LECTURE NOTES

ON

SOLID STATE ELECTRIC MOTOR DRIVES

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III B. Tech II semester (IARE-R16)

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UNIT-I
CONTROL OF DC MOTORS THROUGH PHASE CONTROLLED RECTIFIERS

Electrical Drives:

Motion control is required in large number of industrial and domestic applications like transportation systems, rolling mills, paper machines, textile mills, machine tools, fans, pumps, robots, washing machines etc.

Systems employed for motion control are called DRIVES, and may employ any of prime movers such as diesel or petrol engines, gas or steam turbines, steam engines, hydraulic motors and electric motors, for supplying mechanical energy for motion control. Drives employing electric motors are known as Electrical Drives.

An Electric Drive can be defined as an electromechanical device for converting electrical energy into mechanical energy to impart motion to different machines and mechanisms for various kinds of process control.

Classification of Electric Drives

According to Mode of Operation

- ✓ Continuous duty drives
- ✓ Short time duty drives
- ✓ Intermittent

duty drives According

To Means of Control

- ✓ Manual
- ✓ Semi-automatic
- ✓ Automatic

According to Number of machines

- ✓ Individual drive
- ✓ Group drive
- ✓ Multi-motor drive

According to Dynamics and Transients

- ✓ Uncontrolled transient period
- ✓ Controlled transient

period According to Methods of

Speed Control

- ✓ Reversible and non-reversible uncontrolled constant speed.
- ✓ Reversible and non-reversible step speed control.
- ✓ Variable position control.

Advantages of Electrical Drive

They have flexible control characteristics. The steady state and dynamic characteristics of electric drives can be shaped to satisfy the load requirements.

1. Drives can be provided with automatic fault detection systems. Programmable logic controller and computers can be employed to automatically control the drive operations in a desired sequence.
2. They are available in wide range of torque, speed and power.
3. They are adaptable to almost any operating conditions such as explosive and radioactive environments
4. It can operate in all the four quadrants of speed-torque plane
5. They can be started instantly and can immediately be fully loaded
6. Control gear requirement for speed control, starting and braking is usually simple and easy to operate.

Choice (or) Selection of Electrical Drives

Choice of an electric drive depends on a number of factors. Some of the important factors are.

- ✓ Steady State Operating conditions requirements:

Nature of speed torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrants of operation, speed fluctuations if any, ratings etc

- ✓ Transient operation requirements:

  Values of acceleration and deceleration, starting, braking and reversing performance

- ✓ Requirements related to the source:

  Types of source and its capacity, magnitude of voltage, voltage fluctuations, power factor, harmonics and their effect on other loads, ability to accept regenerative power

- ✓ Capital and running cost, maintenance needs life.
- ✓ Space and weight restriction if any.
- ✓ Environment and location.
- ✓ Reliability.

Group Electric Drive

This drive consists of a single motor, which drives one or more line shafts supported on bearings. The line shaft may be fitted with either pulleys and belts or gears, by means of which a group of machines or mechanisms may be operated. It is also sometimes called as SHAFT DRIVES.

Advantages

A single large motor can be used instead of number of small motors

Disadvantages

There is no flexibility. If the single motor used develops fault, the whole process will be stopped.

Individual Electric Drive

In this drive each individual machine is driven by a separate motor. This motor also imparts motion to various parts of the machine.

Multi Motor Electric Drive

In this drive system, there are several drives, each of which serves to actuate one of the working parts of the drive mechanisms.

E.g. Complicated metal cutting machine
tools Paper making industries, rolling
machines etc.

Classification of Electrical Drives

Another main classification of electric drive is

- DC drive
- AC drive

Applications

- Paper mills
- Cement Mills
- Textile mills
- Sugar Mills
- Steel Mills
- Electric Traction
- Petrochemical Industries
- Electrical Vehicles

Single phase semi controlled converters connected to DC separately excited motors with continuous current operation:

Single phase controlled rectifier fed DC Drives

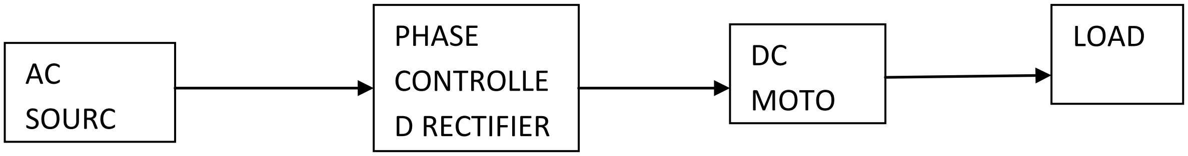

Figure: 1.1. Single phase controlled rectifier fed DC Drives

Here AC supply is fed to the phase controlled rectifier circuit.AC supply may be single phase or three phase. Phase controlled rectifier converts fixed AC voltage into variable DC voltage .

Here the circuit consists of SCR’s. By varying the SCR firing angle the output voltage can be controlled. This variable output voltage is fed to the DC motor. By varying the motor input voltage, the motor speed can be controlled.

Single phase half controlled converter with DC separately excited motors

The diode D2 and D4 conducts for the positive and negative half cycle of the input voltage waveform respectively. On the other hand T1 starts conduction when it is fired in the positive half cycle of the input voltage waveform and continuous conduction till T3 is fired in the negative half cycle. Fig. shows the circuit diagram and the waveforms of a single phase half controlled converter supplying an R – L – E load.

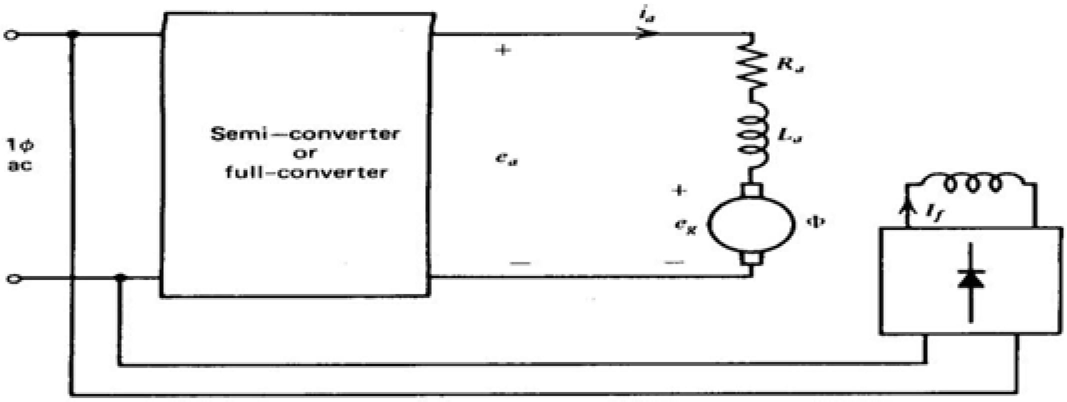

Figure: 1. 2. single phase half controlled converter motor load

Referring to Fig T1 D2 starts conduction at ωt = α. Output voltage during this period becomes equal to vi. At ωt = π as vi tends to go negative D4 is forward biased and the load current commutates from D2 to D4 and freewheels through D4 and T1. The output voltage remains clamped to zero till T3 is fired at ωt = π + α. The T3 D4 conduction mode continues upto ωt = 2π. Where upon load current again free wheels through T3 and D2 while the load voltage is clamped to zero. From the discussion in the previous paragraph it can be concluded that the output voltage (hence the output current) is periodic over half the input cycle. Hence

$$V_{oav} = \frac{1}{\pi}\int_o^{\pi} v_o d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2}V_i \sin \omega t \, d\omega t = \frac{\sqrt{2}V_i}{\pi}(1+\cos\alpha)$$

$$I_{ov} = \frac{V_{oav} - E}{R} = \frac{\sqrt{2}V_i}{\pi R}(1+\cos\alpha - \pi \sin\theta)$$

The back emf equation of DC separately excited motor is $E_b = K_a\phi N$

$E_b = V_t - I_aR_a$

$E_b = \frac{Vm}{\pi}(1+cos\alpha) - IaRa$

$$N=\frac{Vm/\pi\ (1+\cos\alpha)-IaRa}{Ka\emptyset}$$

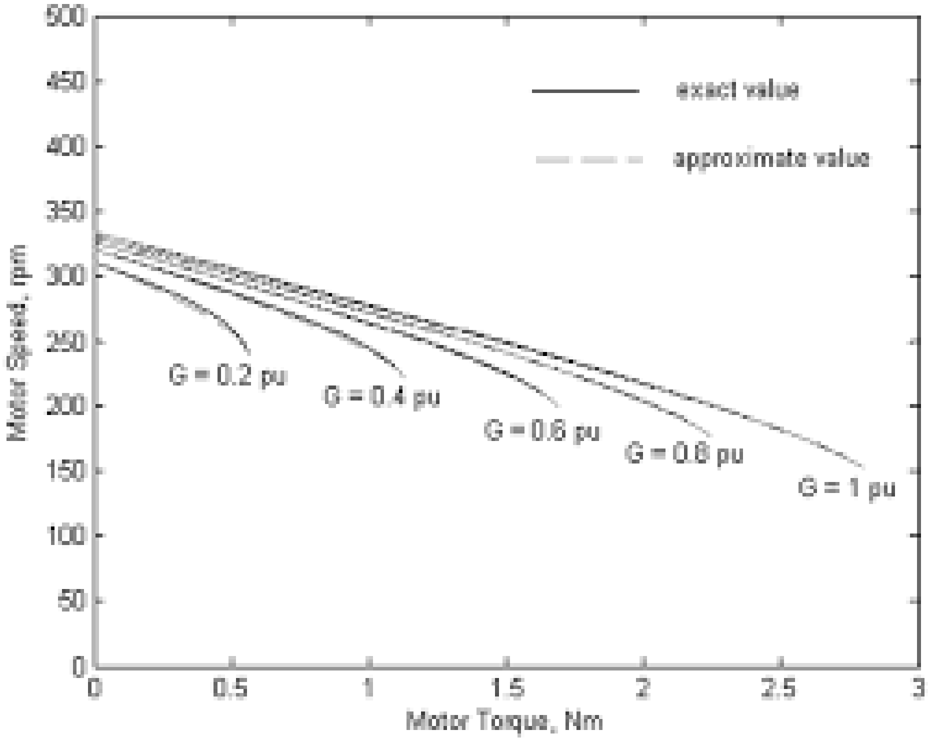

Figure: 1. 3. Speed torque characteristics of seperately excited motor

Single phase half controlled converter with DC series motors

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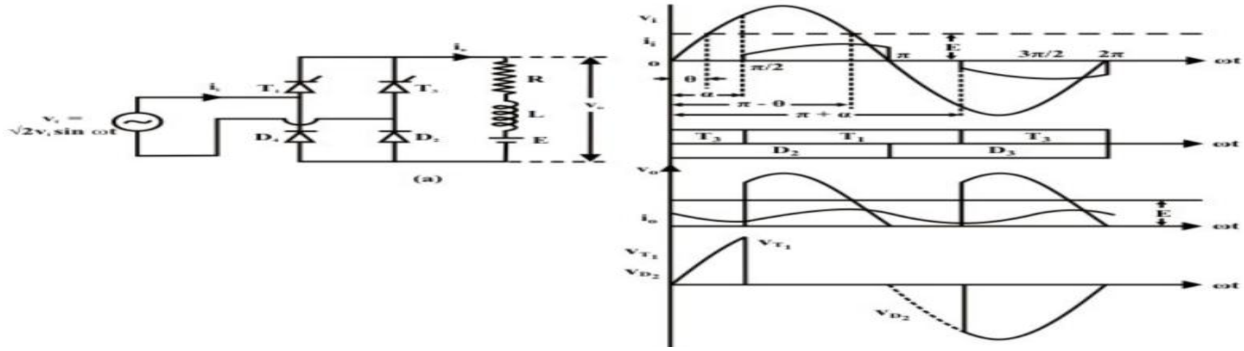

Figure: 1. 4. single phase half controlled converter motor load

Referring to Fig T1 D2 starts conduction at ωt = α. Output voltage during this period becomes equal to vi. At ωt = π as vi tends to go negative D4 is forward biased and the load current commutates from D2 to D4 and freewheels through D4 and T1. The output voltage remains clamped to zero till T3 is fired at ωt = π + α. The T3 D4 conduction mode continues upto ωt = 2π. Where upon load current again free wheels through T3 and D2 while the load voltage is clamped to zero. From the discussion in the previous paragraph it can be concluded that the output voltage (hence the output current) is periodic over half the input cycle. Hence

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The back emf equation of DC series motor is $E_b = K_a\phi N = K_a I_a N$

$T = K_a I_a^2$

$E_b = V_t - I_a R_a$

$E_b = \frac{Vm}{\pi}(1 + cos\alpha) - IaRa$

$N = \frac{Vm/\pi \ (1+cos\alpha) - IaRa}{KaIa}$

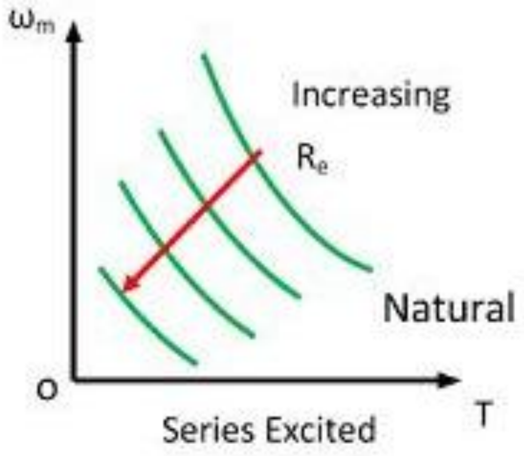


Figure: 1. 5. Speed torque characteristics of series motor

Numerical problems on Single phase semi controlled converters fed DC motors

1. The speed of a 10 HP, 210V, 1000rpm separately excited dc motors is controlled by a single phase semi converter. The rated motor armature current is 30A and the armature resistance is 0.25Ω. The AC supply voltage is 230V; the motor voltage constant is 0.172V/rpm. Assume continuous armature current

For a firing angle of 45^0 and rated armature current determine

i. the motor torque
ii. speed of the motor

ANS:

i. Kaϕ = 0.172V/rpm = 0.172*60/2π = 1.64V-S/ rad

T= KaϕIa = 1.64*30 = 49.2Nm

ii. Vt= $\frac{Vm}{\pi}(1+cos\alpha)$=$\frac{\sqrt{2}*230}{\pi}(1+cos45)$ = 176.724V

Eb = Vt- IaRa = 168.5V

N= Eb/Kaϕ = 168.5/0.172= 980 rpm

2. The speed of a 15hp, 220V, 1000 rpm dc series motor is controlled using a single-phase half controlled bridge rectifier. The combined armature and field resistance is 0.2 Ω. Assuming continuous and ripple free motor current and speed of 1000 rpm and K=0.03 Nm/Amp2 determine a) motor current, b) motor torque for a firing angle α=30° AC source voltage is 250 V.

Single phase fully controlled converter with DC separately excited motors

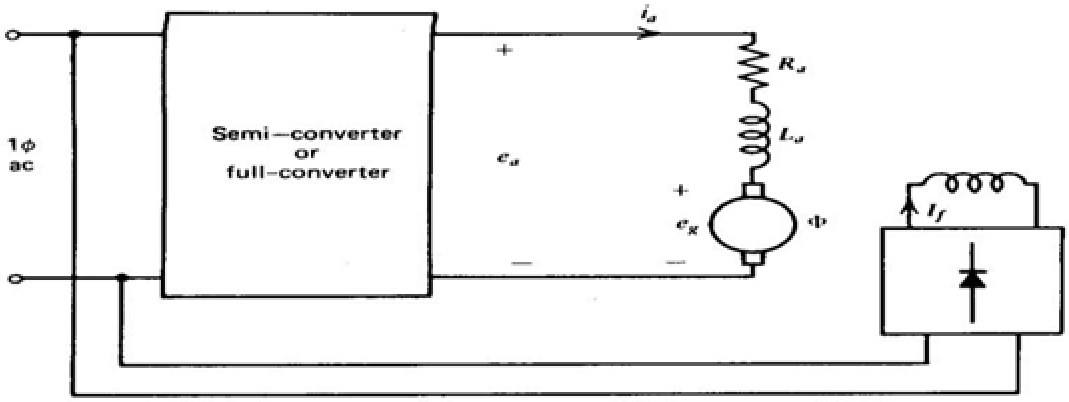


Figure: 1. 6. single phase full controlled converter motor load

The single phase fully controlled rectifier allows conversion of single phase AC into DC. Normally this is used in various applications such as battery charging, speed control of DC motors and front end of UPS (Uninterruptible Power Supply) and SMPS (Switched Mode Power Supply).

- All four devices used are Thyristors. The turn-on instants of these devices are dependent on the firing signals that are given. Turn-off happens when the current through the device reaches zero and it is reverse biased at least for duration equal to the turn-off time of the device specified in the data sheet.

- In positive half cycle Thyristors T1 & T2 are fired at an angle α .
- When T1 & T2 conducts

$V_o=V_s$

$I_O=i_s=V_o/R=V_s/R$

- In negative half cycle of input voltage, SCR's T3 &T4 are triggered at an angle of (π+α)
- Here output current & supply current are in opposite direction

∴ $i_s=-i_o$

T3 & T4 becomes off at 2π.

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} Vmsinwt\, d(wt) = \frac{2Vm}{\pi}\ cos\alpha$$

$$V_0 = \frac{2vm}{\pi} cos\alpha$$

The back emf equation of DC separately excited motor is $E_b = K_a\phi N$

$E_b = V_t - I_aR_a$

$$E_b = \frac{2vm}{\pi} cos\alpha - IaRa$$

$$N= \frac{\frac{2vm}{\pi} cos\alpha - IaRa}{Ka\emptyset}$$

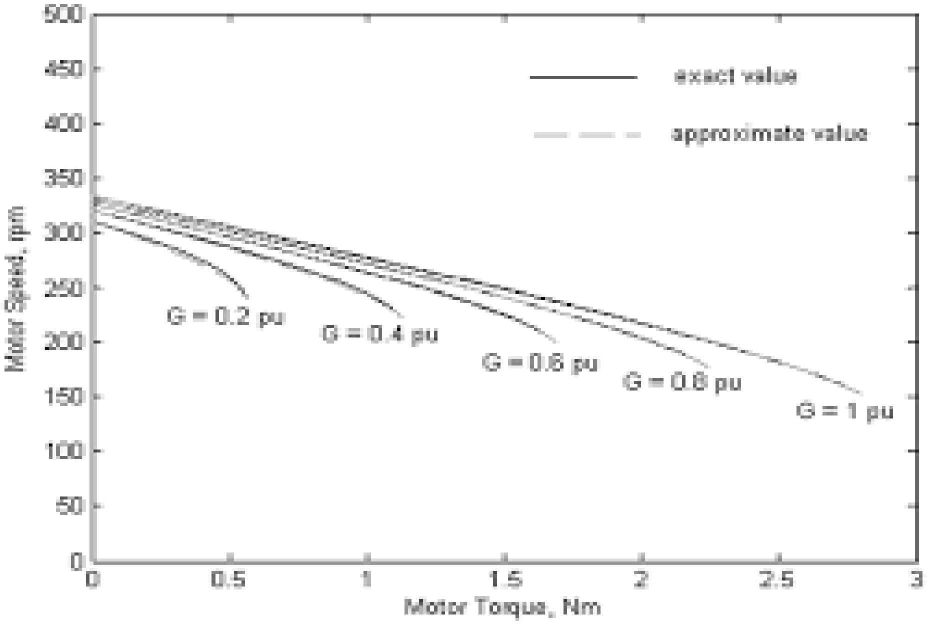
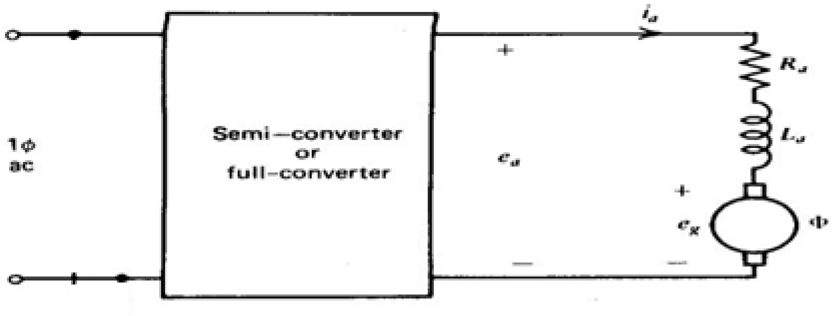


Figure: 1. 7. Speed torque characteristics of separately excited motor

Single phase full controlled converters connected to DC series motors with continuous current operation:



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- When T1 & T2 conducts

Vo=Vs

IO=is=Vo/R=Vs/R

- In negative half cycle of input voltage, SCR’s T3 &T4 are triggered at an angle of (π+α)
- Here output current & supply current are in opposite direction

∴ is=-io

T3 & T4 becomes off at 2π.

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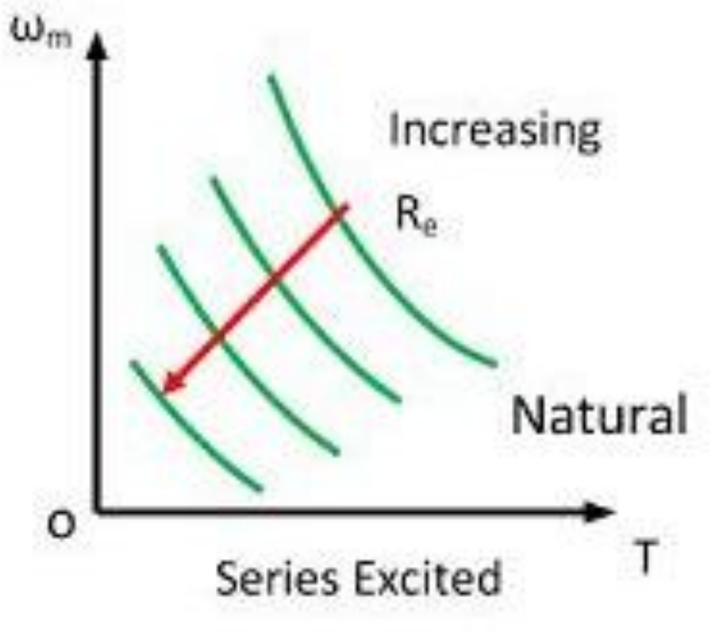

Figure: 1. 9. Speed torque characteristics of series motor

Numerical problems on Single phase fully controlled converters fed DC motors

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For a fring angle of 45^0 and rated armature current determine

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iv. speed of the motor

ANS:

iii. $Ka\phi = 0.172V/rpm = 0.172*60/2\pi = 1.64V\text{-}S/rad$

$T = Ka\phi Ia = 1.64*30 = 49.2Nm$

iv. $Vt = \frac{2Vm}{\pi}(cos\alpha) = \frac{2\sqrt{2}*230}{\pi}(cos45) = 146.42$

$Eb = Vt - IaRa = 138.92$

$N = Eb/Ka\phi = 138.92/0.172 = 807$ rpm

4. A single phase full converter connected to 220 V, 50 Hz at supply is supplying power to a dc series motor. The combined armature resistance and field resistance is 0.5 Ω. The firing angle os the converter is 45°. The back emf is 100 V. The average current drawn by the motor is

Three phase semi controlled converters connected to DC separately excited motors with continuous current operation

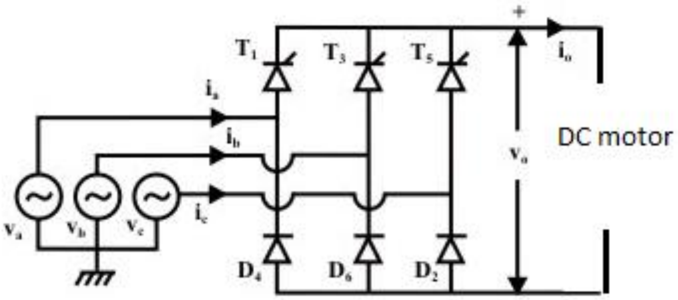


Figure: 1.10 circuit diagram three phase half controlled rectifier

Three phase half wave controlled rectifier output voltage waveforms for different trigger angles with R load

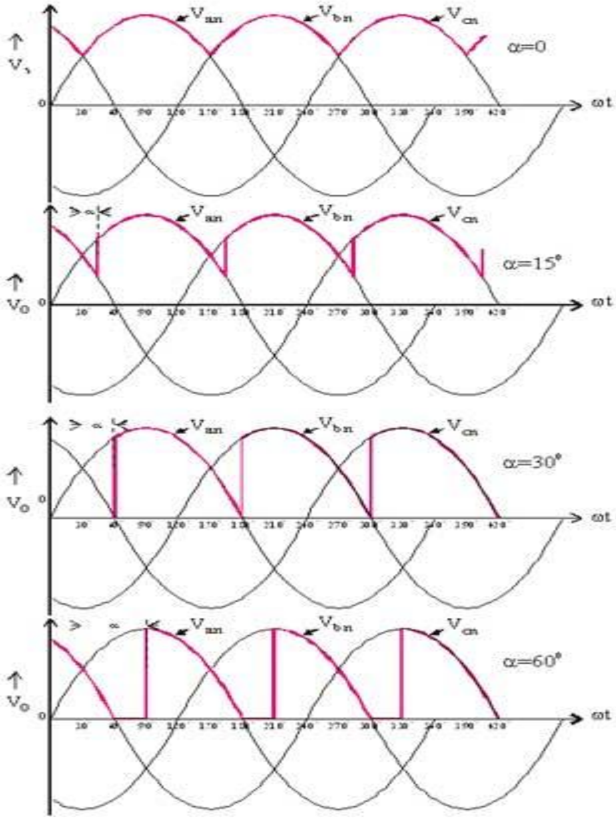


Figure: 1.11 input and output waveforms of three phase half controlled rectifier

Three single phase half wave converters can be connected to form a three phase half wave converter. Similarly three phase semi converter uses 3 SCRs T1, T3 & T5 and 3 diodes D2, D4&D6 In the circuit shown above when any device conducts, line voltage is applied across load. so line voltage are necessary to draw Phase shift between two line voltages is 60 degree & between two phase voltages it is 120 degree Each phase & line voltage is sine wave with the frequency of 50 Hz. R,Y,B are phase voltages with respect to ‘N’.

In the case of a **three-phase half wave controlled** rectifier with resistive load, the thyristor T_1 is triggered at $\omega t=(30^\circ+\alpha)$and T_1 conducts up to $\omega t=180^\circ=$*&pron;* radians. When the phase supply voltage decreases to zero at , the load current falls to zero and the thyristor T_1 turns off. Thus T_1 conducts from $\omega t=(30^\circ + \alpha)$ *to* (180°).

