EE8601 SOLID STATE DRIVES

QUESTION BANK WITH ANSWERS

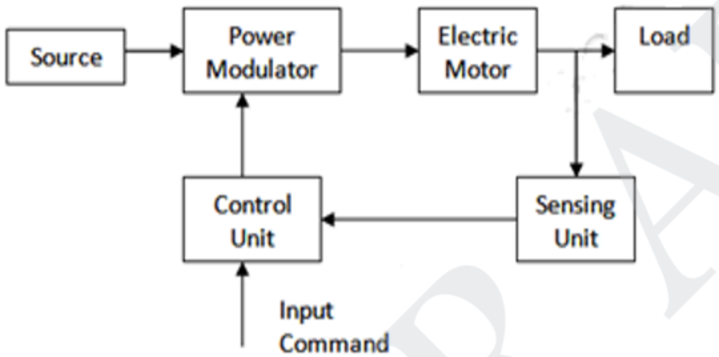
UNIT – I DRIVE CHARACTERISTICS

PART – A

1. What is meant by electrical drives?(Dec 2007)

Systems employed for motion control are called drives and they employ any of the prime movers such as diesel or petrol engines, gas or steam turbines, hydraulic motors and electric motors for supplying mathematical energy for motion control. Drives employing electric motion are called electric drives.

2. Draw the electric drive system.(AU-Dec2009)



Block diagram of an electric drive

3. Specify the functions of power modulator.

Power modulator performs one or more of the following four functions.

a. Modulates flow of power from the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load.

b. During transient operations, such as starting, braking and speed reversal, it restricts source and motor currents within permissible values; excessive current drawn from source may overload it or may cause a voltage dip.

4. Mention the different types of drives.

1) Group drive
2) Individual drive
3) Multi motor drive

5. List the different types of electrical drives.

1) DC drives
2) AC drives

6. What are the functions performed by electric drives?

Various functions performed by electric drives include the following.

a. Driving fans, ventilators, compressors and pumps etc.

b. Lifting goods by hoists and cranes

c. Imparting motion to conveyors in factories, mines and warehouses and

d. Running excavators and escalators, electric locomotives, trains, cars, trolley buses, lifts and drums winders etc.

7. What are the disadvantages of electric drives?

The disadvantages of electric drives,

a. Electric drives system is tied only up to the electrified area.

b. The condition arising under the short circuits, leakage from conductors and breakdown of overhead conductor may lead to fatal accidents.

c. Failure in supply for a few minutes may paralyses the whole system.

8. Mention the parts of electrical drives.

1) Electrical motors and load.
2) Power modulator
3) Sources
4) Control unit
5) Sensing unit

9. What are the methods of operation of electric drives?

Steady state: Acceleration including starting
Deceleration including starting

10. Define four quadrant operations.

The 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 mathematical energy into electrical energy and thus opposes the motion. Motor can provide motoring and braking operations for both forward and reverse directions.

PART – B

1. What are the advantages of Electrical drives?

Advantages of Electrical Drives:

1. They have flexible control characteristics. The steady state and dynamic characteristics of electrical drives can be shaped t satisfy the load requirements.
2. They are available in wide range of torque, speed and torque.
3. Electric motors have high efficiency, low no load losses and considerable short time overloading capability.
4. They are adoptable to any operating conditions such as explosive and radioactive environment, submerged in liquids, vertical mountings, and so on.
5. Do not pollute the environment.
6. Can operate in all four quadrants of the speed- torque plane.
7. Unlike other prime movers, there is no need to refuel or warm-up the motor. They can be started instantly and can be fully loaded.

2. Explain the parts of Electrical Drives?

Parts of Electrical Drives:

Electrical drives have the following major parts:

1. Power modulator.
2. Electric motors
3. Source
4. Control unit

Electrical Motors

Motors commonly used in electrical drives are: DC motors – shunt, series, compound and permanent magnet; Induction motors – squirrel cage, wound rotor and linear; Synchronous motors - wound field and permanent magnet; BLDC motors; Stepper motors and; Switched reluctance motor.

Power Modulators

Drives may employ more than one power modulators. It can be classified in to

1. Controlled rectifiers
2. Inverters
3. AC voltage controllers
4. DC choppers
5. Cycloconverters

Sources

In India 1- phase and 3-phase 50 Hz supplies are readily available in most of the locations. Very low power drives are fed from 1-phase supply and rest of the supply fed from 3-phase source. Single phase source used for economic purpose. Most of drives powered from AC source either directly or through converter link. When fed directly from 50 Hz ac supply, maximum speeds of induction motor and synchronous motor are limited to 3000 rpm. Low and medium power motors are generally fed from 400 V supply: for high power ratings, motor may be rated 3.3 kV, 6.6 kV, 11kV.

In case of aircraft and space applications, 400 Hz AC supply is generally used to achieve high power to weight ratio for motors.

Control unit

Controls for a power modulator are provided in the control unit. Control unit for a particular drive depends on the power modulator used.

When semiconductor converters are used, the control unit consists of firing circuits, which employ the linear and digital integrated circuits and transistor, and a microprocessor when sophisticated control is required. PLC is used when solid state relays are used.

3. Explain the factors to be considered for choice of electric drives. Also state the status of DC and AC drives?

Choice of electrical drive depends on the number of factors. Some of the important factors are:

1. Steady state operation requirements: Nature and of speed torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrant operation.
2. Transient operation requirements: Value of acceleration and deceleration, starting, braking and reversing performance.
3. Requirements related to the source: Type of source, and its capacity, magnitude of voltage, voltage fluctuations, power factor and harmonics.
4. Capital and running cost.
5. Space and weight restrictions.
6. Environment and location.
7. Reliability.

Status of DC and AC Drives

a) In earlier period induction and synchronous motor drives are used for fixed speed application. DC motor drives are used for variable speed applications.
b) In later day's development of variable speed induction motor drives and squirrel cage induction motor over DC motors, DC drives are replaced by induction motor drives for variable speed applications.
c) Even though the induction motor is cheaper than DC motor, the control unit and the converter of the induction motor drives is costly. So that total cost of the induction motor drive higher than the DC drives.
d) AC drives were not as reliable as DC.
e) Development in linear and digital ICs, VLSI were helpful to improve the performance and reliability.
f) AC drives preferred over DC drives with number of application and result.

4. Write the equation governing the motor load dynamics.

Dynamics of Electric Drives

Fundamental Torque Equations

A motor generally used to drive the load through transmission system. When the motor rotates load start to rotate. If the load has many parts, few parts may rotate and some of them under go translational motion.

The motor load system is represented by convenient equivalent rotational system as shown in the Fig 1.1

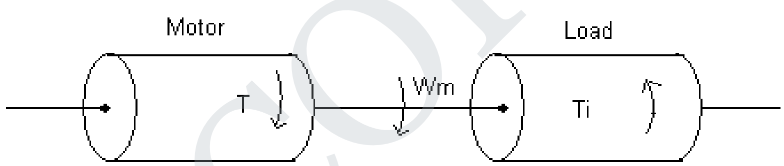


Fig 1.1 Equivalent motor-load system

Motor – load system can be described by the following fundamental equation torque equation:

$$T - T_l = d/dt\,(j\omega_m) = j\,d\omega_m/dt + \omega_m\,dj/dt$$

The above is applicable for variable inertia drives. For drive with constant inertia,

$$jd\omega_m/dt = 0$$

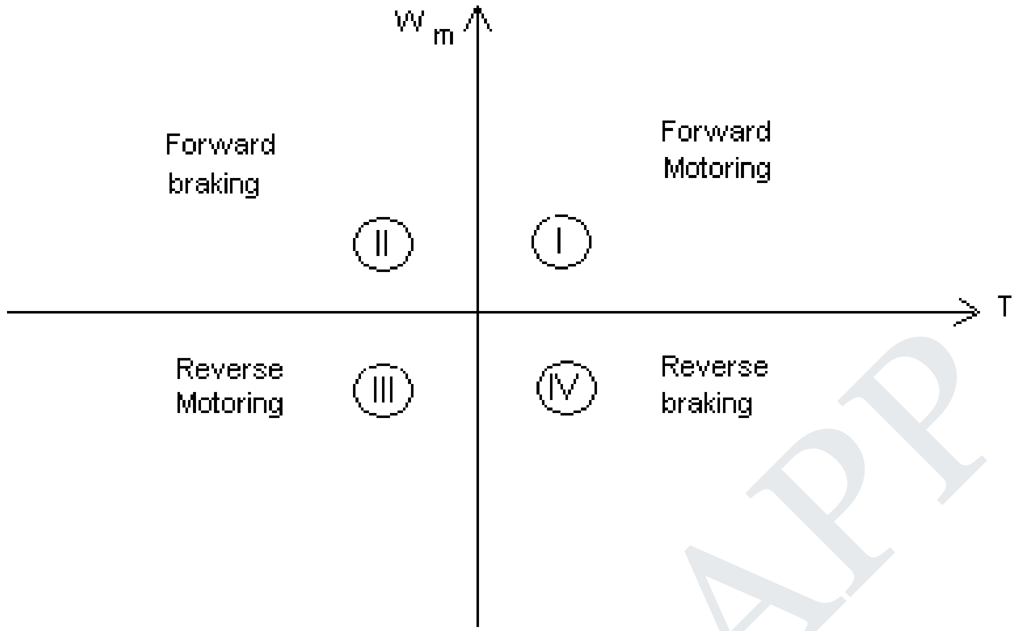
Therefore $\quad T = T_l + j\,d\omega_m/dt$

The torque developed by the motor is counter balanced by a load torque T_l and a dynamic torque $jd\omega_m/dt$.

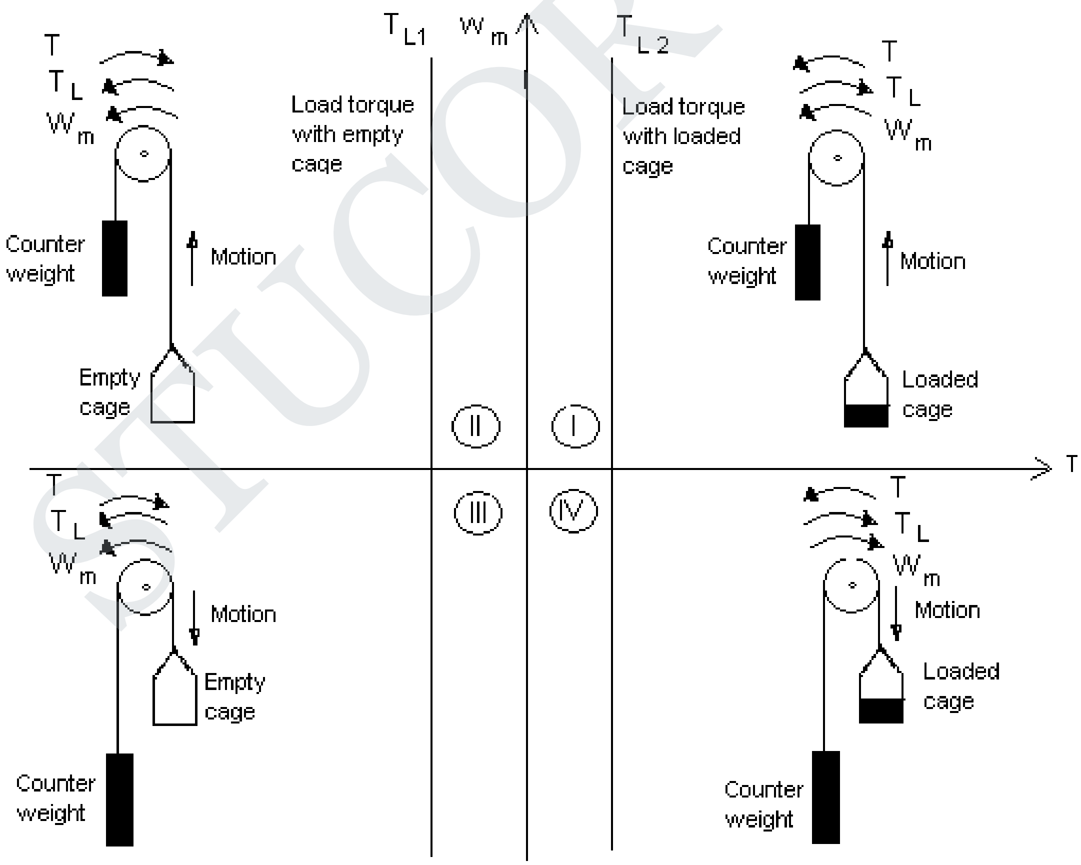
5. Explain in detail the multi quadrant dynamics in the speed-torque plane.

Multiquadrant Operation

A motor can operates in two modes – motoring and braking. In motoring, it converts mechanical energy and in braking it works as a generator which will convert mechanical energy in to electrical energy. Power developed is product of speed and torque.



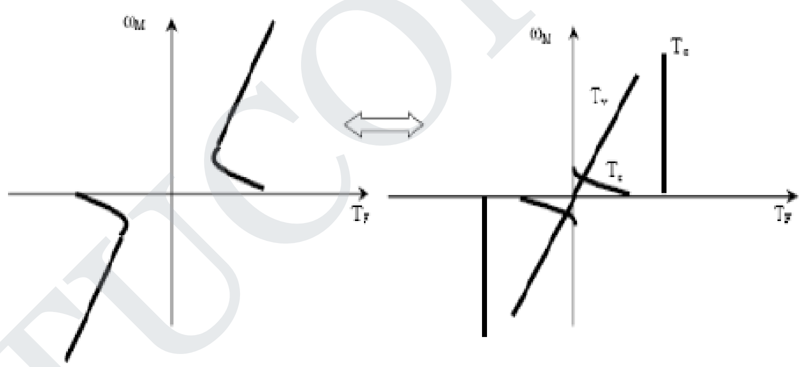
Multi quadrant operation of drives



Four quadrant operation of a motor driving a hoist load

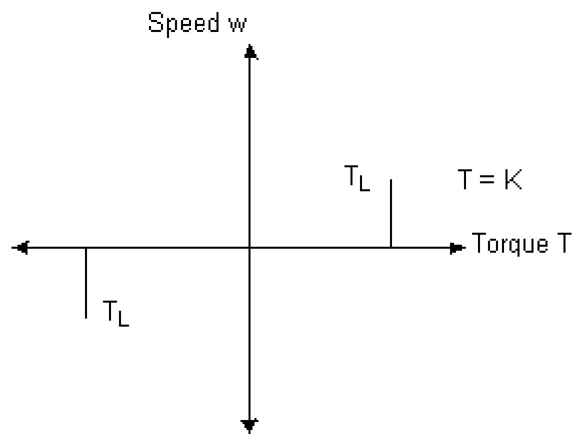
a) The quadrant I operation of a hoist requires the movement of the cage upward. This corresponds to the positive motor speed.
b) Since developed power is positive, this is forward motoring operation.
c) Quadrant IV operation is obtained when a loaded cage is lowered.
d) Counter weight comes down due to gravity itself, it is necessary for the motor to produce positive torque.
e) As power and speed are negative, drive is operating in reverse braking.
f) Operation in quadrant II is obtained when empty cage is moved up. Since a counter weight is heavier than an empty cage, it is able to pull it up.
g) Since speed is positive and developed power negative, it is forward braking operation.
h) Operation in quadrant II is obtained when empty cage is lowered.
i) Since speed is negative and developed power is positive, this is reverse motoring operation.

6. Explain various types of load torques
Components of Load Torques
Load torque can be further divided in to following components:
1. Friction torque Tf: Friction will be present in the shaft and also various part of the load.
2. Windage torque Tw: When motor runs, wind generates a torque opposing the motion.
3. Torque required to do the useful mechanical work TL: Nature of the torque depends on the particular application. It may be constant and independent of speed.



Speed Torque Characteristics of Motor and Load
Different types of loads exhibit the different speed torque characteristics. However most of the industrial loads can be classified into four categories:
1. Constant torque type
2. Generator type – torque proportional to speed
3. Fan type - torque proportional to square of the speed
4. Constant power type - torque inversely proportional to speed

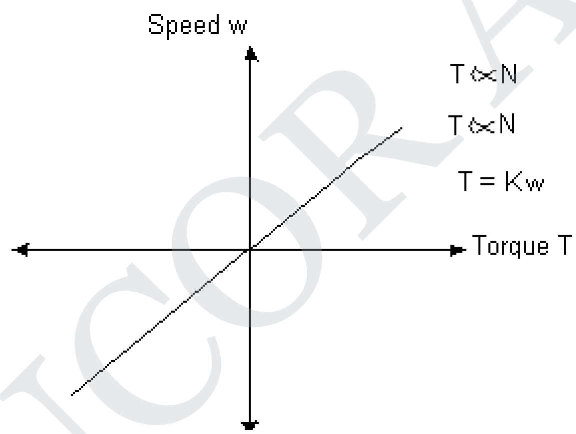
1. Constant torque type load – characteristics
Most of the working machines mechanical nature of work like requires constant torque irrespective of speed. The speed torque characteristics of this type of load is given by T = K and is shown in fig.



Speed torque characteristics of constant torque load

2. Generator type – torque proportional to speed

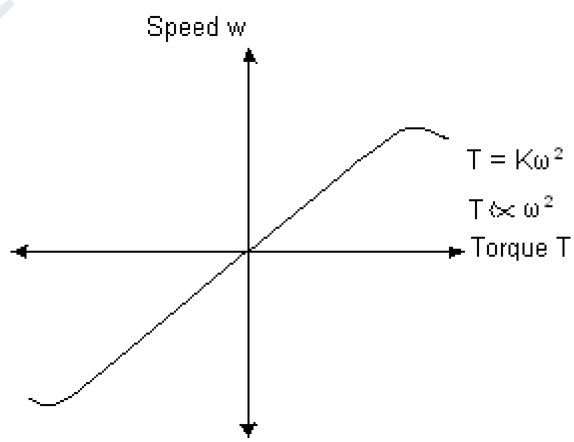
Separately excited DC generators connected to a constant resistance load, eddy current brakes and calendaring machines a speed – torque given by T = Kw



Generator type – torque proportional to speed

3. Fan type - torque proportional to square of the speed

Load torque proportional to the square of the speed. Speed torque is given by $T = K\omega^2$



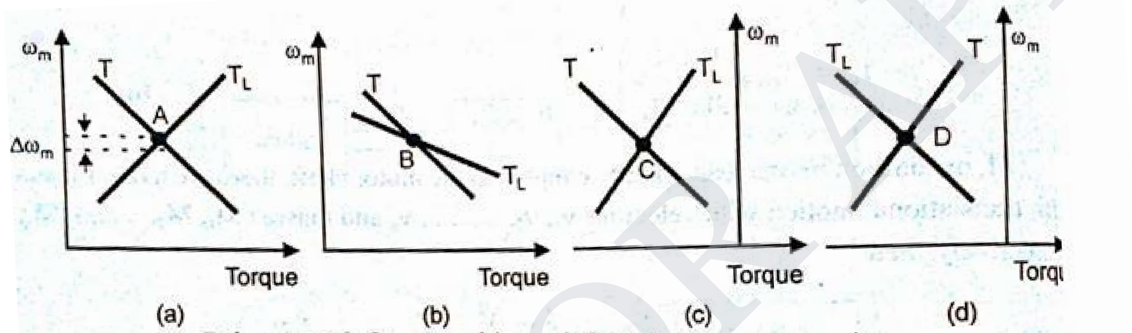
4. Constant power type - torque inversely proportional to speed

Certain type of loads exhibit hyperbolic speed torque characteristics. In such loads torque is inversely proportional to speed. This type of characteristics is given by $T = K/\omega$

7. Derive the mathematical expression for the analysis of steady state stability of equilibrium point.

Equilibrium speed of a motor-Load system can be obtained when motor torque equals the load torque. Electric Drive system will operate in steady state at this speed, provided it is the speed of the stable state equilibrium.

