$
- Estimation of sectors
- Hysteresis comparator
- Switching Logic Table

4.3 CONCLUSION

From the above discussion of simulation result (Fig. 4.1 to 4.9) and tabulated data (Table 4.1 to 4.3, some point for comparative study of vector controlled and direct torque controlled induction motor drive can be pointed out as listed below.

1. Time taken by the DTC mode is lesser than the Vector Control (VC) mode for starting, speed reversal. In general way the dynamic performance of DTC is quite comparable to VC methodology.

2. For the Load application and Load removal (load perturbation), the speed dip and speed overshoot is lesser in the vector control mode then the DTC mode of operation.

3. The ripple content in Electromagnetic Torque, Current and Stator Flux is much more in DTC than Vector Control mode of operation.

Looking in to the tasks necessary for both considered schemes, it can be anticipated that the VCIMD system takes longer execution time than DTCIMD scheme. Longer execution time will tend to lower sampling rate for the controller, consequently, result of the control performance will deteriorate.

CHAPTER 5

SPEED SENSORLESS DIRECT TORQUE CONTROL

Vector control and direct torque control of induction motor drive used when high dynamic performance is required because these control technique are independently control torque and flux of the machine. For variable speed operation of induction motor under these considered scheme speed sensor is required to produce reference torque signal and for VCIMD the position angle to perform coordinate transformation. But these sensors have some disadvantages which can be overcome by using different speed estimation techniques. These techniques are briefly discussed in this chapter and more emphasis is given to one particular i.e. rotor flux based MRAS (Model Reference Adaptive System) technique.

5.1 SENSORLESS SPEED ESTIMATION TECHNIQUES

To perform the closed loop operation for considered variable speed drive speed transducers are required such as techo-generator, resolvers, optical and digital encoders to obtain the speed information [62],[63]-[66]. These sensors have following demerits:

- They usually expensive,
- They requires extra space,
- In harsh environments, the speed sensor need extra care from the failures and need special enclosures.
- Not much reliable.
- They may affect machine inertia.
- Require maintenance.

These above mentioned limitation of speed sensor used in vector control and direct torque control drives leads to sensorless speed estimation techniques for induction motor drive which is inexpensive and reliable. However, sensorless estimation techniques requires additional algorithm and computational power which need high speed processors for real time application.

The main methods of speed sensorless control for induction motor drives are:

1. Open-loop estimations using monitored stator currents/voltages:
2. Estimation using spatial saturation stator-phase third harmonics voltages:
3. Estimation using saliency effect;
4. Model reference adaptive system (MRAS);
5. Observers (Luenberger, Kalman);
6. Estimation using Artificial intelligence (ANN, fuzzy-logic-based system etc.).

In the above listed method, open-loop estimation methods are not much accurate and they highly sensitive machine parameters and other like observers techniques, these methods are difficult to understand and difficult to implement as well. In this dissertation work, concentration will be on MRAS techniques and particularly Rotor flux based MRAS speed estimator.

5.2 MODEL REFERENCE ADAPTIVE SYSTEM (MRAS)

Among all the methodology listed above section, MRAS observer used for estimating the induction motor speed in the fast dynamic control drive is the well-known sensorless technique which has fascinated much attention because of their direct physical implementation and simplicity [69]. The first idea of MRAS methodology is to fine-tune the state variables of system under study using two models, viz. reference model and adaptive model and find out the adaptation mechanism to diminish the error between the two sub-models in ordered to estimate anticipated physical quantity. A basic schematic of MRAS is shown in the Fig.5.1. Where X represents the state variable of the system [64],[65]. In the reference model takes stator current components and voltage components to estimate variables and adaptive model takes stator current and feedback of estimated speed to estimate variables. The variables can rotor flux (Ψ_{dr},Ψ_{qr}), back EMF (e_{ds},e_{qs}) and reactive power. The difference between these state variables is then used in the adaptation mechanism to get the rotor speed ($\widehat{\omega}_r$) as output and it bend the adaptive model until acceptable performance is achieved.

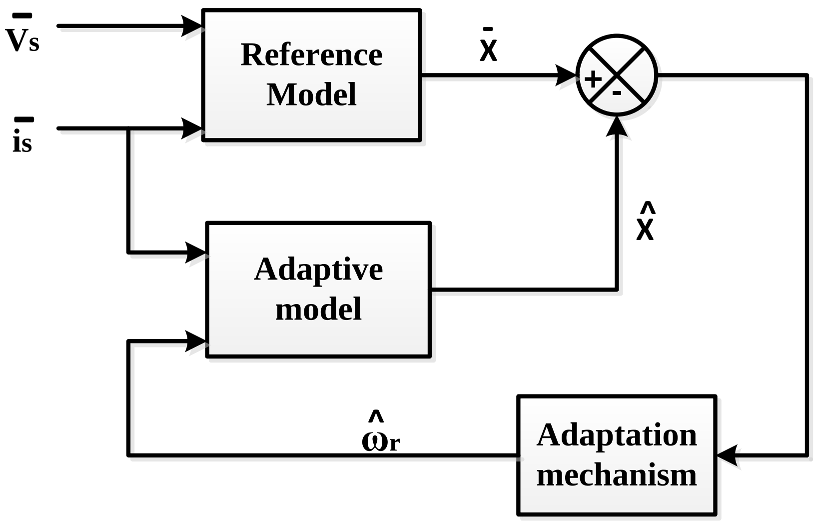


Fig. 5.1 The basic MRAS speed estimation scheme.

There are different type of speed observers using MRAS scheme (for example, rotor flux based, back EMF based, reactive power based etc.). In this dissertation work Rotor flux based MRAS scheme has been discussed and its simulation results with DTC method of induction motor drive have also compiled latter in this chapter.

The suitable adaptation mechanism must be derived by using Popov's criterion of hyperstability [76]-[77], Lyapunov stability theorem [73] and recursive least-square (RLS) algorithm [72] to minimise the error signal. Here, the concept of adaptation mechanism based hyperstability (Popov's criterion of hyperstability) is considered. A system is said to be asymptotically hyperstable if the linear time variant forward path transfer matrix is strictly real-positive and that the non-linear feedback (which includes the adaptation mechanism) satisfies Popov's criterion of hyperstability [77].

5.2.1 Rotor Flux Error Based MRAS

This MRAS scheme first introduce by Tamai et al. For induction motor drives. A basic schematic of rotor flux based MRAS is shown in Fig. 5.2. In the reference model rotor flux ($\overline{\Psi}_r$) calculated from stator voltage and current signals while in adaptive model rotor flux ($\widehat{\Psi}_r$) is calculated from stator current signals and feedback speed signal. The error (ε_r) between these rotor fluxes (state variables) is then to use for estimation of speed ($\widehat{\omega}_r$) from adaptation mechanism [69],[74].

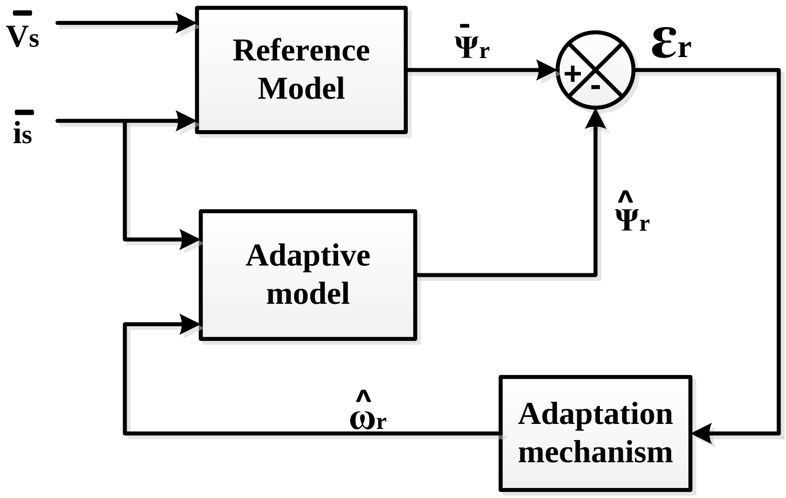


Fig. 5.2 The basic rotor flux based MRAS speed estimation scheme.

Modelling:

The modelling for Adaptive model to generate rotor flux d-q stationary axis components is as follows:

Rotor equations in stationary reference frame (See Fig. 5.3),

$$V_{dr} = r_r i_{dr} + p\Psi_{dr} + \omega_r \Psi_{qr} = 0 \quad (5.1)$$

$$V_{qr} = r_r i_{qr} + p\Psi_{qr} - \omega_r \Psi_{dr} = 0 \quad (5.2)$$

By rearranging the equation (5.1)

$$p\Psi_{dr} + r_r i_{dr} + \omega_r \Psi_{qr} = 0$$

Add $r_r \frac{L_m}{L_r} i_{ds}$ to LHS and RHS of above equation

$$p\Psi_{dr} + r_r i_{dr} + r_r \frac{L_m}{L_r} i_{ds} + \omega_r \Psi_{qr} = r_r \frac{L_m}{L_r} i_{ds}$$

Or, $p\Psi_{dr} + \frac{r_r}{L_r}(L_r i_{dr} + L_m i_{ds}) + \omega_r \Psi_{qr} = r_r \frac{L_m}{L_r} i_{ds}$ (6.3)

As d-axis component of rotor flux can be written as,

$$\Psi_{dr} = L_{lr} i_{dr} + L_m (i_{dr} + i_{ds})$$

Or, $\Psi_{dr} = (L_{lr} + L_m) i_{dr} + L_m i_{ds}$

Or, $\Psi_{dr} = L_r i_{dr} + L_m i_{ds}$ (5.4)

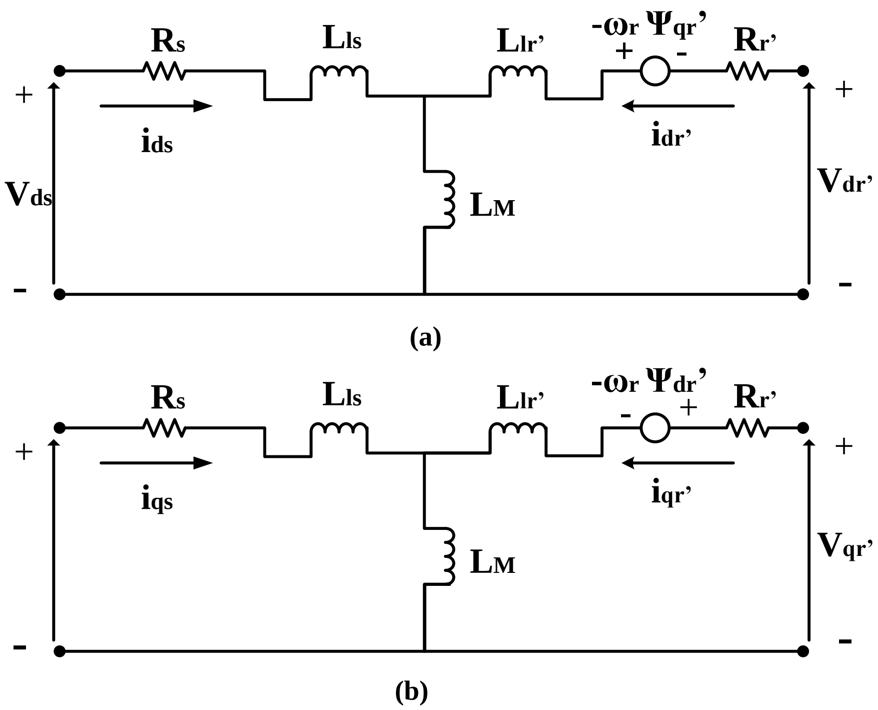


Fig.5.3 Equivalent circuit of Induction Motor with respect to (a) stationary d-axis and (b) stationary q-axis

