SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING
DEPARTMENT OF E.E.E

UNIT – I – Electric Drives And Control-SEE1306

SUBJECT NAME: ELECTRIC DRIVES AND CONTROL
SUBJECT CODE:SEE1306

INTRODUCTION

- Basic elements
- Types of electric drives
- Factors influencing electric drives
- Heating and cooling curves
- Loading conditions and classes of duty
- Selection of power rating for drive motors with regard to thermal overloading and load variation factors
- Load equalization

INTRODUCTION

Drive:

A combination of prime mover, transmission equipment and mechanical Working load is called a drive

Electric drive:

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

BLOCK DIAGRAM OF AN ELECTRICAL DRIVES

The basic block diagram for electrical drives used for the motion control is shown in the following figure1.1

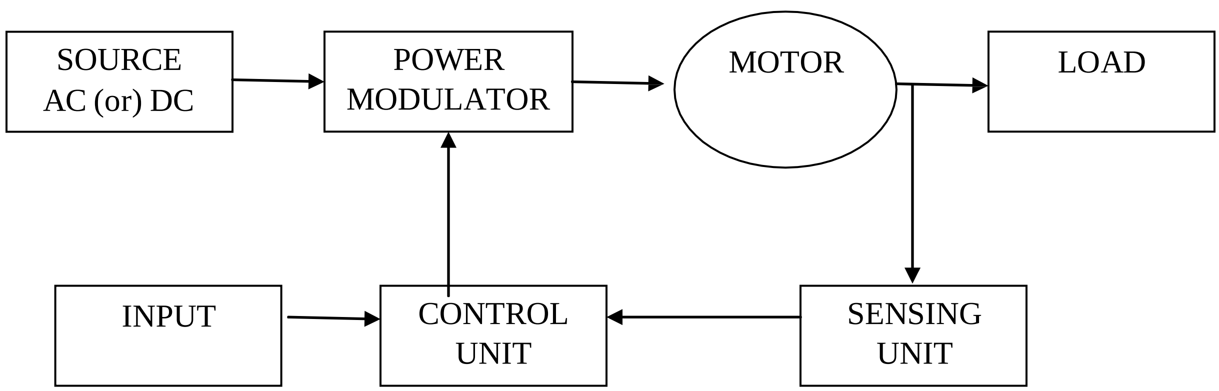

Fig.1.Block Diagram for Electrical Drives

The aggregate of the electric motor, the energy transmitting shaft and the control equipment by which the motor characteristics are adjusted and their operating conditions with respect to mechanical load varied to suit practical requirements is called as electric drive.

Drive system=Drive + load

BASIC COMPONENT (or) ELEMENTS OF ELETCRIC DRIVES

Block diagram of electric drive:

1. **Load:** usually a machinery to accomplish a given task. Eg-fans, pumps, washing machine etc.
2. **Power modulator**: modulators (adjust or converter) power flow from the source to the motion

3. **Motor:** actual energy converting machine (electrical to mechanical)
4. **Source:** energy requirement for the operation the system.
5. **Control:** adjust motor and load characteristics for the optimal mode.

Power modulators:

Power modulators regulate the power flow from source to the motor to enable the motor to develop the torque speed characteristics required by the load.

The common function of the power modulator is,

- They contain and control the source and motor currents with in permissible limits during the transient operations such as starting, braking, speed reversal etc.
- They converts the input electrical energy into the form as required by the motors.
- Adjusts the mode of operation of the motor that is motoring, braking are regenerative.

Power modulators may be classified as,

- Converters uses power devices to convert uncontrolled valued to controllable output.
- Switching circuits switch mode of operation
- Variable impedance

Converters

They provide adjustable voltage/current/frequency to control speed, torque output power of the motor.

The various type of converters are,

- AC to DC rectifiers
- DC to DC choppers
- AC to AC choppers
- AC to AC –AC voltage controllers (voltage level is controlled)
- Cyclo converter (Frequency is controlled)
- DC to AC inverters

Switching circuits

Switching circuits are needed to achieve any one of the following.

- Changing motor connection to change its quadrant of operation.
- Changing motor circuits parameters in discrete steps for automatic starting and braking control.
- For operating motors and drives according to a predetermine sequence
- To provide inter locking their by preventing maloperation
- Disconnect under up normal condition

Eg: electromagnetic contacters,
PLC in sequencing and inter locking operation,
solid state relays etc.

Variable impedance

- Variable resisters are commonly used for AC and DC drives and also needed for dynamic braking of drives
- Semiconductors switch in parallel with a fixed resistance is used where stepless variation

is needed. inductors employed to limit starting current of ac motors.

FACTORS INFLUENCING THE CHOICE OF ELECTRICAL DRIVES

(i) Nature of electric supply
  - ✓ Whether AC or DC supply is to be used for supply

(ii) Nature of the drive
  - ✓ Whether the particular motor is going to drive individual machine or a group of machines

(iii) Capital and running cost
(iv) Maintenance requirement
(v) Space ad weight restrictions
(vi) Environment and location
(vii) Nature of load
  - ✓ Whether the load requires light or heavy starting torque
  - ✓ Whether load torque increases with speed remain constant
  - ✓ Whether the load has heavy inertia which may require longer straight time

(viii) Electrical characteristics of motor
  - ✓ Starting characteristics,
  - ✓ running characteristics,
  - ✓ speed control and
  - ✓ Braking characteristics

(ix) Size, rating and duty cycle of motors
  - ✓ Whether the motor is going to the operator for a short time or whether it has to run continuously intermittently or on a variable load cycle

(x) Mechanical considerations
  - ✓ Type of enclosures, type of bearings, transmission of drive and Noise level.
  - ✓ Due to practical difficulties, it may not possible to satisfy all the above considerations.
  - ✓ In such circumstances, it is the experience and knowledge background which plays a vital role in the selection of the suitable drive.

The following points must be given utmost important for the selection of motor. The factors are:
- ➢ Nature of the mechanical load driven
- ➢ Matching of the speed torque characteristics of the motor with that of the load
- ➢ Starting conditions of the load.

CLASSIFICATION OF ELECTRIC DRIVES WITH FACTOR

The choice of the electric drives

There are three classification namely
- ✓ group drive
- ✓ individual drive
- ✓ multimotor drive

<u>Group drive</u>

One motor is used as a drive for two or more than machines. The motor is connected to a long shaft. All the other machines are connected to this shaft through belt and pulleys**.**

Advantages:

- Group drive is most economical because, the rating of the motor used may be comparatively less than the aggregate of the individual motors required to drive each equipment, because all of they may not be working simultaneously.
- Group drive reduces the initial cost of installing a particular industry.
- Cost is less because of investment in one motor which is lesser in HP rating.

Disadvantages:

The use of this kind of drive is restricted due to the following reasons:

- It is not possible to install any machine as per our wish. so, flexibility of lay out is lost.
- The possibility of installation of additional machines in an existing industry is limited.
- In case of any fault to the main driving motor, all the other motors will be stopped immediately.
- so, all systems will remain idle and is not advisable for any industry.
- Level of noise produced at the site is high.
- Because of the restrictions in placing other motors, this kind of drive will result in untidy appearance, and it is also less safe to operate.
- Since all the motors has to be connected through belts and pulleys, large amount of energy is wasted in transmitting mechanisms. Therefore, power loss is high.

Individual drive

In this drive, there will be a separate driving motor for each process equipment.

One motor is used for transmitting motion to various parts or mechanisms belonging to signal equipment.

Ex: Lathe

One motor used in lathe which rotates the spindle, moves feed with the help of gears and imparts motion to the lubricating and cooling pumps).

Advantages:

- Machines can be located at convenient places.
- Continuity in the production of the processing industry is ensured to a high level of reliability.
- If there is a fault in one motor, the effect on the production or output of the industry will not be appreciable.

Disadvantages:

- Initial cost is very high.

Multimotor Drive:

In this type of drive, separate motors are provided for actuating different parts of the driven mechanism.

Ex: cranes, drives used in paper mills, rolling mills etc.,

In cranes, separate motors are used for hoisting, long travel motion and cross travel motion.

LOAD CONDITIONS IN MOTOR

The load requirements are in either of

- ➢ Speed control
- ➢ Torque control

Depending upon the load requirements the motor has to be chosen.

For example in traction system the load (traction network) needs high starting torque (initiali.e.,high current value is needed at t6he start. A series motor provides a high starting torque as .Hence series motor should be chosen for traction system.

Classification of loads

- Torque dependent on speed
  (Ex-hoists, pumping of water or gas against constant pressure)
- Torque linearly dependent on speed
  (Ex- motor driving a DC generator connected to a fixed resistance load [generator field value is kept constant])
- Torque proportional to square of speed
  (Ex- fans, sentrifugal pumps, propellers)
- Torque inversely proportional to speed
  (Ex-milling and boring, machines)

Different type of industrial loads

There are three types of industrial loads under which electric motors are required to work. they are

- ❖ Continuous load
- ❖ Intermittent load
- ❖ Variable or fluctuating load

➢ **Continuous load**

- ❖ Load is continuous in nature
- ❖ Ex- Pumps or fans require a constant power input to keep them operating**.**

➢ **Intermittent load**

- ❖ This type classified in to two types
- ❖ Motor loaded for short time and then shunt off for sufficiently longer duration temperature is brought to the room temperature

  Eg: kitchen mixie.

- ❖ The electrical loss is more due to constant ON/OFF delay period
- ❖ Moor loaded for short time and shunt off for short time .
- ❖ Here the motor cannot be cooled down to the room temperature comparison of the two methods it can be Inferred.
- ❖ The temperature level of motor is not brought to the room temperature.

HEATING AND COOLING CURVES

A machine can be considered as a homogeneous body developing heat internally at uniform rate and dissipating heat proportionately to its temperature rise,

RELATION SHIP BETWEEN TEMPERATURE RISE AND TIME

Let,

P =heat developed, joules/sec or watts
G =weight of active parts of machine, kg
h =specific heat per kg per deg cell
S = cooling surface, m2
λ = specific heat dissipation (or) emissivity, J per sec per m^2 of
Surface per deg cell difference between surface and ambient cooling medium
θ = temperature rise, deg cell
θ_m =final steady temperature rise, deg cell
t =time, sec
τ =heating time constant, seconds
τ' =cooling time constant, seconds

Assume that a machine attains a temperature rise after the lapse of time t seconds.
In an element of time "dt" a small temperature rise "d" takes place.

Then,
Heat developed = p.dt Heat developed = Gh.dθ Heat dissipated = S$\theta\lambda$.dt

Therefore, total heat developed=heat stored + heat dissipated

$$Ghd\theta + S\theta\lambda.\ dt = p.dt$$

$$\frac{d\theta}{dt} + \theta \cdot \frac{s\lambda}{Gh} = \frac{p}{Gh}$$

This is a differential equation and solution of this equation is,

$$\theta = \frac{p}{s\lambda} + ke^{-(s\lambda/Gh)t}$$

Where k is a constant of integration determined by initial conditions.
Let the initial temperature rise to be zero at t=0.

Then, $0 = \frac{p}{s\lambda} + k$

$$k = \frac{-p}{s\lambda}$$

$$-(\underline{\sigma\lambda})$$

Hence, $$\theta = \frac{p}{s\lambda}(1- e^{\quad Gh\ t}) \text{ ----------------------------------(1)}$$

When t= ∞ , $\theta = \frac{p}{s\lambda} = \theta_m$, the final steady temperature rise.

Represent $\frac{p}{s\lambda} = \theta_m$ and $\frac{Gh}{s\lambda} = \tau$ - - - - - - - - - - - - - -(2)

Equation 1 can be written as

$$\theta = \theta_m(1- e^{-1}) \text{ ----------------------------- (3)}$$

Where is called as heating time constant and it has the dimensions of time.

<u>Heating time constant</u>

Heating time constant is defined as the time taken by the machine to attain 0.623 of its final steady temperature rise.

When t= τ ,

$$\theta = \theta_m(1- e^{-1})$$

$$\theta = 0.632\theta_m$$

- The heating time constant of the machine is the index of time taken by the machine to attain its final steady temperature rise.

- We know that $\tau = \frac{Gh}{s\lambda}$, therefore, the time constant is inversely proportional to has a larger value for ventilated machines and thus the value of their heating time constant is small.

The value of heating time constant is larger for poorly ventilated machines with large or totally enclosed machines, the heating time constant may reach several hours or even days.

- When a hot body is cooling due to reduction of the losses developed in it, the temperature time curve is again an exponential function

$$\theta = \theta_f + (\theta_i - \theta_f)e^{-\frac{t}{\tau}} \text{ --------------------(4)}$$

Where,

θf =final temperature drop (the temperature at which whatever heat is generated is dissipated)

$\frac{p}{s\lambda'}$ = where, λ is rate of heat dissipation while cooling

θi = the temperature rise above ambient in the body at time t=0

τ' = cooling time constant= $\frac{Gh}{s\lambda'}$

If motor where disconnected from supply during cooling, there would be no losses taking place and hence, final temperature reached will be the ambient temperature.

There fore, θ_f =0 and hence equation (4) becomes

$$\theta = \theta_i e^{\frac{1}{\tau'}}$$

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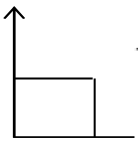
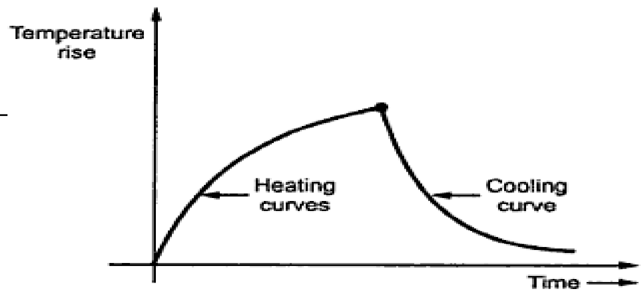
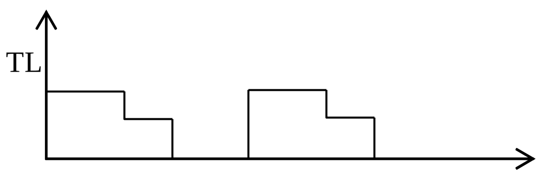






CLASSES OF MOTOR DUTY

various load time variations encountered into eight classes as

(i) continuous duty
(ii) short time duty
(iii) intermittent periodic duty
(iv) intermittent periodic duty with starting
(v) intermittent periodic duty with starting & braking
(vi) continuous duty with intermittent periodic loading
(vii) continuous duty with starting & braking
(viii) Continuous duty with periodic

1. Continuous duty:

- This type drive is operated continuously for a duration which is long enough to reach its steady state value of temperature.
- This duty is characterized by constant motor torque and constant motor loss operation.
- This type of duty can be accomplished by single phase/ three phase induction motors and DC shunt motors.

Examples:

Paper mill drives ,
Compressors
Conveyors,
Centrifugal pumps and
Fans ,

2. Short time duty:

- In this type drive operation, Time of operation is less than heating time constant and motor is allowed to cool off to room temperature before it is operated again.
- Here the motor can be overloaded until the motor temperature reaches its permissible limit.
- This type of duty can be accomplished by single phase/ three phase induction motors and DC shunt motors, DC series motors, universal motors.

Examples:

Crane drives
Sluice gate drives
Valve drives
and Machine tool drives

3. Intermittent periodic duty:

- In this type drive operation, It consists of a different periods of duty cycles
- I.e. a period of rest and a period of running, a period of starting, a period of braking.
- Both a running period is not enough to reach its steady state temperature and a rest period is not enough to cool off the machine to ambient temperature.
- In this type drive operation, heating due to starting and braking is negligible.

This type of duty can be accomplished by single phase/ three phase induction motors andDC shunt motors, universal motors

Examples:

Pressing
Cutting
Drilling machine drives.

4. Intermittent periodic duty with starting:

- This is intermittent periodic duty where heating
- Due to starting can‟t be ignored.
- It consists of a starting period; a running period, a braking period & a rest period are being too short to reach their steady state value.
- In this type of drive operation, heating due to braking is negligible.
- This type of duty can be accomplished by three phase induction motors and DC series motors, DC compound motors, universal motors.

Examples:

Metal cutting,
Drilling tool drives,
Drives for forklift trucks,
Mine hoist etc.

5. Intermittent periodic duty with starting & braking:

- This is an intermittent periodic duty where heating during starting & braking can‟t be ignored.
- It consists of a starting period, a running period; a braking period & a rest period are being too short to reach their steady state temperature value.
- This type of duty can be accomplished by single phase/ three phase induction motors and DC shunt motors, DC series motors, DC compound motors, universal motors.

Examples:

Billet mill drive
Manipulator drive
Ingot buggy drive
Screw down mechanism of blooming mill
Several machine tool drives
Drives for electric suburban trains and

Mine hoist

6. Continuous duty with intermittent periodic loading:

- This type of drive operation consists a period of running at constant load and a period of running at no load with normal voltage to the excitation winding in separately excited machines.
- Again the load and no load periods are not enough to reach their respective temperature limits.
- This duty is distinguished from intermittent periodic duty by running at no load instead of rest period.
- This type of duty can be accomplished by single phase/ three phase induction motors and DC compound motors, universal motor.

Examples:

Pressing
Cutting
Shearing and
Drilling machine drives.

7. Continuous duty with starting & braking:

- It consists a period of starting, a period of running & a period of electrical braking.
- Here period of rest is negligible.
- This type of duty can be accomplished by single phase/ three phase induction motors.

Examples:

The main drive of a blooming mill.

8. Continuous duty with periodic speed changes:

- It consists a period of running in a load with a particular speed and a period of running at different load with different speed which are not enough to reach their respective steady state temperatures.
- Further here is no period of rest.
- This type of duty can be accomplished by single phase/ three phase induction motors and DC series motor in traction.

Examples:

All variable speed drives.

SELECTION OF POWER RATING OF MOTORS

From the point of view of motor rating for various duty cycles in section 1.6 can be broadly classified as:

- Continuous duty and constant load
- Continuous duty and variable load
- Short time rating

<u>Continuous duty and constant load</u>

If the motor has load torque of T N-m and it is running at ω radians/seconds, if efficiency in η , then power rating of the motor is

$$P = \frac{T\omega}{1000} \; KW$$

Power rating is calculated and then a motor with next higher power rating from commercially available rating is selected.

Obviously, motor speed should also match load‟s speed requirement .It is also necessary to check whether the motor can fulfill starting torque requirement also.

<u>Continuous duty and variable load</u>

- The operating temperature of a motor should never exceed the maximum permissible temperature, because it will result in deterioration and breakdown of insulation and will shorten the service life of motors.
- It is general practice to base the motor power ratings on a standard value of temperature, say 35 $^\circ$c.
- Accordingly, the power given on the name plate of a motor corresponds to the power which the motor is capable of delivering without overheating at an ambient temperature of 35 $^\circ$ c. the duty cycle is closely related to temperature and is generally taken to include the environmental factors also.
- The rating of a machine can be determined from heating considerations.
- However the motor so selected should be checked for its overload capacity and starting torque.
- This is because, the motor selected purely on the basis of heating may not be able to meet the mechanical requirements of the basis of heating may not be able to meet the mechanical requirements of the load to be driven by it.
- The majority of electric machines used in drives operate continuously at a constant or only slightly variable load.
- The selection of the motor capacity for these applications is fairly simple in case the approximate constant power input is known
- In many applications, the power input required for a motor is not known before hand and therefore certain difficulties arise in such cases.
- For the determination of ratings of machines whose load characteristics have not been thoroughly studied, it becomes necessary to determine the load diagram i.e., diagram shown the variation of power output versus time.

The temperature of the motor changes continuously when the load is variable. On account of this, it becomes difficult to select the motor rating as per heating.

- The analytical study of heating becomes highly complicated if the load diagram is irregular in shape or when it has a large number of steps.
- Therefore it becomes extremely difficult to select the motor capacity through analysis of the load diagram due to select the motor capacity through analysis of the load diagram due to lack of accuracy of this method.

On the other hand it is not correct to select the motor according to the lowest or highest load because the motor would be overloaded in the first case and under loaded in the second case. Therefore it becomes necessary to adopt suitable methods for the determination of motor ratings.

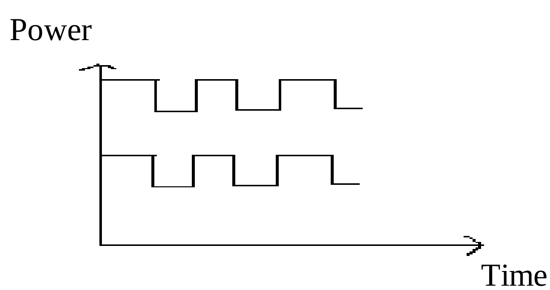
Methods used

The four commonly used methods are:

- ❖ Methods of average losses
- ❖ Equivalent current method
- ❖ Equivalent torque method
- ❖ Equivalent power method

<u>1. Methods of average losses</u>

- ➢ The method consists of finding average losses Q_{av} in the motor when it operates according to the given load diagram.
- ➢ These losses are then compared with the Q , the losses corresponding to the continuous duty of the machine when operated at its normal rating.
- ➢ The method of average losses presupposes that when $Q_{av} = Q_{nomn}$, the motor will operate without temperature rise going above the maximum permissible for the particular class of insulation.
- ➢ The figure shows a simple power load diagram and loss diagram for variable load conditions.
- ➢ The losses of the motor are calculated for each portion of the load diagram by referring to the efficiency curve of the motor.



Average Load Losses

The average losses are given by

$$\boxed{Q_{av} = \frac{Q_1 t_1 + Q_2 t_2 + Q_3 t_3 + \cdots + Q_n t_n}{t_1 + t_2 + \cdots + t_n}}$$

- ➢ In case ,the two losses are equal or differ by a small amount ,the motor is selected .if the losses differ considerably ,another motor is selected and the calculations repeated till a motor having almost the same losses as the average losses is found.
- ➢ Iit should be checked that the motor selected has a sufficient overload capacity and starting torque.
- ➢ The method of average losses dopes not take into account, the maximum temperature rise under variable load conditions .However, this method is accurate and reliable for determining the average temperature rise of the motor during one work cycle.

The disadvantage of this method is that it is tedious to work with and also many a times the efficiencycurve is not readily available and the efficiency has to be calculated by means of empirical formulawhich may not be accurate.

2. Equivalent Current Method

The equivalent current method is based on the assumption that the actual variable current may be replaced by an equivalent current i_{eq} which produces the same losses in the motor as the actual current.

$$\boxed{I_{eq} = \sqrt{\frac{I_1^2 t_1 + I_2^2 t_2 + I_3^2 t_3 + \dots\dots + I_n^2 t_n}{t_1 + t_2 + t_3 + \dots + t_n}}}$$

The equivalent current is compared with the rated current of the motor selected and the conditions $I_{eq} \leq I_{nom}$ should be met. I_{nom} is the rated current of the machine.

The machine selected should also be checked for its overload capacity,

For DC motors,

$$\boxed{\frac{I_{max}}{I_{nom}} \leq 2 to 2.5 and for induction motors, \frac{I_{max}}{nom} \leq 1.65 to 2.75}$$

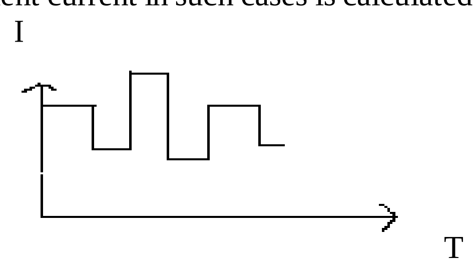
I_{max} = maximum current during the work cycle.

T_{max} = maximum load torque

T_{nom} = torque of the motor at rated power and speed

If the over load capacity of the motor selected is not sufficient, it becomes necessary to select a motor of higher power rating.

The equivalent current may not be easy to calculate especially in cases where the current load diagram is irregular .the equivalent current in such cases is calculated from the following expression.



Equivalent Current

For a triangular shape diagram,

$$I_{eq} = \sqrt{\frac{I^2}{3}}$$

For a trapezoidal shaped diagram,

$$I_{eq} = \sqrt{\frac{I_1^2 + I_1 I_2 + I_2^2}{3}}$$

The above method allows the equivalent current values to be calculated with accuracy sufficient for practical purposes.

3. Equivalent torque method

Assuming constant flux and power factor, torque is directly proportional to current.

$$T = \sqrt{\frac{T_1^2 t_1 + T_2^2 t_2 + \cdots + T_n^2 t_n}{t_1 + t_2 + \cdots + t_n}}$$

4. Equivalent power method

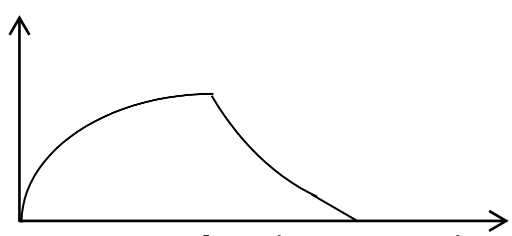
The equation for equivalent power method, power is directly proportional to torque. At constant speed or where the changes in speed are small, the equivalent power is given by the following relationship,

$$P_{eq} = \sqrt{\frac{P_1^2 t_1 + P_2^2 t_2 + \cdots + P_n^2 t_n}{t_1 + t_2 + \cdots + t_n}}$$

Short time rating of motor

An electric motor of rated power P_r subjected to its rated load continuously reaches its permissible temperature rise after due to time. If the same motor is to be used for short time duty, it can take up more load for a short period without increasing the maximum permissible temperature of the motor during this period.

$$\theta = \theta_m (1 - e^{\frac{N}{\tau}}) \qquad \theta_m = \theta_m' (1 - e^{-\frac{N}{\tau}})$$



Short time motor rating

Where=operating time under rated load

θ_m =maximum permissible temperature which the motor running on short time rating will reach if run continuously at that rating.

θ_m = Maximum permissible temperature rise of the motor run continuously at continuous rating.

If it is assumed that the temperature rise is proportional to losses corresponding to the rating of the motor.

$$\frac{\theta_m}{\theta_m} = \frac{W_x}{W_r} = \frac{1}{(1 - e^{\frac{N}{\tau}})}$$

The ratings of the motor will be proportional to the losses .If P_x is the short time load P_r is the continuous rating of the motor, losses for continuous rating are,

$$W_r = W_{const} + W_{cu}$$

$$W_x = W_{const} + \left(\frac{P_x}{P_r}\right)^2 W_{cu}$$

The ratio of $\frac{P_x}{P_r}$ can be determined.

Load Equalisation in Electrical Drives:

Load Equalisation in Electrical Drives – In some drive applications, load torque fluctuates widely within short intervals of time. For example, in pressing machines a large torque of short duration is required during pressing operation, otherwise the torque is nearly zero. Other examples are electric hammer, steel rolling mills and reciprocating pumps. In such drives, if motor is required to supply peak torque demanded by load, first motor rating has to be high. Secondly, motor will draw a pulsed current from the supply. When amplitude of pulsed current forms an appreciable proportion of supply line capacity, it gives rise to line voltage fluctuations, which adversely affect other loads connected to the line. In some applications, peak load demanded may form major proportion of the source capacity itself, as in blooming mills, then load fluctuations may also adversely affect the stability of source.

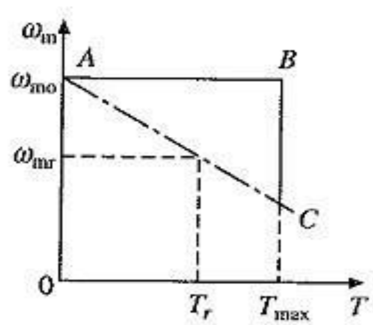


Fig. 2.10 Shapes of motor speed torque curves for fluctuating roads

Above mentioned problems of fluctuating loads are overcome by mounting a flywheel on the motor shaft in non-reversible drives. Motor speed-torque characteristic is made drooping. Alternatively, by closed loop current control torque is prevented from exceeding a permissible value. During high load period, load torque will be much larger compared to the motor torque. Deceleration occurs producing a large dynamic torque component (J $d\omega_m/dt$). Dynamic torque and motor torque together are able to produce torque required by the load (Eq. (2.2)). Because of Fig. 2.10 Shapes of motor speed torque curves for deceleration, the motor speed falls. During light load period, the motor torque exceeds the load torque causing acceleration Speed is brought back to original value before the next high load period.

Variation of motor and load torques, and speed for a periodic load and for a drooping motor speed-torque curve are shown in Fig. 2.11. It shows that peack torque required from the motor has much smaller value than the peak load torque. Hence, a motor with much smaller rating than peak load can be used and peak current drawn by motor from the source is reduced by a large amount. Fluctuations in motor torque and speed are also reduced. Since power drawn from the source fluctuates very little, this is called load equalisation.

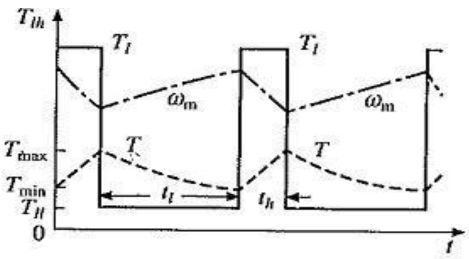


Fig. 2.11

In variable speed and reversible drives, a flywheel cannot be mounted on the motor shaft, as it will increase transient time of the drive by a large amount. If motor is fed from a motor-generator set (Ward-Leonard Drive), then flywheel can be mounted on the shaft of the motor-generator set. This arrangement of Load Equalisation in Electrical Drives on the source, but not the load on motor. Consequently, a motor capable of supplying peak-load-torque is required.

Moment of inertia of the flywheel required for Load Equalisation in Electrical Drives is calculated as follows: Assuming a linear motor-speed-torque curve in the region of interest

$$\omega_m = \omega_{m0} - \frac{\omega_{m0} - \omega_{mr}}{T_r} \cdot T \qquad (2.31)$$

where ω_{m0},ω_{mr} and and T_r are no-load speed, rated speed and rated torque, respectively.

Because of slow response due to large inertia, motor can be assumed to be in electrical equilibrium during transient operation of the motor-load system. In that case Eq. (2.31) will be applicable for the transient operation also. Differentiating (2.31) and multiplying both sides by J gives

$$J\frac{d\omega_m}{dt} = -\frac{J(\omega_{m0} - \omega_{mr})}{T_r}\frac{dT}{dt} \qquad (2.32)$$

$$= -\tau_m \frac{dT}{dt} \qquad (2.33)$$

where

$$\tau_m = \frac{J(\omega_{m0} - \omega_{mr})}{T_r} \qquad (2.34)$$

Term τ_m is defined as the mechanical time constant of the motor. It is the time required for the motor speed to change by $(\omega_{m0} - \omega_{mr})$ when motor torque is maintained constant at rated value T_r.

From Eqs. (2.2) and (2.33)

$$\tau_m \frac{dT}{dt} + T = T_l \qquad (2.35)$$

Consider now a periodic load torque, a cycle of which consists of one high load period with torque T_{lh} and duration t_h, and one light load period with torque T_{ll} and duration t_t (Fig. 2.11). For high load period $(0 \leq t \leq t_h)$ solution of Eq. (2.35) is

$$T = T_{lh}(1 - e^{-t/\tau_m}) + T_{min} e^{-t/\tau_m}$$
$$0 \le t \le t_h \tag{2.36}$$

where T_{min} is the motor torque at t= 0, which is also the instant when heavy load T_{lh} is applied. If motor torque at the end of heavy load period is T_{max}, then from Eq. (2.36)

$$T_{max} = T_{lh}(1 - e^{-t_h/\tau_m}) + T_{min} e^{-t_h/\tau_m} \tag{2.37}$$

Solution of Eq. (2.35) for the light load period ($t_h \le t \le t_h + t_l$) with the initial motor torque equal to T_{max} is

$$T = T_{ll}(1 - e^{-t'/\tau_m}) + T_{max} e^{-t'/\tau_m}$$
$$0 \le t' \le t_l \tag{2.38}$$

$$t' = t - t_h \tag{2.39}$$

When operating in steady-state, motor torque at the end of a cycle will be the same as at the beginning of cycle. Hence at $t' = t_l$, $T = T_{min}$. Substituting in Eq. (2.38) gives

$$T_{min} = T_{ll}(1 - e^{-t_l/\tau_m}) + T_{max} e^{-t_l/\tau_m} \tag{2.40}$$

From Eq. (2.37)

$$\tau_m = \frac{t_h}{\log_e\left(\dfrac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \tag{2.41}$$

From (2.34) and (2.41)

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})}\left[\frac{t_h}{\log_e\left(\dfrac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)}\right] \tag{2.42}$$

Also from Eq.(2.40)

$$\tau_m = \frac{t_l}{\log_e\left(\dfrac{T_{max} - T_{ll}}{T_{min} - T_{ll}}\right)} \tag{2.43}$$

From Eqs. (2.34) and (2.43)

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})} \left[\frac{t_l}{\log_e \left(\frac{T_{max} - T_{ll}}{T_{min} - T_{ll}} \right)} \right] \tag{2.44}$$

Moment of inertia of the flywheel required can be calculated either from Eq. (2.42) or (2.44). Further

$$J = WR^2, \text{ kg-m}^2 \tag{2.45}$$

where W is the weight of the flywheel (kg) and R is the radius (m)

UNIT I

PART A

1	Identify the advantages of adjustable speed drives?	CO1(L3)
2	List the merits of electrical drives	CO1(L1)
3	Enumerate the types of electrical drives	CO1(L2)
4	Differentiate between active and passive load torques	CO1(L4)
5	Draw the speed torque characteristics of mechanical loads	CO1(L3)
6	Identify why regenerative braking cannot be employed for dc series motors?	CO1(L3)
7	Show how the losses during staring can be minimized?	CO1(L2)
8	Enumerate the factors that can influence the choice of a motor to drive the load.	CO1(L2)
9	Explain the process of load equalization	CO1(L2)
10	List the drawbacks of dynamic braking?	CO1(L1)

PART-B

1	Explain four quadrant electrical drive system	CO1(L2)
2	Derive the expression for power rating of the motor used for intermittent loads.	CO1(L4)
3	A motor has a cyclic loading as given below: 250 N-m for 15 minutes 350 N-m for 20 minutes 100 N-m for 15 minutes No load for 10 minutes. The motor runs at a constant speed of 500 rpm. Determine the rating of a suitable motor.	CO1(L3)
4	Explain in details about Regenerative and dynamic braking methods.	CO1(L2)
5	Derive the expression for the power rating of the motor used for short time loads	CO1(L4)
6	The temperature rise of a motor after operating for 30 minutes on full load is $20^0{}_{C,}$ after another 30 minutes on the same load the temperature rise becomes $30^0{}_{C.}$ Assuming that the temperature increases according to an exponential law, determine the final temperature rise and the time constant.	CO1(L3)

UNIT-II

DRIVE MOTOR CHARACTERISTICS

- Starting and braking operation of dc motor drive
- Speed control of dc motors
- Ward Leonard scheme-drawbacks-leonard IIgener scheme
- Thyristor converter fed dc drives: Single,two and four quadrant operations.
- Chopper fed DC Drives: control strategies - single, two and four quadrant operation

STARTING METHODS OF D.C MOTOR

PRIME PURPOSE (or) NECESSITY OF A STARTER FOR MOTORS

The Current drawn by the armature of motor is given by,

$$I_a = (V- E_b) / R_a$$

Where,

V - Supply Voltage
Eb - Back EMF
Ra - Armature Resistance

- When the motor is at rest, there is no back emf developed in the armature. If now full supply voltage is applied across the stationary armature., it will draw a very large current.
- Because armature resistance is very small.
- This excessive current will blow out the fuse and damage the motor.
- To reduce high stating current, a resistance is connected in series with the armature circuit at the time of starting.
- When the motor speed is increased the back emf is also increased.
- Then Ia value is decrease.
- That time external resistance is cut out.

PROTECTIVE DEVICES IN A DC/AC MOTOR STARTER

- Over load Release (O.L.R) or No volt coil
- Hold on Coil
- Thermal Relays
- Fuses (Starting /Running)
- Over load relay

STARTERS FOR DC MOTOR

- Two point Starter
- Three point Starter
- Four point Starter

THREE POINT STARTER

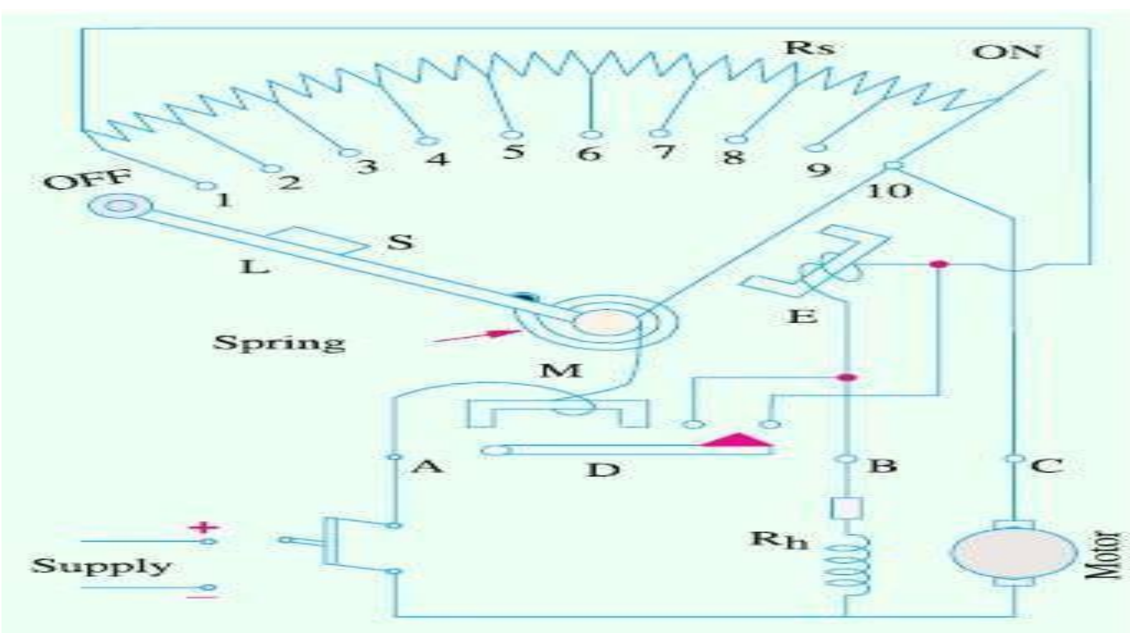
- The component used and the internal wiring for a three point starter are shown.
- Three terminals L, Z, and A are available in the starter circuit for connecting to the motor.
- The starting resistance R_s provided with tapping and each tapping is connected to a brass stud. The handle of the starter, H is fixed in such a way to move over the brass studs.
- Two protective devices namely over load release and no voltage coil provided to protect the motor during over and during failure of supply.
- To start the motor, the starter handle, full resistance is connected in series with the armature and the armature circuit of the motor is closed through the starting resistance and over load release coil.
- Field circuit of motor is also closed through the no voltage coil.
- Then the handle is moved over the studs against the spring force offered by a spring S_p

mounted on the handle.

- As handle movers, the staring resistance is gradually cut out from the motor circuit.
- A soft iron pieces is attached to the handle.
- The no voltage coil, NVC consists of an electro magnet energized by the field current.
- When the handle reaches the ON position, the NVC attracts the soft iron piece and holds the handle firmly.
- Whenever there is a failure of supply, the NVC de-energies and releases the handle.
- The handle position returns to off position due to the spring tension.
- If this arrangement is provided, then when the power supply is restored, the armature alone will be connected to the supply and the current through the armature will be high and it will damage the armature winding.
- Thus the armature is protected against failure of supply by NVC.
- The over load release also has an electromagnet and the line current energizes it.
- When the motor is overloaded, the iron strip P is attracted to the contacts (c and c") due to the electromagnetic force produced by the overload release coil and the contacts c and c" are bridged.
- Thus in this case NVC is de-energized and the handle comes to off position thus the motor is protected against overloading.
- We can see that under normal running of the motor the starting resistance when the handle touches the first stud it also touches the brass arc through which full voltage is supplied to the field coil.