Concept of steady state stability has been developed to readily evaluate the stability of an equilibrium point from the steady state speed-torque curve of the motor and load system.



Point A and C are stable and B and D are unstable

$$\boxed{\frac{dT_L}{d\omega_m} > \frac{dT}{d\omega_m}}$$

The torque equation

$$T = T_L + J\frac{d\omega_m}{dt}$$

$$(T + \Delta T) = (T_L + \Delta T_L) + J\frac{d(\omega_m + \Delta\omega_m)}{dt}$$

or

$$T + \Delta T = T_L + \Delta T_L + J\frac{d\omega_m}{dt} + J\frac{d\Delta\omega_m}{dt}$$

Subtracting (20) from (21) and rearranging terms gives

$$J\frac{d\Delta\omega_m}{dt} = \Delta T - \Delta T_L$$

Thus
$$\Delta T = \left(\frac{dT}{d\omega_m}\right)\Delta\omega_m \qquad \text{....(23)}$$

$$\Delta T_L = \left(\frac{dT_L}{d\omega_m}\right)\Delta\omega_m \qquad \text{....(24)}$$

where $(dT/d\omega_m)$ and $(dT_L/d\omega_m)$ are respectively slopes of the steady-state speed-torque curves of motor and load system at operating point under consideration.

Substituting equation (23) and (24) into (22) and rearranging the terms,

$$J\frac{d\Delta\omega_m}{dt} + \left(\frac{dT_L}{d\omega_m} - \frac{dT}{d\omega_m}\right)\Delta\omega_m = 0 \qquad \text{....(25)}$$

It is a first order linear differential equation. If initial deviation in speed at t = 0 be $(\Delta\omega_m)$ 0 then the solution of differential equation (25) will be

$$\Delta\omega_m = (\Delta\omega_m)_0 \exp\left\{-\frac{1}{J}\left(\frac{dT_L}{d\omega_m} - \frac{dT}{d\omega_m}\right)t\right\} \qquad \text{....(26)}$$

The system operating point will be stable when $\Delta\omega_m$ approaches to zero as t approaches infinity. For this to happen the exponent term in equation (26) must be negative.

8. A motor drive two loads. One has rotation motion. It is coupled to the motor through a reduction gear with a=0.1 and efficiency of 90%. The load has a moment of inertia of 10kg –m2 and a torque of 10N-M. Other load has translation motion and consist of 1000kg weight to be lifted up at an uniform speed of 1.5 m\s. coupling between this load and motor has an efficiency 85%.Motor has an inertia of 0.2kg-m2 and runs at a constant speed of 1420 rpm. Determine equivalent inertia referred to the motor shaft and power developed by the motor.

Solution:

The total moment of inertia referred to the motor shaft.

$$J = J_0 + a_1^2 J_1 + M_1\left(\frac{v_1}{\omega_m}\right)^2$$

$$J_0 = 0.2\text{kg–m}^2, a_1 = 0.1, J_1 = 10\text{kg–m}^2$$

$$v = 1.5\text{m/s and } \omega_m = \frac{1420 \times \pi}{30} = 148.7\text{rad/sec}$$

$$J = 0.2 + (0.1)^2 \times 10 + 1000\left(\frac{1.5}{148.7}\right)^2$$

$$= 0.4 \text{ kg} - \text{m}^2$$

$$T_L = \frac{a_1 T_{L1}}{n_1} + \frac{F_1}{n_1^1}\left(\frac{v_1}{\omega_m}\right)$$

$$n_1 = 0.9, a_1 = 0.1, T_{L1} = 10 - \text{N–m}, \quad n_1^1 = 0.85$$

$$F_1 = 1000 \times 9.81 \text{ N}, v_1 = 1.5 \text{ m/s}$$

$$\omega_m = 148.7 \text{ rad/sec.}$$

$$T_L = \frac{0.1 \times 10}{0.9} \times \frac{1000 \times 9.81}{0.85}\left(\frac{1.5}{148.7}\right)$$

$$\boxed{T_L = 117.53 \text{ N} - \text{m}}$$

$$\text{Power developed} = T_L\omega_m = 117.53 \times 148.7$$

$$= 17.48 \text{ kW}$$

10) **An electric drive has the following parameters: $J=10 kg-m^2$, $T= 100-0.1\ N$, N–m, Passive load torque $T_L= 0.05\ N$, N–m Where N is the speed in rpm. Initially the drive is operating in steady state. Now it is to be reversed. For this motor characteristic is changed to $T = -100 - 0.1N$, N–m. Calculate the time of reversal.**

Solution:

For steady state speed

$$T - T_L = 0$$

$$100 - 0.1N - 0.05N = 0$$

$$0.15\,N = 100$$

$$N = \frac{100}{0.15} = 666.7\text{rpm}$$

After reversal, for steady – state speed, noting that the load is passive

$$-100 - 0.1\,N - 0.05\,N = 0$$

$$N = -666.7 \text{ rpm}$$

When reversing, from equation (2)

$$J\frac{d\omega_m}{dt} = -100 - 0.1N - 0.05\,N$$

$$\frac{dN}{dt} = \frac{30}{J\pi}(-100 - 0.15\,N)$$

$$= -95.49 - 0.143\,N$$

$$t = \int dt = \int_{N_1}^{N_2} \frac{dN}{-95.49 - 0.143\,N}$$

Where $N_1 = 666.7$ rpm, $N_2 = 0.95 \times -666.7$

$$= .633.4 \text{ rpm}$$

Integrating this equation, yields

$$t = 25.58 \text{ sec.}$$

UNIT – II CONVERTER / CHOPPER FED DC MOTOR DRIVE

PART – A

1. What are the advantage and disadvantages of D.C. drives?

The advantages of D.C. drives are,

a. Adjustable speed
b. Good speed regulation
c. Frequent starting, braking and reversing.

The disadvantage of D.C. drives is the presence of a mechanical commutator which limits the maximum power rating and the speed.

2. Give some applications of D.C. drives.

The applications of D.C. drives are,

Rolling mills, Paper mills, Mine winders, Hoists, Machine tools, Traction, Printing Presses, Excavators, Textile mills and Cranes

3. How the D.C. motor is affected at the time of starting?

A D.C. motor is started with full supply voltage across its terminals; a very high current will flow, which may damage the motor due to heavy sparking at commuter and heating of the winding. Therefore, it is necessary to limit the current to a safe value during starting.

4. Define and mention different types of braking in a dc motor?

In braking the motor works as a generator developing a negative torque which opposes the motion. Types are regenerative braking, dynamic or rheostat braking and plugging or reverse voltage braking.

5. List the drawbacks of armature resistance control?

In armature resistance control speed is varied by wasting power in external resistors that are connected in series with the armature. Since it is an inefficient method of speed control it was used in intermittent load applications where the duration of low speed operations forms only a small proportion of total running time.

6. Define positive and negative motor torque.

Positive motor torque is defined as the torque which produces acceleration or the positive rate of change of speed in forward direction. Positive load torque is negative if it produces deceleration.

7. Write the expression for average o/p voltage of full converter fed dc drives?

$Vo = (2Vm/\Pi)cos\alpha$.................continuous conduction

$Vo = [Vm(cos\alpha - cos\,\beta) + (\Pi + \alpha + \beta)]/\Pi]$........discontinuous conduction

8. Mention the drawbacks of rectifier fed dc drives?

a. Distortion of supply.
b. Low power factor.
c. Ripple in motor current

9. What are the advantages in operating choppers at high frequency?

The operation at a high frequency improves motor performance by reducing current ripple and eliminating discontinuous conduction.

10. Why self-commutated devices are preferred over thyristors for chopper circuits?

Self-commutated devices such as power MOSFETs, power transistors, IGBTs, GTOs are preferred over thyristors for building choppers because they can be commutated by a low power control signal and don't need commutation circuit.

11. State the advantages of dc chopper drives?

Dc chopper device has the advantages of high efficiency, flexibility in control, light weight, small size, quick response and regeneration down to very low speed.

12. What are the types of control strategies in dc chopper?

a. Time ratio control.
b. Current limit control.

PART – B

1. Explain the classification of DC Drives.

Classification of DC drives:

1. Single phase drives

a) 1 - Ө half wave drives
b) 1 - Ө full wave drives
   i) 1 - Ө fully controlled converter fed drives
   ii) 1 - Ө half controlled converter fed drives
c) 1 - Ө dual converter fed drives

2. Three phase drives

a) 3 - Ө half wave drives
b) 3 - Ө full wave drives
   i) 3 - Ө fully controlled converter fed drives
   ii) 3 - Ө half controlled converter fed drives
c) 3 - Ө dual converter fed drives

3. DC chopper drives

Classification of chopper fed DC drives:

1) First quadrant chopper or type A chopper
2) Second quadrant chopper or type B chopper
3) Two quadrant type A chopper or type C chopper.
4) Four quadrant chopper or type E chopper.

Advantage of DC chopper Drive:

1) High efficiency
2) Flexibility in controls
3) Light weight
4) Small size
5) Quick response

2. Describe the steady state analysis of single phase fully controlled converter fed separately excited dc motor drive in continuous and discontinuous modes.

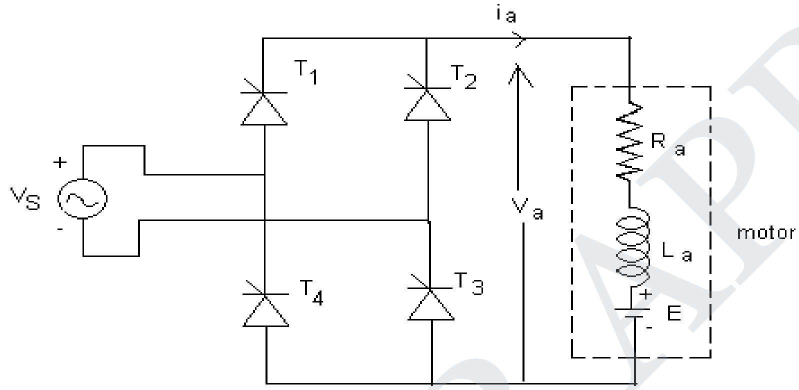
Steady State Analysis of Single Phase DC Drives

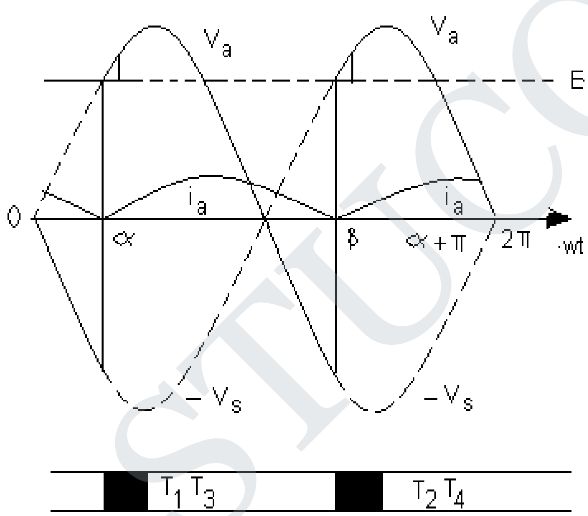
In single phase drives, single phase supply used to drive the motor. The drive has poor speed regulation and it can be overcome by closed loop operation.

Single Phase Fully Controlled Bridge Converter Control of DC Separately Excited Motor

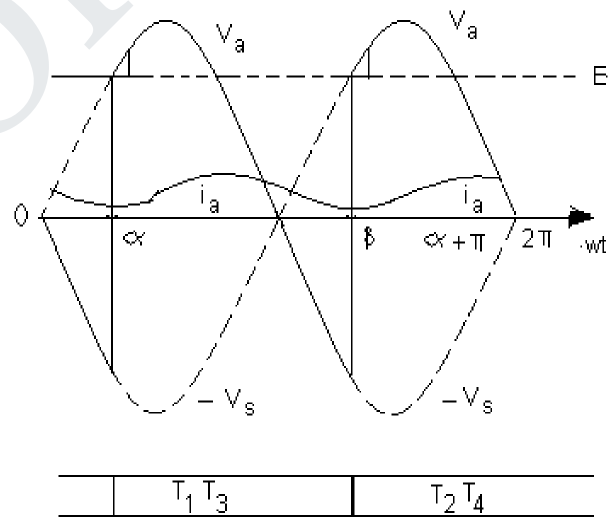
The input voltage is defined by

$$V_S = V_m \, Sin\omega t$$





Discontinuous conduction waveforms



Continuous conduction waveforms

Discontinuous conduction

I) Duty interval $(\alpha \le \omega t \le \beta)$

II) Zero current interval $(\beta \le \omega t \le \pi + \alpha)$

Drive operation is described by the following equation:

$$V_a = R_a\, i_a + L_a\, di_a/dt + E = V_m \sin\omega t, \text{ for } \alpha \le \omega t \le \beta$$

$$V_a = E \text{ and } i_a = 0 \text{ for } \beta \le \omega t \le \pi + \alpha$$

Let these component represented by a single exponent $K_1 e^{-t/\zeta_a}$ then

$$I_a = (\omega t) = v_m/Z \sin(\omega t - \Theta) - E/R_a + K_1 e^{-t/\zeta_a} \quad \text{for } \alpha \le \omega t \le \sin\beta$$

Where $Z = \sqrt{R_a^2 + (wL_a)^2}$ $\quad \Theta = \tan^{-1}(\omega L_a/R_a)$

$I_a = (\omega t) = v_m/Z\, [\sin(\omega t - \Theta) - \sin(\alpha - \Theta)\, e^{-(\omega t - \alpha)\cot\Phi}] - E/R_a\, [1 - e^{-(\omega t - \alpha)\cot\Phi}]$,
for $\alpha \le \omega t \le \beta$

Since $i_a(\beta) = 0$ then
$v_m/Z \sin(\beta - \Theta) - E/R_a + [E/R_a - v_m/Z \sin(\alpha - \Phi)]\, e^{-(\beta-\alpha)\cot\Phi} = 0$

Since voltage drop across the armature inductance due to dc component of armature current i zero

$$V_a = E + I_a R_a$$

$$V_a = 1/\pi [\int_\alpha^\beta V_m \sin\omega t\, d(\omega t) + \int_\alpha^{\alpha+\pi} E\, d(\omega t)]$$

$$= V_m (\cos\alpha - \cos\beta)/k(\beta - \alpha) + (\pi + \alpha - \beta)E/\pi$$

$$\omega_m = V_m (\cos\alpha - \cos\beta)/k(\beta - \alpha) - \pi\, R_a/K^2(\beta - \alpha)\, T$$

ω_{mc} which separates continuous conduction from discontinuous conduction for a given α as

$$\omega_{mc} = R_a V_m / ZK \sin(\alpha - \Phi)[1 + e^{-\pi\cot\Phi} / e^{-\pi\cot\Phi} - 1]$$

Continuous conduction

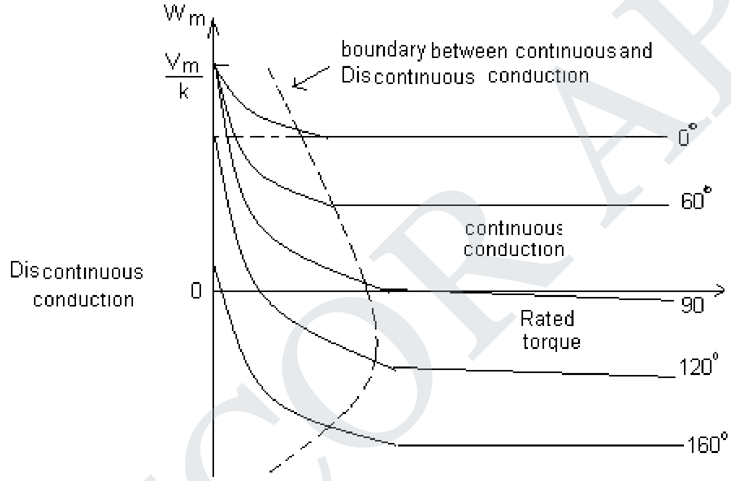
$V_a = 1/\pi \int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \; d(\omega t) = 2 V_m/\pi \cos\alpha$

$\omega_m = 2 V_m/\pi k \cos\alpha - R_a/K^2 T$

No load speed is given by

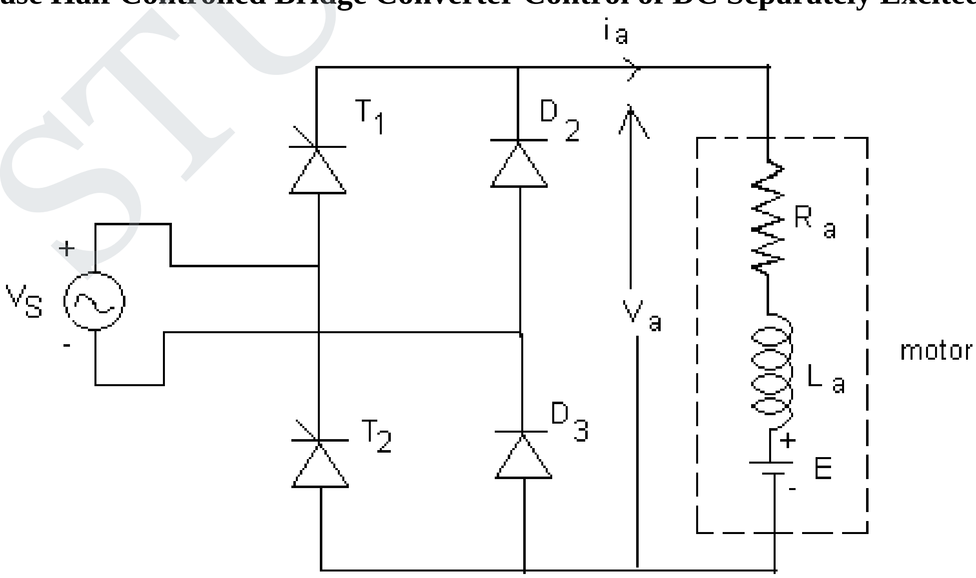
$\omega_{mo} = V_m/k$, for $0 \le \alpha \le \pi/2$
$= V_m \sin \alpha/K$, for $\pi/2 \le \alpha \le \pi$

Boundary between continuous and discontinuous conduction shown in the fig



3. Describe the steady state analysis of single phase half controlled converter fed separately excited dc motor drive in continuous and discontinuous modes.

