CONVERTOR-BASED SPEED CONTROL OF DOUBLY FED INDUCTION MACHINE

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

WATER RESOURCES DEVELOPMENT

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this Dissertation, entitled "**CONVERTOR-BASED SPEED CONTROL OF DOUBLY FED INDUCTION MACHINE**", in partial fulfillment of the requirements for the award of Degree of **Master of Technology** with specialization in **Water Resource Development** submitted to the department of **Water Resource Development & Management**, Indian Institute of Technology Roorkee, is an authentic record of my own work carried out under the supervision of **Dr. C.THANGA RAJ**, Assistant Professor, Water Resource Development & Management Department, Indian Institute of Technology Roorkee, Roorkee, India.

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

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CERTIFICATE

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

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(JAYVEER SINGH)

ABSTRACT

The electric motor applications are increasing speedily with advancement in technology. With the technological progress the adjustable speed drives are preferred. So speed control of electric motors is always a challenge for researchers and technologists. In this thesis the speed control with the help of power electronic converter has been studied. The present thesis based on i) mathematical modeling of doubly fed induction machine (DFIM) ii) rotor resistance controlled DFIM drive and variation of rotor resistance with the help of rectifier and chopper iii) variation of voltage and frequency on stator and rotor side iv) implementation of constant volts/hertz control v) implementation of vector control vi) simulation of drives with matlab simulink.

To use the electrical energy efficiently doubly fed induction machine (DFIM) with the help of power electronics converter are widely used with voltage-controlled voltage source inverters for industrial, traction, large capacity pumps, and wind energy systems, flywheel energy storage applications, because of their high power density, flexibility, smaller speed limitation, part load operation, good transient response and high efficiency.

As a first step towards the objective of this thesis, the speed control by inserting the external resistance in the rotor circuit has been studied. With this method having disadvantages like additional ohmic loss in rotor circuit hence reduced efficiency of the machine and also the loss of energy. If a step has taken to increase or decrease the frequency, flux try to increase or decrease, haveving constant flux machines converter based constant volts/hertz control for keeping flux constant has been implemented at rotor side of doubly fed induction machine (DFIM) for operation below synchronous speed.

For high speed operation i.e the operation above synchronous speed the vector control scheme has been implemented due to some advantageous features like quicker system response, good transient response. Constant volts/hertz cannot be applied for operation above rated speed because we cannot increase the voltage above the rated value also scalar control system is a sluggish system due to inherent system coupling. Sinusoidal pulse width modulation (SPWM) has been implemented to generate gate signals for the inverter. The simulation study has been carried out for the drives in below synchronous speed operation, above synchronous speed operation with load variation.

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INTRODUCTION — CHAPTER -1

1.1 MOTIVATION

Energy is the ability to do work and work is the transfer of energy from one form to another. In practical terms, energy is what we use to manipulate the world around us, whether by exciting our muscles, by using electricity, or by using mechanical devices such as automobiles. Energy comes in different forms - heat (thermal), light (radiant), mechanical, electrical, chemical, and nuclear energy. The first principle of electrical energy conservation is: when we don't need it, turn it off. The second principle is: we should minimize losses or use energy efficiently. For this purpose, doubly fed Induction machines are the most recently used for consumption of electrical energy. The doubly fed induction motor is becoming popular due to some of its advantageous features:

- High efficiency
- Full operating speed range
- High torque to inertia ratio
- High torque to volume ratio
- High air gap flux density
- High power factor
- Ruggedness
- Good speed control

DFIM have significant advantages, attracting the interest of researchers and industry for many applications.

- Doubly Fed Induction Machine is widely used for wind power application due to its operation at different speed and high efficiency.
- Doubly Fed Induction Motors (DFIM) is widely used with current-controlled voltage source inverters for industrial and traction applications, because of their high power density, and high efficiency.
- Doubly Fed Induction Motors (DFIM) is used for centrifugal loads like pumping operation because in pumping operation there is requirement of variable speed operation.

- In electric vehicle DFIM has been used due to good speed control, and also for high torque applications.
- For less maintenance the brushless and sensor less DFIM drive has been developed.

Doubly fed induction motors (DFIMs) offer better efficiency than induction motors, and therefore, using DFIM as the main traction motor for railway vehicles.

1.1.1 Comparative Study of DFIM with Other Motor

With the advancement of technological growth doubly fed induction motor get its popularity in modern world. The advantageous features of DFIM are described as follows.

Advantage over synchronous motor

Doubly fed induction motor have the following advantage over synchronous motor i) Lower maintenance cost ii) Less audible noise iii) Longer life iv) Better heat transfer v) full operating speed range vi) slip power can be transfer to grid i.e slip power recovery vii) better speed control.

Advantage over Induction motor

Doubly fed induction motor is advantageous over Induction motor in following ways. i) It can operate under wide range of power factors both lagging or leading, while Induction motor can operate only in lagging power factor ii) Higher efficiency iii) Better heat transfer iv) Higher power density. v) Operating full speed range vi) slip power recovery vii) good speed control.

1.2 OBJECTIVES OF THE PRESENT WORK

The primary objectives of this dissertation work are

1. To study the performance characteristics of doubly fed induction motor in MATLAB.
2. To implement the scalar control strategy in terms of constant volts per hertz (v/f) control strategy.
3. To implement the vector control strategy above the synchronous speed.
4. To study the behavior of drive for wide speed region.

1.3 LITERATURE REVIEW

The complete thesis can divide in two main different areas as following

- Constructional features and mathematical modeling of DFIM
- DFIM drive

DFIM drive can also divide into four sub Areas as

- DFIM drive with Rotor resistance speed control
- DFIM drive with variation in voltage and frequency at stator and rotor
- DFIM drive with Constant volts per hertz(v/f) control
- DFIM drive with Vector control.

Literature are reviewed for each section and general guidelines are reviewed from the books [1-8]. Review of research papers for different section is discussed in the following section.

Concordia et.al explained the motivation behind the development of doubly fed induction machine. In early days AC excited synchronous machines on both stator and rotor have been used in many applications, like for induction frequency converters and as variable speed drives. In this paper they have considered the equation given [11], however now authors are using their own work equations which are more convenient to them [9].

Wang et.al proposed a rotor chopper controlled DFIM drives considering the case of high inrush current, voltage dip and harmonics at starting due to direct starting of motor. In this they explained the rotor resistance method of starting for DFIM. Rotor chopper controlled scheme has been used to start an induction machine with maximum torque [10].

Ayasun et.al proposed a Matlab/Simulink model for testing for testing of induction motor tests to calculate the equivalent circuit parameters. With the help of these diagram we can developed the complete model for RR control and constant volts/hertz control [11].

Lazhar Ben-brahim further discussed about the improvement of stability for v/f controlled induction motor drives. As Instability of a V/f controlled IM drive system may occur as the V/f control method do not consider the transient operation of the system. In this paper he developed a new approach of V/f control, which is based on current feedback to improve the stability of the conventional V/f control. This new method has also successfully damped out the torque and speed oscillations in V/f control for low power induction motor drive system [12].

Koga et.al proposed a new scheme to reduce the steady state speed error, caused by load changes from no-load, to zero without using a rotor speed sensor for V/f (Voltage/frequency) controlled induction motor drive system. This paper consider as, the frequency of the stator voltage is controlled so as to compensate for the error and strategy is called the frequency compensation control (FCC) [13].

Tsuji et.al proposed a new simplified V/f control system based on vector control theory for induction motor (IM) for precise speed operation. In this a linear model is derived for analyzing the system stability and also include the influences of motor operating states in motoring and regenerating operations, and parameter variation of low pass filter. In this by the help of d-axis current stator resistance is calculated [14].

Munoz-Garcia et.al proposed a new open-loop speed control scheme based on constant volts per hertz for induction motors that provides high output torque and nearly zero steady-state speed error at any frequency and also using low-cost open-loop current sensors [15].

Suetake et.al presents a compact embedded fuzzy system for v/f controlled induction motor drive. In this paper a fuzzy-control system is built on a digital signal processor, which uses speed error and speed-error variation to change both the fundamental voltage amplitude and frequency of a sinusoidal pulse width modulation inverter [16].

Reddy et.al proposed a hybrid pulse width modulation technique for v/f controlled voltage source inverter [VSI] fed induction motors. As VSI fed induction motor generate pulsating torque so in this paper they have discussed space vector pulse width modulation scheme for reduce the voltage ripple and which make it close to sinusoidal. Finally in this paper hybrid PWM has been discussed i.e it has both continuous and discontinuous PWM technique because it has several advantage over conventional PWM technique [17].

Yuan et.al explained the two methods of starting and the complete vector control technique for doubly fed induction motor. In this paper they considered constant v/f control below synchronous speed and vector control technique for above synchronous speed. In this paper they also proposed a grid synchronization scheme for transition from v/f to vector control technique [18]-[39].

Zhang et.al proposed the design of 800KW DFIM system, also discussed the system structure, and vector control technique. The proposed work having cycloconverter and vector control has been achieved the speed control of motor and DFIM leading power factor operation [40].

Yi-ping et.al proposed an integrated system of DFIM soft starting and speed adjusting. This system has the variable reactance converter, electronic power inverter, controller and DFIM. In this paper the principle of vector control has been used in soft design [41].

Zhiqiang Du proposed a novel vector technique for doubly fed induction motor which is based on the computation of speed from the rotor current, rotor voltage directly [42].

Zheng et.al proposed a new current vector control strategy for doubly fed induction machine. This new control technique is based on the rotor flux orientation [43].

Poza et.al proposed a new vector control algorithm for the brushless doubly fed machine (BDFM). The main objective of BDFM control is to have a similar dynamic performance as the vector control philosophy [44].

Sallem et.al proposed the vector control technique for DFIM used in electric vehicle. This proposed control technique is based on a flux orientation of the rotor with scalar control on the stator [45].

BEKAKRA et.al proposed a Direct Field-Oriented Control (DFOC) of DFIM in motor mode based on a sliding mode control (SMC). In this paper the main objective is to make the speed and the flux control robust to parameter variations for good performance of the machine [46].

Zhang et.al proposed the consideration of DFIG used in wind farm for motor applications. In this paper they also explained the characteristics for adoption of DFIMs. As DFIM has four quadrant operation positive speed motoring, regenerative braking, negative speed motoring and braking [47].

Karthikeyan et.al proposed a sensorless position estimator for accurate estimation of rotor position and speed of DFIM. In this proposed work the rotor position is estimated in a straight forward and implicit manner without estimating the stator flux [48].

Pannatier et.al proposed the start-up and synchronization procedures of a variable-speed pump-turbine unit in pumping mode. These procedures have three-level voltage source inverters VSI cascade in the rotor side, the start-up control strategy is based on a stator flux oriented control [49].

Yuan et.al proposed a nonlinear speed controller called as fuzzy controller for doubly-fed induction motor (DFIM). It has been designed to counter the effects of the coupling between the flux and electromagnetic torque. In this paper it is shown that with the fuzzy switching control the controller can achieve good speed tracking and good robustness against parameter variations and load torque disturbance [50].

Zhang et.al proposed a new design for use of doubly fed induction motor (DFIM) used for pumping operation. In this they proposed a strategy of two-step AC excitation for change in working condition of motor from asynchrony to AC excitation. For speed control and power factor control they have been used a three-phase half-wave cycloconverter and stator flux-orientated vector control [51].

Altun et.al proposed a new control strategy for doubly-fed induction motor drive by matrix converter. In this proposed drive system matrix converter has been used to extract the slip energy from the rotor. With this control strategy machine can operate below synchronous speed and above synchronous speed as well [52].

Drid et.al proposed a robust vector control for a doubly fed induction motor drive. In this a speed controller has been designed using two methods (1) with a PI controller and (2) with the Lyapunov method. The second solution shows good robustness with respect to inertia variation and also for torque and speed tracking [53].

Ahmad et.al explained the applications of DFIM drive for high torque low speed applications in pulp, paper and cement industries. With the help of this proposed work motor works as constant speed motor without any problem of stability [54].

Bocquel et.al proposed a cyclo-converter driven doubly-fed induction machine for pump-storage stations. Major benefits of this innovative concept are the increase of the turbine efficiency by means of speed variation and the high dynamic power control for the stabilisation of the grid. Major benefits compared to classical approaches are identified. Emphasis is placed on the behavior of the drive at grid failures. A new modified topology is proposed to meet the grid code requirements at various grid failures [55].

Vicatos et.al proposed an electrical drive model of DFIM for automobiles. In this model the rotor of two doubly fed induction machines connected electrically [56].

Congwei et.al has done the research on stability of vector control technique of doubly fed induction machine (DFIM) [57].

1.4 ORGANIZATION OF THE THESIS

This master's thesis presents the converter based speed control of doubly fed induction motor drive. For this purpose modeling of DFIM and DFIM drive with different control technique has been studied. This thesis is divided in six different chapters.

Chapter 1, "INTRODUCTION," introduces the motivation to use DFIM motor and historical aspect. Comparative study of DFIM with other motor and the objective of the thesis have been discussed. The recent research on DFIM also discussed.

Chapter 2 'DOUBLY FED INDUCTION MOTOR," This chapter presents the general system of doubly fed machine and basic concept of DFIM like torque and force, slip concept, relationship between active and reactive power and modes of operation of doubly fed machine. In the next portion of this chapter the mathematical modeling and equivalent circuit of DFIM has been discussed.

Chapter 3 is titled "DIFFERENT CONTROL TECHNIQUES FOR SPEED CONTROL," Initial section of this chapter explains the rotor resistance speed control technique with rheostat and with the help of rectifier and chopper. Next this chapter explained the motivation behind applying the scalar control with the variation in voltage and frequency at stator and rotor side. Finally explains the constant volts/hertz controlled DFIM drive for speed below synchronous speed at rotor side.

Chapter 4 "VECTOR CONTROLLED DFIM DRIVE," firstly introduces the development history of vector control and theory of reference frame and different type of reference frames. Finally describe the complete vector control model for DFIM drive and block diagram for vector controlled DFIM drive and also described the selection of PI parameters. It also explained the flow chart representation showing different type of control technique for speed control of DFIM drive.

Chapter 5 "SIMULATION RESULT OF DFIM DRIVE," This portion of the thesis includes the performance analysis of doubly fed induction motor drive for wide speed range operation. Simulation results with rotor resistance control of DFIM drive has been shown. The simulation result with variation in voltage and frequency at stator and rotor side both has been given. In next portion of this chapter the simulation result with constant v/f controlled DFIM drive for operation below synchronous speed has been given. Finally simulation result for vector controlled DFIM drive for high speed application has been discussed.

Chapter 6 "CONCLUSION AND FUTURE SCOPE," In this chapter the conclusion of this thesis and the future scope has been discussed.

2.1 INTRODUCTION

The Doubly Fed Induction Motor (DFIM) is an induction machine with a wound rotor where the rotor and stator are both connected to electrical sources, hence called as 'doubly-fed'. The rotor has three phase windings which are energized with three-phase currents. These rotor currents establish the rotor magnetic field. The rotor magnetic field interacts with the stator magnetic field to develop torque. The magnitude of the torque depends on the strength of the two fields (the stator field and the rotor field) and the angular displacement between the two fields. Mathematically, the torque is the vector product of the stator and rotor fields.

2.2 SYSTEM CONFIGURATION

The systematic diagram is shown in fig.2.1.

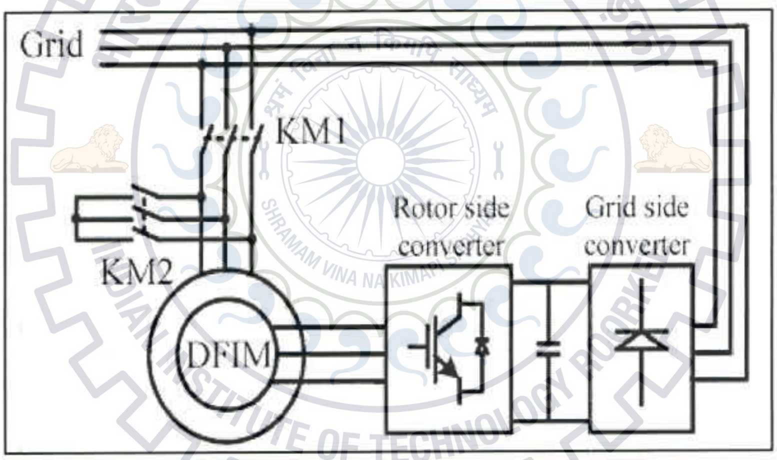

Fig.2.1 systematic diagram of general system of DFIM drive

The system configuration is shown in Fig.2.1. Switch KM1 has been used for connecting the DFIM stator winding to the grid, while the rotor winding has been connected to the grid with the two three-phase voltage-fed converters as shown in figure. To reduce the system cost and control complexity and also to accomplish the one-quadrant operation of motor drive, a grid side diode bridge converter and rotor side PWM converter has been used. Therefore, the slip power can only flow from rotor to grid in this system configuration. These converters can be two fully controlled three phase PWM converters to obtain motor operation below synchronous and above synchronous speed. The grid side converter can reduce the system power factor, and also the converter power is only the slip power. The rotor side converter can introduce the harmonics to the machine and the grid, so certain filter inductance should be use at rotor side to eliminate the system harmonics.

The speed control of DFIM drive can be divided into two parts.

(1). Low speed region operation i.e speed below synchronous speed

(2). high speed operation i.e operation above the synchronous speed

The machine has been started and accelerated like an induction machine from rotor side by constant volts/hertz control. When machine reach at a speed above synchronous, vector control scheme will implemented for DFIM drive.

2.3 BASIC CONCEPTS ON DFIM

This section includes the basic term like force, toque, slip, and frequency relationships.

2.3.1 INDUCED FORCE/TORQUE

DFIM consist of one stator winding and other is rotor winding. Both windings supplied by two three phase source independently but rotor is supplied by the help of two bidirectional converter. The rotor windings can be connected in a star or delta and they are supplied by electrical supply through the slip rings and brushes. DFIM is similar to a cage rotor induction machine, but from construction point of view the rotor of DFIM is bigger and also need maintenance due to brushes and slip rings.

When stator is supplied by balanced three phase source the stator flux is induced and it rotates at constant speed. Therefore the synchronous speed (n_s) is given as:

$$n_s = \frac{60f_s}{p}\ (rev/min) \quad (2.1)$$

By Faraday's law of electromagnetic induction this stator flux induced an emf in rotor windings given as

$$e_{ind} = (v \times B)L \quad (2.2)$$

Where e_{ind}= induced emf , v= speed of the conductor in relation to the stator flux rotation

B= stator flux density vector, L= length of the conductor

Due to induced voltage in the rotor windings a current is induced in the rotor windings which induced a force according to Laplace's law given as:

$$F = I(L \times B) \quad \text{(2.3)}$$

Where F= induced force, I= current of the rotor conductor

B= stator flux density vector, L= length of the conductor

2.3.2 SLIP CONCEPT

The angular frequency of the induced rotor voltages and currents is given by the relation

$$\omega_r = \omega_s - \omega_m \quad \text{(2.4)}$$

Where ω_r= angular frequency of the rotor windings (rad/s)

ω_s= angular frequency of the stator windings (rad/s)

ω_m= angular frequency of the rotor (rad/s)

And

$$\omega_m = p\Omega_m \quad \text{(2.5)}$$

Where Ω_m= mechanical rotational speed at the rotor (rad/s)

Hence, the commonly used term to define the relation between the speed of the stator and the rotor angular frequency is the slip (s) given by the formula.

$$s = \frac{\omega_s - \omega_m}{\omega_s} \quad \text{(2.6)}$$

So we can get easily

$$\omega_r = s\omega_s \quad \text{(2.7)}$$

Also in terms of frequency we have

$$f_r = sf_s \quad \text{(2.8)}$$

Depending on the sign of the slip, we can get different modes of operations given as:

$\omega_m < \omega_s \Rightarrow \omega_r > 0 \Rightarrow s > 0$ Subsynchronous operation

$\omega_m > \omega_s \Rightarrow \omega_r < 0 \Rightarrow s < 0$ Hypersynchronous operation

$\omega_m = \omega_s \Rightarrow \omega_r = 0 \Rightarrow s = 0$ Synchronous operation

2.4 RELATIONSHIPS BETWEEN ACTIVE POWERS, TORQUE, AND SPEEDS

By neglecting the copper power losses in the stator and rotor resistances, the relation between the stator and rotor power is given as:

$$P_r \cong -sP_s \qquad (2.9)$$

Hence the mechanical power can also be expressed as

$$P_{mec} \cong P_s - sP_s = (1-s)P_s \qquad (2.10)$$

On the other hand, we also have the mechanical power as

$$P_{mec} \cong \frac{\omega_m}{\omega_s} P_s \cong T_{em} \frac{\omega_m}{p} \qquad (2.11)$$

Consequently, the relation between the torque and the stator power can be expressed as:

$$P_s \cong T_{em} \frac{\omega_s}{p} \qquad (2.12)$$

Similarly, it easy to deduce Reactive power as

$$P_r \cong T_{em} \frac{\omega_r}{p} \qquad (2.13)$$

2.4.1 FOUR QUADRANT MODES OF OPERATION

From the above power relations (2.9)–(2.13), it can be seen that the DFIM can operate under different operating modes depending on the power and the speed.