Hence the average dc output voltage for a 3-pulse converter (3-phase half wave controlled rectifier) is calculated by using the equation

The average output voltage $V_{avg} = \frac{3}{2\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}} \mathrm{Vmlsinwt}\, d(wt) + \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}+\alpha} \mathrm{Vmlsinwt}\, d(wt)$

$$= \frac{3Vml}{2\pi}\ (1 + cos\alpha)$$

The back emf equation of DC separately excited motor is $E_b = K_a\phi N$

$E_b = V_t - I_aR_a$

$E_b = \frac{Vm}{\pi}(1 + cos\alpha) - IaRa$

$N = \frac{Vm/\pi\ (1+cos\alpha)-IaRa}{Ka\emptyset}$

Three phase semi controlled converters connected to DC series motors with continuous current operation

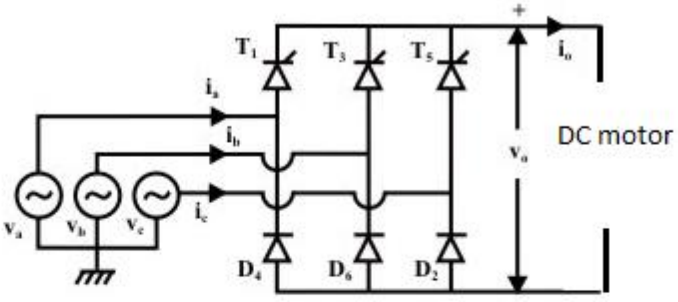
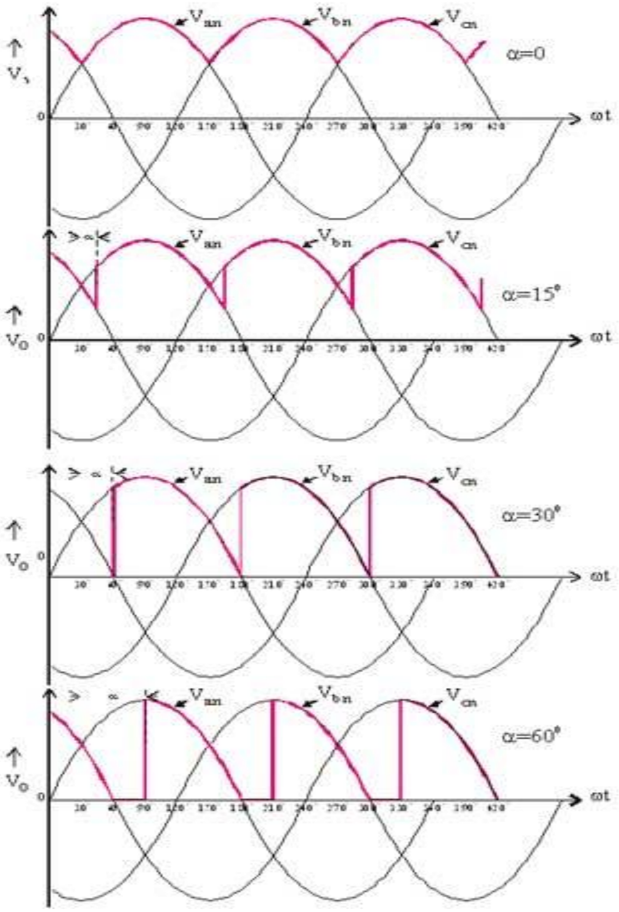


Figure: 1.12 circuit diagram three phase half controlled rectifier

Three phase half wave controlled rectifier output voltage waveforms for different trigger angles with R load



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$$= \frac{3Vml}{2\pi}\ (1 + cos\alpha)$$

The back emf equation of DC series motor is $E_b = K_a\phi N = K_aI_aN$

$T = K_aI_a^2$

$E_b = V_t - I_aR_a$

$E_b = \frac{3Vml}{2\pi}\ (1 + cos\alpha) - IaRa$

$N = \frac{\frac{3Vml}{2\pi}(1+cos\alpha) - IaRa}{KaIa}$

Numerical problems on three phase semi controlled converters fed DC motors

1. The speed of a separately excited dc motors is controlled by a three phase semi converter from a three phase 415V 50Hz supply. The motor constants are inductance 10mH, resistance 0.9Ω and armature constant 1.5 v-s/rad. Calculate the speed of the motor at a torque of 50Nmwhen converter is fired at 45^0. Neglect losses in the converter

Kaϕ = 1.5 v-s/rad

T= KaϕIa = 50Nm

Ia = 50/1.5 = 33.33A

3Vmlcosα/2π = Eb+IaRa

$$\frac{3\sqrt{2}415}{2\pi}cos45 = 1.5 * w + 33.33 * 0.9$$

198.147 = 1.5w+30

W= 168.147/1.5 = 112rps = 1069rpm

2. A 600V, 1500rpm, 80A separately excited dc motor is fed through a three- phase semi converter from 3-phase400supply. Motor armature resistance is 1 Ω the armature current assumed constant. For a firing angle of 45^0 at 1200rpm ,compute the rms value of source and thyristor currents, average value of thyristor current and the input supply power factor

Three Phase Fully Controlled Converter Fed Separately Excited D.C Motor Drive

Three phase controlled rectifiers are used in large power DC motor drives. Three phase controlled rectifier gives more number of voltages per cycle of supply frequency. This makes motor current continuous and filter requirement also less.

The number of voltage pulses per cycle depends upon the number of thyristors and their connections for three phase controlled rectifiers. In three phase drives, the armature circuit is connected to the output of a three phase controlled rectifier.

Three phase drives are used for high power applications up to megawatts power level. The ripple frequency of armature voltage is greater than that of the single phase drives and its requires less inductance in the armature circuit to reduce the armature current ripple

Three phase full converter are used in industrial application up to 1500KW drives. It is a two quadrant converter

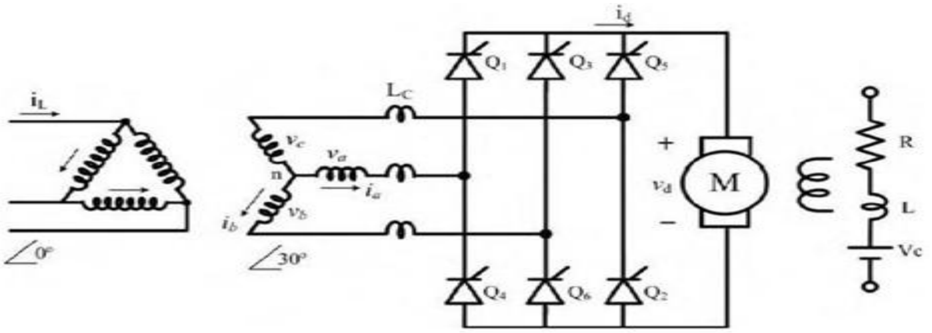


Figure: 1.14 circuit diagram three phase full controlled rectifier

Three phase full converter bridge circuit connected across the armature terminals is shown fig. The voltage and current waveforms of the converter. The circuit works as a three AC to DC converter for firing angle delay $0^0 < \alpha < 90^0$ and as a line commutated inverter for $90^0 < \alpha < 180^0$. A three full converter fed DC motor is performed where generation of power is required.

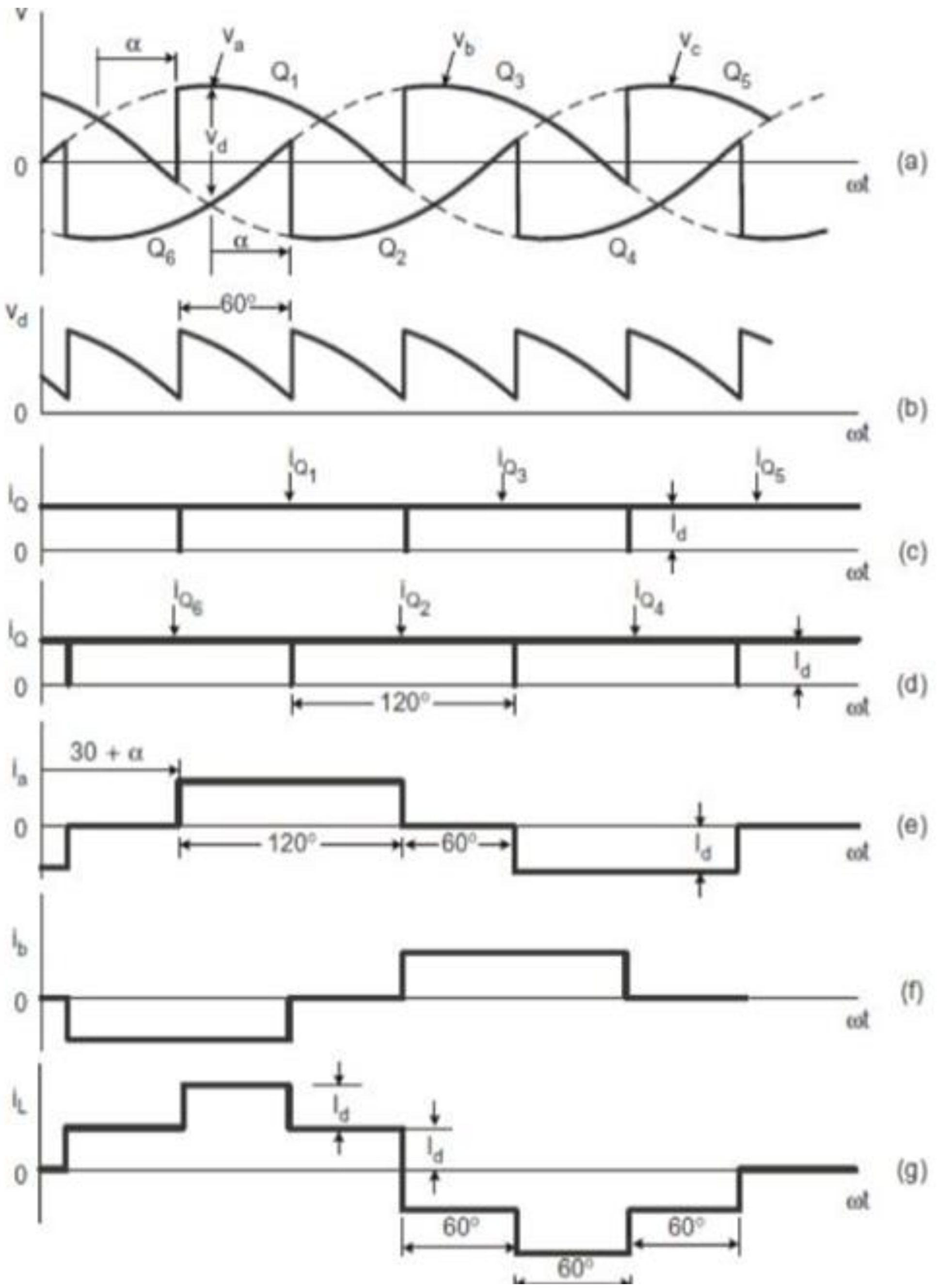


Figure: 1.15 output waveforms of three phase full controlled rectifier

The back emf equation of DC separately excited motor is $E_b = K_a\phi N$

$E_b = V_t - I_aR_a$

$$V_{avg} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \mathrm{Vod(wt)}$$

$$V_o = V_{ab} = \sqrt{3}\,\mathrm{Vm}\sin\left(\mathrm{wt}+\frac{\pi}{6}\right)$$

$$V_{avg} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}\,\mathrm{Vm}\sin\left(\mathrm{wt}+\frac{\pi}{6}\right)\mathrm{d(wt)}$$

$$= \frac{3\sqrt{3}Vm}{\pi}\ cos\alpha$$

$$= \frac{3Vml}{\pi}\ cos\alpha$$

$E_b = \frac{3Vml}{\pi}\ cos\alpha - I_aR_a$

N= Eb/ Kaϕ

Numerical problems on three phase fully controlled converters fed DC motors

5. The speed of a separately excited dc motors is controlled by a three phase semi converter from a three phase 415V 50Hz supply. The motor constants are inductance 10mH, resistance 0.9Ω and armature constant 1.5 v-s/rad. Calculate the speed of the motor at a torque of 50Nmwhen converter is fired at 45^0. Neglect losses in the converter

   Kaϕ = 1.5 v-s/rad

   T= KaϕIa = 50Nm

   Ia = 50/1.5 = 33.33A

   3Vmlcosα/2π = Eb+IaRa

   $$\frac{3\sqrt{2}415}{2\pi}cos45 = 1.5 * w + 33.33 * 0.9$$

   198.147 = 1.5w+30

   W= 168.147/1.5 = 112rps = 1069rpm

6. A 100kW, 500 V, 2000 rpm separately excited dc motor is energized from 400 V, 50Hz, 3-phase source through a 3-phase full converter. The voltage drop in conducting thyristors is 2V. The dc motor parameters are as under: Ra =0.1Ω,Km=1.6V-s/rad, La=8mH. Rated armature current=21A. No-load armature current =10% of rated current. Armature current is continuous and ripple free.
   i. Find the no-load speed at firing angle of 30^0
   ii. Find the firing angle for a speed of 2000 rpm at rated armature current. Determine also the supply power factor.

UNIT-II

SPEED CONTROL OF DC MOTORS

Introduction to four quadrant operation: Motoring operations

For consideration of multi quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed.

A motor operates in two modes – Motoring and braking. In motoring, it converts electrical energy into mechanical energy, which supports its motion. In braking it works as a generator converting mechanical energy into electrical energy and thus opposes the motion.

Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure. A decrease in speed causes the load torque to become greater than the motor torque, electric drive decelerates and operating point moves away from point B.

Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B

Similarly operation in quadrant III and IV can be identified as reverse motoring and reverse braking since speed in these quadrants is negative.

For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction of motor and load torques and direction of speed are marked by arrows

The figure represents a DC motor attached to an inertial load. Motor can provide motoring and braking operations for both forward and reverse directions.

Figure shows the torque and speed co-ordinates for both forward and reverse motions. Power developed by a motor is given by the product of speed and torque. For motoring operations Power developed is positive and for braking operations power developed is negative.

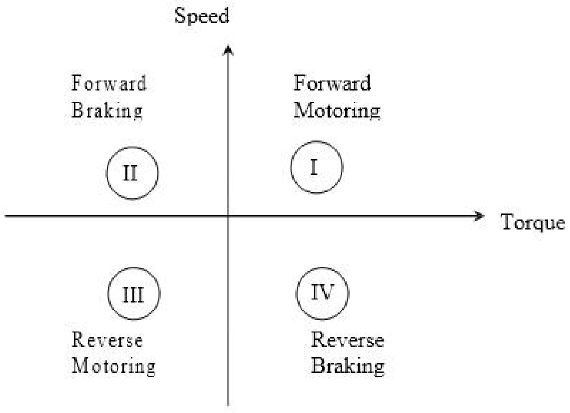


Figure 2.1: Four quadrant operations

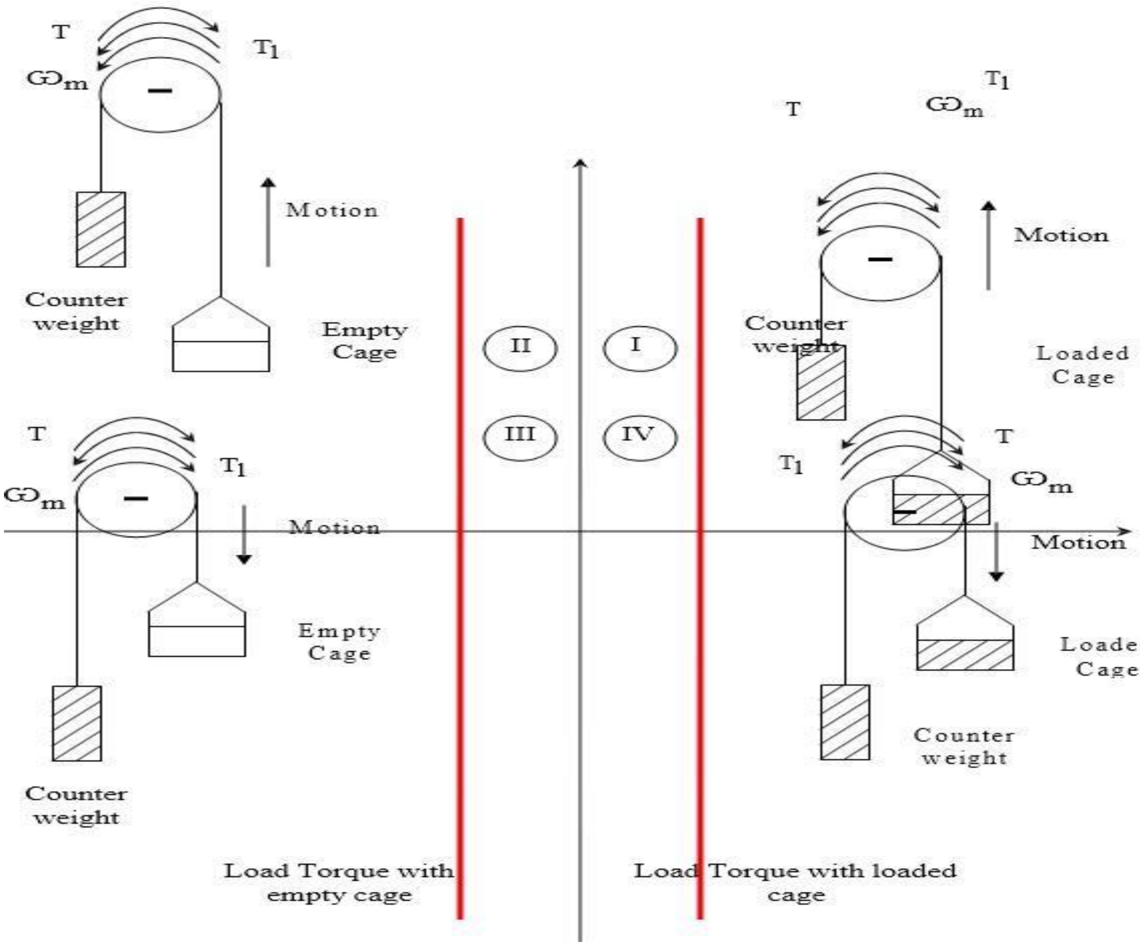


Figure 2.2: Four quadrant operations of DC motor

For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction of motor and load torques and direction of speed are marked by arrows.

A hoist consists of a rope wound on a drum coupled to the motor shaft one end of the rope is tied to a cage which is used to transport man or material from one level to another level . Other end of the rope has a counter weight. Weight of the counter weight is chosen to be higher than the weight of empty cage but lower than of a fully loaded cage.

Forward direction of motor speed will be one which gives upward motion of the cage. Load torque line in quadrants I and IV represents speed-torque characteristics of the loaded hoist. This torque is the difference of torques due to loaded hoist and counter weight. The load torque in quadrants II and III is the speed torque characteristics for an empty hoist.

This torque is the difference of torques due to counter weight and the empty hoist. Its sigh is negative because the counter weight is always higher than that of an empty cage. The quadrant I operation of a hoist requires movement of cage upward, which corresponds to the positive motor speed which is in counter clockwise direction here. This motion will be obtained if the motor products positive torque in CCW direction equal to the magnitude of load torque T_{L1}.

Since developed power is positive, this is forward motoring operation. Quadrant IV is obtained when a loaded cage is lowered. Since the weight of the loaded cage is higher than that of the counter weight. It is able to overcome due to gravity itself.

In order to limit the cage within a safe value, motor must produce a positive torque T equal to T_{L2} in anticlockwise direction. As both power and speed are negative, drive is operating in reverse braking operation. Operation in quadrant II is obtained when an empty cage is moved up. Since a counter weigh is heavier than an empty cage, its able to pull it up.

In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{L2} in clockwise direction. Since speed is positive and developed power is negative, it's forward braking operation.

Operation in quadrant III is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in CW direction. Since speed is negative and developed power is positive, this is reverse motoring operation. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient state operation.

Electric braking operations plugging, dynamic braking

The term braking comes from the term brake. We know that brake is an equipment to reduce the speed of any moving or rotating equipment, like vehicles, locomotives. The process of applying brakes can be termed as braking. Now coming to the term or question **what is braking**. First of all we can classify the term braking in two parts i) mechanical braking and the ii) electrical braking. Mechanical braking is left out here because as it is an electrical engineering site, we should only focus on electrical braking here. In mechanical braking the speed of the machine is reduced solely by mechanical process but electrical braking is far more interesting than that because the whole process is depended on the flux and torque directions. We will further see through the various types of braking but the main idea behind each type of barking is the reversal of the direction of the flux. So, we can understand that when it is asked that **what is braking**? We can say that it is the process of reducing speed of any rotating machine. The application of braking is seen at almost every possible area, be it inside the motor used in factories, industrial areas or be it in locomotives or vehicles. Everywhere the use of mechanical and electrical brakes is inevitable.

Types of Braking

Brakes are used to reduce or cease the speed of motors. We know that there are various types of motors available (DC motors, induction motors, synchronous motors, single phase motors etc.) and the specialty and properties of these motors are different from each other, hence this braking methods also differs from each other. But we can divide braking in to three parts mainly, which are applicable for almost every type of motors.

i) Regenerative Braking

ii) Plugging type braking

iii) Dynamic braking

Dynamic Braking

Another method of reversing the direction of torque and braking the motor is **dynamic braking**. In this method of braking the motor which is at a running condition is disconnected from the source and connected across a resistance. When the motor is disconnected from the source, the rotor keeps rotating due to inertia and it works as a self –excited generator. When the motor works as a generator the flow of the current and torque reverses. During braking to maintain the steady torque sectional resistances are cut out one by one.

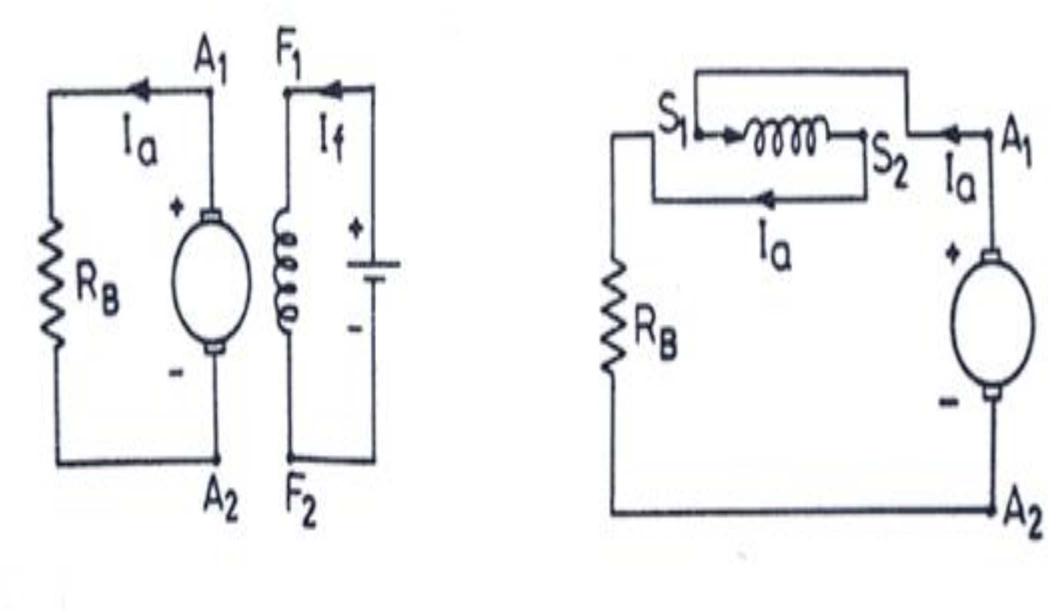


Figure 2.3: Dynamic braking of DC motors

Plugging Type Braking

Another type of braking is **plugging type braking**. In this method the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases. During plugging external resistance is also introduced into the circuit to limit the flowing current. The main disadvantage of this method is that here power is wasted.

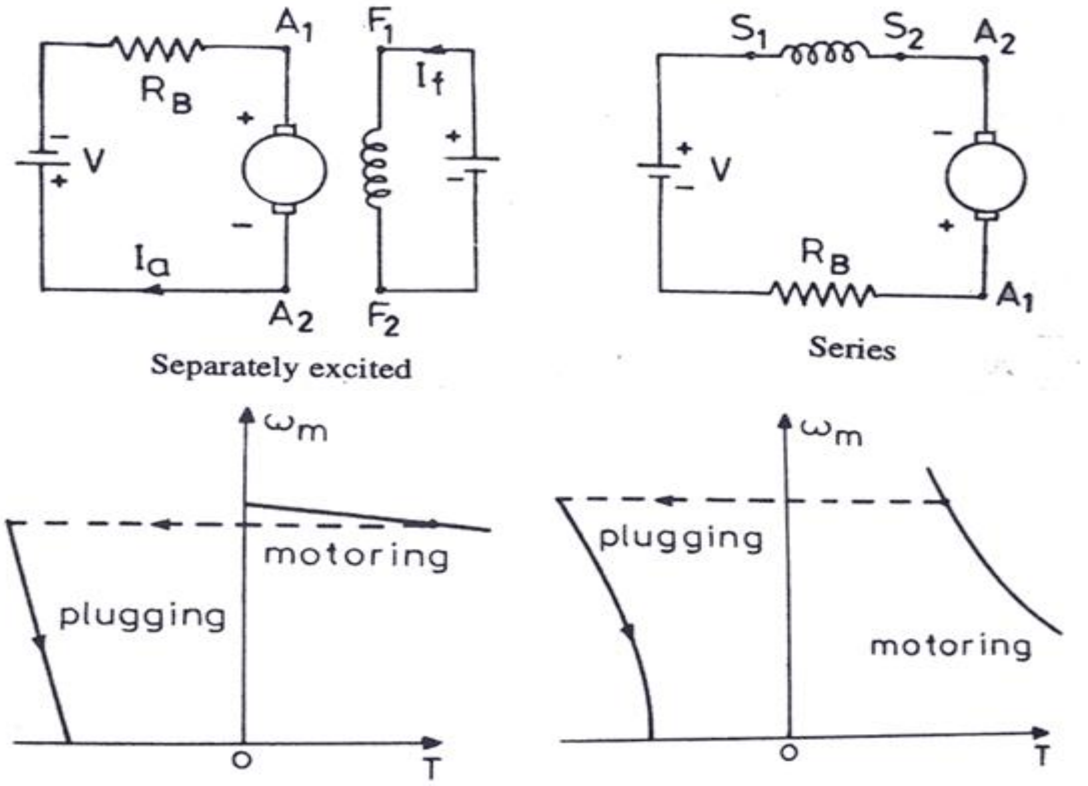


Figure: 2.4: plugging of DC motor

Regenerative braking operations:

Regenerative braking takes place whenever the speed of the motor exceeds the synchronous speed. This baking method is called regenerative braking because here the motor works as generator and supply itself is given power from the load, i.e. motors. The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed, only then the motor will act as a generator and the direction of current flow through the circuit and direction of the torque reverses and braking takes place. The only disadvantage of this type of braking is that the motor has to run at super synchronous speed which may damage the motor mechanically and electrically, but regenerative braking can be done at sub synchronous speed if the variable frequency source is available.