Single Phase Half Controlled Bridge Converter Control of DC Separately Excited Motor



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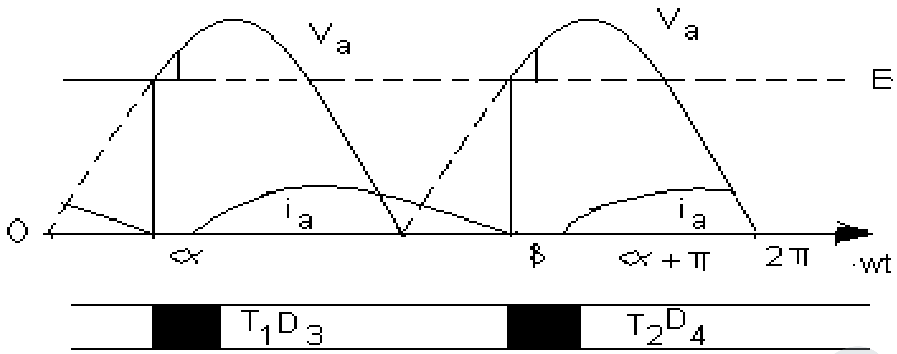
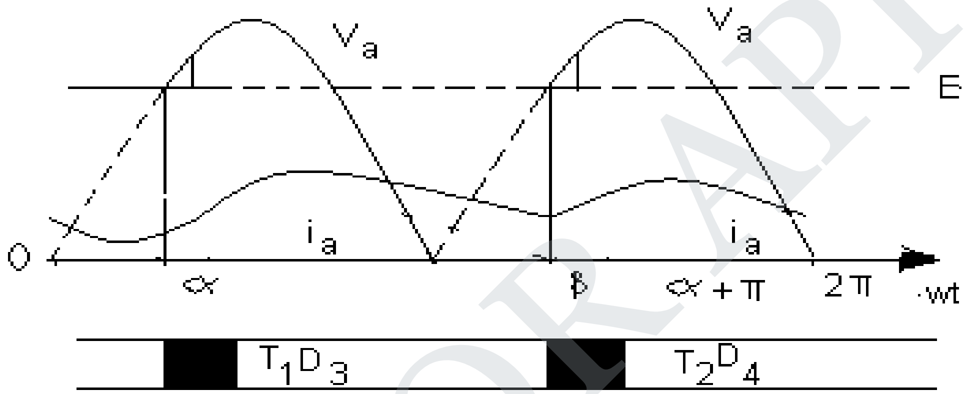


Discontinuous conduction waveforms



Continuous conduction waveforms

Discontinuous conduction

A cycle of motor terminal consist of three intervals

i) Duty interval ($\alpha \leq \omega t \leq \pi$)

ii) Freewheeling interval ($\alpha \leq \omega t \leq \beta$) : operation governed by the following equation:

$I_a R_a + L_a\, di_a/dt + E = 0$

The initial current yields

$I_a(\omega t)\ V_m/Z[\ \sin\Phi\ .\ e^{-(\omega t-\pi)\cot\Phi} - \sin(\alpha - \Phi).\ e^{-(\omega t-\pi)\cot\Phi}] - E/R_a[1 - e^{-(\omega t-\alpha)\cot\Phi}]$

iii) Zero current interval($\beta \leq \omega t \leq \pi+\alpha$)

$e^{\beta\cot\Phi} = R_a V_m/ZE[\sin\Phi\ \ e^{\pi\cot\Phi} - \sin(\alpha-\Phi)\ e^{\alpha\cot\Phi}] + e^{\alpha\cot\Phi}$

$$V_a = \frac{1}{\pi}\left[\int_{\alpha}^{\pi} V_m \, Sin\, wt\, d(wt) \; + \; \int_{\beta}^{\pi+\alpha} E d(wt) \right]$$

$$w_m \; = \; V_m(1 + \cos\alpha) \div K(\beta - \alpha) \; - \; \pi R_a \; \div K^a((\beta - \alpha)\; T$$

Boundary between continuous and discontinuous conduction is reached when $\beta = \pi + \alpha$

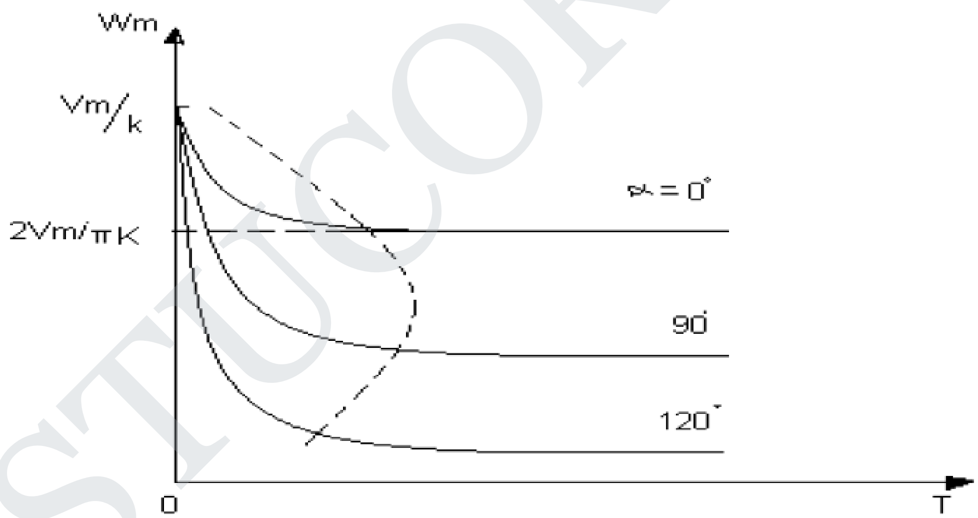
substituting $\beta = \pi + \alpha$ above equation gives the critical speed w_{mc}

$$w_{mc} = \frac{R_a}{K}\frac{V_m}{k}\left[\frac{\sin\Phi .\, e^{-\alpha\cot\phi} - \sin(\alpha - \phi) e^{-\pi\cot\phi}}{1 - e^{-\pi\cot\phi}}\right.$$

Continuous conduction

$$V_a \; = \; \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin wt \; d(wt) \; = \frac{V_m}{\pi}(1 + \cos\alpha)$$

$$w_m = \; \frac{V_m}{\pi K}(1 \; + \; \cos\alpha) \; - \; \frac{R_a}{K^2}\, T$$

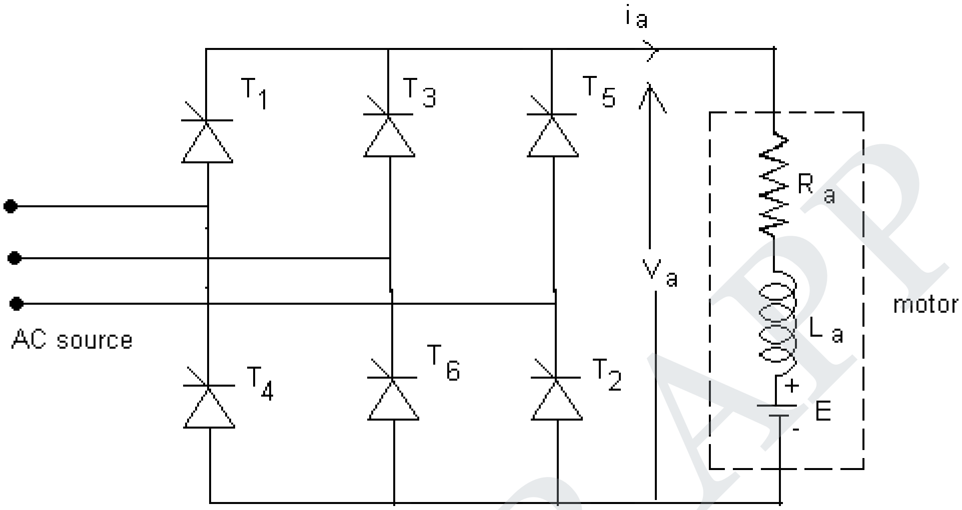


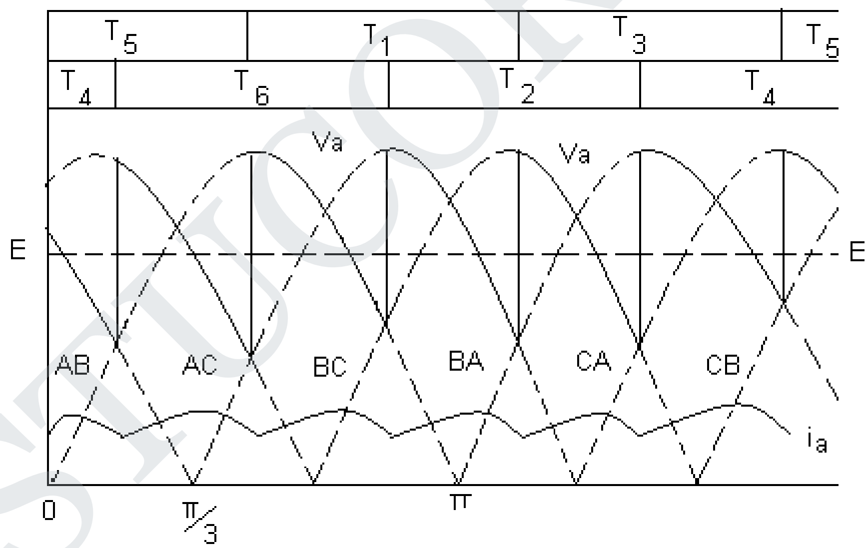
Speed torque curves of single phase half controlled rectifier fed separately excited motor

4. Describe the steady state analysis of three phase fully controlled rectifier control of DC separately excited motor

Three phase fully controlled rectifier control of DC separately excited motor

Thyristor are fired in the sequence of their numbers with phase difference of 60º by gate pulse of 120º duration. Each thyristor conduct for 120 º and two thyristor conduct at time one from lower group and another from upper group applying voltage to the motor respectively.





Motoring operation $\alpha = 30^{o}$

If the line voltage taken as the reference voltage, then

$$V_{AB} = V_m \sin wt$$

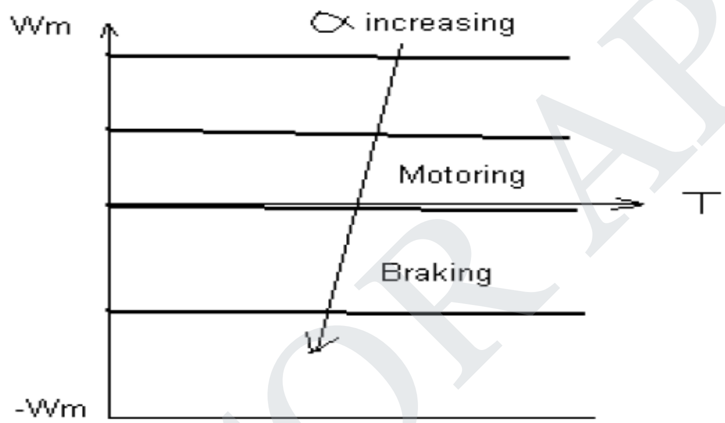
$$\alpha = wt - \frac{\pi}{3}$$

For the motor terminal voltage cycle from $\alpha + \frac{\pi}{3}$ to $\alpha + \frac{2\pi}{3}$

$$V_a = \frac{3}{\pi}\int_{\alpha+\frac{\pi}{3}}^{\alpha+\frac{2\pi}{3}} V_m \sin wt \, d(wt)$$

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

$$w_m = \frac{3v_m}{\pi K}\cos\alpha - \frac{R_a}{K^2}T$$



Speed torque curve of drive after neglecting discontinuous conduction

5. Describe the steady state analysis of three phase half controlled rectifier control of DC separately excited motor

Three phase half controlled rectifier control of DC separately excited motor

For the rectifier above shown in the, under continuous conduction

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

$$w_m = \frac{3v_m}{2\pi K}(1+\cos\alpha) - \frac{R_a}{K^2}T$$

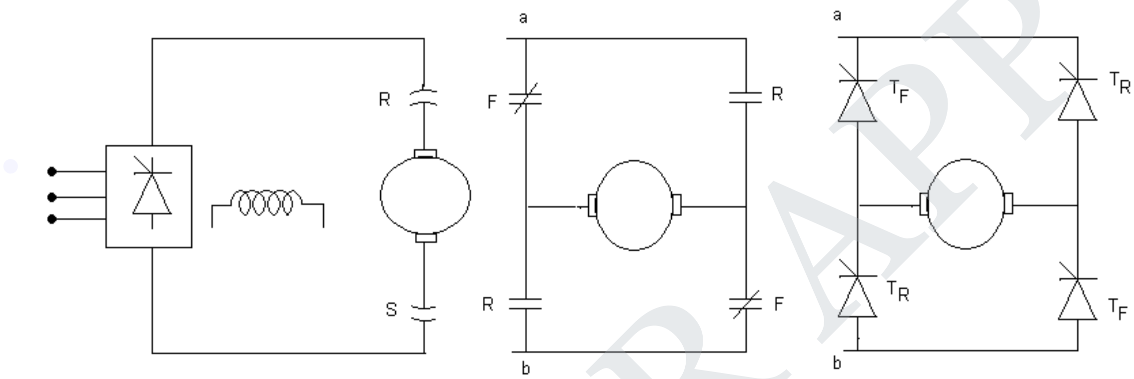
6. Multiquadrant Operation

Here, multiquadrant is considered with regenerative braking. In these drives, current control is always is provided to limit the current within safe limit.

Three schemes are used

1. Single fully controlled rectifier with a reversing switch.
2. Dual converter
3. Single fully controlled rectifier in the armature with field current reversal.

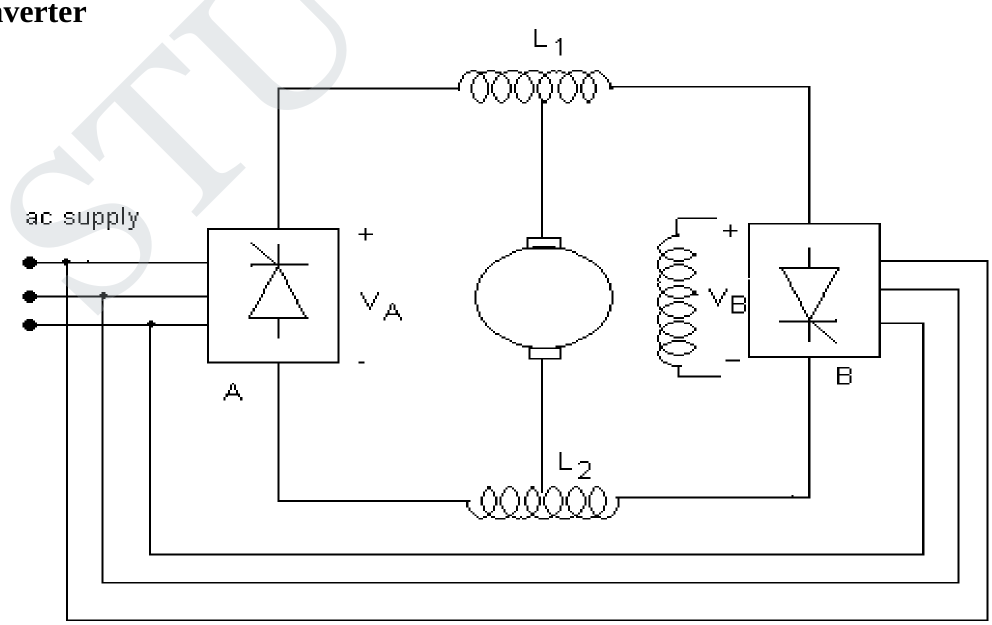
Single fully controlled rectifier with a reversing switch.



Four quadrant employing single converter and reversing switch

- A fully controlled rectifier feed the motor through reversing switch.
- A fully controlled rectifier can provide the operation of quadrant I and IV and reversal armature connection of can provide the operation of quadrant II and III.
- Thyristor switch is realized in the circuit over the relay contactor to avoid the maintenance.

Dual converter



Dual converter

- Dual converter consists of two fully controlled converters in anti-parallel across the armature.
- Rectifier A, provides the positive motor current and voltage in either direction and allows motor control in I and IV. Rectifier B, negative motor current and voltage in either direction and allows motor control in II and III.

There are two methods of control

a) In simultaneous control both the rectifiers are controlled together.

Thus,

$V_A + V_B = 0$, $\cos\alpha + \cos\beta = 0$, $\alpha_A + \alpha_B = 180^\circ$

b) Non circulating current control method only one thyristor controlled at a time.

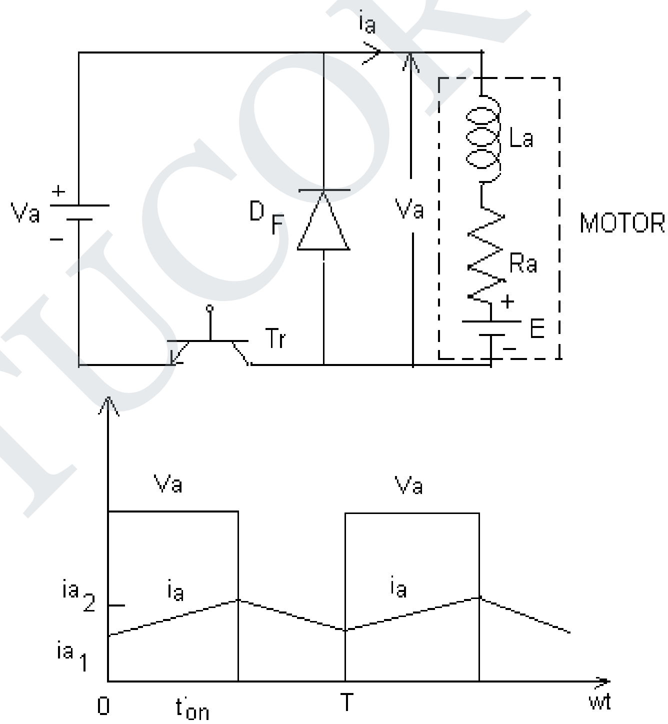
7. Chopper Fed DC Drives

Choppers, also commonly known as dc- to dc converters, are used to get variable voltage from the fixed voltage.

Chopper control separately excited DC motor

Motoring control

Transistor Tr is operated with periodically time T and with on for a period of ton



Chopper control of separately excited motor

During the on period of the transistor, $0 \leq t \leq t_{on}$, the motor terminal voltage is V. The operation is described by

$$R_a i_a + L_a \frac{d i_a}{d t} + E = 0$$

At $t = t_{on}$ T_r turned off and motor current freewheels through the diode and motor terminal voltage is zero during the interval $t_{on} \leq t \leq T$, Motor operation during the interval is known as freewheeling interval, is described by

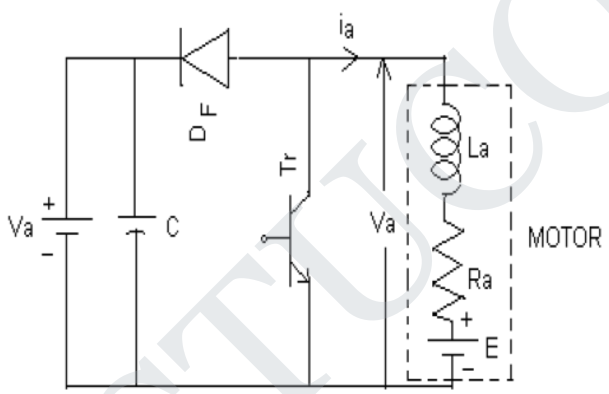
$$R_a i_a + L_a \frac{d i_a}{d t} + E = 0$$

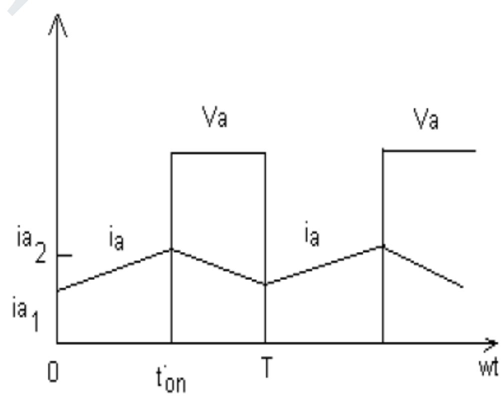
Ratio of duty interval t_{on} to chopper period T is called duty ratio or duty cycle (δ). Thus

δ = Duty interval/T = t_{on}/T

$$V_a = \left(\frac{1}{T}\int_0^{t_{on}} Vdt\right) = \delta V \qquad I_a = \frac{\delta V - E}{R_a} \qquad w_m = \frac{\delta V}{K} - \frac{R_a}{K^2}T$$

Regenerative Braking





Transistor T_r operated periodically with a period T and on period of t_{on}.