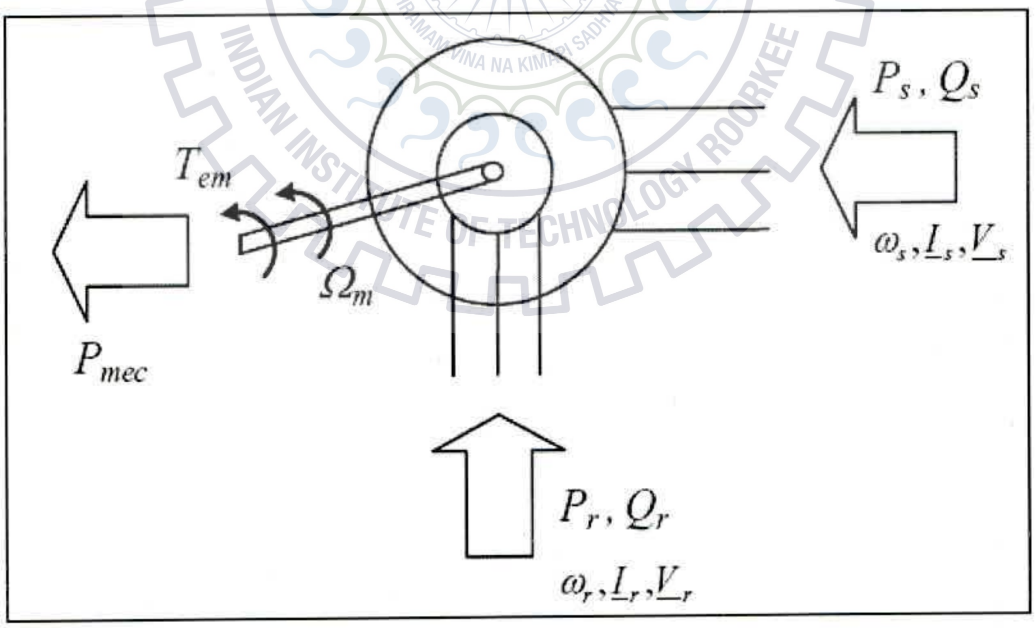

Fig.2.2 systematic diagram showing the power relationships with torque and speed

Figure 2.2 shows a simplified scheme of the power flow. Table 2.1 shows the four operations of DFIM drive. Note that only in generator mode at hyper synchronism power can delivered through both the stator and rotor side to the grid.

Table 2.1 four modes of operation

Sr No.	MODE	SPEED	P_{mec}	Ps	Pr
1	Motor (Tem>0)	S<0 $(\omega_m > \omega_s)$ hyper synchronism	>0 (the machine delivers mechanical power)	>0 receives power through stator	>0 receives through rotor
2	Generator (Tem<0)	S<0 $(\omega_m > \omega_s)$ Hyper synchronism	>0 (the machine receives mechanical power)	<0 delivers power through stator	<0 delivers through rotor
3	Generator (Tem<0)	S>0 $(\omega_m < \omega_s)$ Sub synchronism	<0 (the machine receives mechanical power)	<0 delivers power through stator	>0 receives through rotor
4	Motor (Tem>0)	S>0 $(\omega_m < \omega_s)$ Sub synchronism	>0 (the machine delivers mechanical power)	>0 receives power through stator	<0 delivers through rotor

2.5 MATHEMATICAL MODEL OF DFIM

The stator of the DFIM and the wound rotor induction motor is similar. In DFIM the rotor has the winding those are excited with the three phase supply with the two bidirectional converter. From the equivalent circuit we can easily see that rotor also have voltage source due to winding at rotor. Hence the mathematical model of DFIM is slightly different from that of conventional induction motor.

2.5.1 ASSUMPTIONS FOR MODELING OF DFIM DRIVE

The assumption made for modeling the DFIM has been given as.

1. The three phase stator windings of the DFIM are balanced and produce sinusoidally distributed Magneto-motive force (MMF) in the space.
2. The wound rotor produce sinusoidally distributed Magnetic flux in the air gap.
3. Saturation and iron losses in the machine are neglected.
4. The three phase sinusoidal currents following into the motor are also assumed ripple free (fundamental current are assumed to simplify the motor model).
5. The stator current was assumed positive when flowing toward the machine.
6. The equations were derived in the synchronous reference frame using direct (d) and quadrature (q) axis representation.
7. The q -axis was assumed to be 90 ahead of the d-axis in the direction of rotation.
8. The q component of the stator voltage used within the model is chosen to be equal to the real part of the generator busbar voltage obtained from the load flow solution that is used to initialize the model.
9. The dc component of the stator transient current was ignored, permitting representation of only fundamental frequency components.
10. The higher order harmonic components in the rotor injected voltages are neglected.

For describe the steady state analysis of we have to consider the steady state model of the machine and for describe the machine dynamic and transient behaviors we have to consider the corresponding dynamic model so that the corresponding control technique we can use. Let consider the steady state model first.

2.5.2 STEADY STATE MODEL OF DFIM

For describing the steady state model and equivalent circuit we have the two equations given below

$$V_s - E_s = (R_s + X_{\sigma s})I_s \text{ at } f_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.14)$$

$$V_r' - E_{rs}' = (R_r' + X_{\sigma r}')I_r' \text{ at } f_r \ldots\ldots\ldots\ldots\ldots\ldots(2.15)$$

2.5.2.1 SINGLE PHASE STEADY STATE EQUIVALENT CIRCUIT

From equation we can draw the equivalent circuit for single phase and similarly we can draw the three phase circuit. Single phase equivalent circuit is shown in fig. 2.3.

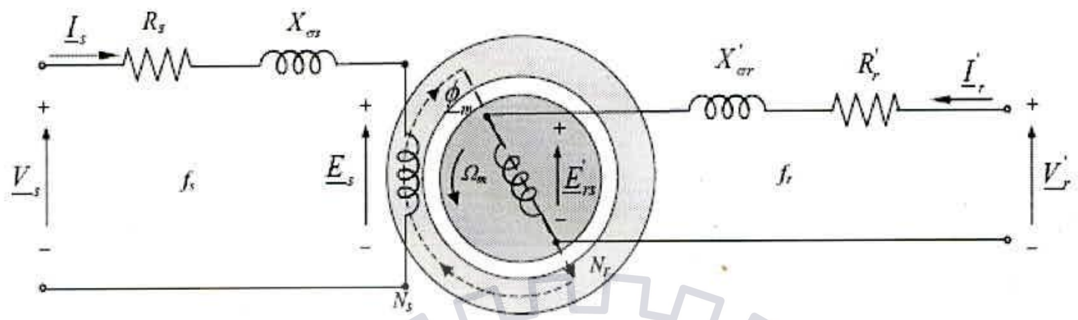

Fig.2.3 equivalent circuit considering the one phase

2.5.2.2 EQUIVALENT CIRCUIT REFER TO STATOR

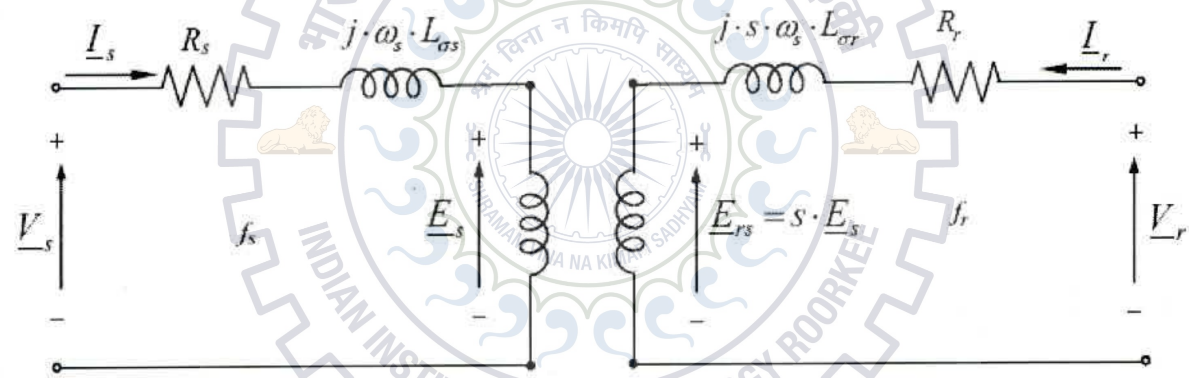

Fig. 2.4 One-phase steady state equivalent electric circuit of the DFIM with different stator and rotor frequencies and rotor parameters, current, and voltages referred to the stator.

2.6 PHASOR DIAGRAM IN MOTORING MODE

From the equivalent circuit it is easy to draw the phasor diagram for a particular operating condition either as a motor or generator. For developing the phasor diagram we can easily calculate the stator and rotor fluxes from the stator and rotor currents from the following expressions:

$$\psi_s = L_m(I_s + I_r) + L_{\sigma s}I_s = L_sI_s + L_mI_r \quad (2.16)$$

$$\psi_r = L_m(I_s + I_r) + L_{\sigma r}I_r = L_mI_s + L_rI_r \quad (2.17)$$

The stator and rotor inductances can be calculated as

$$L_s = L_m + L_{\sigma s} \quad (2.18)$$

$$L_r = L_m + L_{\sigma r} \quad (2.19)$$

Also we can have the stator and rotor voltage equations

$$V_s - R_s I_s = j\omega_s \psi_s \quad (2.20)$$

$$V_r - R_r I_r = js\omega_s \psi_r \quad (2.21)$$

Where all the variables in above equations given in the vector form.

From the above equations we can draw the phasor diagram given in fig.2.5.

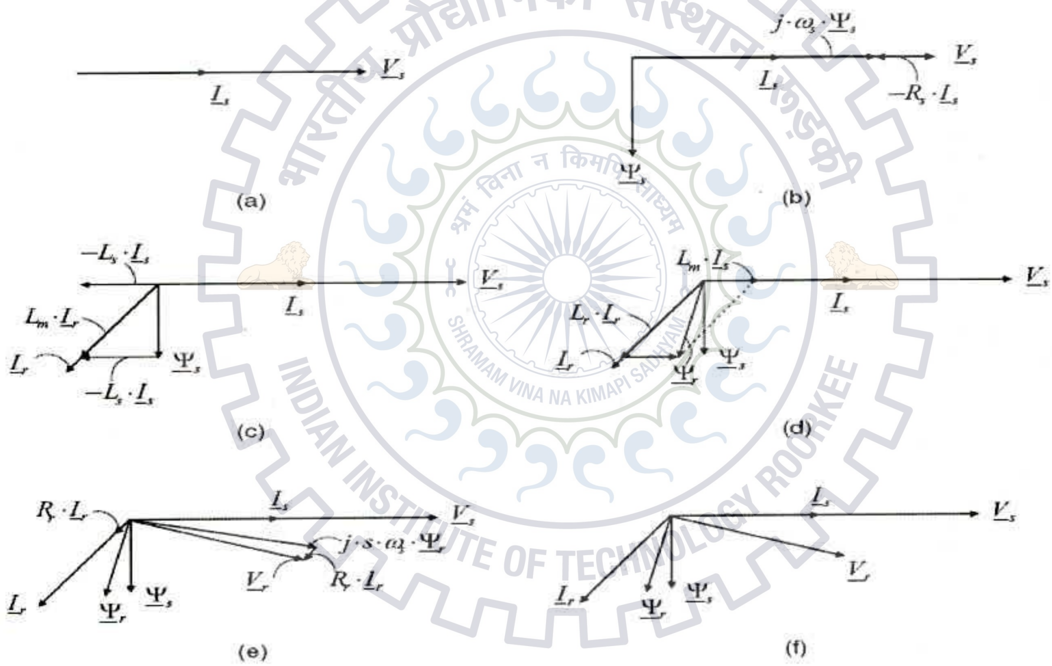

Fig. 2.5 Phasor diagram of a DFIM operating as a motor

2.7 DYNAMIC MODELING OF THE DFIM

A very simple and convenient DFIM model can be derive by considering the three stator winding and three rotor winding as DFIM rotor has the winding not the rotor bars can be shown in the fig.2.6.

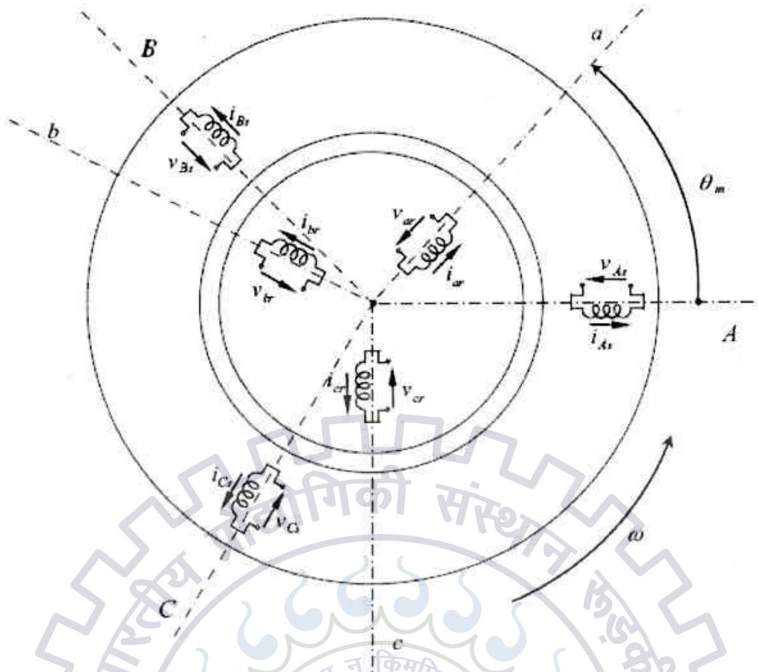

Fig.2.6 diagram showing stator and rotor windings

These three windings on stator and rotor we can draw the electric equivalent circuit given in fig 2.7.

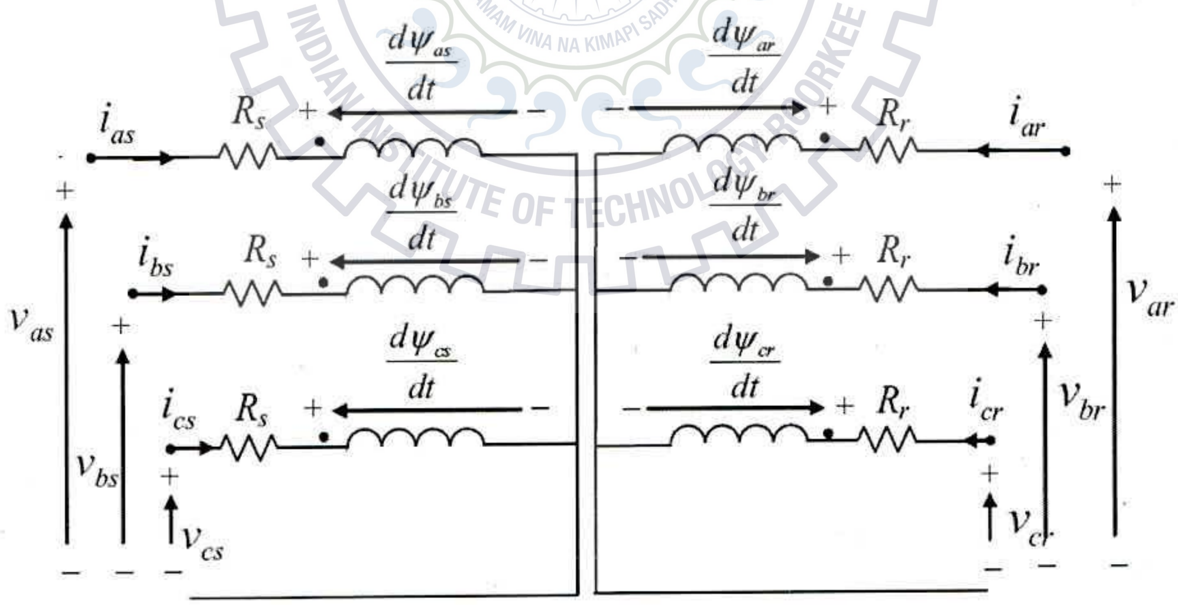

Fig.2.7 dynamic electrical equivalent circuit

From this electric equivalent circuit we can write the instantaneous stator voltage, current and flux equations.

Stator voltage equations can be given as.

$$v_{as}(t) = R_s i_{as}(t) + \frac{d\psi_{as}(t)}{dt} \quad \text{......} (2.22)$$

$$v_{bs}(t) = R_s i_{bs}(t) + \frac{d\psi_{bs}(t)}{dt} \quad \text{......} (2.23)$$

$$v_{cs}(t) = R_s i_{cs}(t) + \frac{d\psi_{cs}(t)}{dt} \quad \text{......} (2.24)$$

where R_s is the stator resistance; $i_{as}(t)$, $i_{bs}(t)$ and $i_{cs}(t)$ are the stator currents and $v_{as}(t)$, $v_{bs}(t)$, and $v_{cs}(t)$ are the applied stator voltages; and $\psi_{as}(t)$, $\psi_{bs}(t)$, and $\psi_{cs}(t)$ are the stator fluxes.

Similarly the rotor voltages can be given as

$$v_{ar}(t) = R_s i_{ar}(t) + \frac{d\psi_{ar}(t)}{dt} \quad \text{......} (2.25)$$

$$v_{br}(t) = R_s i_{br}(t) + \frac{d\psi_{br}(t)}{dt} \quad \text{......} (2.26)$$

$$v_{cr}(t) = R_s i_{cr}(t) + \frac{d\psi_{cr}(t)}{dt} \quad \text{......} (2.27)$$

All the parameter referred to stator side with different turns of stator and rotor.

2.8 DQ MODEL

From the space vector notation in the synchronous reference frame we have stator and rotor voltage as given in equation.

$$v_s^a = R_s i_s^a + \frac{d\psi_s^a}{dt} + j\omega_s \psi_s^a \quad \text{......} (2.28)$$

$$v_r^a = R_r i_r^a + \frac{d\psi_r^a}{dt} + j\omega_r \psi_r^a \quad \text{......} (2.29)$$

Where ω_r can be given as

$$\omega_r = \omega_s - \omega_m \quad \text{......} (2.30)$$

The superscript "a" denotes space vectors referred to a synchronously rotating frame. We also have the stator and rotor fluxes as:

$$\psi_s^a = L_s i_s^a + L_m i_r^a \quad \text{......} (2.31)$$

$$\psi_r^a = L_m i_s^a + L_r i_r^a \quad \text{......} (2.32)$$

Hence, the d-q equivalent circuit model of the DFIM is shown in fig.2.8.