Put equation (5.4) in equation (5.3)

Or, $p\Psi_{dr} + \frac{1}{\tau_r}\Psi_{dr} + \omega_r\Psi_{qr} = r_r \frac{L_m}{L_r} i_{ds}$

$$\mathbf{Or,}\ p\Psi_{dr} = \frac{L_m}{\tau_r} i_{ds} - \frac{1}{\tau_r}\Psi_{dr} - \omega_r\Psi_{qr} \qquad \mathbf{(5.5)}$$

Similarly,

$$p\Psi_{qr} = \frac{L_m}{\tau_r} i_{qs} - \frac{1}{\tau_r}\Psi_{qr} + \omega_r\Psi_{dr} \qquad \mathbf{(5.6)}$$

For adaptive model, rotor flux components is expressed as $\widehat{\Psi}_{dr}$, $\widehat{\Psi}_{qr}$ and estimated speed is expressed as $\widehat{\omega}_r$. Now the mathematical equation can be written as:

$$\boxed{\begin{aligned} p\widehat{\Psi}_{dr} &= \frac{L_m}{\tau_r} i_{ds} - \frac{1}{\tau_r}\widehat{\Psi}_{dr} - \widehat{\omega}_r\widehat{\Psi}_{qr} \\ p\widehat{\Psi}_{qr} &= \frac{L_m}{\tau_r} i_{qs} - \frac{1}{\tau_r}\widehat{\Psi}_{qr} + \widehat{\omega}_r\widehat{\Psi}_{dr} \end{aligned}}$$

The modelling for Reference model to generate rotor flux d-q stationary axis components is as follows:

$$\Psi_{ds} = \int(\bar{V}_{ds} - \bar{i}_{ds}\, R_s)dt \tag{5.7}$$

$$\Psi_{qs} = \int(\bar{V}_{qs} - \bar{i}_{qs}\, R_s)dt \tag{5.8}$$

To find out rotor flux from stator parameters, need to use some extra equation as follows:

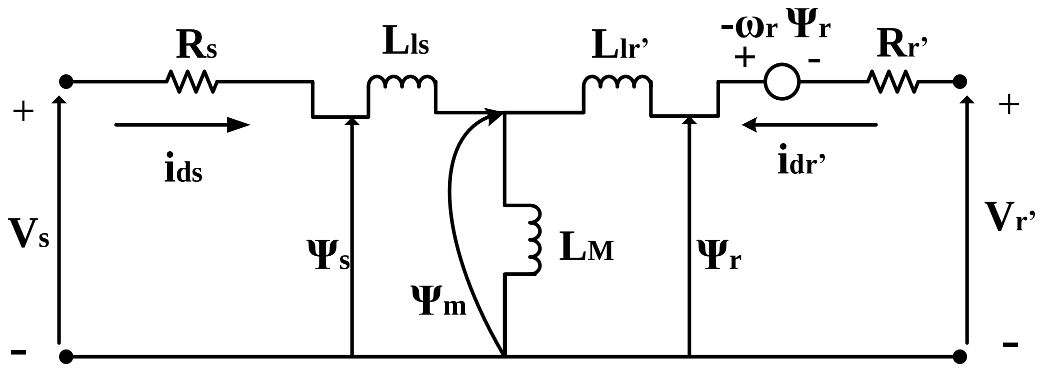


Fig.5.4 Equivalent circuit of Induction Motor in stationary reference frame

From the Fig.5.4, the expression for stator flux linkage can be written as,

$$\Psi_{ds} = L_s\, i_{ds} + L_m\, i_{dr} \tag{5.9}$$

And rotor flux can be written as,

$$\Psi_{dr} = L_r\, i_{dr} + L_m\, i_{ds} \tag{5.10}$$

Or, $i_{dr} = \frac{\Psi_{dr} - L_m i_{ds}}{L_r}$

Put the above equation in equation 5.9,

Or, $\Psi_{ds} = L_s\, i_{ds} + L_m \left(\frac{\Psi_{dr} - L_m i_{ds}}{L_r}\right)$

$$= L_s\, i_{ds} + \frac{L_m}{L_r}\Psi_{dr} - \frac{L_m^2}{L_r}\, i_{ds}$$

$$= L_s \left(1 - \frac{L_m^2}{L_s L_r}\right) i_{ds} + \frac{L_m}{L_r}\Psi_{dr}$$

Or, $\Psi_{dr} = \frac{\mathbf{L_r}}{\mathbf{L_m}}(\Psi_{\mathbf{ds}} - \boldsymbol{\sigma}\mathbf{L_s}\, \mathbf{i_{ds}})$ **(5.11)**

Similarly,

$\Psi_{\mathbf{qr}} = \frac{\mathbf{L_r}}{\mathbf{L_m}}(\Psi_{\mathbf{qs}} - \boldsymbol{\sigma}\mathbf{L_s}\, \mathbf{i_{qs}})$ **(5.12)**

For reference model rotor flux components can be estimated from equation 5.7, 5.8, 5.11 and 5.12. Full expression can be written as:

$$\Psi_{dr} = \frac{L_r}{L_m}\left\{ \int (\bar{V}_{ds} - \bar{i}_{ds} R_s)dt - \sigma L_s i_{ds} \right\}$$

$$\Psi_{qr} = \frac{L_r}{L_m}\left\{ \int (\bar{V}_{qs} - \bar{i}_{qs} R_s)dt - \sigma L_s i_{qs} \right\}$$

The full notation block diagram of rotor flux based MRAS speed estimation scheme is shown in the Fig.5.5 and complete block diagram of Sensorless DTC is shown in Fig.5.6.

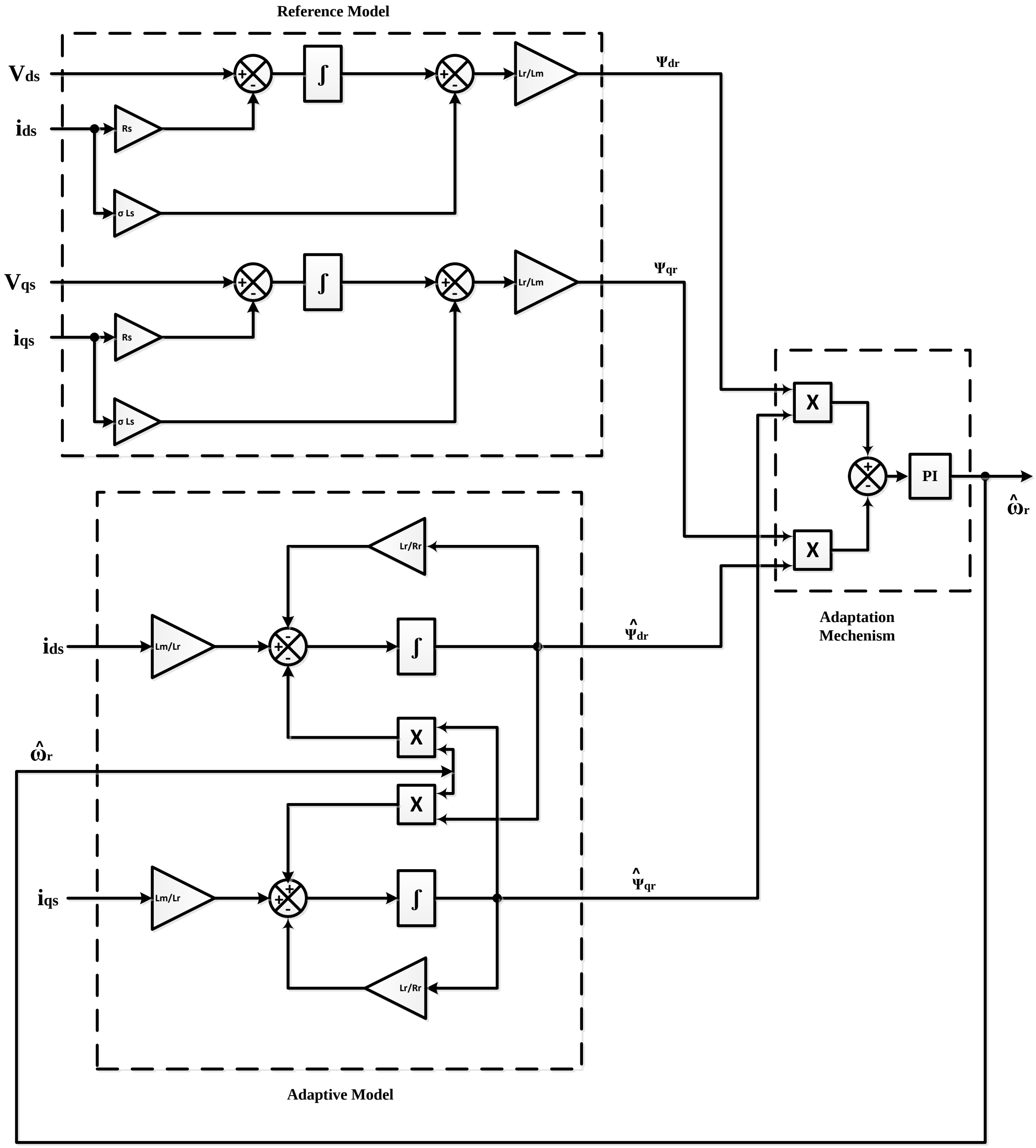


Fig.5.5 Rotor Flux based MRAS speed estimation scheme (using full space vector notation)