The mechanical energy converted into electrical energy by the motor, now working as generator, partly increase the stored magnetic energy in armature circuit inductance and reminder is dissipated in armature resistance and transistor.

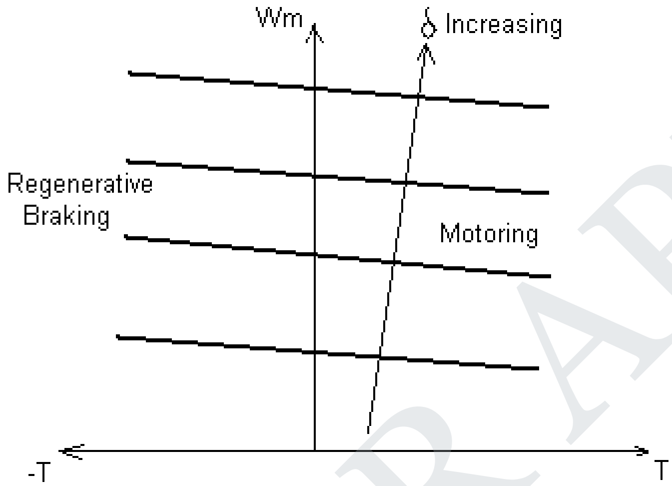
If the δ is again defined as the ratio of duty interval to period T, then

δ = Duty interval/T = T- t_{on}/T

$$V_a = \frac{1}{T}\int_{t^\circ n}^{T} Vdt = \frac{T - t_{\circ n}}{T}, \quad I_a = \frac{E - \delta V}{R_a},$$

Since I_a has reversed

$$T = K I_a, \quad \omega = \frac{\delta V}{K} - \frac{R_a}{K^2} T$$



Speed torque curves of chopper controlled separately excited motor

UNIT – III INDUCTION MOTOR DRIVES

PART – A

1. What are the different methods of braking applied to the induction motor?

- Regenerative braking
- Plugging
- Dynamic braking.

2. What are the different methods of speed control of IM?

- Stator voltage control
- Supply freq. control
- Rotor resistance control
- Slip power recovery control.

3. What is meant by stator voltage control?

The speed of the IM can be changed by changing the stator voltage, because the torque is proportional to the square of the voltage.

4. Mention the application of stator voltage control.

This method is suitable for applications where torque demand reduced with speed, which points towards its suitability for fan and pump drives.

5. Mention the applications of ac drives.

AC drives are used in a no. of applications such as fans, blowers, mill run-out tables, cranes, conveyors, traction etc.

6. What are the three regions in the speed-torque characteristics in the IM?

Motoring region $(0 \leq s \leq 1)$

Generating region $(s < 0)$

Plugging region $(1 \leq s \leq 2)$ where s is the slip.

7. What is the advantage of stator voltage control method?

- The control circuitry is simple
- Compact size
- Quick response time

8. What is meant by soft start?

The ac voltage controllers show a step less control of supply voltage from zero to rated voltage is this control is employed in motor then it is called soft start.

9. List the advantages of squirrel cage induction motor?

- Cheaper
- light in weight
- Rugged in construction
- More efficient
- Require less maintenance
- It can be operated in dirty and explosive environment

10. Define base speed.

The synchronous speed corresponding to the rated frequency is called the base speed.

11. What is meant by frequency control of IM?

The speed of IM can be controlled by changing the supply frequency because the speed is directly proportional to supply frequency. This method of speed ctrl is called frequency control.

12. What is meant by V/F control?

When the frequency is reduced the input voltage must be reduced proportionally so as to maintain constant flux otherwise the core will get saturated resulting in excessive iron loss and magnetizing current. So maintaining constant Voltage/Frequency ratio is called V/F control.

13. What are the advantages of V/F control?

- Smooth speed ctrl
- Small input current and improved power factor at low frequency start
- Higher starting torque

14. What are the 3 modes of region in the adjustable-frequency IM drives characteristics?

- Constant torque region
- Constant power region
- High speed series motoring region

15. What are the advantages of induction motors over D.C. motors?

The main drawback of D.C. motors is the presence of commutate and brushes, which require frequent maintenance and make them unsuitable for explosive and dirty environments. On the other hand, induction motors, particularly squirrel-cage are rugged, cheaper, lighter, smaller, more efficient, require lower maintenance and can operate in dirty and explosive environments.

16. Why the control of a three-phase indication motor is more difficult than D.C. motors.

The control of a three-phase induction motor, particularly when the dynamic performance involved is more difficult than D.C. motors. This is due to

a. Relatively large internal resistance of the converter causes voltage fluctuations following load fluctuations because the capacitor cannot be ideally large.

b. In a D.C. motor there is a decoupling between the flux producing magnetizing current and torque producing armature current. They can be independently controlled. This is not the case with induction motors.

c. An induction motor is very poorly damped compared to a D.C. motor.

17. What is indirect flux control?

The method of maintaining the flux constant by providing a voltage boost proportional to slip frequency is a kind of indirect flux control. This method of flux control is not desirable if very good dynamic behavior is required.

18. What is the purpose of inductance and capacitance in the D.C. link circuit?

The inductance in the D.C. link circuit provides smoothing whereas the capacitance maintains the constancy of link voltage. The link voltage is a controlled quality.

19. What are the effects of harmonics in VSI fed induction motor drive?

If the motor receives square wave voltages this voltage has harmonic components the harmonics of the stator current cause additional losses and heating. These harmonics are also responsible for torque pulsations. The reaction of the fifth and seventh harmonics with the fundamental gives rise to the seventh harmonic pulsations in the torque developed.

20. Where is rotor resistance control used?

Where the motors drive loads with intermittent type duty, such as cranes, ore or coal unloads, skip hoists, mine hoists, lifts, etc. slip-ring induction motors with speed control by variation of resistance in the rotor circuit are frequently used. This method of speed control is employed for a motor generator set with a flywheel (Ilgner set) used as an automatic slip regulator under shock loading conditions.

21. Why the static scherbius drive has a poor power factor?

Drive input power is difference between motor input power and the power fed back. Reactive input power is the sum of motor and inverter reactive power. Therefore, drive has a poor power factor throughout the range of its options.

22. How is super synchronous speed achieved?

Super synchronous speed can be achieved if the power is fed to the rotor from A.C. mains. This can be made possible by replacing the converter cascade by a cycloconverter. A cycloconverter allows power flow in either direction making the static sherbets drive operate at both sub and supper synchronous speeds.

23. What is static Kramer drive?

Instead of wasting the slip power in the rotor circuit resistance, it can be converted to 60 Hz A.C. and pumped back to the line. The slip power controlled drive that permits only a sub synchronous range of speed control through a converter cascade is know as static Kramer drive.

24. What are the advantages of static Kramer drive?

The static Kramer drive has been very popular in large power pump and fan-type drives, where the range of speed control is limited near, but below the synchronous speed. The drive system is very efficient and the converted power rating is low because t has to handle only the slip power, In fact, the power rating becomes lower with a more restricted range of speed control. The additional advantages are that the drive system has
D.C. machine like characteristics and the control is very simple.

25. What are the causes of harmonic currents in static Kramer drive?

The rectification of slip power causes harmonic currents in the rotor, and these harmonics are reflected to the stator by the transformer action of the machine. The harmonic currents are also injected into the A.C. line by the inverter. As a result, the machine losses are increased and some amount of harmonic torque is produced. Each harmonic current in the rotor will create a reading magnetic field and its direction of rotation will depend on the order of the harmonic.

26. Give the four modes of operation of a Scherbius drive

The four modes of operation of static Scherbius drive are,

- Sub synchronous motoring.
- Sub synchronous regeneration
- Super synchronous motoring
- Super synchronous regeneration

27. How is the static Scherbius drive operated in super synchronous motoring mode?

In super synchronous motoring mode, the shaft speed increases beyond the synchronous speed, the slip becomes negative and the slip power is absorbed by the rotor. The slip power supplements the air gap power for the total mechanical power output. The line therefore supplies slip power in addition to stator input power. At this condition, the phase sequence of slip frequency is reversed so that the slip current – induced rotating magnetic field is opposite to that of the stator

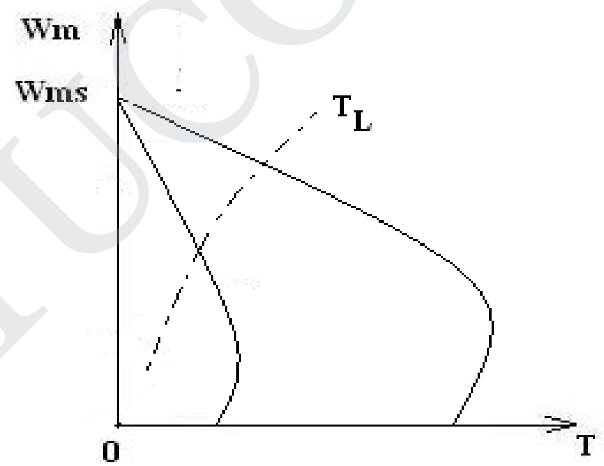
PART – B

1. Explain the stator voltage control of Induction motor drives.

Stator Voltage control

By reducing stator voltage, speed of an induction motor can be reduced by an amount which is sufficient for speed control of pump drives.

If stator copper loss, core loss and friction loss are ignored, then the motor efficiency is given by $Efficiency = \frac{P_m}{P_g} = (1 - S)$



Stator voltage control

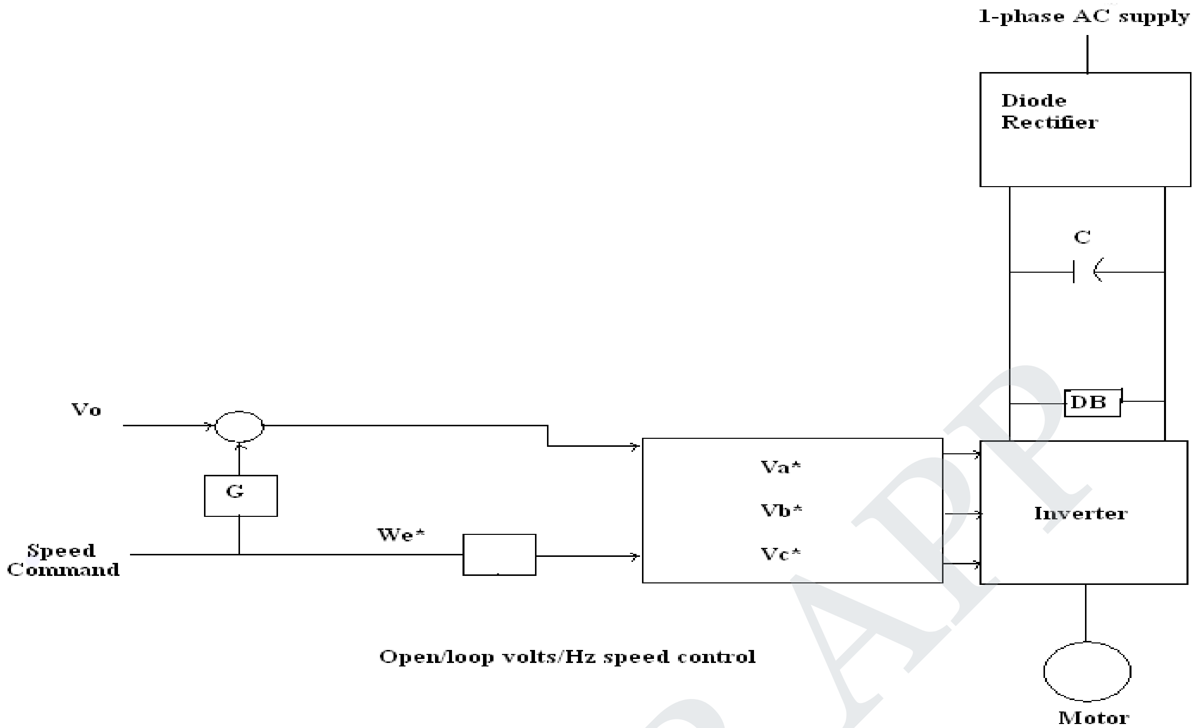
2. Explain the voltage\frequency control of Induction motor drives.

Open Loop Volts/Hz Control

Open loop volts/Hz control of an induction motor is very familiar in the industry.

For adjustable speed applications, frequency control is natural.

The phase voltage command Vs* is generated from frequency command and the flux is remain constant.



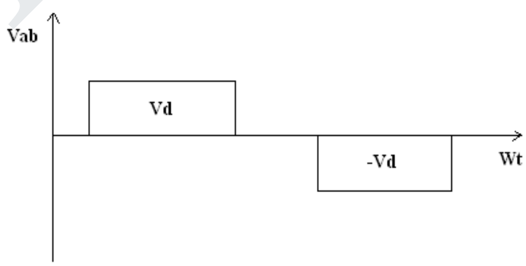
Open/loop volts/Hz speed control

3. Explain the closed loop speed control of VSI fed & CSI fed induction motor drive.

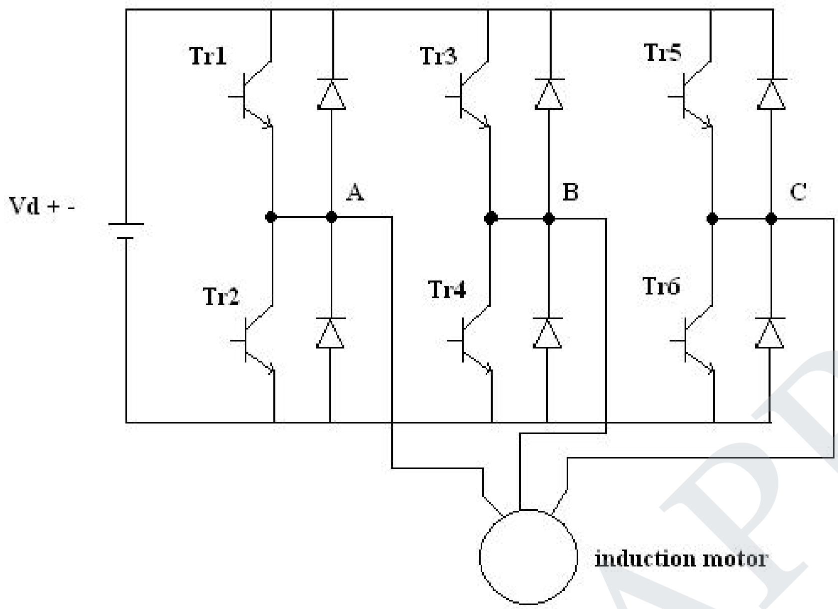
VSI fed Induction Motor Drives

- Voltage source inverter allows a variable frequency supply to be obtained from a dc supply.
- VSI can be operated as a stepped wave inverter or PWM inverter. When operated as stepped wave inverter, transistors are switched in sequence with time difference.
- Frequency of the inverter operation varied by varying the T and output of the inverter also varied accordingly.
- Inverter output line and phase voltage are given by the following Fourier series:

$$V_{AB} = \frac{2\sqrt{3}}{\pi} V_d \Big[\text{Sin}$$

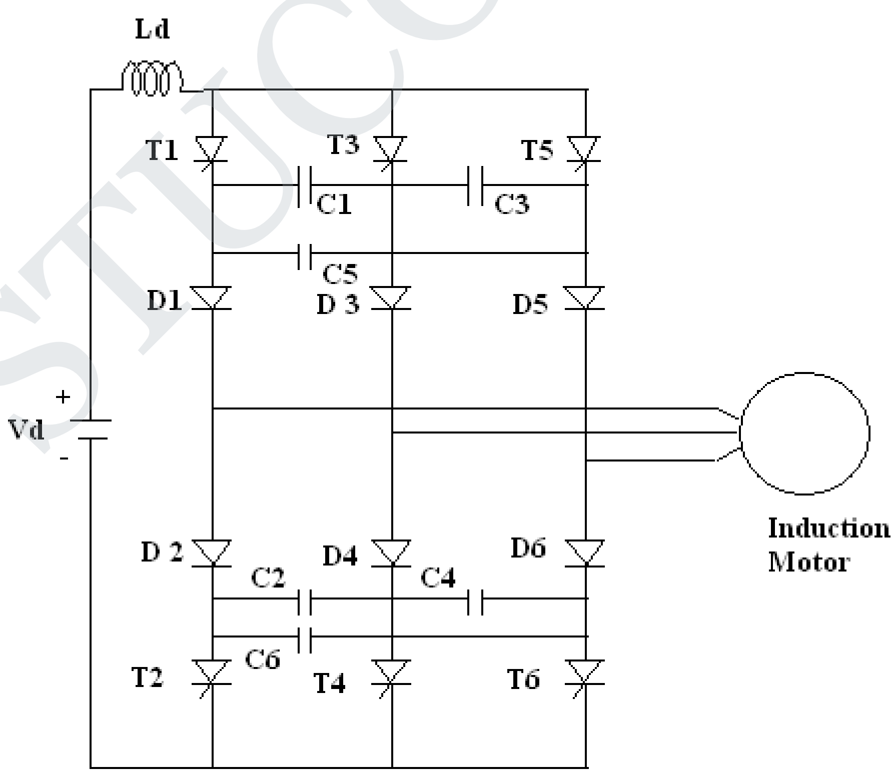


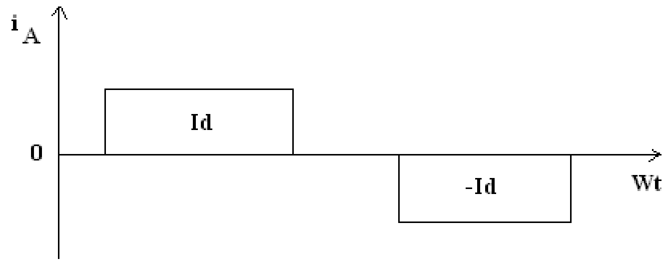
Stepped wave inverter line voltage waveform



CSI fed Induction Motor Drives

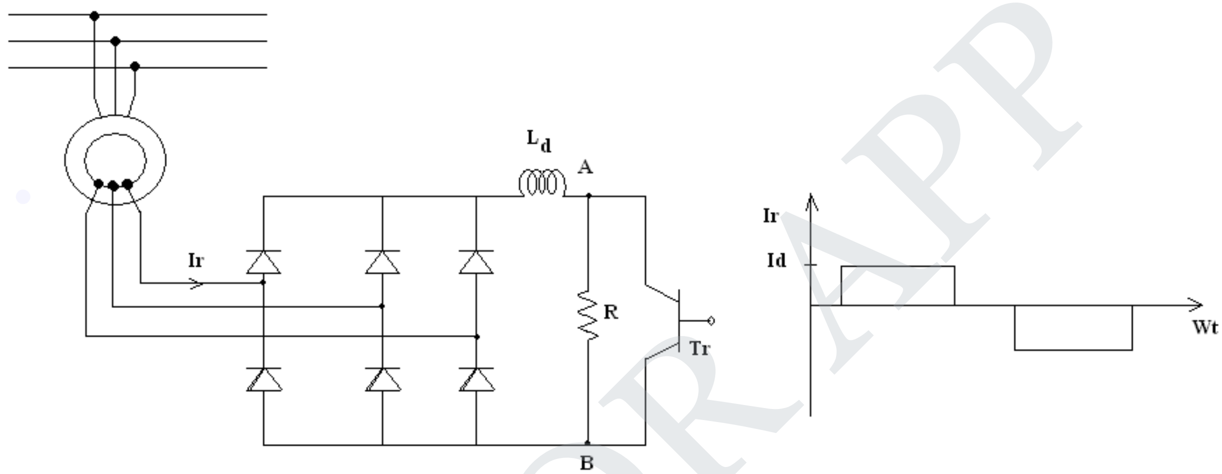
- CSI consist of diodes D1-D6 and capacitors C1-C6 to provide commutation for the thyristor T1-T6, which are fired in with a phase difference of 60˚ in sequence of their numbers.
- Inverter behaves as current source because of presence of large inductance Ld in dc link.
- The fundamental component of motor phase current is $I_S = \frac{\sqrt{6}}{\pi} I_d$





CSI fed induction drive

4. Static Rotor Resistance Control



Static rotor resistance control

- Rotor resistance can also vary steplessly using the above circuit. The ac output voltage of the rotor can be converted with Diode Bridge and it is given to parallel combination of the resister and transistor switch.
- The resistance value can be varied with help of the duty ratio of the transistor.