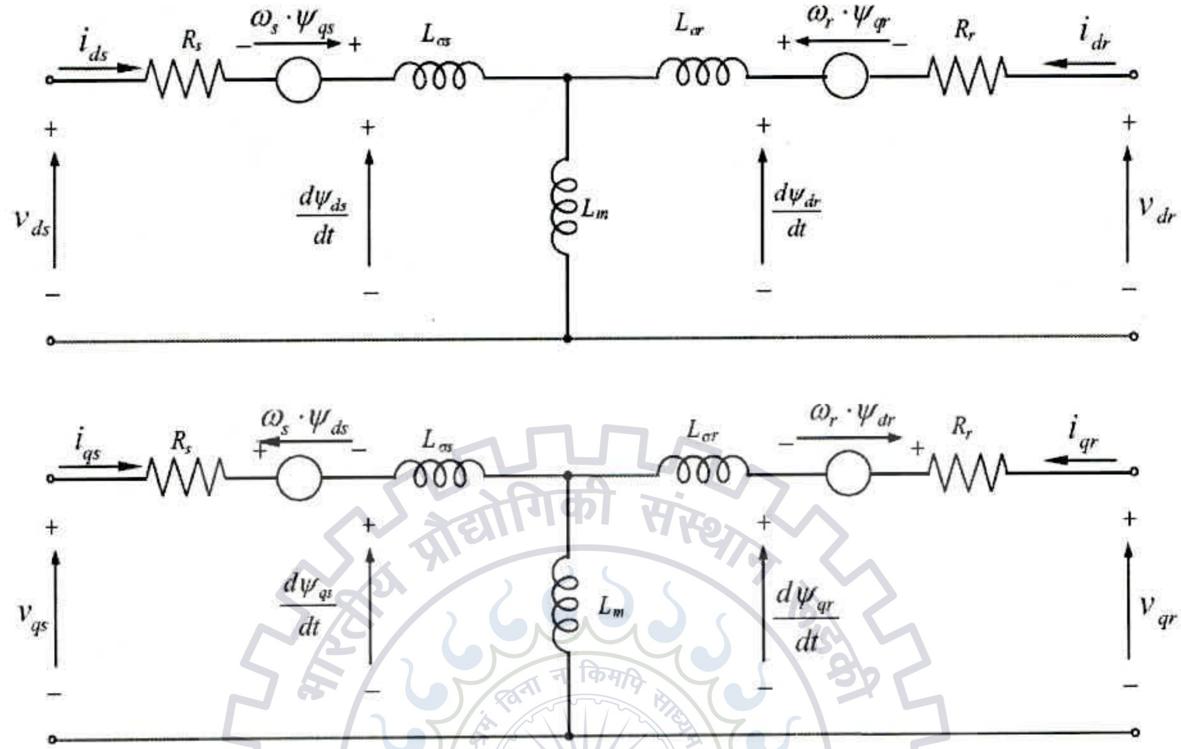

Figure 2.8 dq Model of the DFIM in synchronous coordinates

The torque and power expressions in the dq reference frame

$$P_s = \frac{3}{2}(v_{ds}i_{ds} + v_{qs}i_{qs}) \quad \text{.......................... (2.33)}$$

$$P_r = \frac{3}{2}(v_{dr}i_{dr} + v_{qr}i_{qr}) \quad \text{.......................... (2.34)}$$

$$Q_s = \frac{3}{2}(v_{qs}i_{ds} - v_{ds}i_{qs}) \quad \text{.......................... (2.35)}$$

$$Q_r = \frac{3}{2}(v_{qr}i_{dr} - v_{dr}i_{qr}) \quad \text{.......................... (2.36)}$$

The torque expression can be given as

$$T_{em} = \frac{3}{2}p\frac{L_m}{L_s}(\psi_{qs}i_{dr} - \psi_{ds}i_{qr}) \quad \text{......... .... (2.37)}$$

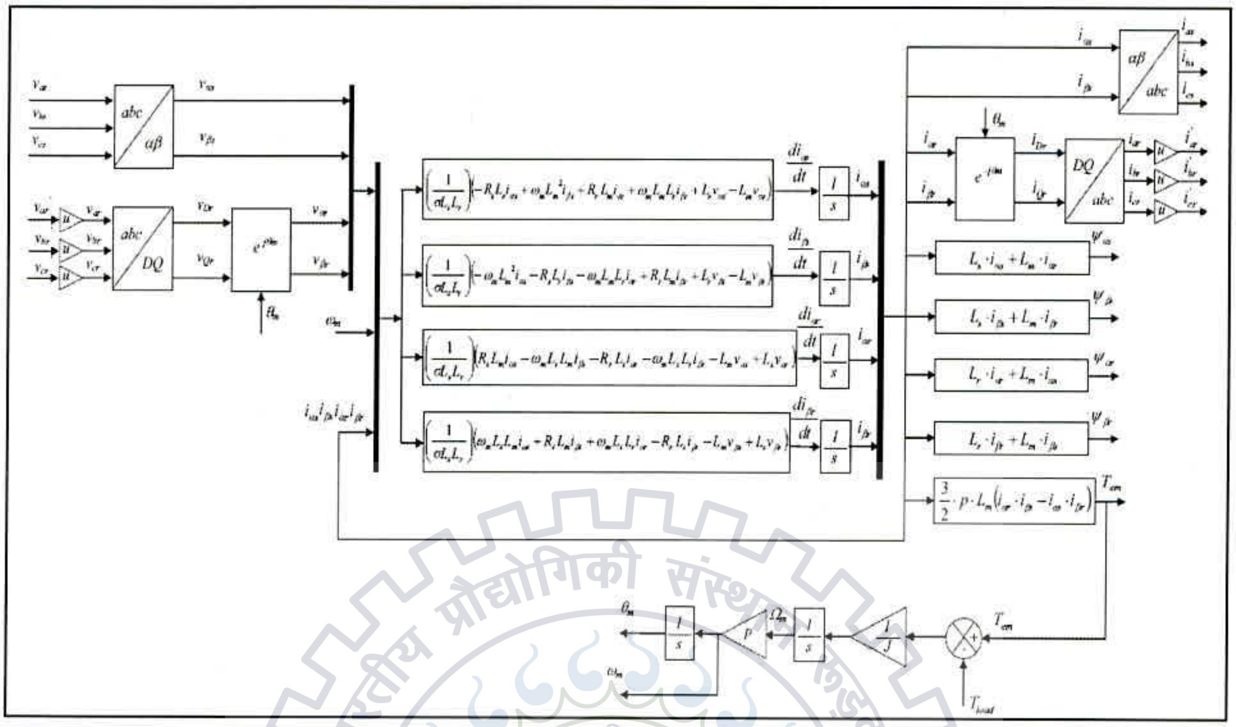

Fig.2.9 Simulation block diagram of the DFIM

2.9 SUMMERY

This chapter presents the general system of doubly fed machine and operation of DFIM drive. Basic concept of DFIM like torque and force, slip concept, relationship between active and reactive power and modes of operation of doubly fed machine has been discussed. In the next portion of this chapter the mathematical modeling, equivalent circuit and phasor diagram of DFIM has been discussed. Simulation block diagram has been discussed. The different control techniques for speed control for DFIM drive will explain in next chapter.

3.1INTRODUCTION

In this section different type of controller for speed control has been discussed. Doubly fed induction machine (DFIM) drives have been increasingly applied in wind power applications which require variable speed operation for generation of electricity. Now DFIM has applied for pumping operation where significantly head variation occur as hydroelectric potential depends upon the head of water. DFIM has been used for centrifugal load where load torque has cubic relationship with speed of the machine.

3.1.1 Graphical representation of various types of control techniques

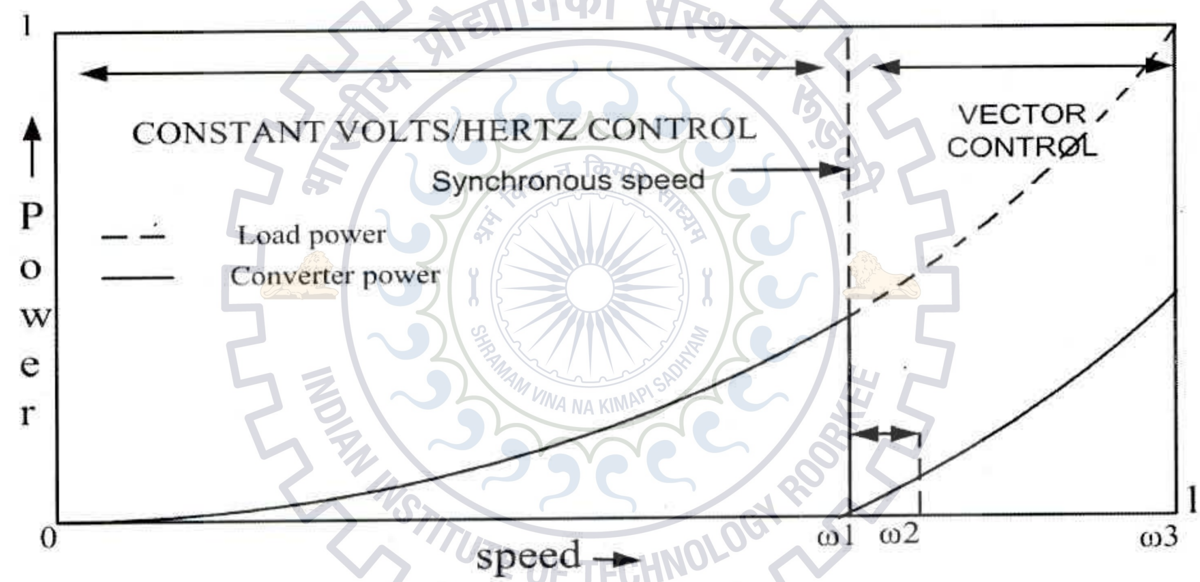

Fig.3.1 Graphical representation showing various types of control techniques

From the graph it is clear that for low speed region constant volts/hertz i.e scalar control used and for operation above synchronous speed vector control will use. Let discuss the various control techniques for speed control.

3.2 ROTOR RESISTANCE CONTROLLED DFIM DRIVE

A simple and primitive method of speed control of a wound rotor induction motor either doubly fed or single fed is mechanical variation of rotor resistance. In this with the help of rheostat vary the rotor resistance. Speed can vary significantly by variation of rotor resistance. As by adding of rotor resistance has the inherent disadvantage. Slip energy is wasted so this method is very inefficient. On the other hand by adding the rotor resistance maximum or breakdown torque remains constant, but the starting torque increases and stator current also reduced.

3.2.1 The systematic diagram is shown in fig.3.2.

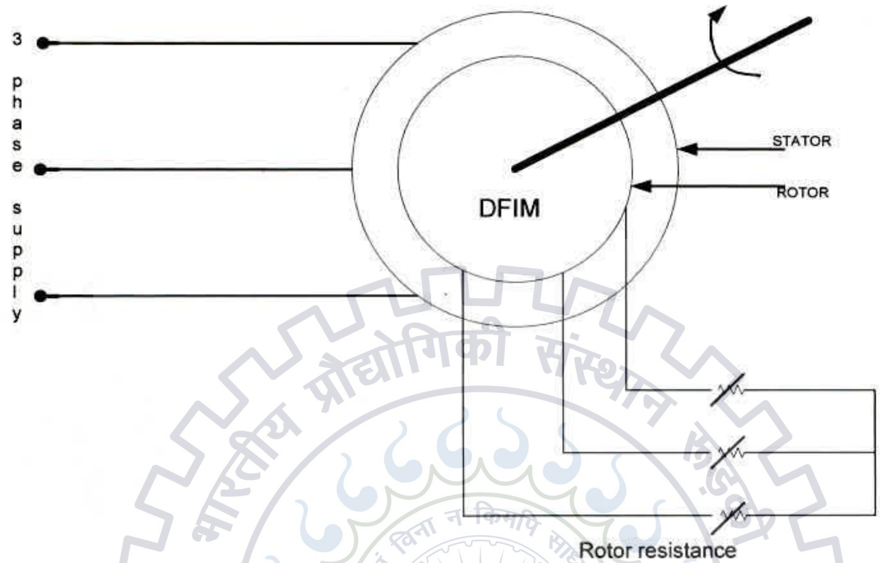

Fig.3.2 systematic diagram with rotor rheostat

These speed variations are shown by graph below for a given load torque.

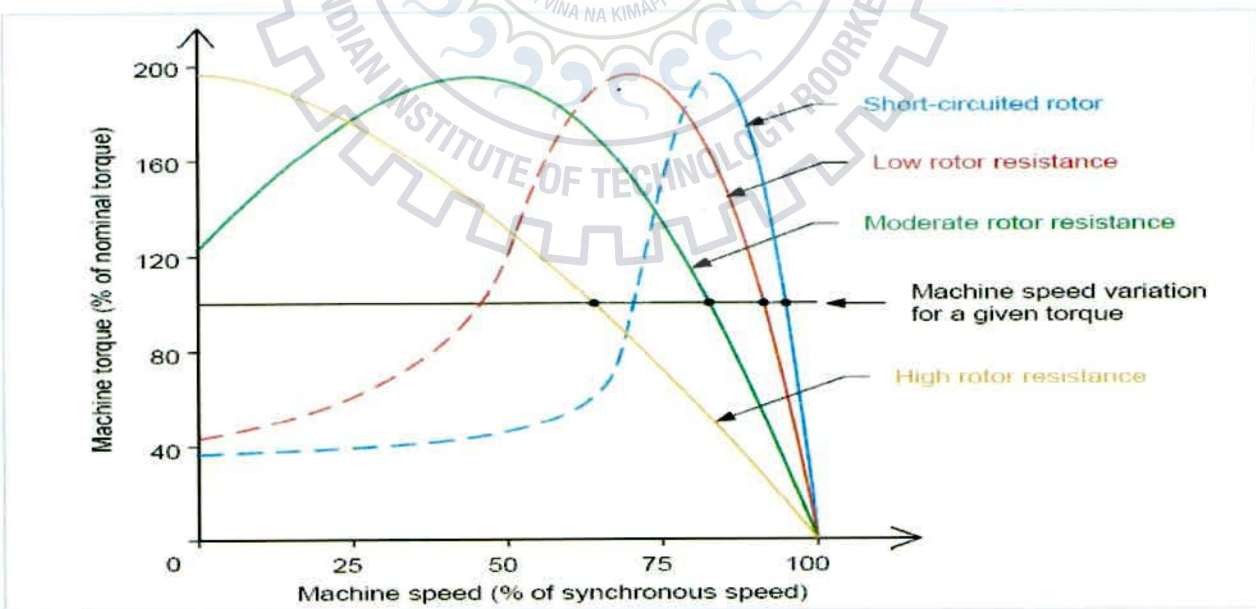

Fig.3.3 variation in speed with variation in rotor resistance for a given torque

Variation of stator current with variation in rotor resistance is shown in fig.3.4.

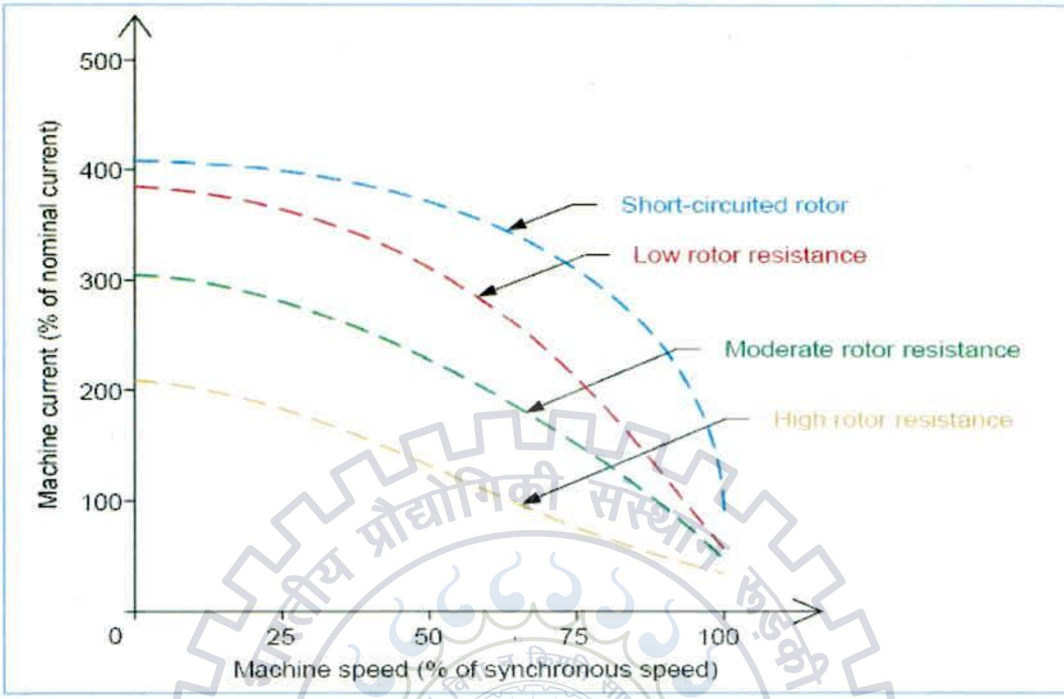

Fig.3.4 Variation of stator current with variation in rotor resistance

3.2.2 Advantages of rotor resistance speed control

- Absence of in-rush current at starting
- Availability of full rated torque at starting
- High line power factor
- Absence of line current harmonics. Smooth and wide range of speed control

3.2.3 Drawbacks of rotor resistance speed control

- Adding resistance to the machine rotor increases the machine copper losses
- It reduces the machine efficiency and mechanical power output in comparison with SCIM operating at the same speed.
- In addition, higher the rotor resistance the greater the variation in the rotation speed as the torque varies.
- This means that three-phase wound-rotor induction machines having a high rotor resistance are more susceptible to speed variations as the load torque changes.

3.2.4 ALTERNATIVE METHOD FOR ROTOR RESISTANCE CONTROL WITH CHOPPER AND RECTIFIER

The systematic diagram is shown in figure 3.5.

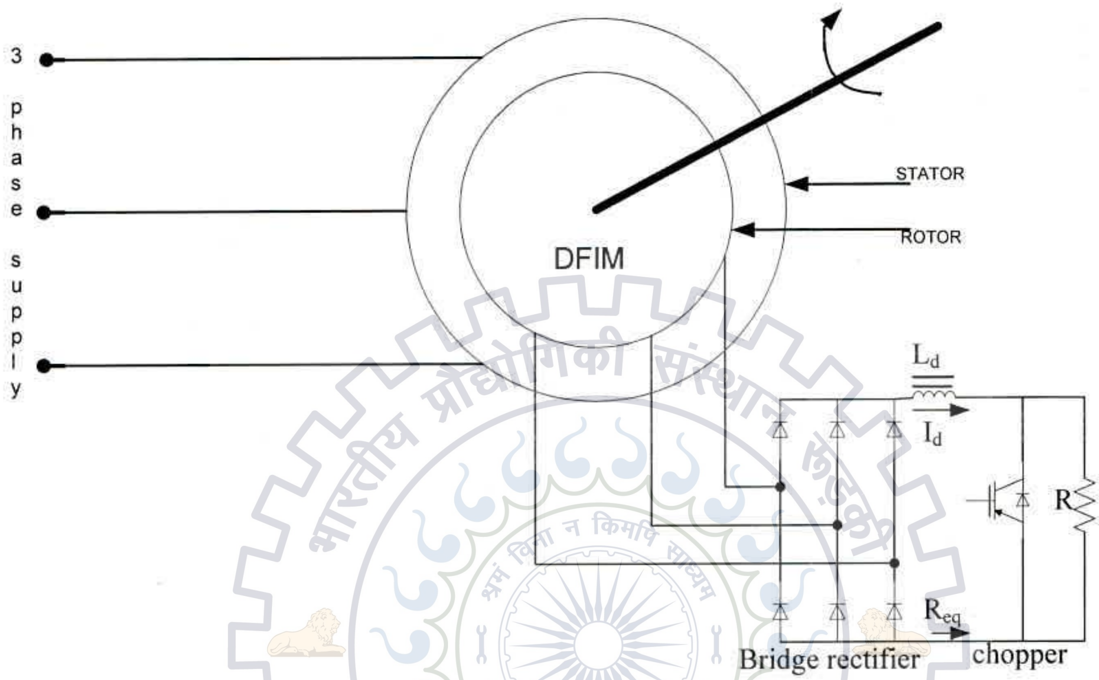

Fig.3.5 systematic diagram with rectifier and chopper

In this control scheme the rotor resistance can be varied by using a diode bridge rectifier and chopper. In this control scheme the slip voltage first rectified by rectifier and this dc voltage is converted to current by a large series inductor. Finally this current is fed to an IGBT shunt chopper with resistance as shown in the figure. The PWM technique is used for chopper with duty cycle$\delta = \frac{T_{on}}{T}$, T_{on}= on time and T= time period. When IGBT is off, the resistance directly connected to rotor and a current flow through it. When IGBT is on, this current bypass through it and resistance get short circuited.

The equivalent resistance offer by the duty cycle control of chopper is given as:

$$R_{eq} = (1 - \delta)R \quad \text{.......} (3.1)$$

So speed and developed torque can be controlled by variation in duty cycle of chopper. This speed control technique has been used for limited speed range and efficiency is not a problem.