In the regenerative braking operation, the motor operates as generator, while it is still connected to the supply. Here, the motor speed is greater than the synchronous speed.

Mechanical energy is converted into electrical energy, part of which is returned to the supply and rest of the energy is last as heat in the winding and bearings of electrical machines pass smoothly from motoring region to generating region, when over driven bythe load.

An example of regenerative braking is shown in the figure below. Here an electric motor is driving a trolley bus in the uphill and downhill direction. The gravity force can be resolved into two components in the uphill direction.

One is perpendicular to the load surface (F) and another one is parallel to the road surface Fl. The parallel force pulls the motor towards bottom of the hill.

If we neglect the rotational losses, the motor must produce force Fm opposite to Fl to move the bus in the uphill direction.

Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power flows from mechanical load to source.

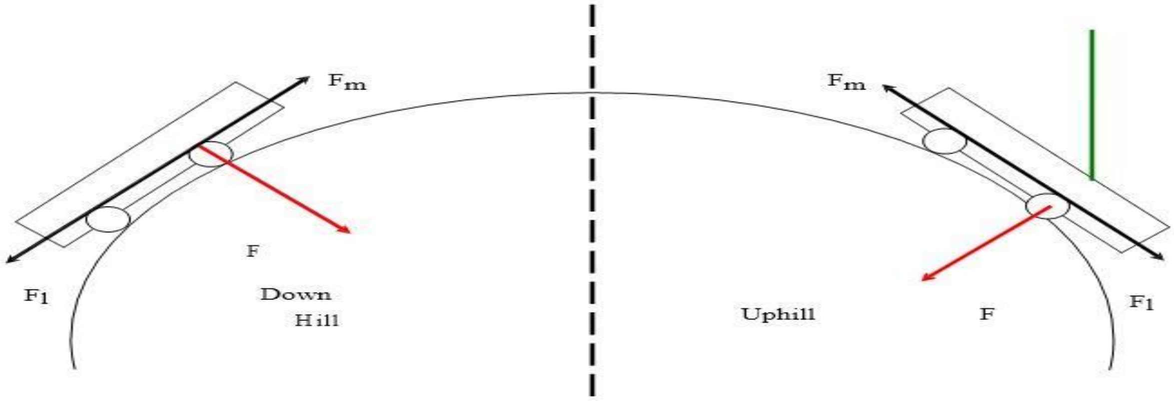


Figure 2.5: Regenerative braking of electric vehicle

This operation is indicated as shown in the figure below in the first quadrant. Here the power flow is from the motor to load.

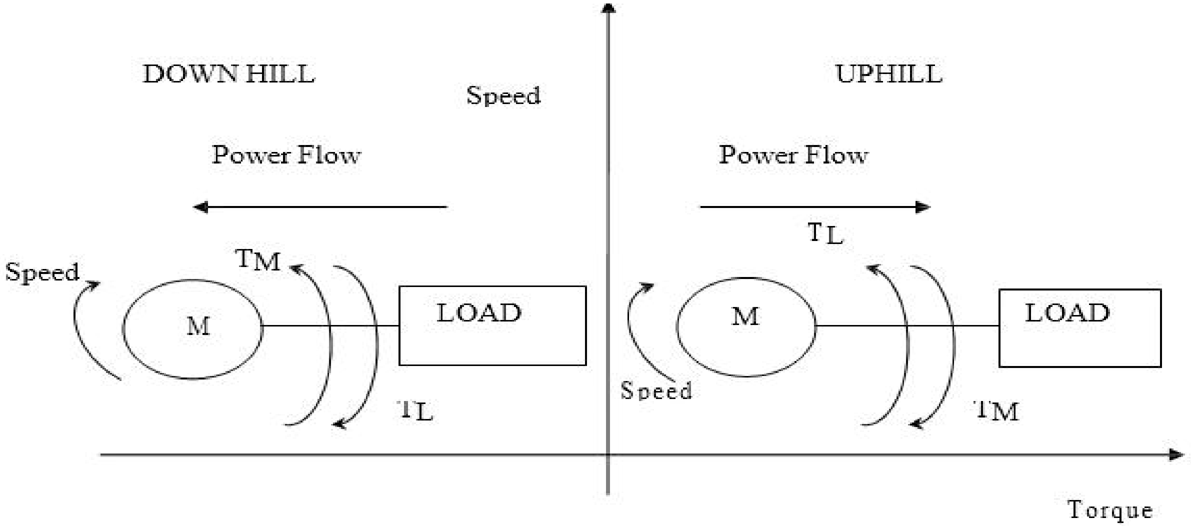


Figure 2.6: Regenerative braking operations of electric vehicle

Now we consider that the same bus is traveling in downhill, the gravitational force doesn't change its direction but the load torque pushes the motor towards the bottom of the hill. The motor produces a torque in the reverse direction because the direction of the motor torque is always opposite to the direction of the load torque.

Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power flows from mechanical load to source. Hence, the load is driving the machine and the machine is generating electric power that is returned to the supply.

Regenerative Braking for DC motor:

In regenerative braking of dc motor, generated energy is supplied to the source. For this the following condition is to be satisfied.

$E > V$ and I_a should be negative

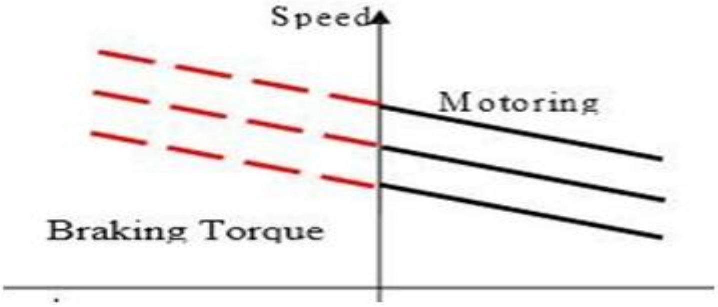


Figure 2.7: Regenerative braking speed torque characteristics of dc shunt motor

Analyze the four quadrant operation of DC Drive with dual converter and closed loop operation:

Separately-excited dc shunt motor can be operated in either direction in either of the two modes, the two modes being the motoring mode and the regenerating mode. It can be seen that the motor can operate in any of the four quadrants and the armature of the dc motor in a fast four-quadrant drive is usually supplied power through a dual converter. The dual converter can be operated with either circulating current or without circulating current. If both the converters conduct at the same time, there would be circulating current and the level of circulating current is restricted by provision of an inductor. It is possible to operate only one converter at any instant, but switching from one converter to the other would be carried out after a small delay. This page describes the operation of a dual converter operating without circulating current.

As shown in Fig. the motor is operated such that it can deliver maximum torque below its base speed and maximum power above its base speed. To control the speed below its base speed, the voltage applied to the armature of motor is varied with the field voltage held at its nominal value. To control the speed above its base speed, the armature is supplied with its rated voltage and the field is weakened. It means that an additional single-phase controlled rectifier circuit is needed for field control. Closed-loop control in the field-weakening mode tends to be difficult because of the relatively large time constant of the field.

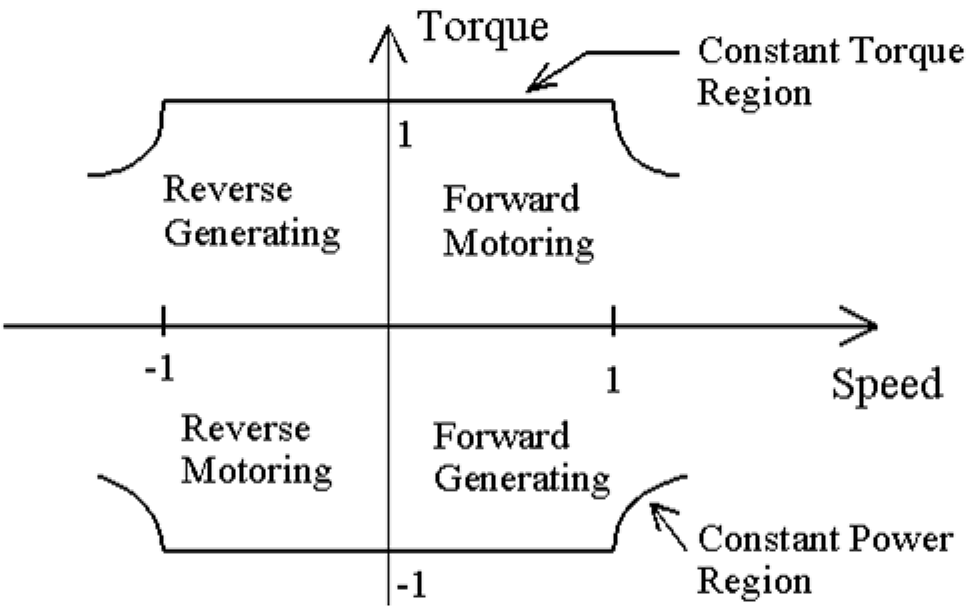


Figure 2.8: Four quadrant operations

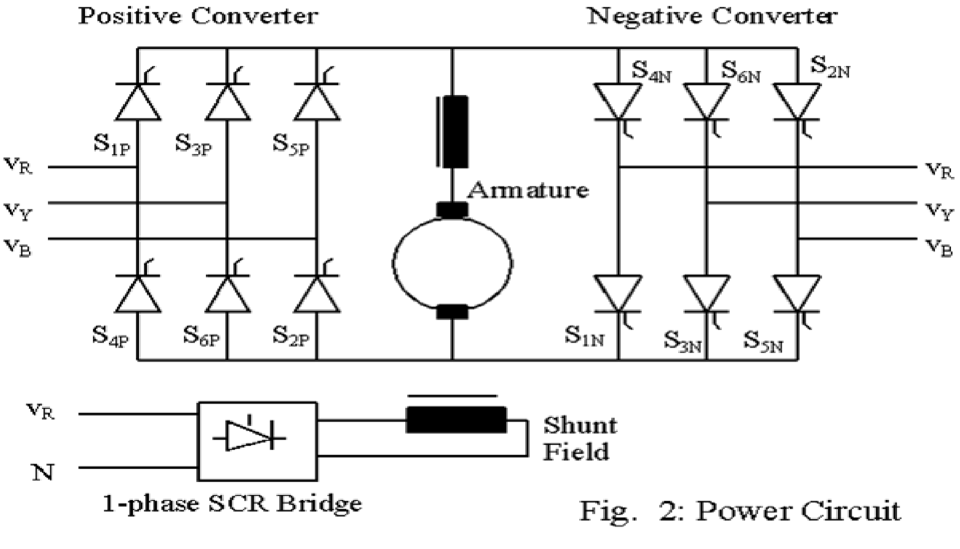


Figure 2.9: Dual converter fed DC motor

Each converter has six SCRs. The converter that conducts for forward motoring is called the positive converter and the other converter is called the negative converter. The names given are arbitrary. Instead of naming the converters as positive and negative converter, the names could have been the forward and reverse converter. The field is also connected to a controlled-bridge in order to bring about field weakening.

The circuit shown above can be re-drawn as shown in Fig. Usually an inductor is inserted in each line as shown in Fig. and this inductor reduces the impact of notches on line voltages that occur during commutation overlap.

Closed loop operation of DC motor with four quadrant operations:

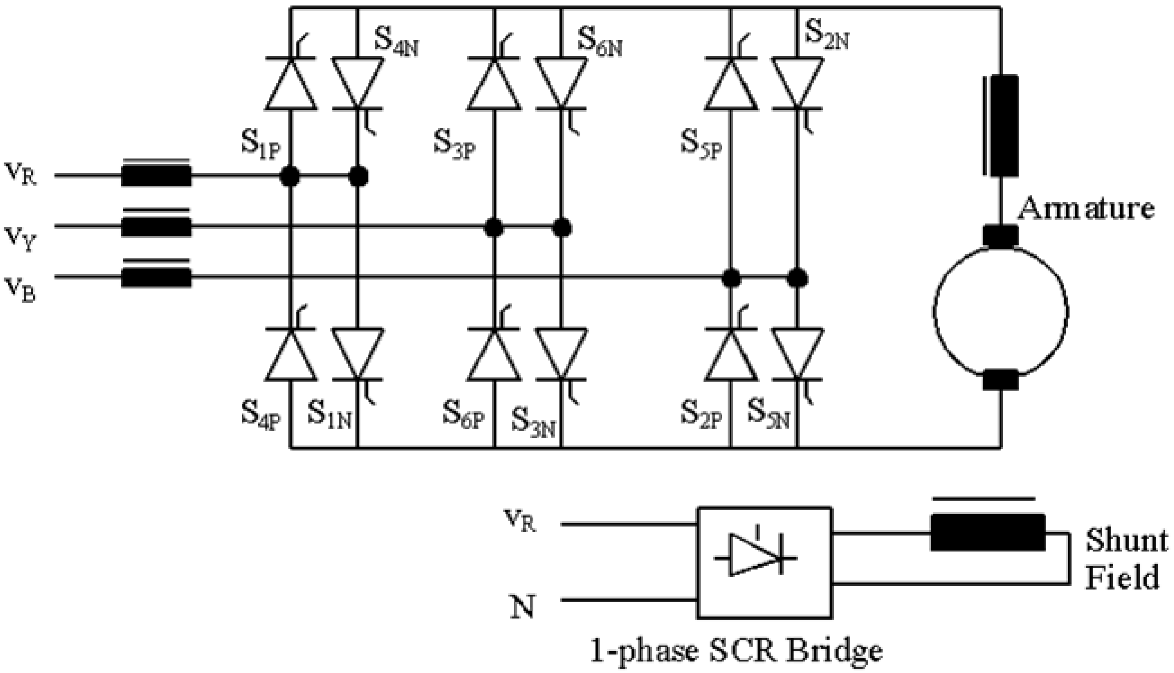


Figure 2.8: Dual converter fed DC separately excited motor

Circuit Operation

The operation of the circuit in the circulating-current free mode is not very much different from that described in the previous pages. In order to drive the motor in the forward direction, the positive converter is controlled. To control the motor in the reverse direction, the negative converter is controlled. When the motor is to be changed fast from a high value to a low value in the forward direction, the conduction has to switch from the positive converter to the negative converter. Then the direction of current flow changes in the motor and it regenerates, feeding power back to the source. When the speed is to be reduced in the reverse direction, the conduction has to switch from the negative converter to the positive converter. The conduction has to switch from one converter to the other when the direction of motor rotation is to change.

At the instant when the switch from one converter to the other is to occur, it would be preferable to ensure that the average output voltage of either converter is the same. Let the firing angle of the positive converter be $a_{P,}$ and the firing angle of the negative converter be $a_{N\,.}$ If the peak line voltage be U, then equation (1) should apply. Equation (1) leads to equation (2). Then the sum of firing angles of the two converters is p, as shown in equation (3).

$$\frac{3U}{\pi} \times \mathrm{Cos}\ (\alpha_P) = -\frac{3U}{\pi} \times \mathrm{Cos}\ (\alpha_N) \quad (1)$$

$$\mathrm{Cos}\ (\alpha_P) = \mathrm{Cos}\ (\pi - \alpha_N) \quad (2)$$

$$\alpha_P + \alpha_N = \pi \quad (3)$$

In a dual-converter, the firing angles for the converter are changed according to equation (3). But it needs to be emphasized that only one converter operates at any instant.

When the speed of the motor is to be increased above its base speed, the voltage applied to the armature is kept at its nominal value and the phase-angle of the single phase bridge is varied such that the field current is set to a value below its nominal value. If the nominal speed of the motor is 1500 rpm, then the maximum speed at which it can run cannot exceed a certain value, say 2000 rpm. Above this speed, the rotational stresses can affect the commutator and the motor can get damaged.

Single quadrant chopper fed DC separately excited and series motors with continuous current operation:

Time Ratio Control (TRC)

In this control scheme, time ratio Ton/T (duty ratio) is varied. This is realized by two different ways called Constant Frequency System and Variable Frequency System as described below:

Constant Frequency System

In this scheme, on-time is varied but chopping frequency f is kept constant. Variation of Ton means adjustment of pulse width, as such this scheme is also called pulse-width-modulation scheme.

Variable Frequency System

In this technique, the chopping frequency f is varied and either (i) on-time T_{on} is kept constant or

(ii) off-time T_{off} is kept constant. This method of controlling duty ratio is also called Frequency-modulation scheme.

Current- Limit Control

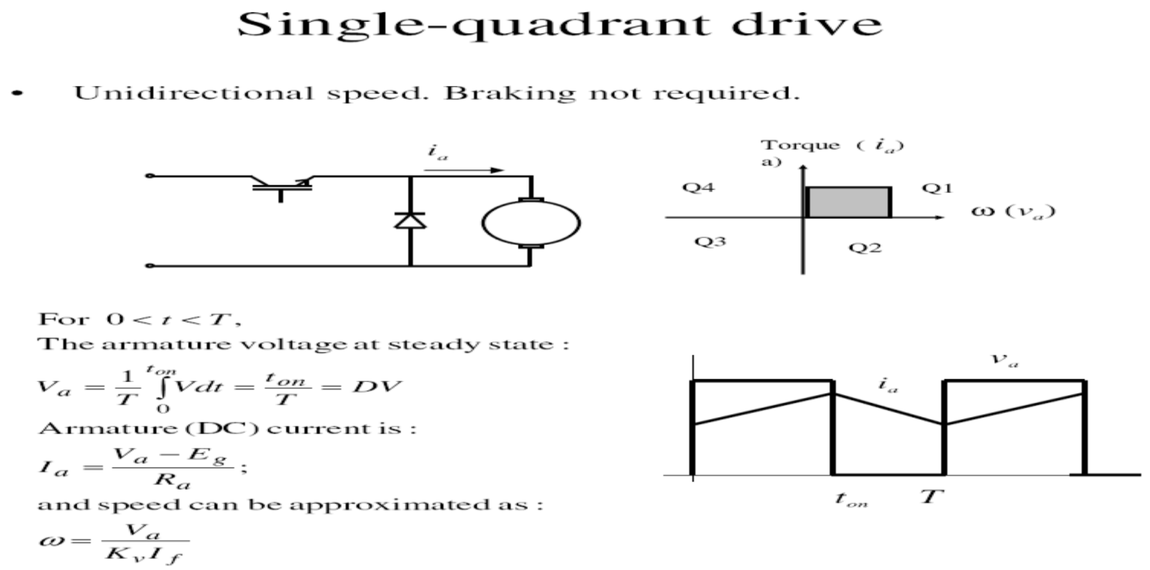
In this control strategy, the on and off of chopper circuit is decided by the previous set value of load current. The two set values are maximum load current and minimum load current.

When the load current reaches the upper limit, chopper is switched off. When the load current falls below lower limit, the chopper is switched on. Switching frequency of chopper can be controlled by setting maximum and minimum level of current.

Current limit control involves feedback loop, the trigger circuit for the chopper is therefore more complex. PWM technique is the commonly chosen control strategy for the power control in chopper circuit

Chopper fed DC drives

- Supply is DC (maybe from rectified-filtered AC, or some other DC sources).
- DC-DC converters (coppers) are used.
- suitable for applications requiring position control or fast response, for example in servo applications, robotics, etc.
- Normally operate at high frequency



Single-quadrant drive

- Unidirectional speed. Braking not required.

For $0 < t < T$,

The armature voltage at steady state :

$$V_a = \frac{1}{T}\int_0^{t_{on}} V dt = \frac{t_{on}}{T} = DV$$

Armature (DC) current is :

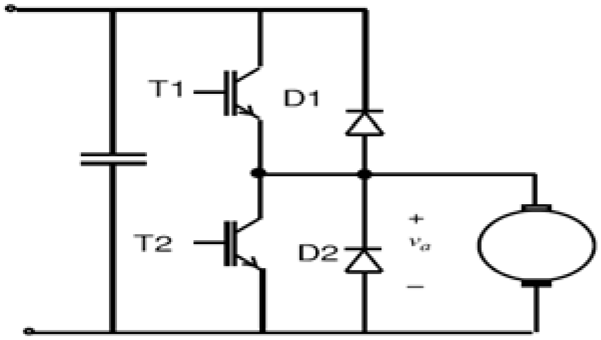
$$I_a = \frac{V_a - E_g}{R_a};$$

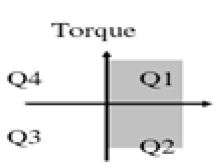
and speed can be approximated as :

$$\omega = \frac{V_a}{K_v I_f}$$

Two quadrant chopper fed DC separately excited and series motors with continuous current operation

- FORWARD MOTORING (T1 and D2 operate)
  - T1 on: The supply is connected to motor terminal.
  - T1 off: The armature current freewheels through D2.
  - V_a (hence speed) is determined by the duty ratio.
- REGENERATION (T2 and D1 operate)
  - T2 on: motor acts as a generator
  - T2 off:, the motor acting as a generator returns energy to the supply through D2.





Class C Chopper can be used as a step-up or step-down chopper

- Class C Chopper is a combination of Class A and Class B Choppers.
- For first quadrant operation, CH1 is ON or D2 conducts.
- For second quadrant operation, CH2 is ON or D1 conducts.
- When CH1 is ON, the load current is positive.
- The output voltage is equal to ‘V’ & the load receives power from the source.
- When CH1 is turned OFF, energy stored in inductance L forces current to flow through the diode D2 and the output voltage is zero.
- Current continues to flow in positive direction.
- When CH2 is triggered, the voltage E forces current to flow in opposite direction through L and CH2 .
- The output voltage is zero.
- On turning OFF CH2 , the energy stored in the inductance drives current through diode D1 and the supply

- Output voltage is V, the input current becomes negative and power flows from load to source.
- Average output voltage is positive
- Average output current can take both positive and negative values.
- Choppers CH1 & CH2 should not be turned ON simultaneously as it would result in short circuiting the supply.
- Class C Chopper can be used both for dc motor control and regenerative braking of dc motor.

Numerical problems on Chopper fed DC motors:

1. A step up chopper has an input voltage of 150V. The voltage output needed is 450V. Given, that the thyristor has a conducting time of 150μseconds. Calculate the chopping frequency.

Solution −

The chopping frequency (f)

$$f = \frac{1}{T}$$

Where **T** − Chopping time period = $T_{ON} + T_{OFF}$

Given − $V_S = 150V$ $V_0 = 450V$ $T_{ON} = 150\mu sec$

$$V_0 = V_S\left(\frac{T}{T - T_{ON}}\right)$$

$$450 = 150\frac{T}{T - 150^{-6}} \quad T = 225\mu sec$$

Therfore, $f = \frac{1}{225*10^{-6}} = 4.44KHz$

The new voltage output, on condition that the operation is at constant frequency after the halving the pulse width.

Halving the pulse width gives −

$$T_{ON} = \frac{150 \times 10^{-6}}{2} = 75\mu sec$$

The frequency is constant thus,

$$f = 4.44KHz$$

$$T = \frac{1}{f} = 150\mu sec$$

The voltage output is given by −

$$V_0 = V_S\left(\frac{T}{T - T_{ON}}\right) = 150 \times \left(\frac{150 \times 10^{-6}}{(150 - 75) \times 10^{-6}}\right) = 300Volts$$

2. A d.c. series motor, fed from 400 V dc source through a chopper, has the following parameters. Ra = 0.05 Ω, Rs = 0.07 Ω, k = 5* 10-3 Nm/amp^2 the average armature current of 200a ripple free. or a chopper duty cycle of 50%. Determine Input power from the source and ii) Motor speed

Four quadrant chopper fed DC separately excited and series motors with continuous current operation:

A full-bridge DC-DC converter is used.

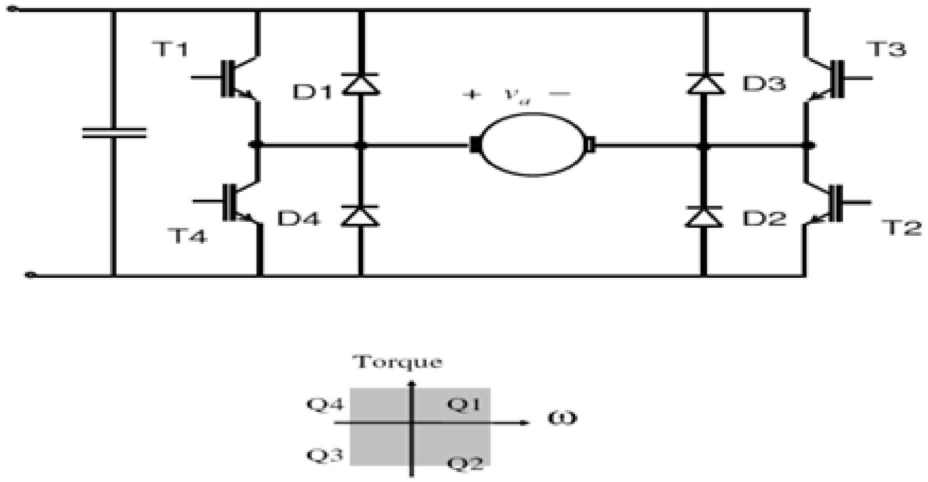


Figure 2.9: Four quadrant chopper drive

- Class E is a four quadrant chopper
- When CH1 and CH4 are triggered, output current i_O flows in positive direction through CH1 and CH4, and with output voltage v_O = V.
- This gives the first quadrant operation.
- When both CH1 and CH4 are OFF, the energy stored in the inductor L drives i_O through D2 and D3 in the same direction, but output voltage v_O = -V.
- Therefore the chopper operates in the fourth quadrant.
- When CH2 and CH3 are triggered, the load current i_O flows in opposite direction & output voltage v_O = -V.
- Since both i_O and v_O are negative, the chopper operates in third quadrant.
- When both CH2 and CH3 are OFF, the load current i_O continues to flow in the same direction D1 and D4 and the output voltage v_O = V.
- Therefore the chopper operates in second quadrant as v_O is positive but i_O is negative.