The RMS rotor current will be $I_S = \sqrt{\frac{2}{3}} I_d$

Therefore average value of resistance between the terminals is given by

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

Power consumed by RAB is $P_{AB} = I_d^2 R_{AB} = I_d^2 R(1-\delta)$

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

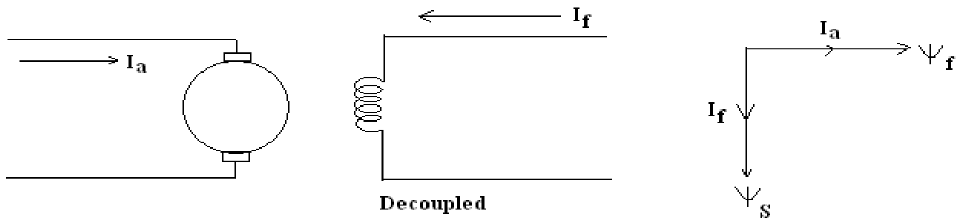
Thus total rotor circuit resistance per phase will be $R_{rT} = R_T + 0.5R(1-\delta)$

5. With necessary diagrams explain the vector control of induction motor drives.

Vector Control of Induction motor

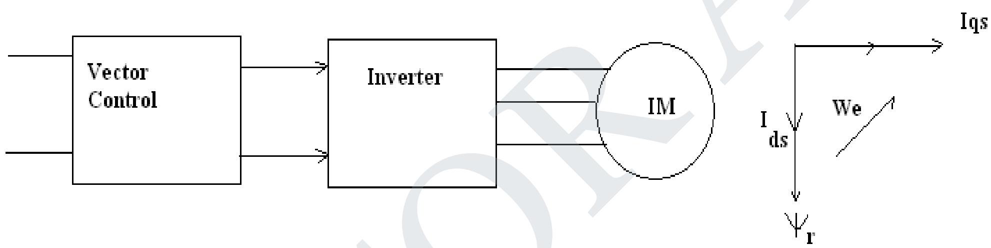
- Vector control of induction can be controlled like a separately excited DC motor. Vector control applicable for both induction as well synchronous motor.

- In a DC machine neglecting the armature reaction effect and field saturation, the developed torque is given by $T_e = K_t' I_a I_f$

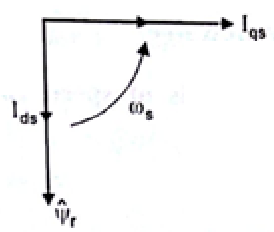


$$T_e = K_t \psi_a \psi_f = K_t' I_a I_f$$

Torque Component Field Component



$$T_e = K_t \hat{\psi}_r I_{qs} = K_t' I_{qs} I_{ds}$$



UNIT – IV SYNCHRONOUS MOTOR DRIVES

PART – A

1. Mention the main difference between the wound field and permanent magnet motors.

When a wound filed motor is started as an induction motor, D.C. field is kept off. In case of a permanent magnet motor, the field cannot be 'turned off'.

2. What are the advantages and applications of PMSM?

The advantages of PMSM are,

- ✓ High efficiency
- ✓ High power factor
- ✓ Low sensitivity to supply voltage variations

The application of PMSM is that it is preferred of industrial applications with large duty cycle such as pumps, fans and compressors.

3. What are the uses of a hysteresis synchronous motor?

Small hysteresis motors are extensively used in tape recorders, office equipment and fans. Because of the low starting current, it finds application in high inertia application such as gyrocompasses and small centrifuges.

4. Mention the two modes employed in variable frequency control.

Variable frequency control may employ and of the two modes.

- ✓ True synchronous mode
- ✓ Self-controlled mode

5. Which machine is said to be self-controlled?

A machine is said to be self-controlled if it gets its variable frequency from an inverter whose thrusters are freed in a sequence, using the information of rotor position or stator voltages. In the former a rotor position sensor is employed which measures the rotor position with respect to the stator and sends pulses to the thyristors. Thus frequency of the inverter output is decided by the rotor speed.

6. What is Commutator Less Motor (CLM)?

The self-controlled motor has properties of a D.C. Motors both under steady state and dynamic conditions and therefore is called Commutator less motor (CLM). These machines have better stability behaviors. They do not fall out of step and do not have oscillatory behaviors, as in normal synchronous motors.

7. Give the application of self-controlled synchronous motor.

A self-controlled synchronous motor is a substitute for a D.C. motor drive and finds application where a D.C. motor is objectionable due to its mechanical Commutator, which limits the speed range and power output.

8. What are the applications of synchronous motors?

Synchronous motors were mainly used in constant speed applications. The development of semiconductor variable frequency sources, such as inverters and Cycloconverter, has allowed their use in draft fane, main line traction, and servo drives.

9. How are the stator and rotor of the synchronous motor supplied?

The stator of the synchronous motor is supplied from a thyristor power converter capable of providing a variable frequency supply. The rotor, depending upon the situation, may be constructed with slip rings, where it conforms to a conventional rotor. It is supplied with D.C. through slip rings. Sometimes rotor may also be free from sliding contacts (slip rings), in which case the rotor is fed from a rectifier rotating with rotor.

10. What is the difference between an induction motor and synchronous motor?

An induction motor operates at lagging power factor and hence the converter supplying the same must invariable is a force commutated one. A synchronous motor, on the other hand, can be operated at any power factor by controlling the field current.

11. List out the commonly used synchronous motors in industry.

Commonly used synchronous motors are,

- ✓ Wound field synchronous motors.
- ✓ Permanent magnet synchronous motors
- ✓ Synchronous reluctance synchronous motors.
- ✓ Hysterias motors.

12. List out the advantages of load commutation over forced commutation.

- ✓ Load commutation has a number of advantages over forced commutation
- ✓ It does not require commutation circuits Frequency of operation can be higher
- ✓ It can operate at power levels beyond the capability of forced commutation.

13. Give some application of load commutated inverter fed synchronous motor drive.

Some applications of load commutated inverter fed synchronous motor drive are high speed and high power drives for compressors, blowers, conveyers, steel rolling mills, and main-line traction and aircraft test facilities.

14. How the machine operation is performed in self-controlled mode?

For machine operation in the self-controlled mode, rotating filed speed should be the same as rotor speed. This condition is realized by making frequency of voltage induced in the armature. Firing pulses are therefore generated either by comparison of motor terminal voltages or by rotor position sensors.

15. What is meant by margin angle of commutation?

The difference between the lead angle of firing and the overlap angle is called the margin angle of commutation. Safe commutation is assured if this angle has a minimum value equal to the turn off angle of the thyristor.

16. What are the disadvantages of VSI fed synchronous motor drive?

VSI synchronous motor drives might impose fewer problems both on machine as well as on the system design. A normal VSI with 180o conduction of thyristors required forced commutation and load commutation is not possible.

17. How is PWM inverter supplied in VSI fed synchronous motor?

When a PWM inverter is used, two cases may arise the inverter may be fed from a constant D.C. source in which case regeneration is straight forward. The D.C. supply to the inverter may be obtained from a diode rectifier. In this case an additional phase controlled converter is required on the line side.

18. What is D.C. link converter and cyclo converter?

D.C. link converter is a two stage conversion device which provides a variable voltage, variable frequency supply.

Cycloconverter is a single stage conversion device which provides a Variable voltage, variable frequency supply.

19. What are the disadvantages of Cycloconverter?

- ✓ A Cycloconverter requires large number of thyristor and its control circuitry is complex.
- ✓ Converter grade thyristors are sufficient but the cost of the converter is high.

20. What are the applications of Cycloconverter?

A Cycloconverter drive is attractive for law speed operation and is frequently employed in large, low speed reversing mils requiring rapid acceleration and deceleration. Typical applications are large gearless drives, e.g. drives for reversing mills, mine heists, etc.

21. Give the application of CSI fed synchronous motor.

Application of this type of drive is in gas turbine starting pumped hydro turbine starting, pump and blower drives, etc.

22. What are the disadvantages of machine commutation?

The disadvantages of machine commutation are,

- ✓ Limitation on the speed range.
- ✓ The machine size is large
- ✓ Due to over exciting it is under-utilized.

23. What is the use of an auxiliary motor?

When the power is small an auxiliary motor can be used to run up the synchronous motor to the desired speed.

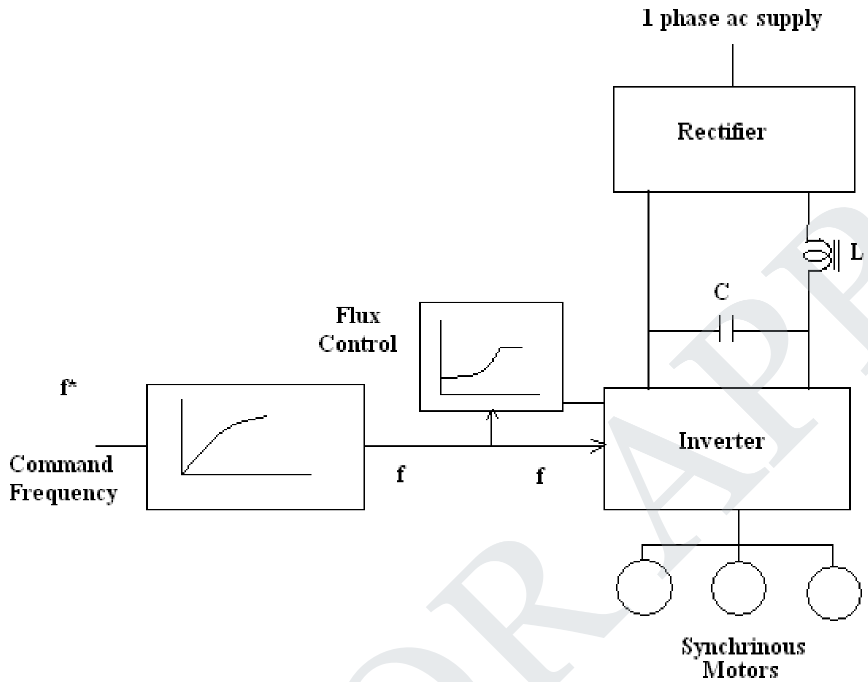
24. What are the advantages of brushless D.C. motor?

The brushless D.C. motor is in fact an inverter-fed self-controlled permanent synchronous motor drive. The advantages of brushless D.C. motor are low cost, simplicity reliability and good performance

PART – B

1. Explain the concept of open loop V\F control of synchronous motor.

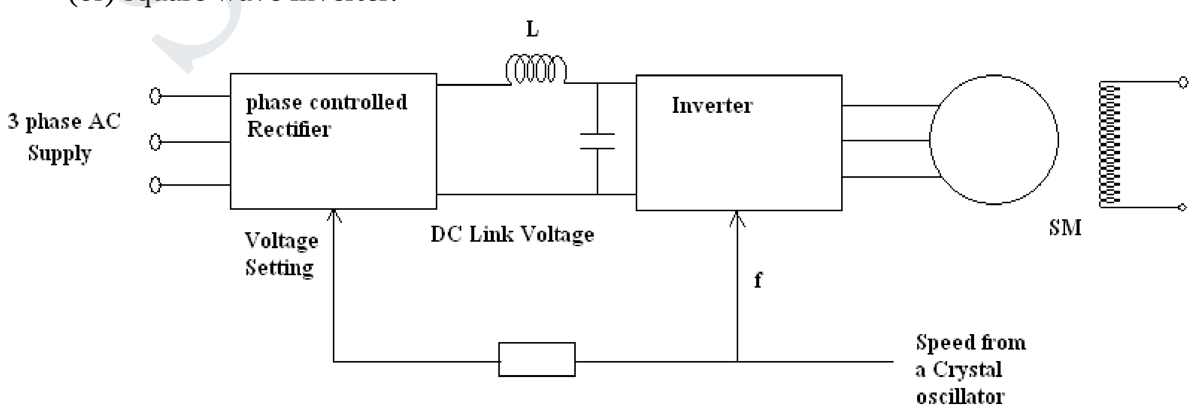
Open Loop Volts/Hz Control:



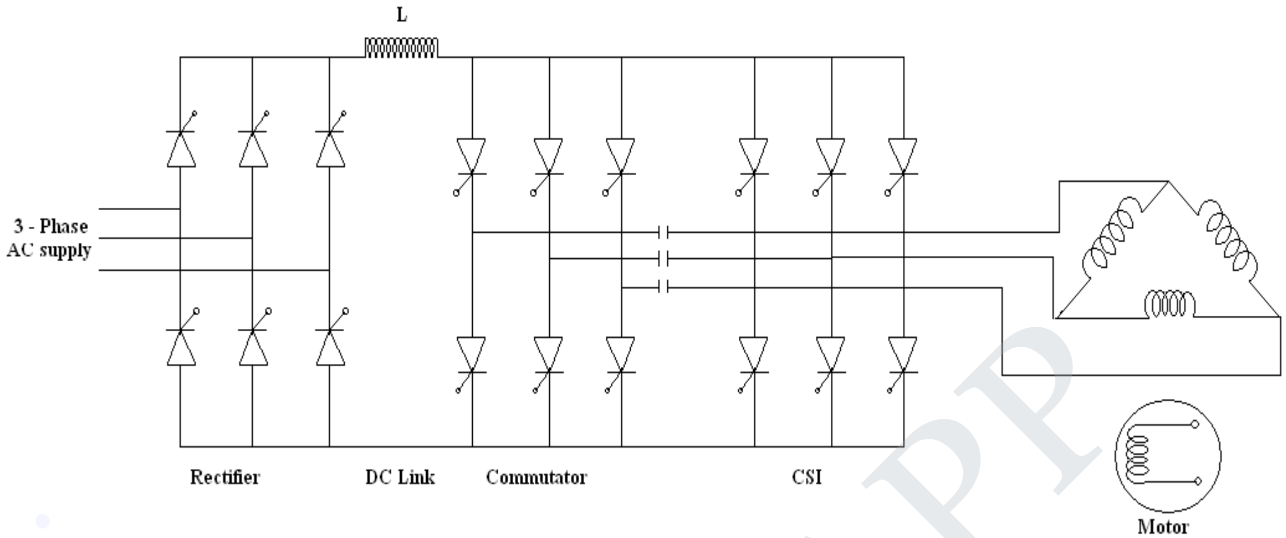
- ✓ Synchronous speed is directly proportional to frequency. So that the rotor always keeps track the changes of speed. Here all the machines are connected in parallel to the same inverter which is response to the command frequency.
- ✓ A flux control black is used which changes the stator voltage with frequency so as to constant flux for speed below base speed and constant terminal voltage for speed above base speed.

Voltage Source inverter Fed Synchronous Motor Drives

- ✓ Here the dc link voltage is variable by using phase controlled rectifier. Disadvantage is commutation is difficult at low speed.
- ✓ Since the output voltage is square wave, the inverter is called variable voltage inverter (or) square wave inverter.



Current Source Inverter Fed Synchronous Motor Drives



CSI with individual commutation

- ✓ When a synchronous motor fed from CSI, the motor currents are quasi – square wave if the commutation is instantaneous. Forced commutation is provided in the inverter circuit to extend the speed range from zero to base speed.
- ✓ The motor may be operated at UPF. Large inductance present in the DC link which makes the source current fed to the inverter a constant are hence it is a current source inverter.

Cycloconverter Fed Synchronous Motor Drive

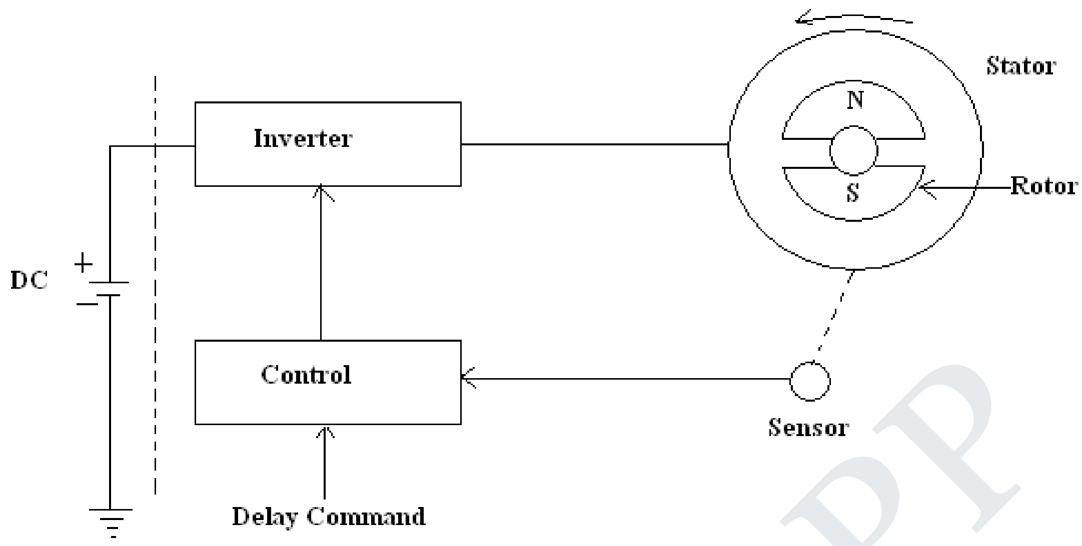
- ✓ The line voltage can be used to commutate the thyristor of a converter. The machine can be over excited and runs we have load commutated Cycloconverter fed synchronous motor.
- ✓ A Cycloconverter provide high quality output voltage and sinusoidal resulting current.
- ✓ Cycloconverter handle power in both directions. The efficiency and dynamic behavior is good. The line power factor is better as the machine power factor can be made unity.