3.3 VARIATION OF SPEED WITH VARIATION IN STATOR VOLTAGE AND STATOR FREQUENCY

In this section variation in stator voltage and stator frequency has been done. From this experiment it is observe that if we vary the stator voltage keeping frequency constant than there is no significant change in speed of machine. If we reduced the supply frequency keeping supply voltage constant, speed reduce but for enough change in supply frequency flux will increase and machine will go in saturation because voltage proportional to multiplication of frequency and flux. That's why this method is not suitable for use.

3.3.1 The circuit diagram as shown in fig.3.6.

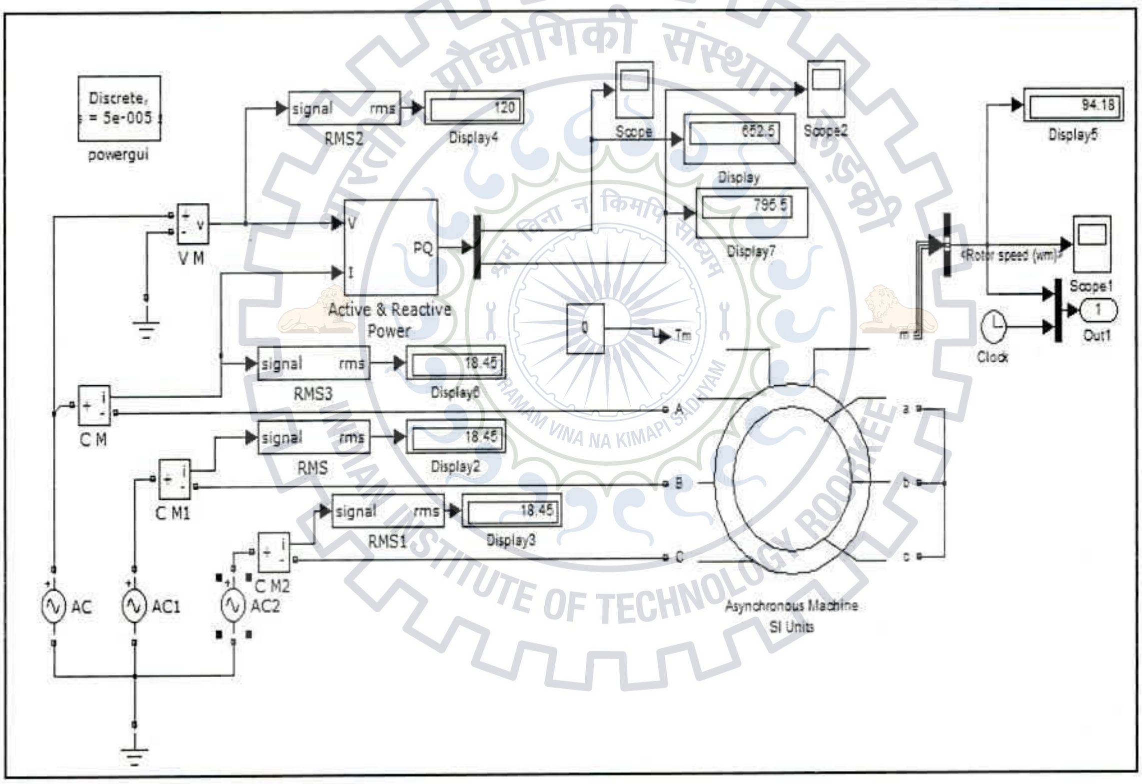

Fig.3.6 The circuit diagram for variation in stator voltage and frequency

3.4 VARIATION IN SPEED BY APPLIED VOLTAGE AND THE ROTOR CURRENT FREQUENCY

In this section vary the applied voltage and rotor current frequency has been done at matlab simulink and results are taken with the help of simulation.

3.4.1 Circuit diagram for this speed control is shown in fig.3.7.

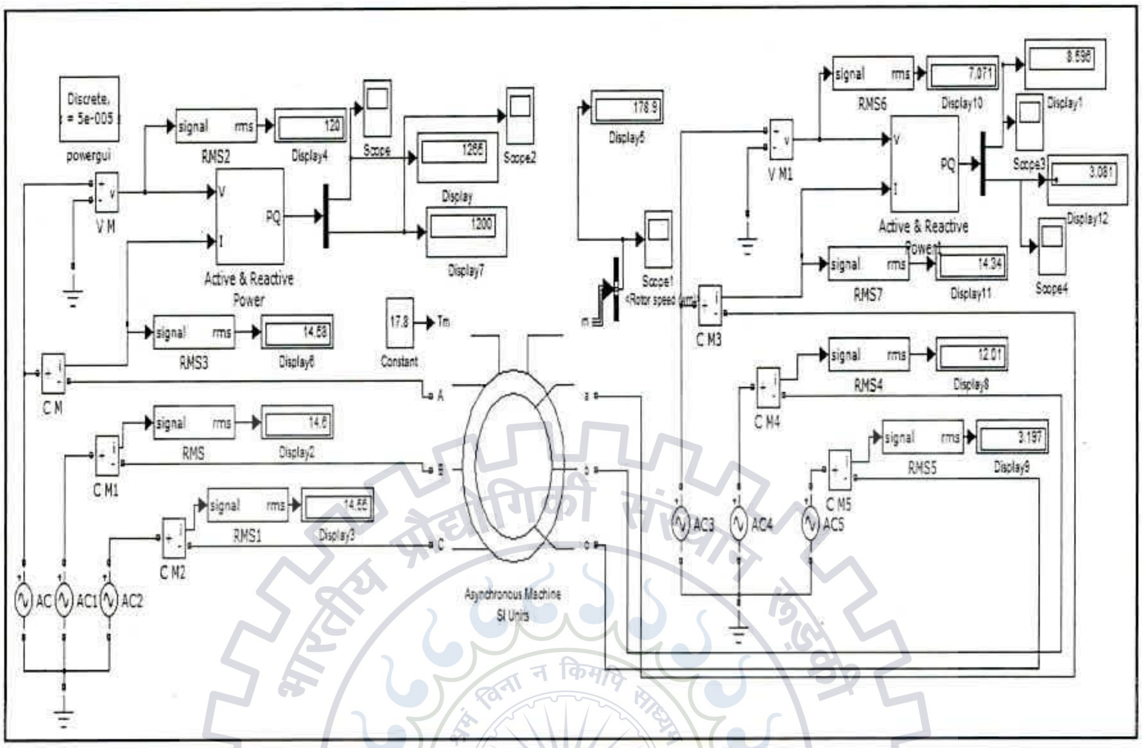

Fig.3.7 Circuit diagram for variation in applied voltage and rotor current frequency

When voltage is applied in phase opposition, and also making variation in rotor current frequency there are variations in speed and rotor current occur.

From the simulation results we can observe that by applied voltage with constant frequency speed is constant but stator current increase significantly. These due to that net flux increases by apply the voltage at rotor side.

Further if we change the applied rotor voltage frequency than there are corresponding change in speed and speed variation with torque variation also shown in the table.

3.5 CONSTANT V/F CONTROLLED DFIM DRIVE

As in doubly fed induction motor the speed control below the synchronous speed is done at rotor side with the help of constant volts/hertz control. In this basically rotor is excited by the rated voltage and rated frequency keeping stator short-circuited. By varying the voltage and frequency keeping v/f constant we get different speed.

3.5.1 The circuit diagram for v/f control is shown in fig.3.8.

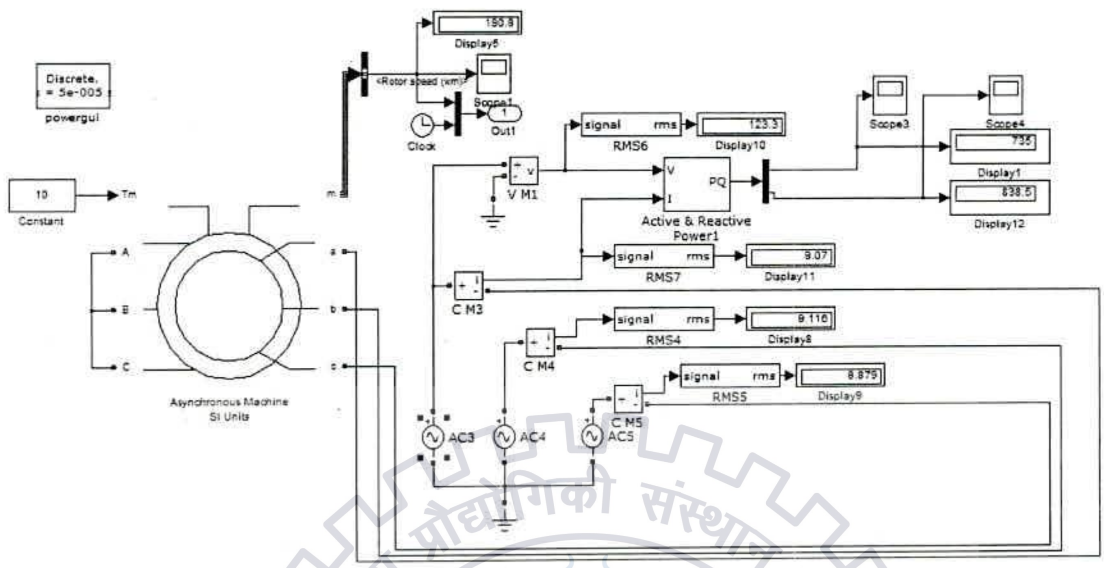

Fig.3.8 circuit diagram of constant v/f controlled DFIM drive

When we vary the voltage and frequency keeping v/f ratio constant then speed varies from rated to a very low speed. Also at low speed there is less active power requirement and corresponding saving in electricity.

3.6 INVERTER

Voltage Source Inverters are devices that convert a DC voltage to AC voltage of variable frequency and magnitude. They are very commonly used in adjustable speed drives and are characterized by a well defined switched voltage wave form in the terminals. Figure shows a voltage source inverter. The AC voltage frequency can be variable or constant depending on the application.

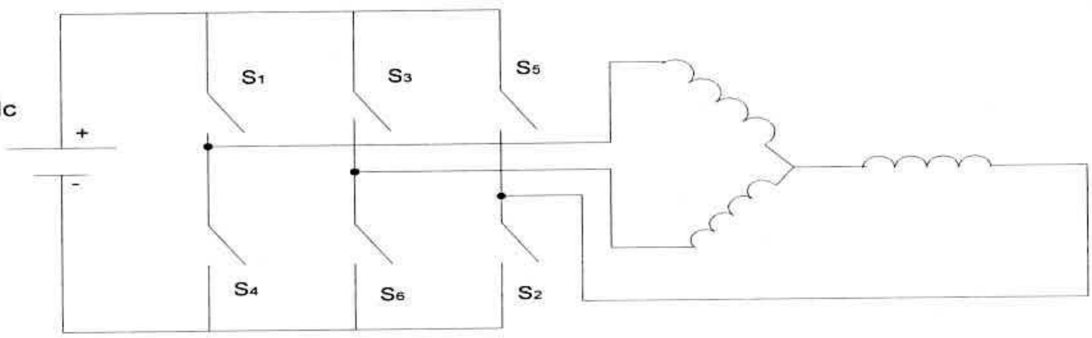

Figure 3.9 Voltage Source Inverter Connected to a Motor

Three phase inverters consist of six power switches connected as shown in figure to a DC voltage source. The inverter switches must be carefully selected based on the requirements of operation, ratings and the application. There are several devices available today and these are thyristors, bipolar junction transistors (BJTs), MOS field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs) and gate turn off thyristors (GTOs). The devices list with their respective power switching capabilities are shown in table 3.1 MOSFETs and IGBTs are preferred by industry because of the MOS gating permits high power gain and control advantages. While MOSFET is considered a universal power device for low power and low voltage applications, IGBT has wide acceptance for motor drives and other application in the low and medium power range.

Table 3.1 Power Devices and Switching Capabilities

Device	Power Capability	Switching Speed
BJT	Medium	Medium
GTO	High	Low
IGBT	Medium	Medium
MOSFET	Low	High
THYRISTOR	High	Low

3.7 ADVANTAGES OF SPEED CONTROL WITH THE HELP OF POWER ELECTRONIC CONVERTER

- High efficiency of operation also for partial load
- Can control and separate the active and reactive power as well electronically
- It is easy to control the power factor
- System response will be quicker
- Can reduce the number of starts

- Grid synchronization problem will be less
- The speed can be adjusted to the actual water need
- Improve the network stability by reactive power control
- For efficient use of electric energy
- Speed control is good (inherently there is speed variation)
- During braking can retransmit the power into supply
- Provide quiet, smooth operation and environmentally friendly

3.8 SUMMERY

Rotor resistance controlled DFIM drive has been discussed. The variation in rotor resistance with the help of rectifier and chopper has been discussed. Further advantage and disadvantage of RR controlled DFIM drive has been discussed. The variation in voltage and frequency at stator and rotor side has been discussed. From this discussion we got the general idea that speed is depend on the frequency of either side stator or rotor not on voltage. Finally constant volts/hertz controlled DFIM drive has been discussed. Advantage of speed control with the help of power electronics converter and scalar control has been discussed. The vector control of DFIM drive will discussed in the next chapter.

4.1 INTRODUCTION

With advancement in technology the electric motors application is increasing continuously. With the technological progress Doubly Fed Induction Machine (DFIM) with the help of converter are widely used with voltage-controlled voltage source inverters for industrial, traction, large capacity pumps, and wind energy systems, flywheel energy storage applications, because of their high power density, and smaller speed limitation, and high efficiency. Wide speed range can be achieved with appropriate reduction of rotation field. For high speed operation field oriented vector control scheme has been implemented.

4.2 DEVELOPMENT HISTORY

Technical University Darmstadt's K. Hasse and Siemens' F. Blaschke have developed the vector control of AC motors in 1968 and in the early 1970s, Hasse in terms of proposing indirect vector control, Blaschke in terms of proposing direct vector control. Technical University Braunschweig's Werner Leonhard further developed field oriented control (FOC) techniques and was instrumental in opening up opportunities for AC drives to be a competitive alternative to DC drives. Before describe the vector control technique first discuss about the reference frames.

4.3 THEORY OF REFERENCE FRAME

From the differential equations (voltage equations) of induction machine and synchronous machine that describe the behavior of these machines are time-varying except when the rotor is stalled. Also we have some of the machine inductances are functions of rotor speed. It is very common to use change in variables to reduce the complexity of these differential equation. It was originally thought that each change of variables was different and therefore they were treated separately. It was later learned that all change in variables used to transform real variables are contained in one. This general transformation refers machine variables to a frame of reference that rotates at an arbitrary angular velocity. All these transformations can obtain by simply assigning the speed of rotation of the reference frame.

4.3.1Commonly used reference frames

REFFERENCE FRAME SPEED	INTERPRETATION
ω (unspecified)	Stationary circuit variables referred to the arbitrary reference frame
0	Stationary circuit variables referred to the stationary reference frame
ω_r	Stationary circuit variables referred to a reference frame fixed in the rotor
ω_s	Stationary circuit variables referred to the synchronously rotating reference frame

4.3.2 Conversion a, b, c to d, q reference frame

The d q variable are obtained from a, b, c variable through park transformation as defined below

$$f_{qd0s}=K_s f_{abcs} \quad \text{.......... (4.1)}$$

Where

$$(f_{qd0s})^T = [f_{qs}\ f_{ds}\ f_{0s}] \quad \text{.......... (4.2)}$$

$$K_s=\frac{2}{3}\begin{bmatrix} cos(\theta) & cos(\theta-\frac{2\pi}{3}) & cos(\theta+\frac{2\pi}{3}) \\ sin(\theta) & sin(\theta-\frac{2\pi}{3}) & sin(\theta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad \text{......... (4.3)}$$

For inverse transformation we can write

$$(K_s)^{-1}=\frac{2}{3}\begin{bmatrix} cos(\theta) & \sin(\theta) & \frac{1}{2} \\ cos(\theta-\frac{2\pi}{3}) & sin(\theta-\frac{2\pi}{3}) & \frac{1}{2} \\ cos(\theta+\frac{2\pi}{3}) & sin(\theta+\frac{2\pi}{3}) & \frac{1}{2} \end{bmatrix} \quad \text{................ (4.4)}$$

In the above equation f can be represents voltage, current flux linkage or electric charge. The subscript T denotes the transpose of matrix. The's' subscript indicates the variables, parameters and transformation associated with stationary circuits.

The total instantaneous power to the machine in terms of the a, b, c variable may be expressed as

$$P_{abcs} = v_{as}i_{as} + v_{bs}i_{bs} + v_{cs}i_{cs} \quad (4.5)$$

It can be written in q d variable for 3-Φ balance system such as

$$P_{qds} = \frac{3}{2}(v_{qs}i_{qs} + v_{ds}i_{ds}) \quad (4.6)$$

4.3.3 Conversion of a, b, c to αβ

It can be obtained by the following equations given bellow.

$$i_\alpha = \sqrt{\frac{2}{3}}(i_a - \frac{1}{2}i_b - \frac{1}{2}i_c) \quad (4.7)$$

$$i_\beta = \sqrt{\frac{2}{3}}(0 + \frac{\sqrt{3}}{2}i_b - \frac{\sqrt{3}}{2}i_c) \quad (4.8)$$

4.4 VECTOR CONTROLLED MODEL FOR DFIM

Vector control, also called field-oriented control (FOC) as name implies it deal with flux vector i.e magnitude as well as angle. The speed regulation of the DFIM in the setting-speed region i.e above synchronous speed will be done by the stator-field-oriented vector control scheme, where the reference frame rotates synchronously with respect to the stator flux, with the *d*-axis aligned to the stator flux position as shown in fig.4.1.

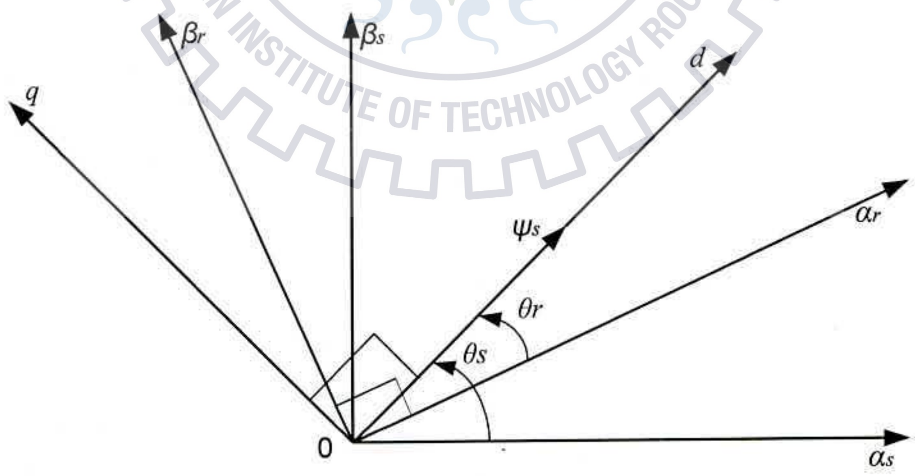

Fig.4.1 reference frame with stator flux orientation

Where α_s, β_s, α_r and β_r are the α- and β-axes of the stator and rotor stationary coordinates, respectively. θ_s and θ_r are the stator flux angle and the rotor position angle. In this control scheme all the variables are transformed to the stator side.

From fig.4.1, we have a decoupled control between the excitation current and electromagnetic torque. We also have stator and rotor fluxes as given below.

$$\varphi_{sd} = L_s i_{sd} + L_m i_{rd} = L_m i_{ms} = \varphi_s \quad \text{.......................... (4.9)}$$

$$\varphi_{sq} = L_s i_{sq} + L_m i_{rq} = 0 \quad \text{.................................... (4.10)}$$

$$\varphi_{sd} = \frac{L_m^2}{L_s} i_{sd} + \sigma L_r i_{rd} \quad \text{.. (4.11)}$$

$$\varphi_{rq} = \sigma L_r i_{rd} \quad \text{.. (4.12)}$$

Where φ_{sd}, φ_{sq}, φ_{rd} and φ_{rq} are the stator and rotor fluxes along the d- and q-axes respectively, and i_{sd}, i_{sq}, i_{rd} and i_{rq} are the stator and rotor currents along the d- and q-axes respectively. L_s and L_r are the stator and rotor self-inductances, and L_m is the mutual inductance; i_{ms} is the magnetizing current. σ is the leakage factor, and $\sigma = (1 - \frac{L_m^2}{L_s L_r})$.

