2.2 Conventional methods of speed control

\[ N = \frac{E_b}{\phi} \]

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.

2.3 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

2.4 Single phase controlled rectifier fed DC Drives

![Fig (2.4) Single phase controlled rectifier fed DC Drives](image)

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.
2.5 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. If 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 (2.5) 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

\[ E_b = K_m \omega_m \]  

(Here flux is constant)

where  

- \( E_b \) = Back emf of the motor  
- \( K_m \) = Motor constant  
- \( \omega_m \) = Motor speed in rad/sec  
- \( \phi \) = 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

\[ \omega_m = \frac{V_a - I_a R_a}{K_m} \]

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

\[ T = K_m \phi I_a \]
\[ = K_m I_f I_a \]
\[ = K_m K_f I_f I_a \]

2.6 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 $\omega t = \alpha$, SCR T is triggered and comes to the on state, then the positive voltage is fed to the motor.

At $\omega t = \Pi$, freewheeling diode comes to the forward biased state and SCR comes to the off state, because of reverse voltage. During the negative half cycle, SCR T is in off state, and freewheeling diode conducts upto $2\Pi + \alpha$

- at $\Pi$ to $\Pi + \alpha$ - FD on
- $\Pi$ to $2\Pi + \alpha$ - FD on

During the period, $\Pi$ to $2\Pi + \alpha$ current is positive but output voltage is zero because of closed path (FD - motor - FD).
Fig (2.6.1) Single Phase Half wave controlled Rectifier fed DC Drives, Wave form

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

\[ V_0 = \frac{V_m}{2\pi} (1 + \cos \alpha) \quad \text{for } 0<\alpha<\pi \]

where \( V_m \) = maximum value of input voltage = \( \sqrt{2} \) \( V_s \)

= delay angle

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

\[ E_b = K_m \omega_m \]

\[ V_a = K_m \omega_m + I_a R_a \]

\[ \omega_m = \frac{V_a - I_a R_a}{K_m} \]

\( K_m = \text{motor constant} \)

Torque of the separately excited motor is given by

\[ T \propto \varphi I_a \]

\( \Phi - \text{constant} \)

\[ T \propto I_a \]

\[ T = K_m I_a \]
RMS value of armature current

\[ I_{\text{rms}} = I_a \]

RMS value of source or thyristor current

\[ I_s = \left( \frac{1}{2\pi} \int_0^{\pi} I_a^2 (\omega t) \, dt \right)^{\frac{1}{2}} = \left[ \frac{I_a^2}{2\pi} \left( \pi - \alpha \right) \right]^{\frac{1}{2}} \]

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

RMS value of freewheeling diode current

\[ I_{\text{f rms}} = \left( \frac{1}{2\pi} \int_0^{2\pi} I_s^2 (\omega t) \, dt \right)^{\frac{1}{2}} = \left[ \frac{I_s^2}{2\pi} \left( 2\pi + \alpha - \pi \right) \right]^{\frac{1}{2}} \]

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

Input supply power factor

\[ = \frac{V_a I_a}{V_s I_s} \]
2.7 Single phase fully controlled rectifier fed DC drives

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

\[ V_s = V_m \sin \omega t \]
Fig (2.7) Single phase fully controlled rectifier fed DC drives
Fig (2.7.1) Single phase fully controlled rectifier fed DC drives, Discontinuous Conduction waveforms.
Fig (2.7.2) Single phase fully controlled rectifier fed DC drives, Continuous Conduction waveforms.
Fig (2.7.3) Single phase fully controlled rectifier fed DC drives, continuous Conduction waveforms. (Rectification Mode)
Fig (2.7.4) 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 $\omega t = \alpha$, these SCRS will get turned on only if $V_m \sin \alpha > E$. Thyristors T1 and T2 are given gate signals from $\alpha$ to $\pi$ and thyristors T3 and T4 are given gate signals from $(\pi+\alpha)$ to $2\pi$.

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.

In discontinuous conduction modes, the current starts flowing with the turn-on thyristors T1 and T2 at $\omega t = \alpha$. Motor gets connected to the source and its terminal voltage equals $V_s$. At some angle $\beta$, known as extinction angle load current decays to zero. Here $\beta > \pi$. As T1 T2 are reverse biased after $\omega t = \pi$, this pair commutated at $\omega t = \beta$.