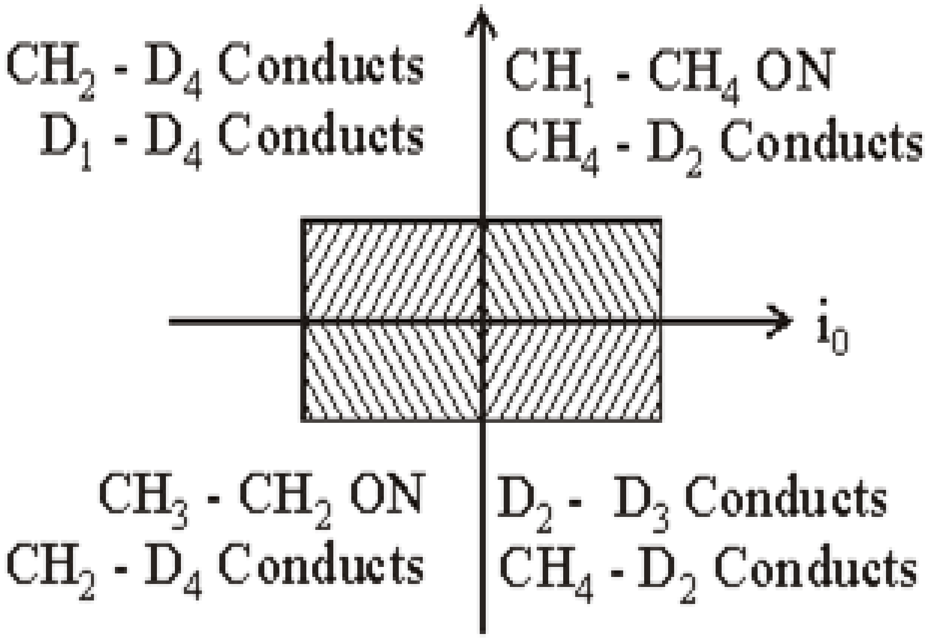


Figure 2.10: Four quadrant operations

Numerical problems on Chopper fed DC motors:

1. In a dc chopper, the average load current is 30 Amps, chopping frequency is 250 Hz. Supply voltage is 110 volts. Calculate the ON and OFF periods of the chopper if the load resistance is 2 ohms.

Solution:

$$I_{dc} = 30 \text{ Amps}, \quad \text{f} = 250 \text{ Hz}, \quad \text{V} = 110 \text{ V}, \quad R = 2\Omega$$

Chopping period, $$T = \frac{1}{f} = \frac{1}{250} = 4\times10^{-3} = 4 \text{ msecs}$$

$$I_{dc} = \frac{V_{dc}}{R} \text{ and } V_{dc} = dV$$

Therefore $$I_{dc} = \frac{dV}{R}$$

$$d = \frac{I_{dc}R}{V} = \frac{30\times2}{110} = 0.545$$

Chopper ON period, $$t_{ON} = dT = 0.545\times4\times10^{-3} = 2.18 \text{ msecs}$$

Chopper OFF period, $$t_{OFF} = T - t_{ON}$$

$$t_{OFF} = 4\times10^{-3} - 2.18\times10^{-3}$$

$$t_{OFF} = 1.82\times10^{-3} = 1.82 \text{ msec}$$

2. A chopper used for ON and OFF control of a dc separately excited motor has supply voltage of 230Vm Ton = 10ms, Toff = 15ms. Neglecting armature inductance and assuming continuous conduction of motor current, Calculate the average load current when the motor speed is 1500 rpm, has a voltage constant Kv = 0.5 V/rad/sec. The armature resistance is 2 Ω.

Closed loop operation of chopper fed DC motors:

Closed Loop Control with Current and Speed Feedback

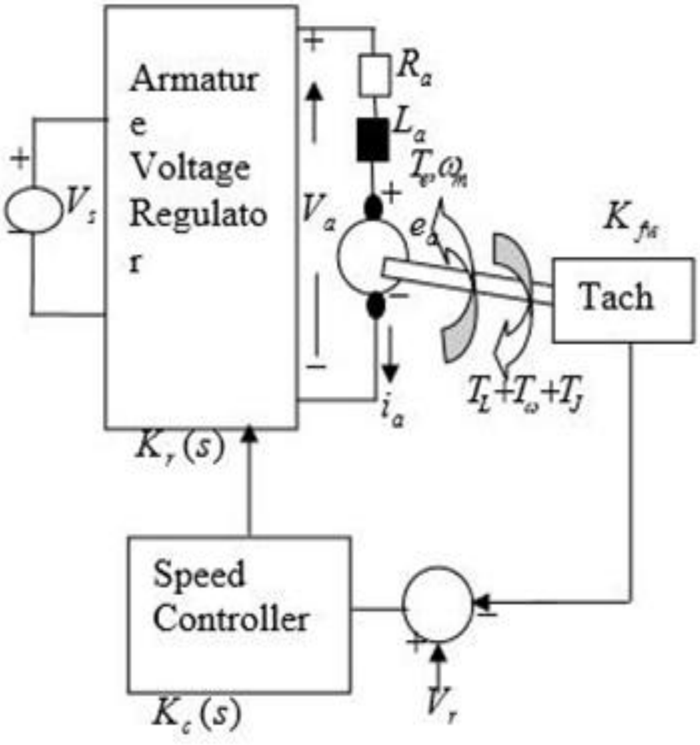


Figure 2.11: closed loop operation of DC motor

Closed loop control improves on the drives performance by increasing speed of response and improving on speed regulation. So the function of closed loop control is that ω_n is increased, ε is reduced, t_s are reduced, and Speed Regulation (SR) is reduced. A closed loop speed control scheme is shown above

Where, $K_{f\omega}$ is the tachometer

feedback gain $K_c(s)$ is the

speed controller gain

$K_r(s)$ is the armature voltage regulator gain

The block diagram representation of the control configuration is shown below.

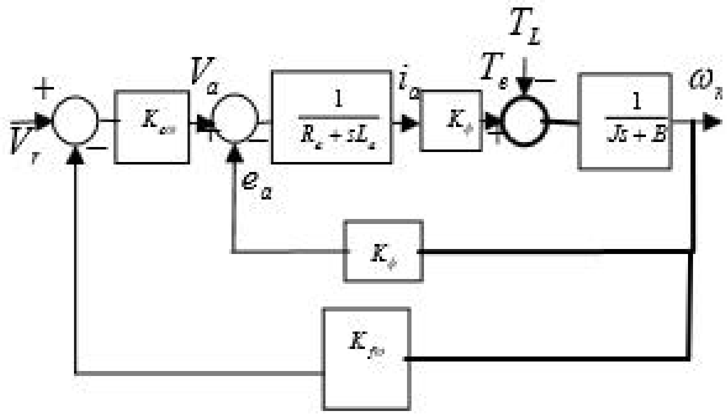


Figure 2.12: Block diagram of closed loop operation of DC motor

If the tachometer loop does not contain a filter, the feedback gain can be a constant designated as Kfw

Kcw(s) = Kcwp + KcwI/ s +sKcwd

Where,

Kcwd is the proportional gain component of Kcw(s)

Kcwp is the integral gain component of Kcw(s)

& Kcwd Three possible controller configurations

is possible:

1.For KcwI & Kcwd zero Kcw(S) = KcwpWhich is a Proportional Controller

2. For Kcwp & Kcwd zero Kcw(S) = KcwI/S Which is an Integral Controller

3. For Kcwd zero Kcw(S) = Kcwp+ KcwI/S Which is a Proportional Integral Controller

Now taking the Proportional Controller as a case study, with Kcw(S) = Kcwp , the dynamic equation is

$$\begin{pmatrix} \omega_m \\ i_a \end{pmatrix} = \frac{\begin{pmatrix} K_\phi K_{c\omega p} & -(R_a + sL_a) \\ (Js+B)K_{c\omega p} & K_\phi K_{f\omega} K_{c\omega p} \end{pmatrix} \begin{pmatrix} V_r \\ T_L \end{pmatrix}}{D_o(s)}$$

UNIT III

SPEED CONTROL OF INDUCTION MOTORS THROUGH VARIABLE VOLTAGE AND VARIABLE FREQUENCY

Introduction to Variable voltage characteristics of induction motor:

A three phase induction motor is basically a constant speed motor so it's somewhat difficult to control its speed. The speed control of induction motor is done at the cost of decrease in efficiency and low electrical power factor. Before discussing the methods to control the speed of three phase induction motor one should know the basic formulas of speed and torque of three phase induction motor as the methods of speed control depends upon these formulas.

Synchronous speed

$$N_s = \frac{120f}{P}$$

Where f = frequency and P is the number of poles The speed of induction motor is given by,

$$N = N_s(1 - s)$$

Where N is the speed of rotor of induction motor, N_s *is the synchronous speed, S is the slip.* The torque produced by three phase induction motor is given by,

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

When rotor is at sand still slip, s is one. So the equation of torque is,

$$T = \frac{3}{2\pi N_s} X \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Where E_2 is the rotor emf N_s is the synchronous speed R_2 is the rotor resistance X_2 is the rotor inductive reactance

The Speed of Induction Motor is changed from Both Stator and Rotor Side

The speed control of three phase induction motor from stator side are further classified as :

1. V / f control or frequency control.

2. Changing the number of stator poles.
3. Controlling supply voltage.
4. Adding rheostat in the stator circuit.

The speed controls of three phase induction motor from rotor side are further classified as:

1. Adding external resistance on rotor side.
2. Cascade control method.
3. Injecting slip frequency emf into rotor side.

Speed Control from Stator Side

1. V / f control or frequency control - Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

   $$N_s = \frac{120f}{P}$$

   In three phase induction motor emf is induced by induction similar to that of transformer which is given by

   $$E\ or\ V = 4.44\phi K.T.f\ or\ \phi = \frac{V}{4.44KTf}$$

   Where K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, its important to maintain flux , φ constant and it is only possible if we change voltage. i.e if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/ f as constant. Hence its name is V/ f method. For controlling the speed of three phase induction motor by V/ f method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

2. Controlling supply voltage: The torque produced by running three phase induction motor is given by

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

In low slip region $(sX)^2$ is very very small as compared to R_2 . So, it can be neglected. So torque becomes

$$T \propto \frac{sE_2^2}{R_2}$$

Since rotor resistance, R_2 is constant so the equation of torque further reduces to

$$T \propto sE_2^2$$

We know that rotor induced emf $E_2 \propto V$. So, $T \propto sV^2$. From the equation above it is clear that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remains the same and it is only possible if we increase the slip and if the slip increases the motor will run at reduced speed . This method of speed control is rarely used because small change in speed requires large reduction in voltage, and hence the current drawn by motor increases, which cause over heating of induction motor.

Control of induction motor by AC voltage controllers:

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.

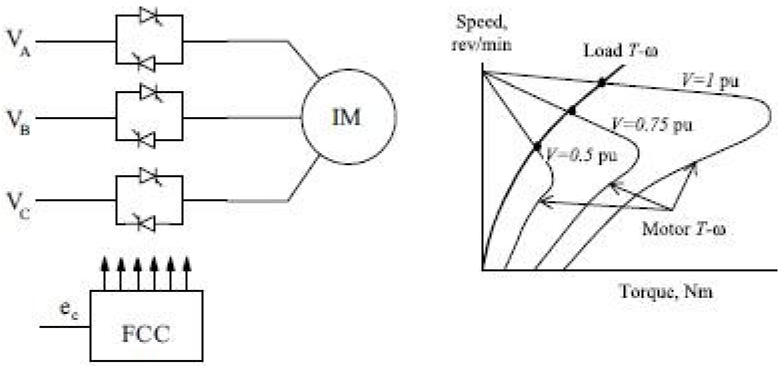


Figure: 3.1 Stator voltage controller and speed characteristics under voltage control.

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

When rotor is at sand still slip, s is one. So the equation of torque is,

$$T = \frac{3}{2\pi N_s} X \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Where E_2 is the rotor emf N_s is the synchronous speed R_2 is the rotor resistance X_2 is the rotor inductive reactance

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

Introduction to variable frequency characteristics of induction motor:

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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

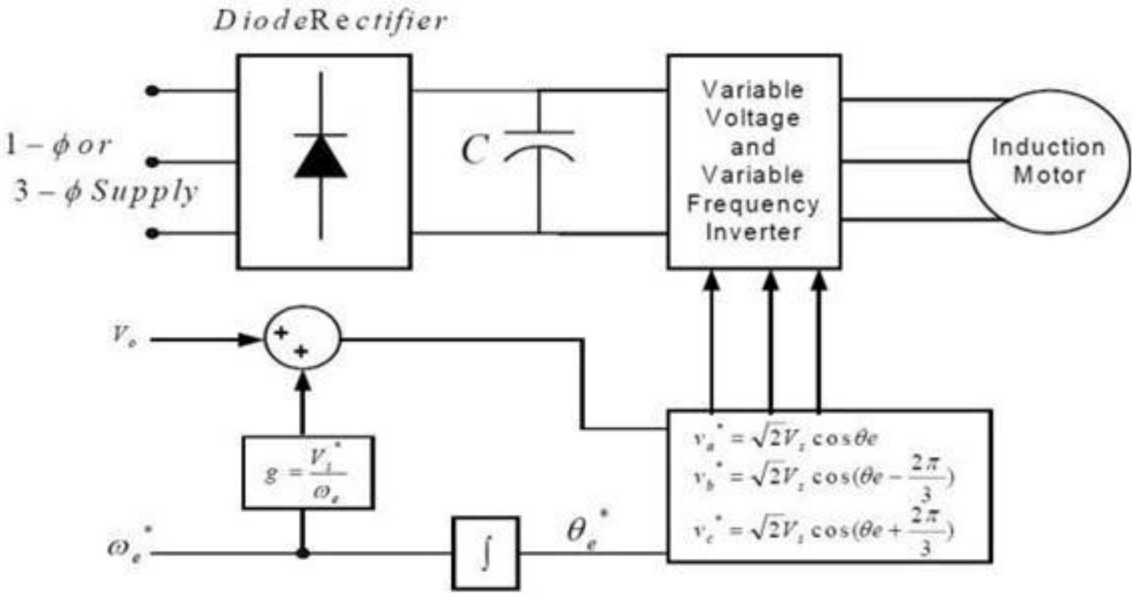

Figure: 3.3: Block diagram of open loop V/F Control for an IM

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

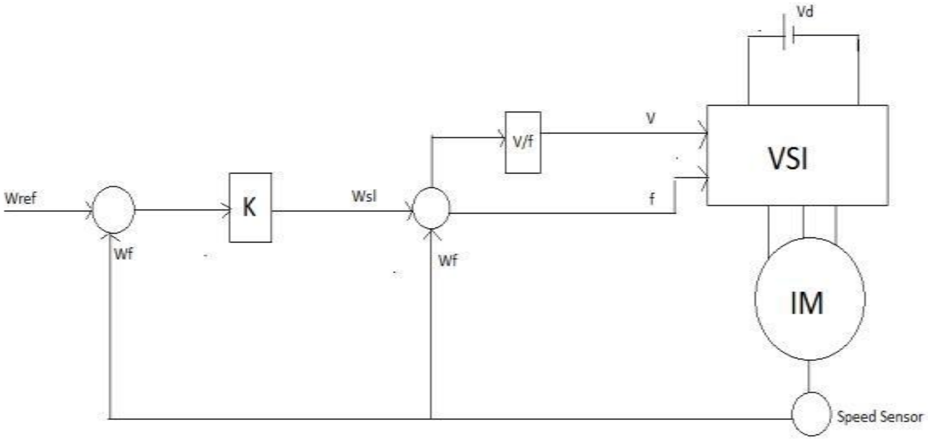

Figure: 3.4: Block diagram for closed loop V/F control for an IM

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. The

synchronous speed, obtained by adding actual speed Ꞷf and the slip speed ꞶSI, determines the inverter frequency The reference signal for the closed-loop control of the machine terminal voltage Ꞷf is generated from frequency

Variable frequency control of induction motor by voltage source inverter:

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.

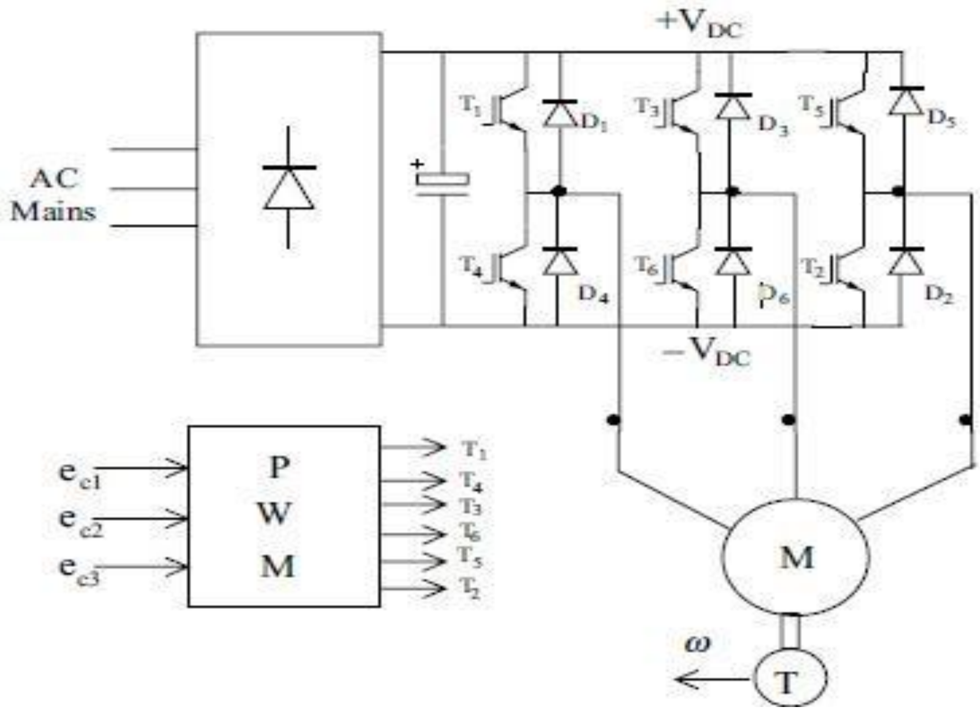

Figure: 3.5: Voltage source inverter fed Induction Motor drive

V/F Control

Open Loop V/F Control

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$$\Psi_S = V_S / \omega_S$$

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:

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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

Field Weakening Mode

In the field of closed loop controlled voltage source inverter- fed induction motors the rotor flux oriented control scheme can be regarded as the state of the art for various applications [6]. In some applications as spindles, traction and electric vehicle drives the availability of constant power operation is very important. A field-oriented induction motor drive is a suitable candidate for such applications because the flux of the induction machine can be easily weakened. In this case the drive operates close to the voltage limit and the reference flux has to be carefully selected to achieve the maximum torque Control of an induction motor with weakened flux has been investigated by many authors and three methods for establishing the flux were suggested

1) The flux reference can be set according to a fixed flux- speed characteristic
2) it can be calculated from simplified motor equations, which can be improved through consideration of additional variables

3) it can be provided by a voltage controller, which sets the flux in such a way that the voltage required by the motor matches the voltage capability of the inverter

The third strategy seems to be optimal because it is not sensitive to parameter variations in a middle speed region. At high speed the current has to be reduced for matching the maxi- mum torque and for avoiding a pull-out. In this is done with a fixed current-speed characteristic which is sensitive to parameter and DC link voltage variations. A remedy is possible if a parameter insensitive feature of the induction machine is used for the current reduction. Such a criterion is presented and an extension of the voltage control is presented in this paper which allows an operation with maximum torque in the whole field weakening region

Variable frequency control of induction motor by current source inverter:

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.

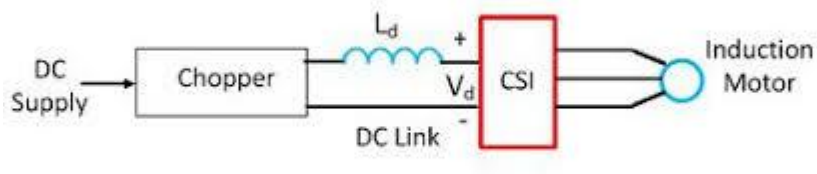

Figure: 3.6: Current source inverter fed Induction Motor drive

V/F Control

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Variable frequency control of induction motor by cycloconverter:

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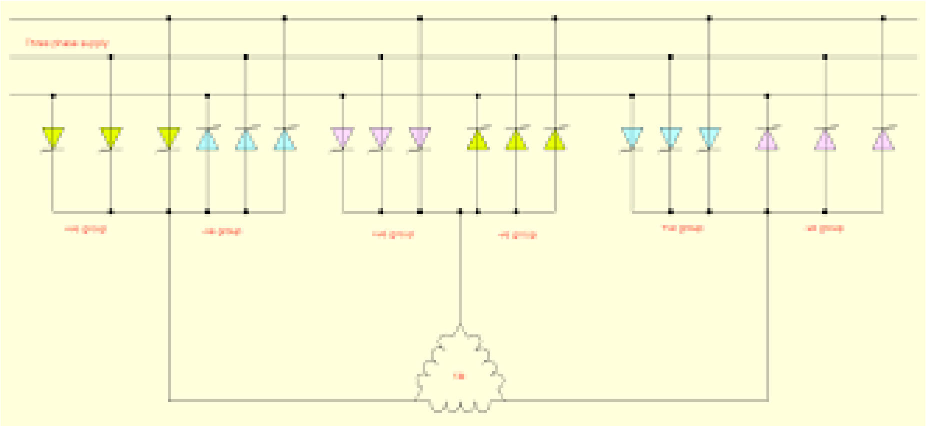

Figure: 3.7: cycloconverter fed Induction Motor drive

V/F Control

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Variable frequency control of induction motor by pulse with modulation control:

Voltage-source Inverter-driven Induction Motor

A three-phase variable frequency inverter supplying an induction motor is shown in Figure. The power devices are assumed to be ideal switches. There are two major types of switching schemes for the inverters, namely, square wave switching and PWM switching.

Square wave inverters

The gating signals and the resulting line voltages for square wave switching are shown in Figure. The phase voltages are derived from the line voltages assuming a balanced three-phase system.

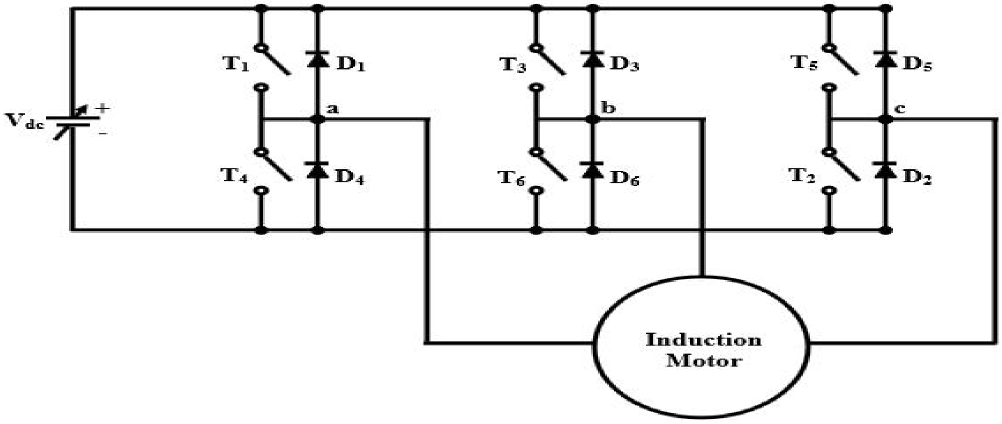


Figure: 3.8. A schematic of the generic inverter-fed induction motor drive

The square wave inverter control is simple and the switching frequency and consequently, switching losses are low. However, significant energies of the lower order harmonics and large distortions in current wave require bulky low-pass filters. Moreover, this scheme can only achieve frequency control. For voltage control a controlled rectifier is needed, which offsets some of the cost advantages of the simple inverter

PWM Principle

It is possible to control the output voltage and frequency of the PWM inverter simultaneously, as well as optimize the harmonics by performing multiple switching within the inverter major cycle which determines frequency. For example, the fundamental voltage for a square wave has the maximum amplitude (4Vd/π) but by intermediate switching, as shown in Fig. 34.12, the magnitude can be reduced. This determines the principle of simultaneous voltage control by PWM. Different possible strategies for PWM switching exist. They have different harmonic contents. In the following only a sinusoidal PWM is discussed.

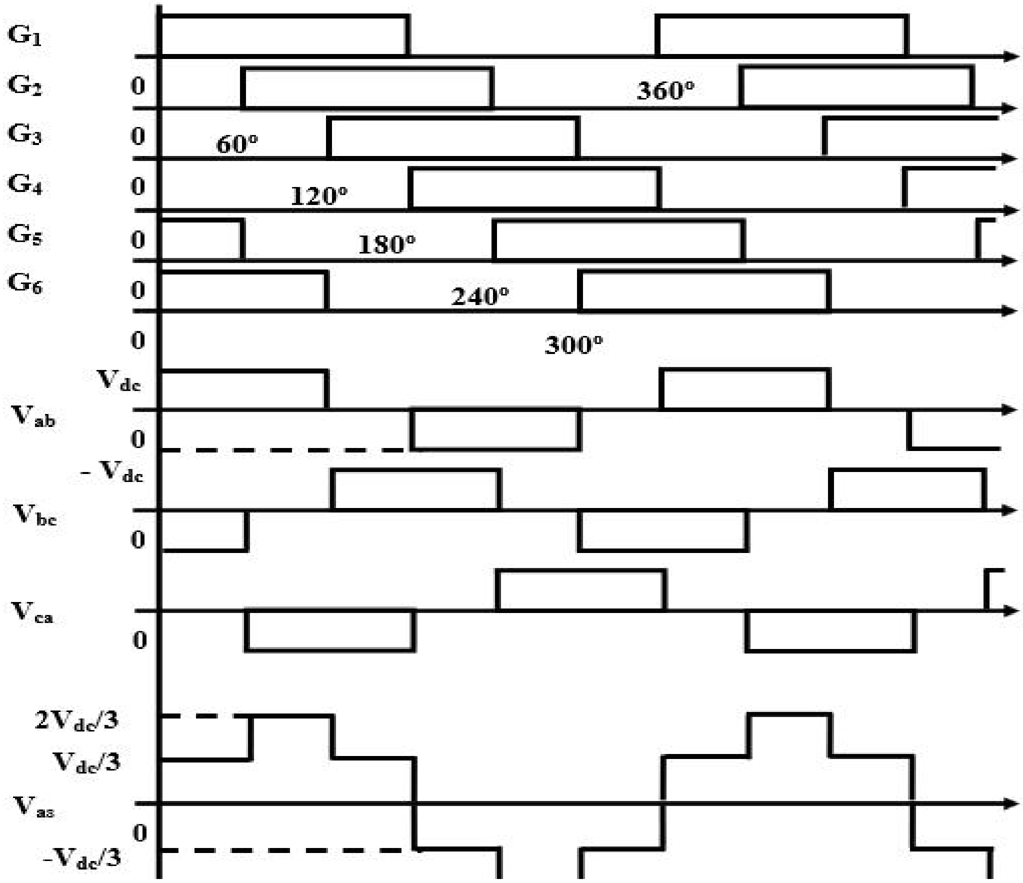


Figure: 3.9. Inverter gate (base) signals and line-and phase-voltage waveforms

Comparison of voltage source inverter and current source inverter operations:

There are following difference between current source inverter and voltage source inverter.