The stator and rotor side voltage equations in the $d-q$ frame can be given as

$$u_{sd} = R_s i_{sd} + p\varphi_{sd} \quad \text{.. (4.13)}$$

$$u_{sq} = R_s i_{sq} + \omega_s \varphi_{sd} \quad \text{.. (4.14)}$$

$$u_{rd} = R_r i_{rd} + p\varphi_{rd} - \omega_{sl} \varphi_{rq} \quad \text{.............................. (4.15)}$$

$$u_{rq} = R_r i_{rq} + p\varphi_{rq} + \omega_{sl} \varphi_{rd} \quad \text{.............................. (4.16)}$$

Where u_{sd}, u_{sq}, u_{rd}, and u_{rq} are the d- and q-axis rotor voltages respectively, ω_s is the grid angular frequency, and ω_{sl} is the slip angular frequency. R_s and R_r are the stator and rotor resistances respectively.

The electromagnetic torque Te can be given as

$$T_e = -\frac{3}{2} p_n \frac{L_m^2}{L_s} i_{ms} i_{rq} \quad \text{.. (4.17)}$$

Where p_n is the number of pole pairs.

From the torque expression, if we controlled the magnetizing current i_{ms} constant, T_e can be controlled by the q-axis rotor currenti_{rq}. The cross-coupling term between the d- and q-axes we can get easily from the voltage equation expressed as:

$$u_{rdc} = -\omega_{sl}\sigma L_r i_{rq} \quad \ldots\ldots (4.18)$$

$$u_{rqc} = -\omega_{sl}\frac{L_m^2}{L_s} i_{ms} + \omega_{sl}\sigma i_{rd} \quad \ldots\ldots (4.19)$$

4.5 BLOCK DIAGRAM OF VECTOR CONTROLLED DFIM DRIVE

The block diagram of vector controlled DFIM drive has been given in fig.4.2.

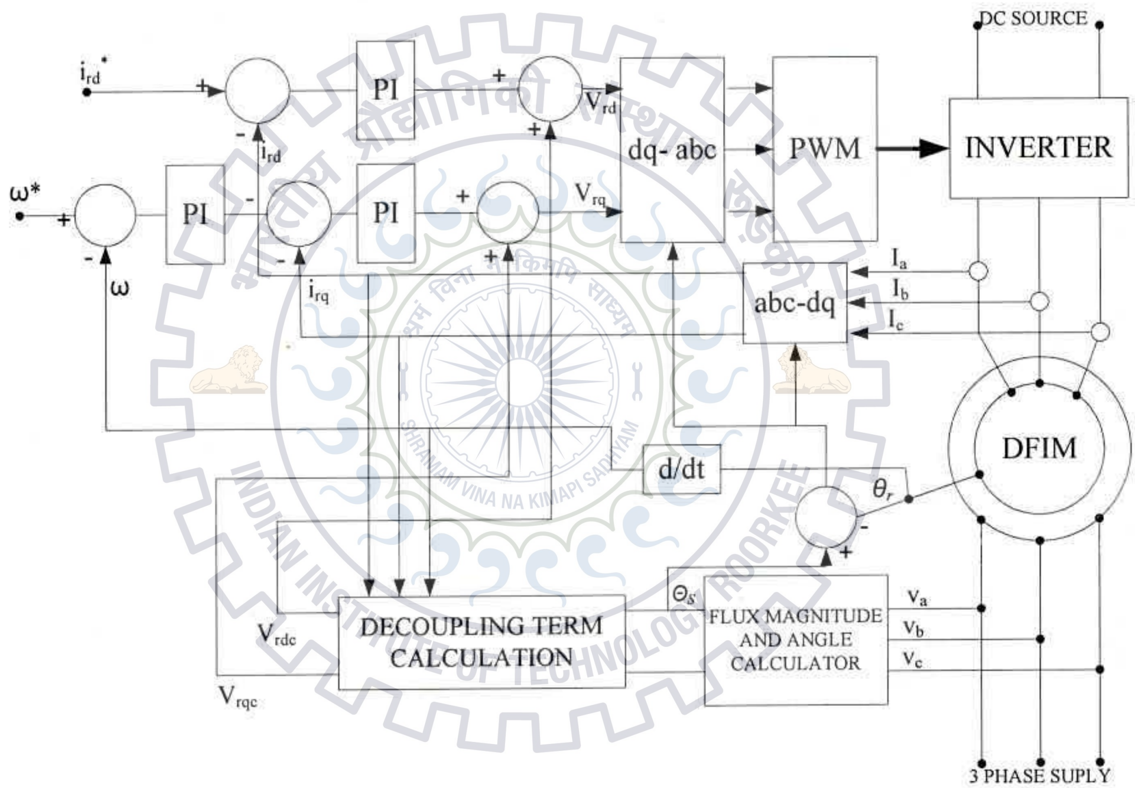

Fig.4.2 block diagram of vector controlled DFIM drive

From the block diagram it is clear that in vector control we are considering the flux vector i.e magnitude as well as flux angle. In this control scheme we are also taking the stator voltage and rotor current. With the help of stator voltage we are calculating the flux and rotor current has been used for comparison to reference current signal. This error has been given to the PI controller and it generated the voltage signal. Further for sppe control loop the PI controller generate the voltage signal. Finally by transformation the signal has given to PWM and it generated the pulses for inverter.

The simulation carried out with the following motor data.

Table 4.2 Specification of simulated Motor

Nominal power, voltage(line-line), frequency	3*746, 415, 50
Stator resistance and inductance	4.42, 0.0257
Rotor resistance and inductance	3.467, 0.12934
Mutual inductance	0.29750
Friction factor and pole pairs	0.002985, 2

4.6 CURRENT LOOP DIAGRAM

For current loop a proportional–integral (PI)-type controller has been used. The schematic diagram of PI controller is shown in fig.4.3.

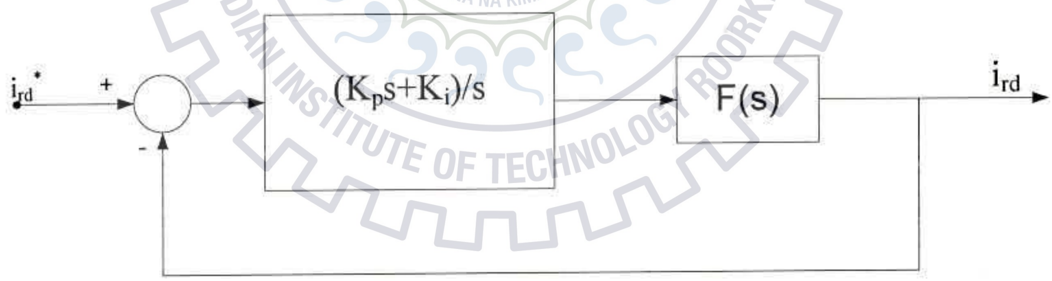

Fig.4.3 Diagram for current control loop

4.6.1PI CONTROLLER DESIGN

We can select the parameter of PI controller given by the relations as $K_p = \sigma L_r \omega_c$ and $K_i = R_r \omega_c$ where ω_c is current loop bandwidth. It can be shown easily that the parameter of PI controller depends on several parameters like bandwidth, rotor inductance, and rotor resistance and controlled constant.

4.7 SPEED LOOP DIAGRAM

For the speed loop design, if it is assumed that the current loop is ideal, which means that it is designed much faster than the speed loop (higher bandwidth). The schematic diagram for speed loop is given in fig.4.4.

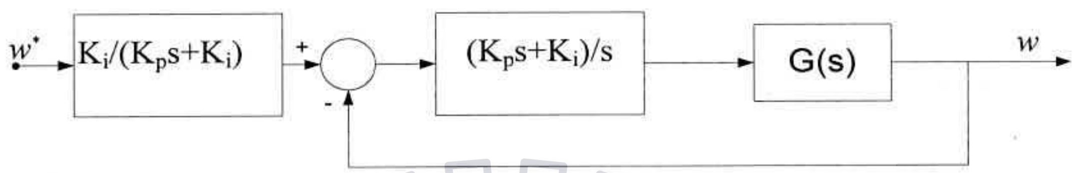

Fig.4.4 Diagram for speed control loop

4.7.1 PI CONTROLLER DESIGN

We can select the PI parameters for the speed loop controller by the help of equation 4.20.

$$K_p = 2\xi\,\omega_T\left(\frac{2J_m}{K_T p_n}\right) \text{ and } K_i = \omega_T^2\left(\frac{2J_m}{K_T p_n}\right) \qquad (4.20)$$

Where $K_T=\left(-\frac{3}{2}\right)\left(\frac{L_m^2}{L_s i_{ms}}\right)$, and J_m is the system inertia, ω_T is desired speed loop bandwidth, ξ is the damping factor. From the above relationships we can easily choose the parameter of PI for speed loop diagram by selecting the desired bandwidth.

4.8 SINUSOIDAL PULSE WIDTH MODULATION (SPWM)

Circuit diagram is shown in fig. 4.5.

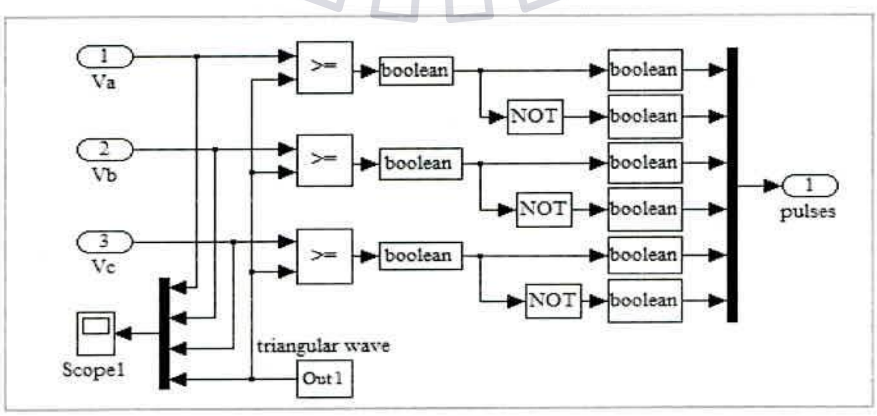

Fig.4.5 circuit diagram of sinusoidal pulse width modulation

In this SPWM firstly comparison between sinusoidal voltage and triangular wave has been done with the help of comparator. With the help of digital logic the corresponding switches on/off and finally we get the pulses to control the inverter.

4.9 CALCULATION OF GRID ANGLE

By neglecting the voltage drop on the stator resistance, the stator voltage will be same as grid voltage and in this case it will be along the q-axis, so u_{sd}=0. The stator flux vector along the d-axis is orthogonal to the stator voltage vector (the stator voltage vector is along the q-axis). So, stator flux angle θ_s is lagging the grid angle θ_n by 90° and calculated as

$$\theta_s = \theta_n - \frac{\pi}{2} \qquad (4.21)$$

The grid angle can be calculated by direct calculation or through a phase-locked loop (PLL). From the direct calculation method we can calculate the grid angle as given below.

$$\theta_s = \tan^{-1}\frac{u_{n\beta}}{u_{n\alpha}} - \frac{\pi}{2} \qquad (4.22)$$

Where $u_{n\alpha}$ and $u_{n\beta}$ are the grid voltages in the $\alpha\beta$coordinate.

4.10 SELECTION OF ANGLE FOR COORDINATE TRANSFORMATION

The whole vector control diagram is shown in Fig.4.2, where the inner loop is the current control loop and outer loop is the speed control the loop. For the coordinate transformation the angle difference between stator flux angle and rotor position $(\theta_s - \theta_r)$ has been used.

4.11 SELECTION OF REFERENCE VALUE OF ROTOR CURRENT

The stator voltage amplitude is determined by the magnetizing current. It is assume that all the magnetizing current is provided from the rotor side, then $i_{rd} = i_{ms}$ and the reference value of i_{rd} calculated as

$$i_{rd}^* = i_{ms} = \frac{\varphi_s}{L_m} = \frac{\varphi_{sd}}{L_m} = \frac{u_{sq}}{\omega_s L_m} = \frac{u_s}{\omega_s L_m} = \frac{u_n}{\omega_s L_m} \qquad (4.23)$$

4.12 FLOW CHART SHOWING DIFFERENT CONTROL TECHNIQUE

To explain flow chart refers fig.1 firstly disconnect the DFIM stator from the grid and by shorted the terminals of stator as switch KM2 closed and switch KM1 open the motor start and accelerate with help of constant volts/hertz control. For speed slightly greater than the synchronous speed with the switch KM2 open and KM1 closed vector control scheme has been implemented.

The flow chart for different control technique used has been shown in fig.4.6.

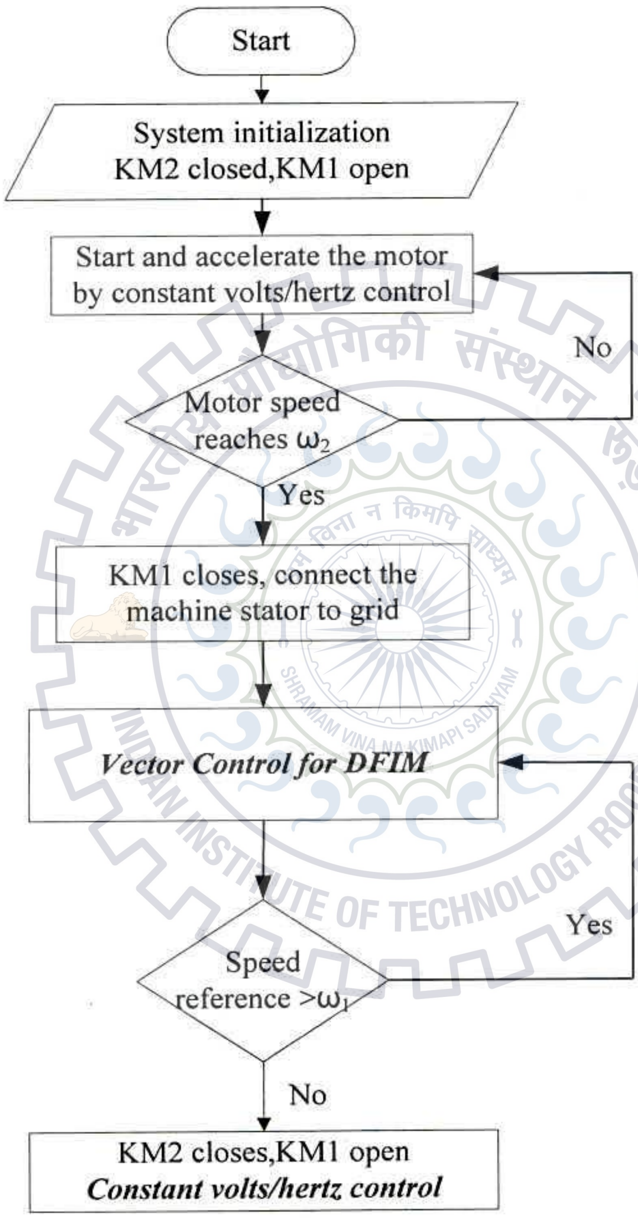

Fig.4.6 flow chart for different control technique used

When speed will go less than synchronous speed the whole procedure again implemented. So in this manner the complete speed control has been achieved.

4.13 SUMMERY

In this chapter firstly discussed about the application of DFIM and need of vector control scheme. Development history of vector control and theory of reference frame has been discussed. Finally the complete vector control scheme has been discussed. The complete block diagram of vector controlled DFIM drive has been discussed. Further for current and speed loop the selection of PI parameter has been discussed. Selection of grid angle, flux angle, and selection of angle for coordinate transformation has been discussed. Finally the complete flow chart showing the sequence of control techniques has been discussed. The simulation result of the DFIM Drive with different speed range operation will discuss in next chapter.

5.1 INTRODUCTION

In this section of the thesis includes the performance analysis of doubly fed induction motor drive for wide speed range application. Simulation results have been taken in operation below the synchronous speed and above the synchronous speed up to certain level. Up to rated speed of motor start and control with constant volts/hertz control and above rated speed vector control scheme take over the system. First of all simulation results of scalar control has been studied. Finally simulation results of vector control scheme have been studied. Vector control is only applicable for operation in setting speed region.

5.2 DOUBLY FED MACHINE SPEED CONTROL BY ROTOR RHEOSTAT

The Matlab simulink model of rotor rheostat controlled DFIM drive is shown in the fig 5.1.

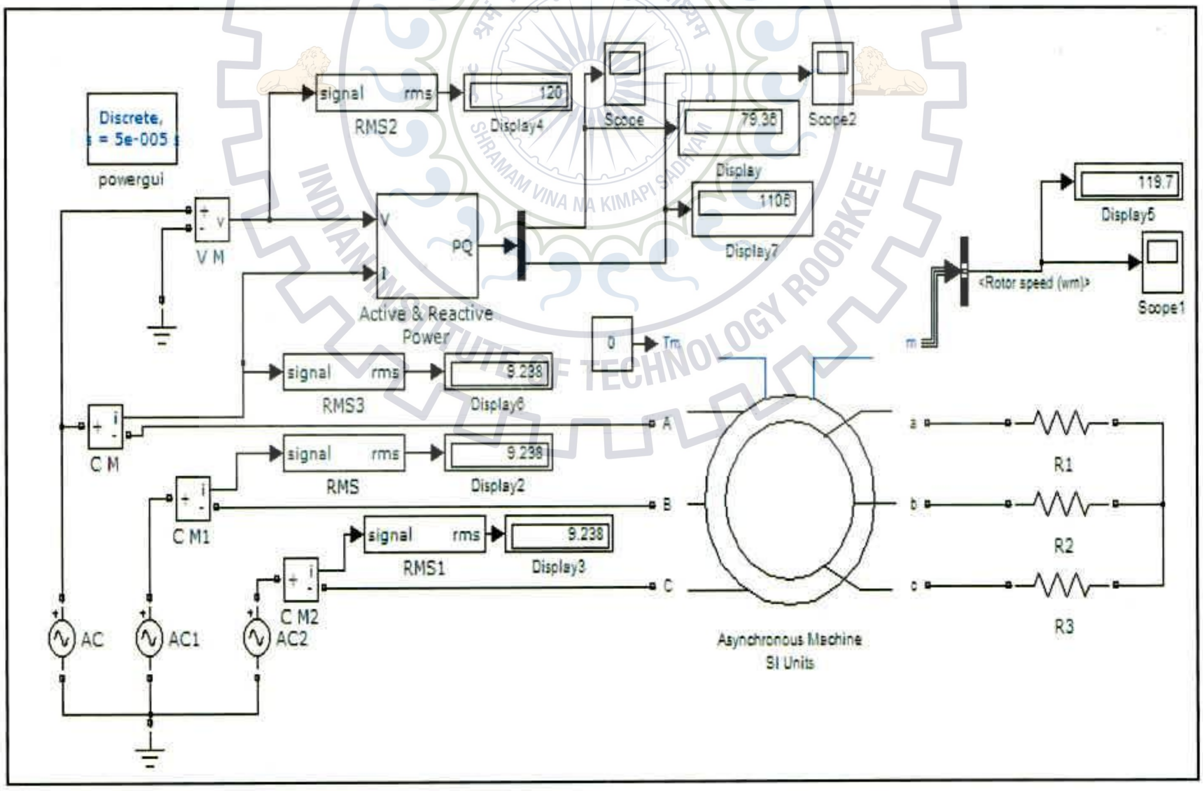

Fig 5.1: Matlab simulink model of RR controlled DFIM drive

The simulation carried out with the following motor data.

