3.5 Closed-loop control of induction motor

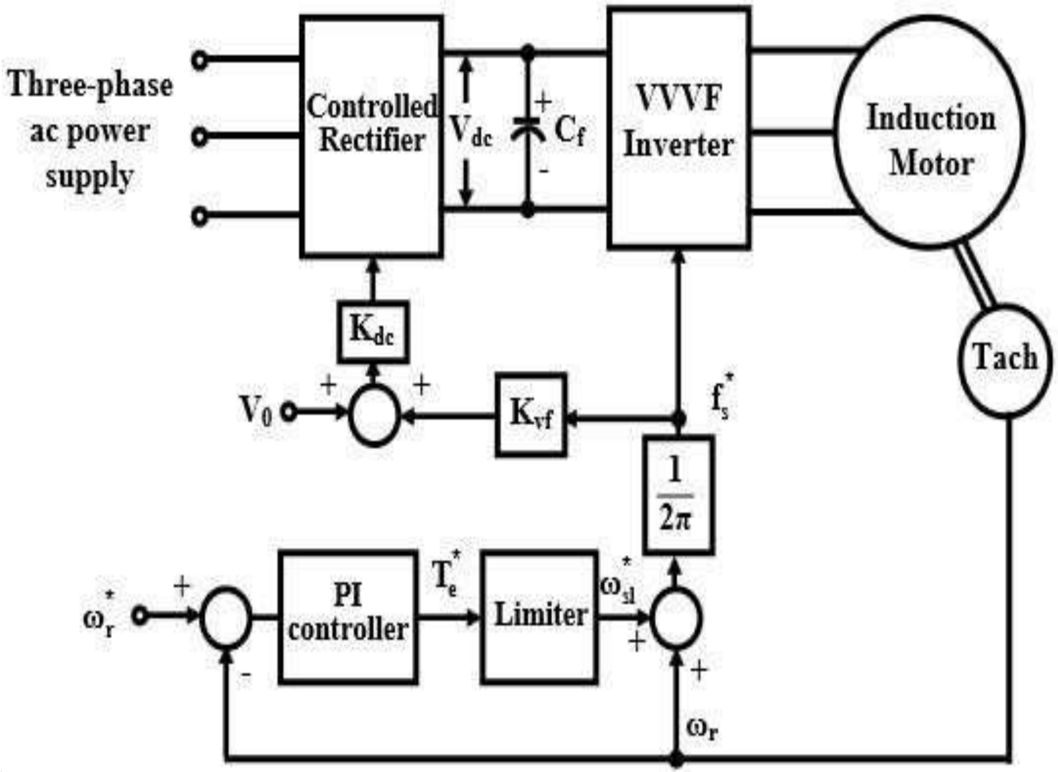


Fig 3.5.1 Closed-loop induction motor drive with constant volts/Hz control strategy

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-198)

An outer speed PI control loop in the induction motor drive, shown in Figure computes the frequency and voltage set points for the inverter and the converter respectively. The limiter ensures that the slip-speed command is within the maximum allowable slip speed of the induction motor. The slip- speed command is added to electrical rotor speed to obtain the stator frequency command. Thereafter, the stator frequency command is processed in an open-loop drive. Kdc is the constant of proportionality between the dc load voltage and the stator frequency.

Constant air gap flux control:

1. Equivalent separately-excited dc motor in terms of its speed but not in terms of decoupling of flux and torque channel.
2. Constant air gar flux linkages

$\lambda_m = L_m i_m = E_1/\omega_s$

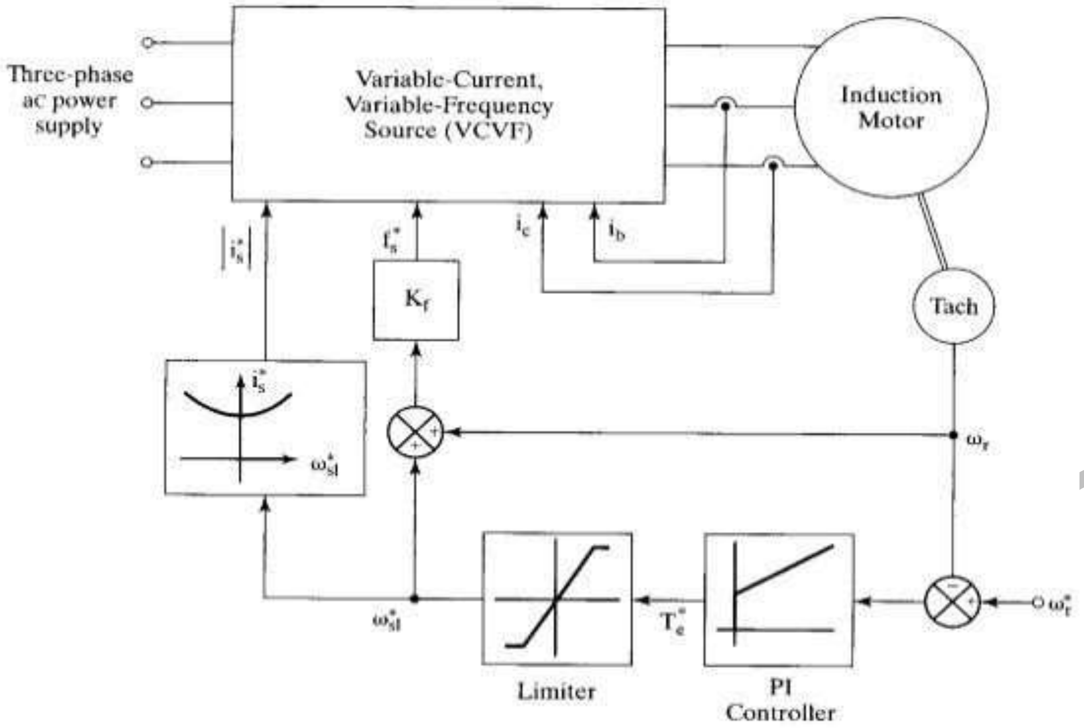


Fig 3.5.2 Closed-loop VCVF Control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-208)