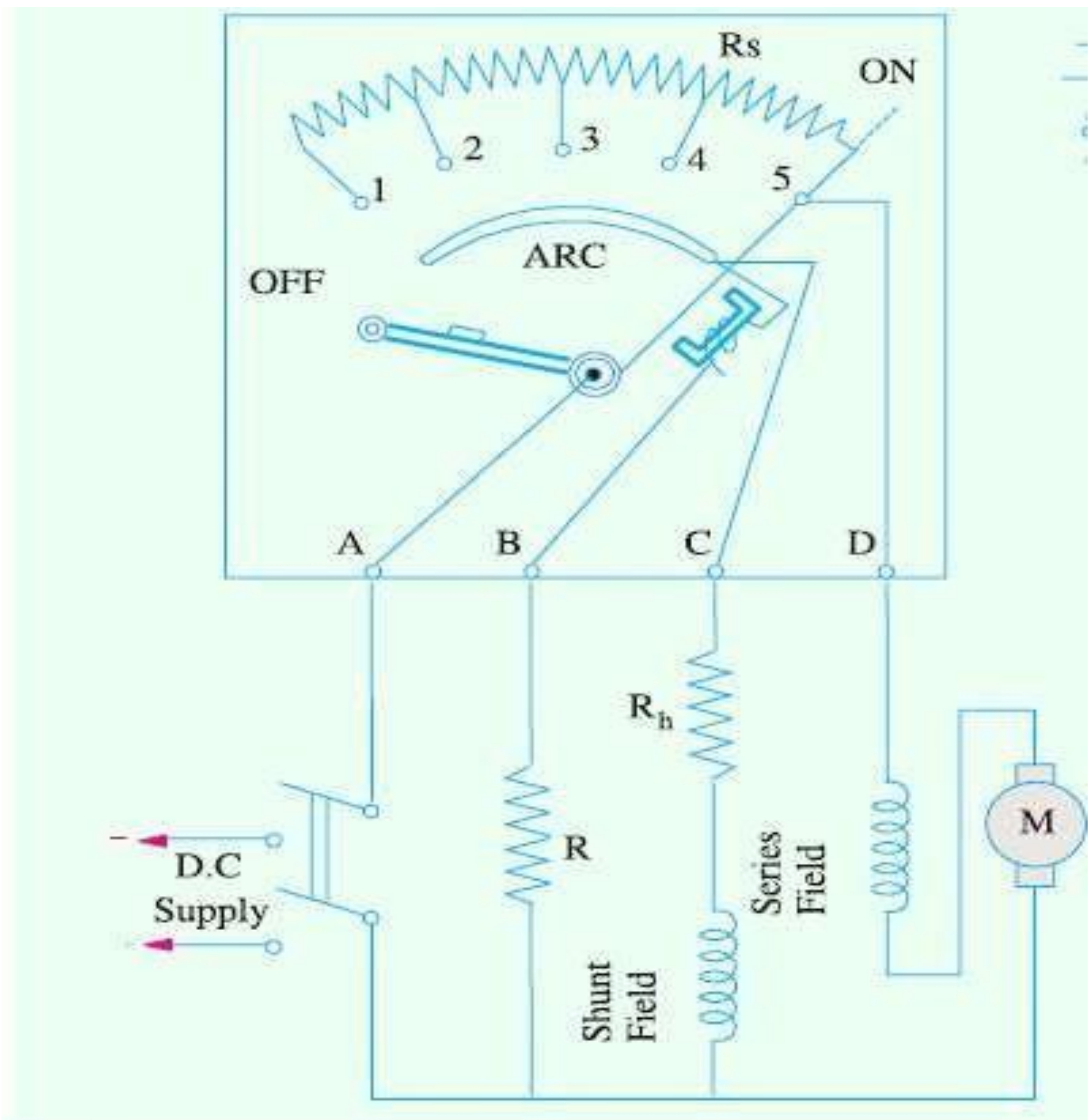
Disadvantage

- This three point starter is not suitable when we have to control the speed of the motor by connecting a variable resistance in series with the field winding.
- When the speed, the no voltage coil will be de-energized and handle will return the off position.
- Due to this disadvantage, four point starters is widely used for starting shunt and compound motors.



FOUR POINT STARTER

- The basic difference between three point and four starters is the connection of NVC.
- In three point, NVC is in series with the field winding while in four point starter NVC is connected independently across the supply through the fourth terminal called „N" in addition to the „L", „F" and „A".
- Hence any change in the field current does not affect the performance of the NVC.
- Thus it is ensured that NVC always produce a force which is enough to hold the handle in
- „Run"position, against forces of the spring, under all the operating conditions.
- Such a current is adjusted through NVC with the help of fixed resistance R connected in series with the NVc using fourth point „N" as shown

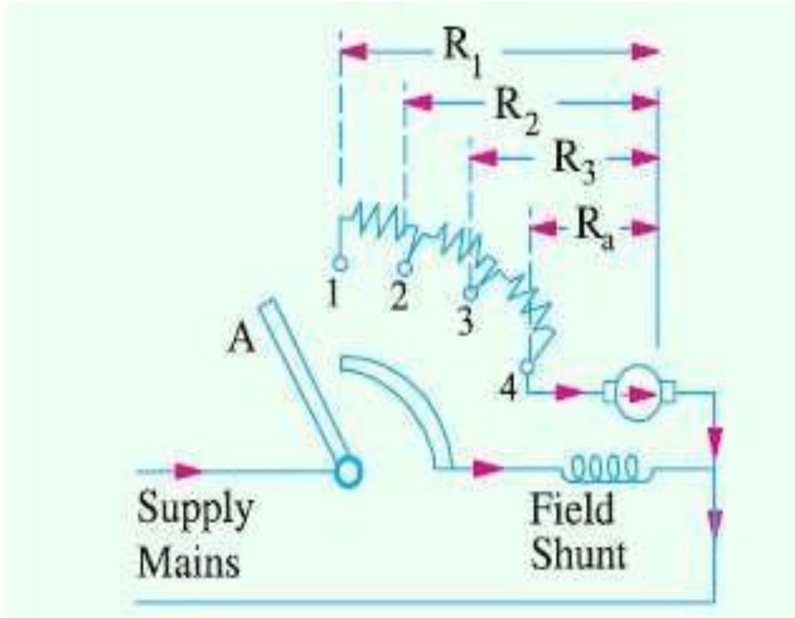


Disadvantages:

- The only limitation of the four point starter is , it does not provide high speed protection to the motor.
- If under running condition, field gets opened, the field current reduces to zero.
- But there is some residual flux present and $N \alpha \frac{1}{\phi}$ the motor tries to run with dangerously high speed.
- This is called high speeding action of the motion. in three point starter as NVC is in series with the field, under such field failure, NVC releases handle to the OFF position.
- But in four point starter NVC is connected directly across the supply and its current is maintained irrespective of the current through the field winding, hence it always maintains handle in the RUN position, as long as supply is there.
- And thus it does not protect the motor from field failure condition which result into the high speeding of the motor.

TWO POINT STARTER

- Three point and four point starters are used for d.c. shunt motors.
- In case of series motors, field and armature are inserted and hence starting resistance is inserted in series with the field and armature.
- Such a starter used to limit the star4ting current in case of dc series motor is called two point starters.
- The basic construction of two point starter is similar to that of three point starter the fact that is has only two terminal namely line (L) and field F.
- The terminal is one end of the series combination of field and the armature winding.
- The action of the starter is similar to that of three point starter.
- The handle of the starter is in OFF position.
- When it is moved to on, motor gets the supply and the entire starting resistance is in series with the armature and field. It limits the starting current.
- The current through no volt coil energizes it and when handle reaches to RUN position, the no volt coil holds the handle by attracting the soft iron piece on the handle.
- Hence the no volt coil is also called hold on coil.
- The main problem in case of dc series motor is it over speeding action when the load is less. This can be prevented using two point starters.
- The no volt coil is designed in such a way that it holds the handle in RUN positions only when it carries sufficient current, for which motor can run safely.
- If there is loss of load then current drawn by the motor decreases, due to which no volt coil losses its required magnetism and releases the handle.
- Under spring force, handle comes back to OFF position, protecting the motor from over speeding.
- Similarly if there is any supply problem such that voltage decreases suddenlyconditions.



- The overload condition can be prevented using overload magnet increases.
- This energizes the magnet up to such an extent that it attracts the lever below it.
- When lever is lifted upwards, the triangular piece attached to it touches the two pints, which are the two ends of no volt coil
- Thus no volt coil gets shorted, losing its magnetism and releasing the handle back to OFF position.
- This protects the motor from overloading conditions.

CHARACTERISTICS OF DC MOTORS

To select the electric motor for a particular purpose it is necessary to know the characteristics of electric motors. Hence the performance of DC motor can be judged from its characteristics curves.

1. Electrical characteristics

- Torque / Armature current characteristics
- Speed / Armature current characteristics

2. Mechanical characteristics

- Speed / Torque characteristics

TYPES OF ELECTRIC BRAKING

There are three types of electric braking namely,

- Rheostatic or Dynamic braking
- Plugging or counter current braking or reverse current braking
- Regenerative braking

REGENERATIVE BRAKING

- In the regenerative braking operation, the motor operates as a generator, while it is still connected to the supply here, the motor speed is grater that the synchronous speed.

- Mechanical energy is converter into electrical energy, part of which is returned to the supply and rest as heat in the winding and bearing.

DYNAMIC BRAKING

- In this method of breaking, the motor is disconnected from the supply, the field connections are reversed and motor is connected in series with a variable resistance **R.**

PLUGGING

- The plugging operation can be achieved by changing the polarity of the motor there by reversing the direction of rotation of the motor.
- This can be achieved in ac motors by changing the phase sequence and in dc motors by changing the polarity

DC SHUNT MOTORS

CHARACTERISTICS OF DC SHUNT MOTOR

1. Electrical characteristics

Torque / Armature current characteristics
Speed / Armature current characteristics

2. Mechanical characteristics

Speed / Torque characteristics

Characteristics of dc shunt motor

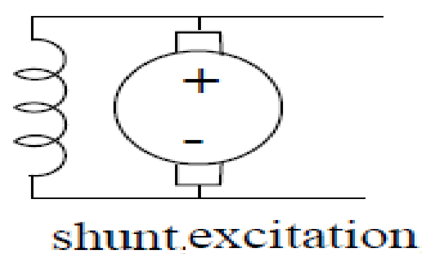


FIG- DC Shunt Motor

Torque vs Armature current characteristics.

The torque developed by the dc motor $\boxed{\mathbf{T \propto Ia}}$

In case of dc shunt motors the field excitation current is constant and supply voltage is kept constant. Therefore flux per pole will be constant.

$$T \propto Ia$$

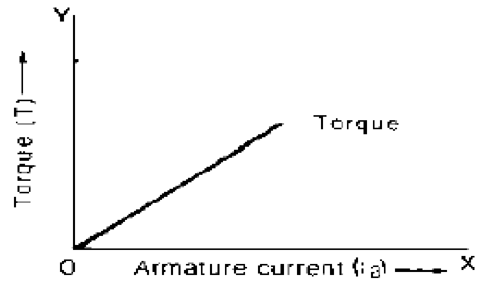


Fig T- I Characteristics

- ❖ Therefore torque developed in a dc shunt motor will be directly proportional to the armature current. The graph representing the variation of torque with armature current.
- ❖ Speed/Armature current characteristics

The back emf equation for dc motor is **Eb = PNZ /60A = V– Ia Ra**

Therefore

$$\boxed{\mathbf{N=}\ \frac{V - IaRa}{\phi PZ} 60A = \frac{K(V - IaRa)}{\phi}}$$

Where K = 60A/ ZP and it is constant.

- ❖ In dc shunt motor, when supply voltage V is kept constant the shunt field current and hence flux per pole will also be constant.

N α V– Ia Ra

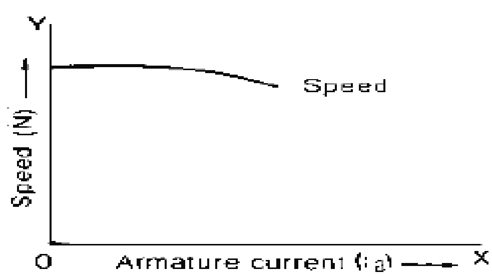


Fig N- I Characteristics

- ❖ The speeds of the dc shunt motor decreases with increase in armature current due to loading.
- ❖ The graph representing variation of speed with armature current is drooping slightly.
- ❖ The drop is speed from no load to full load will be about 3 to 6 percent.

- ❖ But the armature reaction effect weakens the field on load and tends to oppose drop in speed so
- ❖ so that the rarely drops by more than about 5 percent from no load to full load.
- ❖ Therefore shunt motor is considered as constant speed motor.

Speed vs Torque characteristics:

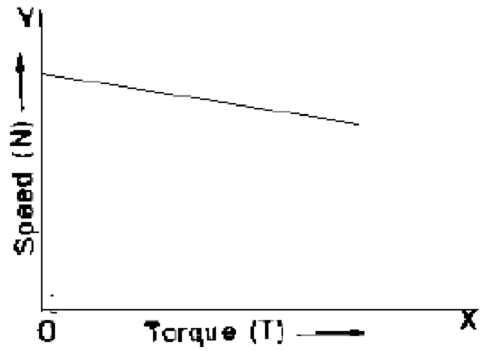


Fig N - T Characteristics

- ❖ From the above two characteristics of dc shunt motor, the torque developed and speed at various armature currents of dc shunt motor may be noted.
- ❖ If these values are plotted, the graph representing the variation of speed with torque developed is obtained.

This curve resembles the speed Vs current characteristics as the torque is directly proportional to the armature current.

ELECTRIC BRAKING IN DC SHUNT MOTOR

There are three types of electric braking namely,

- ❖ Rheostatic or Dynamic braking
- ❖ Plugging or counter current braking or reverse current braking
- ❖ Regenerative braking

3. Electric braking of DC shunt motors

A. Rheostatic braking

In this method of braking, the armature is disconnected from the supply and is connected across a variable resistance R.

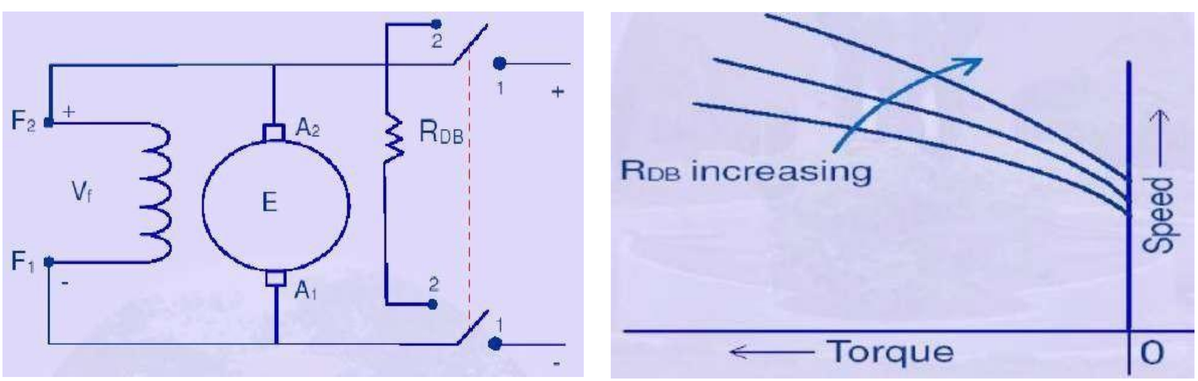


Fig Rheostatic braking

The field winding is left connected across the supply and it is undisturbed.
The braking effect is controlled by varying the series resistance R.

Speed-torque characteristics under dynamic braking

- It will be a straight line through the origin in the second quadrant .
- In the first quadrant ,the curve shows that the motor is operating steadily for a given load torque TL at the point A on its natural characteristics.
- The speed no represents ideal no load speed.
- Due to braking the operating point shifts to point B on the characteristics in the II quadrant from point A.
- The motor then decelerates along B O to stand still condition.
- The slope of the braking characteristics in II quadrant can be controlled by varying the braking resistor R.
- Hence, any braking time can be obtained by proper choice of the braking resistor R.

B. Plugging (or) Counter current braking

In this method of breaking, connections to the armature terminals are reversed so that motor tends to run in the opposite direction.

- Due to the reversal of armature connections, both V and E_b start acting in the same direction around the circuit.
- In order to limit the armature current to a safe value, it is essential to insert a resistor in the circuit while reversing the armature connections.
- When compared with rheostat braking, plugging gives better braking torque.
- This method is commonly used for Printing presses, elevators, rolling mills and machine tools.

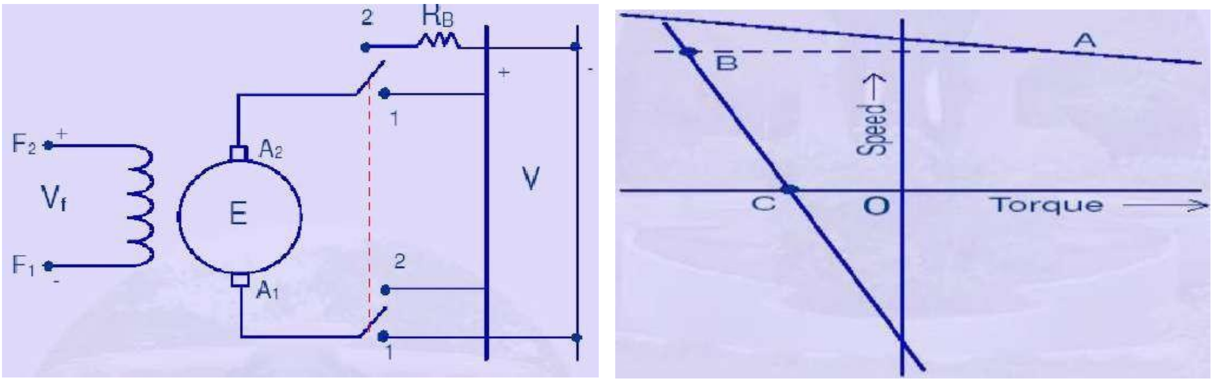


Fig Plugging condition and Speed torque characteristics

- Plugging is executed at a time when the motor is operating at the point E characteristics A for a load torque T_L.
- Due to plugging, the operating point shifts to point F on characteristics B as the speed of the motor cannot change instantaneously due to inertia.

- Due to braking torque developed ,the motor decelerates along the characteristics B until the motor stops when reversal of rotation is not required, the supply must be switched off when the motor speed becomes very near to zero.

- If the supply is not switched off,the motor will gain speed in the opposite direction along GH on characteristics B .as soon as the direction of the rotation is reversed ,the induced emf in the armature changes its polarity and again acts against the applied voltage so that the drive will rotate in the reverse direction under motoring condition.
- At point H,additional resistance are cut out from the armature circuit and hence the operating point shifts to point I on the natural characteristics C for a load torque,T_L
- If plugging is executed again at the point J,then braking and acceleration in the forward direction will corresponded to J –K-L-M-E.

C. Regenerative braking

This method is used when the load on the motor has overhauling characteristics as in the lowering of the case of a hoist or downgrade motion of electric train.

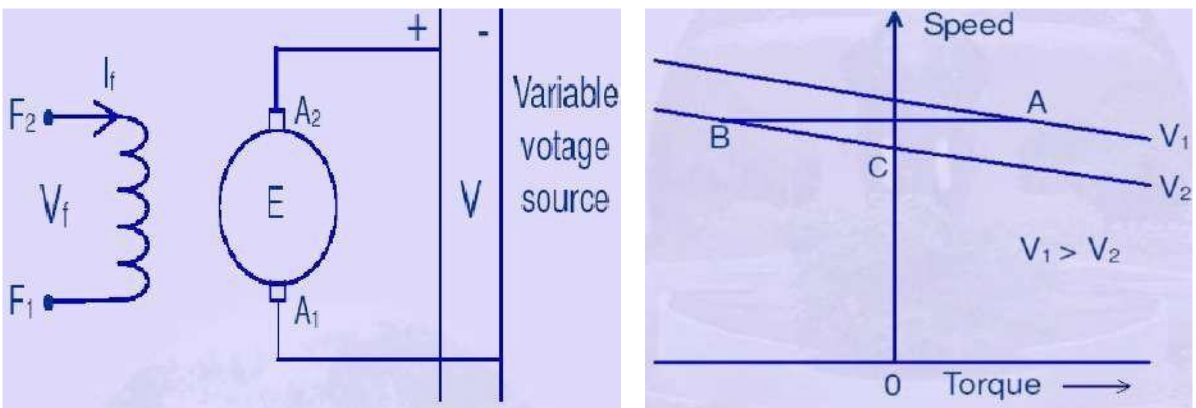


Fig Regenerative braking Characteristics and N-T Characteristics

- Regenerative takes place when Eb becomes greater than V.this happens when the overhauling load acts as a prime mover and so drives the machine asa generator.
- Hence ,the direction of Ia and armature torque is reversed and speed falls until eb becomes less than V.
- During slowing down of the motor ,power is returned to the line which may be used for supplying another train on an upgrade motion there by essential to have some type of mechanical braking also in order to hold the load in the event of power failure.

- At zero torque characteristics passes through the point corresponding to ideal no load speed, no as in the case of motoring.
- From the characteristics curves, it is clear that, higher the armature circuit resistance ,the higher is the speed at which the motor has to run for a given braking torque.

DC SERIES MOTOR

CHARACTERISTICS OF DC SERIES MOTORS

In dc series motors, the load current drawn from the supply passes through both armature and field windings as they are in series.

- Therefore when the load on the motor changes, field flux also changes.
- Hence the characteristics of D.C. series motors entirely differ from the characteristics of D.C. shunt motors.

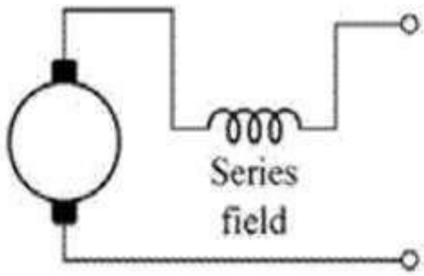


Fig DC Series motor

Torque Vs Armature current characteristics

- Torque developed in any dc motor **T α Ia.**

In series motors since field current is equal to armature current.

Therefore,

- When Ia is small, it is proportional to Ia.

Then torque developed in dc series motor **T α Ia^2.**

Therefore

- The torque is proportional to square of the armature current at low values of armature current.

When Ia is large remains constant due to saturation.

Then **T** α **Ia**.

- Therefore torque is proportional to armature current at large values of armature current.

Thus, the torque Vs armature current characteristics begins to rise parabolic ally at low values of armature current and when saturation is reached it becomes a straight line as shown in the following figure.

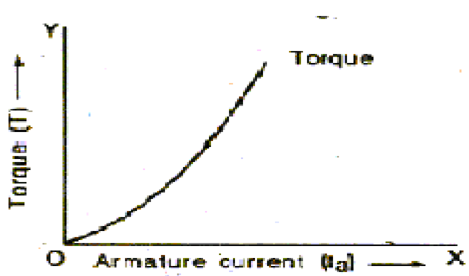


Fig T-I characteristics

Speed Vs Armature current characteristics

Consider the speed equation

$$\boxed{N = \frac{K(V - IaRa)}{\phi}}$$

- When supply voltage V is kept constant, speed of the motor will be inversely proportional to flux.
- In dc series motors field exciting current is equal to armature current which happened to load current.
- Therefore at light loads, when saturation is not attained, flux will be proportional to armature current and hence **speed will be inversely proportional to the armature current**.
- Hence **speed Vs armature current** characteristics of dc series motor will be rectangular hyperbola as shown in the following figure.

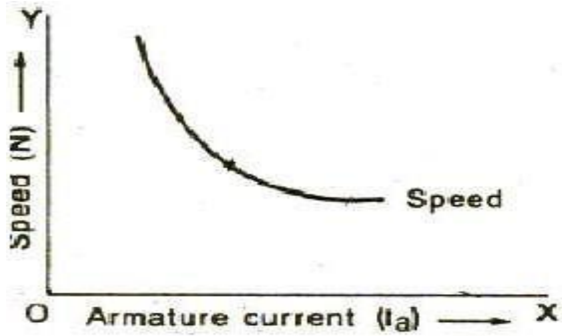


Fig N-I characteristics

- As the load on the motor is increased armature current increases and field gets saturated.
- Once field is saturated flux will be constant irrespective of increase in armature current.
- Therefore at heavy loads, speed will be constant.
- This type dc series motor has high starting torque.

Speed Vs Torque characteristics

The speed Vs Torque characteristics of series motor will be similar to the speed Vs armature current characteristics. It will be a rectangular hyperbola as shown in the following figure.

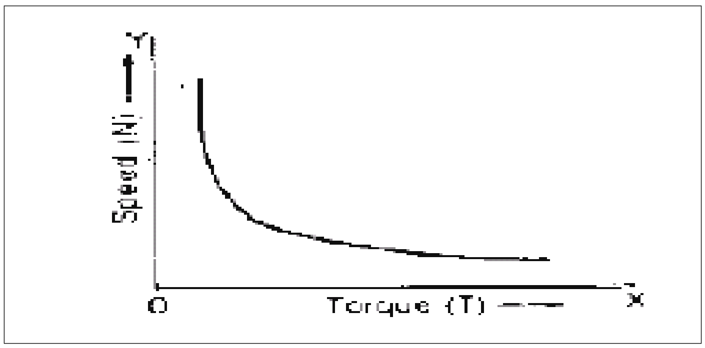


Fig N-T characteristics

In dc series motors, torque increases with decrease of speed and they are most suitable for operating cranes, lifts, trains, etc.

4. **Electric braking of DC series motor**

D. Rheostatic braking

In this method of breaking, the motor is disconnected from the supply, the field connections are reversed and motor is connected in series with a variable resistance R as shown in

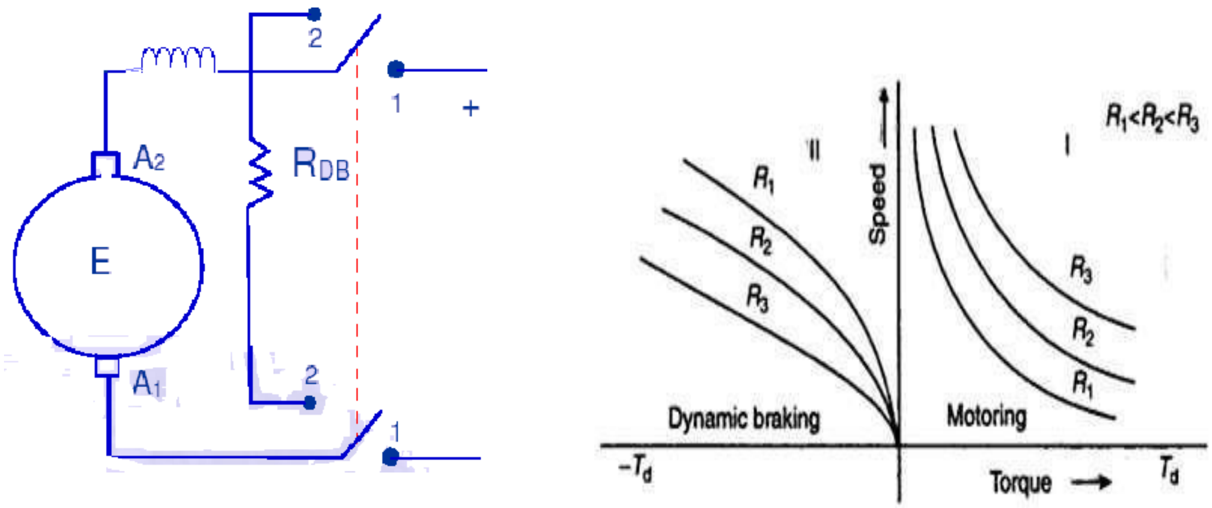


Fig Rheostatic braking

- The field connections are reversed to make sure that,the current through the field winding flows in the same direction as before (i.e., from A to B)in order to assist for residual magnetism.
- In practice, the variable resistance used for starting purpose is itself used for braking purposes.
- The speed-torque characteristics of DC series motor during rheostatic braking is shown in the following figure. explanations are similar to rheostatic braking method applied to DC shunt motor.

E. Plugging

In this method of braking, the connections of the armature are reversed and a variable resistance R is put in series with the armature .

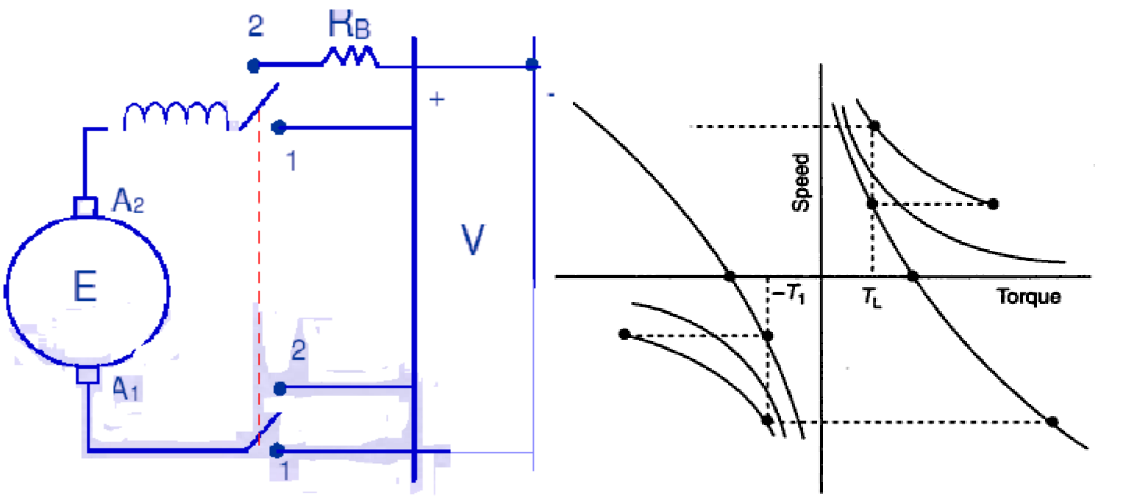


Fig Plugging

The above characteristics have been constructed in the same manner as that of plugging conditions applied to DC shunt motor.

F. Regenerative braking

- In DC series motor, regenerative braking is not possible without necessary modifications, because reversal of Ia would result in reversal of field and hence of E_b.
- This method is however used in traction motors with special arrangements.

COMPOUND DC MOTOR

CHARACTERISTICS OF DC COMPOUND MOTOR

Characteristics of D.C. compound motors:

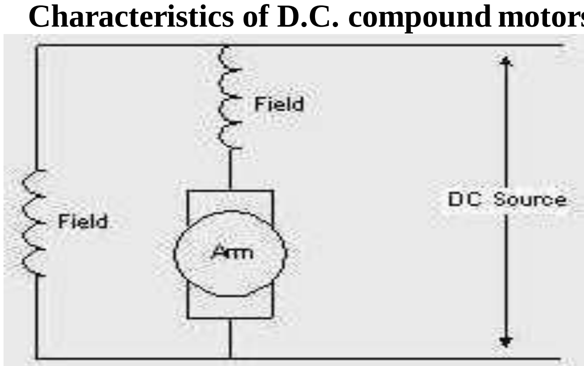


Fig Compound DC Motor

- In dc compound motors both shunt field and series field will be acting simultaneously.
- In cumulative compound motors the series field assists the shunt field.
- In such motors when armature current increases the field flux increases.
- So for given armature current the torque developed will be greater and speed lower when

compared to a shunt motor.

- In differentially compounded motors the series field opposes the shunt field.
- Therefore when armature current increases the field flux decreases.

- So for given armature current, the torque developed will be lower and the speed greater when compared to shunt motor.

Torque Vs armature current and speed Vs armature current characteristics of dc compound motors are shown in the following figure.

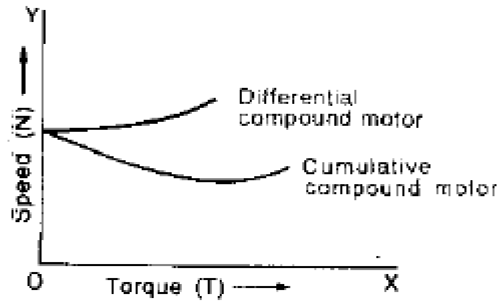


Fig speed Vs torque characteristics

The speed Vs torque characteristics are compared with that of shunt motor as shown in the following figure.

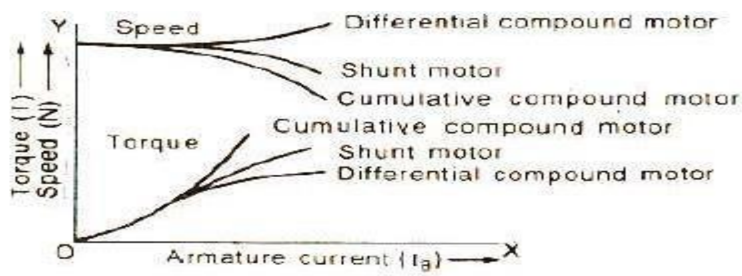


Fig speed Vs Current and torque Vs Current characteristics

ELECTRIC BRAKING IN DC COMPOUND

The Dc compound motor has the series as well as the shunt field.

- Regenerative braking
- Dynamic braking
- Counter braking

- In the regenerative braking operation of the compound motor, the direction of the armature and the series field are reversed.
- This may be demagnetized the motor to avoid the demagnetization, the series field winding of the motor is shunt as soon as the speed raises to Wo .

- Therefore the speed torque characteristics of regenerative braking is the straight line.
- The dynamic braking of the compound motor is similar to the dynamic braking of the shunt motor.

- During dynamic braking the armature of the motor is disconnected from the supply and is connected across the braking resister and only the shunt field winding is excited.
- Therefore the field flux is constant.

Counter current braking of the compound motor is similar to the series motor .This is because of the influence of series field winding.

APPLICATIONS OF DC MOTORS

Type of motor	Characteristics	Applications
shunt	Approximately constant speed. Speed can be controlled. Medium starting torque (Upto 1.5 Full load torque)	For driving constant speed line shafting lathes, centrifugal pumps, machine tools, blowers and fans, reciprocating pumps.
Series	Variable speed. Speed can be controlled. High starting torque.	For traction work i.e. electric locomotives rapid transit systems trolley cars etc. cranes and hoists, conveyors
Cumulative compound	Variable speed Speed can be controlled. High starting torque.	For intermittent high torque loads, for shears and punches, elevators, conveyors, heavy planers, rolling mills, ice machines, printing presses, air compressors

SPEED CONTROL OF D.C DRIVES

INTRODUCTION

- ✓ The speed of a given machine (DC) has to be controlled for the required speed variations of an operation.
- ✓ Either armature voltage or field current can be varied or controlled. A separately excited motor is a versatile variable speed motor. The speed control using the variation of the armature voltage can be used for constant torque application in the speed range from zero to base or rated speed.
- ✓ The speed control using the field weakening can be used for constant power application in the speed range from zero to above base or rated speed.

EXPRESSION FOR SPEED FOR A DC MOTOR

Speed $N = \underline{k\,(V - I_a R_a)}$

Where V = Terminal Voltage in volts Ia =
Armature current in Amps
Ra = Armature resistance in ohms
φ= flux per pole.

Applications of DC Drives:

- ✓ Electric Traction
- ✓ Steel mills
- ✓ Printing mills
- ✓ Textile mills
- ✓ Paper mills
- ✓ Machine tools
- ✓ Cranes
- ✓ Hoists

Advantages of DC Drives:

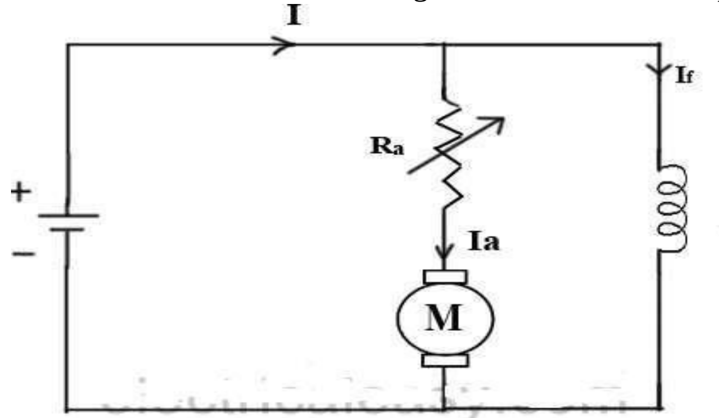
- ✓ Lower cost
- ✓ Reliability
- ✓ Simple control

Conventional Methods of Speed Control
Speed control of DC Shunt Motors:

- ✓ By varying the resistance in the armature circuit
- ✓ By varying the flux (field)
- ✓ By varying the applied Voltage

Armature Resistance Control

- ✓ Speed of the motor is directly proportional to the back emf E_b $E_b = V - I_aR_a$.
- ✓ That is when supply voltage V and armature resistance R_a are kept constant, speed is directly proportional to armature current I_a. Thus if we add resistance in series with armature, I_a decreases and hence speed decreases.
- ✓ Greater the resistance in series with armature, greater the decrease in speed.



Advantages:

- ✓ Simple method of speed control

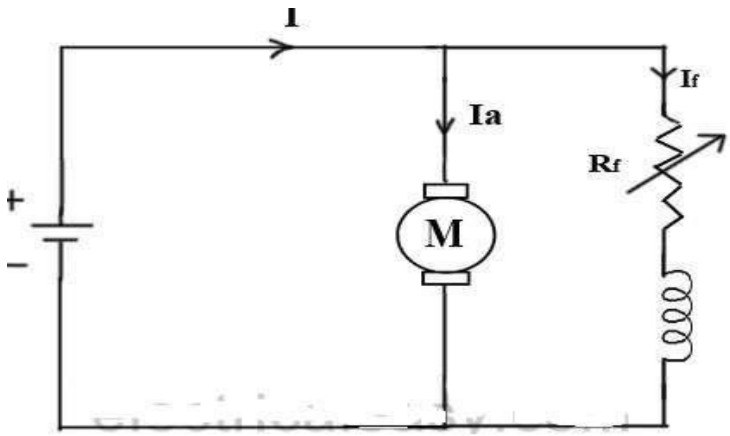
Disadvantages:

- ✓ The change in speed with the change in load becomes large.
- ✓ More power is wasted in this controller resistance.

Field flux control:

- ✓ Speed of the motor is inversely proportional to flux. Thus by decreasing flux speed can be increased and vice versa.
- ✓ To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram.
- ✓ Adding more resistance in series with field winding will increase the speed, as it will decrease the flux.
- ✓ Field current is relatively small and hence I^2R loss is small, hence this method is quiet efficient.

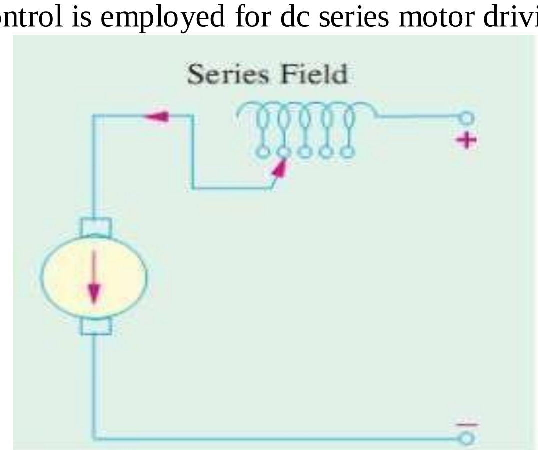
Though speed can be increased by reducing flux with this method, it puts a limit to maximum speed as weakening of flux beyond the limit will adversely affect the commutation



Speed control of DC Series Motors:

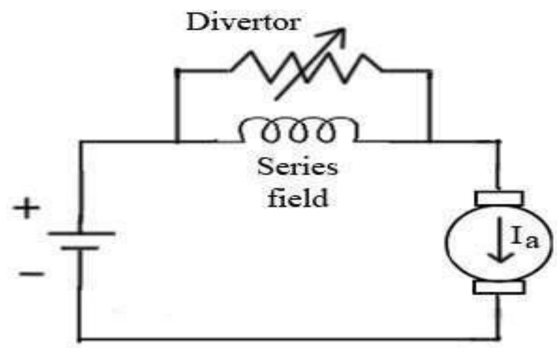
Armature Resistance Control

- ✓ The controlling resistance is connected directly in series with the supply to the motor
- ✓ The power loss in the control resistance of dc series motor can be neglected because this control method is utilized for a large portion of time for reducing the speed under light load condition.
- ✓ This method of speed control is most economical for constant torque.
- ✓ This method of speed control is employed for dc series motor driving cranes, hoists, trains etc



Field Control Method:

a) Field Divertor Method:

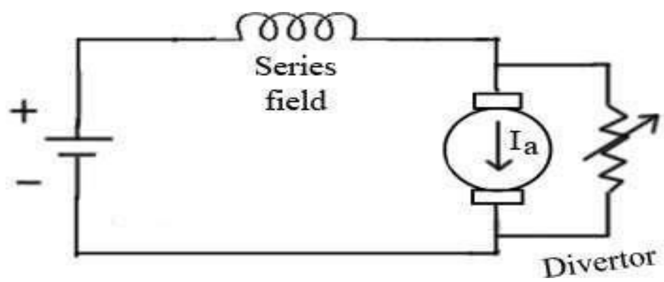


- ✓ A veritable resistance is connected parallel to the series field as shown in fig.

This variable resistor is called as divertor, as desired amount of current can be diverted through this resistor and hence current through field coil can be decreased

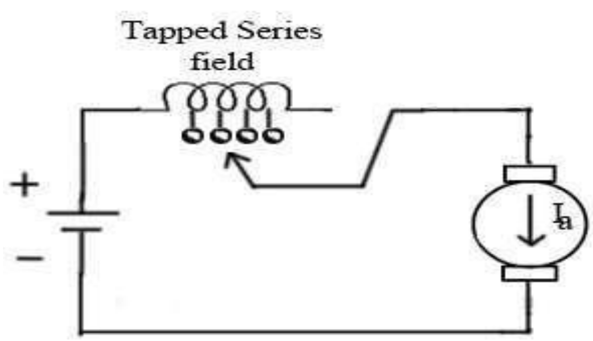
- ✓ Hence flux can be decreased to desired amount and speed can be increased.

b) Armature Divertor Method:

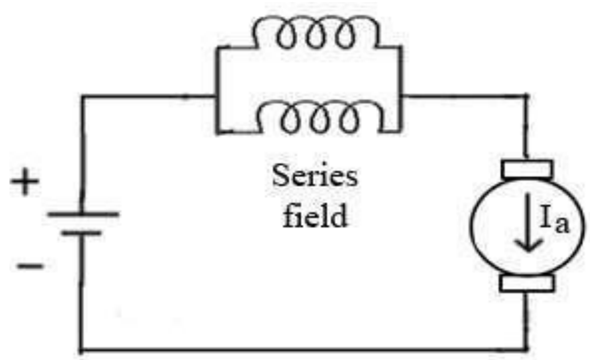


- ✓ Divertor is connected across the armature as in fig.
- ✓ For a given constant load torque, if armature current is reduced then flux must increase. Ta α ØIa
- ✓ This will result in increase in current taken from the supply and hence flux Ø will increase and subsequently speed of the motor will decrease.

C) Tapped field Control:



D) Paralleling field Control:



Ward Leonard Method of Speed Control

Advantages:

- ✓ Full forward and reverse speed can be achieved.
- ✓ A wide range of speed control is possible
- ✓ Short time overload capacity is large
- ✓ The armature current of the motor is smooth.

Disadvantages:

- ✓ High initial cost
- ✓ The overall efficiency is low, less than 80%
- ✓ Costly foundation and a large amount of space is required
- ✓ The drive produces noise
- ✓ It requires frequent maintenance.