- The input voltage in the voltage source inverter is constant whereas the input current may constant or variable. The input current in the current source inverter is constant.
- The input supply source may be short circuited due to misfiring of the switching semiconductor device in the VSI whereas there is not any difficult due misfiring of semiconductor switches to input supply current constant in the CSI.
- The maximum current passes through semiconductor device in the VSI depend upon circuit condition whereas the input current in the CSI is constant therefore the maximum current passes through semiconductor device are limited.
- The commutation circuit of the SCR in the CSI is simple than that of VSI.
- There is no necessary of freewheeling diode in the CSI for reactive power or regenerative load whereas a freewheeling diode is used in the VSI for reactive power or regenerative load.
- The large inductor is connected at the input side in order to keep constant current at the input side of the CSI.
- There is necessary of controlled converter in order to input voltage control in the VSI similarly a converter is necessary to control input current in the CSI.

Inverters can be broadly classified into two types. They are

1. Voltage Source Inverter (VSI)
2. Current Source Inverter (CSI)

When the DC voltage remains constant, then it is called Voltage Source Inverter(VSI) or Voltage Fed Inverter (VFI).

When input current is maintained constant, then it is called Current Source Inverter (CSI) or Current Fed Inverter (CFI).

Sometimes, the DC input voltage to the inverter is controlled to adjust the output. Such inverters are called Variable DC Link Inverters. The inverters can have single phase or three-phase output.

- A voltage source inverter (VSI) is fed by a stiff DC voltage, whereas a current source inverter is fed by a stiff current source.
- A voltage source can be converted to a current source by connecting a series inductance and then varying the voltage to obtain the desired current.
- A VSI can also be operated in current-controlled mode, and similarly a CSI can also be operated in the voltage control mode.

- The inverters are used in variable frequency ac motor drives, uninterrupted power supplies, induction heating, static VAR compensators, etc.

The following table gives us the comparative study between VSI and CSI

VSI	**CSI**
VSI is fed from a DC voltage source having small or negligible impedance.	CSI is fed with adjustable current from a DC voltage source of high impedance.
Input voltage is maintained constant	The input current is constant but adjustable.
Output voltage does not dependent on the load	The amplitude of output current is independent of the load.
The waveform of the load current as well as its magnitude depends upon the nature of load impedance.	The magnitude of output voltage and its waveform depends upon the nature of the load impedance.
VSI requires feedback diodes	The CSI does not require any feedback diodes.
The commutation circuit is complicated	Commutation circuit is simple as it contains only capacitors.
Power BJT, Power MOSFET, IGBT, GTO with self commutation can be used in the circuit.	They cannot be used as these devices have to withstand reverse voltage.

Numerical problems on induction motor drives:

1. A 440V, 60Hz, 6 pole three phase induction motor runs at a speed of 1140rpm when connected to a 440V line. Calculate the speed if voltage increases to 550V.

   Solution:

   $T_1 = S_1V_1^2$

   $T_2 = S_2V_2^2$

   $S_2 = S_1(V_1/V_2)^2$

   $Ns = 120f/p = 120*60/8 = 1200rpm$

   $S_1 = (1200 – 1140)/1200 = 0.05$

   $S_2 = 0.05(440/550)^2 = 0.032$

   $N_2 = N_s(1-S_2) = 1200(1-0.032) = 1161.6rpm$

2. If three phase SCIM runs at a speed of (i) 1455rpm (ii) 1350rpm, determine the maximum current in terms of rated current at these speeds. The induction motor drives a fan and no load rotational losses are ignored.

Closed loop operation of induction motor drives

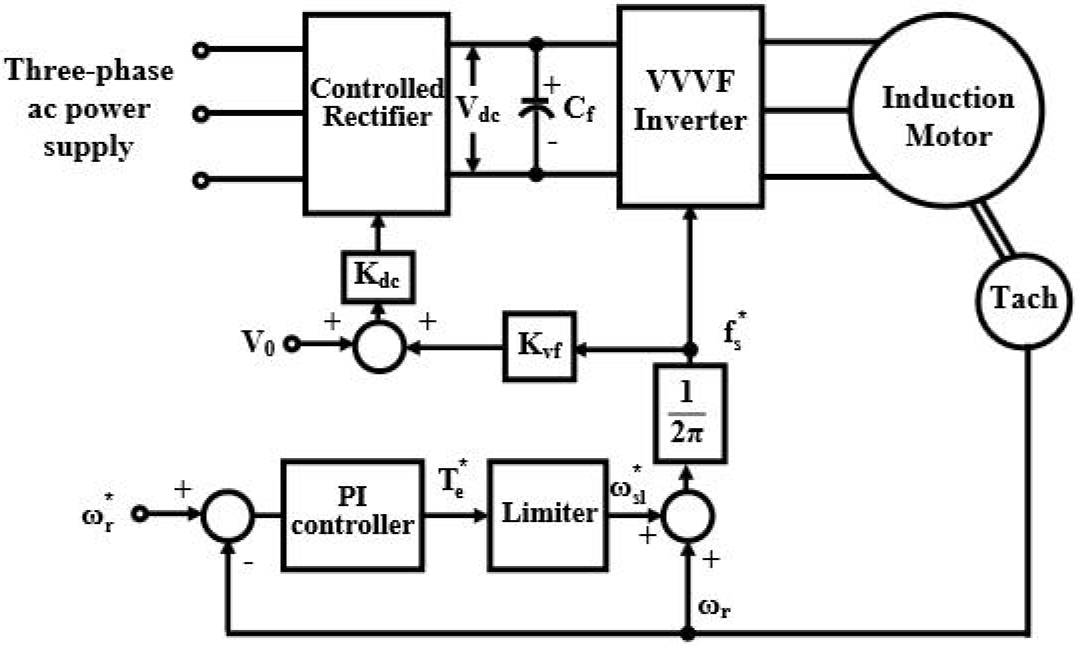


Figure: 3.10. Closed-loop induction motor drive with constant volts/Hz control strategy

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

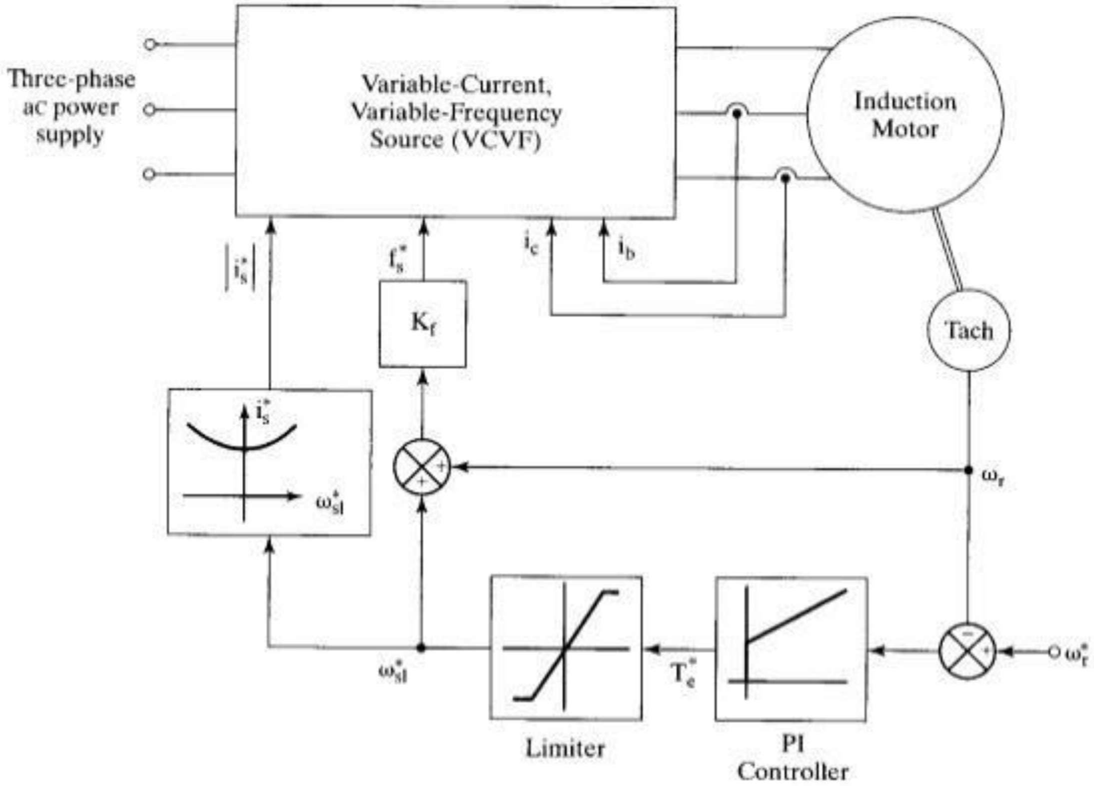


Figure: 3.11. Block diagram of closed loop speed control

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 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

Numerical problems on induction motor drives:

1. A three phase, 400V, 50Hz, 4 pole, 1440rpm delta connected squirrel cage induction motor has a full load torque of 48.13Nm. Motor speed is controlled by stator voltage control. When driving a fan load it runs at rated speed at rated voltage. Calculate motor torque at 1200 rpm

   Solution

   $N_s = 120f/p = 120*50/4 = 1500$rpm

   Rotor speed is 1440 rpm

   $W_m = 1440*2\pi/60 = 150.8$ rad/sec

   $Tawm^2$

   $T = Kwm^2$

$48.13 = K150.8^2$

K= 0.00211

Motor torque at 1200 rpm is

W_m = 1200*2π/60 = 125.66 rad/sec

T = 0.00211*125.66^2

T = 33.32Nm

2. At 50 Hz the synchronous speed and full load speed are 1500 rpm and 370 rpm respectively. Calculate the approximate value speed for a frequency of 30 Hz and 80% of full load torque for inverter fed induction motor drive.

UNIT IV

SPEED CONTROL OF INDUCTION MOTORS THROUGH ROTOR RESISTANCE AND VECTOR CONTROL

Introduction to rotor resistance control of induction motors

Rotor resistance control is one among the various methods for the speed control of induction motor. In this method of speed control, the rotor circuit resistance is varied by connecting a variable external resistance. This method is only applicable for slip ring or wound rotor induction motor (WRIM). As in squirrel cage induction motor (SCIM), rotor windings terminals are not available for external connection; its speed cannot be regulated by rotor resistance control. Therefore, this method is not applicable for squirrel cage induction motor.

We know that, the torque in an induction motor is depends on the rotor circuit resistance. Also, the maximum torque is independent of rotor resistance but the slip at which this maximum torque occurs is directly proportional to the rotor circuit resistance.

Therefore if we change the rotor resistance, the maximum torque will remain constant but the slip will increase. Figure below shows the torque slip characteristics for three different rotor resistance R_1, R_2 and R_3.

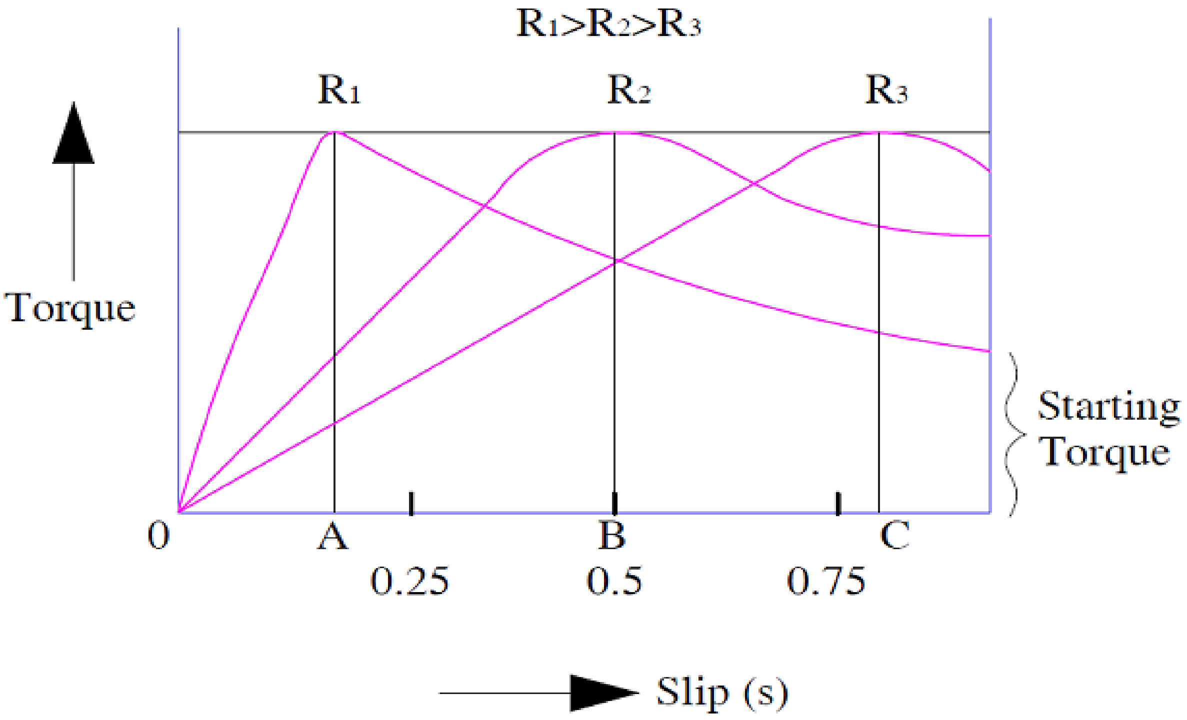


Figure: 3.1 Torque speed characteristics of induction motor through rotor resistance

In the above figure, the maximum torque is same for rotor resistance R_1, R_2 and R_3 but the slip increase from point A to B & C. This means, increasing rotor resistance results in increase in slip. Increase in slip in turn means reduction in induction motor speed. Thus we can say that by rotor resistance control, we can achieve variable speed at a constant torque. This is the reason; this method is suitable for constant torque drive.

It may also be noted from the above torque slip characteristics that, starting torque increases with increase in rotor resistance. Therefore this method is advantageous where we require high starting torque.

In spite of the above two advantages of rotor resistance control, this method have some disadvantage:

- This method cannot be employed for speed control of squirrel cage induction motor. This is because of non-availability of rotor winding terminals for external resistance connection.
- This method is not very efficient. Losses in external resistance and losses in carbon brushes at high slip operation cause wastage of energy.

Static rotor Resistance control of induction motors

- GTO chopper allows the effective rotor circuit resistances to be varied for the speed control of SRIM.
- Diode rectifier converts slip frequency input power to dc at its output terminals.

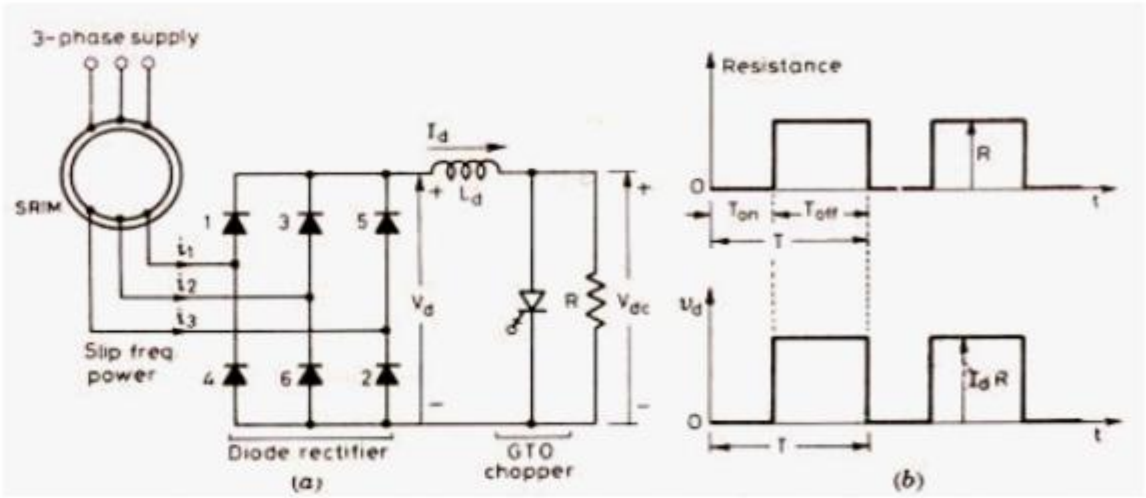


Figure: 3.2 Static rotor Resistance control

a) When chopper is on, Vdc=Vd=0Vdc=Vd=0 and resistance R gets short circuited.
b) When chopper is off, Vdc=VdVdc=Vd and resistance in the rotor circuit is R. This is shown in fig 3.2
c) From this figure, effective external resistance ReRe is
Re=R.ToffT=R(T−Ton)T=R(1−k)where k=TonT=duty cycle of chopper.

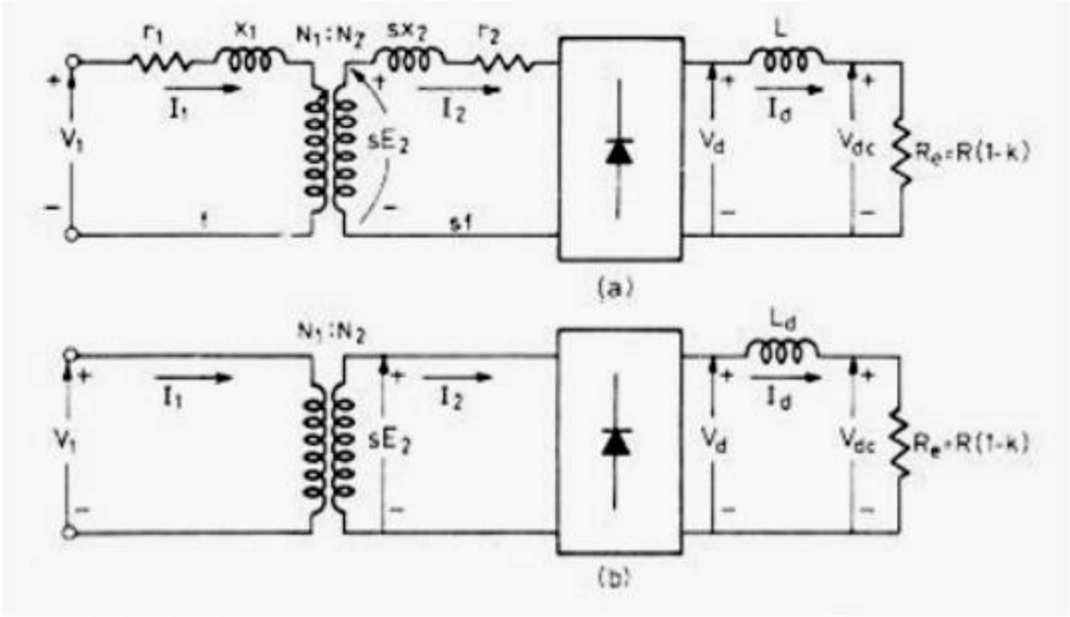


Figure: 3.2 Static rotor Resistance control with chopper control

Slip power recovery schemes of induction motor

Whenever an slip ring induction motors is connected to load such as fans, there excess energy is generated due to virtue of it's momentum and starts to run beyond synchronous speed. Intern emf is induced in rotor and excess energy will be lost which is also called as slip power.

That power can be utilized back to grip that scheme is called slip power recovery system.

In cement industry such system still available with additional recovery transformer arrangements.

During speed control of an Induction motor (WRIM) using rotor resistance control, rotor power is wasted in the external rotor resistance. The same can be utilized to increase the efficiency of the drive. Basically there are two schemes for recovering the wasted power.

1. Scherbius drive

Here the variable frequency (sf) rotor power is converted to dc by a diode bridge rectifier and then an inverter converts it back to ac (50/60 Hz) and is fed back to the supply mains. Thus the slip power is fed back to the source instead of wasting it in the rotor resistance thereby increasing the efficiency of the drive .

2. Kramer Drive

Here the variable frequency (sf) rotor power is converted to dc by a diode bridge rectifier. The dc power is fed to a dc motor which is mechanically coupled to the induction motor. Thus the torque supplied to the load is the sum of the torque produced by induction and dc motor. In this scheme, the slip power is utilized mechanically.

In an induction motor, out of the total power (Pr) transferred to rotor from stator, the fraction sPr (where s=slip) is called slip power and this power is wasted in rotor as rotor copper loss. The remainder is converted into mechanical power.

Efforts have been made to recover this slip power and make use of this power by either giving it back to the motor to enhance shaft power or returning it to supply lines. Any scheme to achieve this objective is a slip power recovery scheme.

Slip Energy Recovery is one of the methods of controlling the speed of an **Induction motor.** This method is also known as **Static Scherbius Drive**. In the rotor resistance control method, the slip power in the rotor circuit is wasted as I^2R losses during the low-speed operation. The efficiency is also reduced. The slip power from the rotor circuit can be recovered and fed back to the AC source so as to utilize it outside the motor. Thus, the overall efficiency of the drive system can be increased.

In a wound-field induction motor the slip rings allow easy recovery of the slip power which can be electronically controlled to control the speed of the motor.
The oldest and simplest technique to invoke this slip-power recovery induction motor speed control is to mechanically vary the rotor resistance.

Slip-power recovery drives are used in the following applications:

- Large-capacity pumps and fan drives
- Variable-speed wind energy systems
- Shipboard VSCF (variable-speed/constant frequency) systems
- Variable speed hydro-pumps/generators
- Utility system flywheel energy storage systems

Static Scherbius drive performance and speed torque characteristics

Static scherbius drive system:

This system provides feedback path i.e. the wastage of slip power is again fed to AC mains supply. The static scherbius system is of two types

i) Conventional Scherbius system

ii) Static Scherbius system

i) Conventional scherbius system:

In this system the recovery scheme is done by feedback path. The output of three phase Induction motor is connected to the DC motor by coupling them the mechanical power input of DC motor is converted into electrical power and fed to Induction generator and again back to mains.

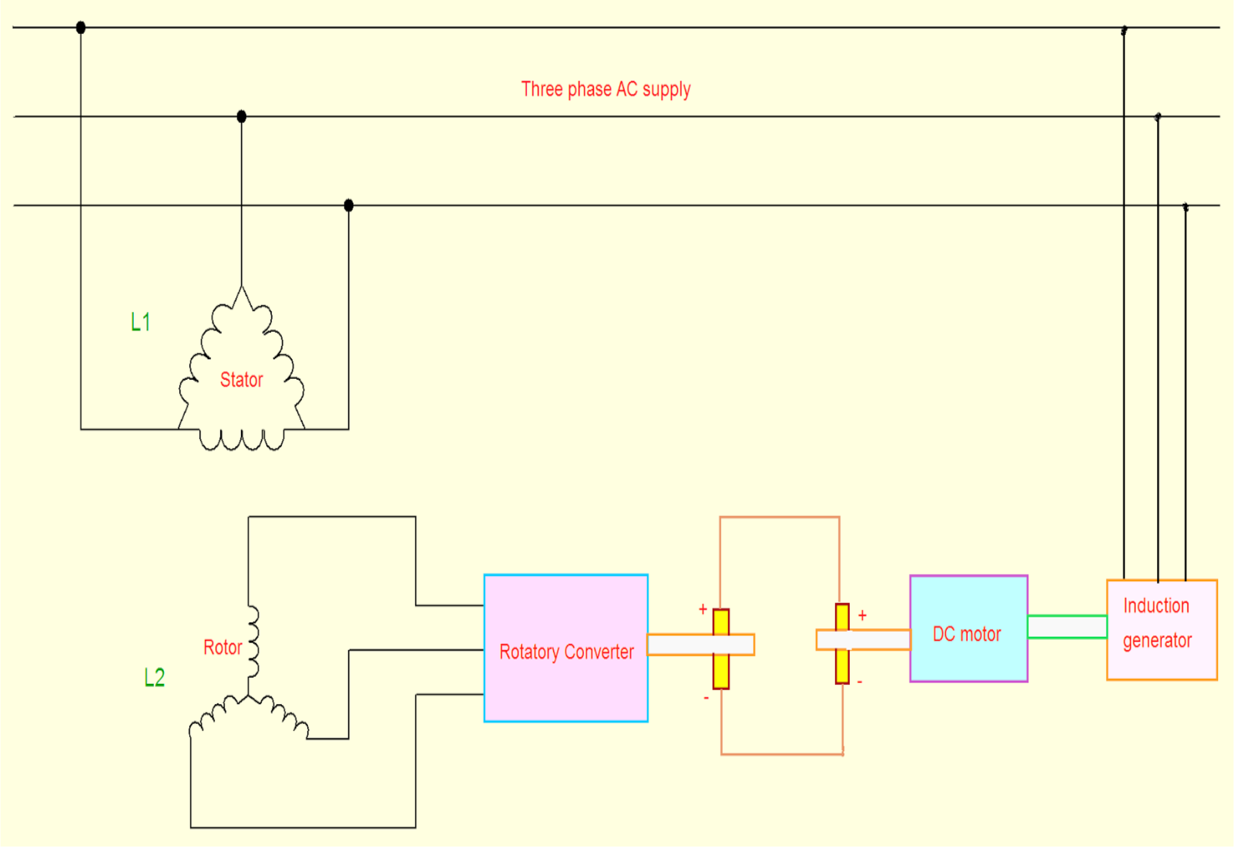


Figure: 4.4 Conventional scherbius system

ii) Static Scherbius drive system:

The phenomenon of this system is same as conventional type but the only difference is this system provides with diode bridge rectifier along with thyristor bridge inverter. This is also known as Sub-synchronous cascade drive.

When Induction motor is operating at slip frequency the rotor slip power is rectified by the diode rectifier. The output of rectifier is fed to inverter three phase bridge again the output is fed back to supply lines with the help of transformer.