The rotor flux magnitude and position is key information for the AC induction motor control. With the rotor magnetic flux, the rotational coordinate system (d-q) can be established. There are several methods for obtaining the rotor magnetic flux. The implemented flux model utilizes monitored rotor speed and statorvoltages and currents. It is calculated in the stationary reference frame (α,β) attached to the stator. The errorin the calculated value of the rotor flux, influenced by the changes in temperature, is negligible for this rotor flux model.

3.4 Qualitative treatment of slip power recovery drives:

Kramer System:

- It consists of main induction motor M, the speed of which is to be controlled.
- The two additional equipments are, d.c. motor and rotary converter.

4 The d.c. side of rotary converter feeds a d.c. shunt motor commutator, which is directly connected to the shaft of the main motor.

5 A separate d.c. supply is required to excite the field winding of d.c. motor andexciting winding of a rotary converter.

6 The variable resistance is introduced in the field circuit of a d.c. motor Which acts as s field regulator.

7 The speed of the set is controlled by varying the field of the d.c. motor with the rheostat R.When the field resistance is changed, the back e.m.f. of motor changes.

Thus the d.c. voltage at the commutator changes

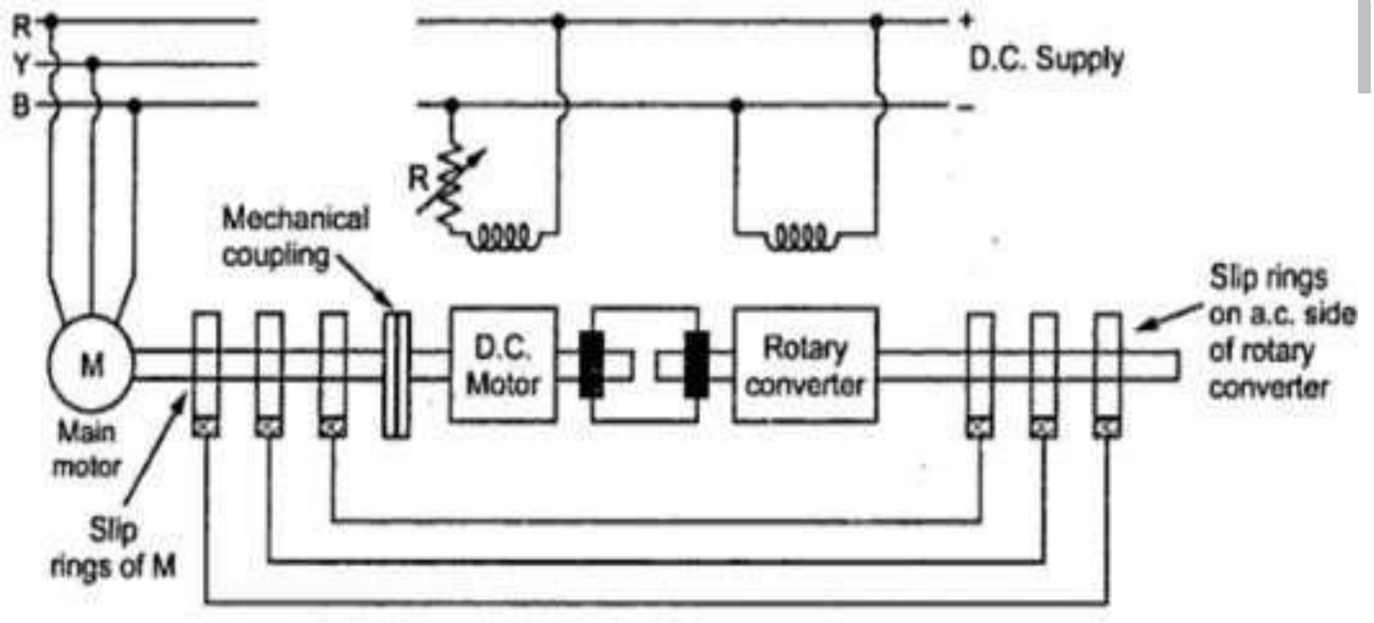


Figure 3.4.1 Static Kramer System

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-222)

- This changes the d.c. voltage on the d.c. side of a rotary converter.
- Now rotary converter has a fixed ratio between its a.c. side and d.c. side voltages.
- Thus voltage on its a.c. side also changes. This a.c. voltage is given to the slip Rings of the main motor.
- So the voltage injected in the rotor of main motor changes which produces the required speed control.
- Very large motors above 4000 kW such as steel rolling mills use such type of Speed control.
- The main advantage of this method is that a smooth speed control is possible. Similarly wide range of speed control is possible.
- Another advantage of the system is that the design of a rotaryconverter is practically independent of the speed control required.
- Similarly if rotary converter is overexcited, it draws leading current and thus power factor improvement is also possible along with the necessary speed control.