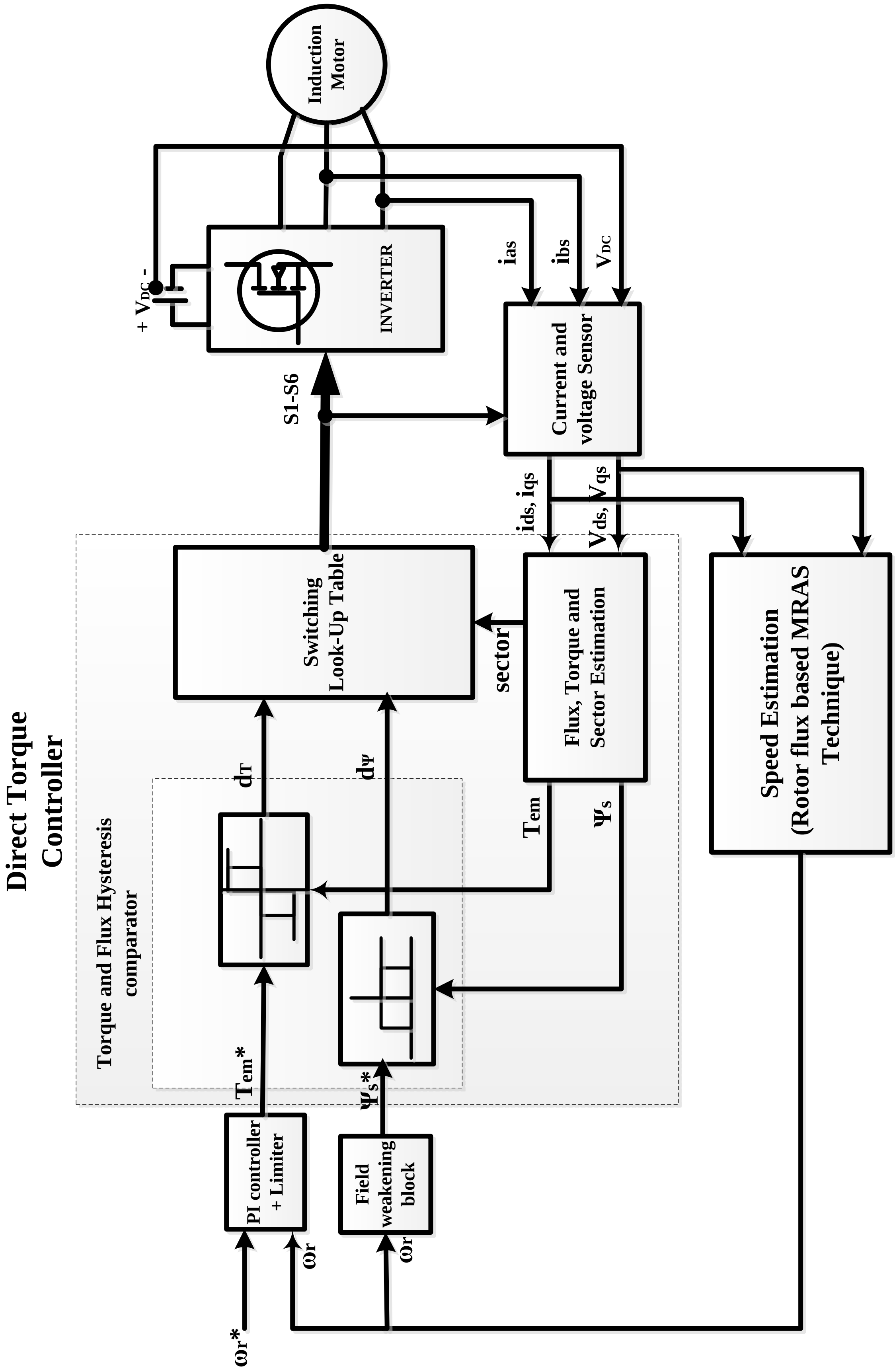


Fig.5.6 Block diagram of Sensorless Direct Torque Control of Induction Motor Drive