Known after the name of its inventor Ward Leonard Method of Speed Control (1891), it consists of a separately excited generator feeding the dc motor to be controlled. The generator is driven at a constant speed by an ac motor connected to 50 Hz ac mains. The driving motor may be an induction or a synchronous. When the source of power is not electrical, generator is driven by a non-electrical prime mover such as diesel engine or gas turbine. While the dc motor may be driven at low speeds, resulting in high torque and relatively large frame size, generator being of the same voltage, current and power ratings as the motor can run at a higher speed with a view to reduce its cost and size.

Motor terminal voltage is controlled by adjusting the field current of the generator. When field winding voltage is smoothly varied in either direction, the motor terminal voltage and therefore, speed can be steplessly varied from full positive to full negative.

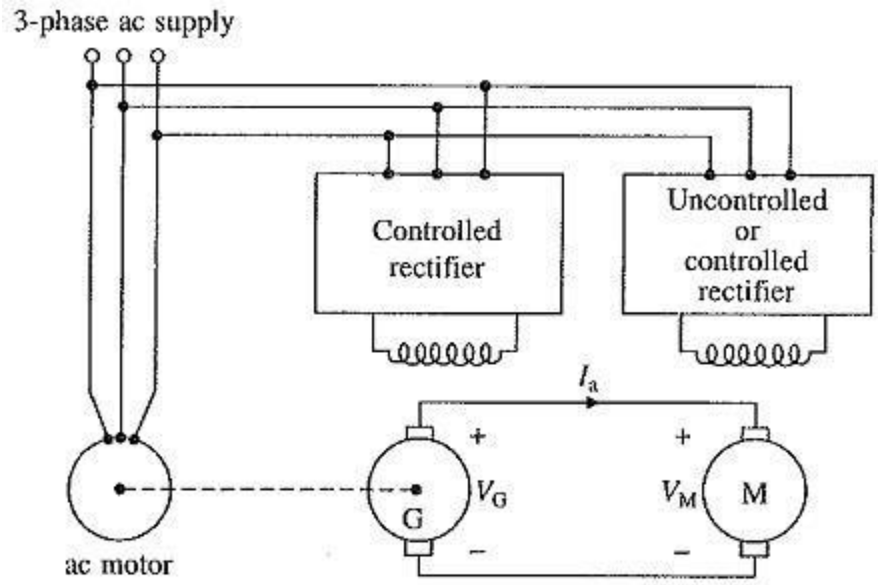


Fig. 5.20 Ward-Leonard drive

Block diagram of a Ward-Leonard scheme employing an ac motor for driving dc generator is shown in Fig. 5.20. One of the important features of this drive is the inherent ability for regenerative braking down to very low motor speeds. This combined with the variation of armature voltage in either direction allows efficient operation of drive in all the four quadrants of speed-torque plane. For regenerative braking, the output voltage of generator G is reduced below the induced voltage of motor M by decreasing the generator field current. This reverses the current flowing through the armatures of machines G and M. Now machine M works as a generator and G as a motor. Mechanical energy provided to machine M, either from the kinetic energy of rotating parts or due to an active load acting on its shaft, is converted into electrical energy. Electrical energy supplied by Machine M is converted into mechanical energy by machine G. The ac motor, which now works as a generator, converts the mechanical energy to electrical energy and feeds it to the ac source.

Control of generator field is obtained by rheostats when low ratings are involved and closed-loop control is not desired. Power requirement of the rheostats is of the order 1 to 2% of the total input to the motor. For higher power applications or for closed-loop control, the field is supplied by a power amplifier which may consists of a controlled rectifier, chopper or transistor amplifier. Old installations may use a magnetic amplifier or amplidyne. For reversible drives, a power amplifier capable of supplying controlled field current in either direction is required. It may, therefore, consists of a single-phase or three-phase dual converter, four quadrant chopper or four quadrant transistor amplifier. When the drive operates only in one direction, a power amplifier capable of supplying controlled field current only in one direction is used in order to reduce cost. The power amplifier may then consists of a half-controlled rectifier, step-down chopper or one quadrant transistor amplifier. In this case the field current can only be reduced, to zero, but cannot be reversed.

When the field is controlled by a power amplifier capable of supplying current only in one direction, the minimum speed obtainable is of the order 0.1 of base speed. This limit on the minimum value of speed is imposed because of the residual magnetism of generator field. Due to residual magnetism, even when field current is zero, enough voltage is generated to make the motor crawl particularly when the load is light.

To prevent crawling and to reduce the motor speed to zero, following three methods are employed:

(a) Armature circuit is opened.

(b) A differential field winding on the generator is connected across the armature terminals. Such a field will oppose the residual flux, and although it will not reduce the residual voltage to zero, it will prevent build-up of a large circulating current.

(c) The field winding of generator is connected across armature terminals such that the current through it produces mmf which opposes the residual mmf. This type of connection is commonly known as **suicide connection**.

The nature of speed-torque curves is similar to that shows earlier. Drop in motor speed due to change in load torque is caused by the drop of voltage across the armature resistances of the two machines. When motor speed, and therefore, generator output voltage is high, armature circuit resistance drop is only a small percentage of generator output voltage and, therefore, percentage speed regulation of the motor is good. At low speed, the armature resistance drop forms a large percentage of generator output voltage. This makes the percentage speed regulation not only large, the motor may stall with even slight increase in load torque.

When Ward Leonard Method of Speed Control in wide range is required, control of generator output voltage is combined with motor field control. Speeds below and above base speed are obtained by armature voltage control and motor field control, respectively. The maximum speed obtainable by motor field control is limited to twice base speed for normally designed and six times for specially designed motors. Combination of field control with armature voltage control permits the ratio of maximum to minimum available speeds to be 20 to 40. With closed loop control, the range can be extended further and can be realized up to 200. When field control is required, the motor field is fed from a half controlled rectifier, step down chopper or a single quadrant transistor amplifier. When not required motor field is fed from an uncontrolled rectifier. For low power application a resistance may be connected in series with the field.

As mentioned earlier, ac motor can be an induction or a synchronous motor. Though cheaper than synchronous, induction motor always operates at a lagging power factor. The synchronous motor can be operated at a leading power factor by overexciting its field. Leading reactive power produced by the motor compensates for the lagging reactive power taken by other loads in the plant, thus improving power factor of the plant. Over excitation of the field also enhances maximum torque capability of the motor. By employing closed-loop control of its reactive power, synchronous motor can be made to generate leading reactive power equal to lagging reactive power of the plant caused by other loads, making the plant power factor unity.

The Ward-Leonard drive is used in rolling mills, mine winders, paper mills, elevators, machine tools etc.

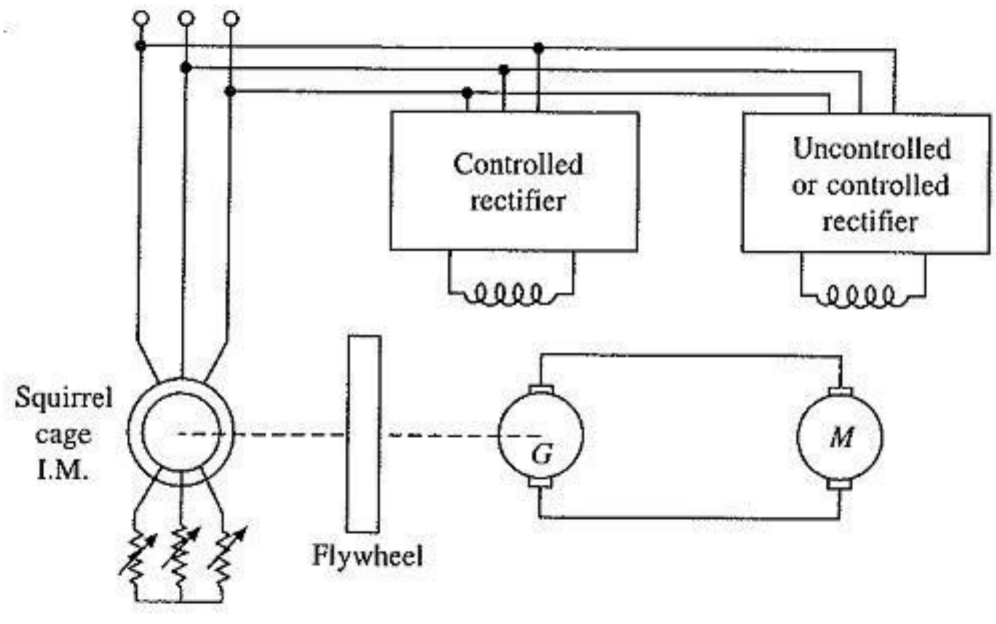


Fig. 5.21 Ward Leonard-Ilgener drive for intermittent loads

When the load is heavy and intermittent, a slip-ring induction motor is employed and a flywheel is mounted on its shaft. This is called the **Ward-Leonard-Ilgener scheme** (Fig. 5.21).

Rotor resistance control is used to restrict the motor current within permissible limits and to give it a drooping speed-torque characteristic. When heavy load demand comes, the flywheel decelerates and gives up some of its stored energy, thus reducing load demand from the supply. During light load periods, power is taken from supply to accelerate the flywheel, which replenishes the energy lost. This scheme provides two beneficial effects. First, it prevents heavy fluctuations in the supply current and secondly it permits the use of a relatively smaller size induction motor. This scheme finds application in the control of blooming mill drives and colliery winder in steel and mining industries, respectively. Because of large capacity of these drives (few megawatts), the fluctuations in supply current can lead to severe fluctuations of the supply voltage, which adversely affect other loads on the supply. Fluctuations can also have adverse effect on stability of the source.

It should be noted that when the ac motor is synchronous, supply current fluctuations cannot be reduced by mounting a flywheel on its shaft, because it operates only at a fixed speed. Therefore, a slip-ring induction motor is preferred over the synchronous when the load is intermittent and particularly when the drive capacity is large.

As explained above, the Ward Leonard Method of Speed Control has a number of advantages. It has inherent regenerative braking capability which allows efficient four quadrant operation. It can be employed for power factor improvement by using a synchronous motor. Because of the inertia of rotating machines, ac supply is dynamically decoupled from the load. For example, in paper mill drives, a short duration fluctuation of the supply voltage will not have any affect. Further, when it is used to supply important loads such as operation theatres, computers etc., where the continuity of supply is maintained at all costs, the inertia makes enough time available for uninterruptible power supply to take over in the event of failure of the mains supply. In intermittent load applications the Ward-Leonard-Ilgner driver prevents load torque fluctuations to cause source current and voltage fluctuations.

Main drawbacks of the Ward Leonard Method of Speed Control are its high initial cost and low efficiency because of the use of two additional machines of same ratings as that of the main motor, requires more frequent maintenance and produces more noise. Furthermore, it has large weight and size, and needs large floor area and foundation. Because of these drawbacks, the new installations mainly employ static Ward-Leonard drive, explained in Sec. 5.9.

Exception is made in the case of high power intermittent load applications, such as blooming mill drives and mine winders, particularly when the supply system is weak. It can also be made for important loads where continuity of supply must be maintained at all costs.

Another form of Ward Leonard Method of Speed Control employs a non-electrical prime mover to drive dc generator, e.g. diesel electric locomotive and ship-propulsion, where the generator is driven by a diesel engine or a gas turbine. The generator-motor combination works as a torque converter, like a step less gear, to impart to the motor speed-torque curves required by the load. While the motor runs at variable speed, the prime mover, and therefore, the generator runs at a fixed higher speed which may reduce their cost and size and optimize efficiency. Regenerative braking is not possible because the prime mover cannot allow the flow of energy in the reverse direction. However, dynamic braking can be used. The block diagram of such a drive for diesel electric locomotive is shown in Fig. 5.22. Here dc series motor is employed.

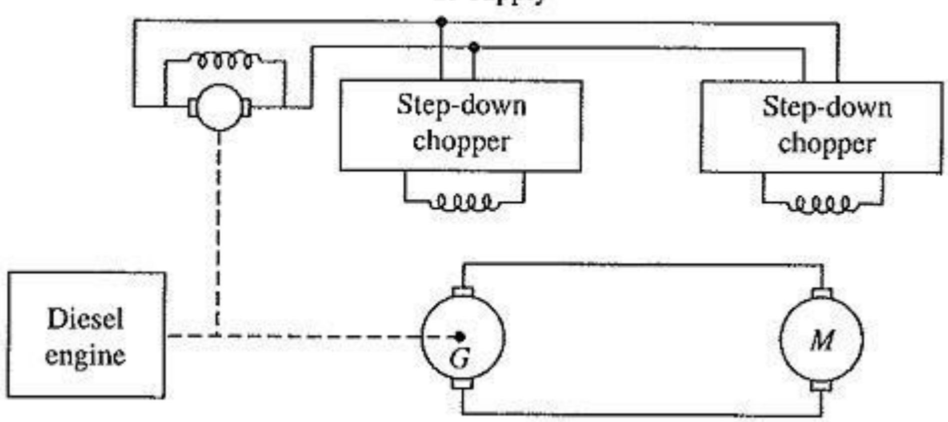


Fig. 5.22 Diesel engine driven Ward Leonard drive

Commutator imposes a restriction on the maximum speed of a dc generator. This may not allow the prime mover to be driven at an optimum speed. Further, commutator also imposes restriction on the maximum power rating of a dc generator. In some large power applications, a number of motors are fed from a common generator. The generator should have a size larger than what can be accomplished by a dc generator. Furthermore, a dc generator also requires frequent maintenance because of commutator. In view of these limitations, a synchronous generator and an uncontrolled rectifier bridge are employed instead of a dc generator. Motor voltage is controlled by varying the field of the synchronous generator.

Conventional methods of speed control

$$N = Eb / \varphi$$

1. By varying the resistance in the armature circuit (Rheostatic control)
2. By varying the flux (flux control)
3. By varying the applied voltage (voltage control)

Solid state speed control of DC motor

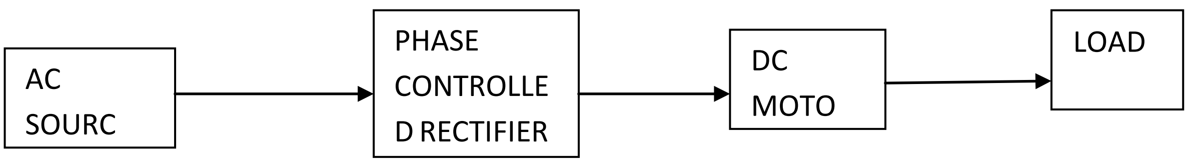
The DC motor speed can be controlled through power semiconductor switches.

Here,the power semiconductor switches are SCR (thyristor),MOSFET, IGBT,This type of speed control is called ward-Leonard drive.

Types of DC drives

1. Phase controlled rectifier fed DC drives
    a. According to the input supply
        i. Single phase rectifier fed DC drives
        ii. Three phase rectifier fed DC drives

    b. According to the quadrant operation
        i. One quadrant operation
        ii. Two quadrant operation
        iii. Four quadrant operation
2. Chopper fed DC drives
    i. One quadrant chopper drives
    ii. Two quadrant chopper drives
    iii. Four quadrant chopper drives



Single phase controlled rectifier fed DC Drives

Fig 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 controlled rectifier fed separately excited DC motor Drives

Figure shows block diagram of single phase controlled rectifier fed separately excited DC motor. The armature voltage is controlled by means of a half wave controlled or half controlled or full convener. l¢ AC supply is fed to the single phase controlled rectifier. This controlled rectifier converts fixed AC voltage into variable DC voltage. By varying the firing angle of this converter, we can get variable DC voltage. The field winding is fed from the AC supply through a diode bridge rectifier.

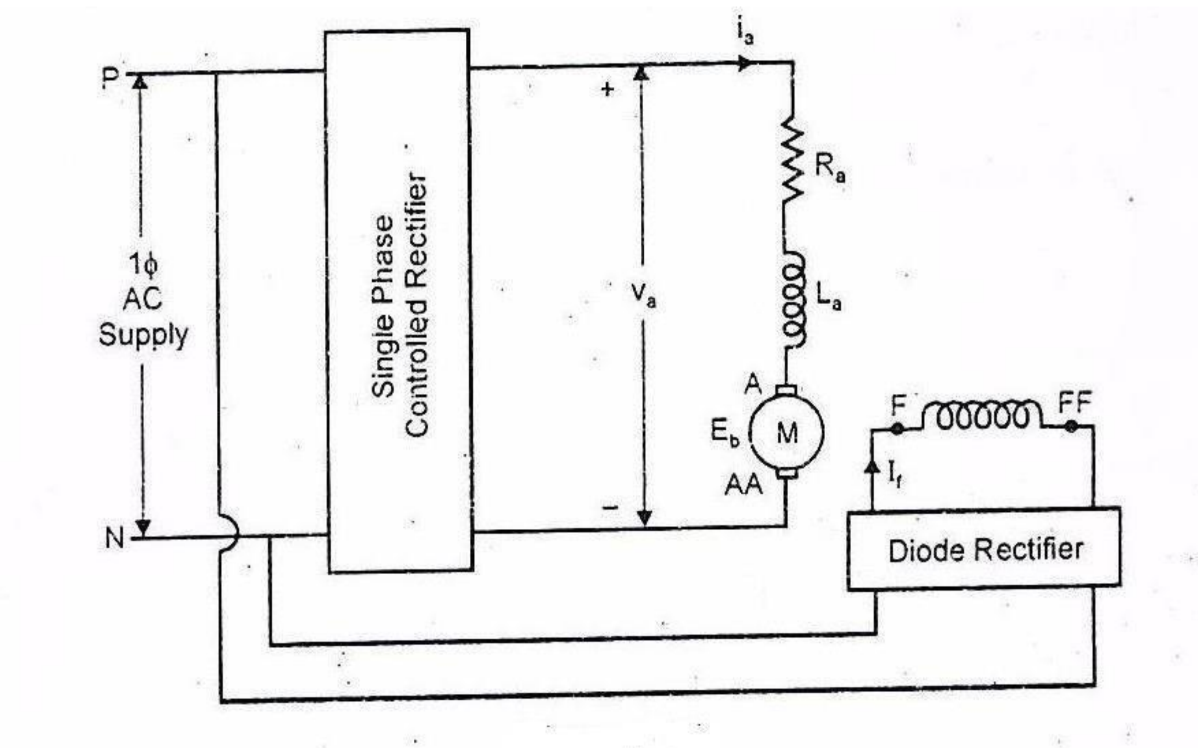


Fig Single phase controlled rectifier fed separately excited DC motor Drives The armature circuit of the DC motor is represented by its back emf Eb, amature resistance Ra and armature inductance La as shown in figure .

The back emf of the motor is given by

$$\boxed{E_b = K_m \omega_m} \qquad \text{[Here flux is constant)}$$

where E_b = Back emf of the motor

K_m = Motor constant

ω_m = Motor speed in rad/sec

ϕ = Flux in the machine

The torque developed in the motor is given by,

$$T = K_m I_a$$

The armature voltage is given by

$$V_a = E_b + I_a R_a$$

$$V_a = K_m \omega_m + I_a R_a$$

Motor speed $\omega_m = \dfrac{V_a - I_a R_a}{K_m}$

Suppose field current is given in the problem, the back emf equation is given by

$$E_b = K_m \phi \omega_m$$

$$\phi \propto I_f$$

$$\therefore E_b = K_m I_f \omega_m$$

Suppose field constant (K_f) is given in problem, the equation becomes

$$E_b = K_m K_f I_f \omega_m$$

Similarly torque equation is also given by

$$T = K_m \phi I_a$$

$$= K_m I_f I_a$$

$$= K_m K_f I_f I_a$$

<u>Single Phase Half wave controlled Rectifier fed DC Drives (one quadrant converter)</u>

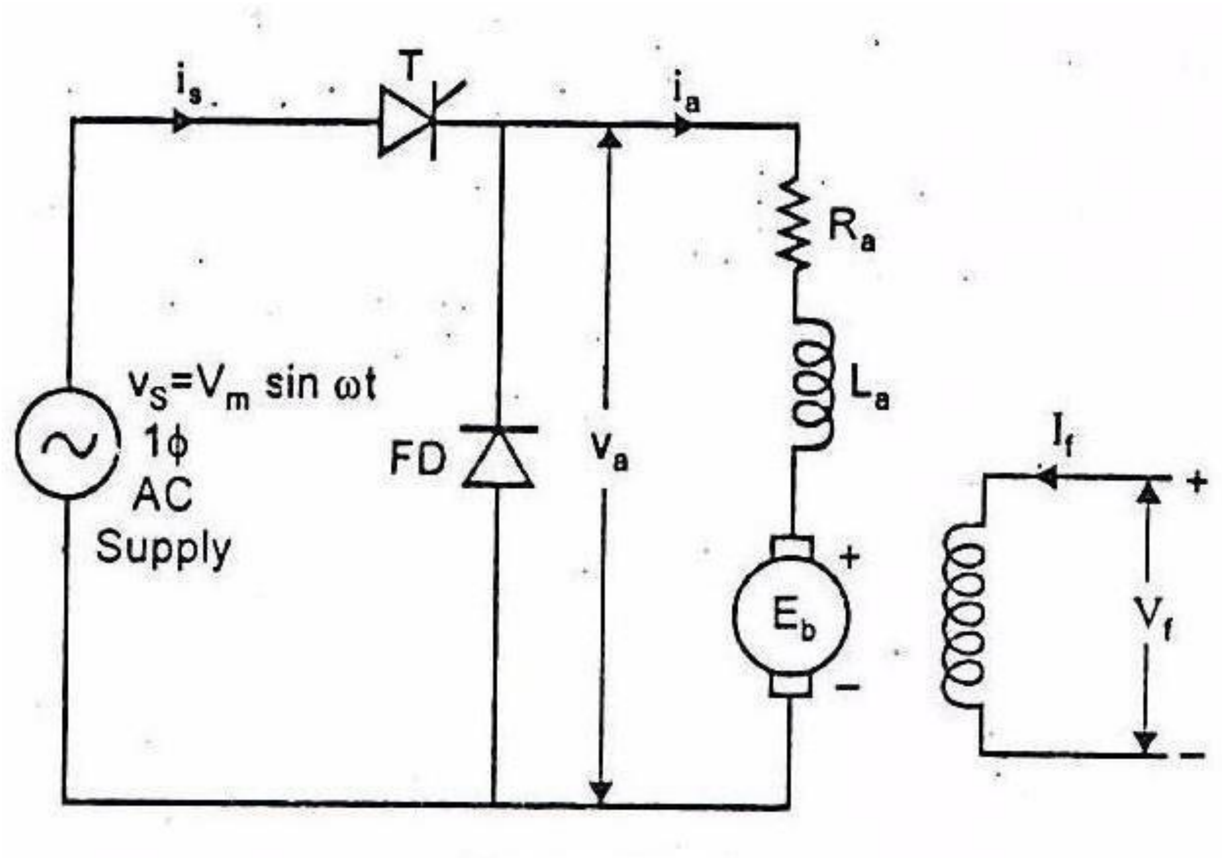


Fig Single Phase Half wave controlled Rectifier fed DC Drives (one quadrant Converter)

Figure shows single phase half wave controlled rectifier drive. Assume armature current Ia is constant. Here, the motor is separately excited DC motor. Motor is operated from single phase half wave controlled rectifier. Motor field winding is fed through separate DC source. During the positive half cycle SCR T is forward biased. At ωt = A, SCR T is triggered and comes to the on state, Then the positive voltage is fed to the motor.

At ωt = Π, freewheellng diode comes to the forward biased state and SCR comes to the off state, because of reverse voltage. Dur.ing the negative half cycle, SCR T is in off state, and freewheeling diode conducts upto 2Π+A

ATOΠ-T on

Π to 2Π +A – FD on

During the period, Π to 2Π+A Current is positive but output voltage is zero because of closed

path (FD - motor -FD).

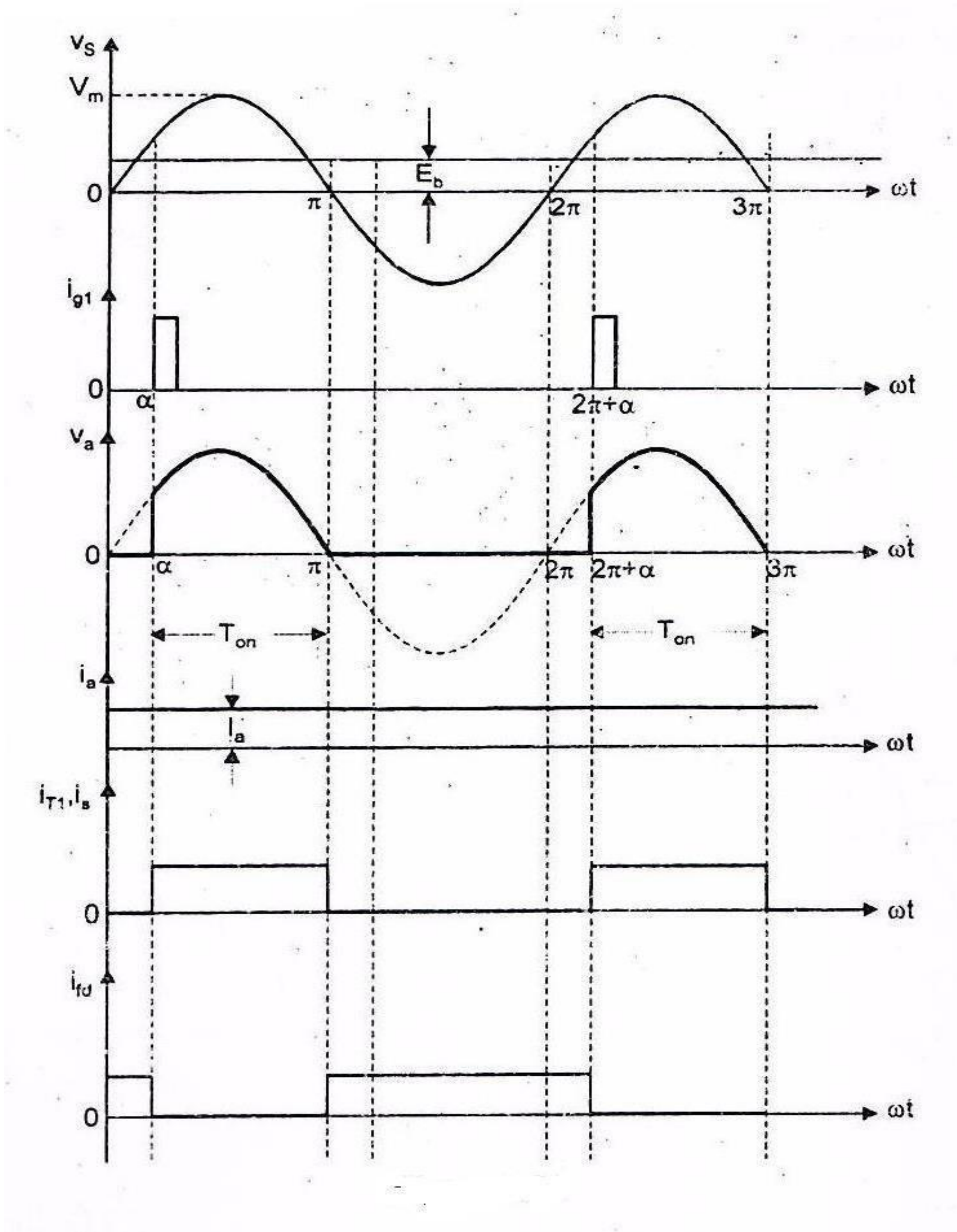

vS
Vm
Eb
0
π
2π
3π
ωt
ig1
α
2π+α
va
Ton
ia
Ia
iT1,is
ifd

Fig Single Phase Half wave controlled Rectifier fed DC Drives, Wave form

$$V_0 = V_a = \frac{1}{2\pi}\int_{\alpha}^{\pi} v_s \, d(\omega t) = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t)$$

$$\boxed{V_0 = \frac{V_m}{2\pi}(1+\cos\alpha)} \qquad \text{for } 0<\alpha<\pi$$

where $V_m =$ maximum value of input voltage $= \sqrt{2}\, V_s$

= delay angle

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

$$E_b = K_m \omega_m$$

$$V_a = K_m \omega_m + I_a R_a$$

$$\boxed{\omega_m = \frac{V_a - I_a R_a}{K_m}}$$

K_m = motor constant

Torque of the separately excited motor is given by

T A φIa

Φ - constant

T A Ia

T = KmIa

RMS value of armature current

$$I_{arms} = I_a$$

RMS value of source or thyristor current

$$I_s = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi} I_a^2\, d(\omega t)\right]^{\frac{1}{2}} = \left[\frac{I_a^2}{2\pi}\left[\pi - \alpha\right]\right]^{\frac{1}{2}}$$

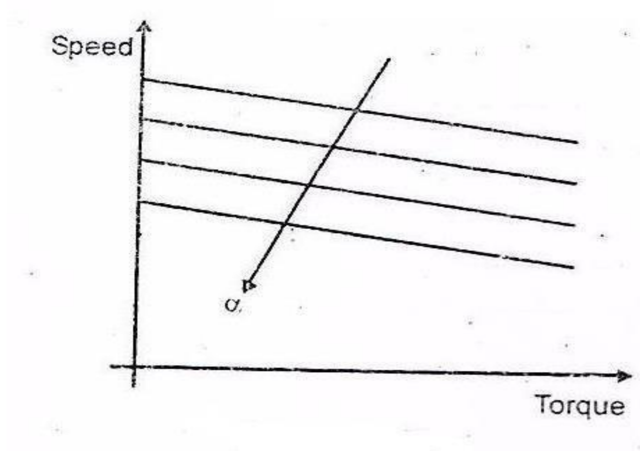
$$I_s = I_a\left(\frac{\pi - \alpha}{2\pi}\right)^{1/2}$$

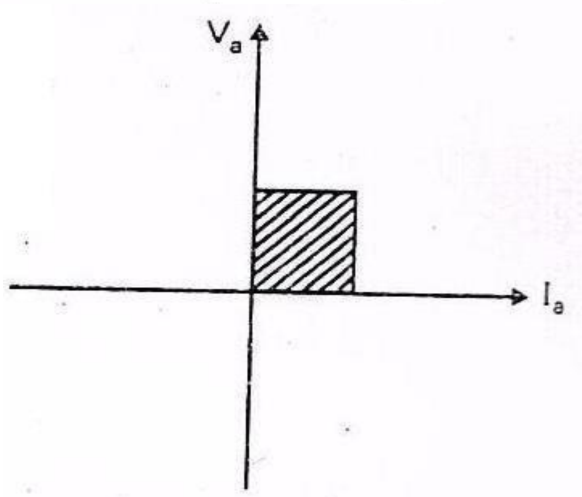
RMS value of freewheeling diode current

$$I_{fdrms} = \left[\frac{1}{2\pi}\int_{\pi}^{2\pi+\alpha} I_a^2\, d(\omega t)\right]^{\frac{1}{2}} = \left[\frac{I_a^2}{2\pi}\left[2\pi + \alpha - \pi\right]\right]^{\frac{1}{2}}$$

$$= I_a\left(\frac{\pi + \alpha}{2\pi}\right)^{1/2}$$

Input supply power factor $= \dfrac{V_a\ I_a}{V_s\ I_s}$





Single phase fully controlled rectifier fed DC drives

The drive circuit is shown in the fig .motor is shown by its equivalent circuit.Filed supply is not shown.The ac input voltage is defined by

$V_s = V_m \sin \omega t$

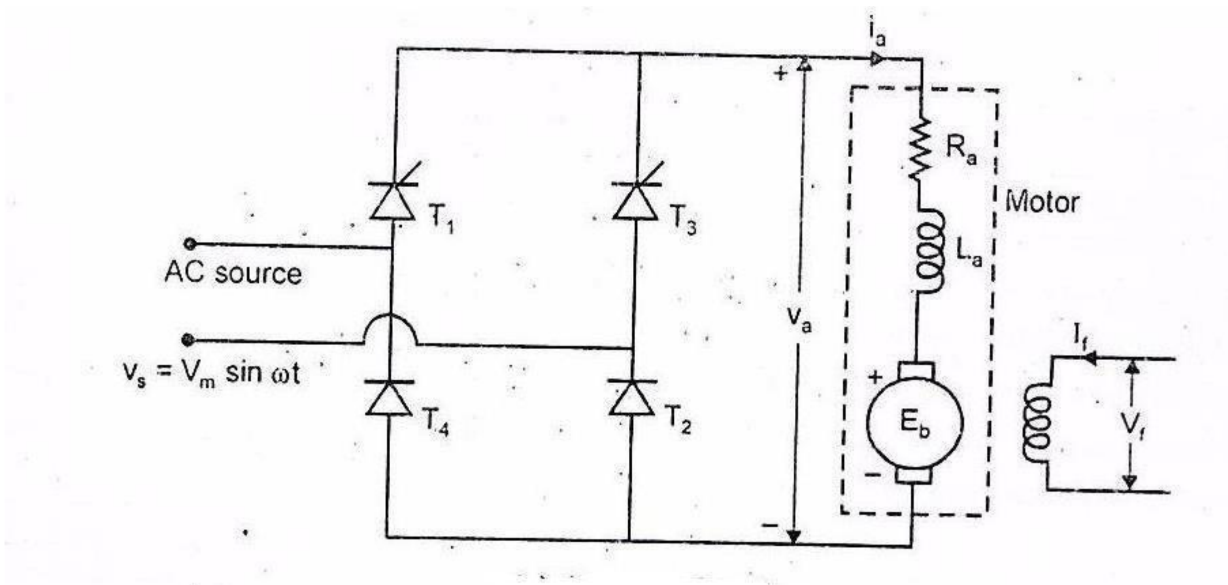


Fig Single phase fully controlled rectifier fed DC drives

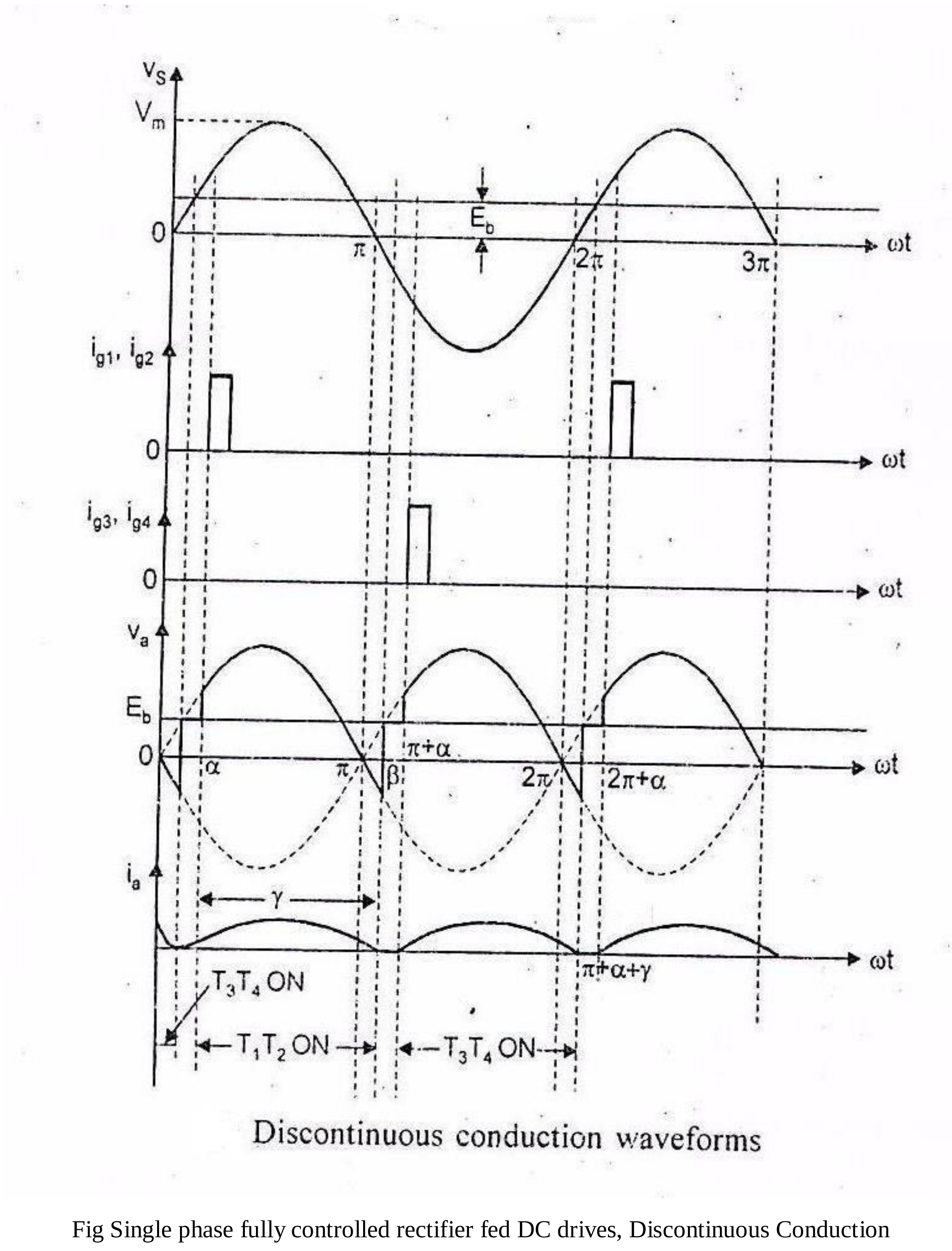
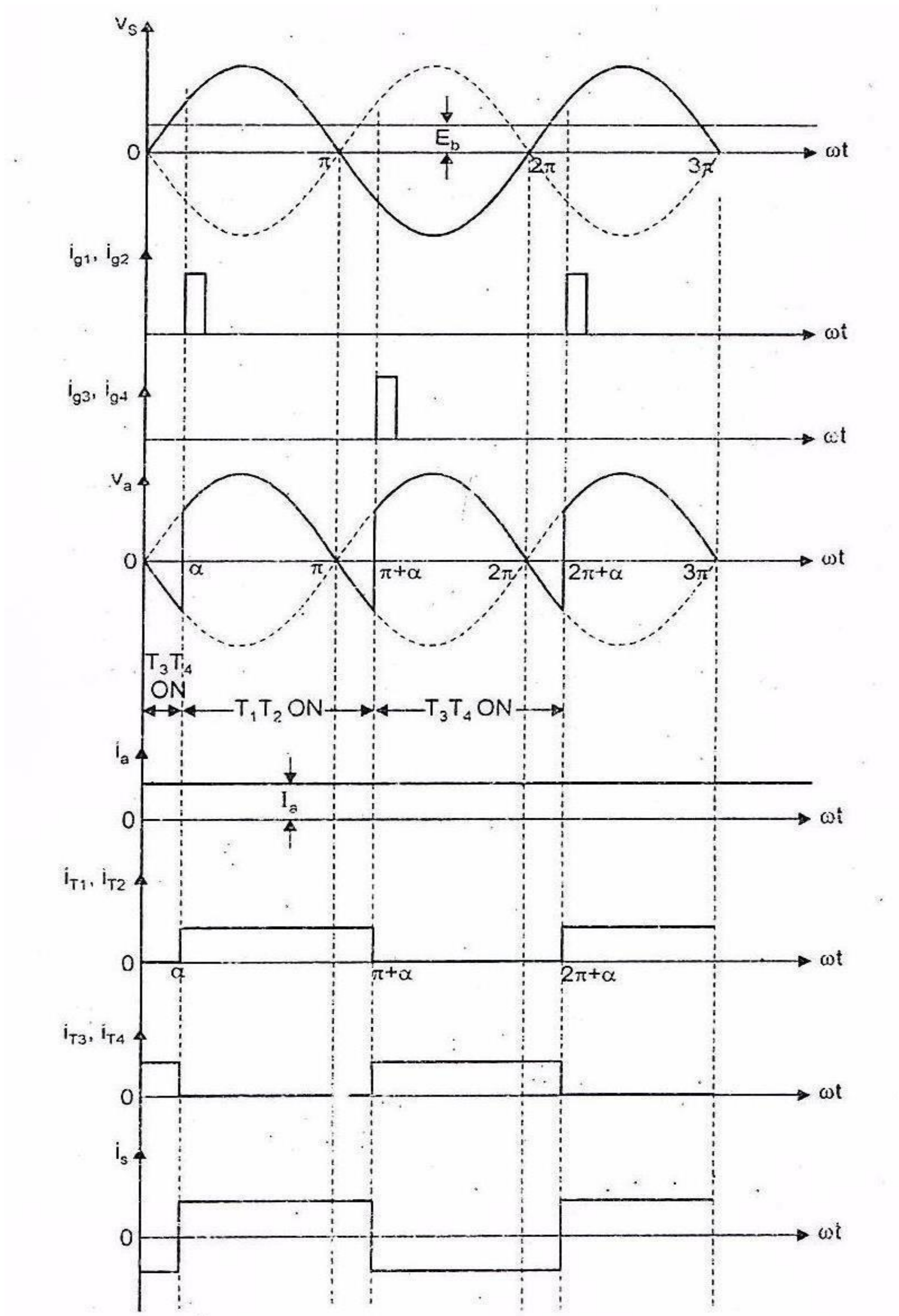
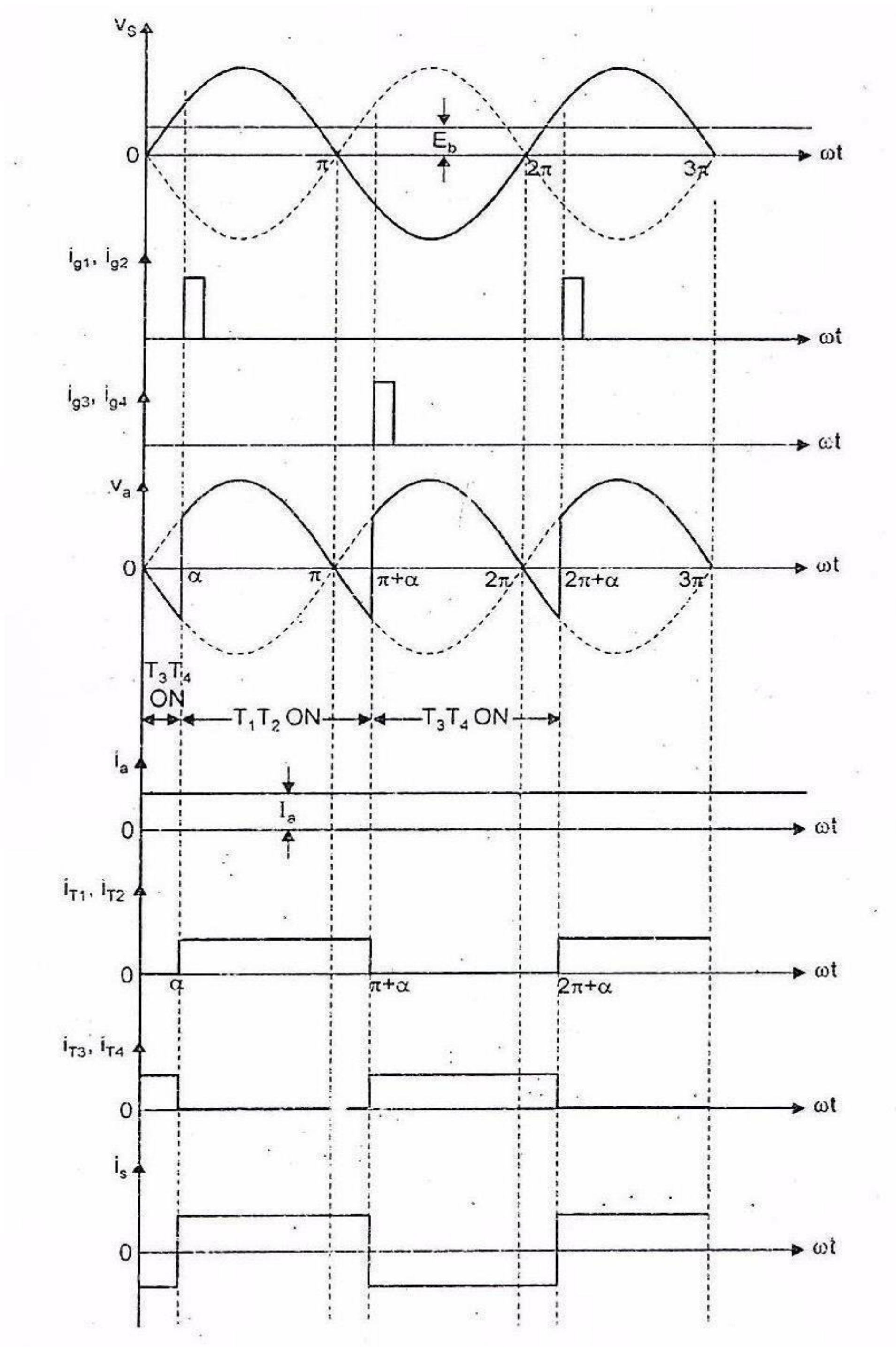


Fig Single phase fully controlled rectifier fed DC drives, Discontinuous Conduction waveforms.