Scherbius System:

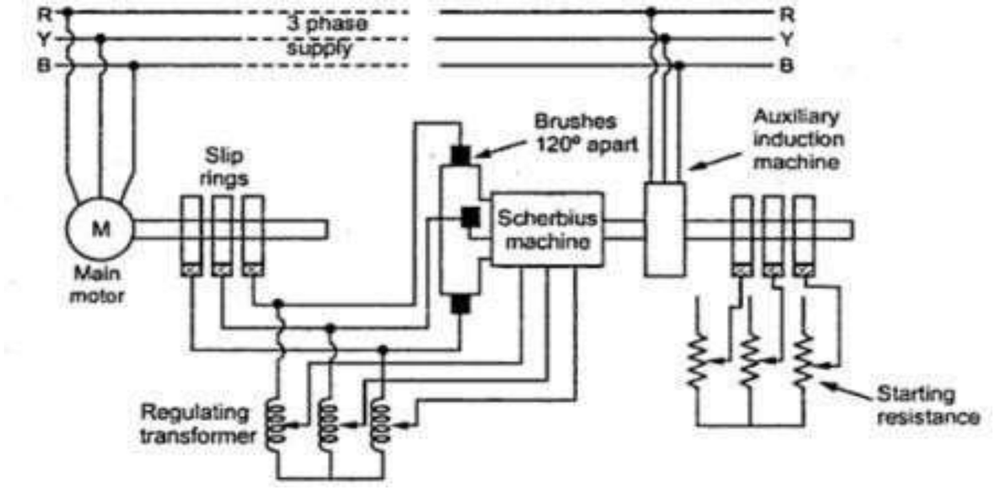


Figure 3.4.2 Static Scherbius System

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-220)

- This method requires an auxiliary 3 phase or 6 phase a.c. commutator machine which is called Scherbius machine.
- The difference between Kramer system and this system is that the Scherbius machine is not directly connected to the main motor, whose speed is to be controlled.
- The Scherbius machine is is excited at a slip frequency from the rotor of a main motor through a regulation transformer.
- The taps on the regulating transformer can be varied, this changes the voltage developed in the rotor Scherbius machine, which is injected into the rotor of main motor.
- This control the speed of the main motor, the scherbius machine is connected directly to the induction motor supplied from main line so that its speed deviates from a fixed value only to the extent of the slip of the auxiliary induction motor.
- For any given setting of regulating transformer, the speed of the main motor remains substantially constant irrespective of the load variations.
- Similar to the Kramer system, this method is also used to control speed of Large induction motors.
- The only disadvantage is that these methods can be used only for slip ring induction motors.

3.3 Rotor Resistance Control of Induction Motor:

Speed-torque curves for Rotor Resistance Control of Induction Motor are given in Fig. 6.50. While maximum torque is independent of rotor resistance, speed at which the maximum torque is produced changes with rotor resistance. For the same torque, speed falls with an increase in Rotor Resistance Control of Induction Motor.

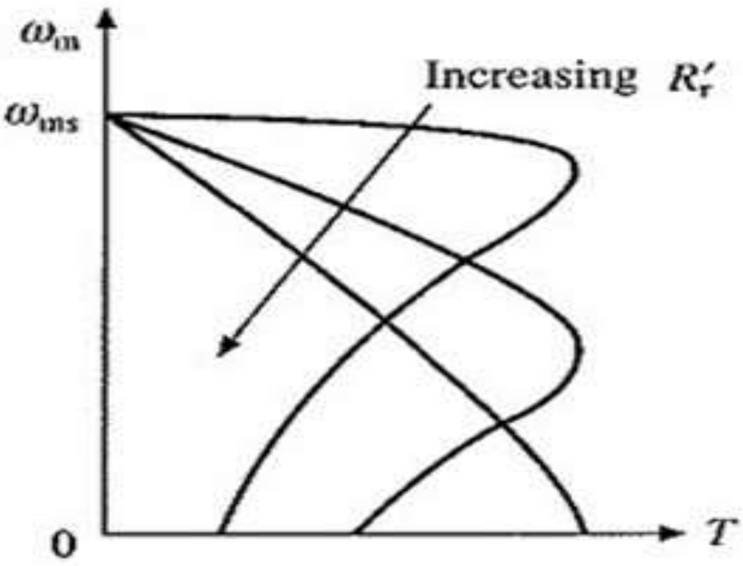


Figure 3.3.1 Rotor resistance control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-214)

Advantage of Rotor Resistance Control of Induction Motor is that motor torque capability remains unaltered even at low speeds. Only other method which has this advantage is variable frequency control. However, cost of Rotor Resistance Control of Induction Motor is very low compared to variable frequency control. Because of low cost and high torque capability at low speeds, rotor resistance control is employed in cranes, Ward Leonard Drives, and other intermittent load applications.