Table 5.1 Specification of simulated Motor

Nominal power, voltage(line-line), frequency	3730, 208, 60
Stator resistance and inductance	0.402, 0.00193
Rotor resistance and inductance	0.512, 0.00193
Mutual inductance	0.0325
Inertia, friction factor and pole pairs	0.089, 0.005752, 2

The simulation result for rotor resistance control by adding the rotor resistance by rheostat from rated speed to a very low speed has been shown in fig. given below:

5.2.1. The simulation result for rotor resistance controlled DFIM drive with $R_{add} = 100\ ohm$ has been shown in the fig 5.2

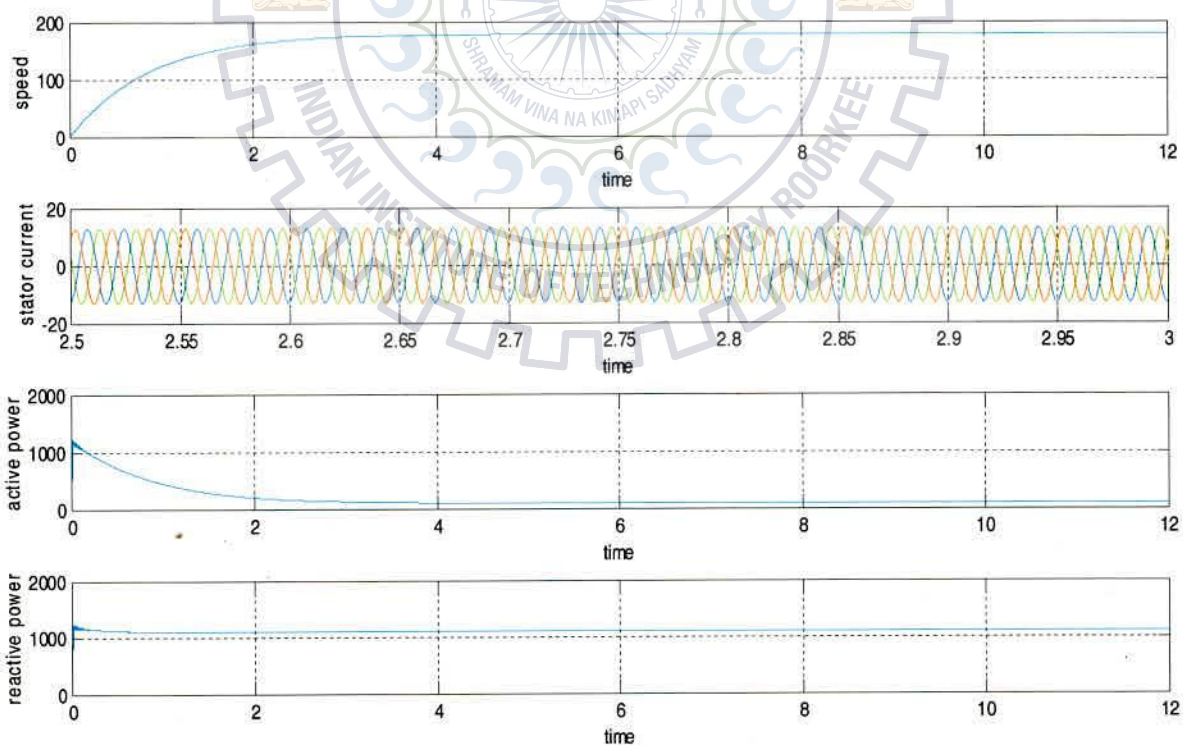

Fig 5.2: Simulation result of RR controlled DFIM drive for $R_{add} = 10\ ohm$

The simulation result for rotor resistance controlled DFIM drive with $R_{add} = 50\ ohm$ has been shown in the fig 5.3

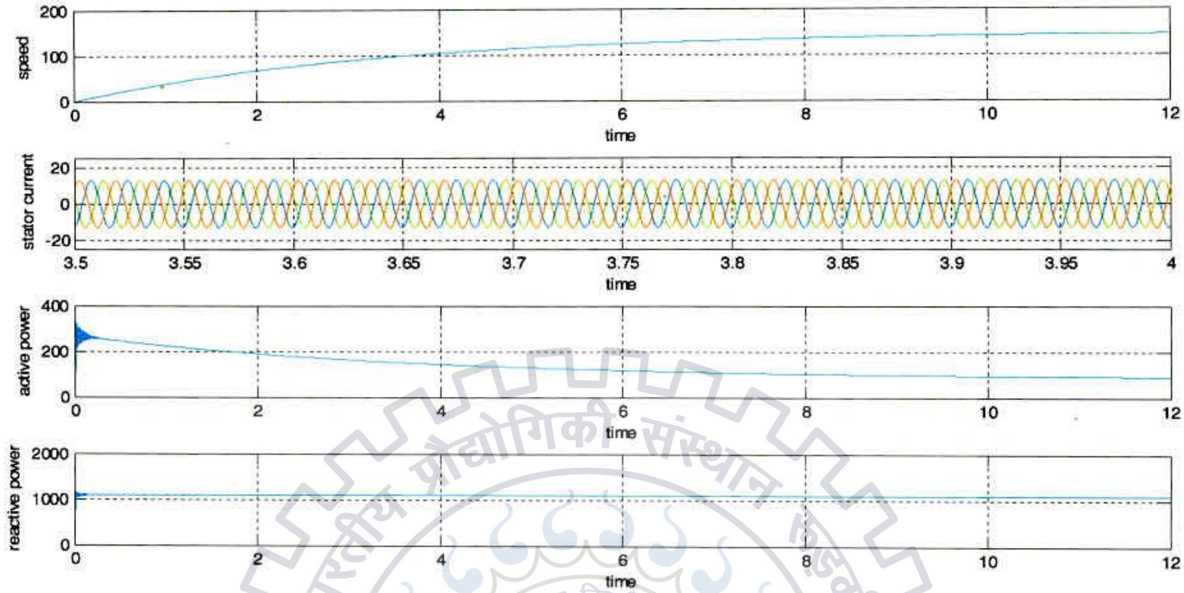

Fig 5.3 Simulation result of RR controlled DFIM drive for $R_{add} = 50\ ohm.$

The simulation result for rotor resistance controlled DFIM drive with $R_{add} = 100\ ohm$ has been shown in the fig 5.4

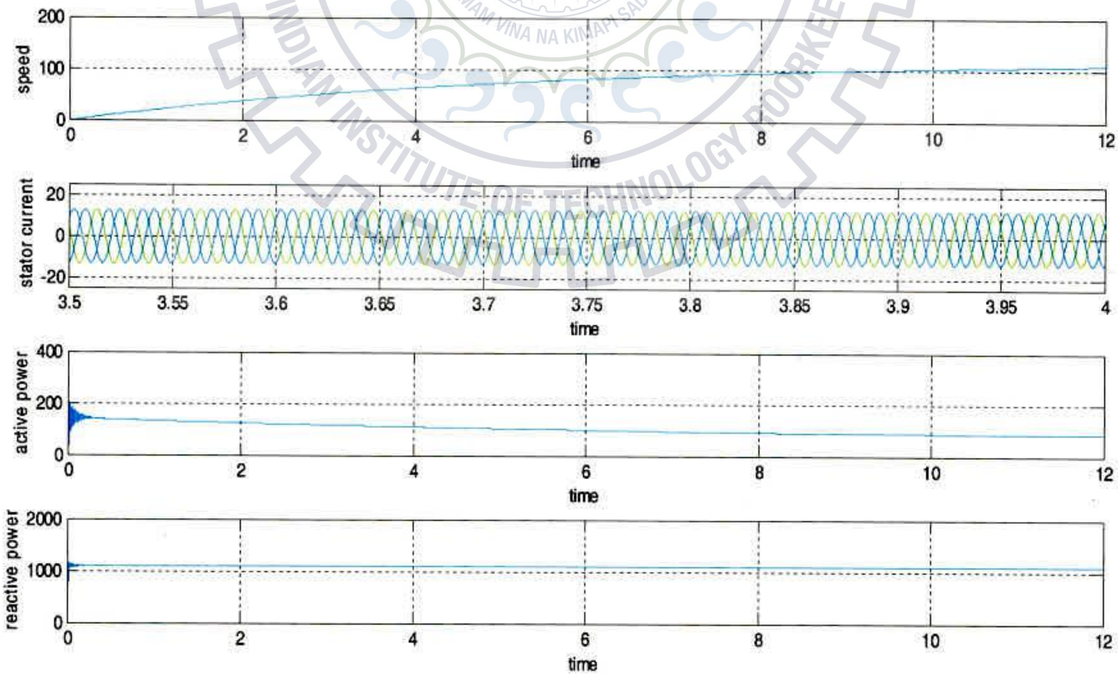

Fig 5.4: Simulation result of RR controlled DFIM drive for $R_{add} = 100\ ohm$

From the above simulation results we can observe that by inserting the resistance in rotor circuit the speed has been used significantly and also the stator current has been reduced.

We can also observe that by added the resistance in rotor circuit the active and reactive power requirement is increasing, so in this control technique there is loss of electrical power. As discuss in chapter (3) there is another method of vary the stator resistance with the help of rectifier and chopper which can be used for control the speed of DFIM derive.

5.3 VARIATION OF SPEED WITH VARIATION IN STATOR VOLTAGE AND STATOR FREQUENCY

5.3.1 The simulation result with variation in stator voltage and stator frequency for DFIM drive has been shown in the fig 5.5.

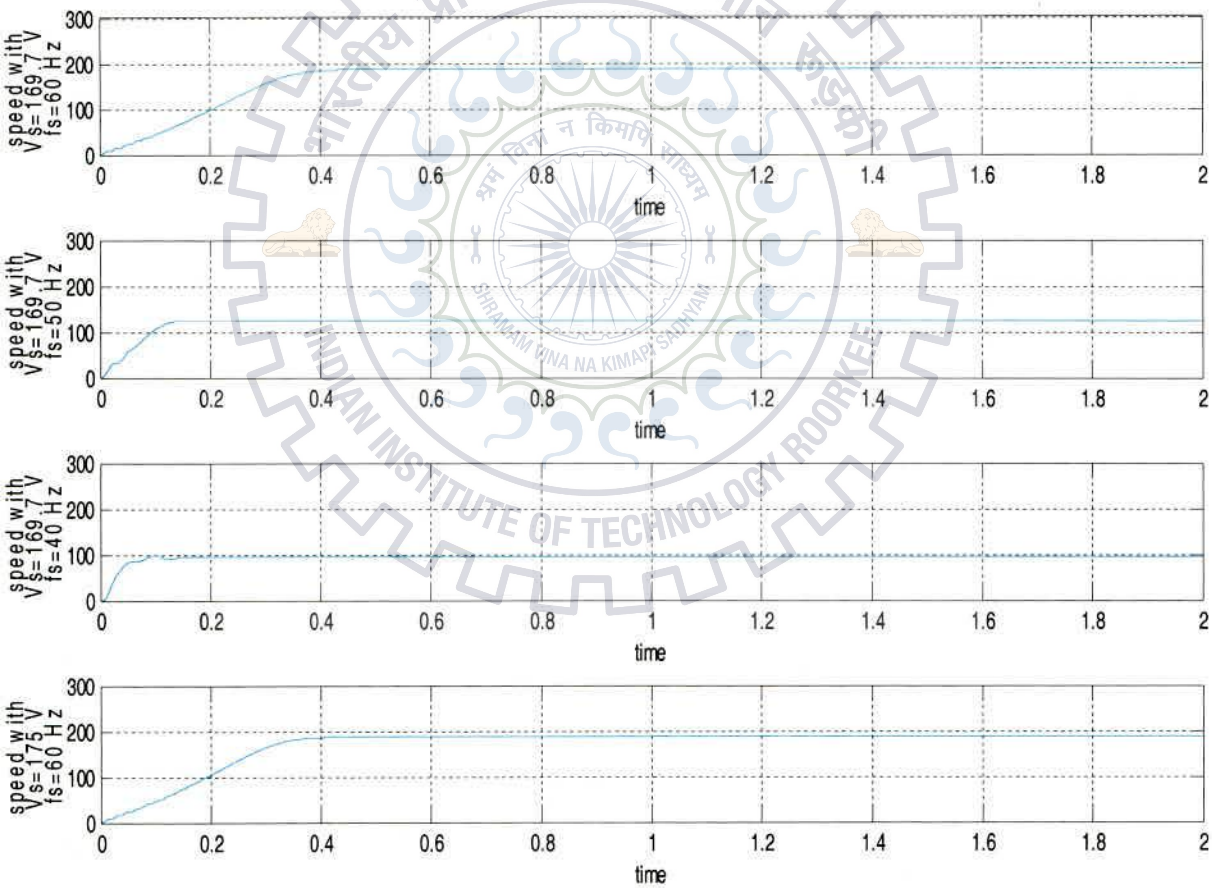

Fig 5.5: Simulation result for DFIM drive with variation in stator voltage and frequency

From the above simulation result we can observe that if we vary the stator frequency keeping stator voltage constant, there is significant change in speed of machine as by reducing the supply frequency speed is reducing. On the other hand if we increase the supply voltage keeping stator frequency constant, there is no significant change in speed. When we reduce the speed with enough change in supply frequency flux try to saturate because voltage proportional to multiplication of frequency and flux. So this control technique is not suitable for use.

5.4 VARIATION IN SPEED BY ROTOR VOLTAGE AND CHANGING THE ROTOR FREQUENCY

When voltage is applied in phase or in phase opposition, and also making variation in rotor current frequency there are variations in speed and rotor current occur.

5.4.1 The simulation result with variation in rotor voltage $V_r = 10$ V and rotor frequency $f_r = 5$ hertz for DFIM drive has been shown in the fig 5.6.

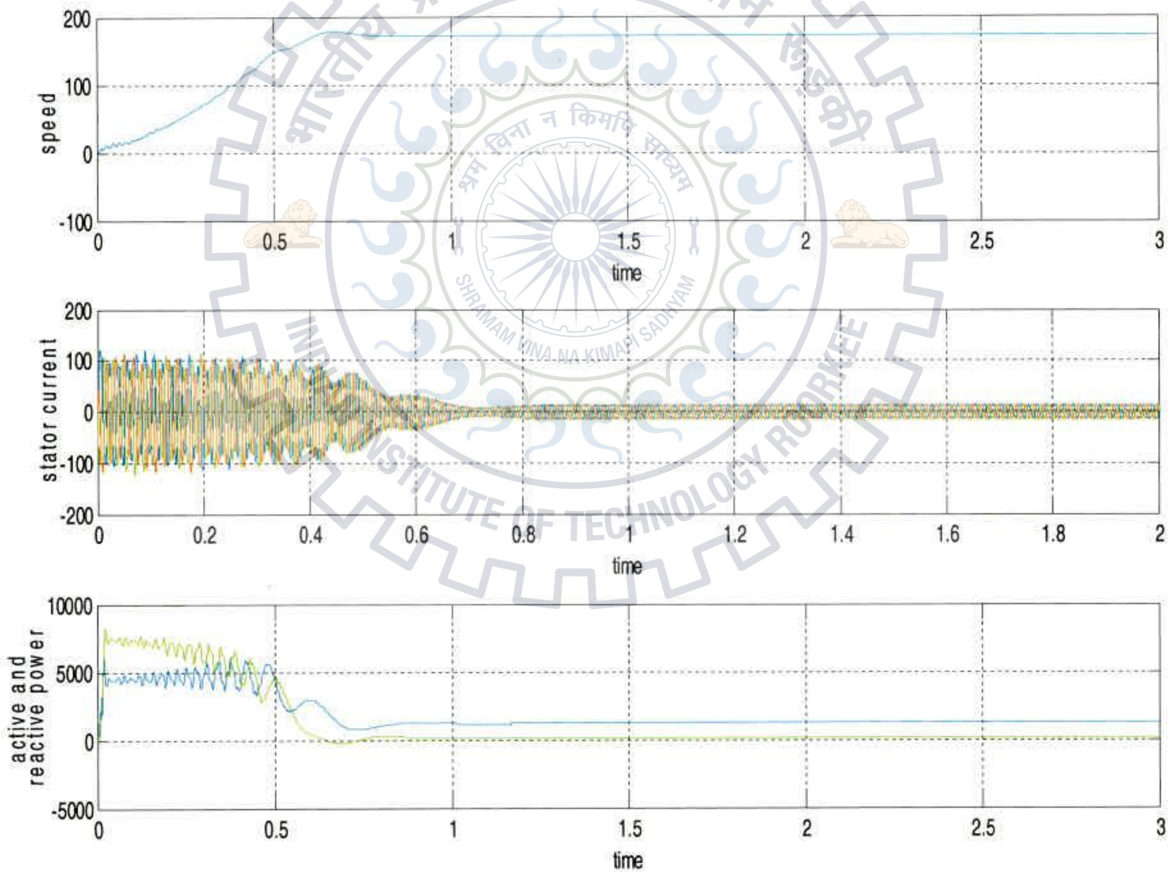

Fig.5.6 simulation result with rotor voltage $V_r = 10$ V and $f_r = 5$ hertz for DFIM drive

The simulation result with variation in rotor voltage $V_r = 20$ V and rotor frequency $f_r = 5$ hertz for DFIM drive has been shown in the fig 5.7.

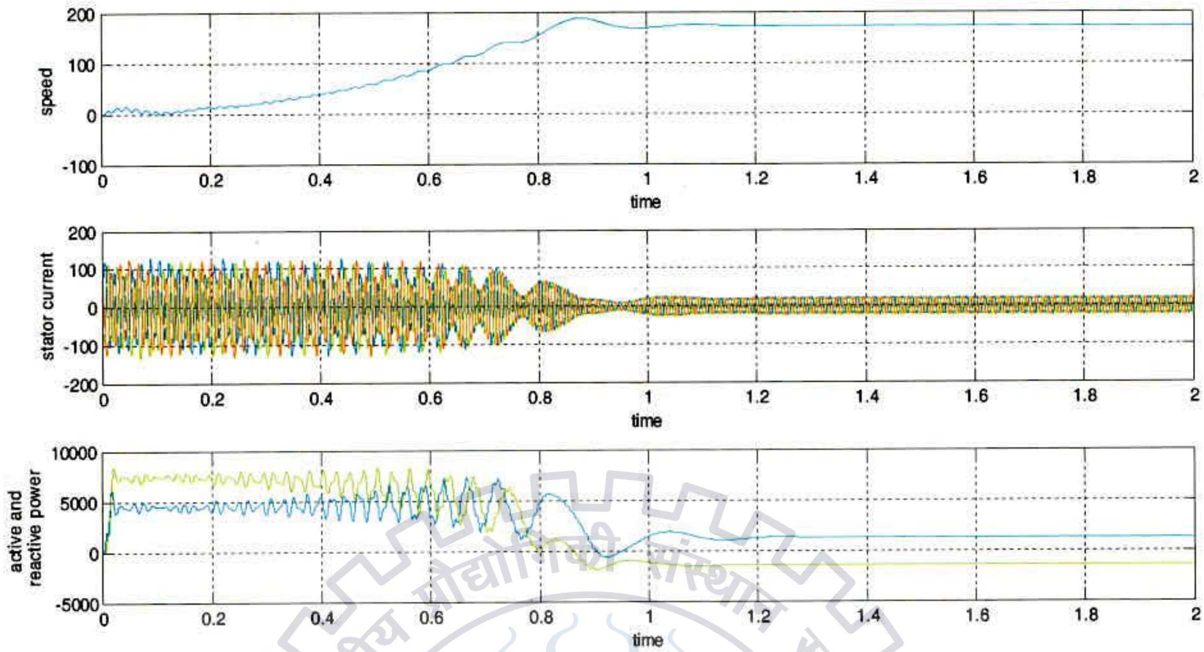

Fig.5.7 simulation result with rotor voltage $V_r = 20$ V and $f_r = 5$ hertz for DFIM drive

The simulation result with variation in rotor voltage $V_r = 10$ V and rotor frequency $f_r = 1$ hertz for DFIM drive has been shown in the fig 5.8.