Continuous conduction (Rectification mode) (α < 90°)

Fig Single phase fully controlled rectifier fed DC drives, Continuous Conduction waveforms.



Continuous conduction (Rectification mode) (α < 90°)

Fig Single phase fully controlled rectifier fed DC drives, continuous Conduction waveforms.(Rectification Mode)

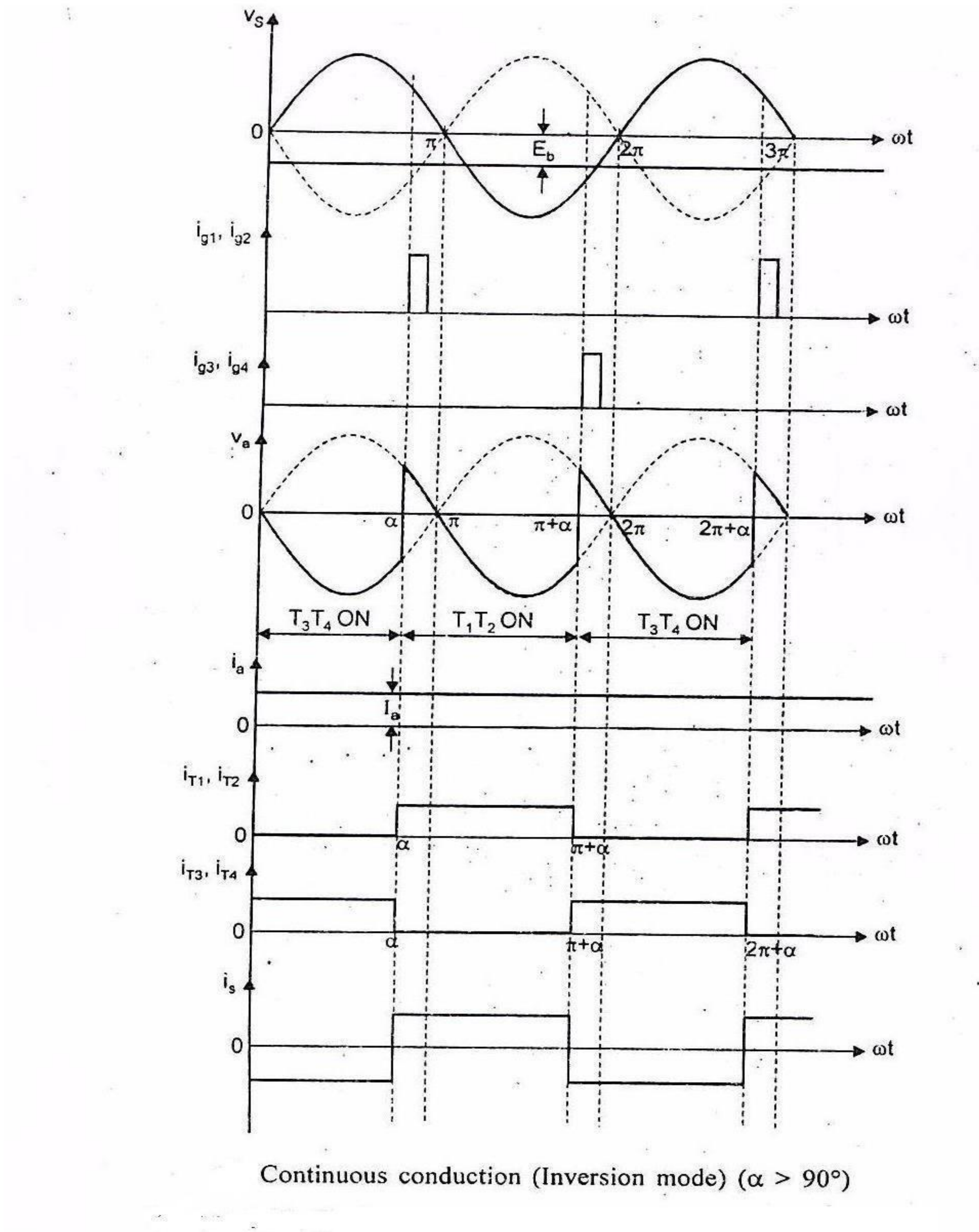


Fig Single phase fully controlled rectifier fed DC drives, Continuous Conduction waveforms.(Inversion Mode)

The motor terminal voltage and current waveforms for the dominant discontinuous and continuous conduction modes are shown in figure .T1, T2 are gated at ωt = A, these SCRS will get turned on only if Vm sin A > E. Thyristors T1 and T2 are given gate signals from A to Π and thyristors T3 and T4 are given gate signals from (Π+ A) to 2Π.

When armature current does not flow continuously the motor is said to operate in discontinuous conduction When current flows continuously the conduction is said to be continuous.

ln discontinuous conduction modes, the current starts flowing with the turn-on thyristors T1 and T2 at ωt = A. Motor gets connected to the source and its terminal voltage equals Vs, At some angle þ, known as extinction angle load current decays to zero Here þ > Π.As T1 T2 are reverse biased after ωt= Π , this pair commutated at ωt= þ,

when ia= 0 From þ to Π + A , no SCR- conducts ,the motor terminal voltage jumps from Vm sinþ to E as shown in figure.

At ωt=Π+A, as pair T3 T4 is triggered, load current starts to build up again as before and load voltage Va follows Vs, waveform as shown. At Π+þ, ia falls zero, Va, changes from Vm sin(Π+þ) to E as no SCR conducts.

In continuous conduction mode during the positive half cycle thyristors T1, T2 are forward biased At ωt = A ,T1,T2 are turned on.As a result ,supply voltage Vm sin A immediately appears across thynstors T3 T4 as a reverse bias, these are turned off by natural commutation At ωt= Π+A forward biased SCRs T3, T4 are triggered causing turn off of T1 and T2 Figure and figure shows rectification and inversion mode voltage and current waveforms.

Steady state Analysis of Discontinuous Conduction.

The drive operates in two intervals.

i) Conduction period ($\alpha \le \omega t \le \beta$), T_1 and T_2 conduct and $V_a = V_s$. Also $(\pi + \alpha) < \omega t < \pi + \alpha + \gamma$, T_3 and T_4 conduct and $V_a = V_s$ and so on.

ii) Idle period ($\beta \le \omega t \le \pi + \alpha$), no devices conducting. Here $i_a = 0$ and $V_a = E_b$.

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E_b = V_m \sin \omega t \quad \text{for } \alpha \le \omega t \le \beta \qquad \text{....(1)}$$

$$V_a = E_b \text{ and } i_a = 0 \quad \text{for } \beta \le \omega t \le \pi + \alpha \qquad \text{....(2)}$$

Average output voltage

$$V_a = \frac{1}{\pi}\left[\int_{\alpha}^{\beta} V_m \sin\omega t.\, d(\omega t) + \int_{\beta}^{\pi+\alpha} E_b\, d(\omega t)\right]$$

$$\boxed{= \left[\frac{V_m}{\pi}(\cos\alpha - \cos\beta) + \frac{E_b}{\pi}(\pi + \alpha - \beta)\right]} \quad \text{....(11)}$$

Average output Current

$$\boxed{I_a = \frac{V_a - E_b}{R_a}}$$

Speed Equation (ωm)

$$\boxed{\omega_m = \frac{V_m}{K_m}\frac{(\cos\alpha - \cos\beta)}{(\beta - \alpha)} - \frac{T}{K_m^2} R_a \left[\frac{\pi}{\beta - \alpha}\right]} \quad \text{....(13)}$$

Steady State Analysis of continuous conduction

Average output voltage

$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t)$$

$$= \frac{V_m}{\pi}\int_{\alpha}^{\pi} \sin\omega t. \, d(\omega t)$$

$$\boxed{V_a = \frac{2V_m}{\pi}\cos\alpha}$$

Average output voltage $V_a = \frac{2V_m}{\pi}\cos\alpha = E_b + I_a R_a$

Average output current

$$I_a = \frac{V_a - E_b}{R_a}$$

$$V_a = K_m \omega_m + I_a R_a$$

Torque $T = K_m I_a$

Speed ωm

$$\text{Speed } \omega_m = \frac{V_a - I_a R_a}{K_m}$$

$$\boxed{\omega_m = \frac{2V_m}{\pi K_m}\cos\alpha - \frac{T}{K_m^2} R_a}$$

RMS value of output current

$$I_{orms} = I_a$$

RMS value of source current

$$I_s = \left[\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} I_a^2 \, d(\omega t)\right]^{\frac{1}{2}}$$

$$= \left[\frac{I_a^2}{\pi}[\pi + \alpha - \alpha]\right]^{\frac{1}{2}}$$

$$\boxed{I_s = I_a}$$

Average Value of thyristor current

$$= \frac{1}{2\pi}\int_{\alpha}^{\pi+\alpha} I_a \, d(\omega t) = \frac{I_a}{2\pi}[\pi + \alpha - \alpha]$$

$$\boxed{I_{TA} = \frac{I_a}{2}}$$

RMS value of Thyristor current

$$I_{TR} = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi+\alpha} I_a^2 \, d(\omega t)\right]^{\frac{1}{2}} = \left(\frac{I_a^2}{2\pi}[\pi + \alpha - \alpha]\right)^{\frac{1}{2}}$$

$$\boxed{I_{TR} = \frac{I_a}{\sqrt{2}}} \qquad \text{....(22)}$$

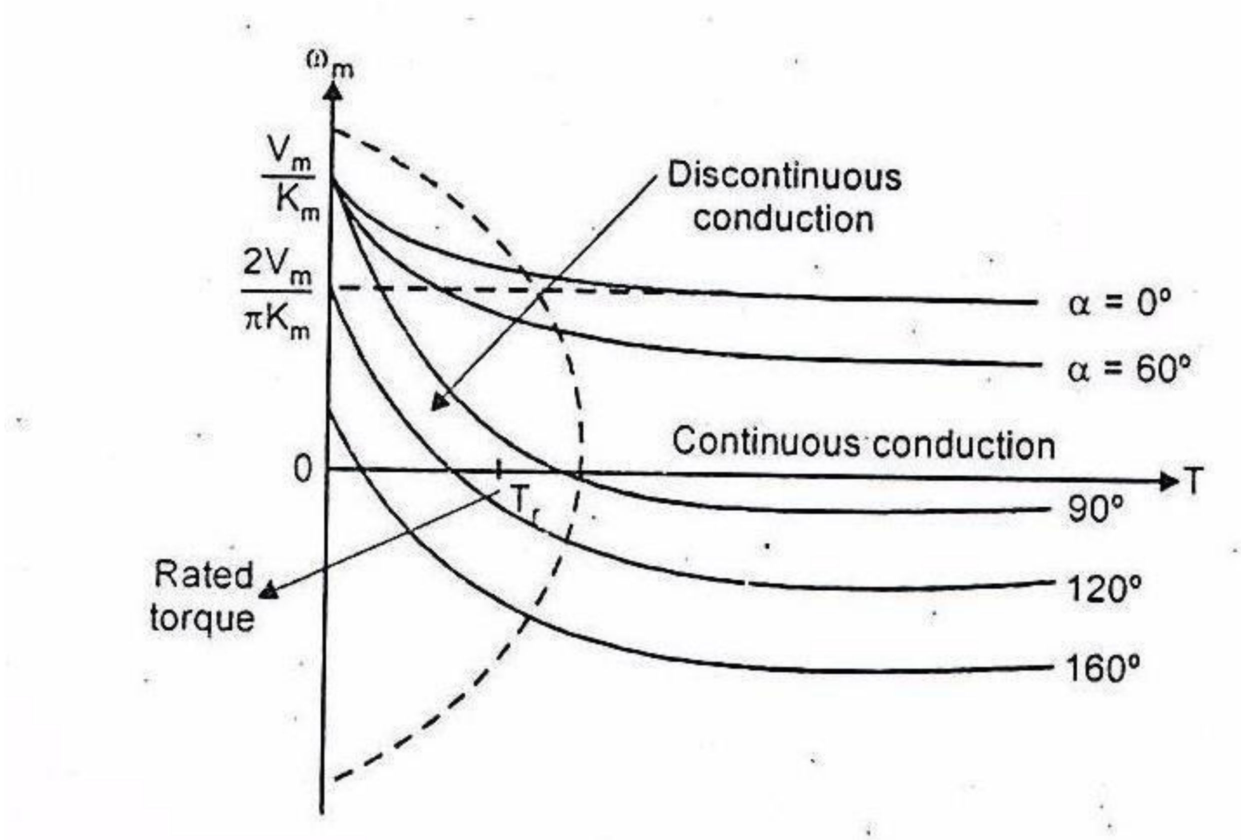
Assume no loss in the converter

Input power = output power

$V_sI_s\cos\varphi = V_aI_a$

$\text{Cos}\varphi = \frac{2\sqrt{2}}{\Pi}$ cosA

Speed –torque characteristics



Three Phase controlled Rectifier fed DC drives

For large power dc drives, three phase controlled rectifiers are used, three phase controlled rectifier circuits give more number of voltage pulses per cycle of supply frequency .this makes motor current continuous and filter requirement also less.

The number of voltage pulses per cycle depends on the number of thyristors and their connections for three phase controlled rectifiers.

Semi converters and full converters are most commonly used in practice.Dual converters are used in reversible drives having power ratings of several mega watts in steel industry and heavy applications.

Three phase fully controlled rectifier fed separately excited DC motor drive.

Three phase-full converters are used industrial applications upto 1500 kW drives. It is a two quadrant convener i.e., the average output voltage is either positive or negative `but average output current is always positive.

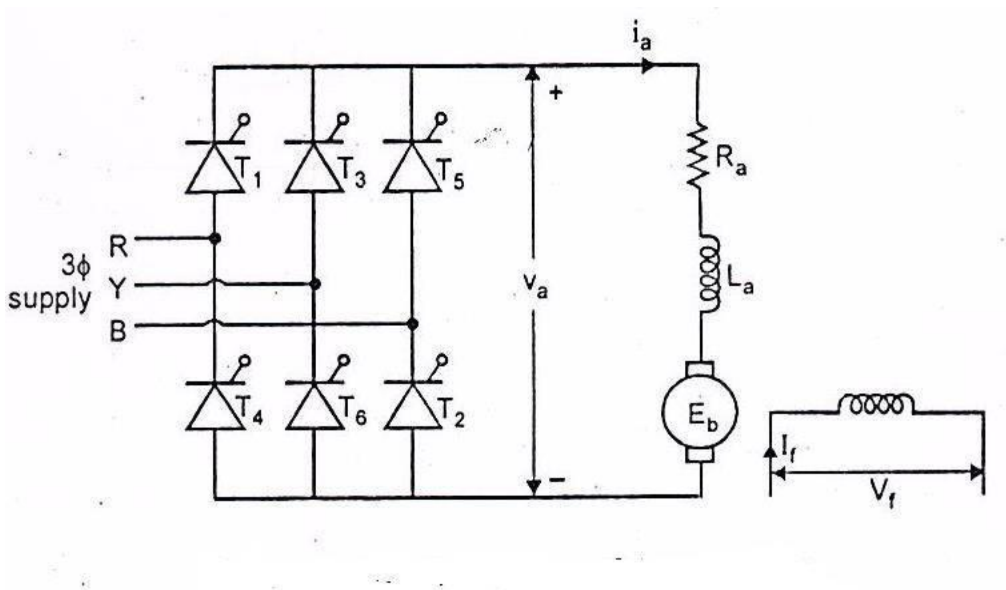


Fig (2.8.1) Three phase fully controlled rectifier fed separately excited DC motor drive. (Circuit Diagram).

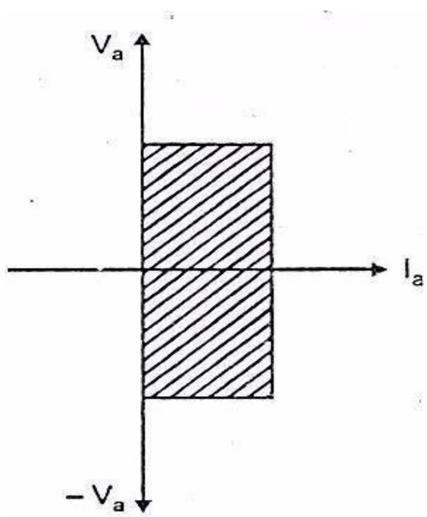


Fig Quadrant Diagram

The circuit consists of six thyristors. Here, there are two groups of thyristors, one is positive group and another one is negative group. Here, thyristors Tl, T3, T5 forms a positive group, whereas thyristors T4, T6, T2 forms a negative group. The positive group thyristors are tumed on when the supply voltages are positive and negative group thyristors are tumed on when the supply voltages are negative. The operation of this convener is easily understand by using line voltages instead of phase voltages,

For or = 60°, T1 is turned on at Π/3+ 60 =120°, T2 at ωt = l80°, T3 at ωt = 240° and so on. When T1 is turned on at ωt = l20°, T5 is turned off. T6 is already conducting. As T1 and T6 are connected to R and Y respectively, load voltage must be very as shown in fig.

When T2 is turned on, T6 is commutated. As T1 and T2 are now eonducting, the load voltage is vrb, figure. In this way, load voltage waveform can be drawn with thyristors in sequence.

For A = 120°, T1 is triggered at ωt = l80°, T2 is triggered at ωt = 240° and so on, The output voltage waveform is shown in figure. From this waveform, the average output voltage is negative. This means that dc source is delivering power to ac source.

This operation is called line commutated inverter operation. For A is 0 to 90°, this converter operates rectification mode (power flows from source to load) and 90° to 180 converter operates an inversion mode (power flows from load to source). It can work in the inverter mode only if the load has a direct emf E. It is a regenerative braking mode.

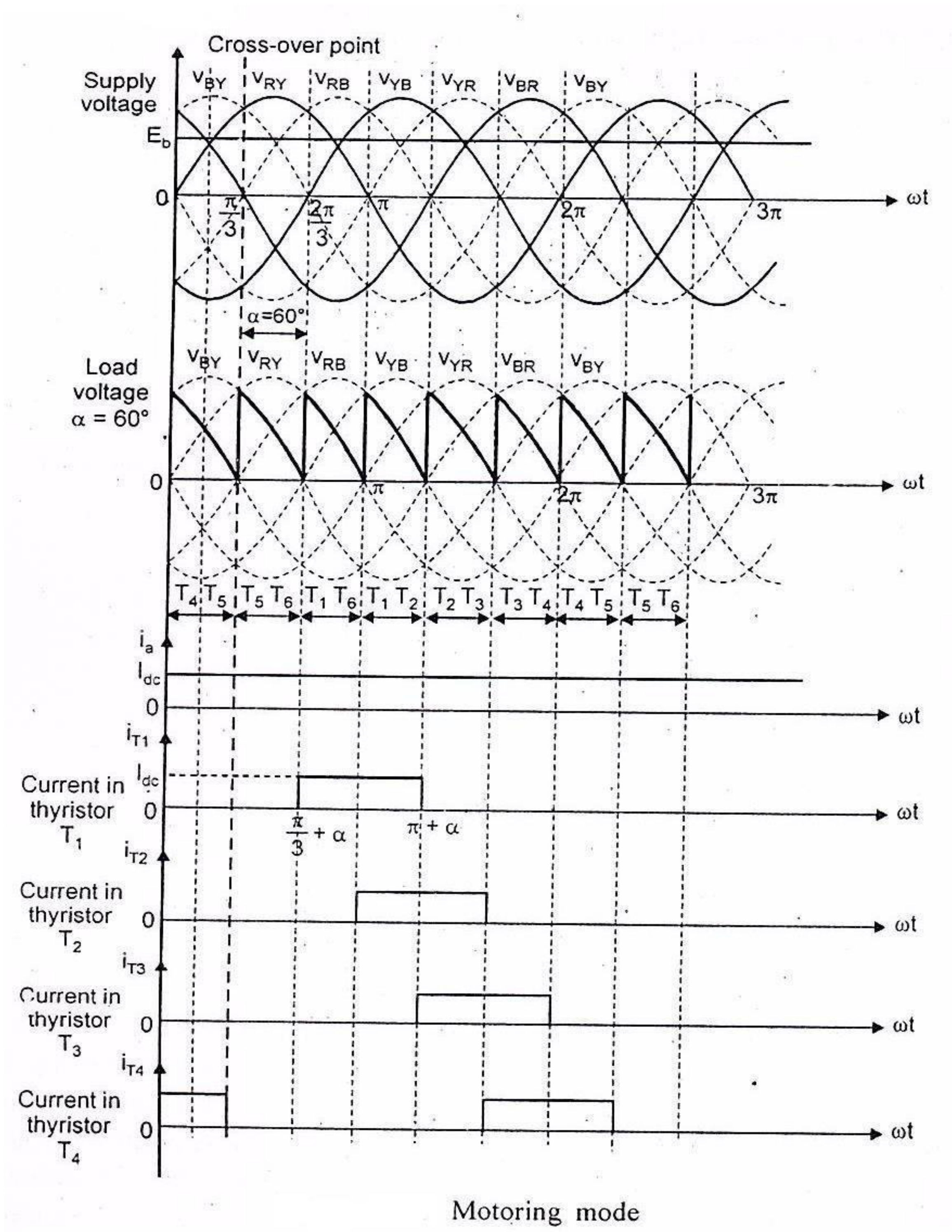


Fig (2.8.3) Three phase fully controlled rectifier (Motoring mode)

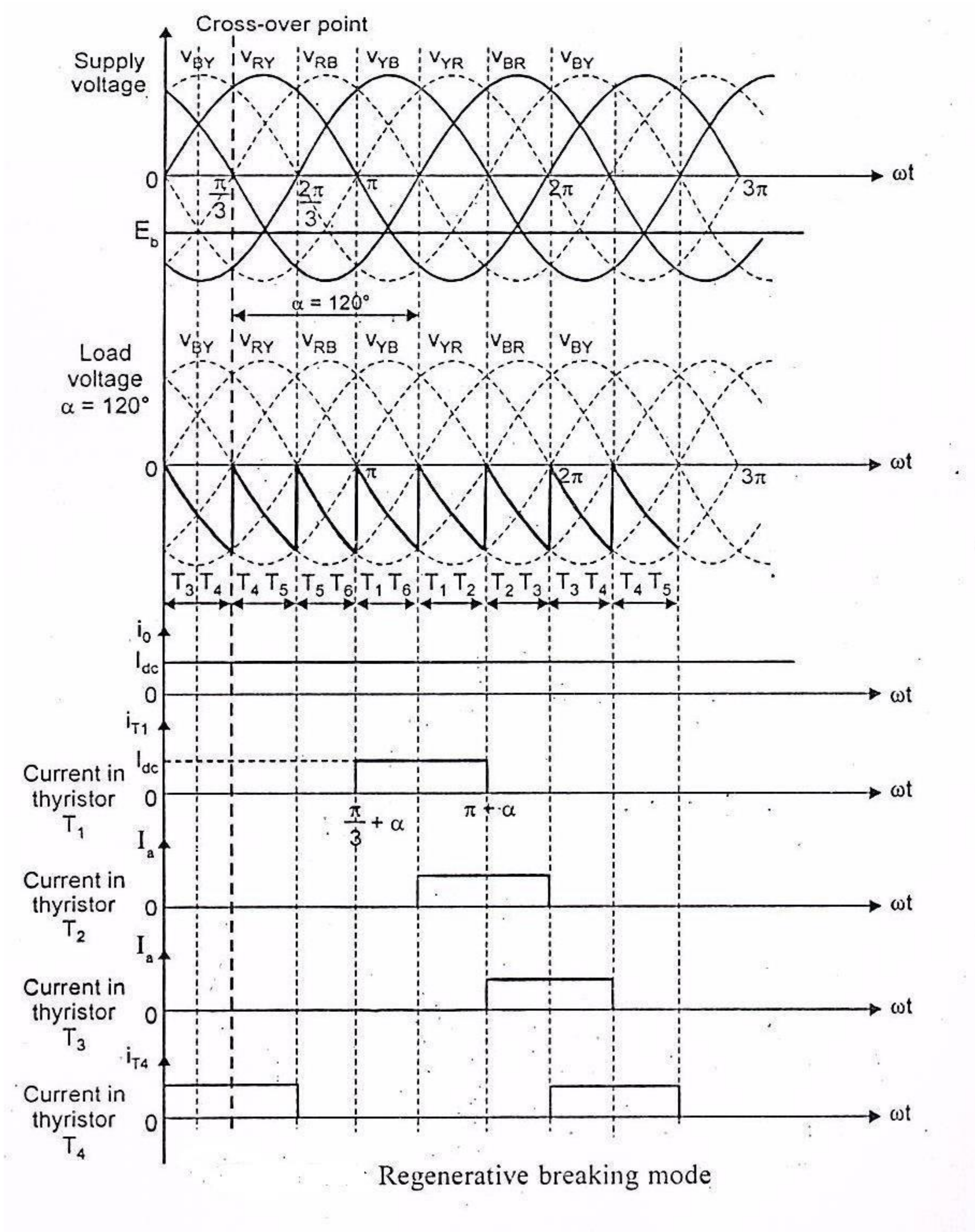


Fig (2.8.4) Three phase fully controlled rectifier (Regenerating Breaking mode)

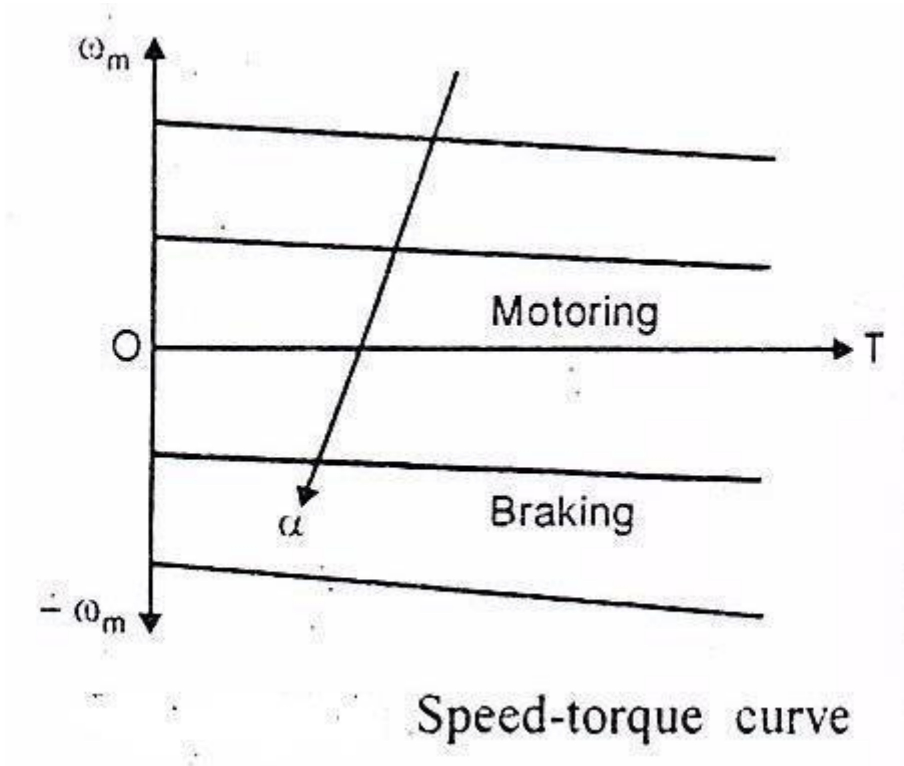


Fig Speed – Torque curve

Average output voltage

$$V_{dc} = \frac{3}{\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} V_{m\ell} \sin\omega t \, d(\omega t) = \frac{3\,V_{m\ell}}{\pi}\cos\alpha$$

where $V_{m\ell}$ = maximum line voltage

The motor speed is given by

$$V_a = E_b + I_a R_a = K_m \omega_m + I_a R_a$$

$$\omega_m = \frac{V_a - R_a I_a}{K_m}$$

In separately excited motor,

$$T = K_m I_a, \text{ therefore}$$

$$\omega_m = \frac{V_a}{K_m} - \frac{R_a}{(K_m)^2} T$$

Control strategies

The average output voltage can be controlled through δ or α by opening and closing of the semiconductor switch periodically.

(i) Time ratio control method (TRC)

1. Fixed frequency
2. Variable frequency

(ii) Current limit control (CLC)

Time ratio control- pulse width control

The ratio of on-time to chopper period is controlled

CONSTANT FREQUENCY TRC

The chopping period T is kept fixed and the on period of the switch is varied to control the duty cycle ratio.

VARIABLE FREQUENCY TRC

The duty ratio is varied by keeping t_{on} constant and varying T, or by varying both T and t_{on}

In this control, low output voltages are obtained at very low chopper frequencies. This will affect the motor performance.

CURRENT LIMIT CONTROL(Point by point control)

The duty ratio is controlled by controlling the load current between certain specified maximum and minimum values. When the load current reaches maximum value, the switch disconnects the load from the source and reconnects ie when the current reaches a specified minimum value.

Two types of control provided for chopper control

3. Power control or motoring control
4. Regenerative braking control

CHOPPER DRIVES

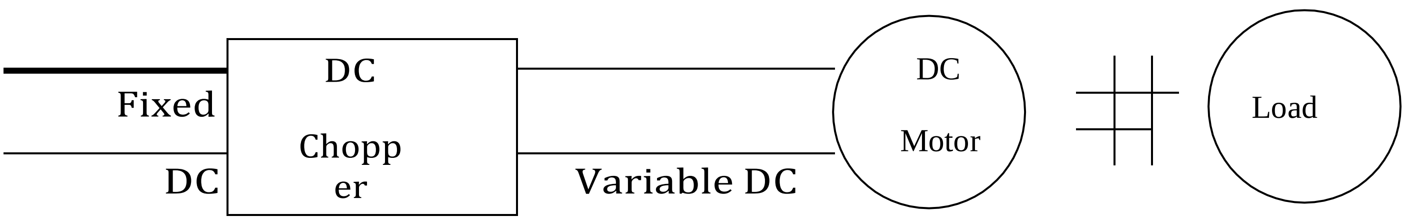


Fig (2.9) Basic block diagram of chopper

Fixed DC voltage is fed to the Dc chopper circuit.DC chopper converts fixed DC into Variable DC voltage.This variable DC voltage is fed to the motor.By varying the DC voltage ,the motor speed can be controlled.

Advantages of DC chopper control

4. High eficiency
5. Flexibility in control
6. Light weight
7. Small size
8. Quick response
9. Regeneration down to very low speeds.

Applications of DC chopper Drives

10. Battery operated vehicle
11. Traction motor control in electric traction
12. Trolly cars
13. Hoists
14. Electric braking

Types of DC chopper drives

15. First quadrant chopper or type A chopper
16. Second quadrant or type B chopper
17. Two quadrant type A chopper or type C chopper
18. Two quadrant type B chopper or type D chopper
19. Four quadrant chopper or type E chopper

First Quadrant or Type-A or Motoring Chopper

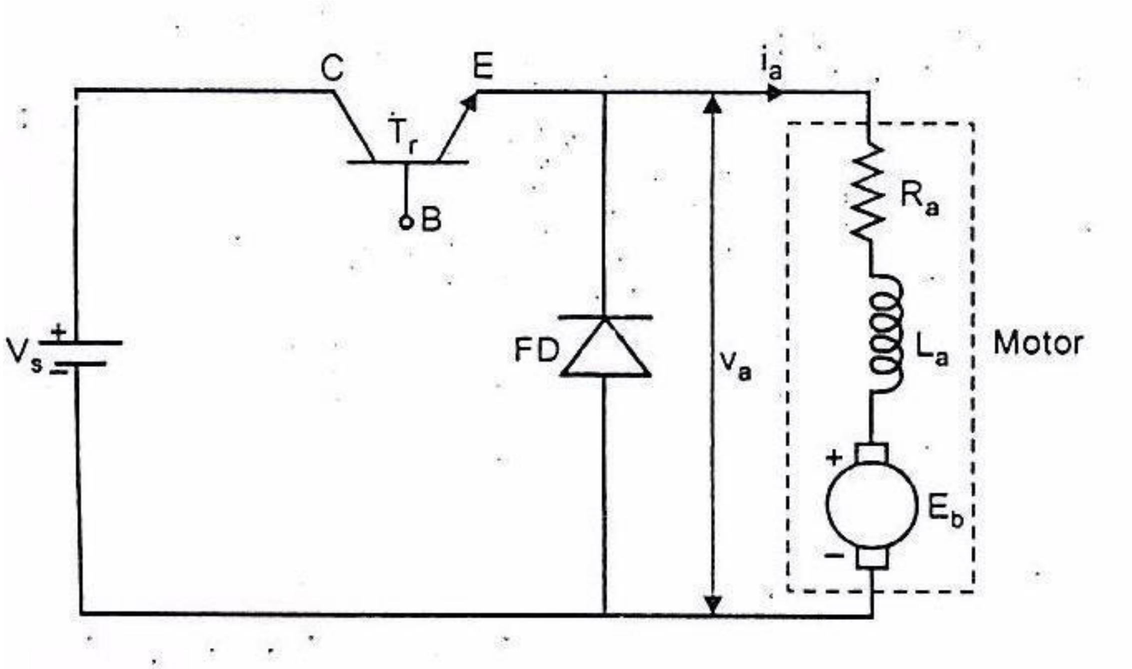
In the past, series motor was used in traction, because it has high starting torque. It has number of limitations. The field of the series motor cannot be controlled easily by static means

If field control is not employed, the series motor must be designed with its base speed equal to the higher desired speed of the drive. The higher base speeds are obtained using fewer turns in the field windings

This reduces the torque per ampere at zero and low speeds. Presently, separately excited motors are also used in traction. Because of limitations of a series motor separately excited motors are now preferred even for traction applications.

Motoring control

A transistor chopper controlled separately excited motor drive is shown in fig



Chopper control of separately excited motor

Fig-First Quadrant or Type-A or Motoring Chopper

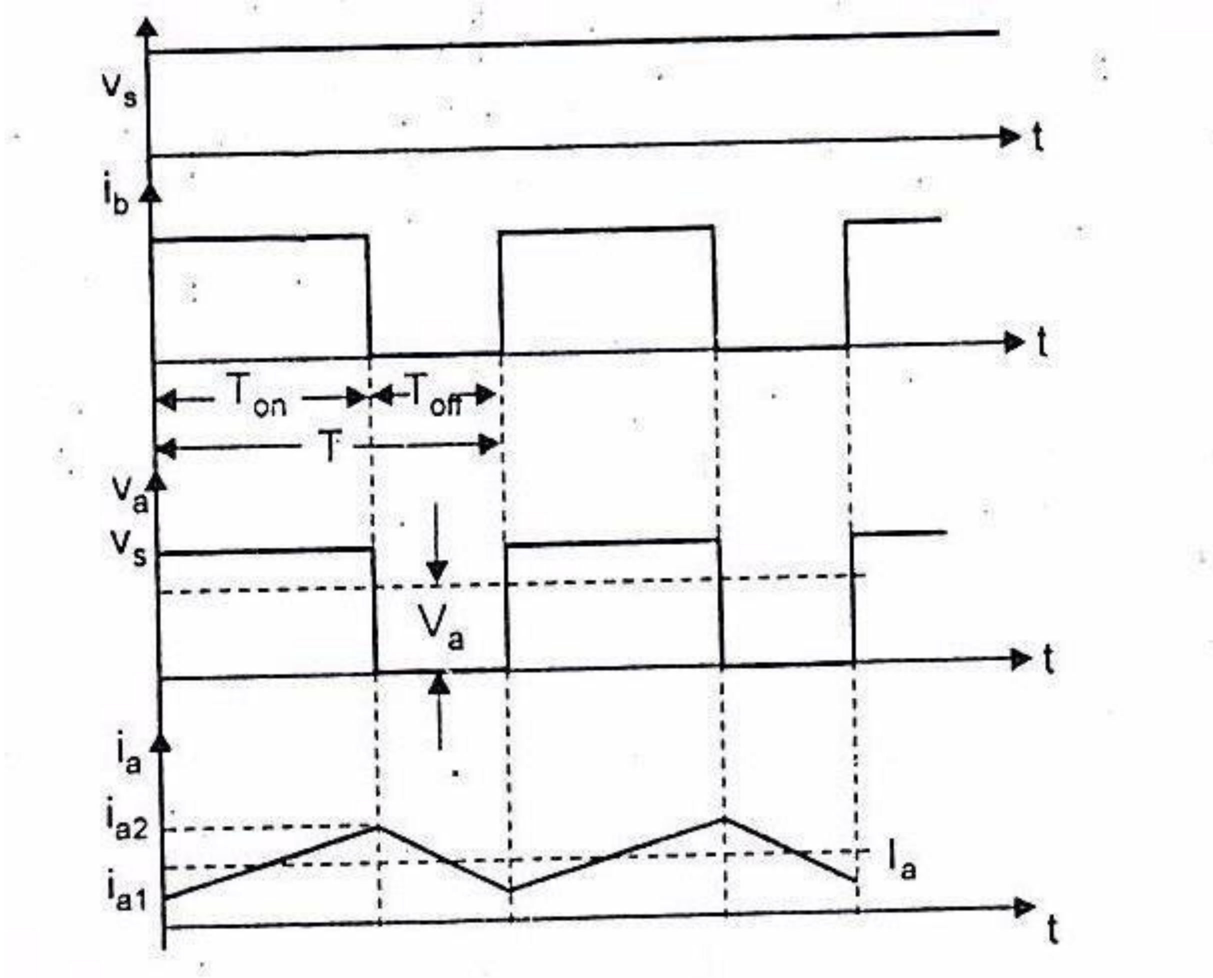


Fig First Quadrant or Type-A or Motoring Chopper(waveform)

Current limit control is used in chopper. in current limit control, the load current is allowed to vary between two given (upper and lower) limits. The ON and OFF times of the chopper adjust automatically, when the current increases beyond the upper limit the chopper is turned off, the load current freewheels and starts to decrease. When it falls below the lower limit the chopper is turned ON. The current starts increasing in the load. The load current 'ia' and voltage 'va' waveform are shown in figure .By assuming proper limits of current, the amplitude of the ripple can be controlled,

The lower the ripple current, the higher the chopper frequency. By this switching losses get increase. Discontinuous conduction avoid in this case, The current limit control is superior one. During ON-period of chopper (i.e.) duty interval,$0 \leq t \leq TON$, motor terminal voltage Va is a source voltage Vs and armature current increases from ia1 to ia2

The operation is described by,

$$i_aR_a + L_a \frac{di_a}{dt} + E_b = V_s \; ; \; 0 \le t \le T_{ON}$$

Chopper is turned off at t = t0N. During off-period of chopper (i.e.) free

wheeling interval, Ton≤ t ≤ T , motor current freewheels through diode FD and motor terminal voltage Va is zero.