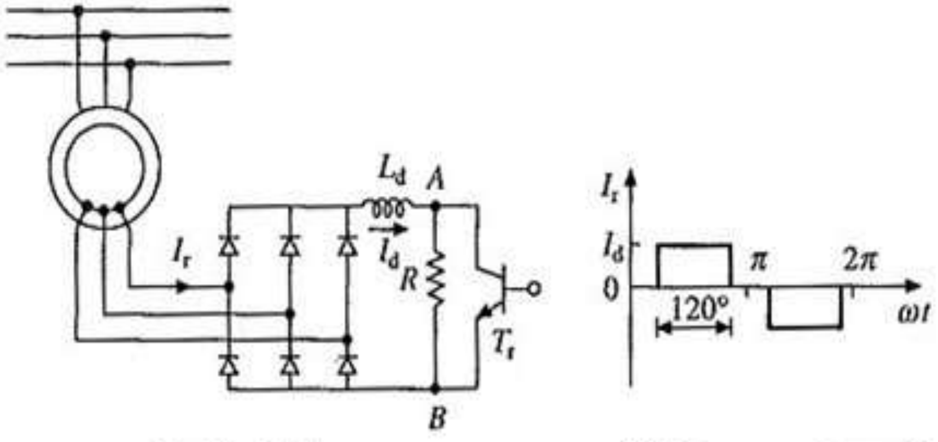
Major disadvantage is low efficiency due to additional losses in resistor connected in the rotor circuit. As the losses mainly take place in the external resistor they do not-heat the motor.

Conventional Methods:

A number of methods are used for obtaining variable resistance. In drum controllers, resistance is varied by using rotary switches and a resistance divided in few steps. Variable resistance can also be obtained by using contactors and resistors in series. High power applications use a slip-regulator, which consists of three electrodes submerged in an electrolyte, consisting of saline water. Resistance is varied by changing the distance between electrodes and earth electrode. When the power is high, electrodes are driven by a small motor. Advantage of this method is that resistance can be changed steplessly.

Static Rotor Resistance Control:

Rotor resistance can also be varied steplessly using circuit of Fig.. The ac output voltage of rotor is rectified by a diode bridge and fed to a parallel combination of a fixed resistance R and a semiconductor switch realized by a transistor Tr.



(a) Circuit diagram (b) Rotor current waveform

Figure 3.3.2 Rotor resistance control employing semiconductor converters

(Source: "Fundamentals of Electrical Drives" by G.K.Dubey,page-216)

Effective value of resistance across terminals A and B, R_{AB}, is varied by varying duty ratio of transistor T_r, which in turn varies rotor circuit resistance. Inductance L_d is added to reduce ripple and discontinuity in the dc link current I_d. Rotor current waveform will be as shown. in Fig. when the ripple is neglected. Thus rms rotor current will be

$$I_r = \sqrt{\frac{2}{3}}\, I_d$$

Resistance between terminals A and B will be zero when transistor is on and it will be R when it is off. Therefore, average value of resistance between the terminals is given by

$$R_{AB} = (1 - \delta)R$$

where δ is the duty ratio of the transistor and is given by Eq

Power consumed by R_{AB} is

$$P_{AB} = I_d^2\, R_{AB} = I_d^2 R(1 - \delta)$$

From Eqs. (6.88) and (6.89), power consumed by R_{AB} per phase is

$$\text{Power consumed per phase} = \frac{P_{AB}}{3} = 0.5R(1 - \delta)\, I_r^2$$

Equation (6.90) suggests that rotor circuit resistance per phase is increased by 0.5R(1 – δ). Thus, total rotor circuit resistance per phase will now be

$$R_{rT} = R_r + 0.5R\,(1 - \delta)$$

R_{rT} can be varied from R_r to (R_r + 0.5R) as δ is changed from 1 to 0.

A closed-loop speed control scheme with inner current control loop is shown in Fig. 6.52. Rotor current I_r and therefore, I_d has a constant value at the maximum torque point, both during motoring and plugging. If the current limiter is made to saturate at this current, the drive will accelerate and decelerate at the maximum torque, giving very fast transient response. For plugging to occur, arrangement will have to be made for reversal of phase sequence.