2. Explain self-controlled mode of operation of synchronous motor.

Self-Control Mode

- ✓ In self-control mode, the supply frequency is changed so that the synchronous speed is same as that of the rotor speed. Unlike, Separate control mode where the control inverter frequency is from an independent oscillator
- ✓ Here the pulse train from position sensor may be delayed external command.
- ✓ The self-controlled motor has the properties of a DC motor both under steady state and dynamic conditions and therefore, is called Commutator less motor.

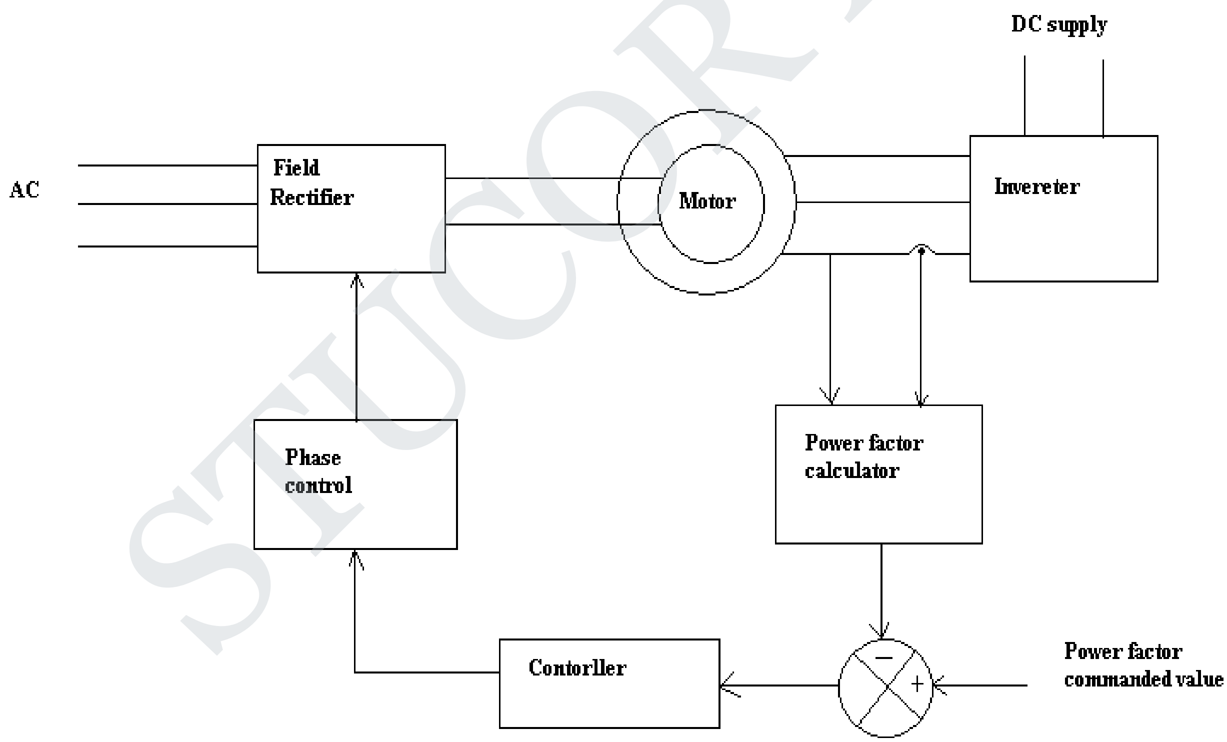
STUCOR APP



Self controlled synchronous motor

3. Explain power factor control of synchronous motor drive.

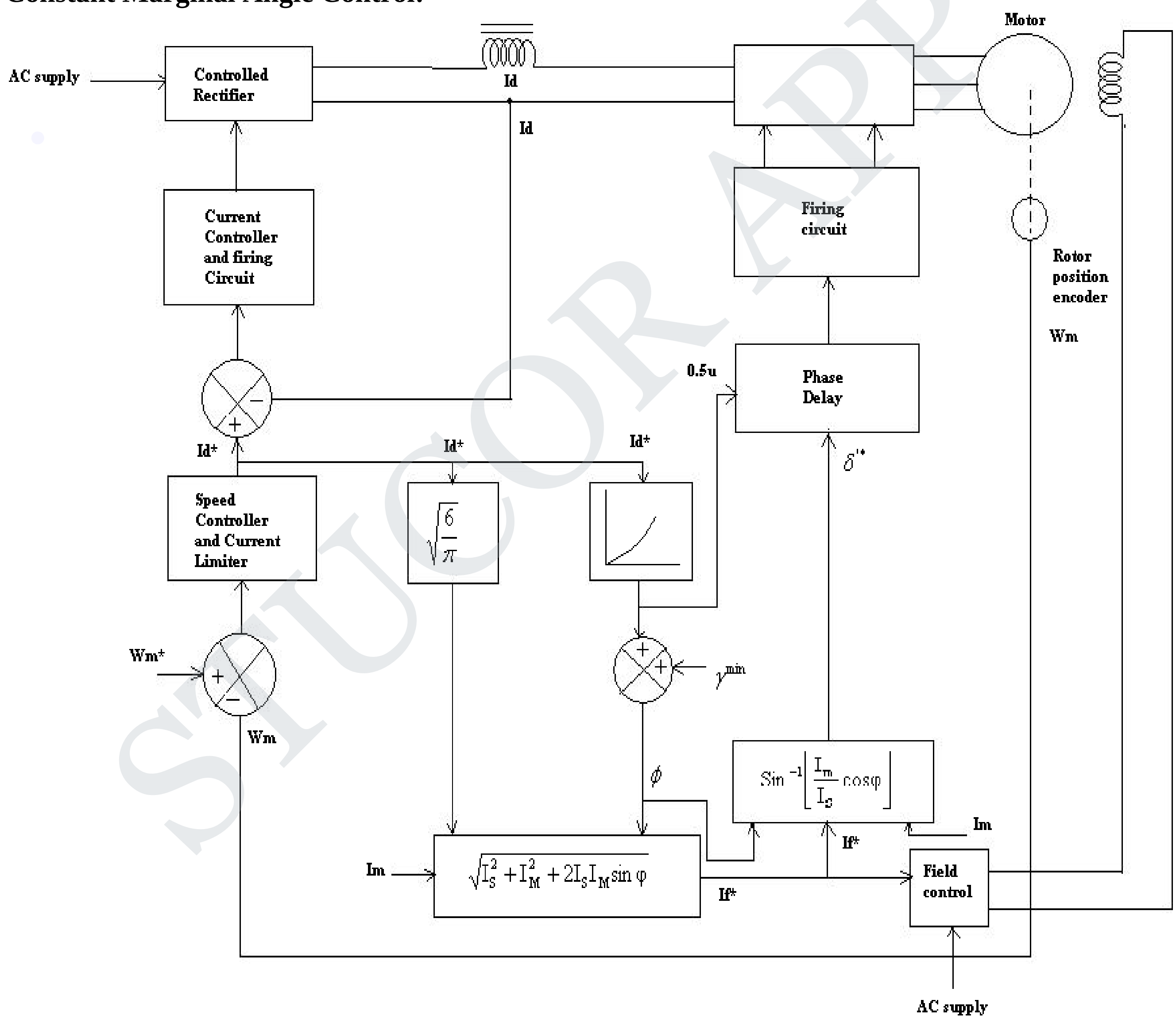
Motor power factor control:



- ✓ The main aim of adjusting power factor to vary the field current.
- ✓ If the motor is operated at a power factor of unity, the current drawn by it will have the lowest magnitude for a given input and therefore the lowest internal copper loss.
- ✓ The motor voltage and current sensed and fed to the power factor calculator.

- ✓ The error is compared by the comparator and is output varies with the field current power factor confirm to the commanded value.
- ✓ It is actual power factor value.
- ✓ The computed power factor value is compare against the power factor commanded value by using error detected.
- ✓ The error is amplified by the error amplifier, and its output varies the field current power factor confirm to the commanded value.

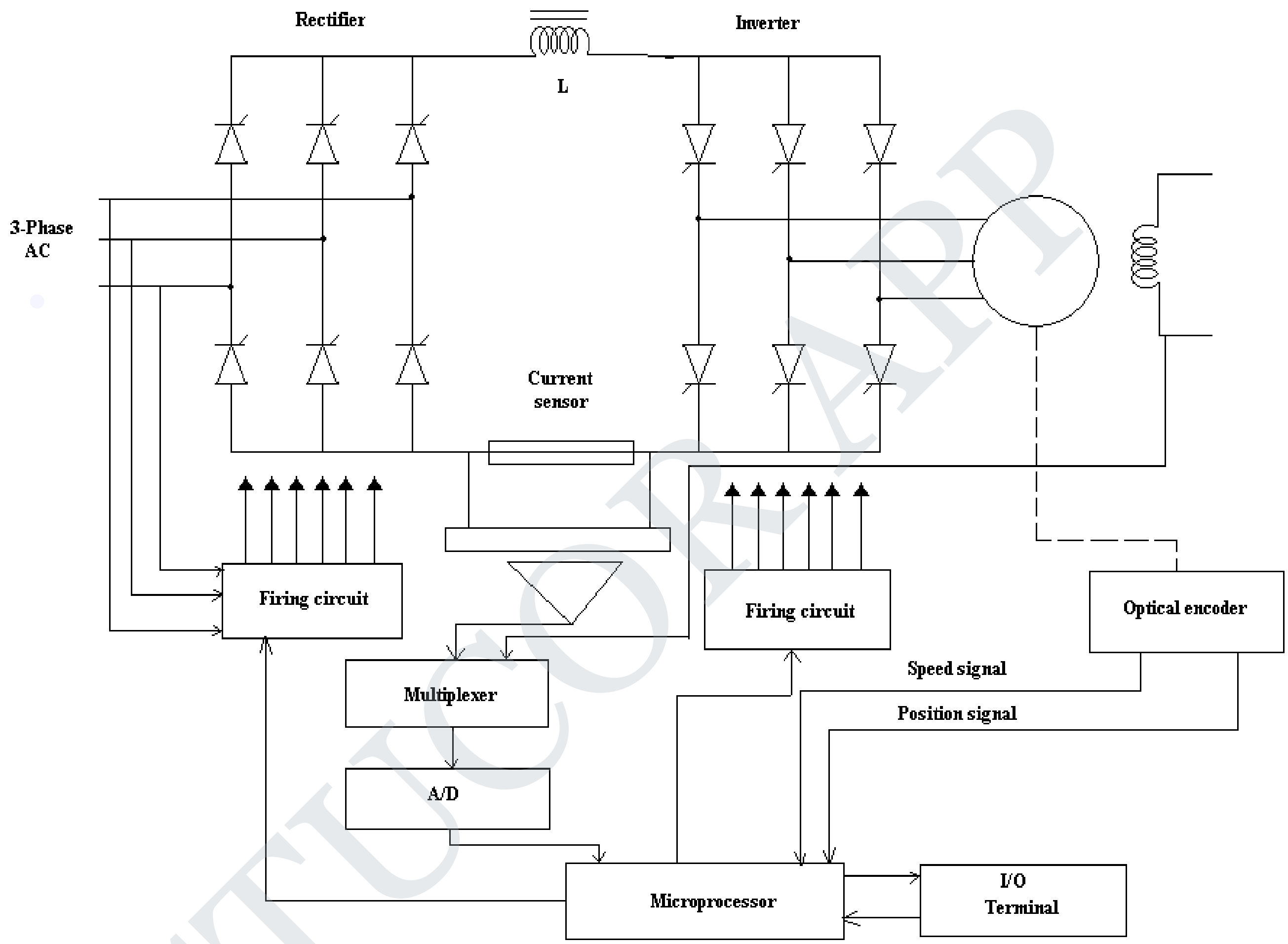
4. Explain self-control technique of synchronous motor with constant margin angle control.
Constant Marginal Angle Control:



- ✓ This drive has an outer speed loop and inner current loop. The rotor position sensed by using rotor position encoder.

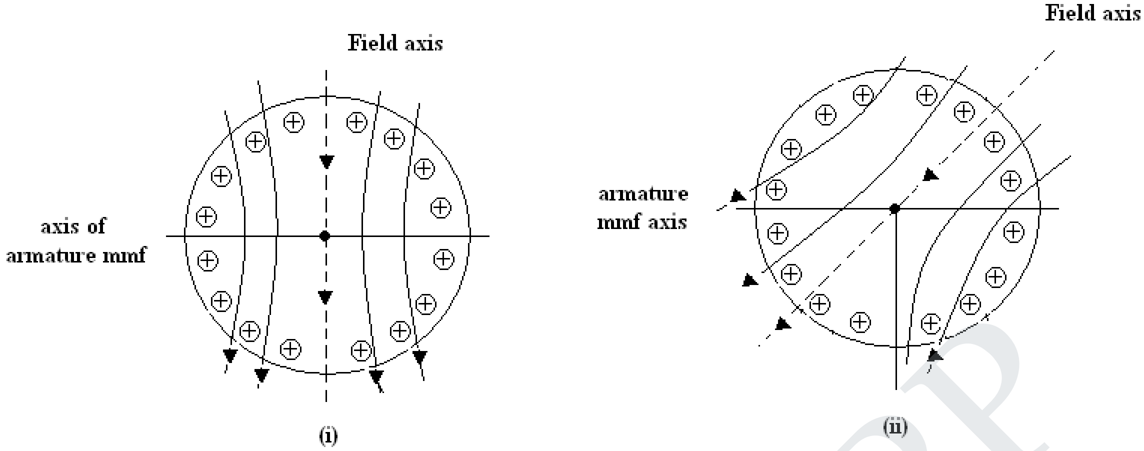
- ✓ The output of comparator fed to the speed controller and current limiter. It generates trigger pulse. If* sets reference for the closed loop control of the field current If.
- ✓ The load commutated inverter drives are in medium, high power drives.
- ✓ This drives are used for the starting of large synchronous machines in gas turbine and pumped storage plants.

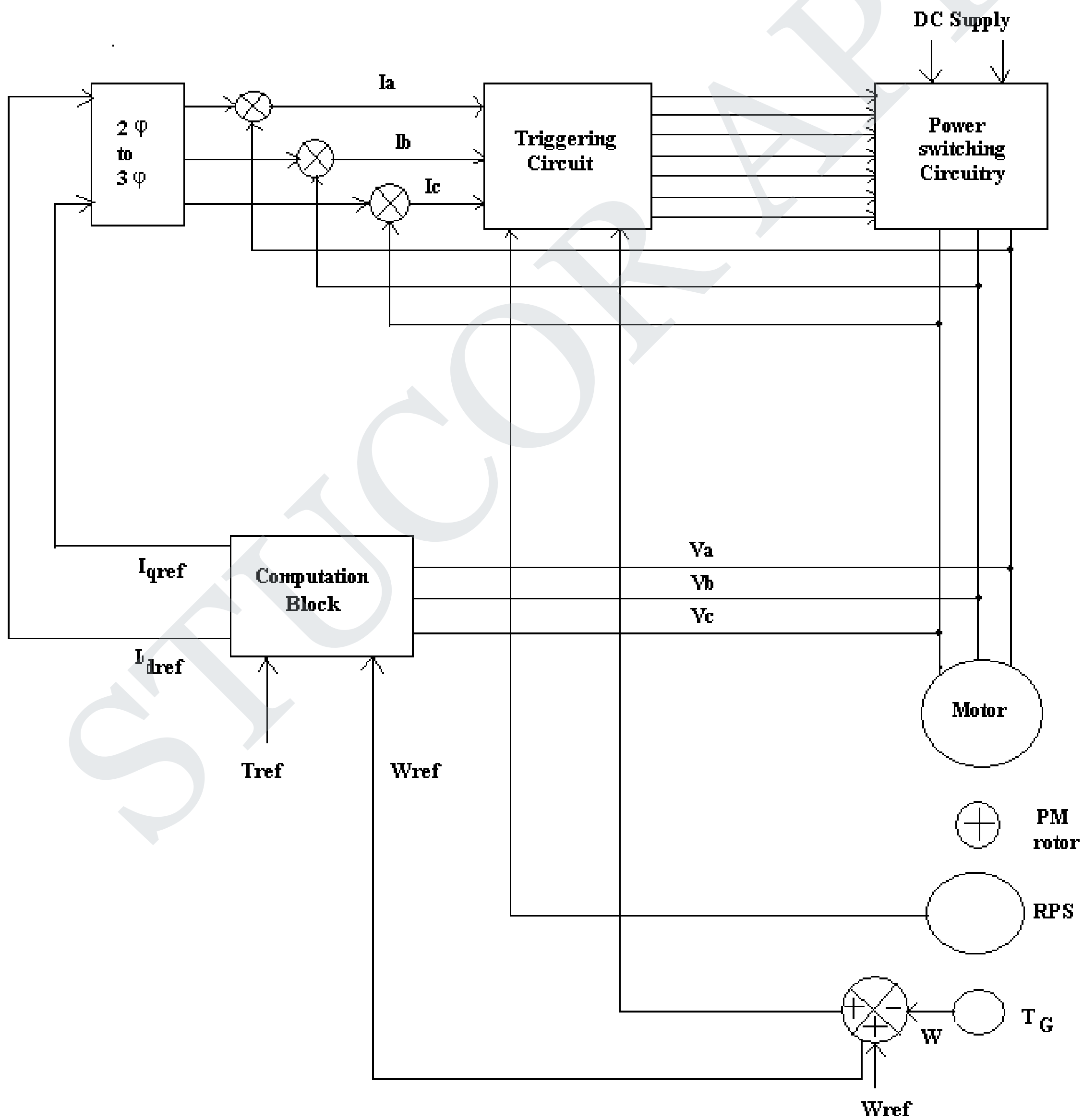
Microprocessor Based Control of Synchronous Motor



- ✓ The microprocessor control offers features, such as improved performance and reliability versatility of the controller, reduced components and reduced manufacturing cost.
- ✓ The microprocessor used in the speed control of a synchronous motor has the following functions.
    - o It has ensured commutation of inverter during at low speeds.
    - o An automatic change over must occur from forced commutation to machine commutation when the motor assumes the capability for machine commutation.
- ✓ Proper distribution of firing pulses to the rectifier, inverter and field circuit converter. A microprocessor based speed control system for synchronous motors consists of 1) Power circuit 2) Microprocessor 3) Suitable interface 4) Software design.

5. Explain Vector Control of Permanent Magnet Synchronous Motor.





Block diagram vector control of a BLPM Synchronous motor

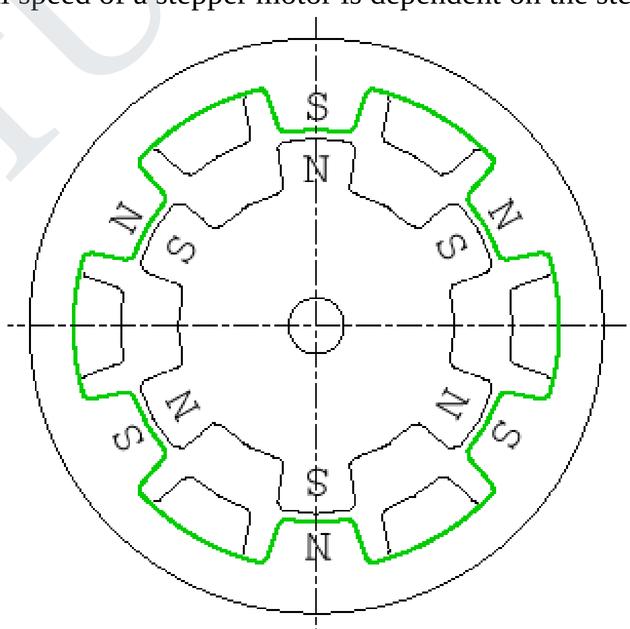
- ✓ Electromagnetic torque developed due to the interaction of the current carrying conductor and magnetic field.
- ✓ In the fig(i) shows the axis is in quadrature with the armature mmf axis. Each and every armature conductor experiences a force which contributes the torque.

$$I = \overline{I_q}\,\overline{I_d}$$

- ✓ Knowing the values of the desired torque and speed and also the parameters and voltage to which the motor is subjected to it is possible to compute values of id and iq ref for the desired dynamic and steady state performance.
- ✓ These currents are compared with actual currents and error values actuate the triggering circuitry which is also influenced by rotor position sensor and speed sensor.