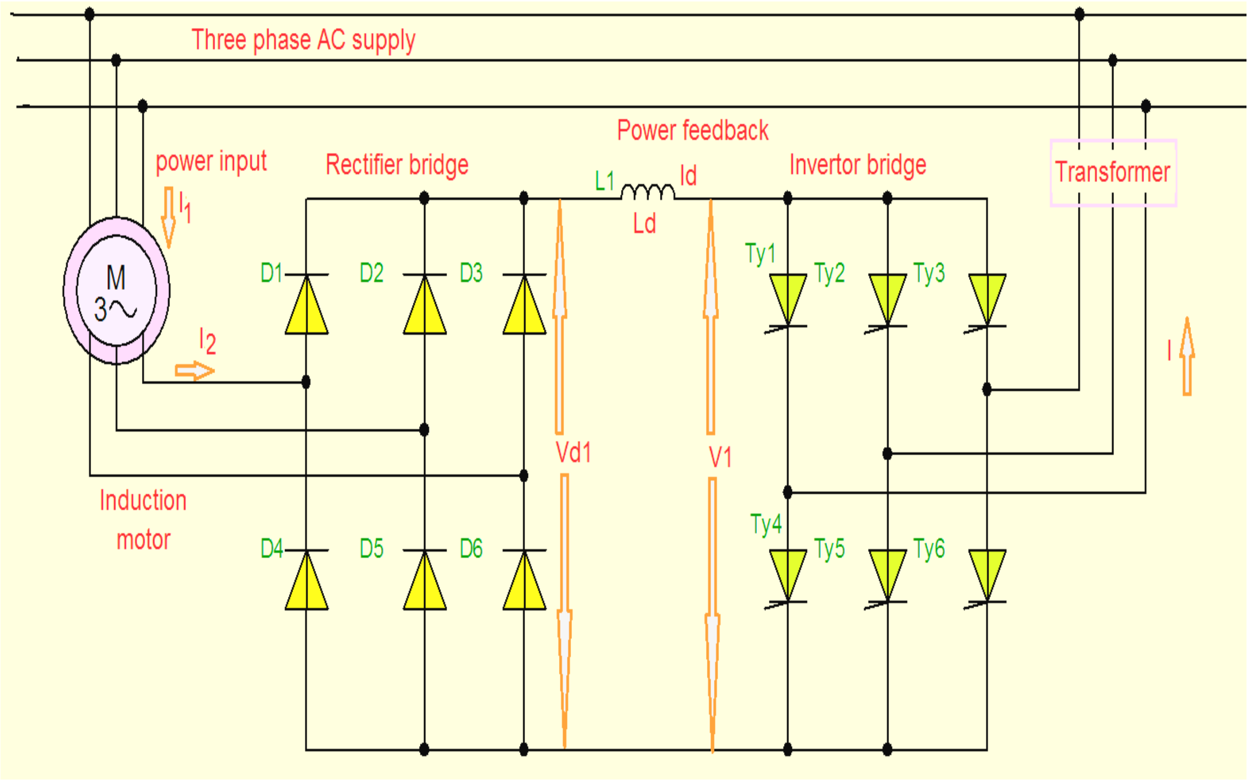


Figure: 4.5 Static scherbius system

* Natural commutation proves involves across slip rings bus-bars. The induced emf frequency is made equal to rotor emf frequency by rectification of slip ring voltage to obtain speed control at injected voltage.

*In this circuit if commutation overlap is negligible the output voltage of uncontrolled three phase bridge rectifier is obtained as

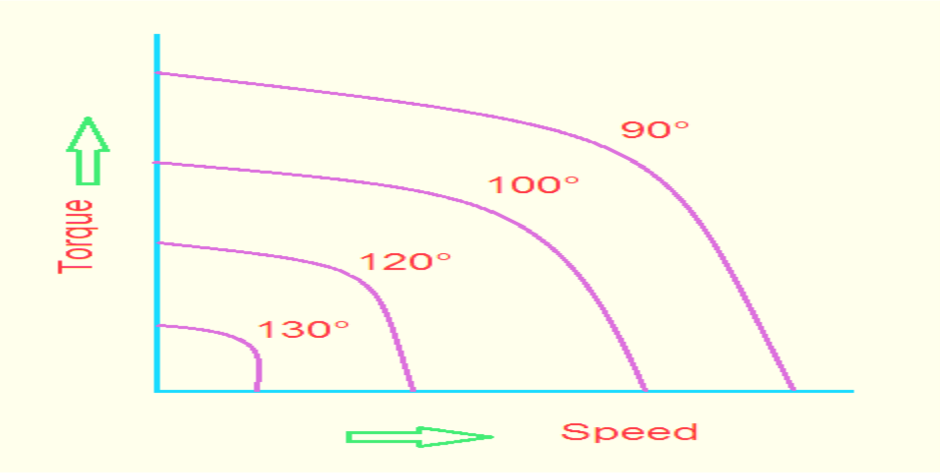


Figure: 4.6 Torque speed characteristics of Induction motor

Static Kramer drive performance and speed torque characteristics

Static Kramer drive:

In this method the rotatory slip power is coverted into DC by a diode bridge. The DC power is fed to the DC motor which is mechanically coupled with the Induction motor. The speed control is done by varying the field current I_f.

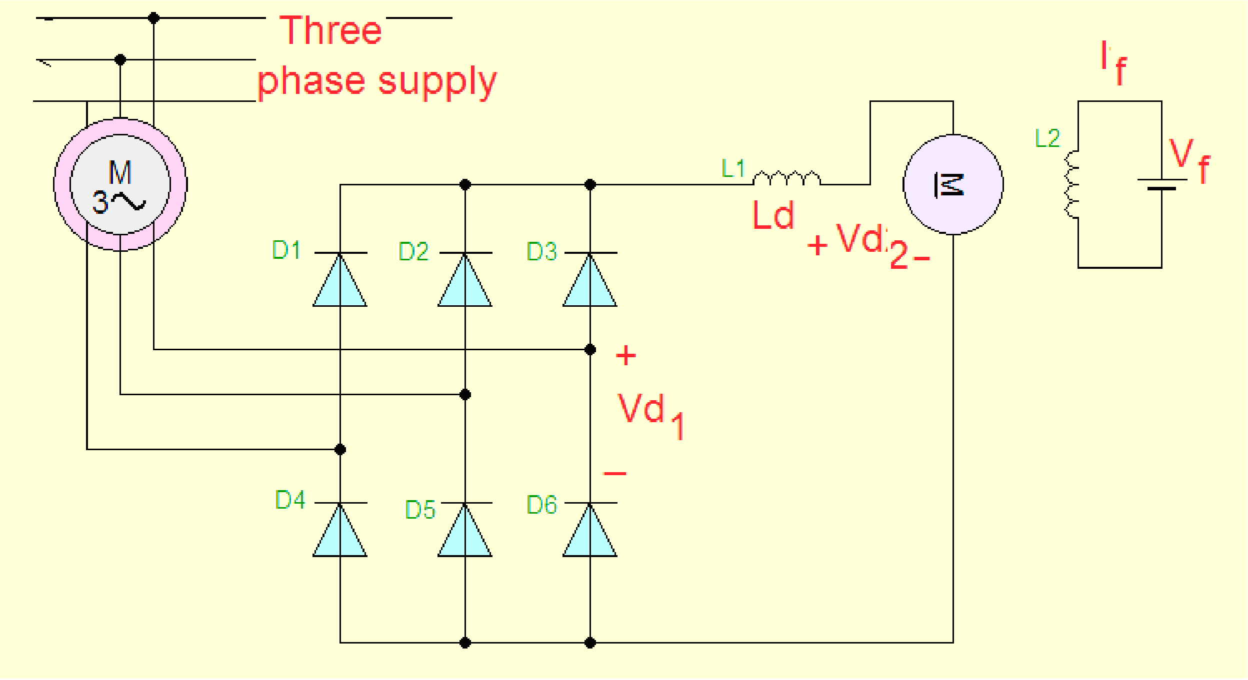


Figure: 4.7. Static Kramer drive

From the characteristics you can easily observe the voltage and field current differences. The steady state operation is possible at $V_{d1} = V_{d2}$

For large speed applications the diode bridge is replaced by using thyristor bridge, the speed can be controlled by varying the firing angle. Upto standstill condition the speed can be controlled.

Modification:

The static Kramer drive system is modified by placing commutator less DC motor instead of DC machine. The DC motor consists of synchronous motor fed by load commutated inverter, the speed is controlled by field current

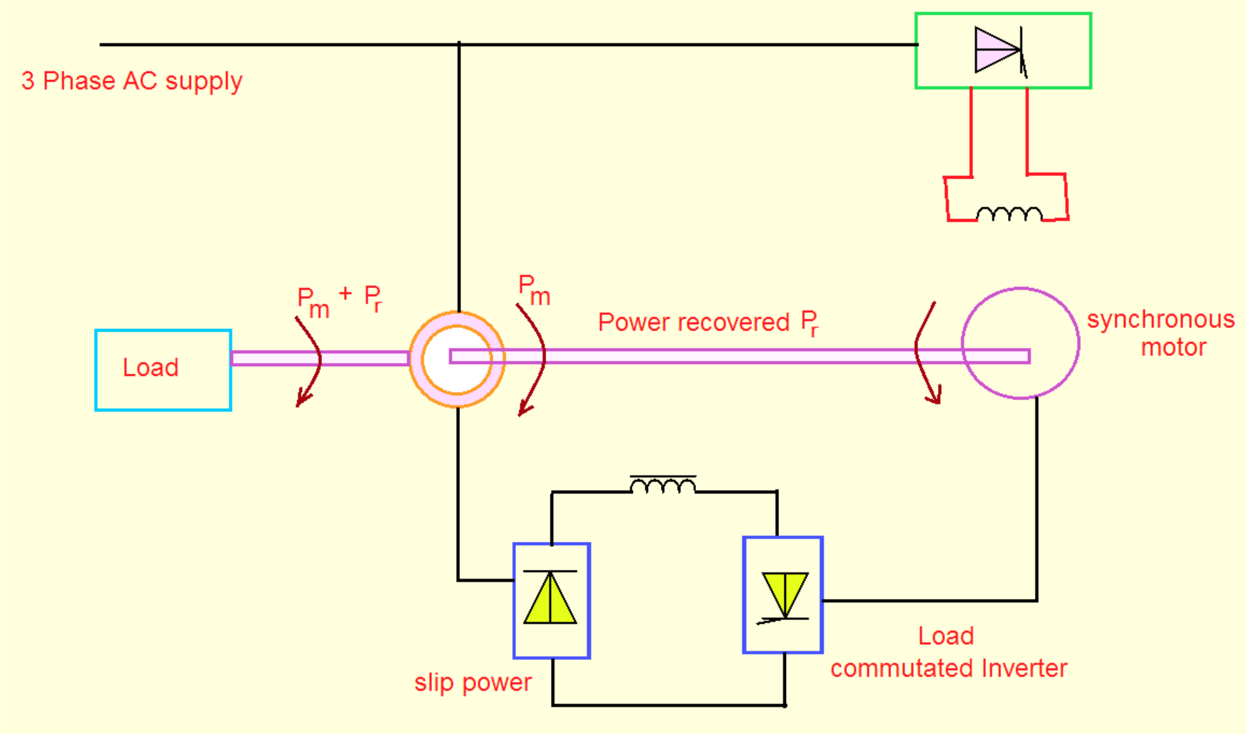


Figure: 4.8. Modified Static Kramer drive

*If field current and inverter voltage reduced to zero then the drive runs at synchronous speed. This drive has better power factor and less harmonic content in line current compared to static Kramer drive. In this system the power is not fed back to the line.

Advantages and applications of slip power recovery schemes

Advantages	Disadvantages
Instead of other speed control methods working range can be obtained at any speed	Motor turns ration is less than unity
If over excitation is occurred at rotor, it will take lead current which improves system performance	For reliable thyristor commutation inverter firing angle kept less than 180°.
------	To improve power factor, capacitor is introduced into stator or rotor sides
-------	PWM technique is employed by replacing thyristor
-------	Slip is inversely proportional to power factor, hence if power factor decreases the slip increases.

Output power cascading: The cascaded set with excessive excitation of auxiliary DC machine will run at high speed with low torque. The speed of main motor in this scheme is controlled by field regulation of auxiliary DC machine. This is called “Constant output power cascading”.

Applications of slip power recovery schemes:

Slip ring motor can deliver higher starting torque as compared to squirrel cage induction motor.The rotor winding is connected to the external circuit to achieve the higher starting torque. The higher rotor resistance at start produces higher starting torque. After accelerating the motor up to its base speed the resistance is bypassed and the motor behaves as a squirrel cage induction motors.

Slip ring motors are most suitable for rolling mills, kilns, centrifugal fans, blowers because all these high inertia equipment demands high starting torque.

Induction motors generally will have low starting torque compared to dc series motor. Slip ring induction motor have big advantage of having high starting torque compared to squirrel cage motor. Therefore slip ring induction motors are generally employed where load requires high starting torque or good speed control. They are employed in hoists, elevators, compressors, printing presses, large ventilating fans, loads requiring speed control such as for driving lifts and pumps.

Ability to obtain the maximum torque (if required) at ***any slip*** and specially at starting (slip=1) is the main advantage of the slip ring IM as compared to a cage IM. High braking torque can also be obtained (slip > 1) easily.

Its application therefore is where high starting and braking torque are required as in hoists, elevators, lifts, railway traction etc.

Slip ring or wound rotor type induction motor are mostly used fot high starting torque applications. Because in rotor circuit you can add external resistance, which is responsible for high starting torque
High starting torque applications Because u can vary the rotor resistance to make the machine acquire maximum torque at starting. Then after enough speed is acquired u can lower the resistance.

Numerical problems on rotor resistance control

1. The speed of a three phase slip ring induction motor is controlled by variation of rotor resistance. The full load torque of the motor is 50Nm at slip of 0.3. the motor drives load having a characteristics $T \alpha N^2$. The motor has 4 poles and operates on 50Hz, 400V supply. Determine the speed of the motor for 0.8 times the rated torque.

   Solution:

   Synchronous speed $N_s = 120f/p = 120*50/4 = 1500$rpm

   Slip = 0.3

   $N= N_s(1-s) = 1500(1-0.3) =1050$rpm

   $T_2 = T_1*0.8 = 50*0.8 = 40$Nm

   $T \alpha N^2$

   $T_1/T_2 = N_1^2/N_2^2$

   $50/40=1050^2/ N_2^2$

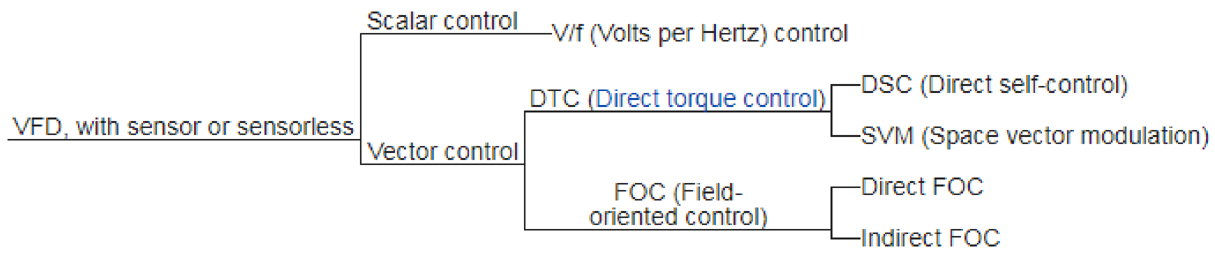
   $N_2 = 939$ rpm

2. A static krammer drive is used for the speed control of a 4 pole SRIM fed from415V, 50Hz supply. The inverter is directly connected to supply. If the motor is required to operate at 1200 rpm, find the firing advance angle of the inverter. Voltage across open circuited slip rings at standstill is 700V. Allow a voltage drop of 0.7V and 1.5V across each of the diodes and SCRs respectively.

Introduction to vector control of induction motor drives

Vector control, also called **field-oriented control** (FOC), is a variable-frequency drive (VFD) control method in which the stator currents of a three-phase AC electric motor are identified as two orthogonal components that can be visualized with a vector. One component defines the magnetic flux of the motor, the other the torque. The control system of the drive calculates the corresponding current component references from the flux and torque references given by the drive's speed control. Typically proportional-integral (PI) controllers are used to keep the measured current components at their reference values. The pulse-width modulation of the variable-frequency drive defines the transistor switching according to the stator voltage references that are the output of the PI current controllers.[1]

FOC is used to control AC synchronous and induction motors. It was originally developed for high-performance motor applications that are required to operate smoothly over the full speed range, generate full torque at zero speed, and have high dynamic performance including fast acceleration and deceleration. However, it is becoming increasingly attractive for lower performance applications as well due to FOC's motor size, cost and power consumption reduction superiority. It is expected that with increasing computational power of the microprocessors it will eventually nearly universally displace single-variable scalar volts-per-Hertz (V/f) control.


Overview of key competing VFD control platforms:

While the analysis of AC drive controls can be technically quite involved ("See also" section), such analysis invariably starts with modeling of the drive-motor circuit involved along the lines of accompanying signal flow graph and equations.

In vector control, an AC induction or synchronous motor is controlled under all operating conditions like a separately excited DC motor. That is, the AC motor behaves like a DC motor in which the field flux linkage and armature flux linkage created by the respective field and armature (or torque component) currents are orthogonally aligned such that, when torque is controlled, the field flux linkage is not affected, hence enabling dynamic torque response.

Vector control accordingly generates a three-phase PWM motor voltage output derived from a complex voltage vector to control a complex current vector derived from motor's three-phase stator current input through projections or rotations back and forth between the three-phase speed and time dependent system and these vectors' rotating reference-frame two-coordinate time invariant system.

Such complex stator current space vector can be defined in a (d,q) coordinate system with orthogonal components along d (direct) and q (quadrature) axes such that field flux linkage component of current is aligned along the d axis and torque component of current is aligned along the q axis. The induction motor's (d,q) coordinate system can be superimposed to the motor's instantaneous (a,b,c) three-phase sinusoidal system as shown in accompanying image (phases b & c not shown for clarity). Components of the (d,q) system current vector allow conventional control such as proportional and integral, or PI, control, as with a DC motor.

Projections associated with the (d,q) coordinate system typically involve:

- Forward projection from instantaneous currents to (a,b,c) complex stator current space vector representation of the three-phase sinusoidal system.
- Forward three-to-two phase, (a,b,c)-to-(d,q) projection using the Clarke transformation. Vector control implementations usually assume ungrounded motor with balanced three-phase currents such that only two motor current phases need to be sensed. Also, backward two-to-three phase, (d,q)-to-(a,b,c) projection uses space vector PWM modulator or inverse Clarke transformation and one of the other PWM modulators.

However, it is not uncommon for sources to use three-to-two, (a,b,c)-to-(d,q) and inverse projections.

While (d,q) coordinate system rotation can arbitrarily be set to any speed, there are three preferred speeds or reference frames:

- Stationary reference frame where (d,q) coordinate system does not rotate;
- Synchronously rotating reference frame where (d,q) coordinate system rotates at synchronous speed;
- Rotor reference frame where (d,q) coordinate system rotates at rotor speed.

Decoupled torque and field currents can thus be derived from raw stator current inputs for control algorithm development.

Whereas magnetic field and torque components in DC motors can be operated relatively simply by separately controlling the respective field and armature currents, economical control of AC motors in variable speed application has required development of microprocessor-based controls with all AC drives now using powerful DSP (digital signal processing) technology.

Principles of vector control

The control of AC machine is basically classified into scalar and vector control. The scalar controls are easy to implement though the dynamics are sluggish. The objective of FOC is to achieve a similar type of controller with an inner torque control loop which makes the motor respond very fast to the torque demands from the outer speed control loop. In FOC, the principle of decoupled torque and flux control are applied and it relies on the instantaneous control of stator current space vectors. Control of induction motor is complicated due to the control of decoupled torque and flux producing components of the stator phase currents. There is no direct access to the rotor quantities such as rotor fluxes and currents. To overcome these difficulties, high performance vector control algorithms are developed which can decouple the stator phase currents by using only the measured stator current, flux and rotor speed.

In this chapter, the mathematical model of induction motor based on space vector theory and the principle of indirect FOC are presented. The simulation model of the induction motor drive is developed using the principle of indirect FOC.

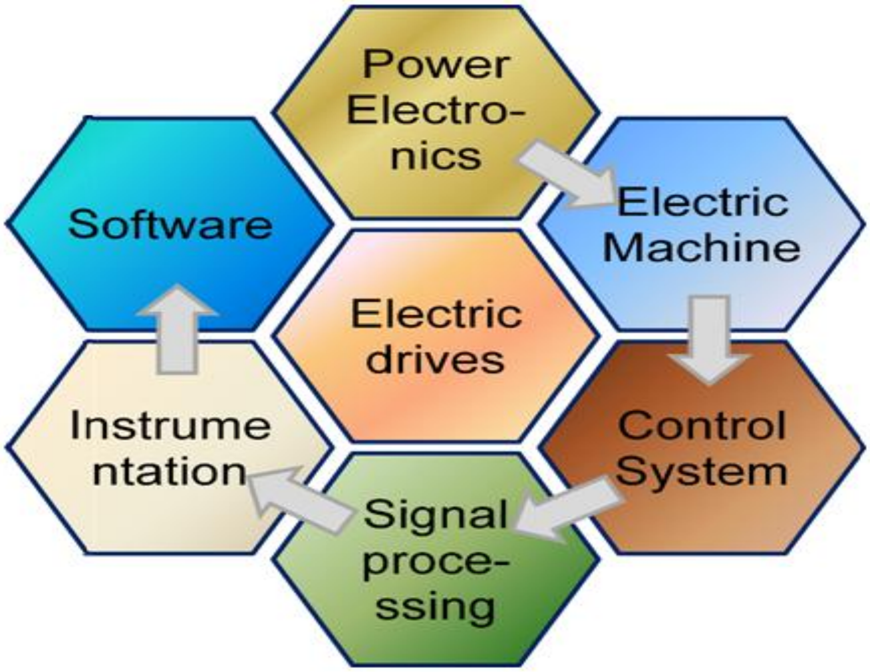
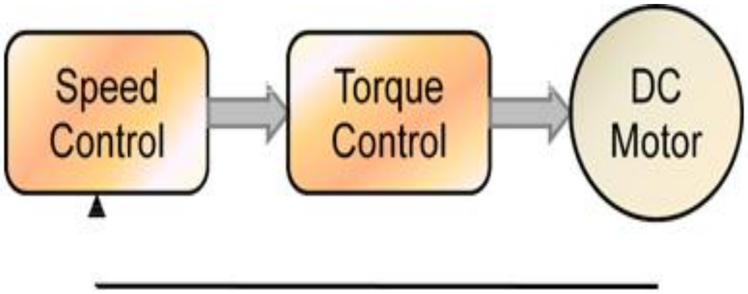
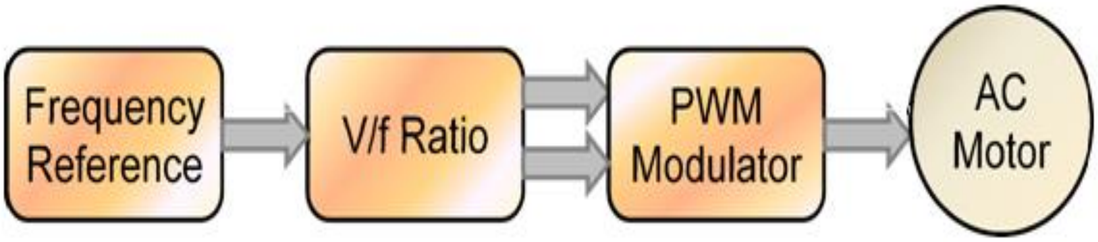


Figure: 4.9: Electric drive system

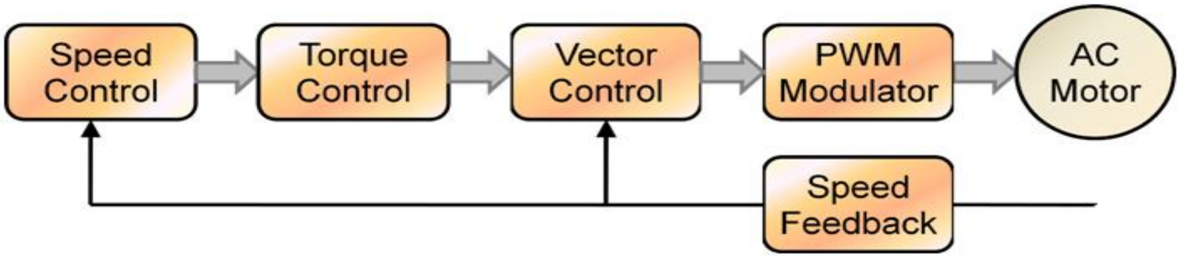
Several control strategies as shown in Fig.4.9 are found in the variable speed drive industry, which includes i) open loop inverter with fixed V/f control, ii) open loop inverter with flux vector control, iii) closed loop inverter with flux vector control and iv) DTC. The controls, namely, FOC, DTC, non- linear control and Predictive Control (PC) are to be implemented with closed- loop feedback control to obtain high precision, good dynamics and steady state response. FOC predominantly relies on the mathematical modeling of AC machine, while DTC makes direct use of physical interaction that takes place within the integrated system of the machine and its supply.



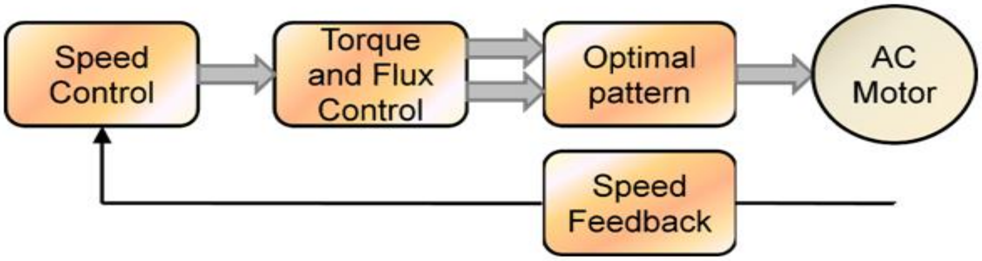
a) DC drive



b) AC drive – scalar control



c) AC drive – Field Oriented Control



d) AC drive – Direct Torque Control

Vector control methods of induction motor

Clarke Transformation

This transformation block is responsible for translating three axes to two axes system reference to the stator. Two of the three phase currents are measured because the sum of the three phase currents equal to zero. Basically the transformation shift from a three axis, two- dimensional coordinate system attached to the stator of the motor to a two axis system referred to the stator. The measured current represents the vector component of the current in a three axis coordinate system which are spatially separated by 120. Clarke transformation transforms the rotating current vector in a two axis orthogonal coordinate system, so that the current vector is represented with two vector components which vary with time. The space vector can be transformed to another reference frame with only two orthogonal axis called, where the axis ‘*d’* and axis ‘*a’* coincide each other. Fig. shows the stator current space vector and its component in stationary reference frame and the Clarke transformation module.