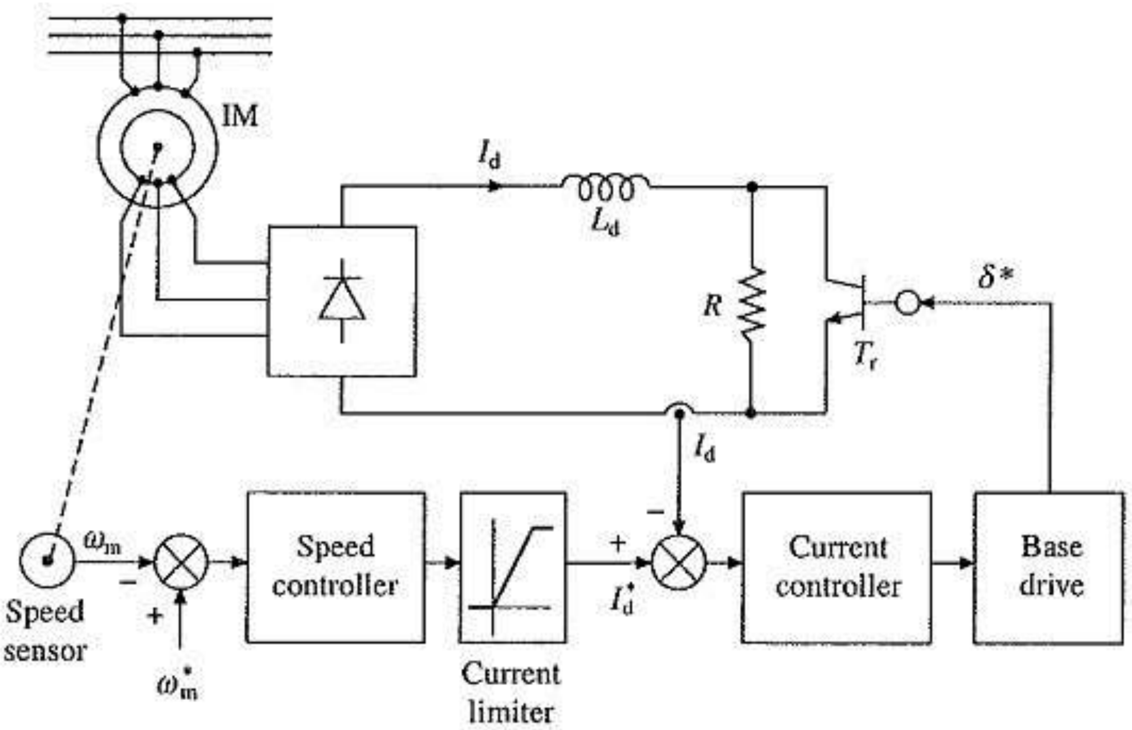


Fig. 6.52 Closed-loop speed control with static rotor resistance control

Compared to conventional Rotor Resistance Control of Induction Motor, static rotor resistance control has several advantages such as smooth and stepless control, fast response, less maintenance, compact size, simple closed-loop control and rotor resistance remains balanced between the three phases for all operating points.

3.1 Stator Voltage Control

In this method of control, back-to-back thyristors are used to supply the motor with variable ac voltage. The analysis implies that the developed torque varies inversely as the square of the input RMS voltage to the motor. This makes such a drive suitable for fan- and impeller-type loads for which torque demand rises faster with speed. For other types of loads, the suitable speed range is very limited. Motors with high rotor resistance may offer an extended speed range. It should be noted that this type of drive with back-to-back thyristors with firing-angle control suffers from poor power and harmonic distortion factors when operated at low speed. If unbalanced operation is acceptable, the thyristors in one or two supply lines to the motor may be bypassed. This offers the possibility of dynamic braking or plugging, desirable in some applications.

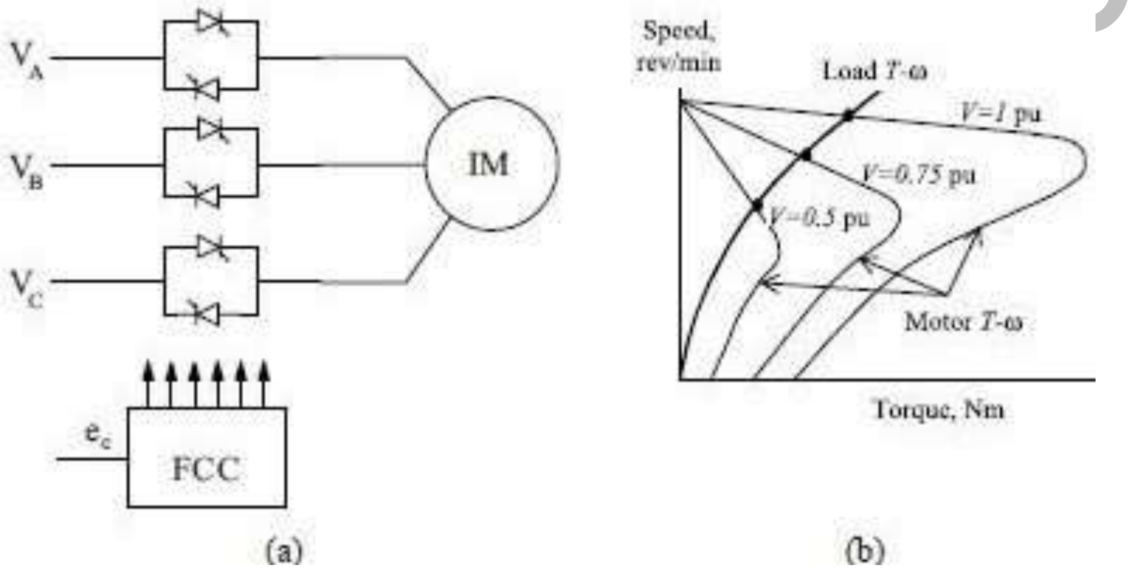


Figure 3.1.1 (a) Stator voltage controller.

(b) Motor and load torque–speed characteristics under voltage control.

(Source:”Fundamentals of Electrical Drives” by G.K.Dubey,page-184)

The induction motor speed variation can be easily achieved for a short range by either stator voltage control or rotor resistance control. But both of these schemes result in very low efficiencies at lower speeds. The most efficient scheme for speed control of induction motor is by varying supply frequency. This not only results in scheme with wide speed range but also improves the starting performance. If the machine is operating at speed below base speed, then v/f ratio is to be kept constant so that flux remains constant.

This retains the torque capability of the machine at the same value. But at lower frequencies, the torque capability decrease and this drop in torque has to be compensated for increasing the applied voltage.