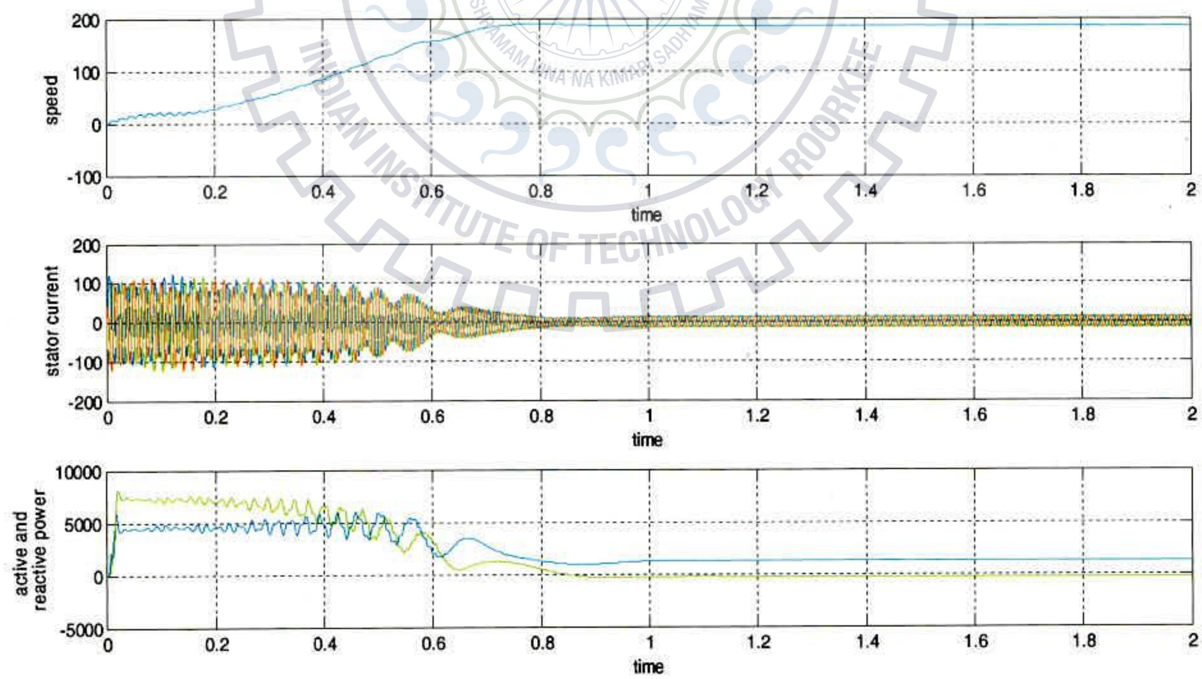

Fig.5.8 simulation result with rotor voltage $V_r = 10$ V and $f_r = 1$ hertz for DFIM drive

The simulation result with variation in rotor voltage $V_r = 23$ V and rotor frequency $f_r = 6$ hertz for DFIM drive has been shown in the fig 5.9.

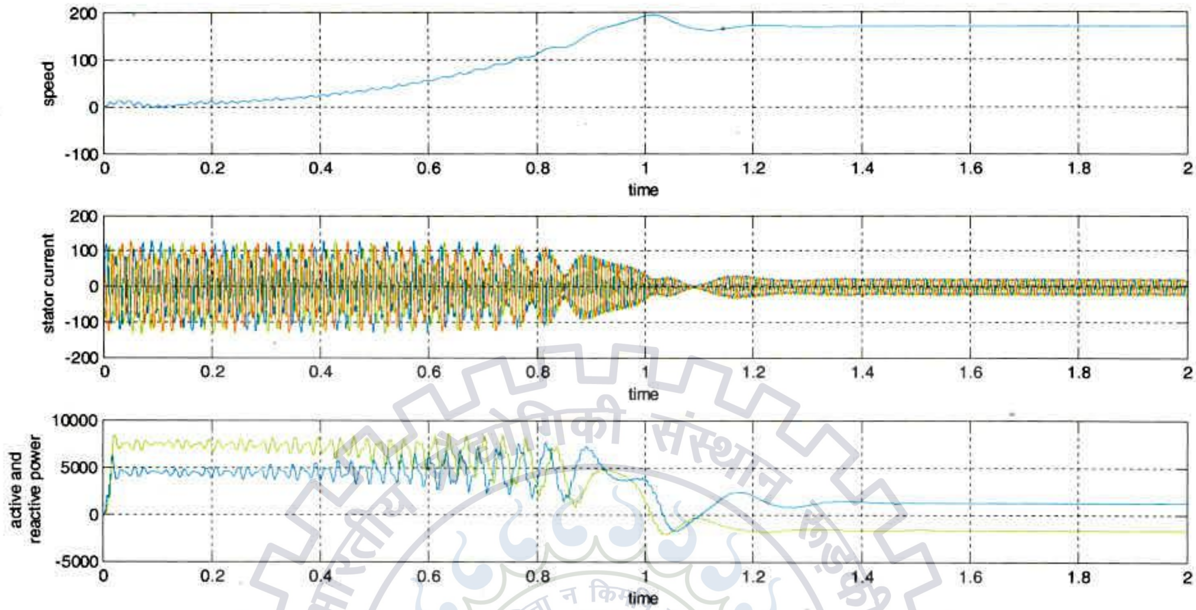

Fig.5.9 simulation result with rotor voltage $V_r = 23$ V and $f_r = 6$ hertz for DFIM drive

The simulation result with variation in rotor voltage $V_r = 10$ V and rotor frequency $f_r = 60$ hertz for DFIM drive has been shown in the fig 5.10.

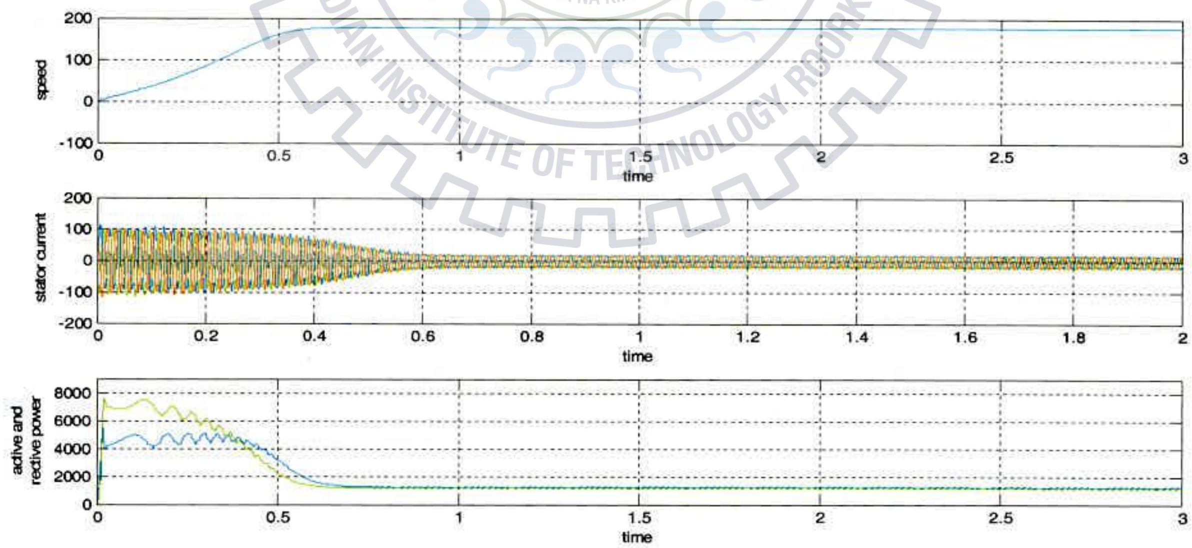

Fig.5.10 simulation result with rotor voltage $V_r = 10$ V and $f_r = 60$ hertz for DFIM drive

From the simulation results we can observe that by applied voltage with constant frequency at rotor circuit speed is constant but stator current increase significantly. These due to that net flux increases by apply the voltage at rotor side.

Further if we change the applied rotor current frequency than there is corresponding change in speed has been occur as if rotor current frequency increases, speed is decreasing. If we reduce the rotor current frequency, speed is increasing so there is dependency on rotor current frequency.

5.5 SPEED CONTROL BY VARIATION IN ROTOR VOLTAGE AND ROTOR FREQUENCY BY CONSTANT V/F RATIO WITH STATOR SHORT CIRCUITED

Simulation result by variation in rotor voltage and rotor frequency by constant v/f ratio with stator short circuited and V_r=169.7 V, f_r=60 Hz has been shown in fig.5.11.

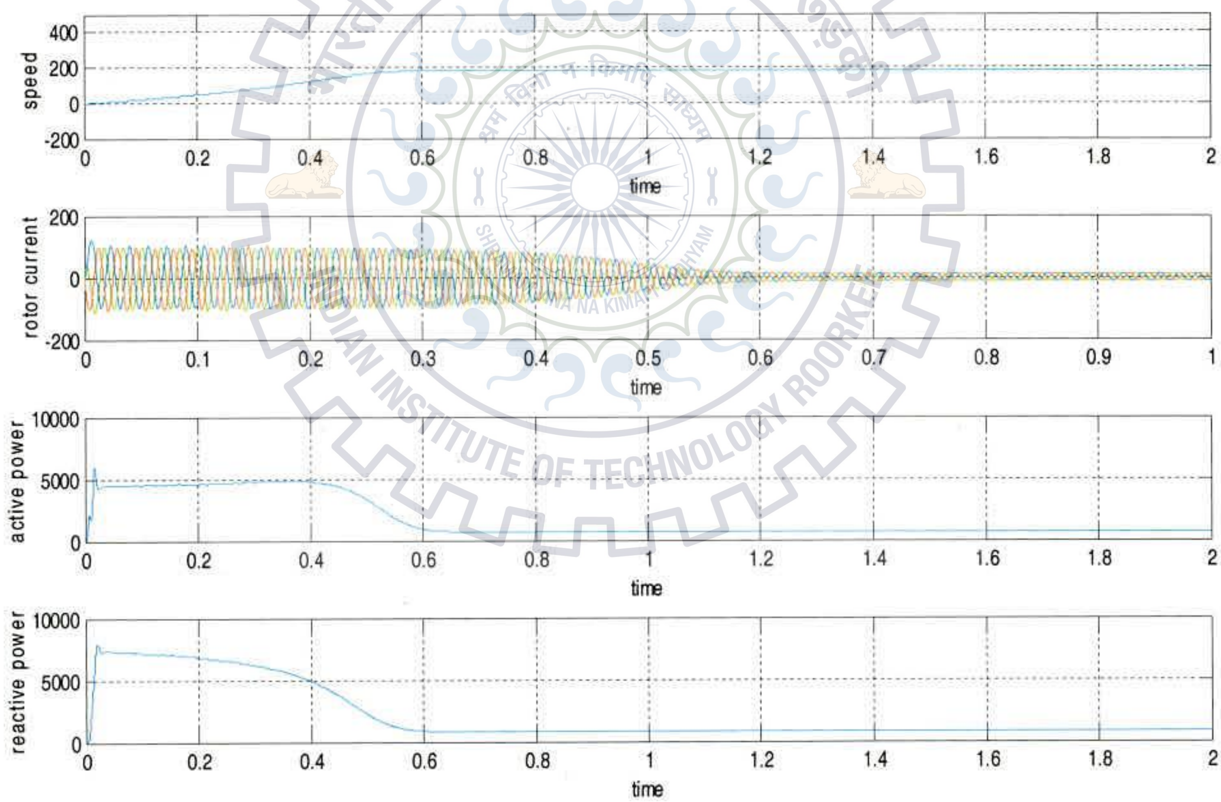

Fig.5.11 Simulation results for voltage V_r=169.7 V, f_r=60 Hz

Simulation result by variation in rotor voltage and rotor frequency by constant v/f ratio with stator short circuited and V_r=140 V, f_r=49.5 Hz has been shown in fig.5.12.

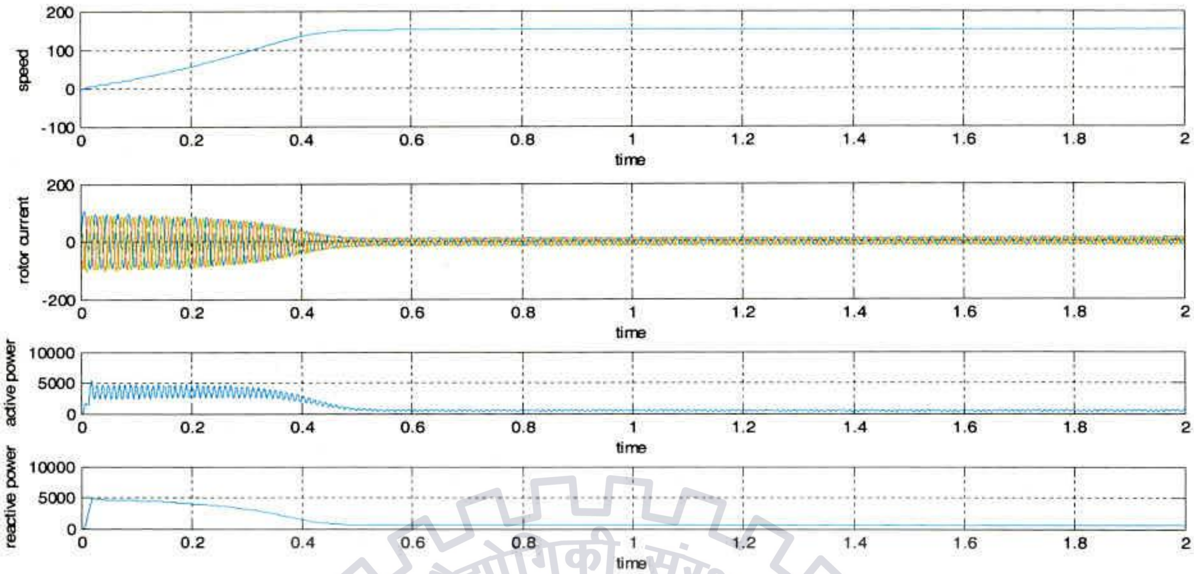

Fig.5.12 Simulation results for voltage V_r=140 V, f_r=49.5 Hz

Simulation result by variation in rotor voltage and rotor frequency by constant v/f ratio with stator short circuited and V_r=120 V, f_r=42.43 Hz has been shown in fig.5.13.

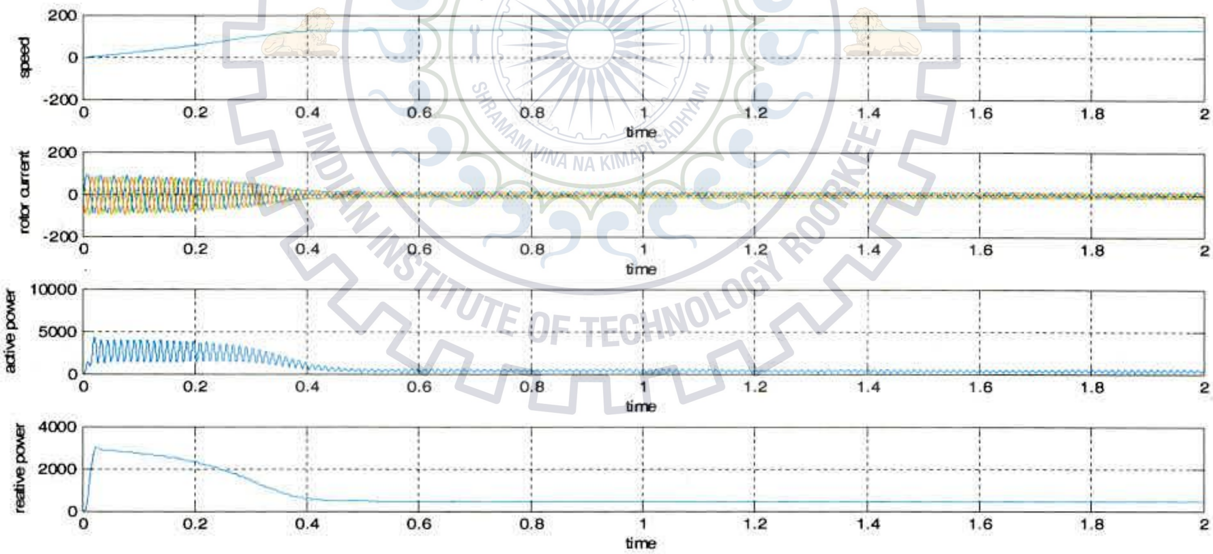

Fig.5.13 Simulation results for voltage V_r=120 V, f_r=42.43 Hz

From the simulation result we can observe that by changing the rotor voltage and rotor current frequency we can get the desired speed. If we reduce the speed then active and reactive power requirement are also less so there are saving in electricity. In this method we are controlling the motor at rotor side keeping machine flux constant.

5.6 CONSTANT VOLTS/HERTZ CONTROLLED DFIM DRIVE

Matlab simulink diagram of constant v/f controlled has been shown in figure 5.14.

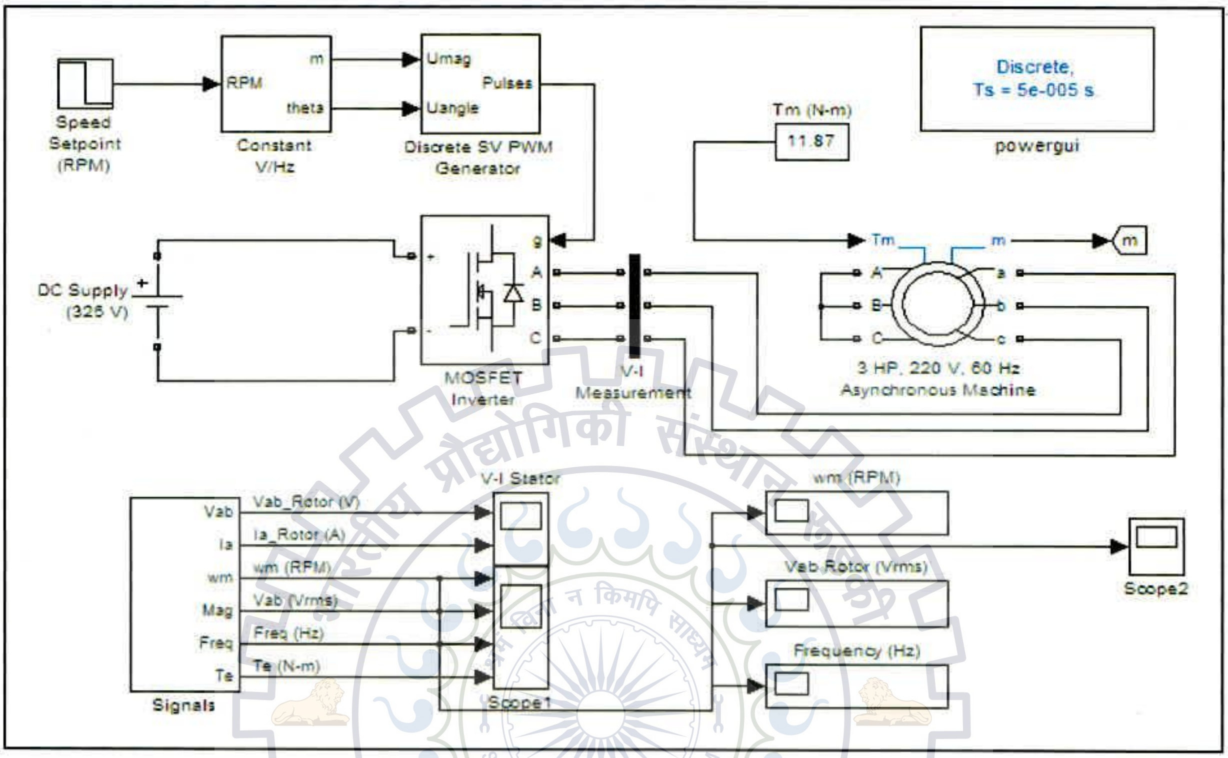

Fig.5.14 constant v/f controlled DFIM drive

Simulation result of constant v/f controlled DFIM drive at 1700 rpm has been shown in fig.5.15.

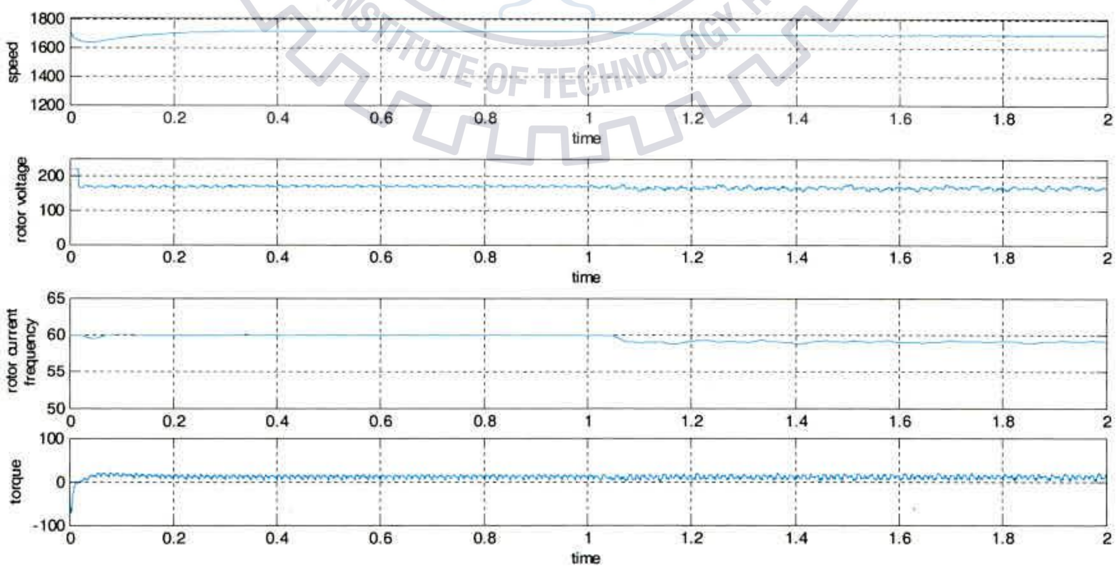

Fig 5.15: Simulation result of constant v/f controlled DFIM drive at 1700 rpm

Simulation result of constant v/f controlled DFIM drive at 1500 rpm has been shown in fig.5.16.