Hybrid Stepper Motor:

The hybrid step motor consists of two pieces of soft iron, as well as an axially magnetized, round permanent magnet rotor. The term hybrid is derived from the fact that the motor is operated under the combined principles of the permanent magnet and variable-reluctance stepper motors. The stator core structure of a hybrid motor is essentially the same as its VR counterpart. The main difference is that in the VR motor, only one of the two coils of one phase is wound on one pole, while a typical hybrid motor will have coils of two different phases wound on one the same pole. The two coils at a pole are wound in a configuration known as a bifilar connection. Each pole of a hybrid motor is covered with uniformly spaced teeth made of soft steel. The teeth on the two sections of each pole are misaligned with each other by a half-tooth pitch. Torque is created in the hybrid motor by the interaction of the magnetic field of the permanent magnet and the magnetic field produced by the stator. Stepper motors are rated in terms of the number of steps per second, the stepping angle, and load capacity in ounce-inches and the pound-inches of torque that the motor can overcome. The number of steps per second is also known as the stepping rate. The actual speed of a stepper motor is dependent on the step angle and step rate.



Modes of Excitation:

There are several methods of excitation are in practice are as follows.

1. Single phase excitation:

Below table shows the sequences of a single phase excitation mode for three phase VR motors. In this mode, only one phase is excited at a time. The shaded parts in the table represent the excited state and un shaded parts show the phases to which current is not supplied and so are not excited.

Clock State	R	1	2	3	4	5	6	7	8
Phase 1									
Phase 2									
Phase 3									

When a motor revolves clockwise in the excitation sequence of Ph1, Ph2, Ph3…, it will revolve counter clock wise direction by simply reversing the sequence of Ph3, Ph2, Ph1…, single phase excitation is known as ‘ one phase on drive’.

2. Two phase excitation:

The operation of a motor in which two phases are always excited is called two phase on operation. Excitation sequences are given in below table.

Clock State	R	1	2	3	4	5	6	7	8
Phase 1									
Phase 2									
Phase 3									

In the two phase on drive, the oscillations damp out more quickly than in the case of single phase on mode. In this excitation, two phases are excited always. The two phases form a closed loop due to electromagnetic induction when oscillation occurs. Thus the oscillatory motion of the rotor results in oscillating current superimposed on the stationary current in phase. Since the torque generated by the oscillating component of the current acts in the opposite direction to the motion, the oscillation is damped out.

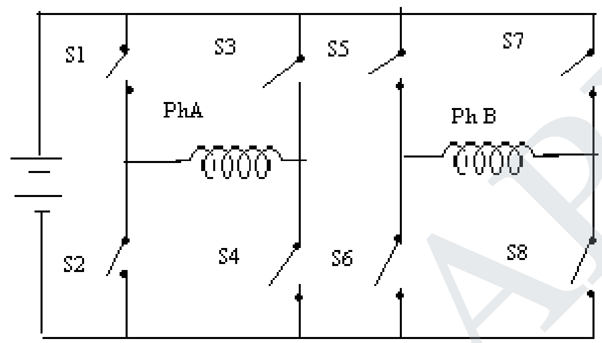
3. Half step excitation:

The excitation scheme which is a combination of the single phase and two phase excitation is called as half step excitation. The sequence for three phase VR motor is given below.

Clock State of method 1	R	1		2		3		4		5	
Clock State of method 2	R	1	2	3	4	5	6	7	8	9	10
Phase 1											
Phase 2											
Phase 3											

4. Excitation of two phase hybrid motor:

There is no necessity to alter the magnetic polarity to drive a VR motor. But, for a PM or hybrid motor magnetic pole reversal is normally needed. If the windings are in bifilar scheme, the situation is similar to 4 phase VR motor. Phase A, B, A and B corresponding to phases 1,2,3 and 4 and the preceding three excitation methods are applied. The bridge circuit shown in below is suitable drive scheme for bipolar mode. One phase on, two phase on and half step mode are available with the bridge circuit, the switching sequence and voltage waveforms applied to each phase are compared below.



Bridge driver scheme for a two phase stepping motor

One Phase ON:

Voltage	R	1	2	3	4	5	6	7
Va								
Vb								

Two Phase ON:

Voltage	R	1	2	3	4	5	6	7
Va								
Vb								

Half Step Mode:

Voltage	R	1	2	3	4	5	6	7	8	9	10
Va											
Vb											

UNIT – V DESIGN OF CONTROLLERS FOR DRIVES

PART – A

1. What are the advantages of closed loop control of dc drives?

Closed loop control system has the advantage of improved accuracy, fast dynamic response and reduced effects of disturbance and system non-linearity.

2. What are the advantages of using PI controller in closed loop control of dc drive?

- ✓ Stabilize the drive
- ✓ Adjust the damping ratio at the desired value
- ✓ Makes the steady state speed error close to zero by integral action and filters out noise again due to the integral action.

3. What are the two types of feedback in DC drives?

- ✓ Current feedback
- ✓ Speed feedback

4. What is speed feedback?

The motor speed can be sensed by any one feedback sensor and this signal is compared with reference speed. The error signal is given to speed controller. The speed controller produce control signal to the power converter.

5. What are two types of speed controller?

- ✓ Proportional controller
- ✓ Proportional-Integral controller

6. What is a current feedback?

The motor current can be sensed by current transducer. This signal is compared with reference signal and the error signal is fed to the current controller. The current controller produces the control signal. This signal is given to the power converter for controlling the output.

7. What are the design procedures for a closed loop speed control system?

- ✓ Assume that the feedback gains are fixed
- ✓ Clamping values of E must be chosen
- ✓ Calculate current controller gain
- ✓ Calculate the speed controller gain

8. What are the functions of feedback loop in an electrical drive?

- ✓ Protection
- ✓ Improvement of speed response
- ✓ Improve steady state accuracy

9. What is a closed loop control system?

A closed loop system is mainly used to maintain constant speed operation. It is a system in which the output has control over the input.

10. What are the basic blocks of a closed loop system of a dc motor?

The system consists of a dc motor, power converter, feedback path, comparator and speed controller.

11. How is the speed of a motor sensed?

The speed of a motor can be sensed by using a tacho generator.

12. What is armature voltage control?

The dc motor sped can be varied by varying armature voltage and field voltage is constant. This voltage can be varied by using power converter. This method is applicable for below base speed control.

13. What is field weakening control?

The dc motor speed can be varied by varying the field current and armature voltage is kept constant. The field current can be controlled by using power converter. By using this method the motor field flux decreases i.e., field weakening mode. This method is only applicable foe speeds above base speed because speed is inversely proportional to flux.

14. What is the purpose of current control in dc drives?

The current control loop is used for the purpose of limiting the transient over current.

15. What happens if the control loop is without current loop?

If inner current loop is not added in the control circuitry, transient over current is produced which is undesirable from the standpoint of converter rating and protection. This is particularly in case of starting or other large changes.

16. What is the advantage of using simulation package?

Simulation packages are used for studying the nature of the system developed without being practically implementing it.

17. What are the main disadvantages of phase controlled converter fed dc motor drives?

The phase controlled rectifiers always consume reactive power. Due to this, they are expensive to operate where the reactive power is to be paid for. It also generates harmonics.

18. What is the advantage of using PI type speed controller?

The addition of an integral feedback can be used to eliminate the steady-state error and to reduce the forward gain required.

19. Which type of converter can be selected if the input is ac?

When the input is ac, the dc motor can be operated from rectifiers. If the motor ratings are low, we can use single phase controlled rectifiers and for high ratings, three phase controlled rectifiers are used.

20. What is the use of current limiter in the closed loop control system?

It saturates and sets current reference for inner current loop at a value corresponding to the maximum allowable current.

21. What are the advantages of using PI controller in closed loop controller of dc drive?

- ✓ Stabilize the drive
- ✓ Adjust the damping ratio at the desired value
- ✓ Makes the steady state speed error close to zero by integral action and filters out noise again due to the integral action

PART – B

1. Derive the closed loop transfer function of converter fed separately excited DC motor.

(or)

Derive the transfer function of dc motor–load system with converter fed armature voltage control.

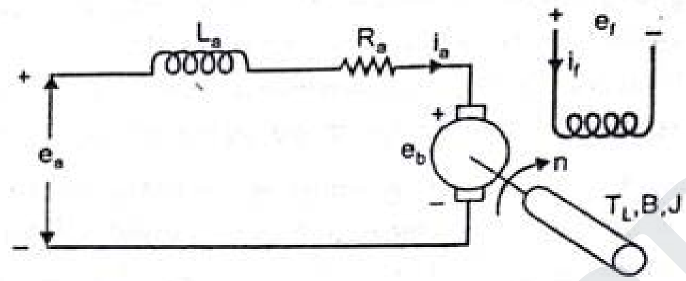
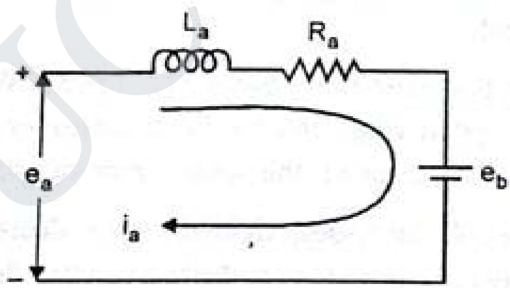


Figure 4.6

where
e_a = armature voltage
R_a = armature resistance
e_b = back emf
e_f = field voltage
T = motor torque
J = moment of inertia
L_a = armature inductance
i_a = armature current
i_f = field current
n = motor speed
B = damping coefficient
T_L = load torque

Electrical analysis



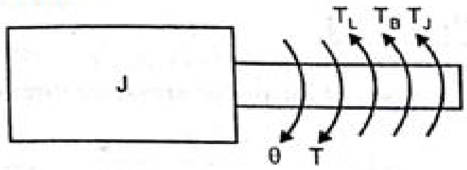
$$e_a = e_b + R_a i_a + L_a \frac{di_a}{dt} \quad \text{... (1)}$$

where

$$e_b \propto \phi \frac{d\theta}{dt} \qquad \left(\frac{d\theta}{dt} = \text{speed (n)}\right)$$

$$e_b = K_a \phi n \quad \text{... (2)}$$

Mechanical analysis



Applying Newton's law, we can get torque balance equation

$$T = T_L + T_B + T_J$$

$$T = T_L + \frac{Bd\theta}{dt} + J\frac{d^2\theta}{dt^2}$$

$$T = T_L + Bn + J\frac{dn}{dt} \quad \text{... (3)}$$

where

$$T \propto \phi i_a$$

$$T = K_a \phi i_a \quad \text{... (4)}$$

Taking laplace transform of equation (1) to (4), we get

$$E_a(s) = E_b(s) + R_a I_a(s) + L_a s I_a(s) \quad \text{... (5)}$$

$$E_b(s) = K_a \phi N(s) \quad \text{... (6)}$$

$$T(s) = T_L(s) + BN(s) + JsN(s) \quad \text{... (7)}$$

$$T(s) = K_a \phi I_a(s) \quad \text{... (8)}$$

From equation (5)

$$E_a(s) = E_b(s) + R_a I_a(s) + L_a s I_a(s)$$

$$E_a(s) = E_b(s) + I_a(s)[R_a + sL_a]$$

$$I_a(s)[R_a + sL_a] = E_a(s) - E_b(s)$$

$$I_a(s) = \frac{E_a(s) - E_b(s)}{R_a + s L_a} = \frac{E_a(s) - E_b(s)}{R_a\left(1 + \frac{sL_a}{R_a}\right)}$$

$$\boxed{I_a(s) = \frac{\frac{1}{R_a}[E_a(s) - E_b(s)]}{1 + s\tau_a}}$$ where $\tau_a = \frac{L_a}{R_a}$

From equation (7)

From equation (7)

$$T(s) = T_L(s) + BN(s) + JsN(s)$$

$$T(s) = T_L(s) + N(s)[B + Js]$$

$$N(s)[B + Js] = T(s) - T_L(s)$$

$$N(s) = \frac{T(s) - T_L(s)}{B + Js} = \frac{T(s) - T_L(s)}{B\left[1 + \frac{J}{B}s\right]}$$

$$\boxed{N(s) = \frac{\frac{1}{B}\left[T(s) - T_L(s)\right]}{1 + \tau_m s}}$$

where $\tau_m = \frac{J}{B}$ = mechanical time constant of the motor

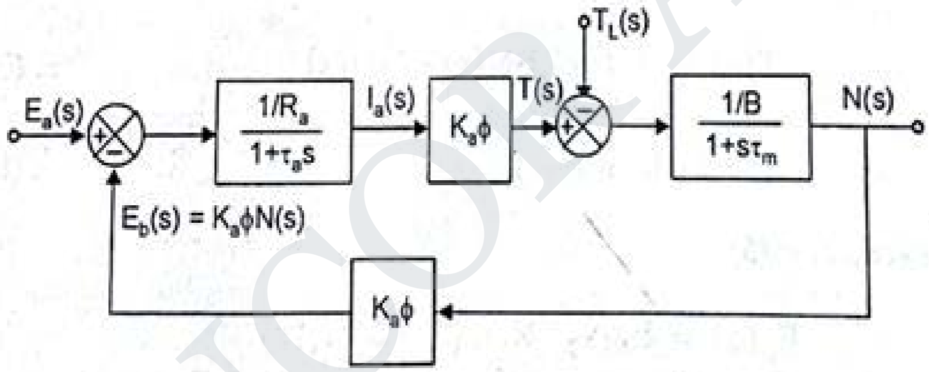
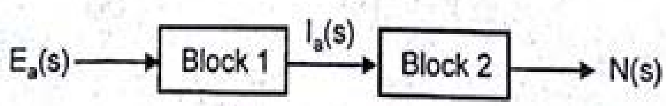


Figure 4.7

From figure 4.7 an expression can be obtained for the change in speed N(s) due to disturbances in applied voltage $E_a(s)$ and load torque $T_L(s)$.



N(s) = block 1 transfer function + block 2 transfer function

block 1 $\Rightarrow \quad \dfrac{G_1(s)}{1+G_1(s)\,H_1(s)}E_a(s)$

block 2 $\Rightarrow \quad \dfrac{G_2(s)}{1+G_2(s)+H_2(s)}T_L(s)$

So, $$N(s) = \frac{G_1(s)}{1+G_1(s)\,H_1(s)}E_a(s)+\frac{G_2(s)}{1+G_2(s)H_2(s)}T_L(s) \qquad \text{... (11)}$$

where

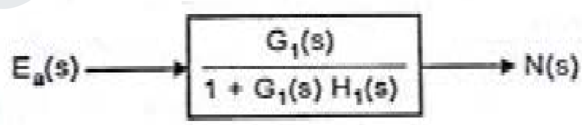
$$G_1(s) = \frac{1/R_a}{1+s\,\tau_a}(K_a\phi)\frac{1/B}{1+s\,\tau_m} \qquad \text{... (12)}$$

$$H_1(s) = K_a\phi \qquad \text{... (13)}$$

$$G_2(s) = \frac{-(1/B)}{1+s\,\tau_m} \qquad \text{... (14)}$$

$$H_2(s) = \frac{-(K_a\phi)^2/R_a}{1+s\,\tau_a} \qquad \text{... (15)}$$

Now neglecting the load torque T_L, the block diagram becomes



$$\frac{N(s)}{E_a(s)} = \frac{\dfrac{(K_a\phi)/R_aB}{(1+s\,\tau_a)(1+s\,\tau_m)}}{1+\dfrac{(K_a\phi)/R_aB}{(1+s\,\tau_a)(1+s\,\tau_m)}.K_a\phi} = \frac{\dfrac{(K_a\phi)/R_aB}{(1+s\,\tau_a)(1+s\,\tau_m)}}{\dfrac{(1+s\,\tau_a)(1+s\,\tau_m)+K_a\phi/R_aB}{(1+s\,\tau_a)(1+s\,\tau_m)}}$$

$$= \frac{(K_a\phi)/R_aB}{(1+s\,\tau_a)(1+s\,\tau_m)+(K_a\phi)^2/R_aB}$$

$$= \frac{(K_a\phi)/R_aB}{\dfrac{R_aB(1+s\tau_a)(1+s\tau_m)+(K_a\phi)^2}{R_aB}}$$

$$\boxed{\frac{N(s)}{E_a(s)} = \frac{K_a\phi}{R_aB(1+s\tau_a)(1+s\tau_m)+(K_a\phi)^2}} \quad \text{... (16)}$$

If $\tau_a << \tau_m$ (which is almost always the case), then τ_a can be neglected in equation (16), we get

$$\frac{N(s)}{E_a(s)} = \frac{K_a\phi}{R_aB(1+s\tau_m)+(K_a\phi)^2}$$

$$= \frac{K_a\phi}{(R_aB+R_aBs\tau_m)+(K_a\phi)^2}$$

Dividing $(R_aB + (K_a\phi)^2)$ in all terms

$$\frac{N(s)}{E_a(s)} = \frac{K_a\phi/R_aB+(K_a\phi)^2}{1+\dfrac{sR_aB}{R_aB+(K_a\phi)^2}\tau_m}$$

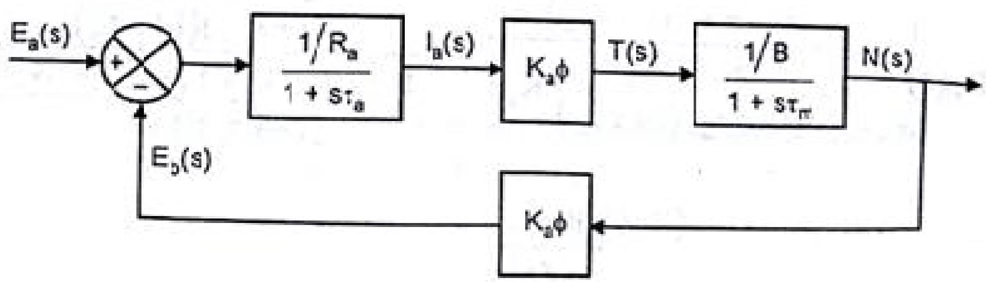
$$\boxed{\frac{N(s)}{E_a(s)} = \frac{K_m}{1+s\tau_{m1}}} \quad \text{... (17)}$$

where $\tau_{m1} = \dfrac{R_aB\tau_m}{R_aB+(K_a\phi)^2}$

$$K_m = \frac{K_a\phi}{(K_a\phi)^2+R_aB}$$

$$\tau_{m1} < \tau_m$$

Neglecting T_L, then block diagram becomes



So.
$$\frac{N(s)}{I_a(s)} = \frac{1/B}{1+s\tau_m} K_a\phi$$

$$= \frac{K_a\phi/B}{1+s\tau_m}$$

$$= \frac{K_{m2}}{1+s\tau_m} \quad \text{... (18)}$$

$$K_{m2} = \frac{K_a\phi}{B}$$

$$\frac{I_a(s)}{E_a(s)} = \frac{N(s)}{E_a(s)} \times \frac{I_a(s)}{N(s)}$$

$$= \frac{K_m}{1+s\tau_{m1}} \times \frac{(1+s\tau_m)B}{K_a\phi}$$

$$= \frac{K_m B(1+s\tau_m)}{K_a\phi(1+s\tau_{m1})}$$

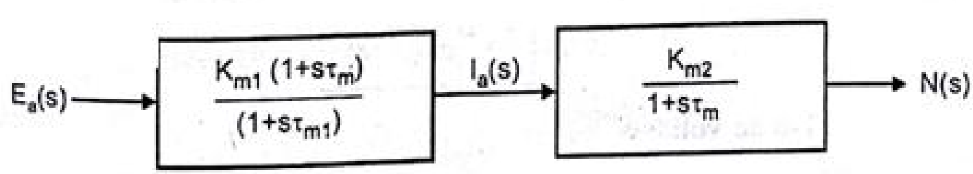
$$\boxed{\frac{I_a(s)}{E_a(s)} = \frac{K_{m1}(1+s\tau_m)}{(1+s\tau_{m1})}} \quad \text{... (19)}$$

where

$$K_{m1} = \frac{K_m B}{K_a\phi}$$

$$K_m = K_{m1}K_{m2} \quad \text{... (20)}$$

Thus the motor can be represented, for the purpose of analyzing it for voltage control, two blocks as shown in figure 4.9.