This is described by,

$$i_aR_a + L_a \frac{di_a}{dt} + E_b = 0; \; T_{on} \le t \le T$$

From output waveform figure (3.3)

$$V_a = \frac{1}{T}\int_0^{T_{ON}} V_s\, dt = \frac{V_s}{T}\int_0^{T_{ON}} dt$$

$$\frac{V_s}{T}\,[t]_0^{T_{on}} = V_s\left[\frac{T_{on}}{T}\right]$$

$$\boxed{V_a = \delta V_s = \alpha V_s}$$

$$\text{where, } \alpha \text{ (or) } \delta \rightarrow \text{duty cycle} = \frac{\text{ON period}}{\text{total time}} = \frac{T_{ON}}{T}$$

$$V_a = E_b + I_a R_a$$

$$\delta V_s = E_b + I_a R_a$$

$$I_a = \frac{\delta V_s - E_b}{R_a}$$

$$E_b = K_m \omega_m$$

$$T = K_m I_a \Rightarrow I_a = \frac{T}{K_m}$$

$$E_b = K_m \omega_m = V_a - I_a R_a$$

$$K_m \omega_m = V_a - \frac{T}{K_m} R_a$$

$$\omega_m = \frac{V_a}{K_m} - \frac{T}{K_m^2} R_a$$

$$\boxed{\omega_m = \frac{\delta V_s}{K_m} - \frac{R_a}{K_m^2} T}$$

Second Quadrant or Type –B or Regenerative braking Chopper

In regenerative mode ,the energy of the load may have to be fed to the supply system.The dc motor works as a generator during this mode.As long as the chopper is ON,the mechnanical energy is converted into electrical by the motor,now working as a generator,increases the stored magnetic energy in armature circuit inductance and remainder is dissipated in armature resistance and transistor.when chopper is switched off,a large voltage occurs across the load terminals.

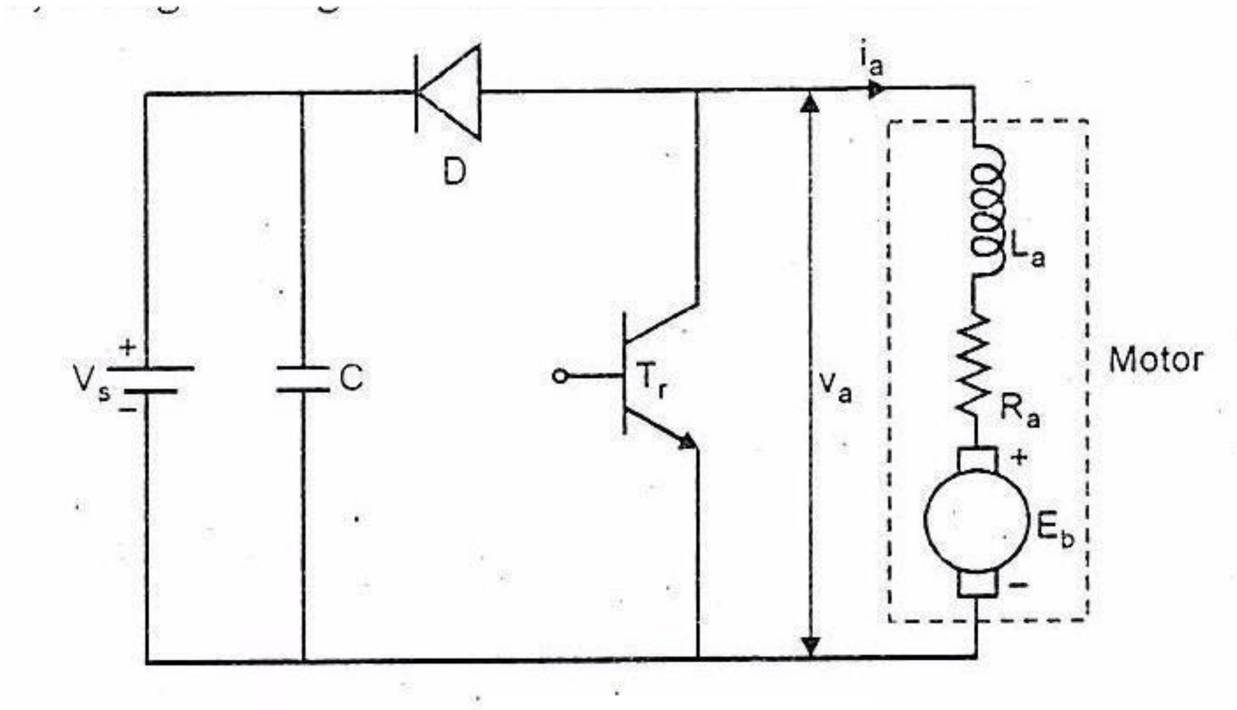
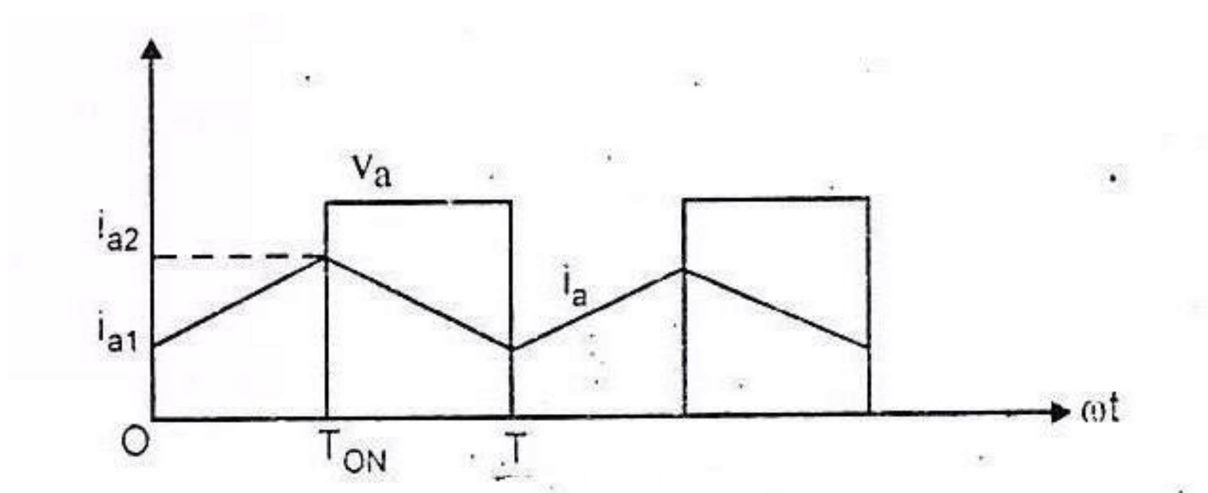


Fig -Second Quadrant or Type –B or Regenerative braking Chopper(circuit diagram

This voltage is greater than the supply voltage Vs and the energy stored in the inductance and the energy supplied by the_machine is fedback to the supply system. When the voltage of the load falls to Vs, the diode in the line blocks the current flow, preventing any short circuit of the load can he supplied to the source. Very effective braking of the motor is possible upto the extreme small speeds. Regenerative braking is achieved here by changing the direction of current flow.



During energy storage interval, $0 \leq t \leq T_{ON}$, motor terminal voltage is zero, armature current increases from i_{a1} to i_{a2}. During duty interval, $T_{ON} \leq t \leq T$, motor terminal voltage is V_a, armature current decreases from i_{a2} to i_{a1}.

$$V_a = \frac{1}{T} \int_{T_{ON}}^{T} V_s \, dt = \frac{V_s}{T} \int_{T_{ON}}^{T} dt = \frac{V_s}{T} [t]_{T_{on}}^{T} = \frac{V_s}{T}(T - T_{ON})$$

$$= V_s \left(\frac{T - T_{ON}}{T} \right) = V_s \left(1 - \frac{T_{ON}}{T} \right)$$

$$\boxed{V_a = (1 - \delta) V_s}$$

$$E_b = K_m\omega_m$$

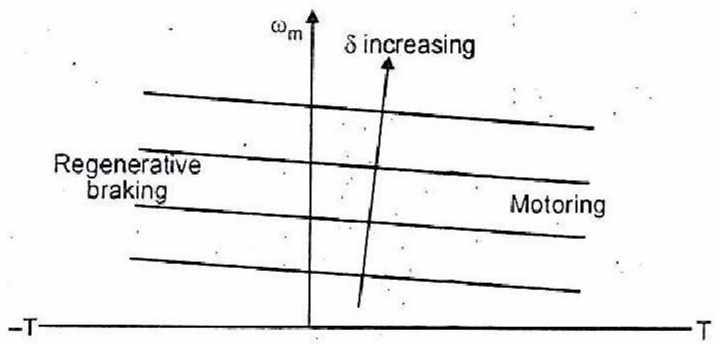
$$T = -K_m I_a \quad ((\because I_a \text{ reversed})$$

$$E = K_m\omega_m = V_a - I_a R_a$$

$$\omega_m = \frac{V_a}{K_m} - \frac{\left(\frac{-T}{K}\right)R_a}{K_m}.$$

$$\boxed{\omega_m = \frac{(1-\delta)V_s}{K_m} + \frac{R_a}{K_m^2}\ T}$$

Figure shows speed-torque characteristics curves of chopper controlled separately excited dc motor for motoring and regenerative braking.



Speed-torque curves of chopper controlled separately excited motor

The regenerated power $P_g = V_a I_a = (1 - \delta) V_s I_a$

The voltage generated by the motor acting as a generator is

$$E_g = K_m \phi \omega_m \qquad [\phi \propto I_f]$$

$$= K_m I_f \omega_m$$

Suppose field current is not given, the equation becomes

$$E_g = K_m \omega_m$$

$$E_g = V_a + I_a R_a$$

$$= (1 - \delta) V_s + I_a R_a$$

where K_m motor constant and ω_m is the machine speed in rad. per second.

Therefore, the equivalent load resistance of the motor acting as a generator by

$$R_{eq} = \frac{E_g}{I_a} = \frac{V_s(1-\delta)}{I_a} + \frac{I_a R_a}{I_a} = \frac{V_s}{I_a}(1-\delta) + R_a$$

By varying the duty cycle δ, the equivalent load resistance seen by the motor ca be varied from R_a to $\left(\frac{V_s}{I_a} + R_a\right)$ and the regenerative power can be controlled.

The conditions for permissible potentials and polarity of the two voltages are

$$0 \leq (E_g - I_a R_a) \leq V_s$$

which gives the minimum braking speed of the motor as

$$E_g = K_m \omega_{min} = I_a R_a$$

$$\omega_{min} = \frac{R_a I_a}{K_m}$$

and $\omega_m \geq \omega_{min}$.

The maximum braking speed of the separately excited motor can be found from equation,

$$E_g - I_a R_a = V_s$$

$$K_m \omega_{max} - I_a R_a = V_s$$

$$K_m \omega_{max} = V_s + I_a R_a$$

$$\omega_{max} = \frac{V_s}{K_m} + \frac{I_a R_a}{K_m}$$

ınd $\omega_m \leq \omega_{max}$.

Two Quadrant Chopper Drives

Motoring control and braking control can be achieved by two quadrant chopper There are two types of two quadrant chopper drives.

1. Two Quadrant type A chopper drive
2. Two Quadrant type B chopper drive

Two Quadrant type A chopper drive

This types of chopper drive provides forward motoring mode and forward braking mode.

Fig shows two quadrant type A chopper drive for separately excited dc motor.It consists of two choppers CH1 and CH2 and two diodes D1 and D2 dc motor.

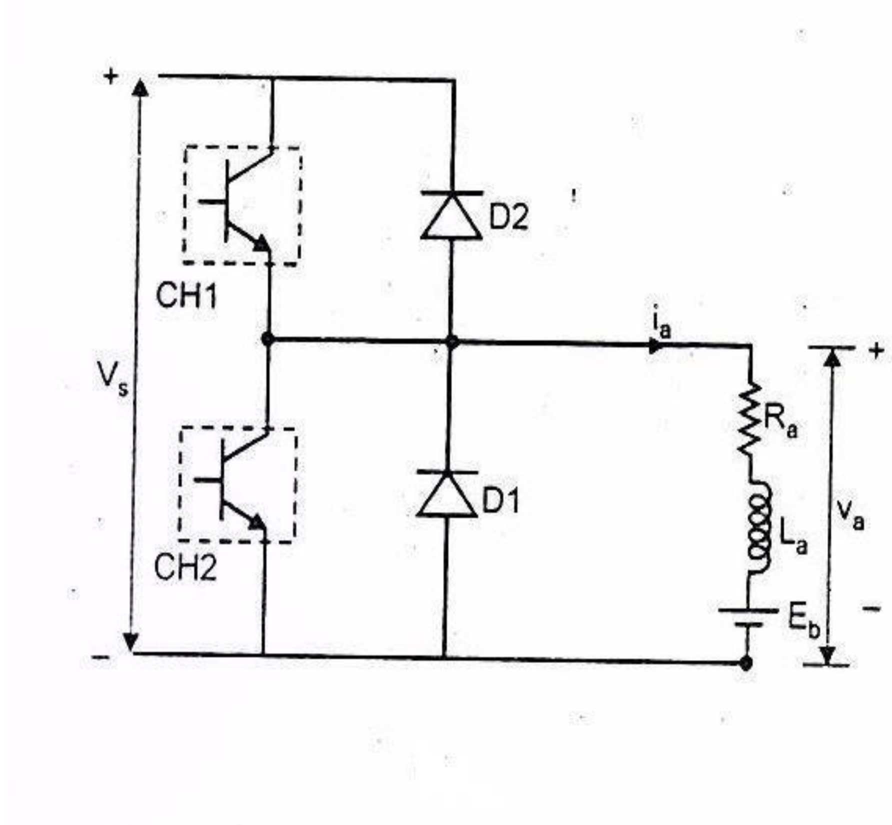


Fig -Two Quadrant type A chopper drive

Fig -Two Quadrant type A chopper drive (Quadrant Diagram)

Forward Motoring Mode

When the chopper CH1 is on, the supply voltage is fed to the motor armature terminals and therefore the armature current increases. Here the voltage and current is always positive. Therefore the motor rotates in forward direction.

When CH1 is in an off state,ia freewheels through diode D1 and therefore ia decreases. It is the forward motoring mode. It is first quadrant operation.

Forward Braking Mode

When chopper CH2 is in an ON state, the motor acts as a generator and armature current ia increases. Due to this energy is stored in the armature inductance.

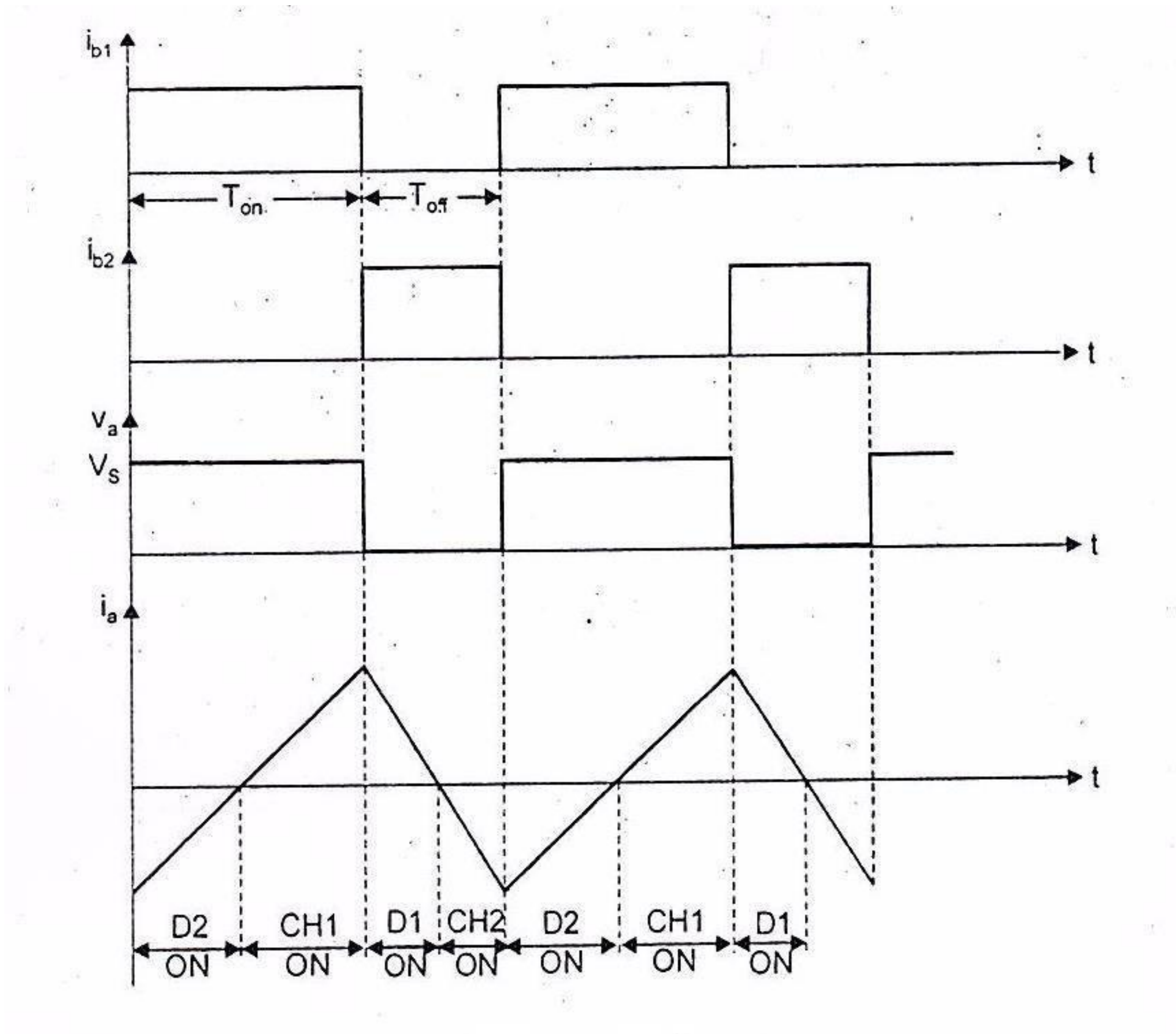


Fig-Wave Form Two Quadrant type A chopper drive

When CH2 is in an off state, diode D2 gets turned on and therefore armature current ia is reversed. It is the second quadrant operation.

In this mode output voltage is positive and output current is negative. It is forward regenerative braking mode.

Two Quadrant type B chopper drive

This type of chopper drive provides forward motoring mode and reverse regenerative braking mode.

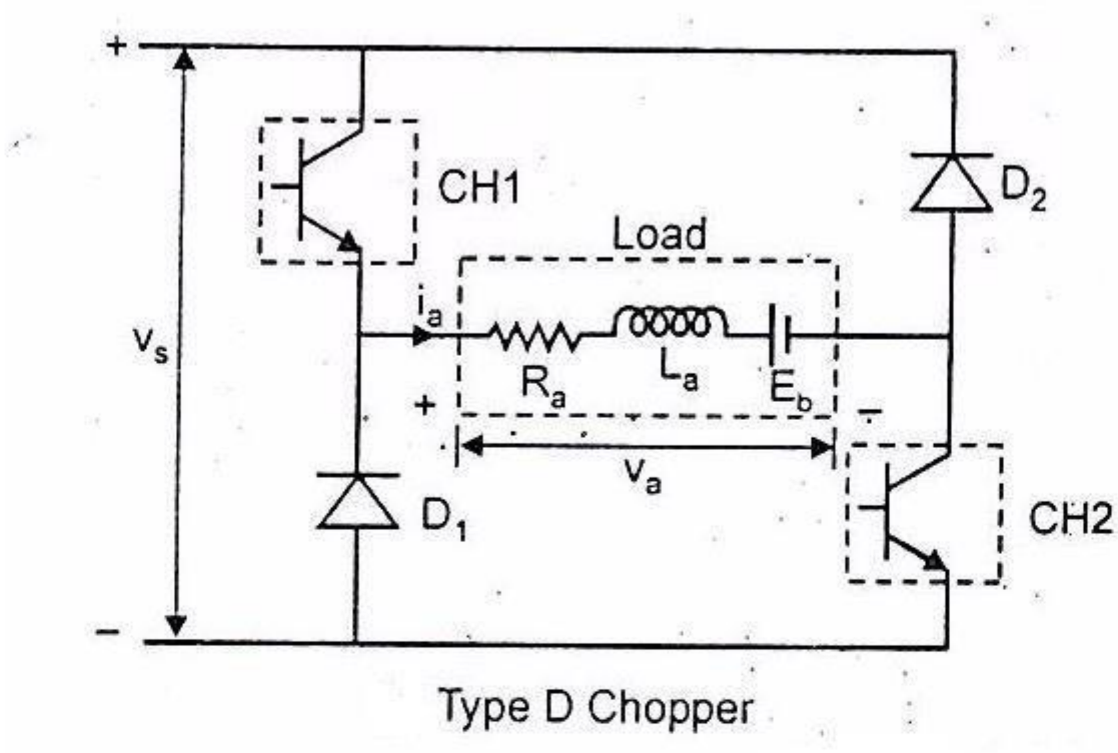


Fig -.Two Quadrant type B chopper drive (circuit diagram)

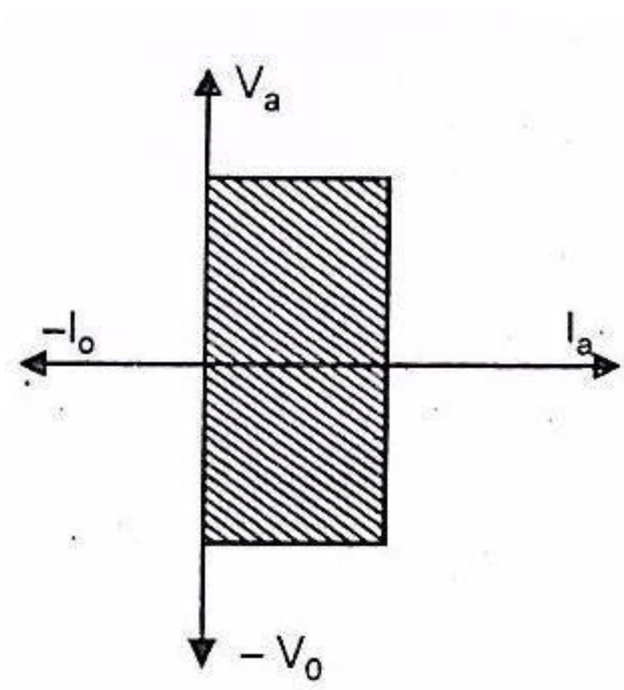


Fig - –Quadrant Diagram Two Quadrant type B chopper drive

It consists of two choppers CH1 and CH2,two diodes and dc motor. This type of chopper operates in the first quadrant and fourth quadrant operation.

Forward motoring mode

When the chopper CH1 and CH2 on, the motor rotates in the forward direction and ia increases. When CH1 is in an off state ,now the current flows through CH2 and diode D1.Here the output voltage current is always positive .It gives forward motoring mode operation. Wave form shows forward motoring mode ($0.5<\delta<1$) of two quadrant type B chopper.

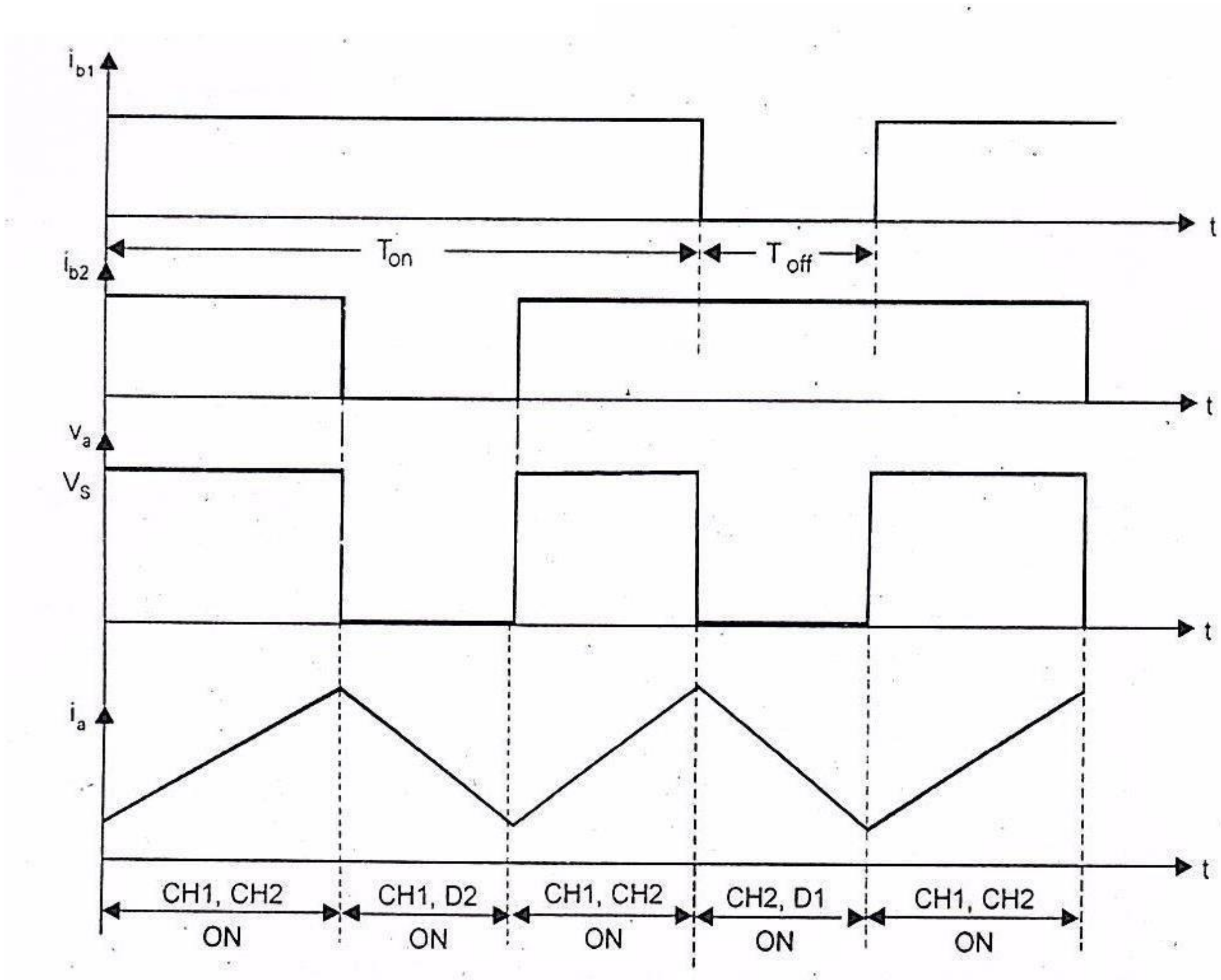


Fig -Forward Motoring mode, Two Quadrant type B chopper drive

Reverse Braking Mode

When both the choppers CH1 and CH2 are off, the current will flows through the diode Di and

D2. Here the output current is positive and output voltage is negative. i.e.,

power flows from load to source. Here we can achieve the reverse braking mode. It is the fourth quadrant operation. It is shown in fig. Here the motor speed can be controlled by changing the duty cycle of the chopper.

Figure shows reverse braking mode ($0 \leq \delta \leq 0.5$) waveforrns of two quadrant type B chopper drive.

Four quadrant Chopper or Type E Chopper

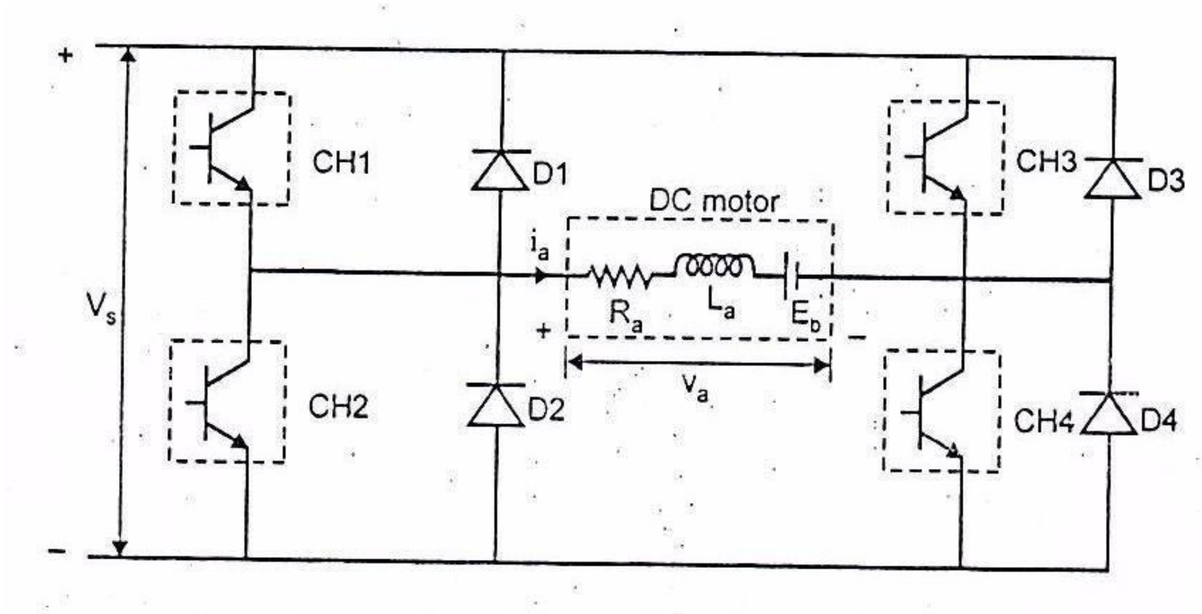


Fig - Four quadrant Chopper or Type E Chopper

It consist of four power semiconductor switches CH1 to CH4 and four power diodes D1 and D4 in antiparallel.working of this chopper in the four quadrants is explained as under,

Forward Motoring Mode

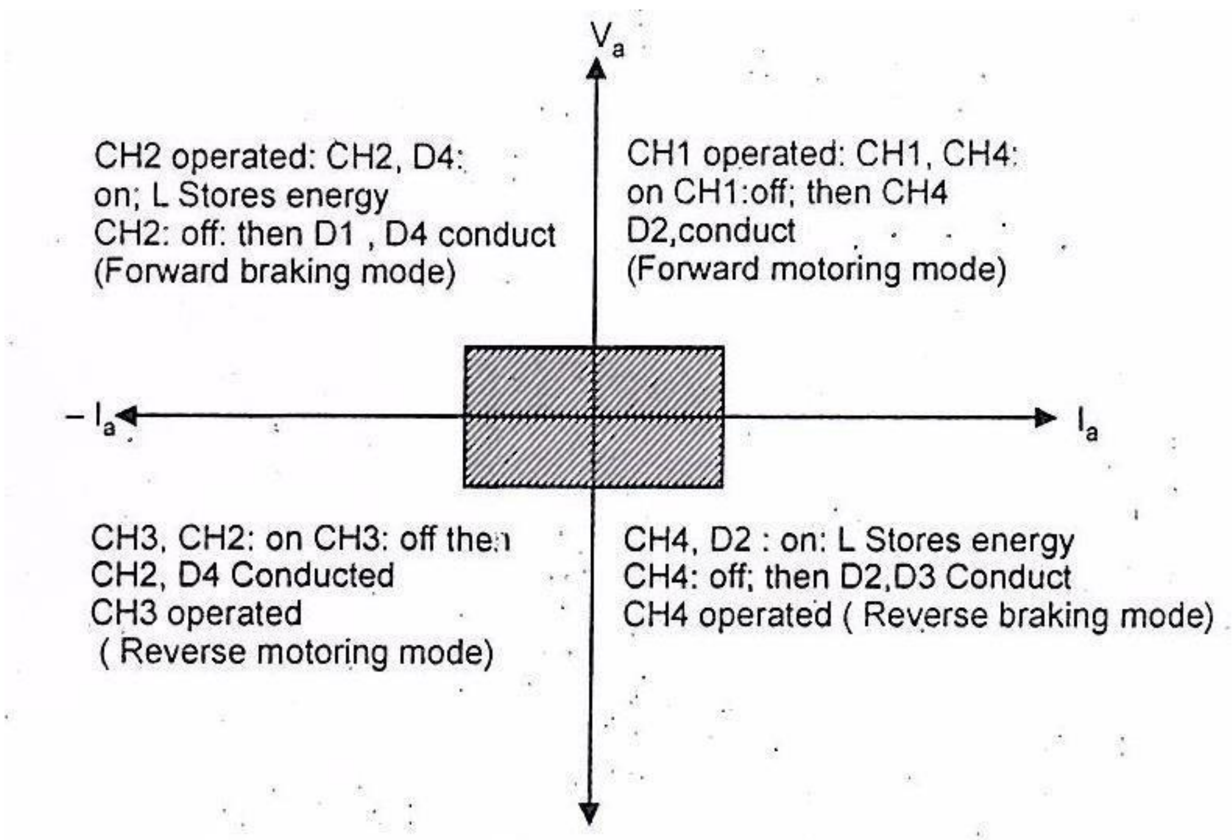
For first quadrant operation of figure CH4 is kept on, Cl-l3 is kept off and CH1 is operated. when CHI and Cl-I4 are on, load voltage is equal to supply voltage i,e, Va = Vs and load current ia begins to flow. Here both output voltage va and load current ia are positive giving first quadrant operation. When CH4 is turned of£ positive current freewheels through CH-4,D2 in this way, both output voltage va, load current ia can be controlled in the first quadrant. First quadrant operation gives the forward motoring mode.

Forward Braking Mode

Here CH2 is operated and CH1, CH3 and CH4 are kept off. With CH2 on, reverse (or negative) current flows through L, CH2, D4 and E. During the on time of CH2 the inductor L stores energy. When CH2 is turned off current is fedback to source through diodes D1, D4 note that there [E+L di/dt] is greater than the source voltage Vs. As the load voltage Va is positive and load current ia is negative, it indicates the second quadrant operation of chopper. Also power flows from load to source, second quadrant operation gives forward braking mode.

Reverse Motoring Mode

For third quadrant operation of figure, CHI is kept off, CH2 is kept on and CH3 is operated. Polarity of load emf E-must be reversed for this quadrant operation. With CH3 on, load gets connected to source Vs so that both output voltage Va and load current ia are negative. it gives third quadrant operation. lt is also known as reverse motoring mode. When CH3 is turned off, negative current freewheels through CH2, D4. ln this way, output voltage Va and load current ia can be controlled in the third quadrant.



Reverse Braking Mode

Here CH4 is operated and other devices are kept of£Load emf E must have its polarity reversed, it'is shown in figure . With CH4 on, positive current flows through CH4, D2, L and E. During the on time of CH4, the inductor L stores energy.

When CH4 is turned off; current is feedback to source through diodes D2, D3. Here load voltage is negative, but load current is positive leading to the chopper operation in the fourth quadrant.

Also power is flows from load to source. The fourth quadrant operation gives reverse braking mode.

Braking

In braking, the motor works as a generator developing a negative torque which oppose the motion. It is of three types

1. Regenerative braking
2. Plugging or Reverse voltage braking
3. Dynamic braking or Rheostatic braking

Regenerative braking

In regenerative braking, generated energy is supplied to the source,for this to happen following condition should be satisfied

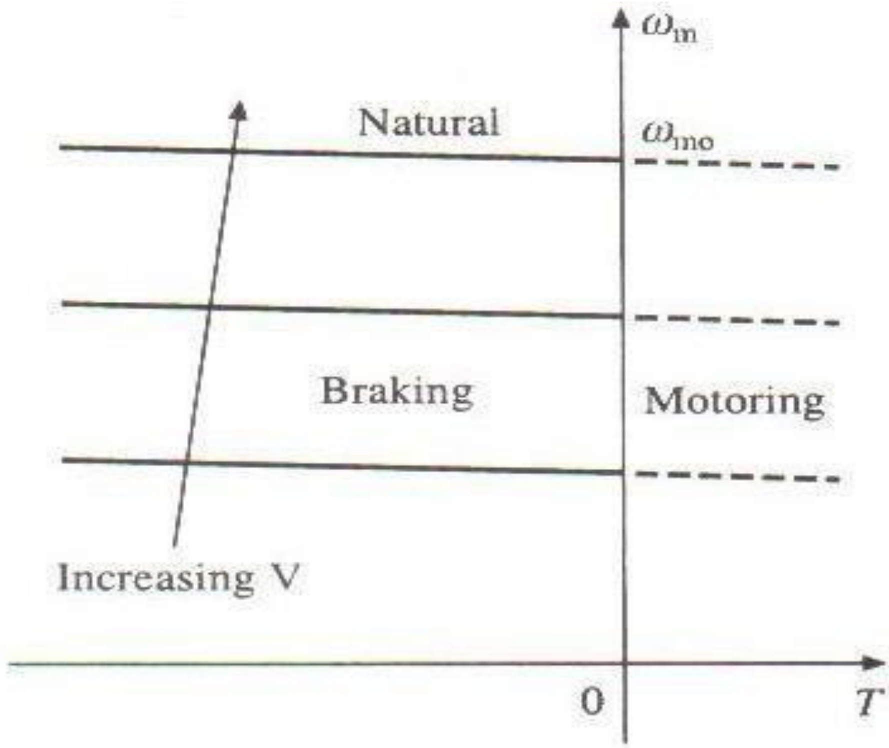
$$E > V \text{ and negative } I_a$$

Field flux cannot be increased substantially beyond rated because of saturation, therefore according to equation ,for a source of fixed voltage of rated value regenerative braking is possible only for speeds higher than rated and with a variable voltage source it is also possible below rated speeds .

The speed –torque characteristics shown in fig. for a separately excited motor.

In series motor as speed increases, armature current, and therefore flux decreases

Condition of equation cannot be achieved .Thus regenerative braking is not possible



Plugging

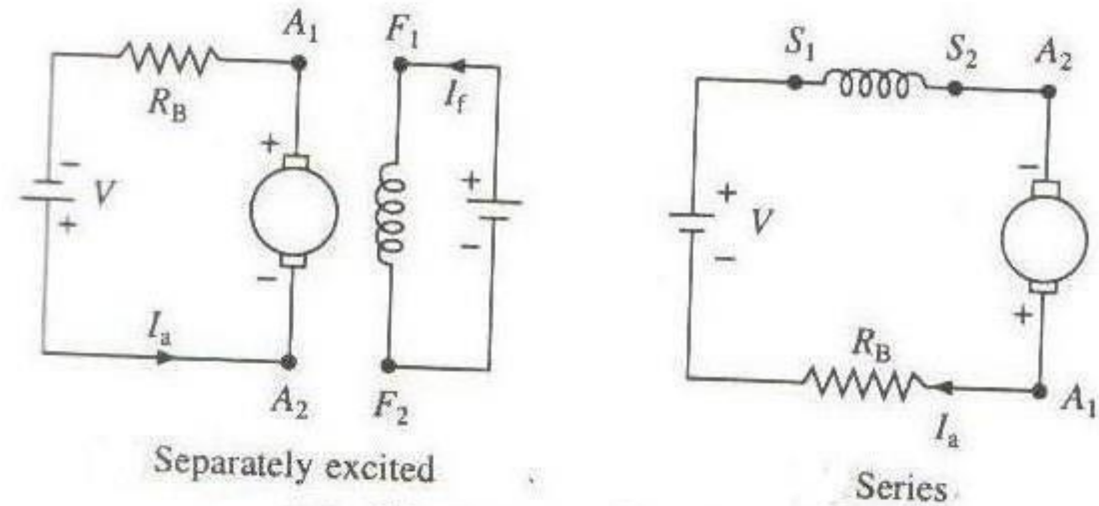
The supply voltage of a separately excited motor is reversed so that it assists the emf in forcing armature current in reverse direction .A resistance R_B is also connected in series with armature to limit the current.For plugging of a series motor armature is reversed.

A particular case of plugging for motor rotation in reverse direction arises .when a motor connected for forward motoring,is driven by an active load in the reverse direction.Here again back emf and applied voltage act in the same direction.However the direction of torque remains positive.

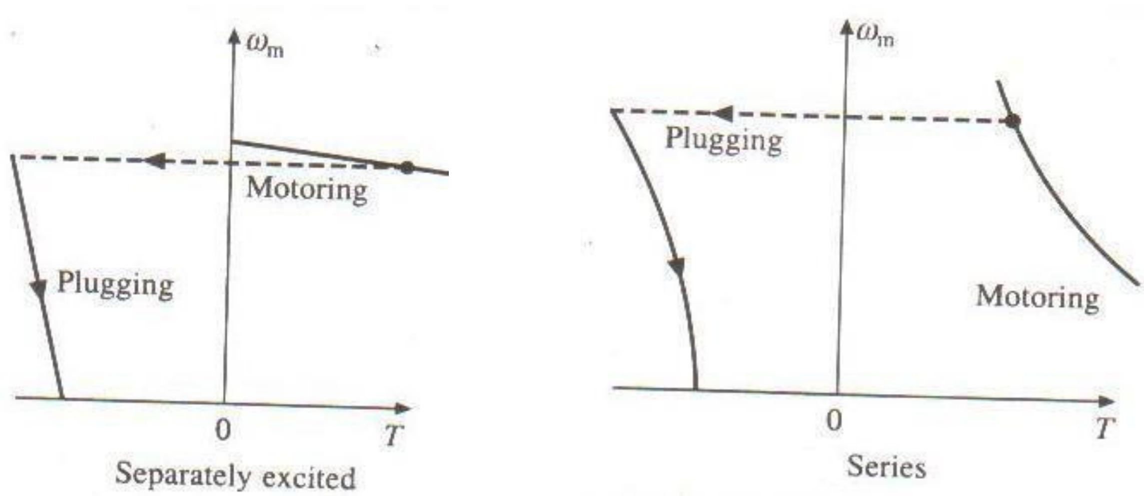
This type of situation arises in crane and the braking is then called counter –torque braking.