When $i_a = 0$ from $\beta$ to $\pi + \alpha$, no SCR conducts, the motor terminal voltage jumps from $V_m \sin \beta$ to $E$ as shown in figure.

At $\omega t = \pi + \alpha$, as pair T3 T4 is triggered, load current starts to build up again as before and load voltage $V_a$ follows $V_s$, waveform as shown. At $\pi + \beta$, $i_a$ falls zero, $V_a$, changes from $V_m \sin(\pi + \beta)$ to $E$ as no SCR conducts.

In continuous conduction mode during the positive half cycle thyristors T1, T2 are forward biased. At $\omega t = \alpha$, T1, T2 are turned on. As a result, supply voltage $V_m \sin \alpha$ immediately appears across thyristors T3 T4 as a reverse bias, these are turned off by natural commutation. At $\omega t = \pi + \alpha$ 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 ($\alpha \leq \omega t \leq \beta$), T1 and T2 conduct and $V_a = V_s$. Also ($\pi + \alpha) < \omega t < \pi + \alpha + \gamma$, T3 and T4 conduct and $V_a = V_s$ and so on.

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

\[ V_a = R_s i_a + L_s \frac{di_a}{dt} + E_b = V_m \sin \omega t \quad \text{for} \quad \alpha \leq \omega t \leq \beta \] \[ V_a = E_b \quad \text{and} \quad i_a = 0 \quad \text{for} \quad \beta \leq \omega t \leq \pi + \alpha \]
Average output voltage

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

\[ \ldots (11) \]

Average output Current

\[ I_a = \frac{V_a - E_b}{R_a} \]

Speed Equation (\( \omega_m \))

\[ \omega_m = \frac{V_m}{K_m} \frac{(\cos \alpha - \cos \beta)}{(\beta - \alpha)} - \frac{T}{K_m^2} \frac{R_a}{\beta - \alpha} \left[ \frac{\pi}{\beta - \alpha} \right] \]

\[ \ldots (13) \]
Steady State Analysis of continuous conduction

Average output voltage

\[ V_a = \frac{1}{\pi} \int_{\alpha}^{\pi + \alpha} V_m \sin(\omega t) d(\omega t) \]
\[ = \frac{V_m}{\pi} \int_{\alpha}^{\pi} \sin(\omega t) \, d(\omega t) \]
\[ V_a = \frac{2V_m}{\pi} \cos \alpha \]

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 $\omega_m$

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

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

RMS value of output current

$$I_{\text{forms}} = I_a$$

RMS value of source current

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

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

$$I_s = I_a$$
Average Value of thyristor current

\[
I_{TA} = \frac{I_a}{2}
\]

RMS value of Thyristor current

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

\[
I_{TR} = \frac{I_a}{\sqrt{2}}
\]

Assume no loss in the converter

Input power = output power

\[V_sI_{scos}\phi = V_{al}\]

\[\cos\phi = \frac{2\sqrt{2}}{\pi}\cos\alpha\]

**Speed – torque characteristics**
2.8 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.
2.8.1 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).

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 T1, T3, T5 forms a
positive group, whereas thyristors T4, T6, T2 forms a negative group. The positive group thyristors are turned on when the supply voltages are positive and negative group thyristors are turned on when the supply voltages are negative. The operation of this converter is easily understood by using line voltages instead of phase voltages.

For $\alpha = 60^\circ$, T1 is turned on at $\omega t = \frac{\pi}{3} + 60 = 120^\circ$, T2 at $\omega t = 180^\circ$, T3 at $\omega t = 240^\circ$ and so on. When T1 is turned on at $\omega t = 120^\circ$, 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 conducting, the load voltage is $v_{rb}$, figure. In this way, load voltage waveform can be drawn with thyristors in sequence.

For $\alpha = 120^\circ$, T1 is triggered at $\omega t = 180^\circ$, T2 is triggered at $\omega t = 240^\circ$ 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 $\alpha$ is 0 to $90^\circ$, this converter operates rectification mode (power flows from source to load) and $90^\circ$ to $180^\circ$ 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 (2.8.5) Speed – Torque curve
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 if the current reaches a specified minimum value.