5.3 SIMULATION RESULTS OF SENSORLESS DTC (5HP INDUCTION MOTOR)

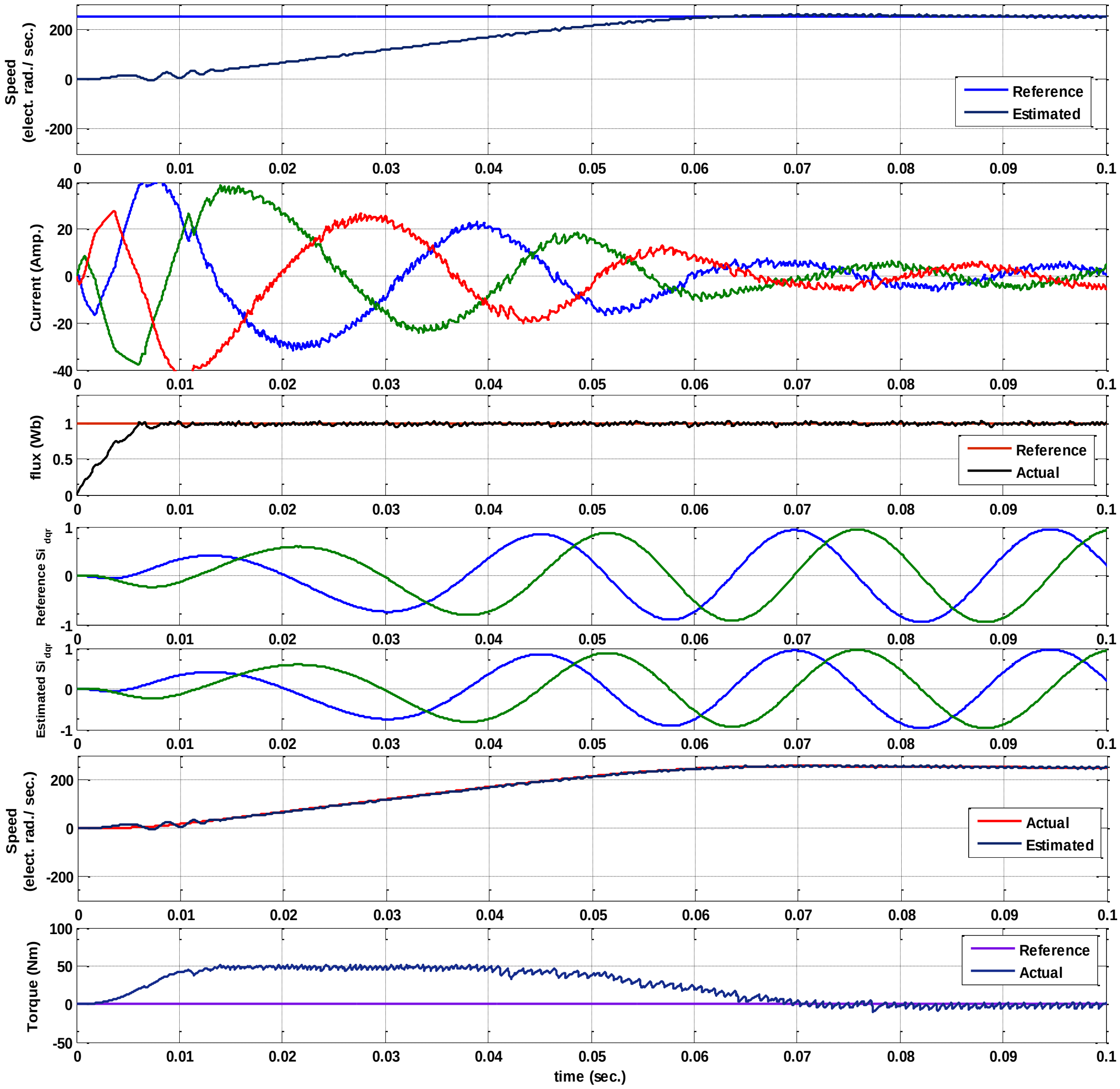


Fig.5.7 Starting dynamic response of Sensorless DTCIMD

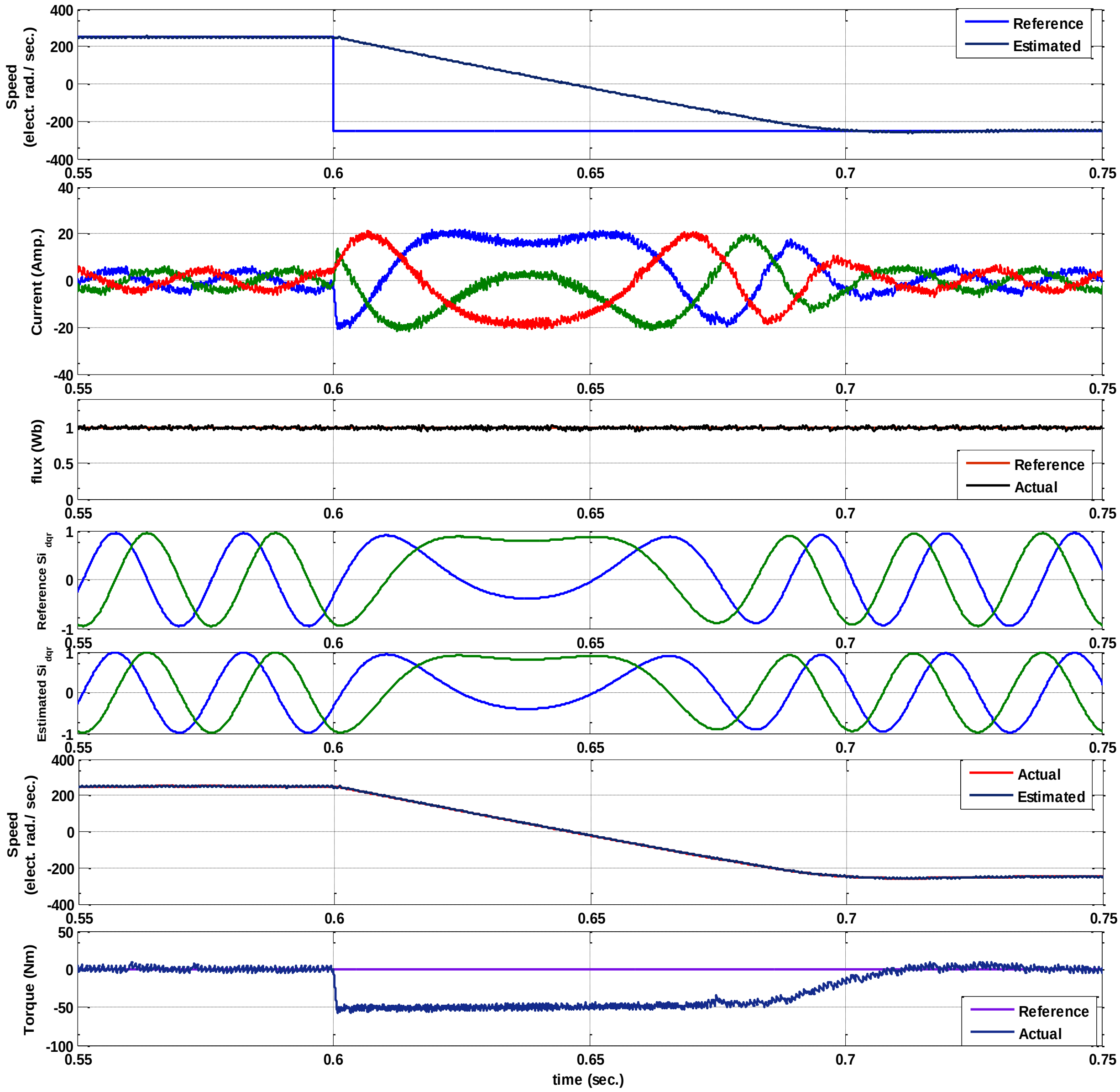


Fig.5.8 Reversal dynamic response of sensorless DTCIMD

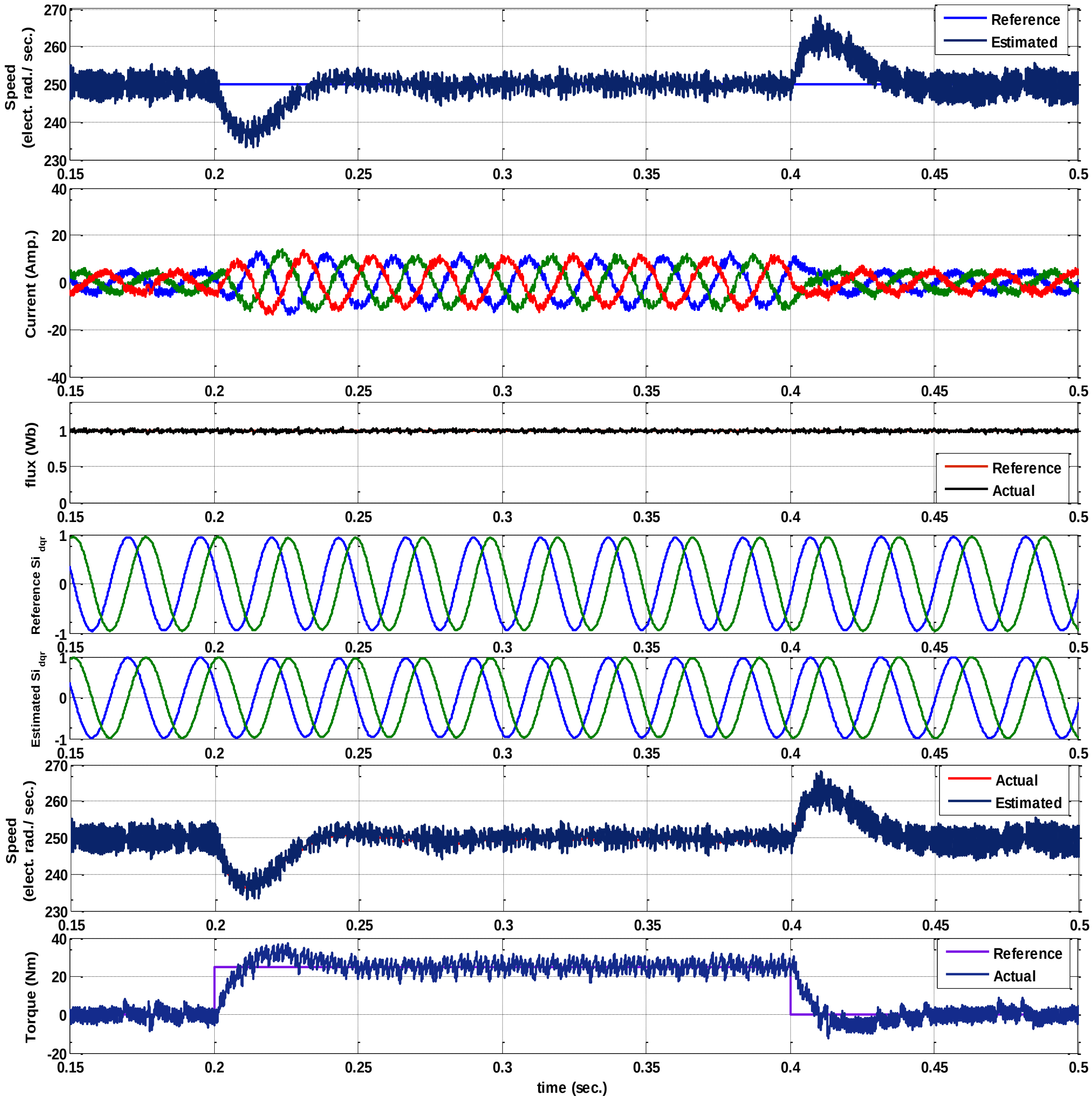


Fig.5.9 Load perturbation response of Sensorless DTCIMD

The above results which are shown in Fig.5.7 to 5.9 for starting, speed reversal and load perturbation respectively.

5.4 CONCLUSION

In this chapter, a brief introduction of sensorless induction motor drive has shown and one close loop technique of speed sensorless has thoroughly discussed i.e. Rotor flux based MRAS technique. The modelling and simulation results have also shown in this chapter.

CHAPTER 6

SYSTEM HARDWARE DEVELOPMENT

6.1 INTRODUCTION

This chapter involves hardware development and implementation of Vector control and direct torque control induction motor drive and various circuits, inverter (three phase two level), current sensor, voltage sensor etc. A DSP (Digital Signal Processor) has been used to generate the firing pulses for switches of inverter and sense the real time current and voltage from Hall Effect current and voltage sensor. For inverter action MOSFET switches is used. The block diagram of complete experimental setup is shown below.

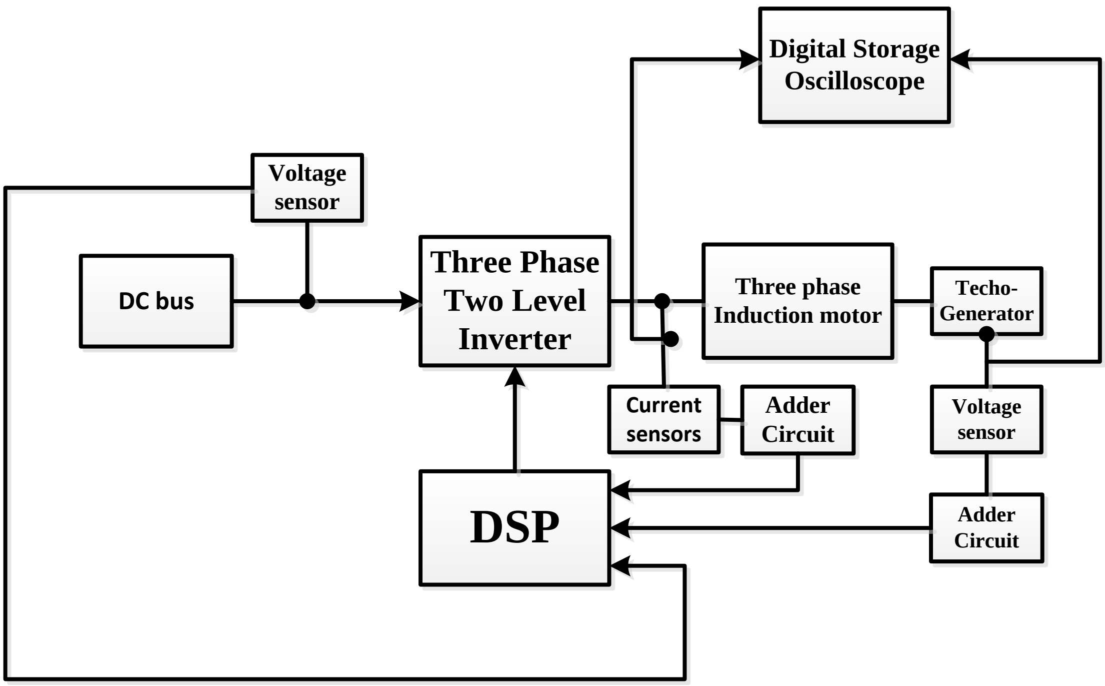


Fig.6.1 Block Diagram showing Hardware setup

6.2 DIGITAL SIGNAL CONTROLLER (DSC TMS320F2812)

The use of a digital controller greatly simplifies the hardware circuitry by reducing the space as well as drastically increasing the speed of computation. Texas Instruments (TI) TMS320F2812, a 32-bit fixes point DSC was used to solve the mathematical equations pertaining to generation of firing pulses. DSC is a single chip microcomputer that uses a Digital Signal Processor (DSP) as its core element along with memory and peripherals like Analog to Digital Converters (ADC), Timers, and PWM generators. It is similar to a microcontroller but is superior as it possesses additional Hardware Multiply Units, Pointer Arithmetic Units, Bus Systems and Hardware shifters for faster multiplications and divisions. This DSC belongs to the C2000 family of TI controllers which are mainly employed for Digital Motor Control. The XDS100 USB (Universal Serial Bus) JTAG (Joint Test Action Group) emulator is used to interface the DSC with Personal Computer (PC). This is a powerful tool in the debug phase of project development as it is used for real time data exchange between the DSC and PC. A c-based code written to implement the control strategy and pulse-generation using the DSC. Code Composer Studio 3.3 software is used for interfacing with DSC.

6.3 POWER CIRCUIT DEVELOPMENT

Power circuit development of total hardware system consist inverter switches circuits, regulated power supplies and Current and Voltage sensor circuit. Each of the six switches in three phase two level inverter have their gate driver circuit and snubber circuit. The regulated power supplies i.e. +15V, -15V, +12V, -12V and +5v are required for providing biasing to various circuits like pulse amplification and isolation circuits, hysteresis controller and voltage detectors etc. using regulator IC’s 7815, 7915, 7812, 7912 and 7805 for +15V, -15V, +12V, -12V and +5v respectively. And the sensors circuits (voltage and current) are required to sense real time voltage and currents which is used as feedback in considered control schemes.

6.3.1 Voltage Source Inverter circuit

Fig.6.2 shows the power circuit of a three phase Voltage Source Inverter (VSI). The power circuit consists of 6 MOSFET switches are placed on heat sinks made of aluminium sheet to dissipate the excessive heat.