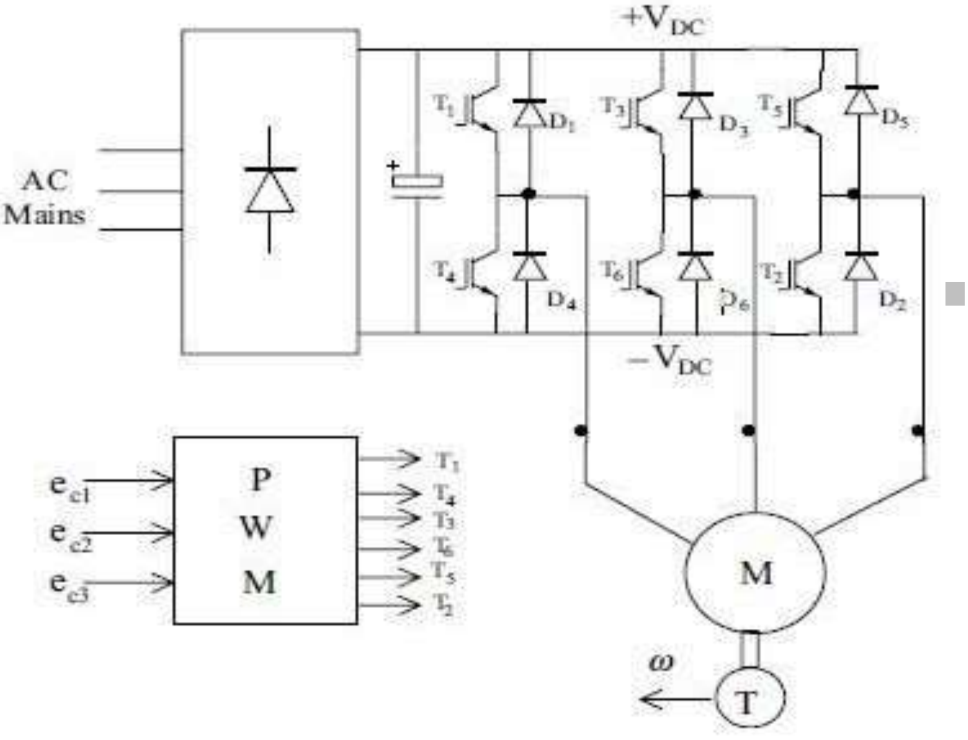


Figure 3.1.2 Inverter fed Induction motor Drive

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-192)

3.2 V/F Control

Open Loop V/F Control

The open loop V/F control of an induction motor is the most common method of speed control because of its simplicity and these types of motors are widely used in industry. Traditionally, induction motors have been used with open loop 50Hz power supplies for constant speed applications. For adjustable speed drive applications, frequency control is natural. However, voltage is required to be proportional to frequency so that the stator flux.

$$\Psi_s=V_s/\omega_s$$

Remains constant if the stator resistance is neglected. The power circuit consists of a diode rectifier with a single or three-phase ac supply, filter and PWM voltage-fed inverter. Ideally no feedback signals are required for this control scheme.

The PWM converter is merged with the inverter block. Some problems encountered in the operation of this open loop drive are the following:

The speed of the motor cannot be controlled precisely, because the rotor speed will be slightly less than the synchronous speed and that in this scheme the stator frequency and hence the synchronous speed is the only control variable.

The slip speed, being the difference between the synchronous speed and the electrical rotor speed, cannot be maintained, as the rotor speed is not measured in this scheme. This can lead to operation in the unstable region of the torque-speed characteristics.

The effect of the above can make the stator currents exceed the rated current by a large amount thus endangering the inverter- converter combination.

These problems are to be suppress by having an outer loop in the induction motor drive, in which the actual rotor speed is compared with its commanded value, and the error is processed through a controller usually a PI controller and a limiter is used to obtain the slip-speed command.

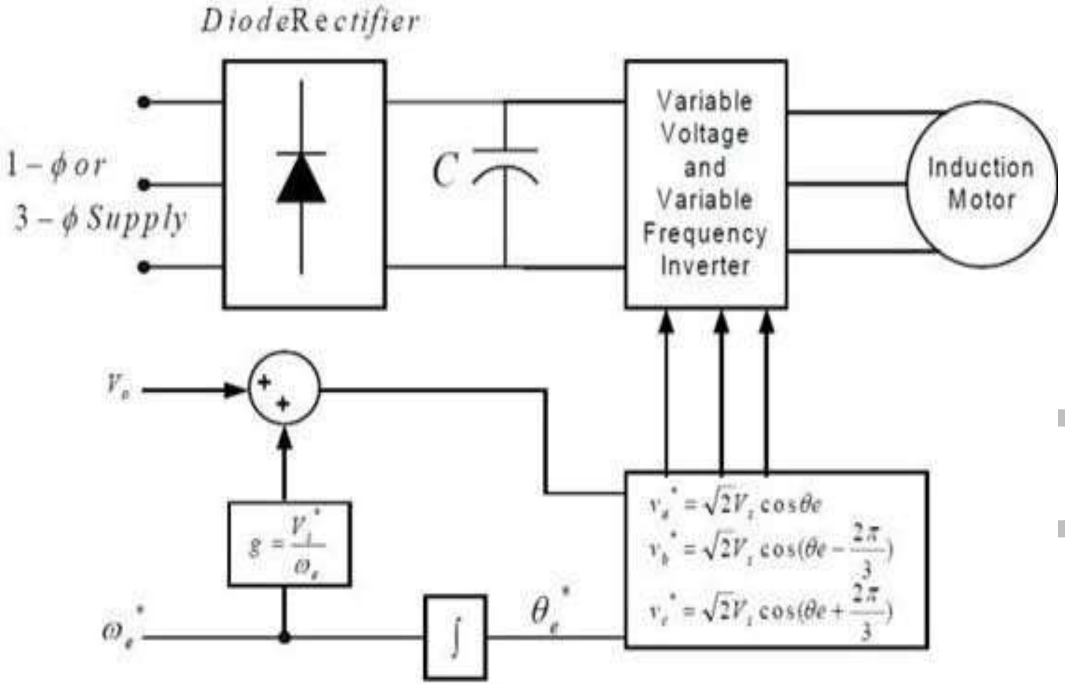


Figure 3.2.1Open loop V/F Control for an IM

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-189)

Closed Loop V/F Control

The basis of constant V/F speed control of induction motor is to apply a variable magnitude and variable frequency voltage to the motor. Both the voltage source inverter and current source inverters are used in adjustable speed ac drives. The following block diagram shows the closed loop V/F control using a VSI.