The projection that modifies the three phase system into two dimensional orthogonal system is expressed as:

$$i_{s\alpha} = \mathrm{Re}\left(\frac{2}{3}\left(i_a(t) + i_b(t)e^{j2\pi/3} + i_c(t)e^{-j2\pi/3}\right)\right)$$

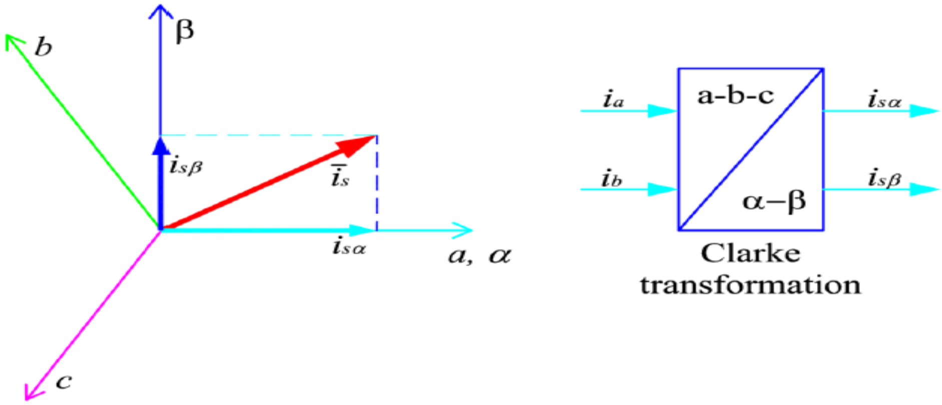


Figure: 4.10 Clark transformations

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Park transformation

It is used to rotate the two axis coordinate system so that it is aligned with the rotating motor and this projection modifies a two phase orthogonal α-β system in the d-q rotating reference frame. The stator reference frame is not suitable for the control process. The space vector i_s is rotating at a rate equal to the angular frequency of the phase currents, the components change with time and speed. In order to gain a complete decoupling of torque and flux, the current phasor is transformed into two components of a rotating reference frame rotating at the same speed as the angular frequency of the phase currents, these components do not depend on time and speed. In FOC this is the most important transformation, the component of stator current which is responsible for the rotor flux can be fix to the d axis. These components depend on the α-β current vector components and the rotor flux position. The separate flux and the torque components of stator current vector in two coordinate time invariant system can be expressed by (3.89). Direct torque control is possible and becomes easy with the flux component

i_{sd} aligned with the d axis representing the direction of the rotor flux and torque component i_{sq} aligned with the q axis perpendicular to the rotor flux. Fig. 3.16 shows the stator current space vector and its component in rotating reference frame and the Park transformation module.

$$\vec{i}_s = i_{sd} + j i_{sq}$$

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}$$

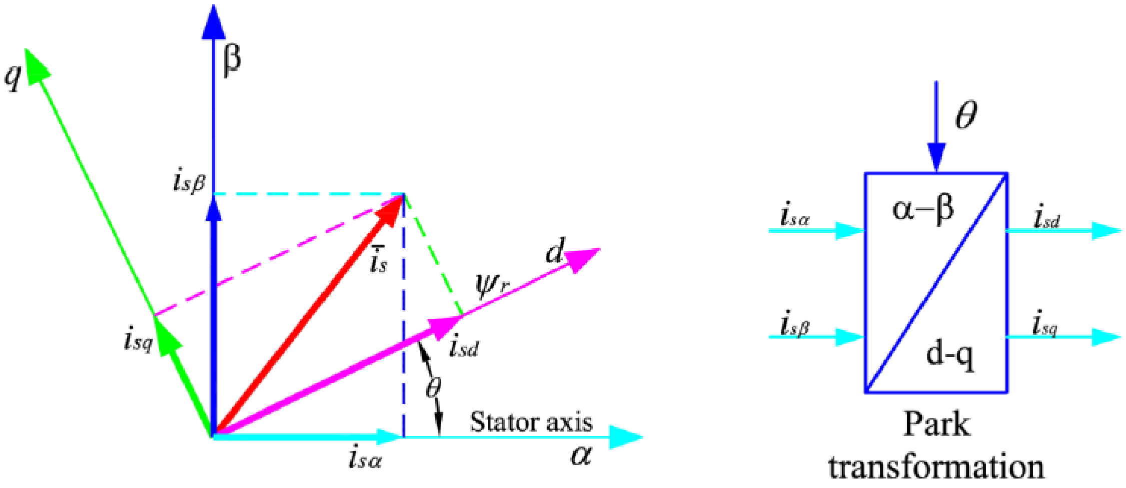
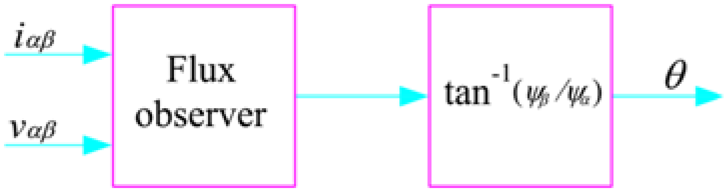


Figure: 4.11 park transformations

Direct methods of vector control

Direct Field Oriented Control

In DFOC, an estimator or observer calculates the rotor flux angle. Inputs to the estimator or observer are stator voltages and currents. In DFOC, rotor flux vector orientation can be measured by the use of a flux sensor mounted in the air gap like Hall-effect sensor, search coil and other measurement techniques introduces limitations due to machine structural and thermal requirements or it can be measured using the voltage equations. Saliency of fundamental or high frequency signal injection is the other flux and speed estimation technique, but this method fails at low and zero speed level. The method may cause torque ripples and mechanical problems when applied with high frequency signal injection. The advantage of this method is that the saliency is not sensitive to actual motor parameters. Flux sensor is expensive and needs special installation and maintenance. Rotor flux cannot be directly sensed by this method but from the directly sensed signal it is possible to calculate the rotor flux, which may result in inaccuracies at low speed due to the dominance of stator resistance voltage drop and due to variation of flux level and temperature and makes it expensive. Fig. shows DFOC drive system.



Field Oriented Control or Vector Control (VC) techniques are being used extensively for the control of induction motor. This technique allows a squirrel cage induction motor to be driven with high dynamic performance comparable to that of a DC motor. In FOC, the squirrel cage induction motor is the plant which is an element within a feedback loop and hence its transient behavior has to be taken into consideration. This cannot be analyzed from the per phase equivalent circuit of the machine, which is valid only in the steady state condition. The induction motor can be considered as a transformer with short circuited and moving secondary where the coupling coefficients between the stator and rotor phases change continuously in the course of rotation of rotor. The machine model can be described by differential equations with time varying mutual inductances but such model is highly complex. For simplicity of analysis, a three phase machine which is supplied with three phase balanced supply can be represented by an equivalent two phase machine. The problem due to the time varying inductances is eliminated by modeling the induction motor on a suitable reference frame. The basic idea behind the FOC is to manage the interrelationship of the fluxes to avoid the issues mentioned above, and to squeeze the most performance from the motor. The basic principle of FOC is to maintain a desired alignment between the stator flux and rotor flux.

In FOC, the stator currents are transformed into a rotating reference frame aligned with the rotor, stator or air-gap flux vectors to produce *d*-axis component of current and *q*-axis component of current. Torque can be controlled by the *q*-axis component of stator current space vector and flux controlled by the *d*-axis component of current vector. The basis of FOC is to use rotor flux angle to decouple torque and flux producing components. Basically, there are two different types of FOC methods depending on the calculation of this rotor flux angle. Field orientation achieved by direct measurement of flux is termed Direct FOC (DFOC). The flux orientation achieved by imposing a slip frequency derived from the rotor dynamic equations is referred to as Indirect FOC (IFOC). IFOC is preferred to DFOC since the fragility of Hall sensors detracts the inherent robustness of an induction machine.

Indirect methods of vector control

The field orientation concept implies the current components supplied to the machine should be oriented in such a manner as to isolate the stator current magnetizing flux component of the machine from the torque producing component. This can be obtained by the instantaneous speed of the rotor flux linkage vector and the *d* axis of the *d*-*q* coordinates are exactly locked in rotor flux vector orientation. In IFOC, the rotor flux angle is obtained from the reference currents, rotor flux vector is estimated by using the field oriented control current model equations and requires a rotor speed measurement. In this, flux position can be calculated by considering terminal quantities in motor model such as voltage and currents, but it is very sensitive to rotor time constant. When rotor time constant is not accurately set, detuning will takes place in the machine and the loss of decoupled control of torque and flux causes a sluggish performance. IFOC of the rotor currents can be implemented using instantaneous stator currents and rotor mechanical position. It does not have inherent low speed problems and is preferred in most applications.

The flux control through the magnetizing current is by aligning all the flux with *d* axis and aligning the torque producing component of the current with the *q* axis. The torque can be instantaneously controlled by controlling the current i_{sq} after decoupling the rotor flux and torque producing component of the current components. The flux along the *q* axis must be zero and the mathematical constraint is,

$$\psi_{rq} = 0$$

The rotational position information is measured from slip frequency. The flux and torque can be controlled independently by providing the slip frequency. The block diagram of IFOC drive system is shown in Fig

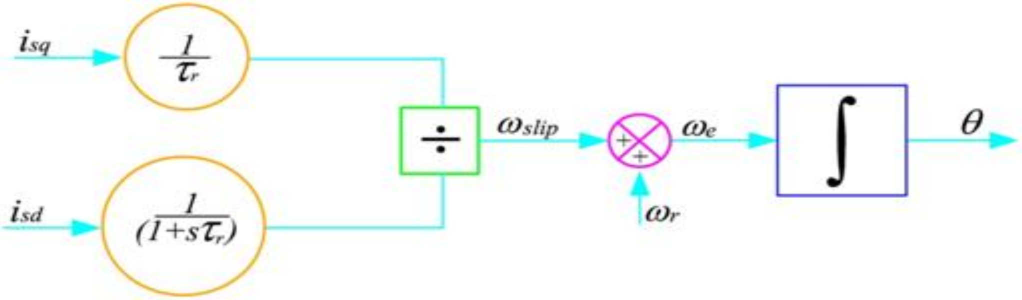


Figure: 4.11. Indirect method of vector control

Properties of the FOC methods are,

i. It is based on the analogy to the control of separately excited DC motor,

ii. Coordinate transformations are required,

iii. PWM algorithm is needed,

iv. Current controllers are necessary,

v. Sensitive to rotor time constant,

vi. Rotor flux estimator is essential in DFOC and

vii. Mechanical speed is required in IFOC.

The goal of FOC is to perform real time control of torque variations demand, to control the mechanical speed and to regulate phase currents. To perform these controls, the equations are projected from a three-phase non- rotating frame into a two coordinate rotating frame. FOC uses a pair of conversions to get from the stationary reference frame to the rotating reference frame which is known as Clarke transformation and Park transformation.

The control task can be greatly simplified by first using the Clarke and Park transforms to perform a two-step transformation on the stator currents. The first is from a three phase to a two phase system with the Clarke transform, and then translating them into the rotor reference frame with the Park Transform. This enables the controllers to generate voltages to be applied to the stator to maintain the desired current vectors in the so- called rotor reference frame. The voltage command is then transformed back by the inverse Park and Clarke transform to voltage commands in the *a*-*b*-*c* stator reference frame, so that each phase can be excited via the power converter.

Numerical problems on vector control of induction motor:

1. A 440V, 50Hz, 6 pole star connected wound rotor motor has the following parameters. Rs=0.5 ohm, R’r=0.4 ohm, Xs=Xr’=1.2 ohm, Xm=50 ohm, stator to rotor turns ratio is 3.5. Motor is controlled by static rotor resistance control. External resistance is chosen such that the breakdown torque is produced at standstill for a duty ratio of zero. Calculate the value of external resistance. How duty ratio should be varied with speed so that the motor accelerates at maximum torque.

Solution

$\text{S} = (Re + Rr')/\surd(Rs^2 + (Xs + Xr\hat{}\,')^2)$

$= (Re + 0.4)/\surd(0.5^2 + (2.4\ )^2)$

$R_e = 2.45\ S - 0.4$

$R_e = 0.5R(1-\alpha)1/a^2$

$R_e = 6.125(1-\alpha)R$

$6.125(1-\alpha)R = 2.45\ S - 0.4$

At standstill s=1

R= 0.3347

2. **A** 440V, 50Hz, 6 pole, 970rpm star connected 3-ph wound rotor motor has the following parameters referred to stator. Rs=0.1 ohm, R’r=0.08 ohm, Xs=0.3 ohm, Xr’=0.4 ohm, stator to rotor turns ratio is 2. Motor speed is controlled by static scherbius drive. Drive is designed for a speed range of 25% below the synchronous speed. Max. value of firing angle 165 deg, calculate (i) transformer turns ratio, (ii) torque for a speed of 780rpm and α=140 deg.

UNIT V

SPEED CONTROL OF SYNCHRONOUS MOTORS

Separate control of synchronous motors:

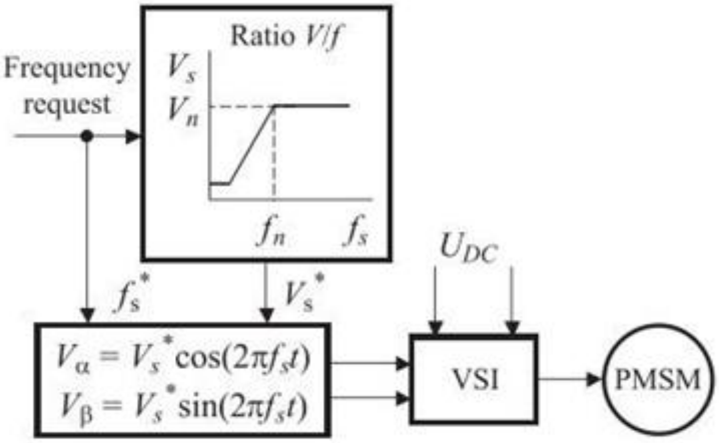


Figure: 5.1 Separate control of synchronous motors

Constant volt per hertz control in an open loop is used more often in the squirrel cage IM applications. Using this technique for synchronous motors with permanent magnets offers a big advantage of sensor less control. Information about the angular speed can be estimated indirectly from the frequency of the supply voltage. The angular speed calculated from the supply voltage frequency ac- cording to (1) can be considered as the value of the rotor angular speed if the external load torque is nothing her than the break down torque.

The mechanical synchronous angular speed ω_S is proportional to the frequency f_S of the supply voltage

$$\omega_s = \frac{2\pi f_s}{p},$$

Where p is the number of pole pairs.

The RMS value of the induced voltage of AC motors is given as

$$E_f = \sqrt{2}\pi f_s N_s k_w \phi \,.$$

By neglecting the stator resistive voltage drop and as sum- in steady state conditions, the stator voltage is identical to the induced one and the expression of magnetic flux can be written as

$$\phi = \frac{V_{sph}}{\sqrt{2}\pi f_s N_s k_w} = c\frac{V_{sph}}{f_s}\,.$$

To maintain the stator flux constant at its nominal value in the base speed range, the voltage- to-frequency ratio is kept constant, hence the name V/f control. If the ratio is different from the nominal one, the motor will become overexcited around excited. The first case happens when the frequency value is lower than the nominal one and the voltage is kept constant or if the voltage is higher than that of the constant ratio V/f. This condition is called over excitation, which means that the magnetizing flux is higher than its nominal value.

An increase of the magnetizing flux leads to arise of the magnetizing current. In this case the hysteresis and eddy current losses are not negligible. The second case represents under excitation. The motor becomes under excited because the voltage is kept constant and the value of stator frequency is higher than the nominal one. Scalar control of the synchronous motor can also be demonstrated via the torque equation of SM, similar to that of an induction motor. The electromagnetic torque of the synchronous motor, when the stator resistance R_S is not negligible, is given

$$T_e = -\frac{m}{\omega_s}\left[\frac{V_{sph}E_f}{Z_d}\sin(\vartheta_L - \alpha) - \frac{E_f^2 R_s}{Z_d}\right]$$

$$T_m = \frac{3p}{2\pi f_s}\frac{V_{sph}E_{PM}}{2\pi f_s L_d} = \frac{3p}{2\pi f_s}\frac{V_{sph}2\pi f_s \Psi_{PM}}{2\pi f_s L_d}\,.$$

The torque will be constant in a wide speed range up to the nominal speed if the ratio of stator voltage and frequency is kept constant

$$\frac{V_{sph}}{f_s} = \text{const.}$$

Self control of synchronous motors

Control of SM motors is performed using field oriented control for the operation of synchronous motor as a dc motor. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor as shown in figure.

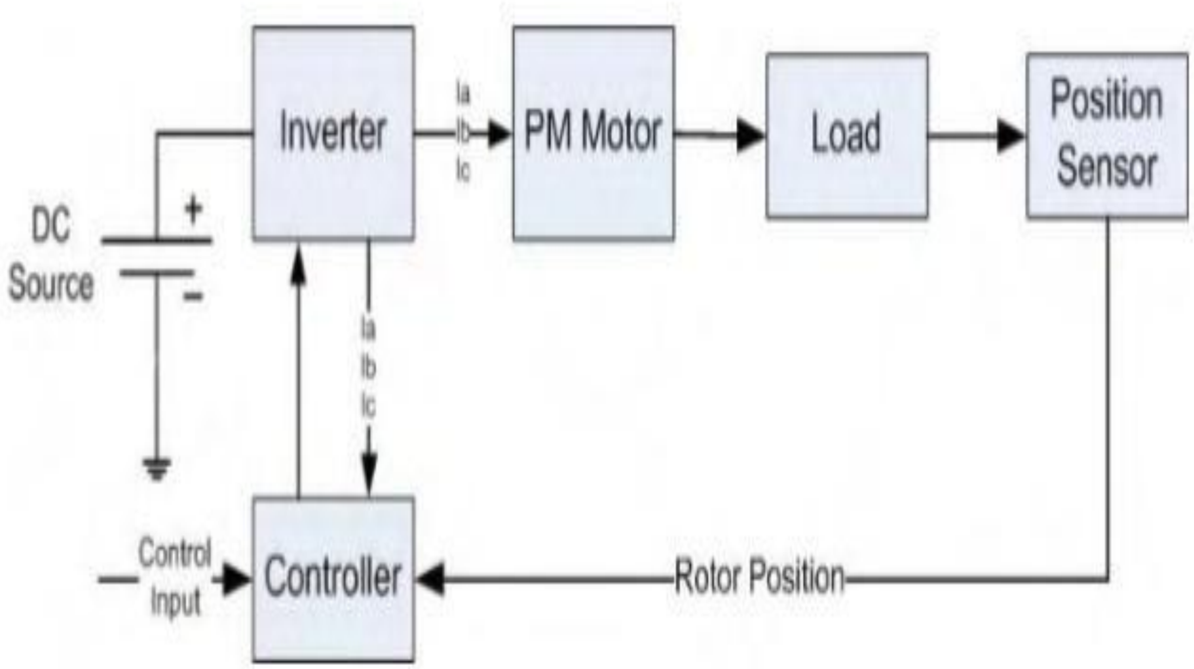


Figure: 5.2. Self control of synchronous motors

Field oriented control was invented in the beginning of 1970s and it demonstrates that an induction motor or synchronous motor could be controlled like a separately excited dc motor by the orientation of the stator mmf or current vector in relation to the rotor flux to achieve a desired objective. In order for the motor to behave like DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of permanent magnet motor. This needs a resolver or an absolute optical encoder. Knowing the position, the three phase currents can be calculated. Its calculation using the current matrix depends on the control desired. Some control options are constant torque and flux weakening. These options are based in the physical limitation of the motor and the inverter. The limit is established by the rated speed of the motor.

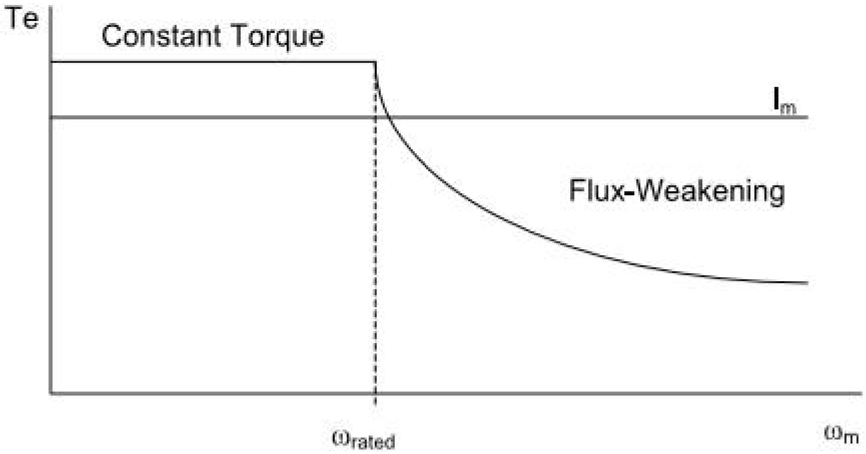


Figure: 5.3. Speed torque characteristics of synchronous motors

Flux-weakening:

Flux weakening is the process of reducing the flux in the d axis direction of the motor which results in an increased speed range.

The motor drive is operated with rated flux linkages up to a speed where the ratio between the induced emf and stator frequency (V/f) is maintained constant. After the base frequency, the V/f ratio is reduced due to the limit of the inverter dc voltage source which is fixed. The weakening of the field flux is required for operation above the base frequency.

This reduces the V/f ratio. This operation results in a reduction of the torque proportional to a change in the frequency and the motor operates in the constant power region.

The rotor flux of PMSM is generated by permanent magnet which cannot be directly reduced as induction motor. The principle of flux-weakening control of PMSM is to increase negative direct axis current and use armature reaction to reduce air gap flux, which equivalently reduces flux and achieves the purpose of flux-weakening control.

This method changes torque by altering the angle between the stator MMF and the rotor d axis. In the flux weakening region where $\omega_r > \omega_{rated}$ angle α is controlled by proper control of i_d and i_q for the same value of stator current. Since i_q is reduced the output torque is also reduced. The angle α can be obtained as:

$$\alpha = Tan^{-1}\left(\frac{i_q}{i_d}\right)$$

The current I_m is related to i_d and i_q by:

$$I_m = \sqrt{i_d^2 + i_q^2}$$

Operation of self controlled synchronous motors by current source inverter

A synchronous motor draws a stator current which is independent of stator frequency when V/f and E/f are maintained constant and armature resistance is neglected. The motor also develops constant torque. The flux also remains constant. Therefore, by controlling the stator current of a synchronous motor we can have flux control as well as torque control. As has been discussed in the case of the induction motor, current control is simple and straightforward. A synchronous motor is fed from a Current Source Inverter Fed Synchronous Motor Drive. A synchronous motor can have either separate control or self control. Due to stable operation self control is normally employed, by using either rotor position sensing or induced voltage sensing. The motor operates in CLM mode. When fed from a CSI the synchronous motor can be operated at leading power factor so that the inverter can be commutated using machine voltages. A load commutated, CSI fed self controlled synchronous motor is very well known as a **converter motor**. It has very good stability characteristics and dynamic behavior similar to a dc motor.

Due to machine commutation the working speed range starts typically above 10% of base speed and extends up to base speed. By using (assisted) forced commutation the lower speed limit can be extended to zero. During the operation in the speed range from 0 to 10% of base speed (above which load commutation is possible) the machine can be operated at UPF.

When fed from a CSI, the synchronous motor is supplied with currents of variable frequency and variable amplitude. The dc link current is allowed to flow through the phases of the motor alternately. The motor currents are quasi-square wave if the commutation is instantaneous. The motor behaviour is very much affected by the square wave currents. The harmonics present in the stator current cause additional losses and heating. They also cause torque pulsations, which are objectionable at low speeds.

A Current Source Inverter Fed Synchronous Motor Drive is inherently capable of regeneration. No additional converter is required, and four quadrant operation is simple and straightforward.

Due to over excitation the machine power factor is leading. The motor is utilized less. The phase control on the line side converter for current control in the dc link causes the power factor to become poor at retarded angles of firing. The cost of the inverter is medium, due to absence of commutation circuit. The drive has moderately good efficiency and is popular as CLM in medium to high power range. Voltage spikes during commutation occur in the terminal voltage. These depend on the sub transient leakage reactance and affect the insulation of the motor also. The motor must have damper windings to limit the Voltage spikes. Application of this type of drive is in gas turbine starting, pumped hydro turbine starting, pump and blower drives, etc.

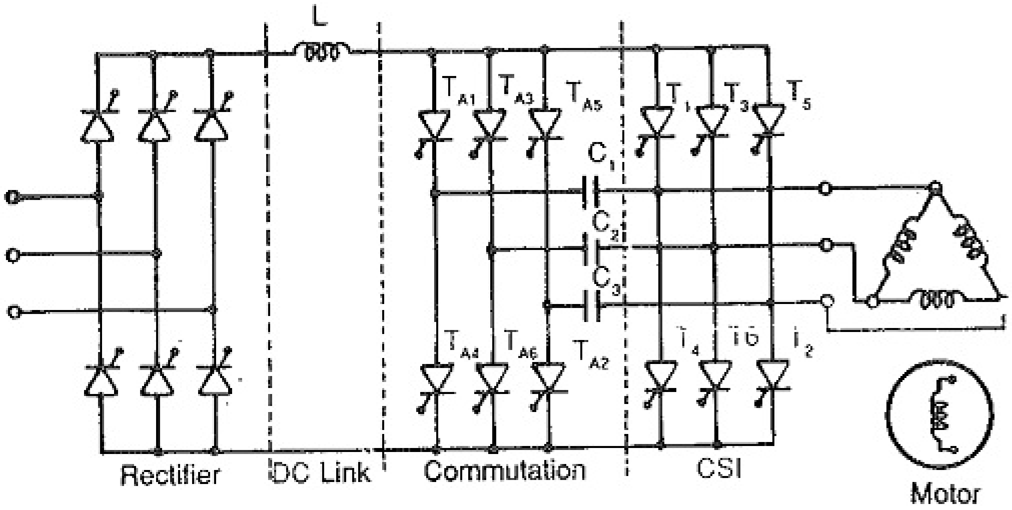


Figure: 5.6. Current source inverter fed Synchronous motor

Third harmonic ASC CSI for use with synchronous motor at low speeds for starting

Sometimes it may be required to provide forced commutation for the inverter. Obviously the speed range can be extended from zero to base speed. The discussion regarding regeneration, harmonics and torque pulsations hold good for this case also. The line power factor is poor. However the machine is operated at UPF to obtain the advantages already discussed. The cost of the inverter increases due to forced commutation. The efficiency of the drive is good and it is popular as a drive in the low to medium power ranges in CLM mode. The drive cannot be operated in open loop. Stability improves in CLM mode. The problem of voltage spikes is present here also and commutation is simple.