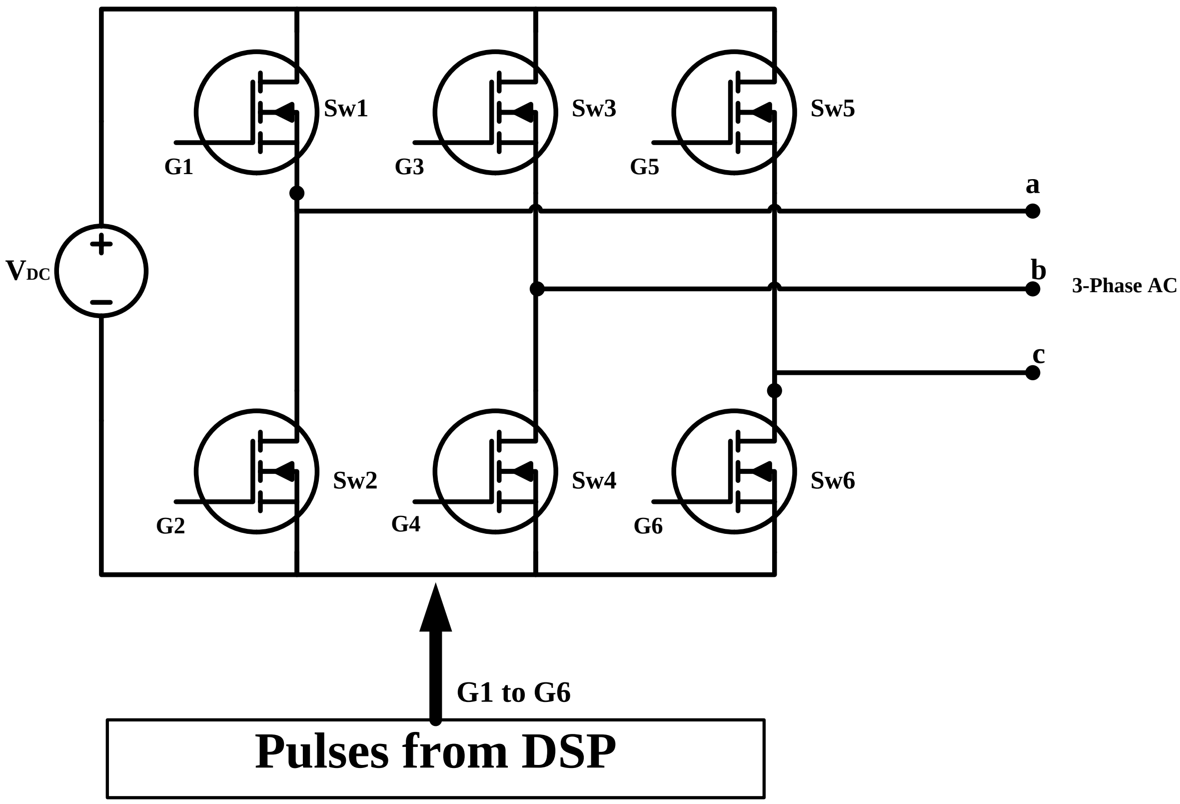


Fig.6.2 Power Circuit of three phase Voltage Source Inverter (VSI)

Specifications:-

- MOSFET – IRFP 460 (500v, 20A) .
- Drain to source voltage (V_{dss}) = 500v
- Source to drain resistance during on period ($R_{DS(on)}$) = 0.27Ω
- Rated drain current (I_D) = 20A

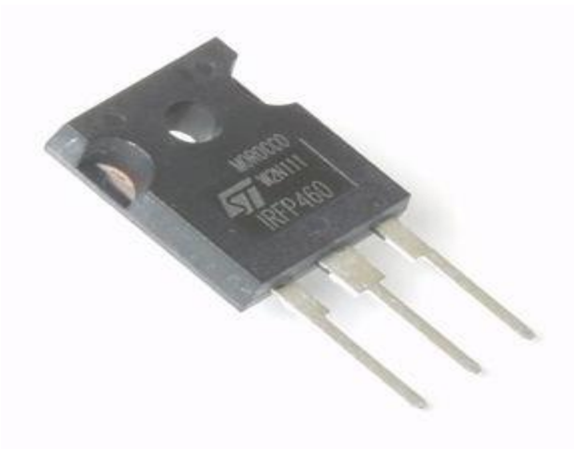


Fig.6.3 MOSFET used in the three Phase VSI.

Each MOSFET switch consists of an inbuilt anti-parallel freewheeling diode. No forced commutation circuits are required for the MOSFET's because these are self-commutated devices (They turn on when the gate signal is high and turn off when the gate signal is low). The load inductance restricts large di/dt through MOSFETS; hence turn off snubber is required for protection. RCD (Resistor, Capacitor and Diode) turn off circuit is connected to protect the switch against high dv/dt and is protected against power voltage by connecting MOV (Metal Oxide Varistor).

6.3.1.1 Snubber Circuit (Protection of MOSFETS)

Since power handled by the prototype circuit is less (up to 10A), RC snubber circuit has been used for protection of main switching device. Switching high current in short time gives rise to voltage transients that could exceed the rating of the MOSFET. Snubbers are therefore needed to protect the switch from transients. Snubber circuit for MOSFET is shown in Fig.6.4.The diode prevents the discharging of the capacitor via the switching device, which could damage the device due to large discharge current. An additional protective metal oxide varistor (MOV) is used across each device to protect against over voltage across the device.

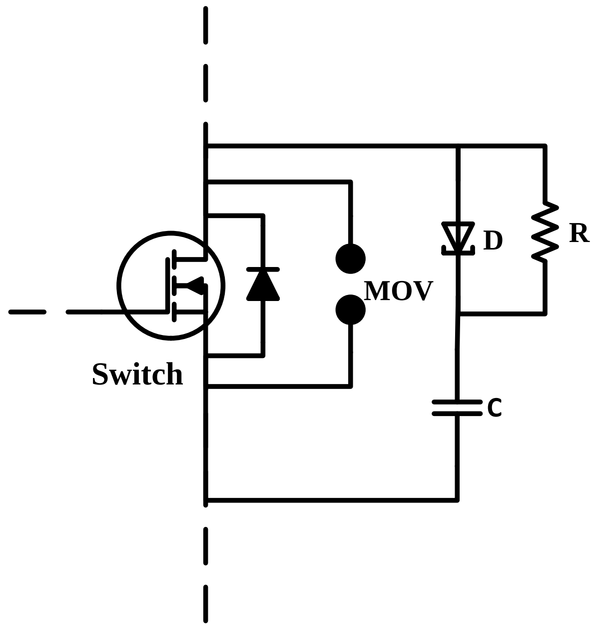


Fig.6.4 Snubber circuit for MOSFET protection

<u>Components</u>

- Capacitance : 0.1µF,1000v
- MOV (Metal oxide Varistor): 320v
- Diode- IN5408

- Capacitor, C = 0.1µF
- Resistor, R= 0.1kΩ,5w

6.3.1.2 Driver Circuit (Pulse Amplification and Isolator)

The pulse amplification circuit for MOSFET is shown in figure 6.4.The opto coupler HCPL-3101 provides necessary isolation between the low voltage isolation circuit and high voltage power circuit. The pulse amplification circuit is provided by the output amplifier transistor 2N2222. When the input gating is +5v level, the transistor saturates , the LED conducts and the light emitted by it falls on the base of the phototransistor, thus forming its forming its base drive. The output transistor thus receives no base drive and remains in the cut-off state and a +12v pulse (amplified) appears at its collector terminal.

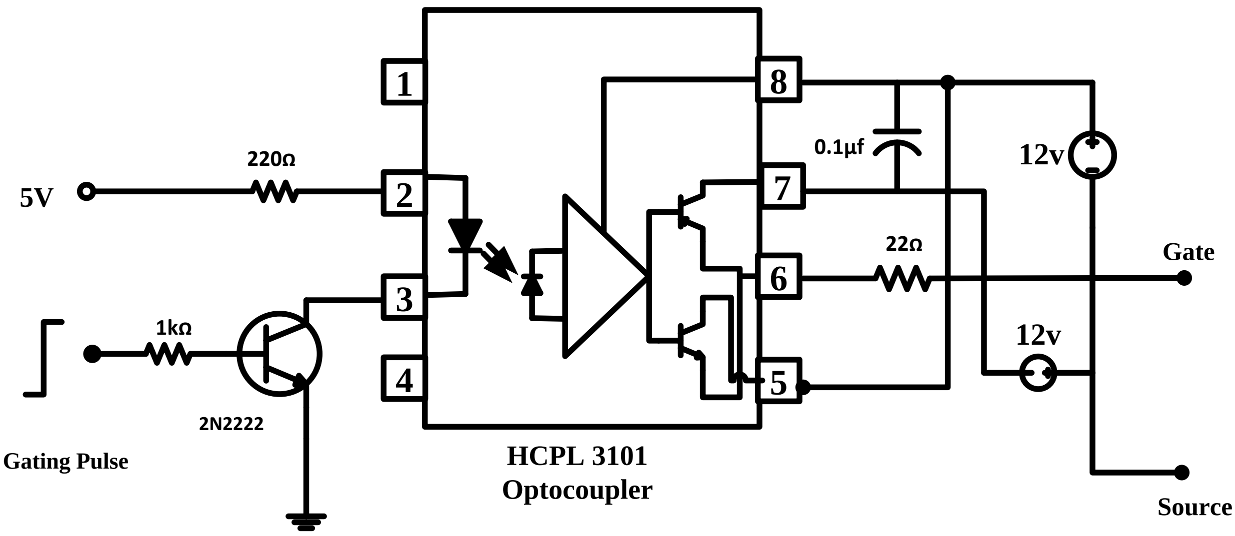


Fig. 6.5 Pulse amplifier and Isolator circuit

The Full layout of Driver circuit and protection (snubber) circuit required for switches is shown in Fig.6.6.

6.3.2 Power Supplies

DC regulated supplies (+15V, -15V, +12V, -12V and +5v) are required for providing biasing to various circuits like pulse amplification and isolation circuits, hysteresis controller and voltage detectors etc. using regulator IC's 7815, 7915, 7812, 7912 and 7805 for +15V, -15V, +12V, -12V and +5v respectively.

The circuit diagram of the power supplies is as shown in following figures below (Fig 6.7 a, b and c).