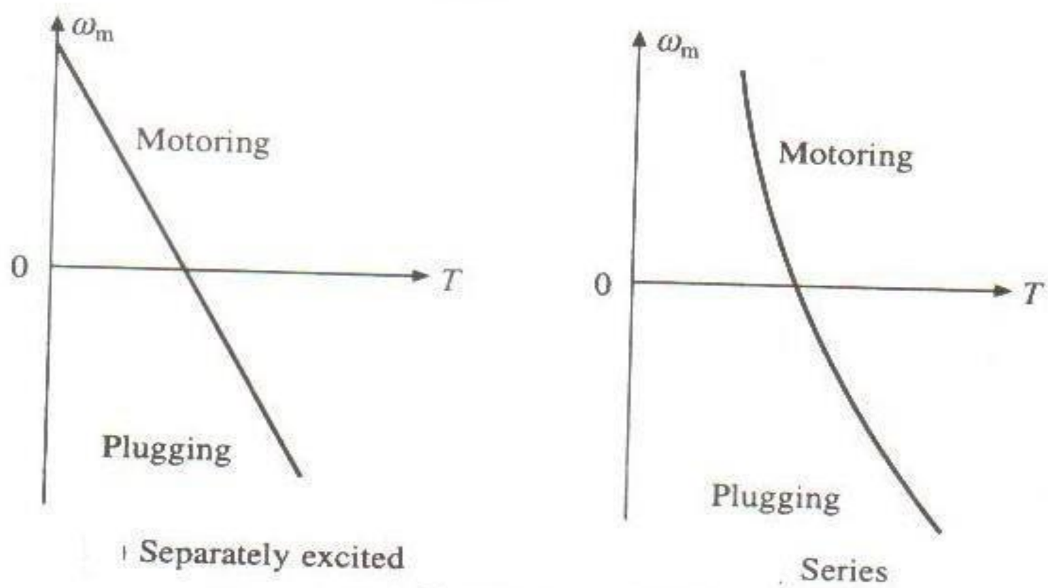
Plugging gives fast braking due to high average torque,even with one section of braking resistance RB.Since torque ia not zero speed,when used for stopping a load,the supply must be disconnected when close to zero speed.

Centifugal switches are employed to disconnect the supply.Plugging is highly inefficient because in addition to the generated power,the power supplied by the source is also wasted in resistances.



Plugging operation of dc motors





Counter-torque braking

Dynamic braking

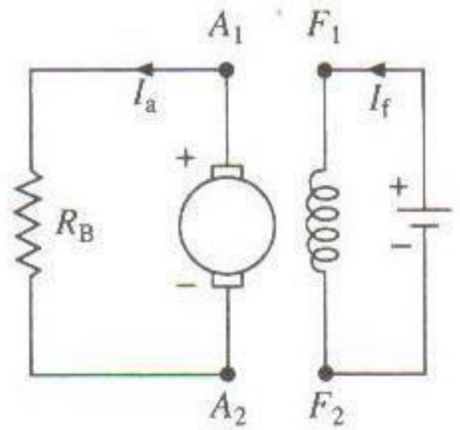
In dynamic braking ,the motor is made to act as a generator,the armature is

disconnected from the supply ,but it continues to rotate and generate a voltage.The polarity of the generated voltage remains unchanged if the direction if field excitation is unaltered.

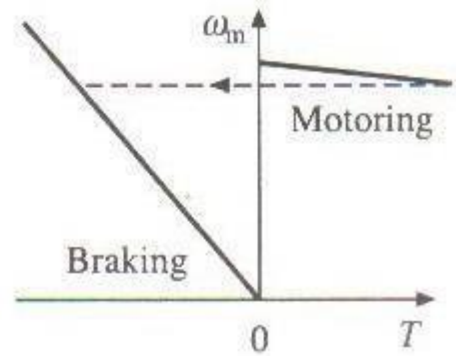
But if a resistance is connected across the coasting motor,the direction of the armature current is reversed ,because the armature represents a source of power rather than a load.

Thus a braking torque is developed ,exactly as in the generator,tending to oppose the motion.

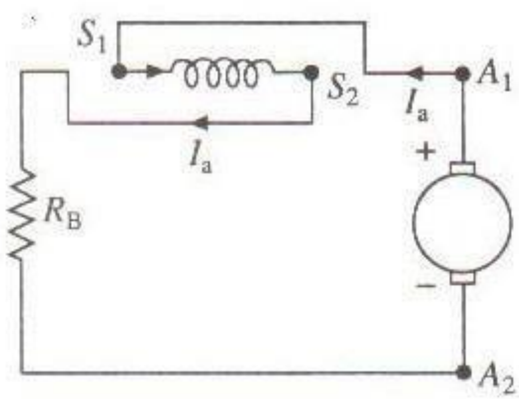
The braking torque can be controlled by the field excitation and armature current.



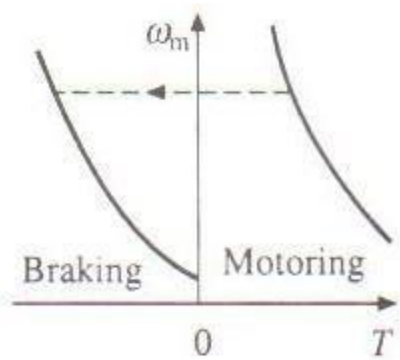
Separately excited motor



Separately excited motor



(b) Series motor



Series motor

UNIT-II

PART-A

1	Show the draw backs of armature voltage method of speed control?	CO2(L2)
2	List which method of speed control is preferable to drive a constant load torque?	CO2(L2)
3	Can you use half controlled converters for a drive with regenerative braking? Justify your answer	CO2(L6)
4	List the advantages of converter fed dc drives?	CO2(L1)
5	Enumerate the methods of controlling a chopper	CO2(L2)
6	Identify why variable frequency chopper control is not suitable for variable speed drives?	CO2(L3)
7	Discuss the importance of form factor and peak factor related to drives	CO2(L2)
8	Interpret the motor emf can be reversed?	CO2(L2)
9	List the advantages of chopper fed dc drives?	CO2(L1)
10	List the self commutated switches? Give two examples.	CO2(L1)

PART-B

1	Explain the Ward-Leonard scheme of speed control and also explain the merits and demerits of the same scheme.	CO2(L2)
2	Illustrate with waveforms converter fed dc motor drive in motoring mode.	CO2(L2)
3	Explain the different conventional methods used to control the speed of DC motors	CO2(L2)
4	Explain with waveforms converter fed dc motor drive in motoring mode	CO2(L2)
5	A dc series motor on load operating at 250V dc mains draws 25A and runs at 1200 rpm. Armature and field resistances are 0.1Ω and 0.3 Ω respectively. A resistance of 25 Ω is placed in parallel with the armature of the motor. Determine: (a). The speed of the motor with the shunted armature connection, if the magnetic circuit remains unsaturated and the load torque remains constant. (b). the no load speed of the motor with the shunted armature.	CO2(L4)
6	Summarise in detail about chopper fed separately excited dc motor drives.	CO2(L2)
7	Illustrate with waveforms converter fed dc motor drive in regenerative mode.	CO2(L2)

UNIT-III

INDUCTION MOTOR FED DRIVE

Induction motors, particularly squirrel cage IM, have many advantages when compared to DC motors. They are,

- Ruggedness
- Lower maintenance requirements
- Better reliability
- Low cost, less weight and volume
- Higher efficiency
- Also induction motors are able to operate in dirty and explosive environments.

Because of the above said advantages, induction motors are predominantly used in many industrial applications. But induction motors were used only for applications requiring constant speed.

DC motors were used for variable speed applications as their speed control is cheap and efficient when compared to induction motors.

After the advent of power electronic converters, it was able to design variable speed drives for induction motors. Because speed control of IM using power electronic converters have become cheap and less costly when compared to dc drives.

SPEED CONTROL

The conventional methods of speed control of induction

motors are, **Stator Side**

- Stator voltage control
- Variable frequency control
- Stator current control
- V/f control
- Changing the number of poles on stator

Rotor Side

- Rotor resistance control
- Injecting emf in the rotor

STATOR VOLTAGE CONTROL

- Speed of induction motor can be varied in a narrow range by varying the voltage applied to the stator winding.
- Torque developed by 3 phase induction motor is directly proportional to the square of the stator voltage as given by the equation,

$$T_m = \frac{3}{2\pi N_s} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} ------1$$

$$N_s = \frac{3}{2\pi T_m} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} ----- 2$$

- In low slip region $(S.X_2)^2$ is very small as compared to R_2. So, it can be neglected. So equation 1 becomes,

$$T_m \propto \frac{S.E_2^2}{R_2}$$

- Since rotor resistance R_2 is constant, the torque equation becomes,

$$T_m \propto S.E_2^2$$

Here E_2 is proportional to the supply voltage V_1. Hence,

$$T_m \propto S.V_1^2 ------3$$

- From equation 2, it is clear that any reduction in supply voltage will reduce the motor speed. But from equation 3, it is seen that any reduction in supply voltage will reduce the torque also.
- So in this method of speed control, torque reduces when supply voltage reduces. Hence this method is used in applications where torque demand reduces with reduction in voltage.
- In general, this method can be used for small range of speed variation.
- In this method of speed control, the slip increases at low speeds. Hence the efficiency of the drive reduces.
- Examples: Fans and pump drives.

Stator voltage control using AC voltage controllers

- The variation of motor voltage is obtained by ac voltage controllers. AC voltage controllers convert fixed ac to variable ac with same frequency.
- But this method produces harmonics in the output and the power factor is low.
- The harmonic content increases and power factor decreases with decrease in output voltage.
- Hence the torque produced by the motor reduces.
- This method is used in applications like fans, pumps and crane drives.
- The circuit for star connected ac voltage controller feeding a 3 phase induction motor is shown in Fig. 4.1

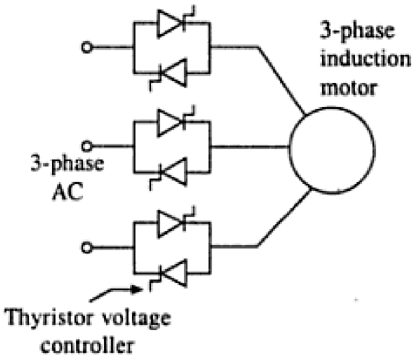


Fig. 4.1 Star connected controller

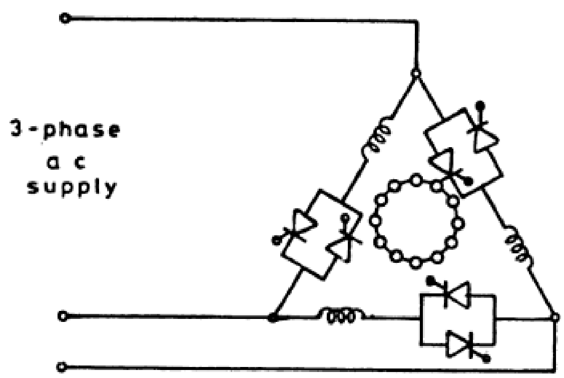


Fig. 4.2 Delta connected controller

- By controlling the firing angle of the thyristors connected in each phase, the rms value of stator voltage can be varied.
- As a result of this, the motor torque and the speed of the motor are varied.
- In star connected controller, all the thyristors carry line currents. But in delta controller shown in Fig. 4.2, all the thyristors carry phase current only. Hence low rating thyristors may be employed in delta controller.
- But delta controller produces circulating currents due to third harmonic voltages. This may increase power loss across each device.
- The speed range is limited in this method of speed control.
- This method is used for applications where load torque requirement reduces with reduction in speed as shown in Fig.below. When a voltage of V_1 is applied, the load load torque required is high and when a voltage V_3 is applied. The load torque is low.

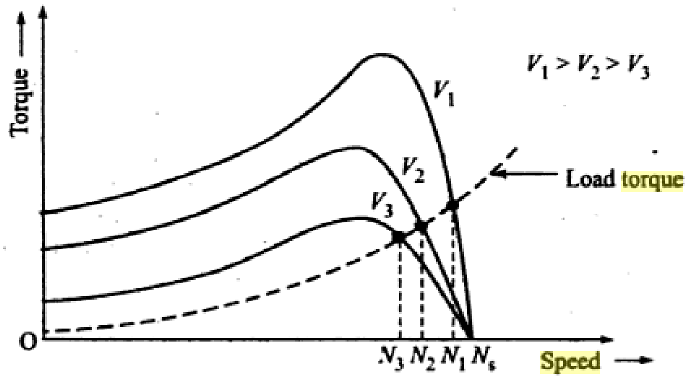


Fig. Speed – Torque characteristics with stator voltage control

- These ac voltage controllers are also used as starters for soft start of motors.
- The power factor of ac voltage circuit is low.
- It can be used for fans and pump drives.

STATOR FREQUENCY CONTROL (OR) FIELD WEAKENING METHOD OF SPEED CONTROL

- In an induction motor, we know that,

$$N_s = \frac{120.f}{P} - - - - - - - 4$$

- From the above equation 4, it is clear that changing the supply frequency will change the synchronous speed and hence the rotor speed.
- Emf equation in ac machines is given by,

$$V_1 = 4.44.f.\varphi.K_w.N_1$$

$$\therefore \varphi = \frac{V_1}{4.44.f.K_w.N_1} - - - - - 5$$

- The above equation 5 states that the flux φ will be constant if V_1 and f are kept constant.

- If frequency is reduced with constant V_1, then the flux φ increases. Hence the core gets saturated.
- This will increase the magnetizing current of the motor. Hence power losses increased and efficiency decreases. It also produces noise.

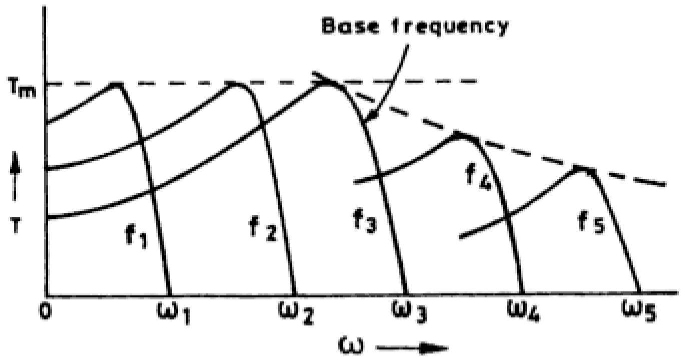


Fig. Speed – Torque characteristics with stator frequency control

- If the frequency is increased by keeping the V_1 constant, then flux decreases. This will reduce the maximum torque produced by the motor as shown in Fig. above
- So this method is rarely used in practice.
- With constant voltage, if the frequency is increased, the air-gap flux reduced. This control is also called as field weakening mode of speed control.

VOLTAGE / FREQUENCY CONTROL (OR) VOLTS / HERTZ CONTROL

- Varying the voltage alone or frequency alone has some disadvantages with regards to the operation of induction motor.
- The maximum torque in an induction motor is given by,

$$T_{max} = \frac{K(V/f)^2}{\frac{R_s}{f} \pm \sqrt{\left[\left(\frac{R_s}{f}\right)^2 + 4\pi^2(L_s + L_r')^2\right]}} ------6$$

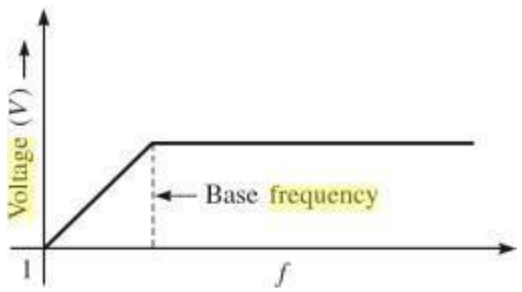
- Here K is a constant and Ls & Lr' are the stator and stator referred rotor inductances.
- At high frequencies, the value of (R_s / f) will be very much less than 2π (Ls+ Lr'). So (R_s / f) can be neglected and hence the torque equation becomes,

$$T_{max} = \pm \frac{K(V/f)^2}{\sqrt{[4\pi^2(L_s + L_r')^2]}}$$

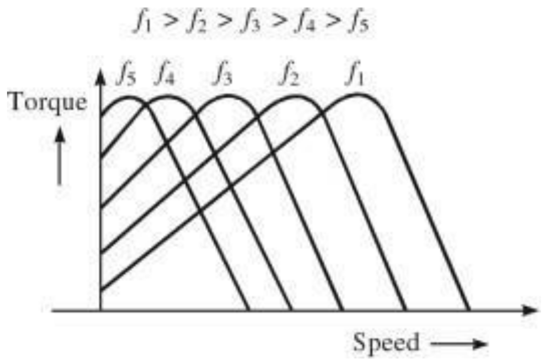
$$T_{max} = \pm \frac{K(V/f)^2}{2\pi(L_s + L_r')} -----7$$

- From equation 7, it is clear that if the ratio (V / f) is kept constant, the motor can produce a constant maximum torque, T_{max}. i.e constant torque operation.

- ❖ At low frequencies (when speed is reduced), the term (Rs / f) will be high and it cannot be neglected in equation 6. Hence the motor torque reduces.
- ❖ This is because of the fact that the flux reduces as the frequency is decreased as per equation 5.
- ❖ Hence if maximum torque needs to be maintained constant at low speeds, then (V / f) ratio must be increased.
- ❖ Near to base speed (or rated speed), the supply voltage will be maximum and it cannot be increased further. Therefore, above base speed, the frequency is changed by keeping supply voltage constant.
- ❖ But this will decrease the maximum torque produced by the motor as per the equation 7.



Graph-1 V – f relationship



Graph-2 Speed – Torque characteristics

- ❖ From the graph -1, it is clear that
  - (V/f) ratio is increased at low frequency to keep maximum torque constant.
  - (V/f) ratio is kept constant at high frequencies up to base frequency
  - V is kept constant and frequency is varied above base frequency.
- ❖ From graph-2 it is clear that the maximum torque is same at all different speeds.
- ❖ This volts / Hertz control offers speed control from standstill up to rated speed of IM.
- ❖ This (V/f) control is achieved by using VSI and CSI fed induction motor drives.
- ❖ If a six step inverter is used, the frequency alone can be varied at the inverter output and the output voltage is controlled by varying the input dc voltage.
- ❖ If a PWM inverter is used, both voltage and frequency can be varied inside the inverter itself by changing the turn on and off periods of the devices.

VOLTAGE SOURCE INVERTER (VSI) FED INDUCTION MOTOR DRIVES

- ❖ In voltage source inverters, the input voltage is kept constant.
- ❖ The magnitude of output voltage of VSI is independent of the load.
- ❖ But the magnitude of output current depends on the type of load.
- ❖ A VSI converts the input dc voltage into an ac voltage with variable frequency at its output terminals.

❖ VSI using normal transistors is shown in Fig. below. Any other self commutated device can be used in place of transistors.

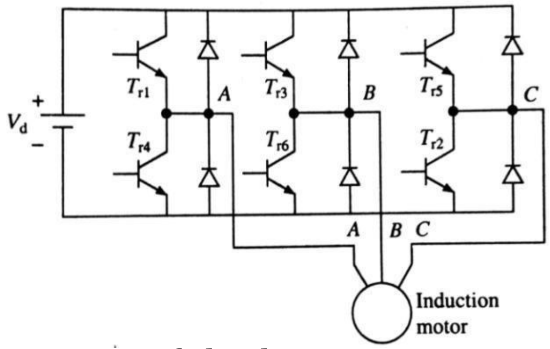


Fig. VSI fed Induction Motor

❖ MOSFET is used in low voltage and low power inverters.
❖ IGBTs and power transistors are used up to medium power levels.
❖ GTO and IGCT are used for high power levels.
❖ VSI may be a six step inverter or a PWM inverter.

❖ When VSI is operated as a six step inverter, the transistors are turned ON in the sequence of their numbers with a time interval of T/6 seconds if T is the total time period of one output cycle.
❖ Frequency of the inverter output is varied by varying the time period (T) of one cycle.
❖ If the supply is dc, then a variable dc voltage is obtained by connecting a chopper between input dc and the inverter as shown in Fig. below

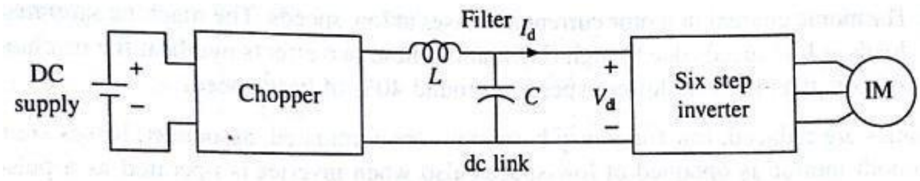


Fig.

❖ If the input supply is ac, then a variable dc is obtained by connecting a controlled rectifier between the input ac and the inverter and the. output voltage waveform of a six step inverter is shown in Figures below

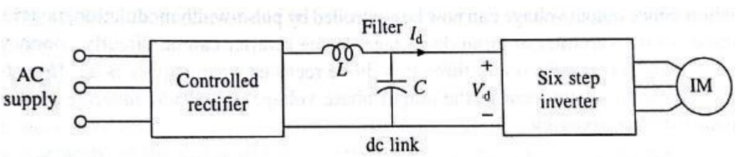


Fig.

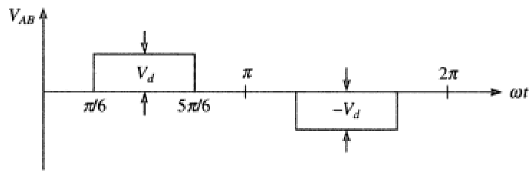


Fig.

Disadvantages of six step inverter

❖ Low frequency harmonics are more and hence the motor losses are increased at all speeds.
❖ Motor develops pulsating torques due to 5th, 7th, 11th and 13th harmonics.
❖ Harmonic content increases further when the motor rotates at low speeds. This will overheat the machine.

The above said problems are rectified when a PWM inverter is used.

- If a PWM inverter is used as VSI as shown in Fig 4.11, then the input voltage may be a constant dc which is obtained from a simple diode rectifier. The output of a PWM inverter is a variable voltage and variable frequency.

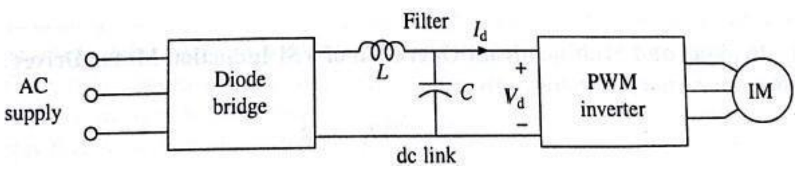


Fig. 4.11

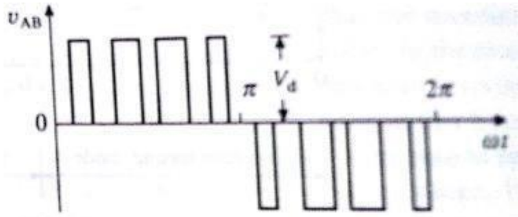


Fig. 4.12

- In a PWM inverter, it is possible to control the output voltage and frequency as well as the harmonic content can be minimized.
- The output voltage waveform of a PWM inverter is shown in Fig. 4.12
- The motors having high leakage inductance are used when a VSI is used to feed the induction motors.

CLOSED LOOP SPEED CONTROL OF INDUCTION MOTOR FED FROM VOLTAGE SOURCE INVERTER

- It employs an inner slip speed loop and an outer speed loop as shown in Fig.below.
- The slip speed loop acts as inner current control loop. It also ensures the motor to operate between synchronous speed and the speed at which maximum torque occurs for all frequencies.
- Thus a high torque will be produced for a small current drawn from supply.
- The drive uses a PWM inverter fed from a dc source. Regenerative braking and four quadrant operation of drive is possible because of the use of PWM inverter.
- The speed error is processed through a speed controller, usually a PI controller, and a slip regulator.

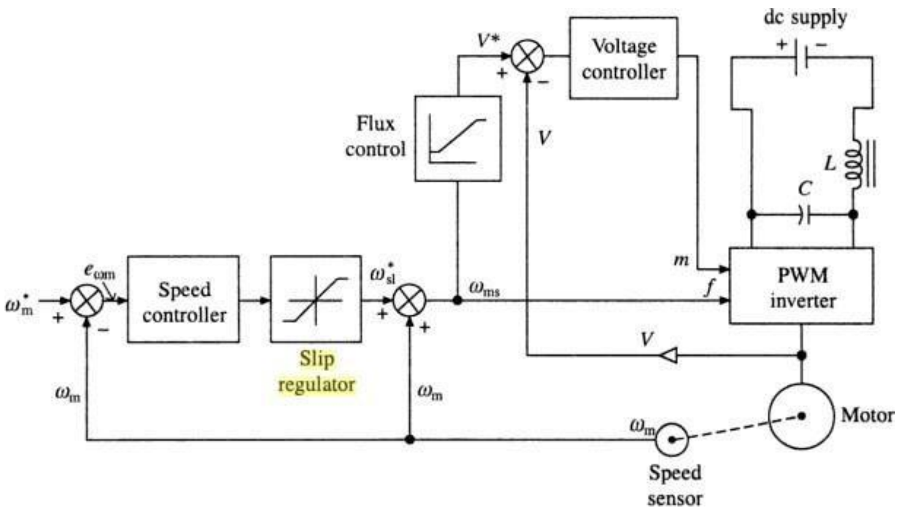


Fig. Closed Loop Speed Control of Induction Motor fed from VSI

- ***P*** controller reduces the steady state error and ***I*** controller reduces the peak overshoot and settling time so that the response will be faster.
- PI controller gives good steady state accuracy and reduces the noise.
- Slip regulator set the slip speed command $\boldsymbol{\omega_{sl}}^*$. This command controls the inverter current to its maximum allowable value.
- The synchronous speed obtained by adding actual speed $\boldsymbol{\omega_m}$ and slip speed $\boldsymbol{\omega_{sl}}^*$ determines the frequency of inverter output voltage.
- Reference signal $\mathbf{V}^*$ for controlling the output voltage of inverter is generated using a flux control block.
- This reference signal ensures a constant flux operation below base speed and constant voltage operation above base speed.

- **If the motor speed is to be increased**, then the reference speed $\boldsymbol{\omega_m}^*$ will be set to the required speed.
- Now the comparator compares the actual speed and reference speed and produces a positive error.
- This will set the slip speed command $\boldsymbol{\omega_{sl}}^*$ at its maximum value.
- Hence the motor starts accelerating (i.e speed increases) at the maximum inverter current and hence the speed error decreases.
- When the actual motor speed reaches the reference value, the drive finally settles at that speed. At this speed, the motor torque equals the load torque.

- **If the motor speed is to be decreased**, then the reference speed $\boldsymbol{\omega_m}^*$ will be set to the required speed.
- Now the comparator compares the actual speed and reference speed and produces a negative error.
- This will set the slip speed command $\boldsymbol{\omega_{sl}}^*$ at its maximum negative value.
- Hence the motor starts decelerating (i.e speed decreases) at the maximum inverter current and hence the speed error decreases. Here regenerative braking is applied.
- When the actual motor speed reaches the reference value, the drive finally settles at that speed. At this speed, the motor torque equals the load torque.

- For operation below base speed, the ratio (V/f) is kept constant.
- For operation above base speed, the terminal voltage is kept constant and frequency is increased.
- For low frequency operation, the ratio (V/f) is increased to maintain constant flux operation.

- **When a fast response is required**, the drive can be made to accelerate at a current more than the rated current of induction motor.
- But the power electronic switches present in the inverter must be selected such that they can withstand for those high currents. Any device with increased current rating will be more costly. This will increase the cost of total drive system.
- When fast response is not required, current ratings of inverter and rectifier can be chosen to be marginally higher than that of the motor.

CURRENT SOURCE INVERTER (CSI) FED INDUCTION MOTOR DRIVES

- In current source inverters, the input current is constant but adjustable.
- The magnitude of output current of CSI is independent of the load.
- But the magnitude of output voltage depends on the type of load.
- A CSI converts the input dc current into an ac current at its output terminals.
- The output frequency of ac current depends upon the triggering of SCRs.
- Magnitude of output current can be adjusted by controlling the magnitude of dc input current.
- Out of the force commutated CSIs, Auto Sequential Commutated Inverter (ASCI) is the most popular CSI.
- A single phase ASCI is shown in Fig. below

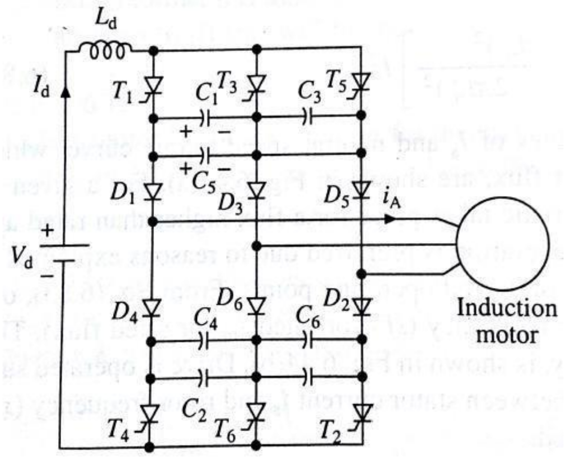


Fig.CSI fed Induction Motor Drive

- A large inductance is connected to make this inverter as current source inverter.
- Capacitors C_1 to C_6 are used for commutating the thyristors. These thyristors are fired in sequence with 60^0 intervals.
- Diodes D_1 to D_6 are connected in series with thyristors to prevent the discharge of capacitors through load.
- The inverter output frequency is controlled by adjusting the period ***T*** through triggering circuits of thyristors.

❖ The fundamental component of motor phase current is,

$$I_s = \frac{\sqrt{6}}{\pi} I_d$$

❖ For any given speed, the motor torque is controlled by varying the dc current $\mathbf{I_d}$. This $\mathbf{I_d}$ can be varied by varying $\mathbf{V_d}$.

❖ Different types of circuit configurations are shown in Figures below.

❖ When the available supply is AC, then a controlled rectifier is connected between the input supply and the inverter as shown in Fig.below

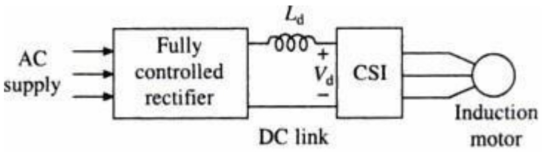


Fig.

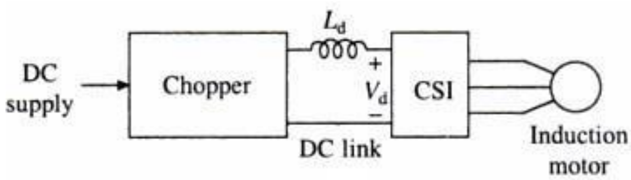


Fig.

❖ The output of fully controlled rectifier will be a variable DC which will vary $\mathbf{I_d}$. This DC current is converted into AC using a CSI and it is given to the induction motor.

❖ If the available supply is a fixed DC, then a chopper may be added between the supply and the inverter as shown in Fig. above.

❖ Chopper will give a variable DC voltage V_d which further varies I_d. This DC current is converted into AC using a CSI and it is given to the induction motor.

❖ In VSI, in case of commutation failure, two SCRs in the same leg may conduct. This will short circuit the input supply and hence the current through SCRs will rise to a high value.

❖ Hence high speed semiconductor fuses are needed to protect the devices and thus making the system costly.

❖ In case of CSI, no such problem arises even if two devices in same leg conduct. Because the current is controlled by the large inductance connected in series with the source.

❖ Hence CSI is more reliable than VSI.

❖ The output current of CSI shown in Fig. 4.15 rises and falls very rapidly. This creates a huge voltage across the leakage inductance of the motor windings. Hence a motor with less leakage inductance is used.

❖ Using large values of commutation capacitors can reduce these voltage spikes. But because of large values of capacitors and inductors, the CSI drive becomes expensive and bulky.

❖ These types of auto sequentially commutated inverters are used widely in medium and large power current source inverter drives.

CLOSED LOOP CONTROL OF CURRENT SOURCE INVERTER (CSI) FED INDUCTION MOTOR DRIVES

- The closed loop CSI shown in Fig. below consists of an inner slip speed loop and outer speed loop as in the case of VSI.
- This drive operates at constant flux up to base speed. Hence it gives constant torque operation.

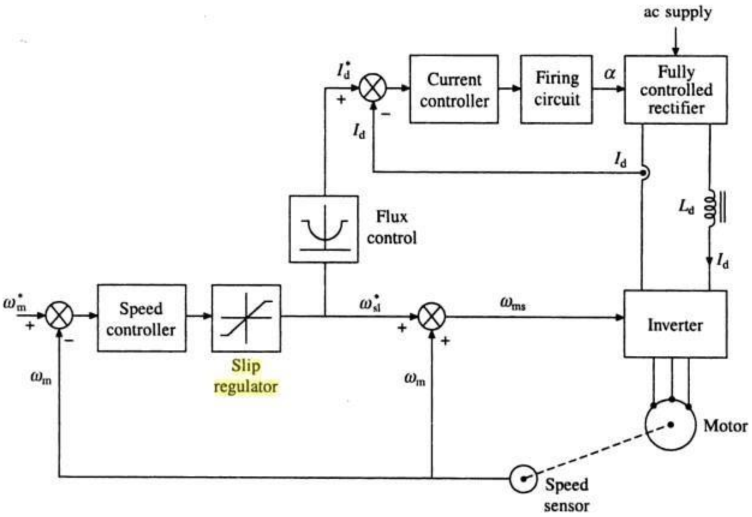


Fig. Closed loop CSI fed IM drive

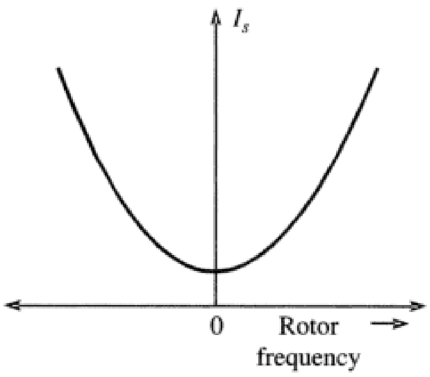


Fig. Is Vs sf curve

- Terminal voltage is kept constant above base speed which gives constant power operation.
- The actual speed ω_m is compared with the reference speed ω_m^*.
- The speed error is processed through a speed controller (normally a PI controller) and a slip regulator.
- Slip regulator controls the slip speed (Ns – Nr). The sum of rotor speed ω_m and slip speed ω_{sl} gives the synchronous speed. This determines the frequency of the inverter output.
- Constant flux operation below base speed is obtained when the slip speed (or rotor frequency) and inverter current **Is** have the relationship as shown in Fig. below
- This relationship is maintained by flux control block. Flux control block produces a reference signal I_d^* based on the value of ω_{sl}^*.
- This I_d^* will adjust the dc link current I_d through a closed loop to maintain constant flux.
- Both speed and current controllers use PI controllers to get good steady state accuracy.
- **If the speed of the drive is to be increased**, then the required speed is set as reference speed ω_m^*. Now the speed error is positive and slip speed (Ns – Nr) also positive.
- The drive now accelerates at maximum current in motoring mode. When the motor speed equals the reference speed, the motor continues to rotate at that speed where the motor torque equals load torque.
- **If the speed of the drive is to be decreased**, then the required speed is set as reference speed ω_m^*. Now the speed error and slip speed (Ns - Nr) are negative.

- The drive now decelerates at maximum current in braking mode. When the motor speed equals the reference speed, the motor continues to rotate at that speed where the motor torque equals load torque.
- Above base speed, the terminal voltage is kept constant to get constant power operation.
- Now flux control block and closed loop control of $\mathbf{I_d}$ become ineffective. Hence $\mathbf{I_d}$ may increase to high value which is not appreciable.
- To control $\mathbf{I_d}$, the slip speed limit of slip regulator must increase proportional to inverter frequency.
- This achieved by adding a signal proportional to frequency with the slip regulator output.

Comparison of Current Source Inverter (CSI) & Voltage Source Inverter (VSI) drives

Current Source Inverter (CSI) drives	Voltage Source Inverter (VSI) drives
CSI is more reliable because conduction of two devices in the same leg does not short circuit the input supply.	Conduction of two devices in the same leg due to commutation failure causes short circuit of the input supply. This may raise the current through the devices and damage them.
Raise of current is prevented because of the presence of large inductance in the current source.	It requires expensive high speed semiconductor fuses for controlling the current due to short circuit.
Motor current rise and fall are very fast and that creates high voltage across windings.	No such problem arises here in case of VSI.
These high voltage spikes are controlled by having large values of commutating capacitors which may increase the cost and size of the inverter.	Less costly than CSI.
Slow response due to large value of input inductance.	Fast dynamic response is possible if VSI uses PWM inverter. If a six step inverter is used, then response becomes slower like CSI drives.
Frequency range of CSI is lower than VSI. Hence CSI drive has lower speed range.	Frequency range is wide and hence the speed range is also wide.
CSI requires a separate rectifier and inverter combination. Hence it is not suitable for multi motor drives.	A single rectifier can be used to feed many VSIs. Hence VSI is suitable for multi motor drives.
Regenerative braking is naturally possible in CSI.	An additional full converter is required to achieve regenerative braking.
If input AC supply fails, electric braking is not possible in CSI.	But VSI can use dynamic braking in case input AC supply fails.

SPEED CONTROL OF INDUCTION MOTOR ON ROTOR SIDE

- This method of speed control is applicable only to wound round or slip ring induction motors.
- The portion of air-gap power which is not converted to mechanical energy is called slip power.
- Hence the mechanical power developed is controlled by varying the slip power by some methods. This further controls the speed of the motor.
- Controlling the slip power is done by three different methods.
  - Static rotor resistance control
  - Emf injection into rotor circuit
    - Static Scherbius drive
    - Static Kramer drive

Rotor resistance control

- In this method of speed control, an external resistance is added with rotor circuit and it is varied to control the speed of the induction motor. This method is applicable only to slip ring induction motor.
- We know that

$$T \propto \frac{S}{R_2} \quad \text{and hence} \quad R_2 \propto \frac{S}{T}$$

- From the above equation, it is clear that any increase in R_2 will increase slip S. Increase in slip means reduction in speed. Hence rotor resistance varies the speed.
- Rotor resistance does not affect the value of maximum torque produced by the motor. But it changes the speed at which the maximum torque is produced. It is shown in Fig. below
- It is clear from Fig. 4.20 that for the same value of motor torque, the speed reduces with an increase in rotor resistance.

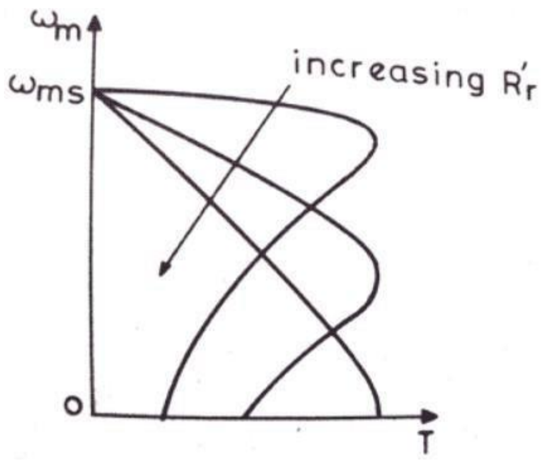


Fig. Speed - Torque char.

- In this method of speed control, the motor torque does not change even at low speeds. Also this method is less costly when compared to variable frequency operations.
- Because of its low cost and high torque producing capabilities, this method is used in cranes.
- But major disadvantage of this method is its low efficiency due to additional power losses in the external resistance connected to the rotor.
- These losses occur in the external resistor. So the heat produced around the external resistor does not
increase the heat of the motor.

Static Rotor resistance control

- In a three phase slip ring induction motor, a three phase diode rectifier, a chopper and a single resistor is connected as shown in Fig. below.

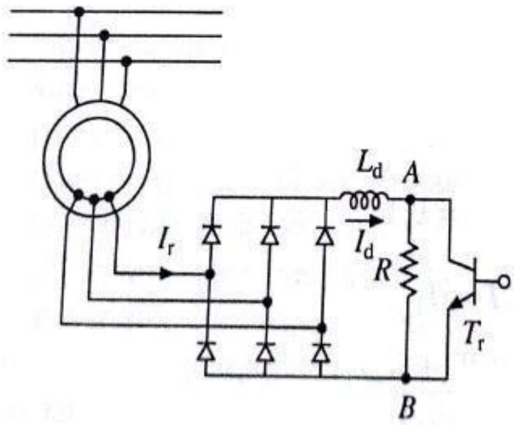


Fig.

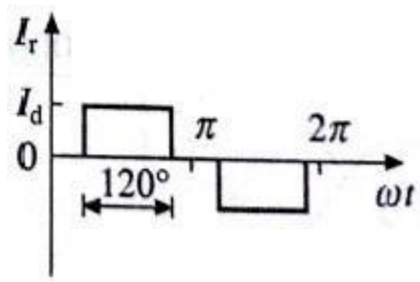


Fig.

- An inductor **Ld** is connected to reduce the ripple present in the dc link current.
- The rotor current waveform is shown in Fig. above
- The rms value of rotor current is given by,

$$I_r = \sqrt{\frac{2}{3}} I_d ------1$$

- The ac output voltage from rotor windings is rectified using diode bridge and it is fed to the parallel combination of fixed resistor and a transistor.
- The effective value of this resistance connected between the terminals A & B is varied by varying the duty cycle of the transistor.
- The resistance between A & B is zero when transistor is ON. Resistance between A & B is maximum (i.e R) when transistor is off.
- The effective resistance connected between A & B is given by,

$$R_{AB} = (1 - \alpha)R ----- 2$$

Where □ is the duty cycle.

- Power consumed by R_{AB} is,

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

- Power consumed by R_{AB} per phase is,

$$\frac{P_{AB}}{3} = \frac{I_d^2(1 - \alpha)R}{3} ----- 3$$

- From eqn. 1,

$$I_d = \sqrt{\frac{3}{2}} I_r ----- 4$$

- Substituting eqn 4 in eqn 3, we get,

$$\frac{P_{AB}}{3} = \frac{I_d^2(1-\alpha)R}{3} = \frac{\frac{3}{2}\mathrm{I}_\mathrm{r}^2(1-\alpha)R}{3}$$

- Therefore power consumed by R_{AB} per phase is,

$$= 0.5.\mathrm{I}_\mathrm{r}^2(1-\alpha).R ----5$$

- From the above equation 5, it is clear that the rotor resistance is increased by 0.5 R(1-α)
- Thus the total resistance in the rotor circuit is,

$$R_{rT} = R_{r} + 0.5\ R(1-\alpha)$$

- From the above equation, it is clear that rotor resistance is varied from R_r to (R_r+0.5R) when is varied from 1 to 0.