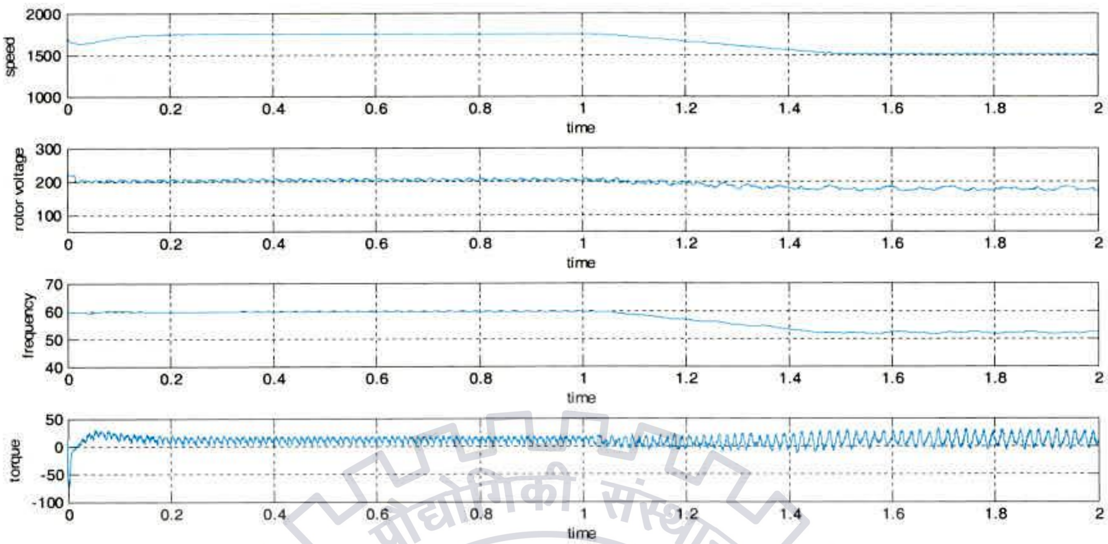

Fig 5.16: Simulation result of constant v/f controlled DFIM drive at 1500 rpm

Simulation result of constant v/f controlled DFIM drive at 1300 rpm has been shown in fig.5.17.

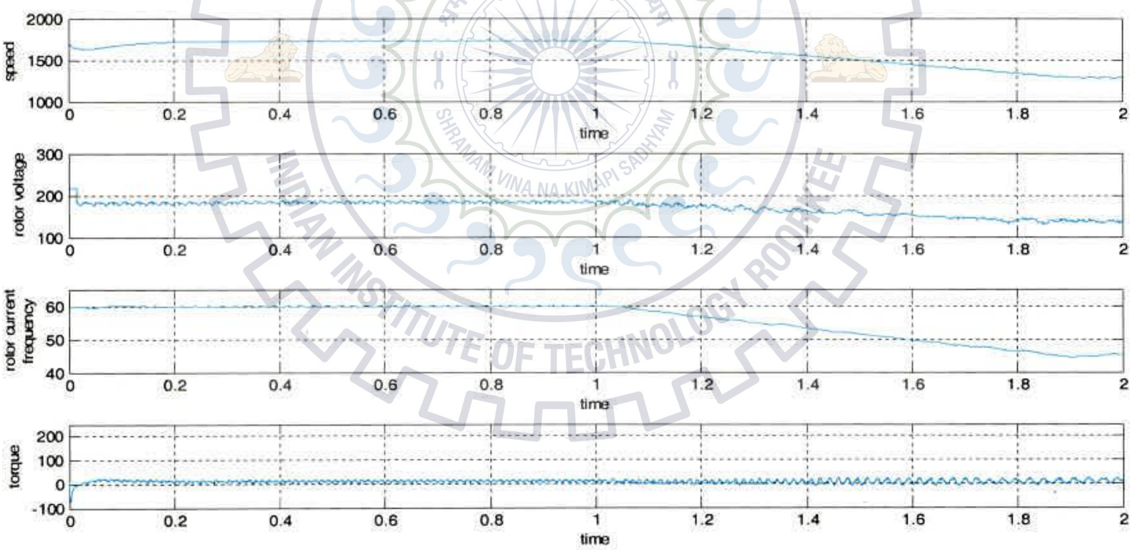

Fig 5.17: Simulation result of constant v/f controlled DFIM drive at 1300 rpm

From the above simulation result we can observe that by changing the reference speed we can get the desired speed and also we can get the corresponding rotor voltage and frequency. As speed is reducing then voltage is also reducing so there is saving in electricity. Further we set the reference speed slightly greater than the synchronous speed and motor speed will increase slightly above the synchronous speed and vector control scheme will take over the control by changes the switch from KM2 open to MK1 close refer to fig.1. So speed control below synchronous speed with the help of v/f control has been done satisfactorily.

5.7 SIMULATION RESULT WITH VECTOR CONTROLLED DFIM DRIVE

The Matlab simulink model of vector controlled DFIM drive for high speed application has been shown in the fig.5.18.

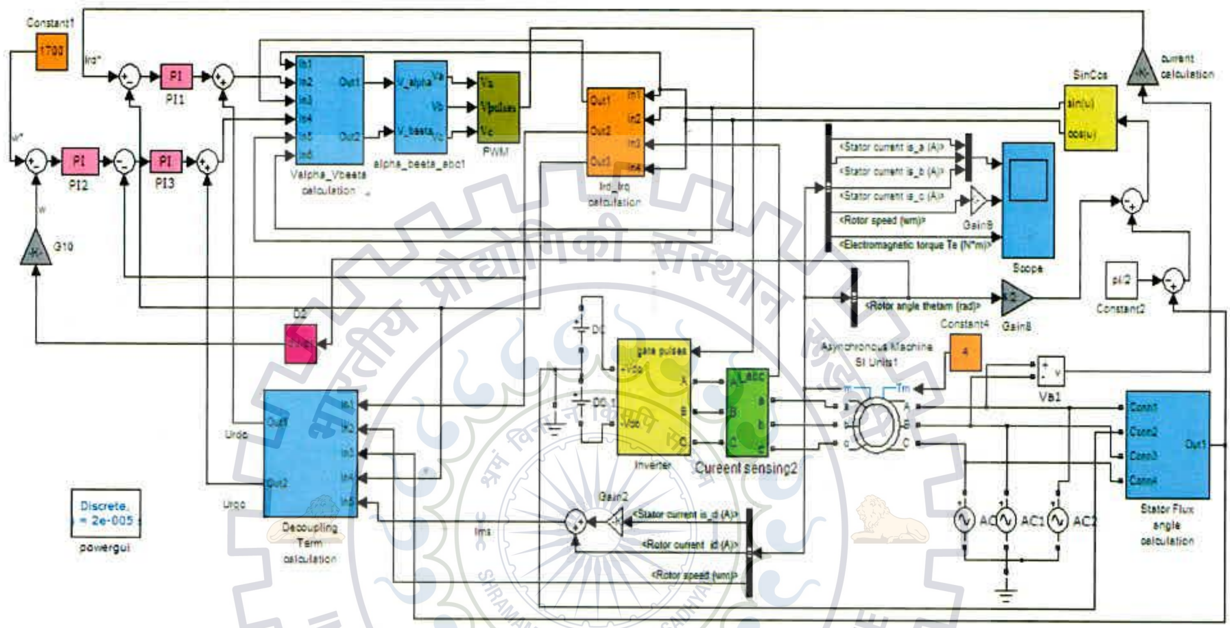

Fig.5.18 Matlab simulink diagram of vector controlled DFIM drive

The simulation result of vector controlled DFIM drive at 1600 rpm has shown in the fig.5.19

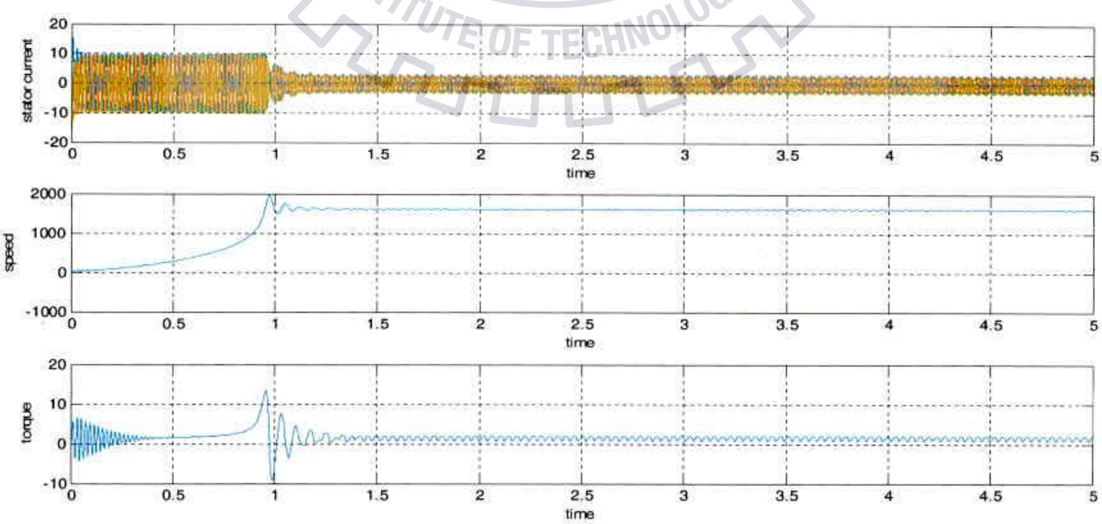

Fig.5.19: Simulation result of vector controlled DFIM drive at 1600 rpm

The simulation result for vector controlled DFIM drive at 1700 rpm has shown in the fig.5.20.

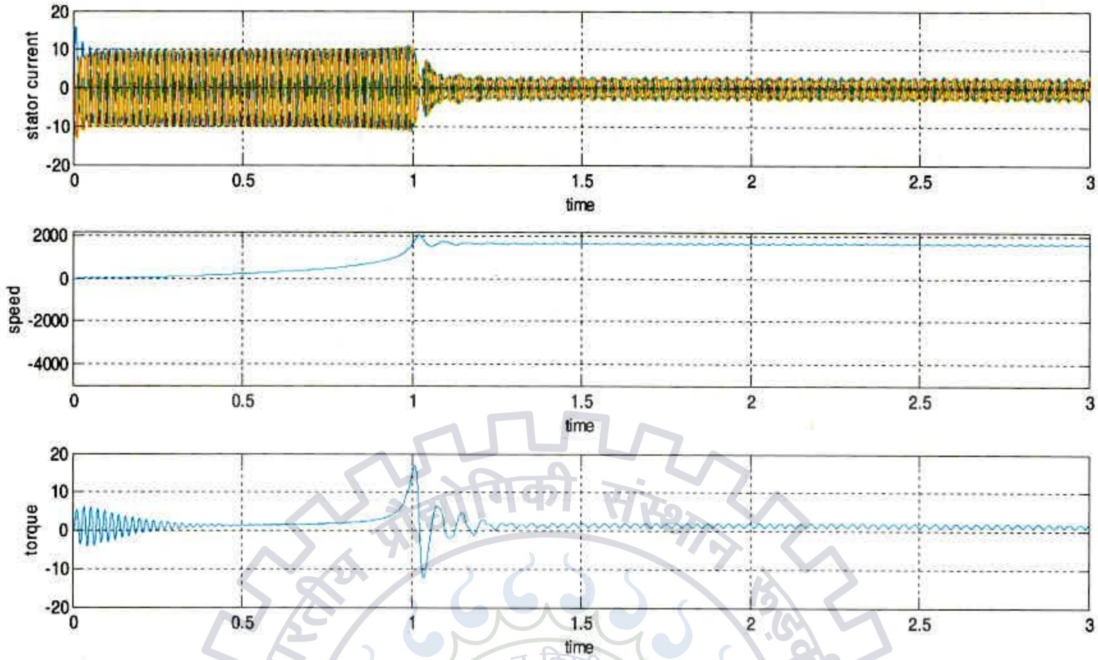

Fig.5.20: Simulation result of vector controlled DFIM drive at 1700 rpm

The simulation result for vector controlled DFIM drive at 1750 rpm has shown in the fig.5.21.

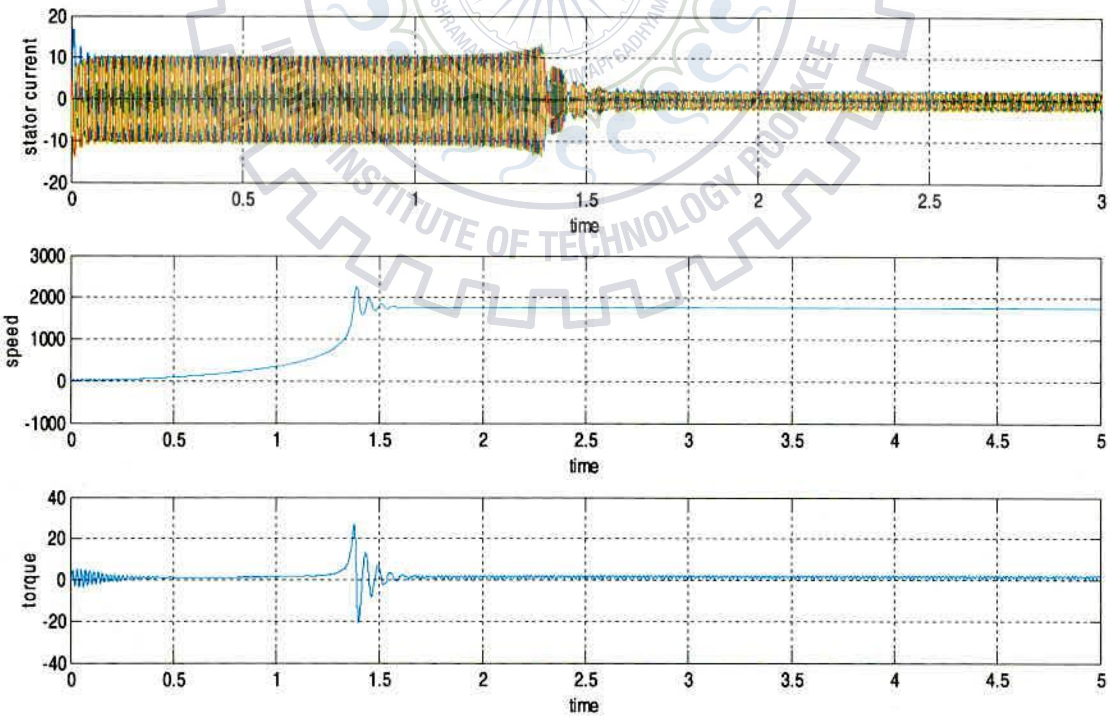

Fig.5.21: simulation result of vector controlled DFIM drive at 1750 rpm

The simulation result for vector controlled DFIM drive at 1800 rpm has been shown in the fig.5.22.

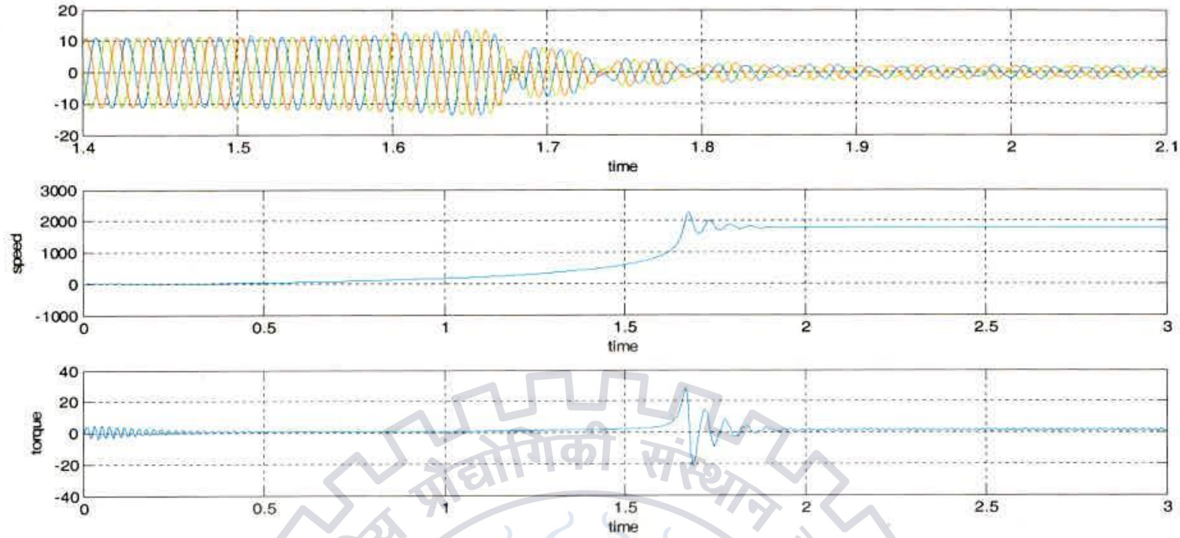

Fig.5.22: simulation result of vector controlled DFIM drive at 1800 rpm

From the above simulation result we can observe that by changing the reference speed we can get the desired speed. In this simulation the motor synchronous speed is at 1500 rpm. From vector control scheme we can increase the speed up to 1800 rpm. So speed control above synchronous speed with the help of vector control has been done satisfactorily.

5.8 RESULT DISCUSSION

It can be observed from the simulation result that with rotor resistance controlled DFIM drive the speed control can be accomplished but it has certain disadvantage so this method of speed control is not used for speed control. Further from the simulation it has been shown that the speed control mainly depends on the frequency not on voltage either on rotor or on stator. As if we increase the frequency only then flux try to increase and machine will go in saturation because our machines are constant flux machines. Finally for maintaining the constant flux in the machine the constant volts/hertz control has been implemented below synchronous speed. As we cannot use the constant v/f control above the rated speed because we cannot increase the voltage above the rated voltage of the machine. The machine operation in high speed region has been done with vector control field oriented control technique. The speed control of DFIM drive has been done satisfactorily.

6.1 CONCLUSION

SPEED control of doubly fed induction motor drive has been done in this thesis. The operation below synchronous speed has been achieved with scalar controllers. For high speed operation i.e operation above synchronous speed vector controller has been implemented. For operation below synchronous speed firstly rotor resistance speed control has been implemented. Further variation of rotor resistance has been achieved by rectifier and chopper because by mechanical variation of rotor resistance have certain disadvantages. The next step has been taken for variation in voltage and frequency at stator and rotor side both. As we have constant flux machines, finally constant volts/hertz control to have the flux constant has been implemented. In this way the operation below synchronous speed has been achieved by scalar controllers. The performance of the drive with the help of scalar controllers also has been analyzed.

High speed operation has been achieved in terms of vector control. In vector control with the help of stator and rotor, voltage and current the speed control has been achieved. The performance of the drive with load changing with the vector control also analyzed.

The simulation result of constant v/f control clearly indicates that by variation in voltage and frequency keeping v/f ratio constant the speed can be varied significantly below synchronous speed. For high speed application it can be observed from the simulation result when we change the speed reference, the corresponding speed we are getting. So speed control of DFIM drive below the synchronous speed and high speed application has been done satisfactorily.

6.2 FUTURE SCOPE

The designed motor parameter for high speed application can be verified with the help of performing the tests on doubly fed induction machine. By controlling the speed with converters there is high efficiency especially at partial load. By controlling the speed there is significant saving of electrical energy. DFIM drive can be used for pumping operation, compressors, hydro electric power plants, isolated generation of electrical energy. This present work with the matrix converter will give the fast system response, and less speed limitations, high operating efficiency. Further fuzzy controller can be implemented for quicker system response in high speed applications. This present work with sensorless scheme can also use for good transient response of the system and also for high speed applications. This present work can also use for electrical vehicle, PV cell etc.

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