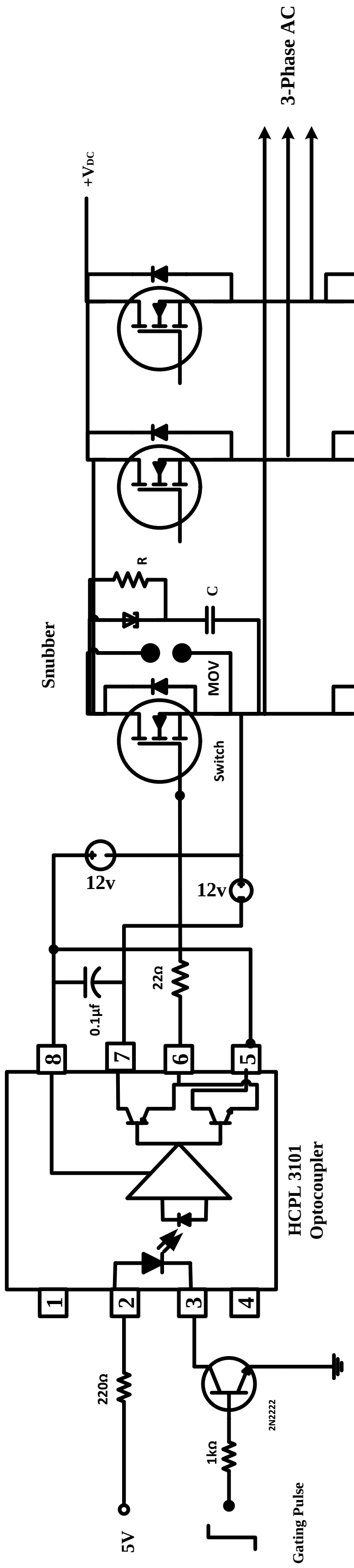
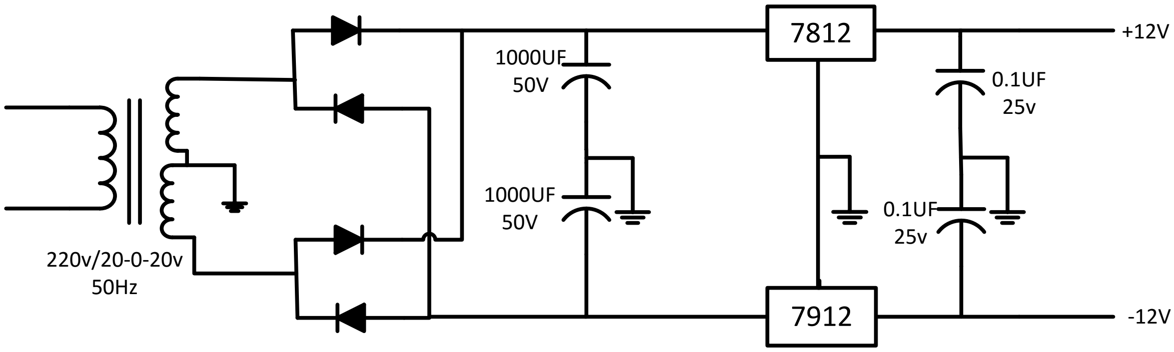
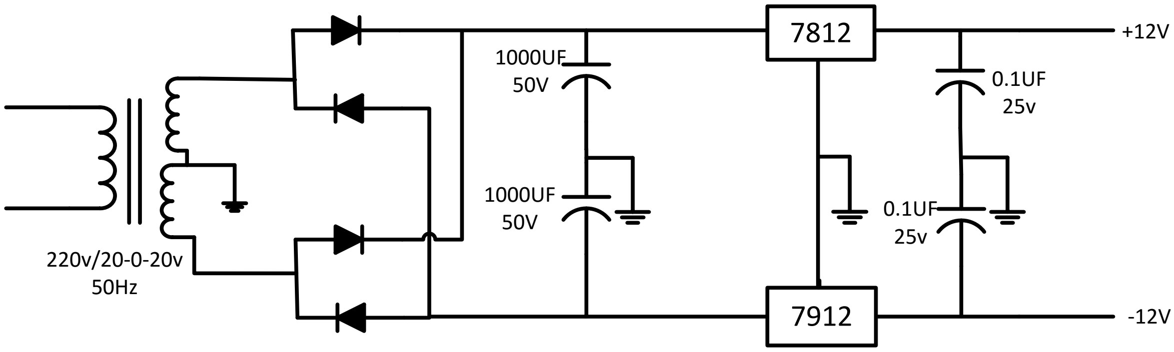


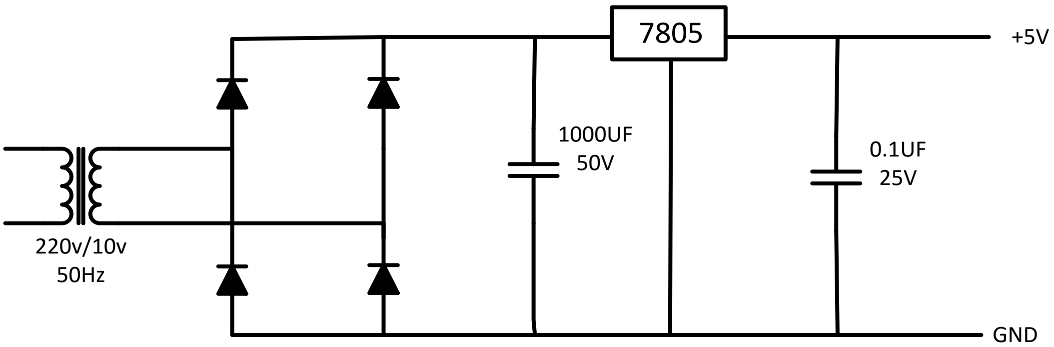
Fig.6.6 Full layout of Driver circuit and protection (snubber) circuit required for switches



(a)



(b)



(c)

Fig.6.7 Connection diagram for power supplies (a) +15V, 0, -15V (b) -12V, 0, +12V and (c) +5V.

6.3.3 Current and Voltage Sensor

6.3.3.1 Current Sensor

For measuring either the Source currents, load currents and compensator currents the Hall Effect current sensors (HTP 25) are used. The circuit diagram of the Hall Effect current sensor along with a buffer and a scalar circuit is shown in Fig.7.8 Here a current of I (A) in power network is converted into ± 5V range. These current sensors provide galvanic isolation between high voltage power circuit and the low voltage control circuit and require a nominal supply voltage of the ±12V to ±15V. For a chosen primary turns (N_P), the conversion ratio (cr_i) of current sensor is 1000:1 and the output resistance of the current sensor is taken as 100 Ω. The voltage input to the buffer circuit is calculated by the equation $v_{oi} = R_o\left(\frac{N_p i}{cr_i}\right)$. Thus the voltage v_{oi} is scaled properly with the scalar circuit. The output voltage is given to the DSP kit with the help of ADC and level shifter circuit.

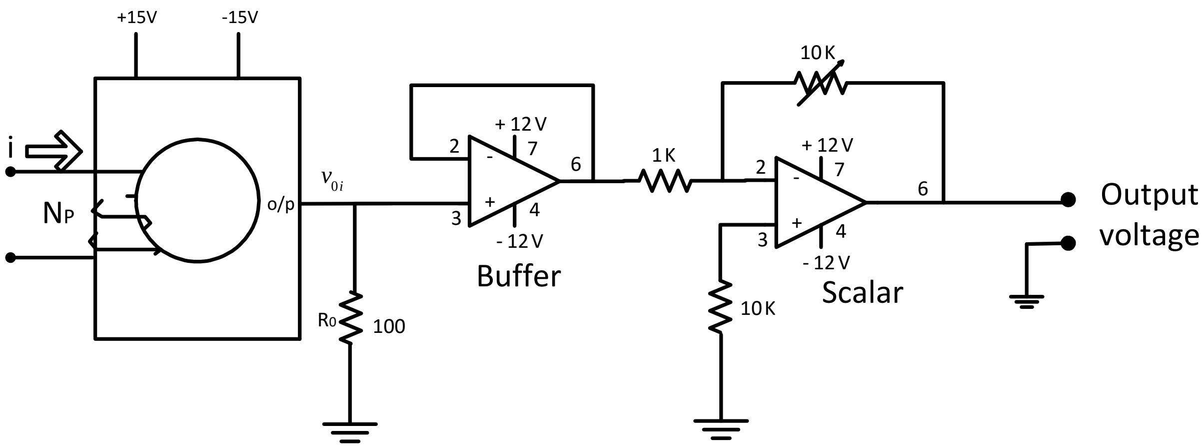


Fig.6.8 Current sensor circuit

6.3.3.2 Voltage Sensor

AC source voltages v_{sa},v_{sb} and v_{sc} (phase to neutral) are given as the inputs to DSP kit through ADC for estimating the flux. Which can estimated by DC link voltage and switching pulses. Only sensing DC link voltages are sufficient for three phase three wire system. The circuit diagram of the sensing voltage along with the buffer and scalar circuit is shown in the Fig.6.9. The AD202JN is an isolation amplifier in the present experimental setup the power circuit voltage which is in the range of ±500 V is converted into ±5V range. The voltage at the output of the isolation amplifier is $v_{ov} = v_1\left(\frac{R_2}{R_1+R_2}\right)$. Thus the output voltage v_{ov} is properly scaled by a scalar circuit and the output voltage is given to the ADC of DSP kit.

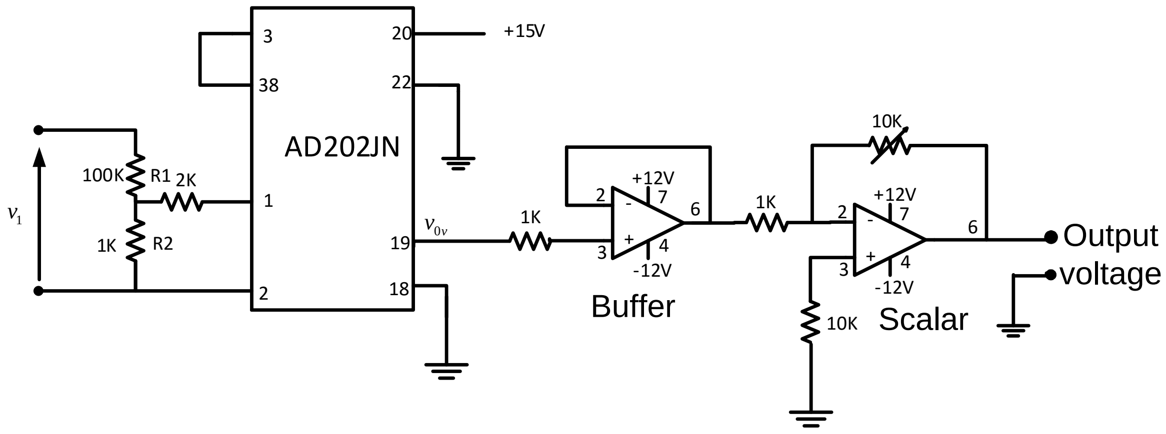
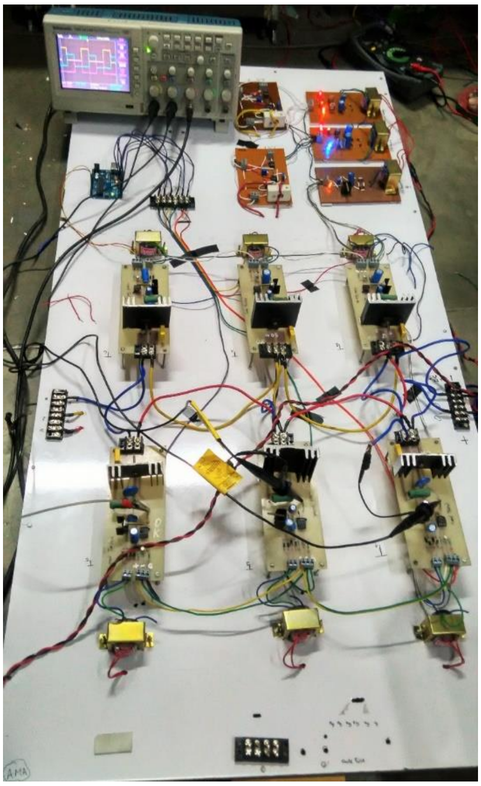
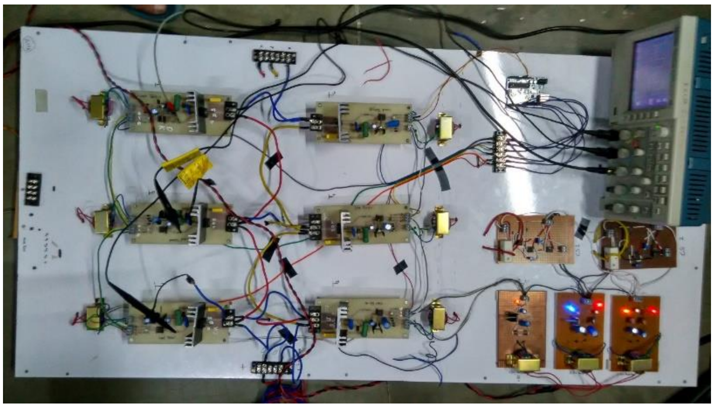