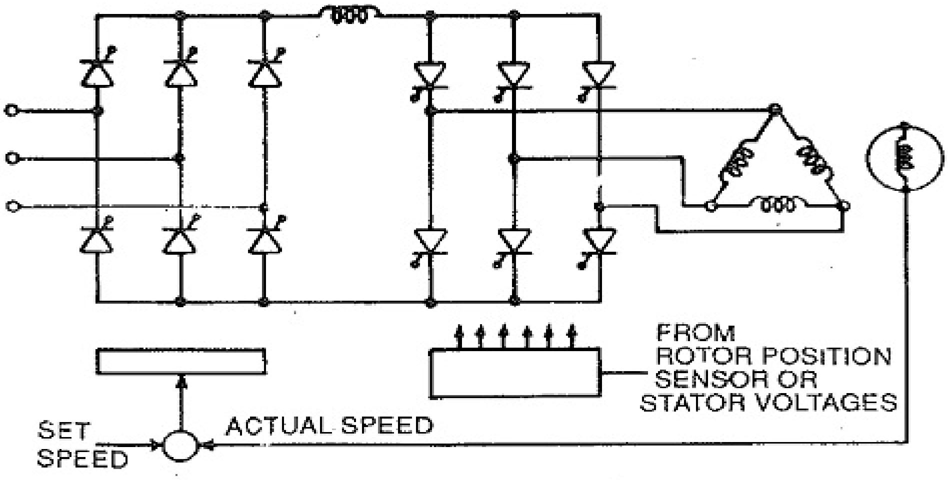


Figure: 5.7. Self control mode with current source inverter

Operation of self controlled synchronous motors by cycloconverter

Cycloconverter is a device which performs the action of fixed AC frequency to variable. The below block diagram shows self controlled synchronous motor fed from a three phase cycloconverter.

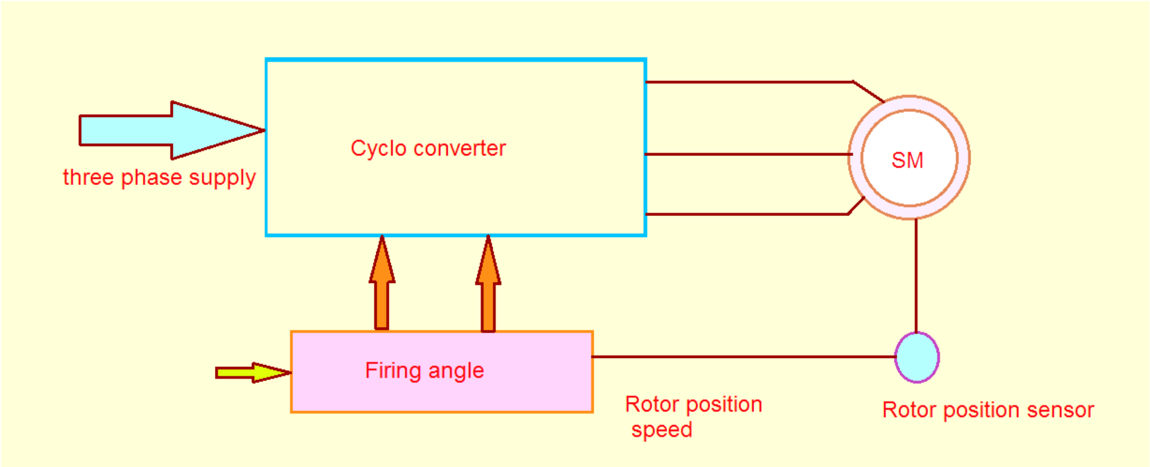


Figure: 5.8. Cycloconverter fed synchronous motor

The three phase supply is given to cyclo converter and the output is fed to synchronous motor. The rotor position sensor is an integral part of the self controlled synchronous motor drive.

Applications of synchronous motor drives:

- Compressors, cement plants
- fan steel rolling mills
- electro optical sensors
- hall effect sensors
- digital encoders.

There are two modes when cyclo converter feeding a synchronous motor

1.Line commutated cyclo converter (VSI):

It is a single stage frequency converter. By using cyclo converter variable frequency of synchronous motor is derived. It is a phase controlled and line commutated.

*At high output frequency the distortion occurs in waveform. So to maintain the limited output frequency they allowed frequency us about one third of the supply frequency which is suitable for low speed and low frequency operations.

*Cyclo converter allows power flow in both the directions, four quadrant drive with regeneration facility can be developed. The harmonic content become minimum by making output voltage waveform into segments.

Advantages:

1. Machine inductance smoothens the current waveforms.
2. The significance of harmonics are low
3. Torque pulsations are minimized
4. Better efficiency
5. Machine power factor improved by decreasing line power factor

Disadvantages:

1. The drive is accepted only at low speeds
2. It requires rotor position sensor.
3. Load commutated (CSI):

Cyclo converter is a single stage frequency conversion equipment. It accomplish four quadrant operation. The converter operates on trapezoidal excitation as a current source to the motor drive load commutation

*There is a necessity of commutation assistance at low speed because at low speed mode the cyclo converter is in voltage source operation. The Field winding of machine rated for large current.

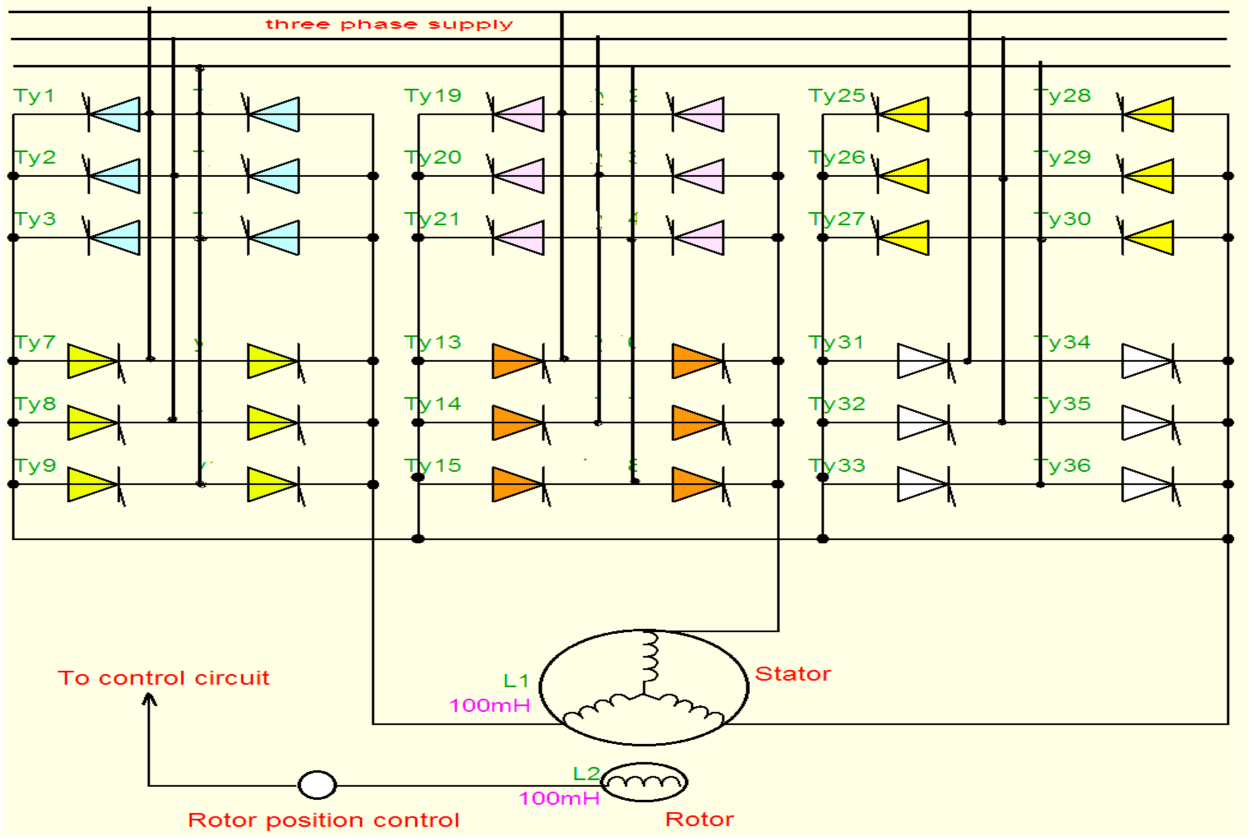


Figure: 5.9. Load commutated Cycloconverter fed synchronous motor

Advantages:

1. Low speed limitation, high speed operation is possible.
2. The harmonics belongs to motor voltage and current are low and don't produce parasitic effects.
3. Motor operates under leading power factor when it is over excited
4. Good efficiency
5. Fast dynamic response
6. Application in large power pumps and blower drives.

Load commutated CSI fed synchronous motor, operation and waveforms

ASCI mode of operation for a single-phase Current Source Inverter (CSI) was presented. Two commutating capacitors, along with four diodes, are used in the above circuit for commutation from one pair of thyristors to the second pair. Earlier, also in VSI, if the load is capacitive, it was shown that forced commutation may not be needed. The operation of a single-phase CSI with capacitive load (Fig. 5.10) is discussed here. It may be noted that the capacitor, C is assumed to be in parallel with resistive load (R). The capacitor, C is used for storing the charge, or voltage, to be used to force-commutate the conducting thyristor pair as will be shown. As was the case in the last lesson, a constant current source, or a voltage source with large inductance, is used as the input to the circuit.

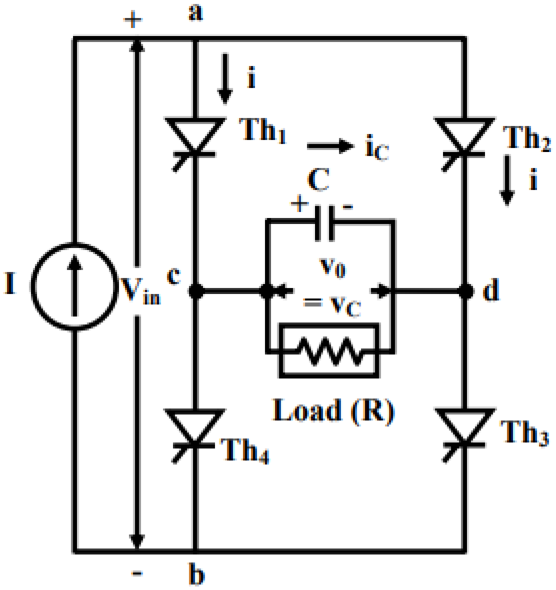


Figure: 5.10. Load commutated Current source inverter fed synchronous motor

The power switching devices used here is the same, i.e. four thyristors only in a full- bridge configuration. The positive direction for load current and voltage is shown in Fig. 5.10. Before t = 0, the capacitor voltage is , i.e. the capacitor has left plate negative and right plate positive. At that time, the thyristor pair, Th C −= Vv 1 2 & Th4 was conducting. When (at t = 0), the thyristors pair, Th1 & Th3 is triggered by the pulses fed at the gates, the conducting thyristors pair, Th2 & Th4 is reverse biased by the capacitor voltage C = −Vv 1 , and turns off immediately. The current path is through Th1, load (parallel combination of R & C), Th3, and the source. The current in the thyristors is Iii , the output current is ThTh 31 = Iiac the capacitor voltage, changes from to , as the capacitor gets charged by the current during the time, . The load voltage is . Thus, the waveform of the current, through load resistance, R has the same nature as that of (Fig. 5.11). Similarly, when (at), the thyristor pair, Th Cv = Tt 2/ 2 & Th4 is triggered by the pulses fed at the gates, the conducting thyristor pair, Th1 & Th3 is reverse biased by the capacitor voltage C = Vv 1 , and turns off immediately. The current path is through Th2, load (parallel combination of R & C), Th4, and the source. The current in the thyristors is IiiTh = Th42, but the output current is ; the capacitor voltage, changes from to , as the capacitor gets charged by the current during the time

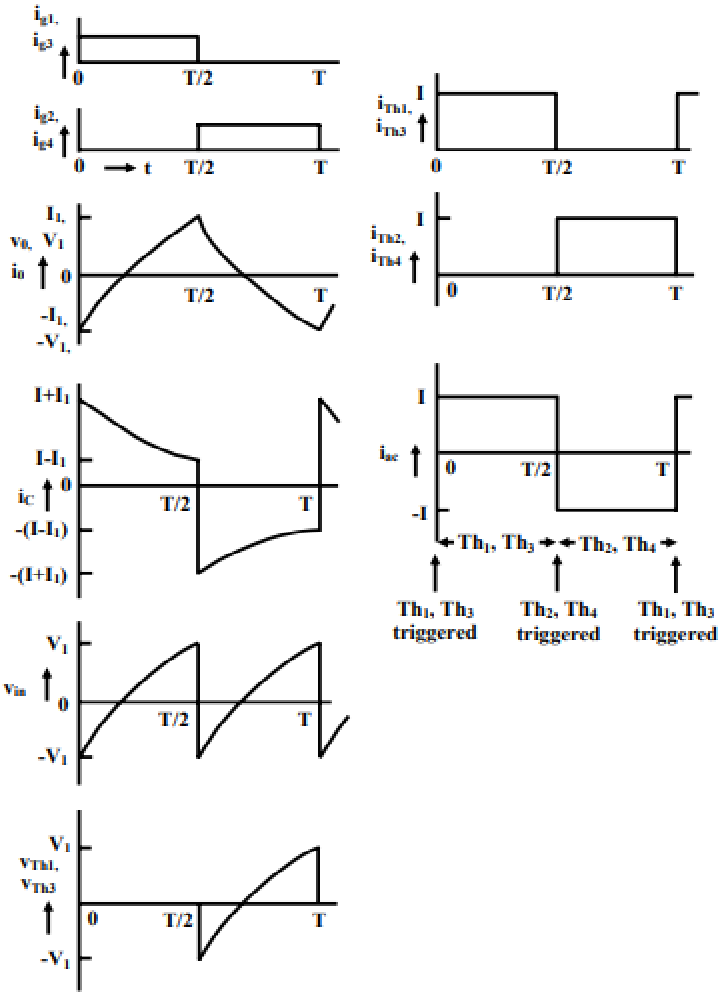


Figure: 5.11. Voltage and current waveforms

Applications and advantages of synchronous motor drives

Synchronous motors find applications in all industrial applications where constant speed is necessary.

Improving the power factor as Synchronous condensers

Electrical power plants almost always use synchronous generators because it is important to keep the frequency constant at which the generator is connected.

Low power applications include positioning machines, where high precision is required, and robot actuators.

Mains synchronous motors are used for electric clocks.

Record player turntables

Speed and position control(by giving DC supply to both stator and rotor position can be fixed)
In positioning machines and robot actuators
As Synchronous condenser : by varying excitation it can made to operate on lagging leading power factor . So can be used for power factor improvement at load side
Constant speed applications

Advantages:

Synchronous motors have the following advantages over non-synchronous motors:

Speed is independent of the load, provided an adequate field current is applied.

Accurate control in speed and position using open loop controls, e.g. stepper motors.

They will hold their position when a DC current is applied to both the stator and the rotor windings.

Their power factor can be adjusted to unity by using a proper field current relative to the load. Also, a "capacitive" power factor, (current phase leads voltage phase), can be obtained by increasing this current slightly, which can help achieve a better power factor correction for the whole installation.

Their construction allows for increased electrical efficiency when a low speed is required (as in ball mills and similar apparatus).

They run either at the synchronous speed else no speed is there.

Synchronous Motor is constant speed motor irrespective of the load so such kind of Motors are used where constant speed is required like heavy industry. In synchronous motor speed is depend only on the supply frequency and such motors are very attractive for low speed drives because the power factor can be adjusted to 1 and the efficiency is high.

A Synchronous motor could also improve the power factor of the plant while operated at rated load.

Syncronous motors operate at constant speeds regardless of voltage and dependent only on the frequency of the power supply.

That means that they are quite useful for driving machinery that operates at a steady speed for long periods of time (conveyor belts, paper-making machines, ball mills, and the like).

One use that you may not think of for synchronous motors is in the turntables of record players. (Which you may not have seen outside of displays of "historical artifacts".)

Numerical problems on synchronous motor drives

1. A three phase 400V, 50Hz, 6 pole, star connected wound rotor synchronous motor has Zs = 0+j2Ω. Load torque is proportional to speed squared, is 340Nm at rated synchronous speed. The speed of the motor is lowered by keeping V/f constant and maintaining unity power factor by field control of the motor. For the motor operation at 600 rpm calculate
   i. Supply voltage
   ii. Armature current

Solution:

i. Frequency f = PN/60 = 6*600/120 = 30Hz

As V/f constant

Vs/30=400/50

Vs = 240V

ii. $T_l = 340(600/1000)^2 = 122.4$Nm

$P = T_l w = 122.4*2\Pi*600/60 = 7690.62W$

$P = \sqrt{3} Vs Is cos\Phi$

Is = 18.5A

2. A synchronous motor is controlled by a load commutated inverter, which in turn is fed from a line commutated converter. Source voltage is 6.6kV, 50Hz. Load commutated inverter operates at a constant firing angle α1 of 130.° and when rectifying αγ = 0 ° dc link inductor resistance Rd = 0.2 Ω. Drive operates in self control mode with a constant (V/f) ratio. Motor has the details; 8MV, 3 phase 6600V, 6pole, 50Hz unity power factor, star connected, Xs = 2.6 Ω, Rs = o. Determine source side converter firing angles for the Motor operation at the rated and 500rpm. What will be the power developed by motor

Closed loop control operation of synchronous motor drives with block diagram

Close loop control shown in Fig. 5.12 employs outer speed control loop and inner current control loop with a limiter the terminal voltage sensor generates reference pulses whose frequency is same as thatϖ of the induced voltages in the rotor. These reference signals are shifted suitably by phase delay circuit to produce a constantϖ commutation lead angle. Based on the speed error, the value of βlc is set to provide either motoring or braking operation. Motoring operation is required to increase the speed and braking is required to reduce the speed. Actual speed of the rotor is sensed either from terminal voltage sensor or by using a separate tachometer.

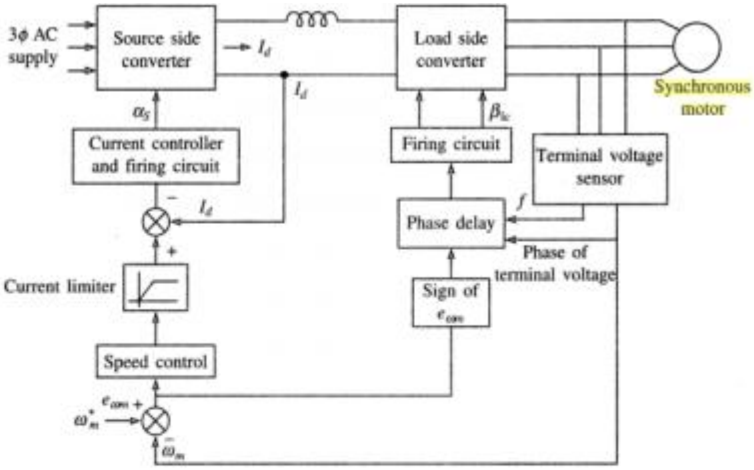


Figure: 5.12. Closed loop control operation of synchronous motor drives

Increasing the speed

If the speed is to be increased, then it is given as reference speed ωm*. Actual speed and reference speed are compared at the comparator and it produces a positive speed error.

Now the firing circuit produces βlc corresponding to motoring operation. The speed controller and current controller set the dc link current reference at the maximum allowable value. Now the machines starts accelerating and when rotor speed reaches the reference speed, the current limiter de-saturates and the acceleration stops. Hence the drive runs at constant speed at which motor torque is equal to load torque

Decreasing the speed

If the speed is to be decreased, then it is set as reference speed ωm*.

Actual speed and reference speed are compared at the comparator and it produces a negative speed error. Now the firing circuit produces βlc corresponding to braking operation. The speed controller and current controller get saturated and set the dc link referencecurrent at the maximum allowable value. Now the machines starts decelerating (braking operation) and when rotor speed reaches the reference speed, the current limiter de-saturates and the deceleration stops. Hence the drive runs at constant speed at which motor torque is equal to load torque.

Advantages of this drive

- High efficiency
- Four quadrant operation with regenerative braking is possible
- Drives are available for high power ratings up to 100 MWϖ High speed operation is possible. (up to 6000 rpm)

Applications of this drive

- High speed and high power drives for compressors, blowers, pumps, fans, conveyers etc

Variable frequency control of synchronous motor with cycloconverter

DC link converter is a two stage conversion device which provides a variable voltage, variable frequency supply. Variable voltage, variable frequency supply can be obtained from a cycloconverter which is single stage conversion equipment. The power circuit of a Three Phase Synchronous Motor Fed From Cycloconverter is shown in Fig. 5.13. This has several differences compared to a dc link converter

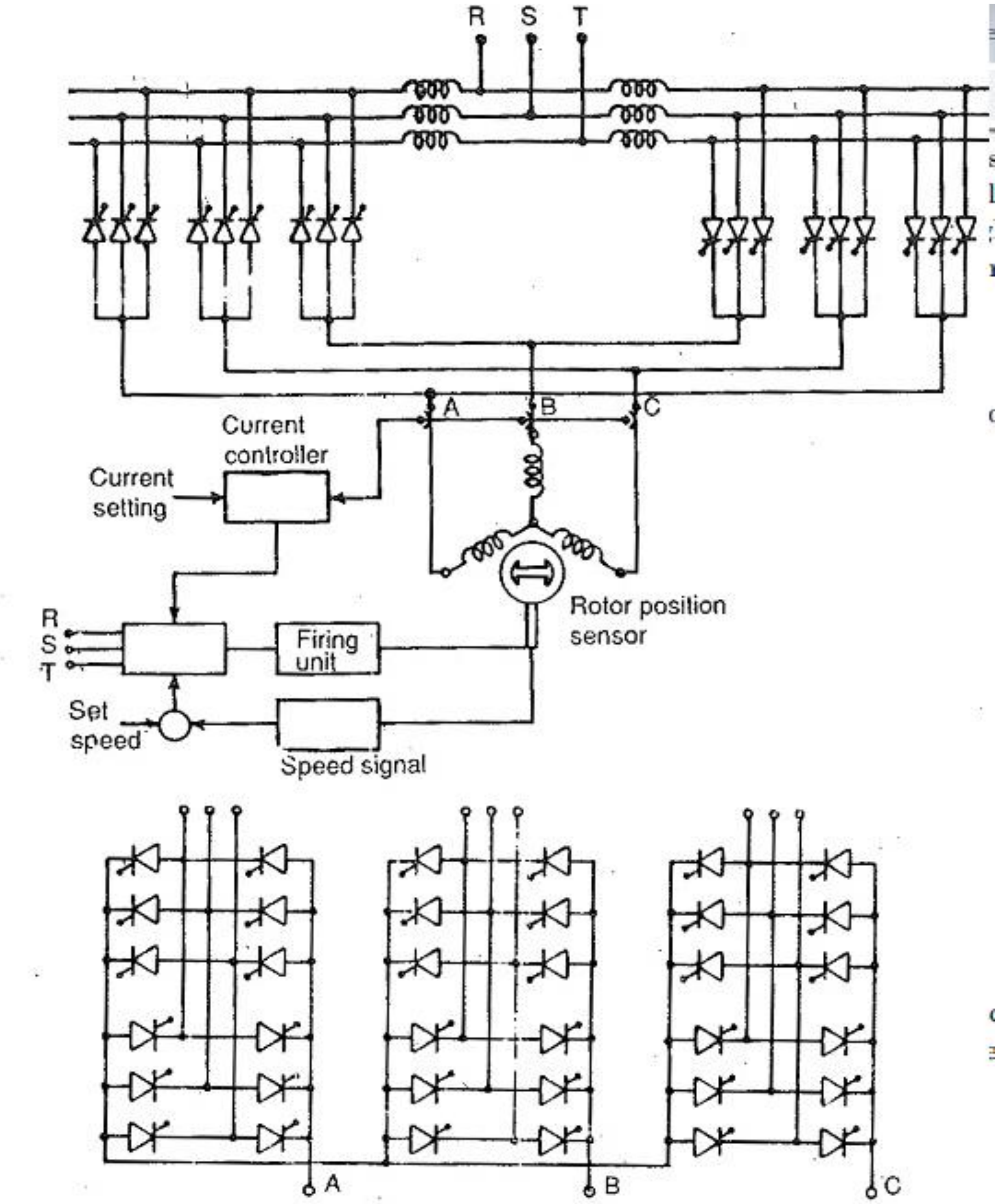


Figure: 5.13. Variable frequency control of synchronous motor with cycloconverter

The line voltages are made use of to commutate the thyristors of a cycloconverter. The output frequency can be varied from 0 — 1/3 of the input frequency. The range of speed control is therefore limited, extending from 0 — 1/3 base speed. Cycloconverters are inherently capable of power transfer in both directions. Four quadrant operation is simple.

A cycloconverter in the above speed range gives a high quality sinusoidal output voltage. The resulting currents are also nearly sinusoidal. The harmonic content of the current is small. Consequent effects of harmonic current, such as losses, heating and torque pulsations are minimal. The line power factor is somewhat better because the machine power factor can be made unity.

A Synchronous Motor Fed from Cycloconverter requires a large number of thyristors and its control circuitry is complex. Converter grade thyristors are sufficient but the cost of the converter is high. The efficiency is good and the drive has a good dynamic behavior. The operation in CLM mode is popular.

A Synchronous Motor Fed from Cycloconverter drive is attractive for low speed operation and is frequently employed in large, low speed reversing mills requiring rapid acceleration and deceleration. Typical applications are large gearless drives, e.g., drives for reversing mills, mine hoists, etc.

A cycloconverter can also be commutated using the load voltages if the load is capable of providing the necessary reactive power for the inverter. An overexcited synchronous motor can provide the necessary reactive power. Hence a cycloconverter feeding such a motor can be load commutated. The range of speed control is from medium to base speed. At very low speeds load commutation is not possible. The speed range can be extended to zero if line commutation is used at low speeds. Four quadrant operations are simple. The problems associated with harmonics are minimal due to high quality of the output. The line power factor depends on the angle of firing and is poor. The cost of the converter is high with complex control. Its efficiency is good and the drive has a fast response. It finds application in high power pump and blower type drives.