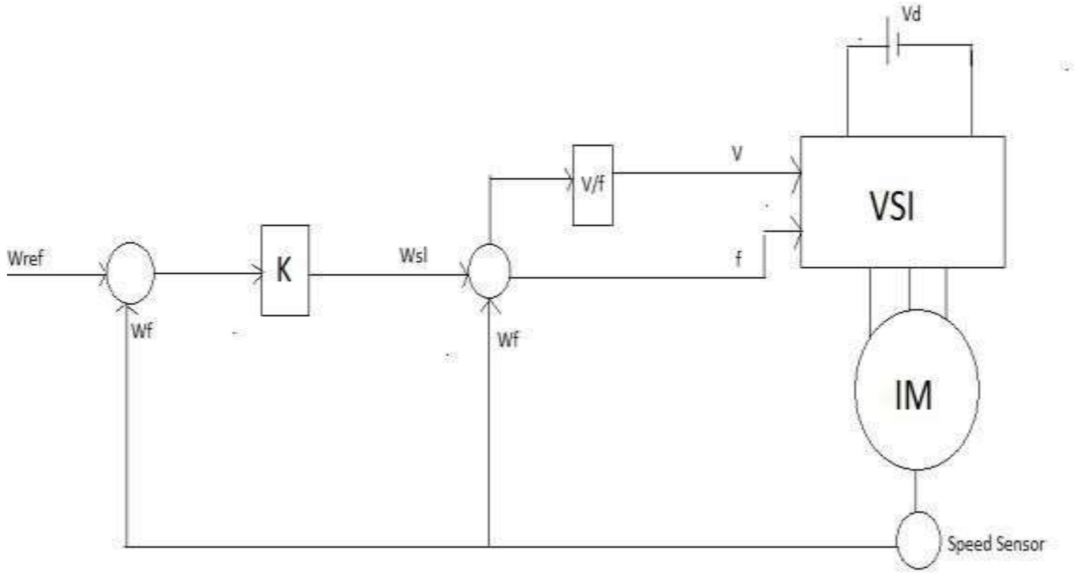


Figure 3.2.2 Closed loop V/F control for an IM

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-189)

A speed sensor or a shaft position encoder is used to obtain the actual speed of the motor. It is then compared to a reference speed. The difference between the two generates an error and the error so obtained is processed in a Proportional controller and its output sets the inverter frequency. Thesynchronous speed, obtained by adding actual speed ωf and the slip speed ωSI, determines the inverter frequency The reference signal for the closed-loop control of the machine terminal voltage ωf is generated from frequency.

3.6 Vector Control of AC Induction Machines

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

$$\Psi_{rq} = 0 \text{ and also } \frac{d}{dt}\Psi_{rq} = 0$$

vector is always zero:

The rotor flux space vector calculation and transformation to the d-q coordinate system require thehigh computational power of a microcontroller. The digital signal processor is suitable for this task. The following sections describe the space vector transformations and the rotor flux space vector calculation.

Block Diagram of the Vector Control

Shows the basic structure of the vector control of the AC induction motor.

To perform vector control, it is necessary to follow these steps:

- Measure the motor quantities (phase voltages and currents)
- Transform them to the 2-phase system (α,β) using a Clarke transformation