Fig.6.9 Voltage sensing circuit

HARDWERE SET-UP





CHAPTER 7

CONCLUSION AND FUTURE SCOPE

In this dissertation work, two very famous and well developed speed control drives have been thoroughly discussed i.e. Vector Control Induction Motor Drive (VCIMD) and Direct Torque Control Induction Motor Drive (DTCIMD). A comparative study between Indirect Vector Control and Direct Torque Control scheme for induction motor drive also done. This study has been done by numerical simulation with a view to stressing on the control strategy, dynamic performance and implementation complexity. For the dynamic performance comparison, starting, speed reversal, load perturbation dynamics have been considered.

On the basis of analysis, it can be conclude that both control schemes are nevertheless comparable. DTC showing high dynamic performance with simple implementation but comparable high torque and current ripples. So, the choice of DTCIMD or VCIMD will rest on mainly requirements of the application.

Apart from the comparison of both considered schemes, at the end main focus shifted to DTC drive. The Sensor less DTC have also simulated and thoroughly discussed in the chapter 5. In that chapter, rotor flux based MRAS have thoroughly discussed with the modeling and their simulation results.

There are certain issue to be taken care in to concern in order to develop a good control technique. The reduction of sensors in both the control techniques can be further be investigated without any loss in quality of the estimated signal which should not be much sensitive to parameter variation of machines due to obvious factors like temperature variation of machines, skin effect etc. and therefore the controller can become more robust in nature. This also can reduce the cost of drive. The control logic for drive nevertheless can further improve by using newly developed artificial neuro fuzzy logics. There are some better control logic such as PID control, sliding mode control, fuzzy logic control etc., which can further improve the dynamics of induction motor drives.

The Direct Torque Control scheme can further improved to simulate or implement it for constant inverter switching operation or ripple free torque and current response by using improved switching table algorithm or by using space vector PWM in over-modulation mode.

REFERENCES

[1]. W. Leonard, “*Control of Electric Drives*”, New Delhi, Narosa Publications, 1985.

[2]. P.C. Krause, *Analysis of Electrical Machinery*, Prentice Hall, 1985.

[3]. Lipo, Thomas A. "*Recent Progress in the Development of Solid State AC Motors Drives*." (1987): 125.

[4]. J.M.D. Murphy and F.G. Turnbull, *Power Electronics Control of AC Motors*, Oxford Pergamum Press, 1988.

[5]. P.Vas, *Vector Control of AC Machines*, Oxford University Press, 1990.

[6]. P.Vas, *Sensorless Vector Control and Direct Torque Control*, Oxford University Press, New York, 1998.

[7]. B.N.Singh, “Investigation of vector control induction motor drive”, Ph.D dissertation, Dept. of Elec. Eng., Indian Institute of Technology, Delhi, India, 1995.

[8]. S.G. Choudhuri, “analysis and development of vector control of induction motor drive”, Ph.D dissertation, Dept. of Elec. Eng., Indian Institute of Technology, Delhi, India, 2004.

[9]. A. Tilak Raja, “Comparative study of vector control abd direct torque control of induction motor drive”, M.Tech dissertation, Dept. of Elec. Eng., Indian Institute of Technology, Roorkee, India, 2008.

[10]. Suneel Kumar Agrawal, “Simulation of Vector Controlled Induction Motor Drive in MATLAB for Various Applications”, M.Tech dissertation, Dept. of Elec. Eng., Indian Institute of Technology, Roorkee, India, 2015.

[11]. Krause, P.C.; Thomas, C.H., "Simulation of Symmetrical Induction Machinery," in *Power Apparatus and Systems, IEEE Transactions on* , vol.84, no.11, pp.1038-1053, Nov. 1965

[12]. F. Blaschke, “The Principle Of Field Orientation As Applied To New Transvector Closed-Loop Control System For Rotating-Field Machines,” *Siemens Review*, vol.34, no.3, pp. 217-220, May 1972.

[13]. Gabriel, R., and W. Leonhard. "Microprocessor control of induction motor."*IEEE/IAS Int. Sem. Power Conv. Conf. Rec*. 1982.

[14]. Leonhard, W. "’Control of AC Machines with the help of Microelectronics,’."*Proc. IFAC Symp. on Control In Power Elec. and Elec. Drives*. 1983.

[15]. Sathikumar, S.; Vithayathil, Joseph, "Digital Simulation of Field-Oriented Control of Induction Motor," in *Industrial Electronics, IEEE Transactions on* , vol.IE-31, no.2, pp.141-148, May 1984.

[16]. Matsuo, Takayoshi, and Thomas Lipo. "A rotor parameter identification scheme for vector-controlled induction motor drives." *Industry Applications, IEEE Transactions on* 3 (1985): 624-632.

[17]. Takahashi, I.; Noguchi, T., "A New Quick-Response and High-Efficiency Control Strategy of an Induction Motor," in *Industry Applications, IEEE Transactions on* , vol.IA-22, no.5, pp.820-827, Sept. 1986.

[18]. I. Takahashi and Y. Ohmori, "High-performance direct torque control of an induction motor," in *IEEE Transactions on Industry Applications*, vol. 25, no. 2, pp. 257-264, Mar/Apr 1989.
[19]. M. Depenbrock, "Direct self-control (DSC) of inverter-fed induction machine," in *IEEE Transactions on Power Electronics*, vol. 3, no. 4, pp. 420-429, Oct 1988.
[20]. van der Broeck, H.W.; Skudelny, H.-C.; Stanke, G.V., "Analysis and realization of a pulsewidth modulator based on voltage space vectors," in *Industry Applications, IEEE Transactions on* , vol.24, no.1, pp.142-150, Jan/Feb 1988.
[21]. Daboussi, Z.; Mohan, N., "Digital simulation of field-oriented control of induction motor drives using EMTP," in *Energy Conversion, IEEE Transactions on* , vol.3, no.3, pp.667-673, Sep 1988.
[22]. Ho, Edward YY, and Paresh C. Sen. "A microcontroller-based induction motor drive system using variable structure strategy with decoupling." *Industrial Electronics, IEEE Transactions on* 37.3 (1990): 227-235.
[23]. Dakhouche, K., et al. "Modelling of microcomputer-controlled induction machine." *Industrial Electronics Society, 1990. IECON'90., 16th Annual Conference of IEEE*. IEEE, 1990.
[24]. Finch, J.W.; Atkinson, D.J.; Acarnley, P.P., "Scalar to vector: general principles of modern induction motor control," in *Power Electronics and Variable-Speed Drives, 1991., Fourth International Conference on* , vol., no., pp.364-369, 17-19 Jul 1990.
[25]. Malesani, Luigi, and Paolo Tenti. "A novel hysteresis control method for current-controlled voltage-source PWM inverters with constant modulation frequency." *IEEE Transactions on Industry Applications* 26.1 (1990): 88-92.
[26]. Atkinson, David J., Paul P. Acarnley, and John W. Finch. "Observers for induction motor state and parameter estimation." *Industry Applications, IEEE Transactions on* 27.6 (1991): 1119-1127.
[27]. Bose, Bimal K. "Recent advances in power electronics." *Power Electronics, IEEE Transactions on* 7.1 (1992): 2-16.
[28]. Habetler, Thomas G., et al. "Direct torque control of induction machines using space vector modulation." *Industry Applications, IEEE Transactions on* 28.5 (1992): 1045-1053.
[29]. Bose, Bimal K. "Power electronics and motion control-technology status and recent trends." *Industry Applications, IEEE Transactions on* 29.5 (1993): 902-909.
[30]. Garcia, G.O.; Stephan, R.M.; Watanabe, E.H., "Comparing the indirect field-oriented control with a scalar method," in *Industrial Electronics, IEEE Transactions on*, vol.41, no.2, pp.201-207, Apr 1994.
[31]. Fodor, D.; Katona, Z.; Szesztay, E., "Field-oriented control of induction motors using DSP," in *Computing & Control Engineering Journal* , vol.5, no.2, pp.61-65, April 1994.
[32]. Pan, Ching-Tsai, and Ting-Yu Chang. "An improved hysteresis current controller for reducing switching frequency." *Power Electronics, IEEE Transactions on* 9.1 (1994): 97-104.

[33]. Fodor, D., Z. Katona, and E. Szesztay. "Digitized vector control of induction motor with /DSP." *Industrial Electronics, Control and Instrumentation, 1994. IECON'94., 20th International Conference on*. Vol. 3. IEEE, 1994

[34]. Vas, P., A. F. Stronach, and M. Neuroth. "DSP-controlled intelligent high-performance AC drives: present and future." (1995): 7-7.

[35]. Raghavendiran, T. A., and David P. Job. "PC based rotor flux oriented control of induction motors using DSP." *Power Electronics, Drives and Energy Systems for Industrial Growth, 1996., Proceedings of the 1996 International Conference on*. Vol. 1. IEEE, 1996.

[36]. Malesani, Luigi, Paolo Mattavelli, and Paolo Tomasin. "Improved constant-frequency hysteresis current control of VSI inverters with simple feedforward bandwidth prediction." *Industry Applications, IEEE Transactions on* 33.5 (1997): 1194-1202.

[37]. Attaianese, C.; Nardt, V.; Perfetto, A.; Tomasso, G., "Vectorial torque control: a novel approach to torque and flux control of induction motor drives," in *Industry Applications, IEEE Transactions on*, vol.35, no.6, pp.1399-1405, Nov/Dec 1999.