2. Mention the factors involved in converter selection and equations involved in controller characteristics.

Converter Selection and Characteristics

The ratings of the power converters and its power switches are derived from the motor and load specifications.

When the input is ac, the dc motor can be operated from rectifiers. If the motor ratings low, we can use single phase controller rectifiers and for high rating three phase controlled rectifiers are used. Some approximate derivations are given below.

I_{max} = maximum current allowed to the motor.

The rms value of the current in each power device is then based on the fact that it is conducting for 120 electrical degrees in a cycle and that the current is constant. The rms value of the current in the power device is

$$I_{rms} = \frac{I_{max}}{\sqrt{3}} = 0.577 I_{max} \quad \text{... (1)}$$

The voltage is the maximum line to line voltage of the supply mains,

$$V_t = \sqrt{2}\, V \quad \text{... (2)}$$

I_1 = fundamental rms component of the ac input current

$$I_1 = \frac{1}{\sqrt{2}} \cdot \frac{2\sqrt{3}}{\pi} I_{max} = \frac{\sqrt{2}\,\sqrt{3}}{\pi} I_{max} = 0.78 I_{max} \quad \text{... (3)}$$

The output power of the power converter is given by

$$P_o = V_a I_{max}$$
$$= (1.35\, V \cos\alpha)\, I_{max}$$
$$= 1.35\, V\, I_{max} \cos\alpha \quad \text{... (4)}$$

Assume no losses in the power converter, the input power equals the output power. Substituting for I_{max} interms of the fundamental ac input current from equation (3) gives

$$P_o = P_i = 1.35\, V\, I_{max} \cos\alpha$$
$$I_{max} = \frac{I_1}{0.078} = 1.282 I_1$$
$$P_i = P_o = \sqrt{3}\, V\, I_1 \cos\alpha \quad \text{... (5)}$$

This equation gives the real power in a balanced three phase ac system. Here $\cos\alpha$ is the input power factor. α is the power factor angle. The reactive power is given by

$$Q_i = \sqrt{3}\, V I_1 \sin\alpha = 1.35\, V I_{max} \sin\alpha \quad \text{... (6)}$$

The input apparent power is

$$P_{VA} = \sqrt{(P_i)^2 + (Q_i)^2} = 1.35 V I_{max} = \sqrt{3}\, V I_1 \quad \text{... (7)}$$

The phase controlled rectifiers always consumes reactive power. Due to this, they are expensive to operate where the reactive power is to be paid for. It also generate harmorics. The above two features are the main disadvantages of the phase controlled converter fed dc motor drives.

3. Explain PI controller for the current – control loop.

Proportional-Integral (PI) controller

The addition of integral feedback can be used to eliminate the steady-state error and to reduce the forward gain required. To obtain this integral component the proportional speed controller is replaced by a proportional integral (PI) type controller. Figure 4.14 shows speed control loop with PI controller.

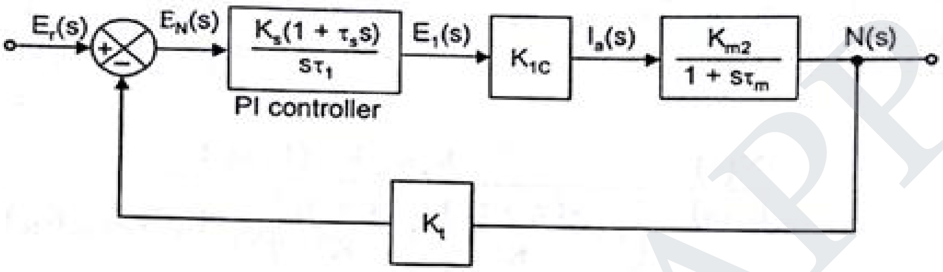


Figure 4.14: Speed-control loop with PI controller

Transfer function of P-controller $= K_s$

Transfer function of PI controller $= \dfrac{K_s(1+s\tau_s)}{s\tau_s}$

From this figure 4.14,

$$G(s) = \frac{K_s K_{1c} K_{m2}(1+\tau_s s)}{s\tau_s(1+s\tau_m)}$$

$$H(s) = K_t$$

Transfer function for the diagram of figure 4.14.

$$\frac{N(s)}{E_r(s)} = \frac{G(s)}{1+G(s)H(s)}$$

$$\frac{N(s)}{E_r(s)} = \frac{\left(\dfrac{K_s K_{1c} K_{m2}(1+s\tau_s)}{s\tau_s(1+s\tau_m)}\right)}{\dfrac{1+K_s K_{1c} K_{m2} K_t (1+s\tau_s)}{s\tau_s(1+s\tau_m)}}$$

$$= \frac{\left(\dfrac{K_s K_{1c} K_{m2}\,(1+s\tau_s)}{s\tau_s\,(1+s\tau_m)}\right)}{\dfrac{s\tau_s\,(1+s\tau_m)+K_s\,K_{1c}K_{m2}K_t\,(1+s\tau_s)}{s\tau_s\,(1+s\tau_m)}}$$

$$= \frac{K_s K_{1c} K_{m2}\,(1+s\tau_s)}{s\tau_s + s^2\tau_s\tau_m + K_s\,K_{1c}K_{m2}K_t + K_s\,K_{1c}K_{m2}K_t\,\tau_s s}$$

$$= \frac{K_s K_{1c} K_{m2}\,(1+s\tau_s)}{K_s\,K_{1c}K_{m2}K_t + s\tau_s\,(1+K_s\,K_{1c}K_{m2}K_t) + s^2\,\tau_s\,\tau_m}$$

Dividing by $K_s\,K_{1c}\,K_{m2}\,K_t$ in numerator and denominator

$$\frac{N(s)}{E_r(s)} = \frac{\dfrac{K_s K_{1C} K_{m2}\,(1+s\tau_s)}{K_s K_{1C} K_{m2} K_t}}{1+\dfrac{s\tau_s\,(1+K_s K_{1c} K_{m2} K_t)}{K_s K_{1c} K_{m2}\,K_t}+\dfrac{s^2\tau_s\tau_m}{K_s K_{1c} K_{m2} K_t}}$$

$K_s\,K_{1C}\,K_{m2}\,K_t >>> 1$, so neglect 1 in the term $1 + K_s\,K_{1c}\,K_{m2}\,K_t$, we get

$$\frac{N(s)}{E_r(s)} = \frac{\dfrac{1}{K_t}(1+s\tau_s)}{1+\dfrac{s\tau_s\,K_s K_{1c} K_{m2} K_t}{K_s K_{1c} K_{m2}\,K_t}+\dfrac{s^2\tau_s\tau_m}{K_s K_{1c} K_{m2} K_t}}$$

Substitute $\tau_2 = \dfrac{\tau_m}{K_s K_{1c} K_m K_t}$, we get

$$\frac{N(s)}{E_r(s)} = \frac{\dfrac{1}{K_t}\,(1+s\tau_s)}{1+s\tau_s+s^2\tau_s\tau_2}$$

$$= \frac{1}{K_t}\,\frac{(1+s\tau_s)}{(1+s\tau_s+s^2\tau_s\tau_2)}$$

We know that

$$\frac{I_a(s)}{E_r(s)} = \frac{N(s)}{E_r(s)} \times \frac{I_a(s)}{N(s)}$$

$$\frac{I_a(s)}{E_r(s)} = \frac{1+s\tau_m}{K_{m2}}$$

$$\frac{I_a(s)}{E_r(s)} = \frac{1}{K_t}\,\frac{1+s\tau_s}{1+s\tau_s+s^2\tau_s\tau_s} \times \frac{1+s\tau_m}{K_{m2}}$$

$$\frac{I_a(s)}{E_r(s)} = \left(\frac{1}{K_t K_{m2}}\right)\frac{(1+s\tau_s)(1+s\tau_m)}{(1+s\tau_s+s^2\tau_s\tau_2)} \qquad ....(35)$$

The equations 29 and 30 are the second order response of the system.

4. Explain the design procedure of speed controller.

Speed Controller

If a DC tachogenerator is attached to the motor shaft, a speed signal can be fedback and the error $E_N(s)$ used to control the armature voltage. This scheme is shown in Figure 4.11. The applied armature voltage is controlled by a single-phase or three-phase full-converter or a DC chopper. Using a cosine firing scheme, a linear relationship between the control voltage E_c and the armature voltage E_a can be obtained.

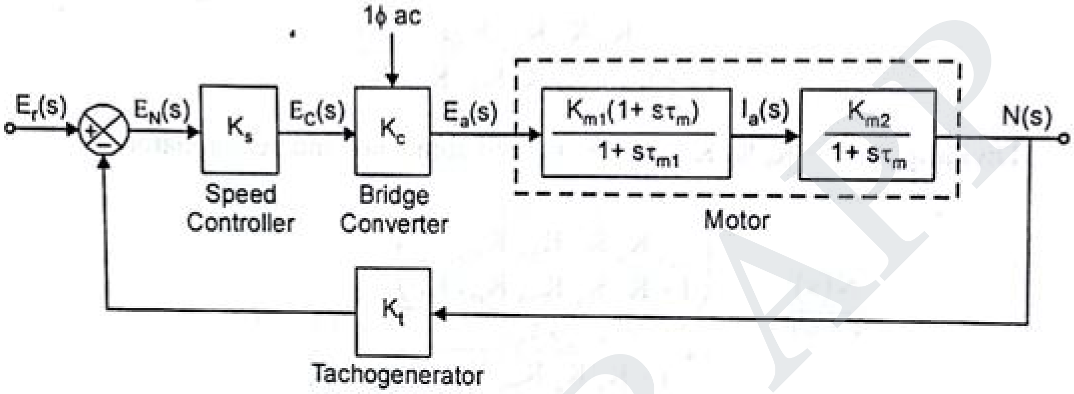


Figure 4.11: Speed-control loop

Several types of speed controllers are possible. Most commonly used speed controllers are:

1. Proportional (P) controller
2. Proportional-integral (PI) controller

Proportional controller (P-controller)

The transfer function of the speed controller (from figure) is

$$\frac{N(s)}{E_r(s)} = \frac{G(s)}{1 + G(s)H(s)} \qquad \text{....(1)}$$

where

$$G(s) = K_s\, K_C\, \frac{K_{m1}(1+s\tau_m)}{1+s\tau_{m1}}\, \frac{K_{m2}}{1+s\tau_m}$$

$$G(s) = \frac{K_s K_c K_{m1} K_{m2}}{1 + s\tau_{m1}} \qquad \text{....(2)}$$

$$H(s) = K_t \qquad \text{....(3)}$$

From equations (1), (2) and (3)

$$\frac{N(s)}{E_r(s)} = \frac{\left(\dfrac{K_s K_c K_{m1} K_{m2}}{1+s\tau_{m1}}\right)}{1+\dfrac{K_s K_c K_{m1} K_{m2}}{1+s\tau_{m1}} \times K_t} = \frac{\dfrac{K_s K_c K_{m1} K_{m2}}{1+s\tau_{m1}}}{\dfrac{1+s\tau_{m1}+K_s K_c K_{m1} K_{m2} K_t}{1+s\tau_{m1}}}$$

$$= \frac{K_s K_c K_{m1} K_{m2}}{1+s\tau_{m1}+K_s K_c K_{m1} K_{m2} K_t}$$

Dividing by $1 + K_s K_c K_{m1} K_{m2} K_t$ in both numerator and denominator

$$\frac{N(s)}{E_r(s)} = \frac{\left(\dfrac{K_s K_c K_{m1} K_{m2}}{1+K_s K_c K_{m1} K_{m2} K_t}\right)}{1+\dfrac{s\tau_{m1}}{1+K_s K_c K_{m1} K_{m2} K_t}}$$

$$\boxed{\frac{N(s)}{E_r(s)} = \frac{K_1}{1+s\tau_1}} \qquad ....(4)$$

where

$$K_1 = \frac{K_s K_c K_{m1} K_{m2}}{1+K_s K_c K_{m1} K_{m2} K_t} \qquad ....(5)$$

$$\tau_1 = \frac{\tau_{m1}}{1+K_s K_c K_{m1} K_{m2} K_t} \qquad ....(6)$$

If $K_s K_c K_{m1} K_{m2} K_t >> 1$, then neglecting the term 1 in the denominator and we can get

$$K_1 = \frac{K_s K_c K_{m1} K_{m2}}{K_s K_c K_{m1} K_{m2} K_t}$$

$$K_1 = \frac{1}{K_t} \qquad ....(7)$$

$$\tau_1 = \frac{\tau_{m1}}{K_s K_c K_{m1} K_{m2} K_t} \qquad ....(8)$$

We know that

$$\frac{I_a(s)}{N(s)} = \frac{1+s\tau_{m1}}{K_{m2}}$$

$$\frac{I_a(s)}{E_r(s)} = \frac{N(s)}{E_r(s)} \times \frac{I_a(s)}{N(s)} \qquad ....(9)$$

$$\frac{I_a(s)}{E_r(s)} = \frac{K_1}{1+s\tau_1} \times \frac{1+s\tau_m}{K_{m2}}$$

$$= \frac{K_1(1+s\tau_m)}{K_{m2}(1+s\tau_1)}$$

$$I_a(s) = \frac{K_1(1+s\tau_m)}{K_{m2}(1+s\tau_1)} E_r(s) \qquad ....(10)$$

If the input $E_r(s)$ is a step input i.e.,

$$E_r(s) = \frac{E_r}{s}$$

$$I_a(s) = \frac{K_1(1+s\tau_m)}{K_{m2}(1+s\tau_1)} \frac{E_r}{s} \qquad ....(11)$$

$$= \frac{K_1E_r(1+s\tau_m)}{K_{m2}\, s\tau_1\left(s+\frac{1}{\tau_1}\right)}$$

Dividing by $K_{m2}\,\tau_1$

$$= \frac{K_1E_r(1+s\tau_m)/K_{m2}\tau_1}{\frac{K_{m2}\, s\tau_1}{K_{m2}\tau_1}\left(s+\frac{1}{\tau_1}\right)}$$

$$= \frac{K_1E_r(1+s\tau_m)/K_{m2}\tau_1}{s\left(s+\frac{1}{\tau_1}\right)}$$

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Using partial fraction

$$\frac{K_1E_r(1+s\tau_m)/K_{m2}\tau_1}{s\left(s+\frac{1}{\tau_1}\right)} = \frac{A_1}{s} + \frac{A_2}{s+\frac{1}{\tau_1}} \quad ....(18)$$

$$\frac{K_1E_r(1+s\tau_m)/K_{m2}\tau_1}{s\left(s+\frac{1}{\tau_1}\right)} = \frac{A_1\left(s+\frac{1}{\tau_1}\right)+A_2s}{s\left(s+\frac{1}{\tau_1}\right)}$$

$$\frac{K_1E_r(1+s\tau_m)}{K_{m2}\tau_1} = A_1\left(s+\frac{1}{\tau_1}\right)+A_2s$$

$$\frac{K_1E_r}{K_{m2}\tau_1}+\frac{K_1E_r\tau_m}{K_{m2}\tau_1}s = s(A_1+A_2)+\frac{A_1}{\tau_1}$$

Equating constant term on both sides

$$\frac{K_1E_r}{K_{m2}\tau_1} = \frac{A_1}{\tau_1}$$

$$\boxed{A_1 = \frac{K_1E_r}{K_{m2}}} \quad ....(12)$$

Equating 's' term on both sides

$$\frac{K_1E_r\tau_m}{K_{m2}\tau_1} = A_1 + A_2$$

$$\frac{K_1E_r\tau_m}{K_{m2}\tau_1} = \frac{K_1E_r}{K_{m2}} + A_2$$

$$\boxed{A_2 = \frac{K_1E_r}{K_{m2}}\left(\frac{\tau_m}{\tau_1}-1\right)} \quad ....(13)$$

$$I_a(s) = \frac{K_1E_r}{K_{m2}s} + \left[\frac{K_1E_r}{K_{m2}}\left(\frac{\tau_m}{\tau_1}-1\right)\Big/ s+\frac{1}{\tau_1}\right]$$

$$I_a(s) = \frac{K_1E_r}{K_{m2}s} + \frac{E_rK_1(\tau_m-\tau_1)}{K_{m2}\tau_1\left(s+\frac{1}{\tau_1}\right)}$$

$$I_a(s) = \frac{E_r K_1}{K_{m2}}\left[\frac{1}{s} + \left(\frac{(\tau_m - \tau_1)}{\tau_1}\right) \times \frac{1}{\left(s + \frac{1}{\tau_1}\right)}\right] \quad ..(14)$$

Taking inverse laplace transform

$$I_a(t) = \frac{E_r K_1}{K_{m2}}\left(1 + \frac{(\tau_m - \tau_1)}{\tau_1} e^{-t/\tau_1}\right) \quad ....(15)$$

Since $\tau_m >>>> \tau_1$, τ_1 can be neglected.

When $t \to \infty$, $I_a(t) \to I_a(\infty)$

$$I_a(\infty) = \frac{E_r K_1}{K_{m2}}\left[1 + e^{-\infty}\right]$$

$$= \frac{E_r K_1}{K_{m2}} \quad ....(16)$$

Normalizing the current $I_a(t)$ with respect to the steady-state current $I_a(\infty)$,

$$\frac{I_a(t)}{I_a(\infty)} = \frac{\frac{E_r K_1}{K_{m2}}\left[1 + \frac{\tau_m - \tau_1}{\tau_1} e^{\frac{-t}{\tau_1}}\right]}{\frac{E_r K_1}{K_{m2}}}$$

$$\frac{I_a(t)}{I_a(\infty)} = 1 + \frac{\tau_m - \tau_1}{\tau_1} e^{-t/\tau_1} \quad ....(17)$$

Equation (15) shows that a small change in the input E_r will results in a large sudden change in current that decays slowly. This transient over current is undesirable is the point of converter rating and protection. This is particularly the case for starting or other sudden changes. For this purpose current controller is used.