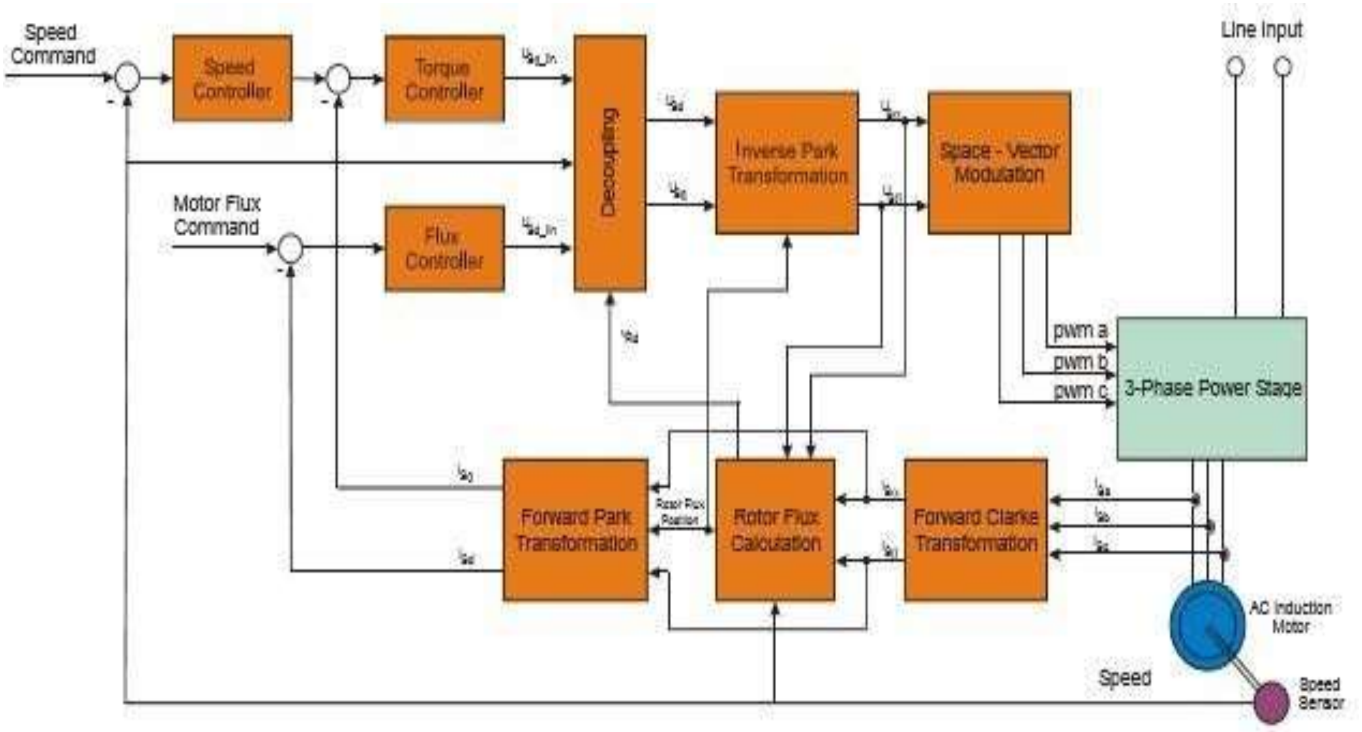


Fig 3.6.1 Vector Control of the AC Induction Motor

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-236)

- Calculate the rotor flux space vector magnitude and position angle
- Transform stator currents to the d-q coordinate system using a Park transformation
- The stator current torque and flux producing components are separately controlled
- The output stator voltage space vector is calculated using the decoupling block
- The stator voltage space vector is transformed by an inverse Park transformation back from the d-q coordinate system to the 2-phase system fixed with the stator
- Using the space vector modulation, the output 3-phase voltage is generated

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

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

The inverse Clarke transformation goes back from a 2-phase (α,β) to a 3-phase isa, isb, isc system. For constant k=2/3, it is given by the following equations:

$$i_{sa} = i_{s\alpha}$$

$$i_{sb} = -\frac{1}{2} i_{s\alpha} + \frac{\sqrt{3}}{2} i_{s\beta}$$

$$i_{sc} = -\frac{1}{2} i_{s\alpha} - \frac{\sqrt{3}}{2} i_{s\beta}$$

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

The components isα and isβ, calculated with a Clarke transformation, are attached to the stator reference frame α, β. In vector control, it is necessary to have all quantities expressed in the same reference frame. The stator reference frame is not suitable for the control process. The space vector isβ is rotating at a rate equal to the angular frequency of the phase currents. The components isα and isβ depend on time and speed. We can transform these components from the stator reference frame to the d-q reference frame rotating at the same speed as the angular frequency of the phase currents. Then the isd and isq components do not depend on time and speed. If we consider the d-axis aligned with the rotor flux, the transformation is illustrated in Figure where θfield is the rotor flux position.

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

$$i_{s\alpha} = i_{sd} \cos\theta_{Field} - i_{sq} \sin\theta_{Field}$$

$$i_{s\beta} = i_{sd} \sin\theta_{Field} + i_{sq} \cos\theta_{Field}$$

Rotor Flux Model

Knowledge of the rotor flux space vector magnitude and position is key information for the AC induction motor vector control. With the rotor magnetic flux space vector, the rotational coordinate system (d-q) can be established. There are several methods for obtaining the rotor magnetic flux space vector. The implemented flux model utilizes monitored rotor speed and stator voltages and currents. It is calculated in the stationary reference frame (α,β) attached to the stator. The error in the calculated value of the rotor flux, influenced by the changes in temperature, is negligible for this rotor flux model.

The rotor flux space vector is obtained by solving the differential equations (EQ 4-2) and (EQ 4-3), which are resolved into the α and β components. The equations are derived from the equations of the AC induction motor model

$$[(1-\sigma)T_s + T_r]\frac{d\Psi_{r\alpha}}{dt} = \frac{L_m}{R_s}u_{s\alpha} - \Psi_{r\alpha} - \omega T_r \Psi_{r\beta} - \sigma L_m T_s \frac{di_{s\alpha}}{dt}$$

$$[(1-\sigma)T_s + T_r]\frac{d\Psi_{r\beta}}{dt} = \frac{L_m}{R_s}u_{s\beta} + \omega T_r \Psi_{r\alpha} - \Psi_{r\beta} - \sigma L_m T_s \frac{di_{s\beta}}{dt}$$

where:

L_s	self-inductance of the stator	[H]
L_r	self-inductance of the rotor	[H]
L_m	magnetizing inductance	[H]
R_r	resistance of a rotor phase winding	[Ohm]
R_s	resistance of a stator phase winding	[Ohm]
ω	angular rotor speed	[rad.s^{-1}]
p_p	number of motor pole-pairs	
$T_r = \frac{L_r}{R_r}$	rotor time constant	[s]
$T_s = \frac{L_s}{R_s}$	stator time constant	[s]
$\sigma = 1 - \frac{L_m^2}{L_s L_r}$	resultant leakage constant	[-]