Two types of control provided for chopper control

1. Power control or motoring control
2. Regenerative braking control

2.9 CHOPPER DRIVES

![Basic block diagram of chopper](image)

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.

2.10 Advantages of DC chopper control

1. High efficiency
2. Flexibility in control
3. Light weight
4. Small size
5. Quick response
6. Regeneration down to very low speeds.


2.11 Applications of DC chopper Drives

1. Battery operated vehicle
2. Traction motor control in electric traction
3. Trolley cars
4. Hoists
5. Electric braking

2.12 Types of DC chopper drives

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

2.12.1 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( 2.12.1) First Quadrant or Type-A or Motoring Chopper
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≤t≤TON, motor terminal voltage Va is a source voltage Vs and armature current increases from ia1 to ia2.
The operation is described by,

\[ i_a R_a + L_a \frac{d i_a}{d t} + E_b = V_s ; \ 0 \leq t \leq T_{ON} \]

Chopper is turned off at \( t = t_0\). During off-period of chopper (i.e.) free wheeling interval, \( T_{ON} \leq t \leq T \), motor current freewheels through diode FD and motor terminal voltage \( V_a \) is zero.

This is described by,

\[ i_a R_a + L_a \frac{d i_a}{d t} + E_b = 0 ; \ T_{ON} \leq t \leq T \]
2.12.2 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 mechanical 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 (2.12.2) Second Quadrant or Type –B or Regenerative braking Chopper(circuit diagram)

This voltage is greater than the supply voltage $V_s$ and the energy stored in the inductance and the energy supplied by the machine is fed back to the supply system. When the voltage of the load falls to $V_s$, 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, $0 \leq t \leq T_{\text{ON}}$, motor terminal voltage is zero, armature current increases from $i_{a1}$ to $i_{a2}$. During duty interval, $T_{\text{ON}} \leq t \leq T$, motor terminal voltage is $V_a$, armature current decreases from $i_{a2}$ to $i_{a1}$.

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

\[
= V_s \left( \frac{T - T_{\text{ON}}}{T} \right) = V_s \left( 1 - \frac{T_{\text{ON}}}{T} \right)
\]

\[
V_a = (1 - \delta) V_s
\]
\[ E_b = K_m \omega_m \]
\[ T = -K_m I_a \quad (\because I_a \text{ reversed}) \]
\[ E = K_m \omega_m = V_a - I_a R_a \]
\[ \omega_m = \frac{V_s}{K_m} - \frac{T}{K} \left( \frac{R_a}{K_m^2} \right) \]
\[ \omega_m = \frac{(1-\delta)V_s}{K_m} + \frac{R_a}{K_m^2} \quad T \]

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
  \[ E_g = K_m \phi \omega_m \quad [\phi \propto I_f] \]
  \[ = K_m I_f \omega_m \]
- 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 \( \omega_m \) 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 $\delta$, the equivalent load resistance seen by the motor can 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,

$$E_g - I_a R_a = V_s$$

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

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

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

and $\omega_m \leq \omega_{\max}$.

### 2.12.3 Two Quadrant Chopper Drives

Motoring control and braking control can be achieved by two quadrant chopper drives.

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 type 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 (2.12.3.) Two Quadrant type A chopper drive]
**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 (2.12.3.) Wave Form Two Quadrant type A chopper drive

When CH2 is in an off state, diode D2 gets turned on and therefore armature current $i_a$ 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.

2.12.4 Two Quadrant type B chopper drive

This type of chopper drive provides forward motoring mode and reverse regenerative braking mode.
Fig (2.12.4) – Quadrant Diagram Two Quadrant type B chopper drive (circuit diagram)
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<δ<1) of two quadrant type B chopper.

![Forward Motoring mode](image)

Fig (2.12.4) 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 ≤ δ ≤ 0.5) waveforms of two quadrant type B chopper drive.

2.12.4 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-I3 is kept off and CH1 is operated. When CH1 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 off, 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 fed back to source through diodes D1, D4 note that there \([E+L \frac{di}{dt}]\) 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, CH1 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. It is also known as reverse motoring mode. When CH3 is turned off, negative current freewheels through CH2, D4. In 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 off. 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.

2.13 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

2.13.1 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.
2.13.2 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 $R_B$. Since torque is 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.
2.13.3 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.