Advantages of rotor resistance control method

- Smooth and stepless control is possible.
- Quick response
- Less maintenance
- Compact size.

Disadvantages of rotor resistance control method

- Increase in rotor resistance leads to increase of power loss in the rotor resistance. This will reduce the system efficiency.

Energy efficient drive (Or) Slip Power Recovery Schemes

- In rotor resistance control method of speed control, the slip power is wasted in the external resistance and hence the efficiency reduces.
- However instead of wasting the slip power in external resistor, it can be recovered and supplied back in order to improve the overall efficiency.
- This scheme of recovering the power is called slip power recovery scheme and this is done by connecting an external source of emf of slip frequency to the rotor circuit.
- The injected emf can either oppose the rotor induced emf or aids the rotor induced emf.
- If it opposes the rotor induced emf, the total rotor resistance increases and hence speed decreases
- If the injected emf aids the main rotor emf the total resistance decreases and hence speed increases.
- Therefore by injecting induced emf in rotor circuit the speed can be easily controlled.

Static Kramer Drive

- In this method of speed control, the slip power flows in only one direction. It flows from the rotor back to main supply. Hence the speed can be controlled below synchronous speed only.
- The circuit for static Kramer drive is shown in Fig. below. The slip power from the rotor circuit is converted to dc voltage V_d by diode rectifier.
- The inductor L_d filters the ripples present in the dc voltage V_d.

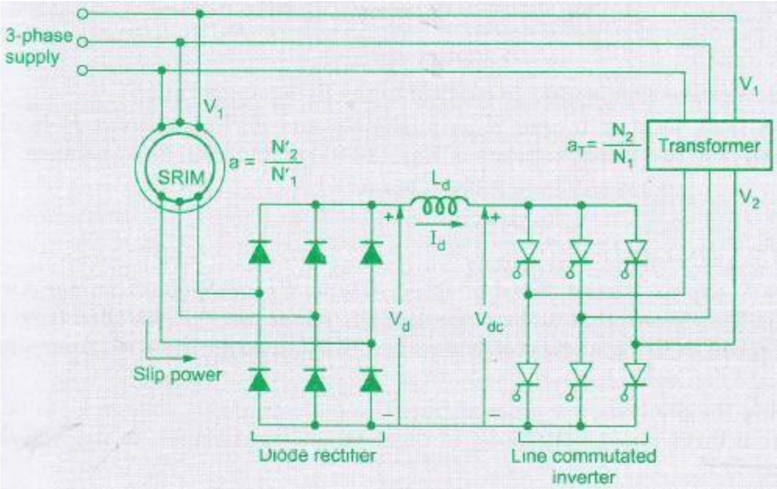


Fig. Static Kramer Drive

- This dc voltage is then converted to ac voltage at line frequency (50 Hz) using a line commutated inverter and pumped back to ac source.
- This drive offers a constant torque operation.

Analysis

This rotor voltage is rectified by diode rectifier. The output voltage of diode rectifier is given by,

$$V_d = \frac{3.V_{ml}}{\pi} ------1$$

Here V_{ml} is the maximum value of line voltage supplied to diode rectifier.

$$Rotor\ voltage\ per\ phase\ = S.E_2 ----2$$

Here E_2 is the per phase rotor emf at standstill and it is given as input to diode rectifier. S is the slip.

$$Rotor\ line\ voltage, V_l = \sqrt{3}.S.E_2$$

$$Maximum\ value\ of\ rotor\ line\ voltage, V_{ml} = \sqrt{2}.\left(\sqrt{3}.S.E_2\right) = \sqrt{6}.S.E_2 ----3$$

$$\therefore V_d = \frac{3.\sqrt{2}\sqrt{3}.S.E_2}{\pi} = \frac{3.\sqrt{6}.S.E_2}{\pi} ----4$$

In induction motor, the turns ratio and voltage ratio is given by,

$$\frac{E_2}{V_1} = \frac{N_2}{N_1}; \qquad \boldsymbol{E_2} = \frac{N_2}{N_1}.V_1 = \boldsymbol{a.V_1} ----5$$

Substituting equation 5 in equation 4, we get,

$$\boldsymbol{V_d} = \frac{3.\sqrt{6}.S.a.V_1}{\pi} = \boldsymbol{2.339.(S.a.V_1)} ----6$$

- DC output voltage of a three phase line commutated inverter without transformer is,

$$V_{dc} = -\frac{3.V_{ml}}{\pi}\cos\alpha$$

$$Here\ V_{ml} = \sqrt{2}.\sqrt{3}.V_1$$

$$\therefore V_{dc} = -\frac{3.\sqrt{2}.\sqrt{3}.V_1}{\pi}\cos\alpha = \frac{3.\sqrt{6}.V_1}{\pi}\cos\alpha$$

$$\therefore V_{dc} = -2.339.V_1.\cos\alpha ----7$$

- At no load, $V_d = V_{dc}$. (Eqn 6 = Eqn 7)

$$2.339.(S.a.V_1) = -2.339.V_1.\cos\alpha$$

$$S.a = -\cos\alpha$$

$$S = -\frac{1}{a}\cos\alpha ----8$$

- $For\ a\ = 1,\ slip, S\ = -\cos\alpha$
- $For\ \alpha = 90^o, then\ Slip, S = 0 \quad (synchronous\ speed) ----9$
- $For\ \alpha = 180^o, then\ Slip, S = 1 \quad (zero\ speed) ----10$
- It is clear from the equations 9 & 10 that, the motor speed can be varied from zero speed to synchronous speed when the firing angle □ of line commutated inverter is varied from 180^0 to 90^0.
- In actual practice, the rotor voltage will be less than the supply voltage. Hence a transformer is required to step up the voltage before feeding t back to supply.
- Let the transformer turns ratio be,

$$a_T = \frac{V_2}{V_1}\ and\ hence\ V_2 = a_T.V_1$$

- DC output voltage of a three phase line commutated inverter without transformer is,

$$V_{dc} = -\frac{3.V_{ml}}{\pi}\cos\alpha$$

$$Here\ V_{ml} = \sqrt{2}.\sqrt{3}.a_T.V_1 = \sqrt{6}.a_T.V_1$$

$$\therefore V_{dc} = -\frac{3.\sqrt{6}.a_T.V_1}{\pi}\cos\alpha = -2.339.a_T.V_1.\cos\alpha ----11$$

- At no load, $V_d = V_{dc}$. (Eqn 6 = Eqn 11)

$$2.339.(S.a.V_1) = -2.339.a_T.V_1.\cos\alpha$$

$$S.a = -a_T.\cos\alpha$$

$$S = -\frac{a_T}{a}\cos\alpha ----12$$

Total slip power is given by,

$$3.S.P_g = V_{dc}.I_d$$

$$3.S.\omega_s.T_e = V_{dc}.I_d$$

$$T_e = \frac{V_{dc}.I_d}{3.S.\omega_s} ----13$$

Substituting the values of V_{dc} and S from equations 7 & 8 in equation 13, we get,

$$T_e = \frac{-2.339. V_1. \cos\alpha . I_d}{\left(-\frac{1}{a}\cos\alpha\right). \omega_s} = \frac{2.339. a. V_1. I_d}{3. \omega_s} ----14$$

When a transformer is used, the values of V_{dc} and S will be given by the equations 11 & 12. Hence substituting equations 11 & 12 in equation 13, we get,

$$T_e = \frac{-2.339. a_T. V_1. \cos\alpha . I_d}{3.\left(-\frac{a_T}{a}\cos\alpha\right). \omega_s} = \frac{2.339. a. V_1. I_d}{3. \omega_s} ----15$$

Looking into the equations 14 & 15, it is clear that Te is same whether a transformer is used in the system or not. Also T_e is

- Proportional to I_d
- Proportional to V_1
- Proportional to the turns ratio, a
- Inversely proportional to ω_S

The dc link current **I_d** is given by,

$$I_d = \frac{V_d - V_{dc}}{R_d}$$

$$V_d = V_{dc} + I_d. R_d = 2.339. S. a. V_1$$

$$\therefore Slip, S = \frac{V_{dc} + I_d. R_d}{2.339. a. V_1} = \frac{-2.339. a_T. V_1. \cos\alpha + I_d. R_d}{2.339. a. V_1}$$

$$\therefore Slip, S = \frac{-2.339. a_T. V_1. \cos\alpha}{2.339. a. V_1} + \frac{I_d. R_d}{2.339. a. V_1} = -\frac{a_T}{a}. \cos\alpha + \frac{I_d. R_d}{2.339. a. V_1} ----16$$

Motor speed is given by,

$$\omega_m = \omega_S(1 - S) ----17$$

Substituting the value of S from equation 16 in equation 17, we get,

$$\omega_m = \omega_S\left[1 + \frac{a_T}{a}. \cos\alpha - \frac{I_d. R_d}{2.339. a. V_1}\right] ----18$$

From equation 15, the total torque $3T_e$ is given by,

$$3. T_e = T_L = \frac{2.339. a. V_1. I_d}{\omega_s}$$

$$I_d = \frac{\omega_s. T_L}{2.339. a. V_1} ----19$$

Substituting equation 19 in equation 18, we get,

$$\omega_m = \omega_S\left[1 + \frac{a_T}{a}. \cos\alpha - \left(\frac{\omega_s. T_L}{2.339. a. V_1} \times \frac{R_d}{2.339. a. V_1}\right)\right] = \omega_S\left[1 + \frac{a_T}{a}. \cos\alpha - \frac{\omega_s. R_d. T_L}{(2.339. a. V_1)^2}\right]$$

$$\omega_m = \omega_S\left[1 + \frac{a_T}{a}.\cos\alpha - \frac{\omega_s.R_d.T_L}{(2.339.a.V_1)^2}\right] - - - - 20$$

$$\omega_m = \omega_S\left[1 + \frac{a_T}{a}.\cos\alpha - K.T_L\right] - - - - 21$$

$$where\ K = \frac{\omega_s.R_d}{(2.339.a.V_1)^2}$$

From equation 21, the no load speed of the drive is given by,

$$\omega_m = \omega_S\left[1 \quad \frac{a_T}{}. \qquad \right] - - - -$$

Using equation 20, the speed - torque characteristics are drawn as shown in Fig.

Fig. 4.24 Speed - Torque characteristics

Static Kramer systems are used in large power pumps and compressor type loads where speed control range is less and below synchronous speed.

Static Scherbius Drive

In static Kramer drive, the speed of slip ring induction motor can be controlled below synchronous speed only.

For controlling the speed below and above synchronous speed, the static Scherbius drive is used.

There are two configurations of this drive. They are,

1. DC link Scherbius Drive
2. Cycloconverter Scherbius Drive

DC link Scherbius Drive

- For controlling the speeds below synchronous speed (Sub Synchronous), the slip power is removed from the rotor circuit and it is fed back into the input AC supply.
- For controlling the speeds above synchronous speed (Super Synchronous), an additional power is fed into the rotor circuit at slip frequency.
- The circuit of dc link Scherbius drive is shown in Fig. below and it has a slip ring induction motor, two controlled converters, a smoothing inductor and a transformer.
- Smoothing inductor is used to suppress the ripples present in the dc link.

Sub synchronous speed control

- Bridge 1 is operated with a firing angle range of 0^0 to 90^0. It means that bridge 1 works as rectifier.
- Bridge 2 is operated with a firing angle range of 90^0 to 180^0. It means that bridge 2 works as inverter.
- Now the slip power flows from the rotor circuit to the supply through bridge 1, bridge 2 and transformer.
- Here transformer steps up the rotor voltage to the level of ac input supply.

Sub synchronous speed control

- Bridge 1 is operated with a firing angle range of 90^0 to 180^0. It means that bridge 1 worksas inverter.
- Bridge 2 is operated with a firing angle range of 0^0 to 90^0. It means that bridge 2 works as rectifier.
- Now the slip power flows from the input ac supply to the rotor circuit through transformer, bridge 2 and bridge 1.
- Here transformer steps down the input ac supply to the level of rotor voltage.

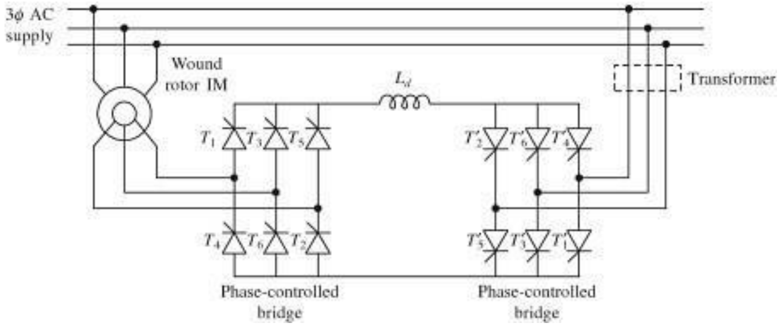


Fig. DC Link Static Scherbius Drive

- Rotor voltages at slip frequency are used to commutate the thyristors present in the converters.
- At low speeds, the voltage across rotor will be less and it may not be sufficient to naturally commutate the thyristors.
- This difficulty can be overcome by using forced commutation. It means that an additional forced commutation circuitry is necessary for Scherbius drives where both below and above synchronous speeds are possible.
- Also this Scherbius scheme requires 6 thyristors in place of 6 diodes present in Kramer drive. Hence the drive becomes costly compared to static Kramer drive.

Cycloconverter Scherbius Drive

- A 3 phase Cycloconverter can be used to control the speed of a 3 phase induction motor.
- Cycloconverter fed induction motors are used in applications such as high power pumps and blower type drives.
- Using a Cycloconverter, it is possible to send power in both the directions and hence speed control below and above synchronous speed is possible.
- Also it allows regenerative braking during which the power is fed back to the supply.
- Like dc link Scherbius drive, this scheme also offers a constant torque operation.

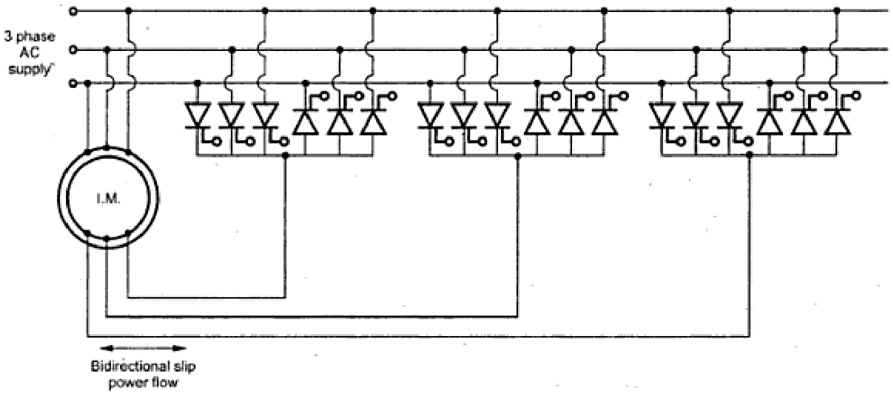


Fig. Cycloconverter Static Scherbius Drive

UNIT-III

PART-A

1	List the parameters on which the speed of an induction motor depends upon?	CO3(L1)
2	Analyse the difficulties in controlling the speed of an induction motor?	CO3(L4)
3	Outline the features of cyclo-converter fed induction motor drives?	CO3(L2)
4	List the advantages of slip controlled induction motor drive.	CO3(L1)
5	Identify the problems associated with the speed control of induction motor using slip power recovery scheme	CO3(L3)
6	Outline the disadvantages of voltage/frequency control of induction motor drives?	CO3(L2)
7	Infer vector control?	CO3(L2)
8	Relate the advantages of vector control?	CO3(L2)
9	List the main advantages of Static Scherbius Drives?	CO3(L4)
10	Summarise the advantages of Kramer's drives?	CO3(L2)

PART-B

1	Analyse about the four quadrant closed loop speed control of induction motor drives.	CO3(L4)
2	Discuss about cycloconverter fed induction motor drives	CO3(L4)
3	Examine the Static Kramer's drive fed induction motor	CO3(L4)
4	Inspect the static Scherbius drive fed induction motor	CO3(L4)
5	Analyse voltage source inverter fed induction motor drive.	CO3(L4)
6	Discuss about voltage / frequency control of induction motor drives	CO3(L4)

UNIT-IV

THREE PHASE SYNCHRONOUS MOTOR FED DRIVES

- Speed control of three phase synchronous motors –
- Types of control , Voltage source and current source converter fed synchronous motors
- Cycloconverter fed synchronous motors –Commutator less DC motor-
- Effects of harmonics on the performance of AC motors
- Closed loop control of drive motors, Marginal angle control and power factor control

Synchronous motor is an AC motor which rotates at synchronous speed at all loads. Construction of the stator of synchronous motor is similar to the stator of an induction motor. But the rotor has a winding.

Types of synchronous motors

Wound field synchronous motor

- Rotor of this motor has a winding for which a dc supply is given.
- Rotor may have either cylindrical structure or salient pole structure. Motors with cylindrical construction are used for high power and high speed applications.
- Salient pole construction is used for low power and low speed applications due to low cost.

Permanent magnet synchronous motor

- It is similar to a salient pole synchronous motor without field winding on the poles.
- Field flux is produced by permanent magnets mounted on the rotor.
- Ferrite magnets are used to construct the permanent magnets.
- Cobalt – samarium made magnets may be used if the volume and weight of the motor is to be reduced.
- The motor losses are less because of the absence of field winding and two slip rings.
- For the same size, a PMSM has higher pull-out torque and more efficiency as compared to salient pole motor.
- These motors are used in medium and low power applications like robots and machine tools.
- The main disadvantage in this motor is the inability to adjust the field current.

Synchronous reluctance motor

- It has salient poles. But there is no field winding or permanent magnet.
- A salient pole synchronous motor connected to a voltage source runs at synchronous speed.
- If its field current is switched off, it continues to run at synchronous speed as a reluctance motor.
- The motor is operated by the reluctance torque. This torque is produced by the alignment of the rotating flux with the stator flux at synchronous speed.
- These motors are used for low power drives where constant speed operation is required.

Hysteresis synchronous motor

- These motors are employed in low power applications requiring smooth start and noise less operation.
- The motor has low starting torque and hence it is suitable for high inertia loads.

Variable Frequency Control

- We know that, the synchronous speed is given by,

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

- From the above equation, it is clear that the speed of a synchronous motor can be controlled by varying the frequency of the supply.
- As in the case of induction motors, the stator flux is maintained constant by keeping the (v/f) ratio constant in this motor also. Constant flux operation ensures that the maximum torque at all frequencies is same.
- v/f ratio is increased at low frequencies to increase the torque producing capability of motor.
- Above rated speed, the stator voltage is kept constant and the frequency alone is increased. In this case, the torque produced by the motor may be reduced.

Variable frequency control may be achieved by any one of the methods listed below.

1. True synchronous mode (or) separate controlled mode.
2. Self synchronous mode (or) self controlled mode.

True synchronous mode (or) Separate controlled mode

- In this mode of speed control, the stator supply frequency is controlled from outside by using a separate oscillator.
- The frequency is changed from one value to the other gradually so that the difference between synchronous speed and rotor speed is small during any speed change.
- This gradual change in frequency helps the rotor to follow the stator speed properly at all operating points.
- When the desired speed is reached, the rotor gets locked with the stator flux speed (rotor pulls into step) after hunting oscillations.
- The block diagram of self control of multiple synchronous motors is shown in Fig. below

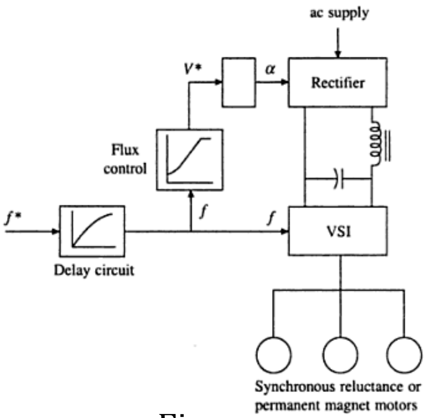


Fig.

- Here a voltage source inverter is used to feed the synchronous motors. It may be either a stepped wave inverter or a PWM inverter.
- A rectifier is used to supply dc voltage to the inverter. The rectifier will be a full converter if a six step inverter is used.
- If a PWM inverter is used, then a diode rectifier is sufficient at the input side.
- A smoothing inductor is used to filter out the ripples present in the dc link voltage.
- The frequency command f* is applied to the VSI through a delay circuit. This delay circuit ensures that the rotor follows the stator speed.

Self control mode of synchronous motor drive

- In self control, the stator supply frequency is changed proportional to the rotor speed.
- Hence the stator rmf rotates at the same speed as the rotor speed.
- This ensures that the rotor moves in synchronism with stator at all operating points.
- Consequently a self controlled motor will never come out of synchronism or step.
- It does not suffer from hunting oscillations.

Disadvantages of open loop control

- Hunting of motor
- Problems of instability
- Poor dynamic behavior
- Harmonic distortion

All the above disadvantages except harmonic distortion may be completely eliminated by using the motor in self control mode.

- The block diagram of a self controlled motor fed from a 3 phase inverter is shown in Fig.below
- The inverter may be a CSI or VSI. Depending on the type of inverter, the input dc source may be a controllable current source or controllable voltage source.

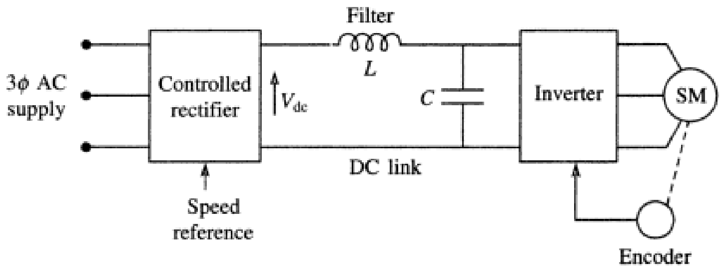


Fig. Self Controlled Synchronous Motor

- The inverter output frequency is determined by the rotor speed.
- The accurate speed of the rotor is tracked by using rotor position sensors.
- The output of rotor position sensor is used to produce firing pulses for the semi conductor switches used in the converter which feeds the motor.
- It means that the instants at which the switching devices operate to turn the stator windings ON and OFF is determined by the rotor position sensors.
- The switches are fired at a frequency proportional to the motor speed.
- With the increase of load if the rotor slows down, then the stator supply frequency automatically changes so that the rotor remains synchronized with the rotating field.
- When the motor starts from rest, the motor current will be large at first and then will decrease with increase of speed.
- The speed of the motor is controlled by varying the dc link voltage to the inverter.
- This dc link voltage is controlled by varying the firing pulses of the controlled rectifier.
- Four quadrant operation is possible if the inverter is fed from a full converter.

Self controlled synchronous motor fed from a load commutated thyristor inverter

- A self controlled synchronous motor employing a load commutated thyristor inverter is shown in Fig. below
- The drive employs two converters. One is called the side converter and the other is called the load side converter.

Source side converter

- It is a line commutated thyristor converter. It works as a line commutated controlled rectifier in the firing angle range of

$$0 \leq \alpha_S \leq 90^\circ$$

- Its output voltage V_{ds} and the output current I_d arepositive.
- Source side converter works as a line commutated inverter in the firing angle range of

$$90^\circ \leq \alpha_S \leq 180^\circ$$

- Now the voltage V_{ds} is negative and the output current I_d arepositive.

Load side converter

- When synchronous motor operates at leading power factor, the thyristors of the load side converter can be commutated by the motor induced voltages.
- It is called load commutation. This converter operates as an inverter and delivers a negative V_{dl} and positive I_d in the firing angle rangeof

$$90^{\circ} \leq \alpha_S \leq 180^{\circ}$$

- It operates as a rectifier and delivers a positive V_{dl} and I_d in the firing angle range of

$$0^{\circ} \leq \alpha_S \leq 90^{\circ}$$

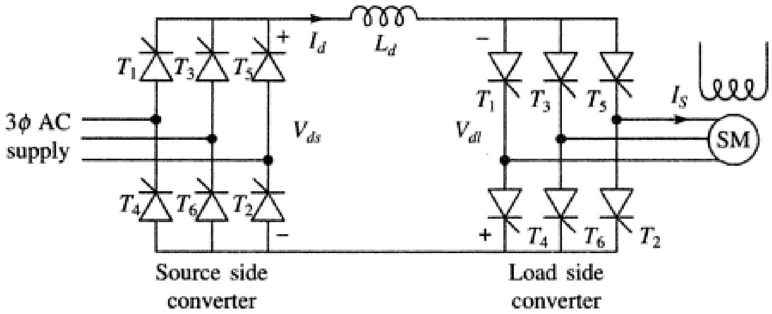


Fig.

Fig. Self controlled synchronous motor drive employing a load commutated inverter

- The synchronous motor can be operated at leading power factor by adjusting the field excitation of it.
- In this condition, the inverter operates as line commutated inverter.
- When source side converter is operated as rectifier and load side converter as inverter, then the power flows from ac source to the motor which gives motoring operation.
- When source side converter is operated as inverter and load side converter as rectifier, then the power flows from the motor to ac source which gives regenerative braking operation.
- The torque produced by the motor depends on the difference in voltages V_{ds} & V_{dl}. i.e(V_{ds} – V_{dl}).
- The speed of the motor is changed by changing the voltage V_{ds} which in turn is changed by varying the firing angle of source side converter.
- When the source side and load side converters are working as inverters, the firing angle of each thyristor switches should be less than 180^0 to avoid the short circuit of the dc supply.
- It may happen if two devices in the same leg conduct when firing angle is 180^0. So care should be taken for commutation overlap and turn off of thyristors.
- Let the commutation lead angle for load side converter as **β_l**. Then,

$$\beta_l = 180^{\circ} - \alpha_l$$

- If commutation overlap is neglected, then the input ac current will lag the input dc voltage by an angle $\_{l}$.
- As the motor current is opposite to converter input current, the motor current will lead the terminal voltage by an angle **β_l**. Hence the motor operates at leading power factor.
- For low values of **β_l**, the power factor will be high and the inverter rating will be low.
- The value of **β_l** may be reduced by reducing the sub transient inductance of the machine. It is done by using damper windings.

- When the load side converter acts as inverter, it is operated with a fixed commutation lead angle β_{lc} and when it acts as rectifier, it is operated with $\beta = 180^0$.
- At high power factor, the rating of the converter required is reduced. This is achieved by operating the load side converter with constant margin angle control.
- If μ is the commutation overlap of thyristor under commutation, then the duration for which reverse bias applied is,

$$\gamma = \beta_l - \mu$$

- For successful commutation,

$$\gamma > \omega t_q$$

Where t_q is the turn off time of thyristors.

- The commutation overlap is proportional to the dc link current I_d. Keeping a minimum value of γ, the value of β_l can be calculated.
- Keeping $\gamma = \gamma_{min}$, the value of β_l will be reduced and hence power factor will improve.
- This control scheme is called constant margin angle control.
- At low speeds, motor voltage will be less and not enough for commutating the thyristors.
- Hence force commutation is used when the motor speed is below 10% of rated speed.

Closed loop speed control of load commutated inverter fed synchronous motor drive

- Close loop control shown in Fig. below 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 that of the induced voltages in the rotor.
- These reference signals are shifted suitably by phase delay circuit to produce a constant commutation lead angle.
- Based on the speed error, the value of β_{lc} 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.

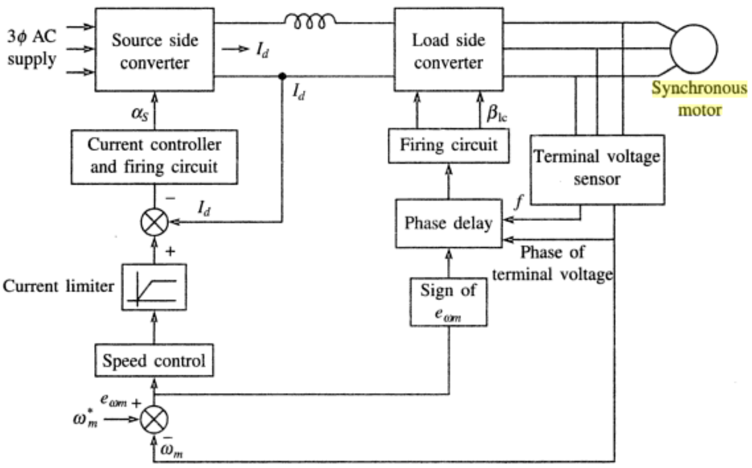


Fig.

Increasingthespeed

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

- Now the firing circuit produces β_{lc} 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 ω_m^*.
- Actual speed and reference speed are compared at the comparator and it produces a negative speed error.
- Now the firing circuit produces β_{lc} corresponding to braking operation.
- The speed controller and current controller get saturated and set the dc link reference current 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 MW
- 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.

CONSTANT MARGINAL ANGLE

The operation of the inverter at the minimum safe value of the margin angle gives the highest power factor and the maximum torque per ampere of the armature current,thus allowing the most efficient use of both the inverter and motor.

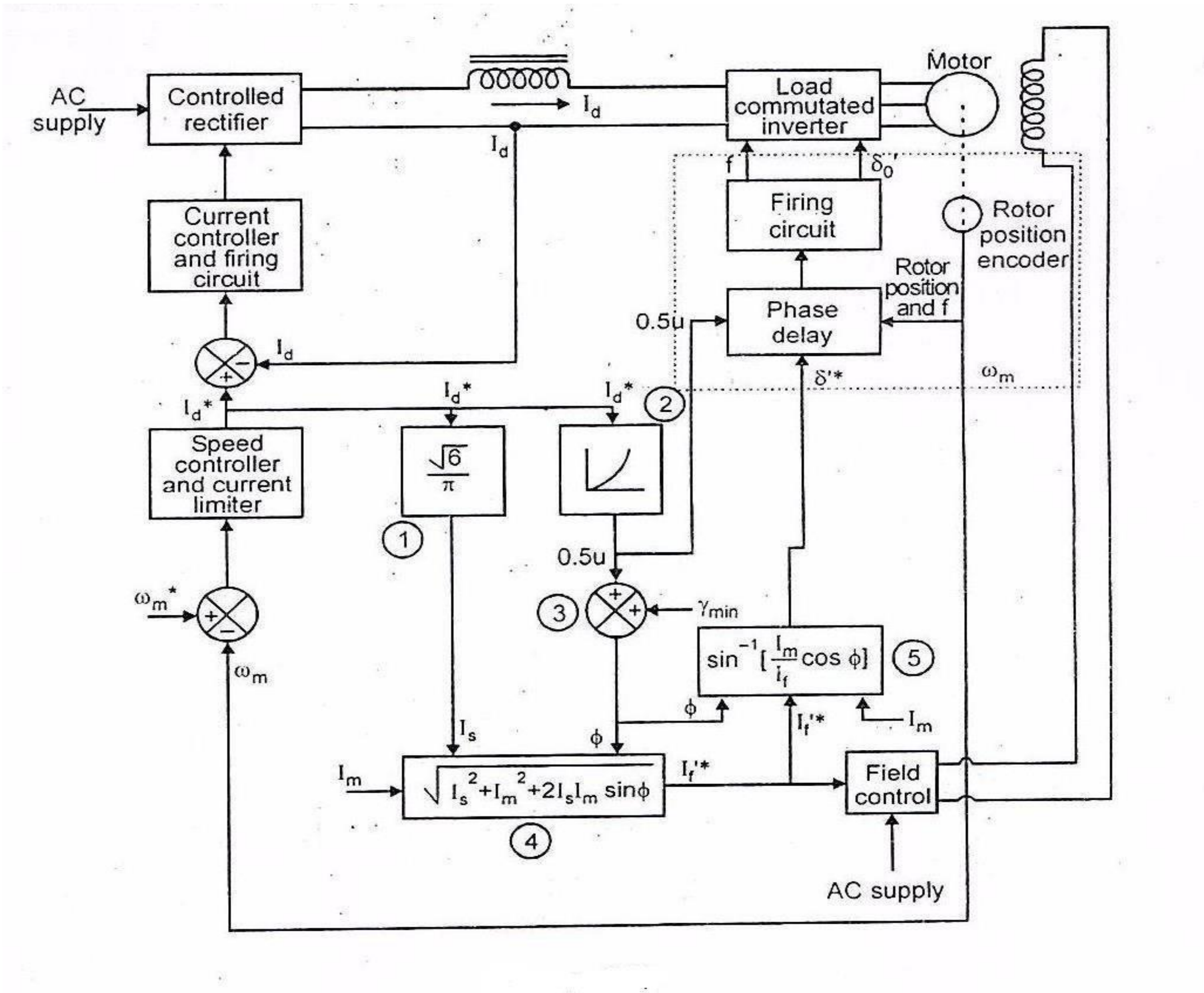


Fig Constant Marginal Angle Control

Fig shows the constant margine angle control for a wound field motor drive employing a rotor position encoder.This drive has an outer speed loop and an inner current loop.The rotor position can be sensed by using rotor position encoder.It gives the actual value of speed ωm.This signal is fed to the comparator.This comparator compares ωm and ωm* (ref value).

The output of the comparator is fed to the speed controller and current limiter.It gives the reference current value Id*.Id is the DC link current.It is sensed by current sensor and fed to the comparator.The comparator compares Id and Id*.The output of the comparator is fed to the currrent controller.It generates the trigger pulses.

It is fed to the cotrolled rectifier circuit.In addition ,it has an arrangement to produce constant flux operation and constant margin angle control.

From the value of dc link current command Id*,Is and 0.5u are produced by blocks (1) and (2) respectivly .The signal φ is generated from ymin and 0.5u in adder (3).

In block (4) If' is calculated from the known values of Is,φ and Im.Note that the magnetizing current Im is held constant at its rated value Im to keep the flux constant.

If* sets reference for the closed loop control of the field current I_F.Blocks (5) calculates δ'* from known,values of φ and If*

The phase delay circuit suitably shifts the pulses produced by the encoder to produce the desired value of δ_0'.This signal is fed to the load commutated inverter.

The load commutated inverter drives are used in medium power,high-power and very high power drives,and high speed drives such as compressors,extructers ,induced and forced draft fans,blowers,conveyers,aircraft test facilities,steel rolling mills,large ship propulsion,main line traction,flywheel energy storage and so on.

This drive also used for the starting of large synchronous machines in gas turbine and pumpled storage plant.

High power drives employ rectifiers with higher pulse numbers,to reduce torque pulsations.The converter voltage ratings are also high so that efficient high voltage motors can be employed.

POWER FACTOR CONTROL

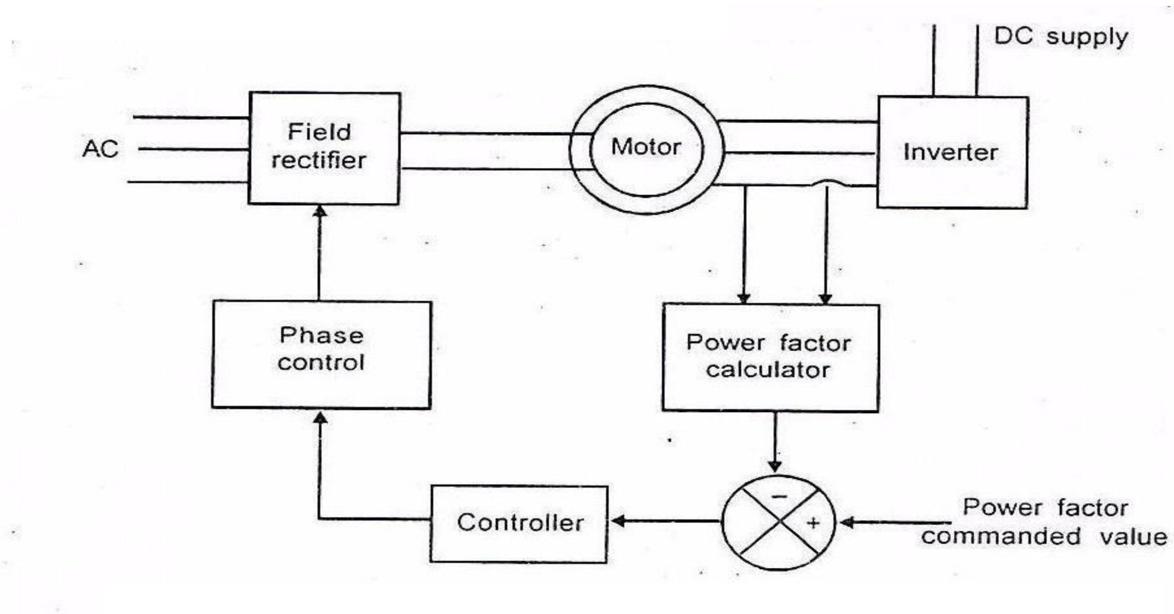


Fig Power Factor Control

Fig shows the block diagram of automatic closed loop adjustment of power factor.The main aim of adjustment of power factor is the variation of the field current.This is possible in a wound field machine. If the motor is operated at a power factor of unity,the current drawn by it will have the lowest magnitude for a given power input and therfore the lowest internal copper losses.

From this diagram ,the motor voltage and current are sensed and fed to the power factor calculator.The power factor calculator computes the phase angle between the two and therefore the power factor.It is the actual power factor value.The computed power factor value is compared against the power factor commanded value by using error detector.The error is amplified by thye error amplifier,and its output varies the field current power factor confirm to the commanded value

UNIT-IV
PART-A

1	List the features of synchronous motors which made them suitable for drive applications?	CO4(L4)
2	Compare voltage source inverter and current source inverter	CO4(L4)
3	List the merits of load commutated synchronous motor drives?	CO4(L4)
4	Infer the advantages of cycloconverter fed synchronous motor drives?	CO4(L2)
5	List some applications of self-controlled synchronous motor drives	CO4(L4)
6	Interpret the advantages of margin angle control of synchronous motor drives?	CO4(L2)
7	When operated with variable frequency synchronous motor has an advantage over an induction motor-true or false. Justify your answer.	CO4(L6)
8	Explain the ways of harmonics reduction?	CO4(L2)
9	Explain the starting of self controlled large synchronous motors?	CO4(L2)
10	Summarize the disadvantages of self commutated synchronous motor drives?	CO4(L2)

PART-B

1	Analyse the voltage source inverter fed synchronous motor drive.	CO4(L4)
2	Examine the current source inverter fed synchronous motor drive.	CO4(L4)
3	Analyse cycloconverter fed synchronous motor drive.	CO4(L4)
4	With neat block diagram inspect brushless or commutatorless dc motor drive fed from a voltage source	CO4(L4)
5	Discuss about the effects of harmonics on the performance of AC motors.	CO4(L4)
6	Examine load commutated synchronous motor drives.	CO4(L4)

UNIT 5

DRIVE APPLICATIONS

- Selection of drives and control schemes
- steel rolling mills,
- Paper mills,
- textile mills
- cranes
- Traction-Conventional-DC and AC Traction drives
- DC Traction using Chopper Controlled Drives
- Poly phase AC motors for Traction Motors

Drives for Specific Applications

Steel Mill:

The major function of rolling of steel mill is to reduce the cross section of the metal s while increasing the length proportionally. Steel mill usually produce blooms, slabs, rails, sheets, strips, beams, bar and angles. Technologically steel mill is divided into four categories :

Continuous cold rolling mills

- Reversing cold rolling mills
- Continuous hot rolling mills
- Reversing hot rolling mills

In reversing mill there is only one stand carrying the rolls that press the metal and metal is passed through this stand alternately forward and backward several times in order to reduce it to desired size. Each motion or travel is known as pass. A continuous mill consists of several stands, each one of them carrying pressing rolls. The metal passes through all the stands in only one direction and gets rolled.

Drives used in steel mills:

Dc motors is usually used in both reversible and continuous mills. Motor for reversing mills must have high starting torque, wide speed range, precise speed control, be able to withstand overload and pull out torque. Acceleration from zero to base speed and then to top speed and subsequent reversal from top speed backward to top speed forward must be achieved in few second. The moment of inertia of armature must be as small as possible and motors are enclosed and force ventilated. Ward-Leonard method for speed control is used. However, the speed control is replaced by thyristorised converter.

Paper Mills:

Pulp making and paper making are the two main important job for paper mills. The drive required each of them is quite different.

Pulp Making:

Pulp making requires grinding machines which almost run at constant speed that is acquired by synchronous motor. Motors run at speed of 200-300 rpm. However, pulp by mechanical means ,the motor runs at speed of 2000-3000 rpm for large grinder. Pulp is made by cutting the logs into several pieces and treated with alkalies and grass, rags etc. During the chemical treatment the material is continually motor is used. The end product of the beater is passed to chipping and refining .so, synchronous motor is used.

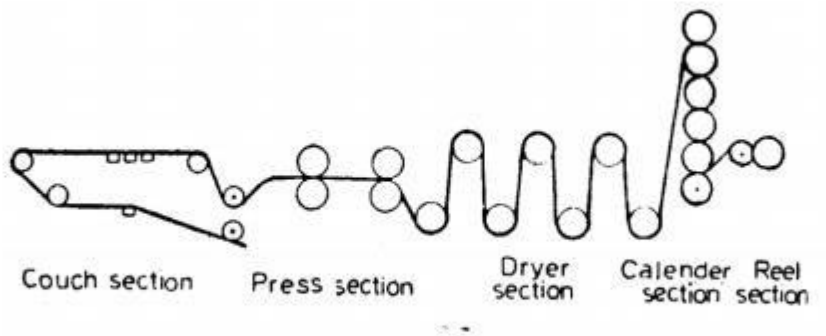
Paper making:

The machine that makes the paper from pulp has to perform several jobs from five sections. i)Couch section(Wire section) ii) Press section iii) Dryer section iv) Calender section v) Reel section

Drive Requirement:

Speed should be adjustable over a range of as large as 10:1

- In the wet end of paper machine the speed section should be independently adjustable.
- In the last two sections, speed control circuit must be good enough for tension control
- Control system employed should be flexible in nature.



Textile Mills:

From the raw material to finishing of cloths the mill has to perform several processes such as cotton to slivers, spinning, weaving and finishing. Cotton to slivers: The process by which the seeds are separated from cotton is called ginning. The cottons are converted into slivers and then processed by drawing machine. The slivers are then made lap form.