[38]. Le-Huy, Hoang. "Comparison of field-oriented control and direct torque control for induction motor drives." *Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE*. Vol. 2. IEEE, 1999.

[39]. Kang, Jun-Koo, and Seung-Ki Sul. "New direct torque control of induction motor for minimum torque ripple and constant switching frequency." *Industry Applications, IEEE Transactions on* 35.5 (1999): 1076-1082.

[40]. El Moucary, C.; Mendes, E.; Razek, A., "Decoupled direct control for PWM inverter-fed induction motor drives," in *Industry Applications, IEEE Transactions on* , vol.38, no.5, pp.1307-1315, Sep/Oct 2002no.3, pp.837-854, June 2005451, 2000.

[41]. B. singh, B.P. singh and S.G. Choudhuri, “Comparative Study Of Different Speed Controllers for Vector Control of An Induction Motor Drive,” in proc. *National System Conf.*, pp.446-451, 2000.

[42]. Xu, Huangsheng, Hamid Toliyat, and Lynn J. Petersen. "Five-phase induction motor drives with DSP-based control system." *Power Electronics, IEEE Transactions on* 17.4 (2002): 524-533.

[43]. Casadei, D.; Profumo, F.; Serra, G.; Tani, A., "FOC and DTC: two viable schemes for induction motors torque control," in *Power Electronics, IEEE Transactions on*, vol.17, no.5, pp.779-787, Sep 2002.

[44]. Rong-Jong Wai; Kuo-Min Lin, "Robust decoupled control of direct field-oriented induction motor drive," in *Industrial Electronics, IEEE Transactions on* , vol.52, no.3, pp.837-854, June 2005.

[45]. Singh, Bhim, et al. "Direct torque control: a practical approach to electric vehicle." *Power India Conference, 2006 IEEE*. IEEE, 2006.

[46]. Panigrahi, Bibhu Prasad, Dinkar Prasad, and Sabyasachi SenGupta. "A simple hardware realization of switching table based direct torque control of induction motor." *Electric Power Systems Research* 77.2 (2007): 181-190.

[47]. Tekwani, P. N., R. S. Kanchan, and K. Gopakumar. "Novel current error space phasor based hysteresis controller using parabolic bands for control of switching frequency variations." *Industrial Electronics, IEEE Transactions on*54.5 (2007): 2648-2656.

[48]. Choudhuri, S. Ghatak, and Bhim Singh. "DSP Based Implementation of Digital Speed Controller for Vector Controlled Induction Motor Drive." *JOURNAL-INSTITUTION OF ENGINEERS INDIA PART EL ELECTRICAL ENGINEERING DIVISION* 85 (2005): 203.

[49]. Bose, Bimal K. "Power electronics and motor drives recent progress and perspective." *Industrial Electronics, IEEE Transactions on* 56.2 (2009): 581-588.

[50]. Holmes, Donald Grahame, Brendan Peter McGrath, and Stewart Geoffrey Parker. "Current regulation strategies for vector-controlled induction motor drives." *Industrial Electronics, IEEE Transactions on* 59.10 (2012): 3680-3689.

[51]. Suneel Kumar Agrawal and Sumit Ghatak Choudhuri, "Simulation of Vector Controlled Induction Motor Drive in MATLAB for Various Applications: A Comparative Study," in *Proc. Michael Faraday IET International Summit-2015*, 12-13 Sept, 2015, pp.533-540.

[52]. S. H. Kim, S. K. Sul and M. H. Park, "Maximum torque control of an induction machine in the field weakening region," *Industry Applications Society Annual Meeting, 1993., Conference Record of the 1993 IEEE*, Toronto, Ont., 1993, pp. 401-407 vol.1.

[53]. J. N. Nash, "Direct torque control, induction motor vector control without an encoder," in *IEEE Transactions on Industry Applications*, vol. 33, no. 2, pp. 333-341, Mar/Apr 1997.

[54]. A. Thilak Raja, P. Agarwal and S. Ghatak Choudhuri, "Vector Controlled Induction Motor Drive and Direct Torque Controlled Induction Motor Drive: A Comparative Study," *ICFAI University of Electrical and Electronics Engineering,*vol.2, No.2, pp.28-46, April 2009.

[55]. Singh, Bhim, et al. "Direct torque control: a practical approach to electric vehicle." *Power India Conference, 2006 IEEE*. IEEE, 2006.

[56]. Kumar, Rakesh, et al. "Review on model reference adaptive system for sensorless vector control of induction motor drives." *Electric Power Applications, IET* 9.7 (2015): 496-511.

[57]. Lascu, Cristian, Ion Boldea, and Frede Blaabjerg. "A modified direct torque control for induction motor sensorless drive." *Industry Applications, IEEE Transactions on* 36.1 (2000): 122-130.

[58]. Maes, Jehudi, and Jan A. Melkebeek. "Speed-sensorless direct torque control of induction motors using an adaptive flux observer." *Industry Applications, IEEE Transactions on* 36.3 (2000): 778-785.

[59]. Maiti, Suman, et al. "Model reference adaptive controller-based rotor resistance and speed estimation techniques for vector controlled induction motor drive utilizing reactive power." *Industrial Electronics, IEEE Transactions on* 55.2 (2008): 594-601.

[60]. Kim, Young-Real, Seung-Ki Sul, and Min-Ho Park. "Speed sensorless vector control of induction motor using extended Kalman filter." *Industry Applications, IEEE Transactions on* 30.5 (1994): 1225-1233.

[61]. Po-Ngam, Sakorn, and Somboon Sangwongwanich. "Stability and dynamic performance improvement of adaptive full-order observers for sensorless PMSM drive." *Power Electronics, IEEE Transactions on* 27.2 (2012): 588-600.

[62]. Kubota, Hisao, Kouki Matsuse, and Takayoshi Nakano. "DSP-based speed adaptive flux observer of induction motor." *IEEE Transactions on Industry Applications* 29.2 (1993): 344-348.
[63]. Hinkkanen, Marko. "Analysis and design of full-order flux observers for sensorless induction motors." *Industrial Electronics, IEEE Transactions on*51.5 (2004): 1033-1040.
[64]. Ohtani, Tsugutoshi, Noriyuki Takada, and Koji Tanaka. "Vector control of induction motor without shaft encoder." *Industry Applications, IEEE Transactions on* 28.1 (1992): 157-164.
[65]. Peng, Fang-Zheng, and Tadashi Fukao. "Robust speed identification for speed-sensorless vector control of induction motors." *Industry Applications, IEEE Transactions on* 30.5 (1994): 1234-1240.
[66]. Huang, Shoudao, et al. "The vector control based on MRAS speed sensorless induction motor drive." *Intelligent Control and Automation, 2004. WCICA 2004. Fifth World Congress on*. Vol. 5. IEEE, 2004.
[67]. Landau, Yoan D. "Adaptive control: The model reference approach."*Systems, Man and Cybernetics, IEEE Transactions on* 1 (1984): 169-170.
[68]. Lorenz, Robert D. "A simplified approach to continuous on-line tuning of field-oriented induction machine drives." *Industry Applications, IEEE Transactions on* 26.3 (1990): 420-424.
[69]. Rashed, M., and A. F. Stronach. "A stable back-EMF MRAS-based sensorless low-speed induction motor drive insensitive to stator resistance variation." *Electric Power Applications, IEE Proceedings-*. Vol. 151. No. 6. IET, 2004.
[70]. Said, MS Nait, and M. E. H. Benbouzid. "Induction motors direct field oriented control with robust on-line tuning of rotor resistance." *Energy Conversion, IEEE Transactions on* 14.4 (1999): 1038-1042.
[71]. Kojabadi, Hossein Madadi. "Active power and MRAS based rotor resistance identification of an IM drive." *Simulation Modelling Practice and Theory* 17.2 (2009): 376-389.
[72]. Chakraborty, Chandan, et al. "A New V× I based adaptive speed sensorless four quadrant vector controlled induction motor drive." *Power Electronics Conference (IPEC), 2010 International*. IEEE, 2010.
[73]. Land, Ioan Dore. "A hyperstability criterion for model reference adaptive control systems." *Automatic Control, IEEE Transactions on* 14.5 (1969): 552-555.
[74]. Popov's V.M.: "hyperstability of control system" (Springer-verlag, New York, 1973).

Appendix I

Specification of motors considered in the investigation

Cage Induction Motor I

30 HP, 3-Phase, 4-Pole, Y-connected, 415V, 45.0A, 50HZ

R_s =0.25Ω , R_r=11.72Ω, X_{ls} = 0.439Ω, X_{lr} = 0.439Ω, X_m = 13.085Ω, J=0.305Kg m^2

Cage Induction Motor II

5 HP, 3-Phase, 4-Pole, Y-connected, 415V, 8A, 50HZ

R_s =1.996Ω , R_r=2.011Ω, X_{ls} = 3.14Ω, X_{lr} = 3.14Ω, X_m = 70.439Ω, J=0.0185Kg m^2

Cage Induction Motor III

2 HP, 3-Phase, 4-Pole, Y-connected, 415V, 3.3A, 50HZ

R_s =5.4Ω , R_r=3.1093Ω, X_{ls} = 8.1976Ω, X_{lr} = 8.1976Ω, X_m = 110.371Ω, J=0.004363641 kg m^2

Appendix II

The values of parameter of speed controllers considered in the investigation Simulation analysis are as follows:

Speed Controller Parameters (For 30HP VCIMD):

K_P 9

K_I 2.6

Speed Controller Parameters (For 30HP DTCIMD):

K_P 90

K_I 5.8

Speed Controller Parameters (For 30HP Sensorless DTCIMD):

K_P 6

K_I 0.05

Adaptive Mechanism Parameters (For 30HP Sensorless DTCIMD):

K_P 600

K_I 200

Speed Controller Parameters (For 5HP VCIMD):

K_P 6

K_I 0.2

Speed Controller Parameters (For 5HP DTCIMD):

K_P 6.5

K_I 0.2

Speed Controller Parameters (For 5HP Sensorless DTCIMD):

K_P 1.2

K_I 0.01

Adaptive Mechanism Controller Parameters (For 5HP Sensorless DTCIMD):

K_P 1000

K_I 500

Speed Controller Parameters (For 2HP VCIMD):

K_P 2.35

K_I 0.104

Speed Controller Parameters (For 2HP DTCCIMD):

K_P 2.35

K_I 0.1

Speed Controller Parameters (For 2HP Sensorless DTCIMD):

K_P 0.15

K_I 0.001

Adaptive Mechanism Controller Parameters (For 2HP Sensorless DTCIMD):

K_P 1000

K_I 500

Induction Motor Operated in Vector Control Mode and Direct Torque Control Mode: A Comparative Study

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