Spinning:

In this process, the slivers are made yarn is made of sufficient strength. This yarn is wound on bobbins by winding machine. Weaving: The yarn is made in uniform layers. Weaving consists of two sets of threads, one which extends throughout the length of the fabric and other whose thread go across. This process is done in a loom.

Finishing:

This consists a number of processes such as bleaching, dying, printing, calendaring, stamping and packing. The impurities like oil and grease are removed and the fabric is made white by bleaching.

Drives used in different sections:

In loom process loom motor is used where frequent start and stop is required. These results high temperature rise and sufficient ventilation is required. High torque three phase squirrel cage induction motor is used in loom motor. The motor is totally enclosed and must have capacity to absorbs the moisture content during the process. Card motor: It is similar to loom motor but it runs continuously for card drum.

Spinning motor:

For good quality of spinning the acceleration must be smooth. Three types of drives are required here, single speed motor (4 or 6 pole squirrel cage induction motor),two speed motor(4/6 or 8/6 pole motor) and two motor drive (two separate motor for driving single pulley)beaten by the beater. Beater requires speed less than 200 rpm so, slip ring induction

Textile mill drives

The textile mill has various processes like ginning. Spinning and looms. The ginning means the separation of seeds from cotton. The process requires standard starting torque and standard overload capacity, at constant speed. No speed control is required. The operation is at constant speed. The standard squirrel cage induction motor is the proper choice. The twisting to produce continuous yam of sufficient strength is called as spinning process. The moderate starting torque and high overload capacity is necessary. Acceleration must be constant or uniform so that there is no breakage of thread. The operation is at constant speed hence no speed control is necessary but two speed motors are preferred. Normally a 4 pole to 6 pole squirrel cage induction motor is used. Before the yarn is actually woven, it is made into a uniform layer. The process is called as weaving and done in a loom. This requires 2 to 2.3 times rated torque at start. There are frequent starts and stops. But operation is at constant speed and no speed control is necessary. The totally enclosed high torque squirrel cage induction motors are preferred. The motors are usually of 6 or 8 poles. The ratings of the motors for light fabrics such as cotton silk, rayon etc. are 0.37, 0.55 to 1.5 kW while for wool it is 2.2 to 3.7 kW.

From the stage cotton is picked in the field to the stage it leaves the mills as finished cloth; it undergoes different processes, viz., cotton to slivers, spinning, weaving and finishing.

Cotton to slivers: The process of separating the seeds from cotton is known as ginning. Ginning mills are usually located in the cotton growing areas. Bales oft ginned cotton are first transported to the textile mills. There, they are opened and the impurities are picked up and removed in the blow room. After further opening and cleaning, cotton is transformed into laps and fed to cording section. Here it is opened completely and is converted into slivers. The slivers are gathered in cans and then processed on a drawing machine, which makes then uniform by straightening the fiber. The slivers are then changed into lap form before feeding them for combing, which parallels the fiber and upgrades it.

Spinning: The sliver at this stage is in a fragile condition and is also bulky. After reducing the diameter in two or three stages, it is processed on 'speed frame', which makes it suitable for final spinning. Due to twisting a continuous yarn of sufficient strength is produced during spinning. This yarn is wound on bobbins located in cone winding machines.

Weaving: Before the yarn is actually woven, it is 'warped', i.e., made into a uniform layer. Weaving consists of joining two sets of threads, one which extends throughout the length of the fabric and the other whose threads go across. This process is done in a loom.

Finishing: This consists of a number of processes like bleaching, dyeing, printing, calendaring, stamping and packing. The impurities like oil and grease are removed and the fabric is made white during bleaching. Dyeing involves giving a colour or shade to the cloth. Printing produces designs and patterns in multicolor.

Motors Used/or Different Textile Processes

All machines used in accomplishing the different processes described above require electric motors as their drives. Special environmental, operating and drive conditions demand specially designed motors for textile industry.

Loom motors; In order to accomplish the 'pick up' process in a short time, the starting torque of the loom motor should be high being essentially a reciprocating mechanism causes both torque and current pulsations. Also, loom motors are subjected to frequent starts and stops, these results in a higher temperature rise and is taken care by having good thermal dissipation capacity of the motor.

Loom motors are either totally enclosed or totally enclosed fan cooled, three phase high torque squirrel cage induction motors. Presence of lot of fluff in the atmosphere requires a smooth surface finish of the housing and end shields so that the fluff does not get collected on the surface of the motor. The insulation of the motor must be able to withstand high moisture content.

The ratings of the motors used for driving looms for light fabrics such as cotton, silk, rayon, nylon etc. are 0.37, 0.55,0.75, 1.1 and 1.5 kW, while those of the motors used for making heavy fabrics (wool and canvas) are 2.2 and 3.7 kW. They are usually of 6 or 8 poles.

Card motors: The general requirement of card motors is almost similar to that of 100m motors except that the former are required to have a very high starting torque and must be able to withstand a prolonged starting period. Both the above requirements for the card motor are due to the very high inertia of the card drum. Once the drum is started, the operation is continuous and un interrupting, unlike that of a loom, where frequent starts and stops are involved.

The commonly used drives for card motors arc again totally enclosed and totally enclosed fan cooled three phase high torque squirrel cage induction motors. The usual ratings of motors for cards of light fabrics are 1.1 and 1.5 kW and those for cards of heavy fabrics are 2.2, 3, 3.7 and 5.5 kW. Here again, the preferred synchronous speeds are 750 and 1000 rpm.

Spinning motors: For good quality spinning, it is essential that the starting torque of spinning motors should be moderate and the acceleration should be smooth. If the starting torque were low, the tension of the yarn would be insufficient and hence the yarn would get entangled and break. If the starting torque were high, the acceleration would be high and the yam would snap.

In general, three types of drives are used for spinning frame operation: single speed motor, two-speed motor and two motor drive.

Normally, a 4 pole or 6 pole squirrel cage induction motor is used as single speed drive.

In order to maximize production with minimum breakage, two speed motors (4/6 or 6/8 poles) are used. Although these motors would be larger in size and costlier, the increased production may compensate for the additional initial outlay.

Microprocessor Based drive: Advantages:

The complexity of the system is reduced

- The software supported control using micro-processors performs the function of controllers,

- feedback, decision making of the drive system The hardware implementation in thyristerised controller unit four-quadrant operation using dual

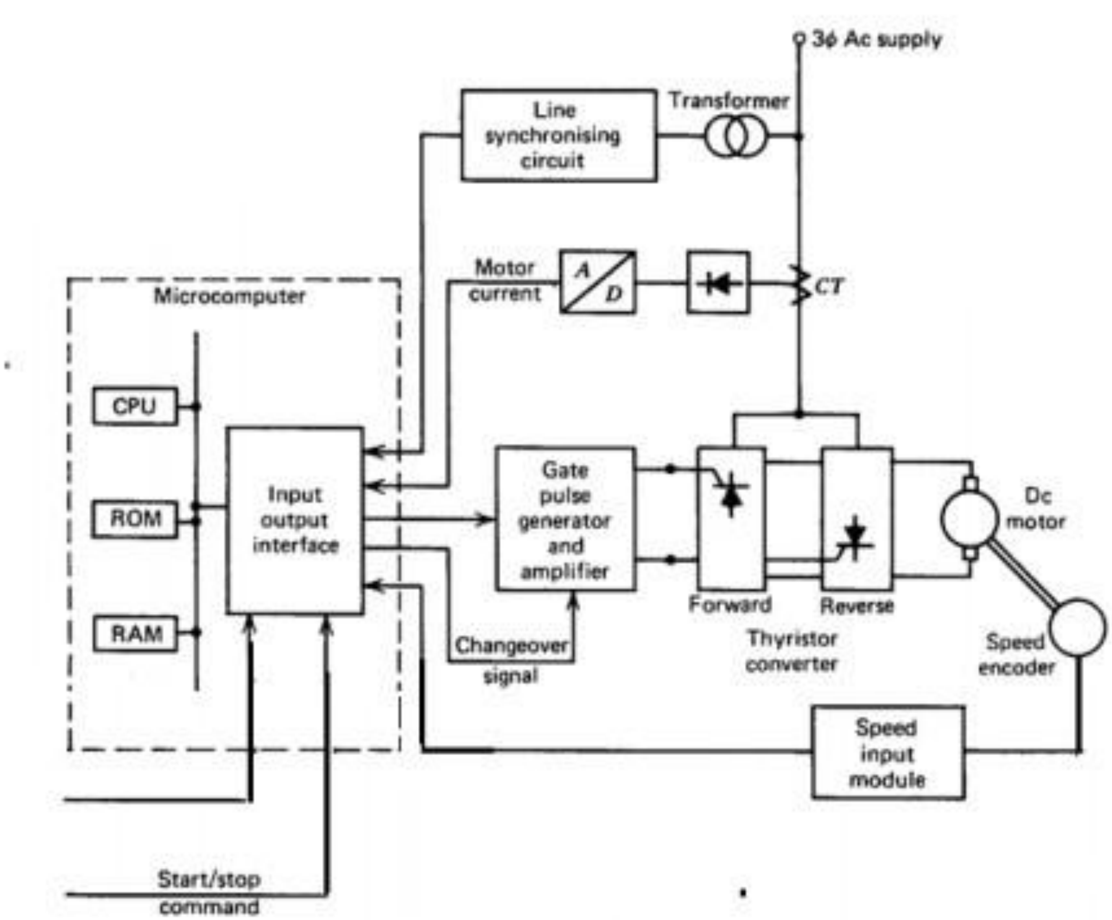
- converter, vector control can be realized with software programs on micro-processor with least possible hardware Digital control has an inherent improved noise immunity

- The control is free from drift and parameter variation due to temperature

Limitations:

Due to communication between the microprocessor and the analog circuitry done by A/D and• D/A converter, there are sampling and quantizing error The response in micro-processor is slow in comparison with dedicated hardware The development of software may be costly and time consuming.

Closed loop dc drive microprocessor based speed control



Block diagram of a reversing dc drive using microcomputer control system.

Conventional DC and AC Traction Drives:

The commonly used Conventional DC and AC Traction Drives are

The dc Traction Drives Employing Resistance Control:

The dc traction drives employing resistance control are:

- **1500 V dc traction on Bombay-Igatpuri-Pune section for main line and Bombay suburban**
- **750 V dc traction in underground trains at Calcutta.**
- **550 V dc traction in Calcutta tramways.**

Each motor coach of 1500 and 750 V dc tractions have four dc series motors with voltage ratings of 750 and 375 V, respectively; two motor are permanently connected in series. Similar connection is used in locomotives for 1500 V main line dc traction. The 550 V dc traction of Calcutta tramways use two dc series motors each rated 550 V.

Basic control scheme for all these drives is essentially the same. When four motors are used, two motors are permanently connected in series to form one pair. Thus, the drive will have two pairs each having two motors permanently connected in series. Starting, speed control and torque control up to base speed is carried out with the help of contactor-controlled sectionalised resistors. At start both motor-pairs are connected in series with the sectionalised resistors in series as shown in Fig. 10.10(a). As the train accelerates resistor-sections are cut out one by one so as to limit the starting current within prescribed maximum and minimum limits. When all sections of resistance controller are cut out, the motor speed will be nearly half of base speed.

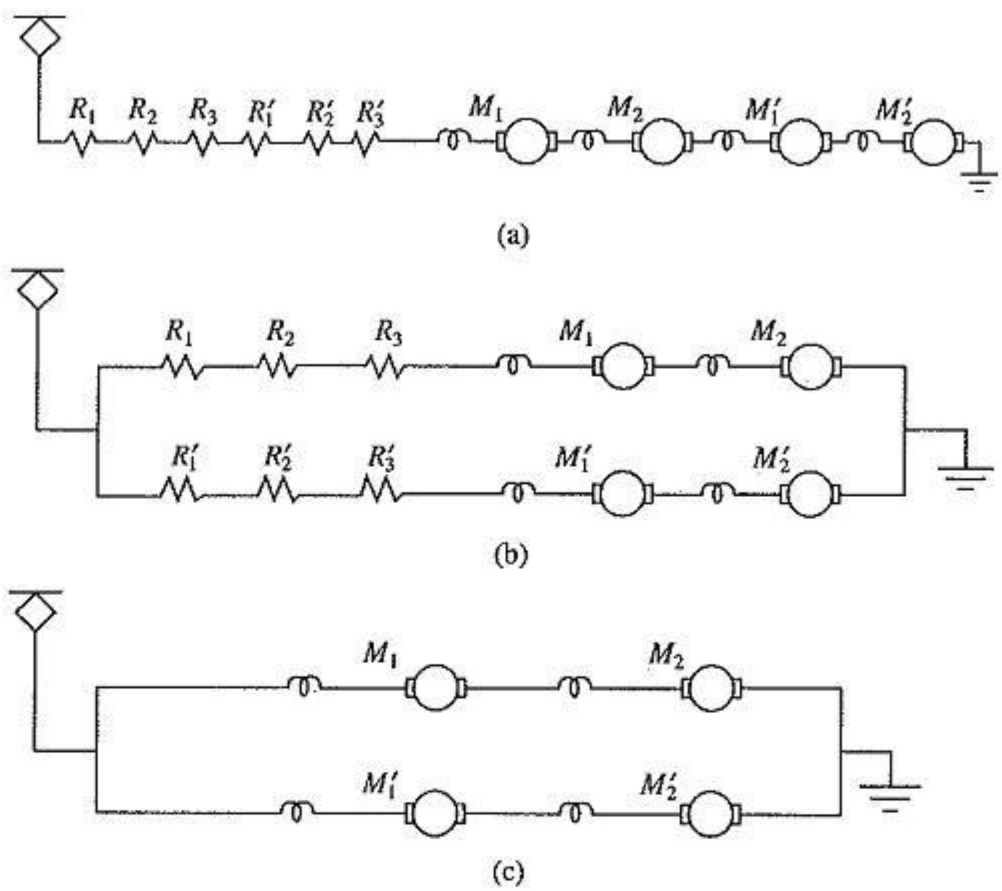


Fig. 10.10 dc Series motor traction drive with resistance control: (a) Control from zero to half of base speed; (b) Control from half to full of base speed and (c) Operation at base speed

For further acceleration, the two motor pairs are connected in parallel with the sectionalised resistor in series with each of them (Fig. 10.10(b)). The resistor-sections are now cut out, one by one to limit the current within prescribed maximum and minimum limits. When all resistor-sections are cut out (Fig. 10.10(c)), motors will be running around the base speed. Speeds higher than base speeds are obtained by field control. For changing the field current, diverter resistors are connected in parallel with field windings. Different steps of control for a motor coach with two motors is obtained when each pair in Fig. 10.10 is replaced by one motor.

During transition from series to parallel connection closed circuit transition has to be applied, because it is not desirable to break such a high current. Further, the sudden change of current at the time of opening and reconnection will produce step change in torque, causing discomfort to passengers and increasing tendency for wheel slip. To avoid this, closed circuit transition is used. Figure. 10.11 shows the closed circuit transition using what is known as bridge circuit transition.

Different steps of control are:

(i) close 1L, 1S and 2S, which connects both motor pairs 1 and 2 in series with sectionalised resistors R1 and R2;

(ii) close progressively 1A to 6A, now motor speeds are nearly half of base speed;

(iii) close 1B;

(iv) open 1S and 1A to 6A;

(v) close 2L and 2B;

(vi) open 1B, this connects two motor pairs with a sectionalised resistance in series with each, in parallel; without opening motors armature and field circuits

(vi) close contacts 1A-2A, 3A-4A and 5A-6A in pairs successively. This connects two motor pairs in parallel and starting process is completed.

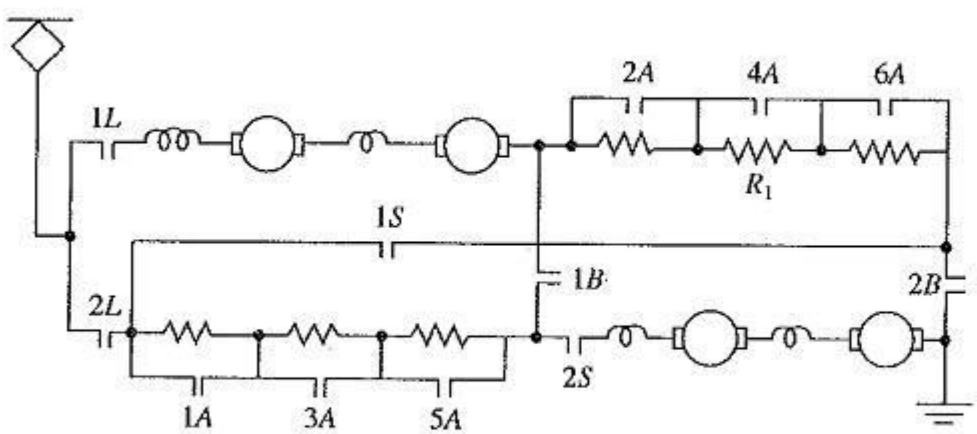


Fig. 10.11 Resistance control of dc traction drive with bridge transition

For dynamic braking, supply is switched off, fields are reversed and sectionalised resistors are connected across each motor pair. The motors work as self-excited generator. As the train decelerates, resistor's sections are cut out one by one to maintain good braking torque. As the braking ceases at a finite speed, mechanical brakes are applied to stop the train. During dynamic braking, larger resistance is required than during starting. Therefore, additional sectionalised resistor is employed along with starting resistor.

Dynamic braking is not always used. For example in India while underground trains in Calcutta use dynamic braking but not the trains of 1500 V dc traction in Bombay. The torque control during motoring and braking is realised by changing the value of armature circuit resistance.

Additional features are incorporated for smooth acceleration of the train. The first few steps during starting are chosen such that the current, and therefore, torque is build up in small steps to avoid any jerk. These steps may be implemented based on the values of dl/dt, whereas later steps are based on the value of I.

As a number of operations are involved, it will be very tiring for the driver to carry them out manually. Automatic controls using contactors and servo drives are used to simplify the job of the driver.

The above dc traction schemes have several disadvantages.

- **Low efficiency due to resistance control.**
- **Poor adhesion due to: (a) step change in torque and (b) more drooping speed-torque curves because of resistance control.**
- **Frequent maintenance due to large number of moving contacts.**
- **Unless very large sections are used in the starting and braking resistances, average accelerating and decelerating torques are substantially lower compared to the maximum torque the motors can produce. This slows down the average speed of a suburban train.**

The 25 kV, 50 Hz ac Traction Using On-Load Transformer Tap Changer:

This scheme has been used both for main line and suburban trains. In India it is widely used for main line traction. All main line electric traction schemes, except Bombay-Igatpuri-Pune route, are using this scheme. The drive scheme is shown in Fig. 10.12.

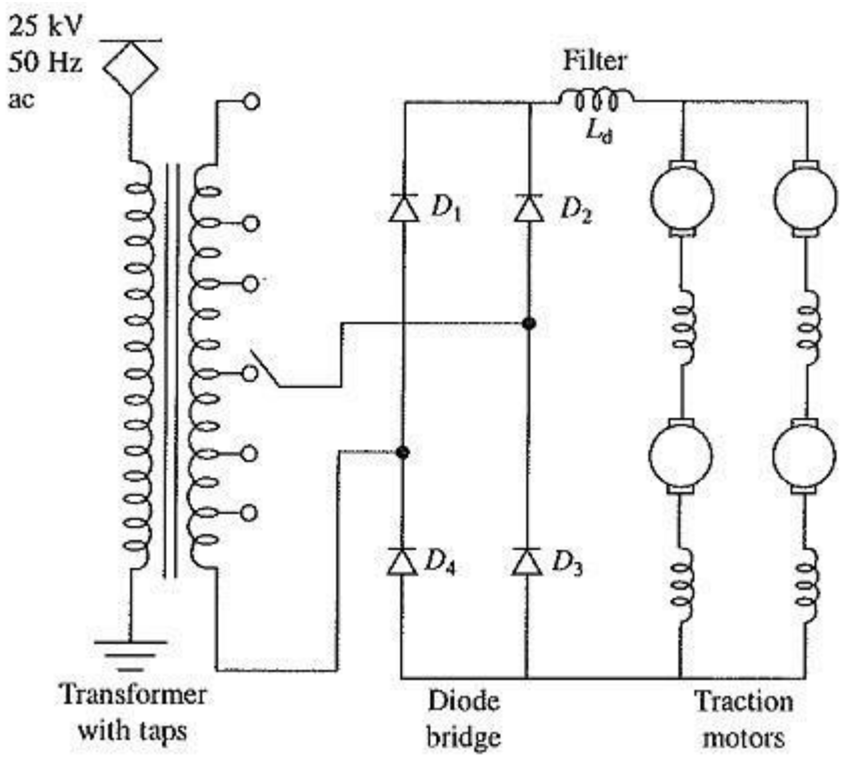


Fig. 10.12 25 kV, 50 Hz ac traction using transformer with tap changer

A step down transformer reduces the voltage from 25 kV to a suitable value. The secondary winding is provided with tappings. An on-load tap changer (Fig. 5.24) is used to vary the taps on transformer without voltage surges. A diode rectifier bridge converts ac to dc and through somoothing reactor L_d feeds dc series traction motors, which are connected in appropriate series- parallel combinations. Usually a locomotive with four motors will have series-parallel connection as shown in Fig. 10.12.

As explained earlier, the tendency for wheel slip will be lowest when all motors are connected in parallel, but then the transformer secondary current rating will be the highest. On the other hand, the transformer current rating will be the lowest and the tendency for wheel slip will be highest when all four motors are connected in series. The connection of Fig. 10.12 provides a compromise between the two contradictory requirements. The smoothing reactor L_d may be divided into four sections, one in series with each traction motor, so that in the event of a motor fault, a high impedance is in the circuit and motor protection is simplified. For starting, and speed and torque control up to base speed, the motor terminal voltage is varied by changing taps on the transformer. The speed control above base speed is obtained by connecting a diverter resistor in parallel with the field of each motor. Braking is generally provided by mechanical brakes. Dynamic braking has also been used. For this, motors have been connected as separately excited generators. Fixed braking resistors are connected across armatures of each motor. The fields of all motors are connected in series across an auxiliary dc generator driven by an auxiliary induction motor. The current through the motor fields is controlled by controlling the field current of the auxiliary dc generator. As the motor decelerates under braking, the motor field current is increased to maintain a specified current through the motor armature.

The tap-changer may have 20 to 40 taps. Varying them manually can be very tiring for the driver. Therefore, tap changer control has to be automatic. Contactors and servo drives are used to realise automatic control of the tap-changer.

The following advantages over dc drives employing resistance control:

- **Higher efficiency as the starting, speed and torque control are done by varying armature voltage instead of armature resistance.**
- **Better adhesion, because with armature voltage control the motor speed-torque characteristics are less drooping compared to armature resistance control.**
- **In underground trains, one is forced to use low voltage due to limited space available between the train and tunnel. No such restriction is applicable to over ground traction. In case of dc traction, the maximum transmission voltage depends on the number of motors in series and their voltage rating because no simple means were available for stepping down the dc voltage. As the dc motor voltage rating because of commutator is restricted to 750 V dc and since two motors are permanently connected in series, the dc transmission voltage is chosen as 1500 V. In ac transmission as the voltage can be stepped down easily and efficiently by a transformer, it is possible to use 25 kV voltage for transmission. Because of the much higher transmission voltage, the cost of transmission and power loss in transmission are much lower in 25 kV ac traction than in 1500 V dc traction. Because of high cost, 1500 V dc traction is not used in new installation. Although because of the prohibitive cost of replacement it continues to be there wherever it was installed prior to the development of 25 kV ac traction.**

The 25 kV ac traction using transformer with tap changer has following limitations:

- **Due to a larger number of moving contacts and parts, the tap changer requires frequent maintenance and is susceptible to frequent failures and fire hazards.**
- **As the motor voltage is controlled in steps, adhesion is poor and maximum accelerating torque is lower compared to what can be achieved with stepless control using semiconductor converters**

DC Traction using Semiconductor Chopper Controlled DC Motors:

Chopper control has replaced resistance control in all dc traction schemes, such as 1500 V dc main line and suburban traction, 750 V dc underground traction and electric buses. The chopper control has following additional advantages over the resistance control:

- **Regenerative braking can be carried out almost up to zero speed. Reduction in energy consumption compared to resistance control can be from 30 to 50%.**
- **With single section of resistance, excellent dynamic braking performance can be obtained.**
- **Composite braking can be easily implemented.**
- **Light weight and volume.**

- **A chopper without provision for regenerative braking is now cheaper than a cam-controller (resistance control).**

Traction drives have been built using both dynamic and regenerative brakings but the drives with regenerative braking have been preferred.

In dc traction, dc supply is obtained by rectifying ac into dc by uncontrolled (diode) rectifiers which permit energy to flow in one direction only, i.e. from ac to dc. When a chopper controlled train is regenerating, the energy regenerated must be absorbed by other trains which are motoring since it cannot be transferred to ac supply. Further, energy regenerated by a train is greater than the energy required by a single train when motoring. This suggests that a DC Traction supply will not be able to always utilise the regenerated energy. If the regenerated energy is pumped into the supply when it cannot use it, the supply voltage rises due to charging of capacitances between line and ground and will lead to insulation failure and damage to the equipment. It is, therefore, necessary that the energy which cannot be utilised is dissipated in a resistance by dynamic braking. The regenerative braking with a provision to dissipate excess energy through dynamic braking is known as composite braking. As regenerative braking of series motor is not reliable, mostly separately excited motor is used in regenerative drives. A chopper controlled drive with composite braking is shown in Fig. 10.18. dc supply feeds the drive through a L_F-C_F filter which keeps the harmonics in the source current within a tolerable range by filtering out the harmonics generated by the chopper. SS is semiconductor switch, and MS_1 and MS_2 are the mechanical switches. RS is the reversing switch, which allows reversal of motor connection with respect to terminals A and B. Inductor L is added when the motor armature inductance is not enough to keep the armature current ripple within permissible value and to provide good regenerative braking performance.

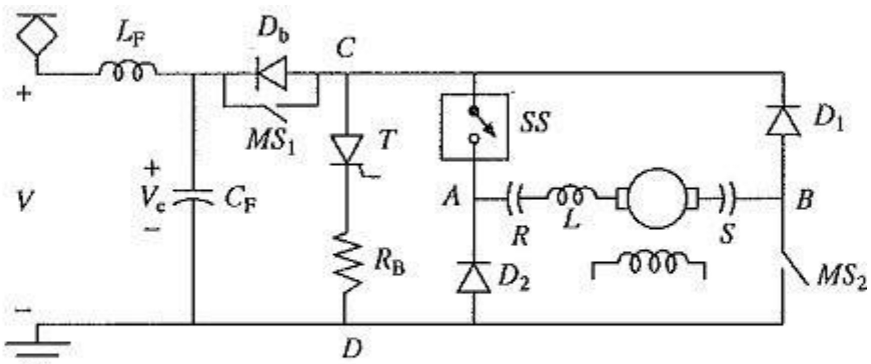


Fig. 10.18 Chopper controlled traction drive with composite braking

The drive operates as follows:

Motoring operation: For motoring operation mechanical switches MS_1 and MS_2 are kept closed and the semiconductor switch SS is periodically operated. During the on period of the semiconductor switch current flows through the path consisting of source, L_F, MS_1, SS, L, motor armature and MS_2, giving duty interval of the chopper. During the off period of the semiconductor switch, the armature current freewheels through the path consisting of closed switch MS_2, D_2 and L.

Composite braking: For braking operation mechanical switches MS_1 and MS_2 are kept open, armature connection is reversed with respect to terminals A and B with the help of the reversing switch RS and the semiconductor switch SS is operated periodically. The polarity of the motor emf is so as to make the terminal B positive with respect to terminal A. During the on period of the semiconductor switch SS, the armature current builds up through the path consisting of diode D_1, switch SS and inductance L. During the off period of the switch SS, the armature current flows against the source voltage through the path consisting of diode D_1, diode D_b, L_F, source, diode D_2, inductance L and energy is fed to the source. If source does not have enough load to absorb this energy, it flows into capacitor C_F increasing its voltage. When capacitor voltage V_F: exceeds the source voltage by more than 10%, thyristor T is triggered to connect the braking resistor R_B across chopper inputs terminals CD, and the regenerated energy is dissipated in R_B. When the switch SS is turned on to start the on period, armature current is transferred to path D_1, SS and L, and T is turned off, disconnecting R_B, due to want of current. In each cycle of the chopper, during off period of switch SS, first the drive operates in regenerative braking and only when the regeneration is not possible, due to absence of enough load to absorb this energy, dynamic braking is resorted to. Thus, drive regenerates as much energy as the source is capable of absorbing; and what cannot be absorbed by the source is only dissipated by dynamic braking.

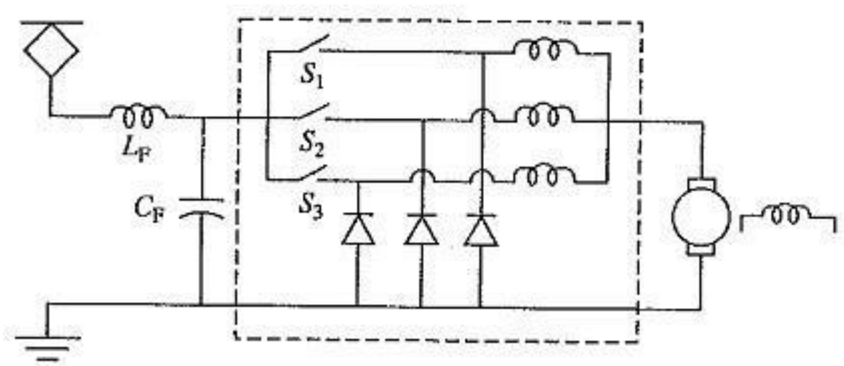


Fig. 10.19 Three-phase chopper fed dc motor traction drive

As in case of converter control, the drive is operated with closed-loop current control both during motoring and braking operations. For low power drives required for electric buses and rail cars (single bogie motor coach) transistor (or IGBT) chopper is employed, because transistor chopper operates at a frequency around 2500 Hz. This keeps the motor current ripple low and an inexpensive input filter is required to keep the source current harmonics within a tolerable limit. For higher power ratings required for locomotives and EMUs, thyristor and more recently GTO choppers are used. Because of low frequency operation of these devices (around 300-800 Hz) source current harmonics can pose a problem. Two or three phase choppers are used to overcome these problems. Fig. 10.19 shows a motor fed from a three-phase chopper.

Polyphase AC Motors for Traction Drives:

Polyphase AC Motors for Traction Drives – Advantages of ac motors over dc we already know. Because of negligible maintenance, ruggedness and higher power per unit weight or volume, the squirrel-cage induction motor is ideally suitable for traction applications. Because of higher efficiency, and simpler and cheaper inverter, compared to an induction motor, the synchronous motor has also been employed in the traction drives.

Variable frequency control is used both for induction motor and synchronous motor.

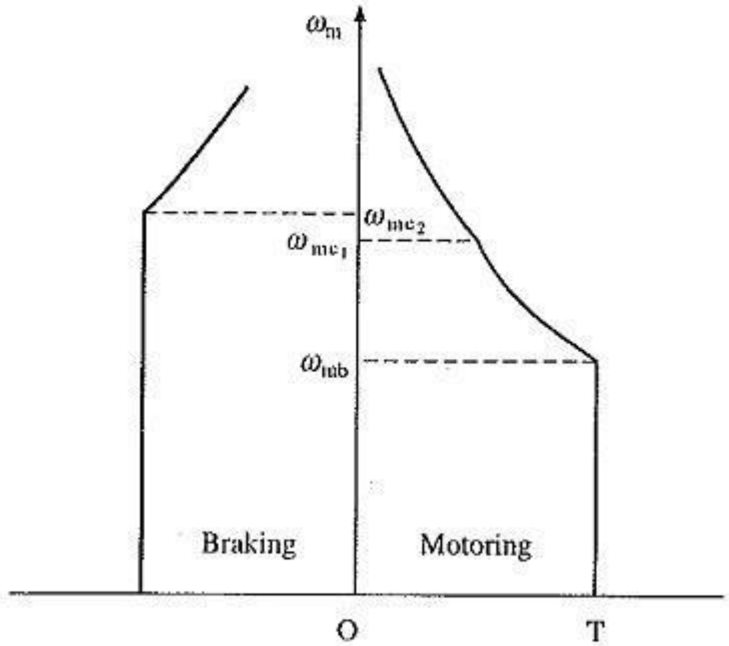


Fig. 10.20 Modes of operation of ac motors with variable frequency control

Fig. 10.20 shows the modes of operation employed for variable frequency control of an induction motor. From zero to the base speed ω_{mb}, the motor is accelerated at a constant torque, by keeping the V/f ratio constant and increasing it at low speeds. Above the base speed the motor accelerates in the constant power mode with a constant V and variable f.

At a critical speed ω_{mc1} motor's break-down-torque limit is reached, therefore, the motor power is gradually reduced by operating it with lesser and lesser stator current. The figure also shows modes of motor operation during braking. From zero to a speed ω_{mc2} motor is braked at a constant torque. Above ω_{mc2}, the motor is braked at a decreasing braking torque so as to avoid exceeding wheel to rail adhesion capability and to limit the peak power requirements of the drive. Similar curves are obtained in case of synchronous motor.

Several drives employing squirrel-cage induction and synchronous motors are in use in traction. Here only those drives are presented which have received wide acceptance.

Electrical Drives for Crane Application

1. Introduction

A crane is the type of machine mainly used for handling heavy loads in different industry branches: metallurgy, paper and cement industry. By the construction, cranes are divided into the overhead and gantry cranes. An overhead crane, also known as a bridge crane, is a type of crane where the hook and line mechanism runs along a horizontal beam that itself travels on the two widely separated rails. Often it is in a factory building and runs along rails mounted on the two long walls. A gantry crane is similar to an overhead crane designed so that the bridge carrying the trolley is rigidly supported on two or more legs moving on fixed rails embedded in the floor. Stationary or mobile units can be installed outdoors or indoors. Some industries, for example port containers application or open storage bins, require wide span gantry cranes. In outdoor applications, the influence of the wind on the behavior of the drive may be considerable (Busschots, 1991). Wind and skew can significantly influence a safe operation of the crane. This will certainly dispose the type design of the crane (lattice or box type design) from a mechanical aspect as well as the selection, size and control of crane electrical drives.

Electrical technology for crane control has undergone a significant change during the last few decades. The shift from Ward Leonard system to DC drive technology and the advent of powerful Insulated Gate Bipolar Transistors (IGBTs) during the 1990s enabled the introduction of the AC drive . Conventional AC operated crane drives use slip ring induction motor whose rotor windings are connected to power resistance in 4 to 5 steps by power contactors. Reversing is done by changing the phase sequence of the stator supply through line contactors. Braking is achieved by plugging. The main disadvantage is that the actual speed depends on the load. An electronic control system has recently been added to continuously control rotor resistor value. Nowadays, these systems are replaced by frequency converters supplied squirrel-cage induction motors for all types of motion . Control concept based on application of Programmable Logic Controllers (PLC) and industrial communication networks (Field- buses) are a standard solution which is used in complex applications .

An overhead and gantry cranes are typically used for moving containers, loading trucks or material storage. This crane type usually consists of three separate motions for transporting material. The first motion is the hoist, which raises and lowers the material. The second is

the trolley (cross travel), which allows the hoist to be positioned directly above the material for placement. The third is the gantry or bridge motion (long travel), which allows the entire crane to be moved along the working area. Very often, in industrial applications additional drives as auxiliary hoist, power cable reel and conveyer belt are needed. Therefore, generally, a crane is complex machinery.

Depending on the crane capacity each of the mentioned drives, can be realized as multi- motor. The term multi-motor drive is used to describe all the drives in a technological process. If the controlled operation of the drives is required by the process based on the controlled speed of the individual drives, the expression controlled multi-motor drives is adequate. For many of such drives, the mechanical coupling on the load side is typical . In applications with cranes, coupling of the individual motors is realized by the mechanical transmition device, and it is usually technologically unbreakable.

2. Possible load sharing configurations overview

Controlled drives are usually fed from the power converter, which is also true for controlled multi-motor drives. The kind, the type and the number of converters used depend on the type of motors, their power ratings, and of the kind of the multi-motor drive. The control and regulation also depend on the type of the multi-motor drive, but also on the type of the converter selected, therefore the selection of the converter and the controller for these drives must be analyzed together. Regarding the power supply of the motor, the following cases are possible

- multiple motors fed by a single converter (multiple motors - single converter),
- motors controlled by separate converters (multiple motors - multiple converters).

In crane applications multi-motor drives are used very often and a proportional share of power between motors is required. Load sharing is a term used to describe a system where multiple converters and motors are coupled and used to run one mechanical load. In the strictest sense, load-sharing means that the amount of torque applied to the load from each motor is prescribed and carried out by each converter and motor set. Therefore, multiple motors and converters powering the same process must contribute its proportional share of power to the driven load.

Multiple motors that are run from a single converter do not load share because torque control of individual motors is not possible. The load distribution, in that case, is influenced only by the correct selection of the torque-speed mechanical characteristic. For the squirrel- cage induction motors, there is no economical method for the adjustment of the mechanical characteristic of the ready-made motors, but this has to be done during the selection. For the slip-ring induction motor, the mechanical characteristic can be adjusted afterwards, with the inclusion of the rotor resistors. Motors that are controlled by separate converters without any interconnection also do not share the load. The lack of interconnection defeats any possible comparison and error signal generation that is required to compensate for the differences in the load that is applied to any single drive and motor set.

Control topologies for load sharing consider the presence of interconnection, i.e. information knowledge about load (motor current or torque). There are three categories of load sharing techniques: common speed reference, torque follower and speed trim follower

The common speed reference is the simplest the least precise and the less flexible form of load sharing to set up, Fig. 1a). The precision of this control depends on the drives control algorithm, the motor characteristics and the type of load to be controlled.

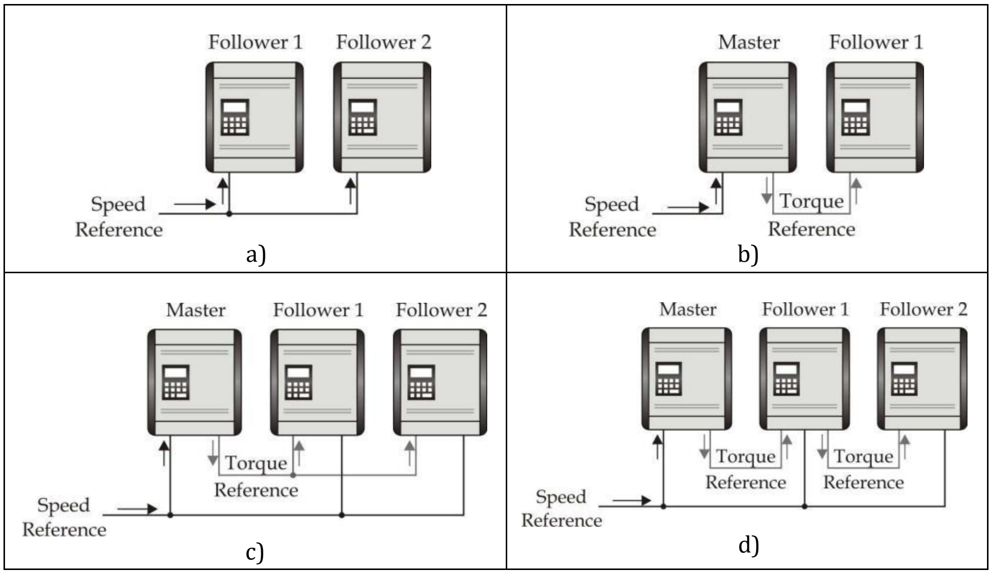


Fig. 1. Load sharing configuration a) Common speed reference, b) Torque follower, c) and d) Speed trim follower.

The torque follower type of load sharing requires the frequency converter to have the capability of operation in "torque mode", Fig. 1b). If speed regulation is required, one of the converters ("master") may be in "speed mode". In speed mode controller provides a torque command at output which can be distributed to the other converters ("slaves" or "torque followers"). The second converter operates in torque regulation mode with the torque reference of the master as command. This torque signal may be scaled to divide load sharing in any desired ratio.

In speed trim follower configuration, Fig. 1.c) and d), all converters are operated in speed regulation mode and receive the same speed reference. The torque reference of the master is sent to the follower converters. Each follower converter compares its own torque reference with that of the master, Fig. 1c). The output of the comparator is an error signal that trims the speed of the follower. Alternative configuration cascades the torque reference comparison, Fig. 1d). The first follower compares the master to its internal value. The second follower compares the foregoing follower to its internal value etc

UNIT-V

PART-A

1	List the advantages of digital controllers?	CO5(L4)
2	Identify the limitations of digital controllers?	CO5(L3)
3	Compare line shaft drive and sectional drive.	CO6(L4)
4	Classify the types of drives used for paper machine?	CO6(L4)
5	Infer the factors to be considered while selecting a motor for crane duty?	CO6(L2)
6	List the factors to be considered while selecting a motor for a steel mill?	CO6(L4)
7	Summarize the advantages of DSP based speed control?	CO5(L2)
8	Categorize the types of digital controllers used in drive system.	CO5(L4)
9	List few applications of microprocessors in the area of drives.	CO5(L4)
10	Interpret the factors to be considered while selecting a motor for a paper mill?	CO6(L2)

PART-B

1	Develop the several stages in the steel rolling mills and the requirement of drive motor for each stage.	CO6(L6)
2	Discuss the requirements of the cranes and hoist drives?	CO6(L5)
3	Analyse about DC systems for cranes and also compare dc and ac drive for crane application.	CO6(L4)
4	Discuss in detail about AC systems for cranes.	CO6(L5)
5	With neat block diagram develop DSP based control of electric drives.	CO5(L6)
6	Discuss the different stages in the paper mill and the requirement of drive motor for each stage.	CO6(L5)