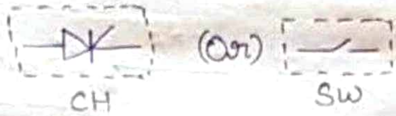
UNIT – III

CONTROL OF DC MOTORS BY CHOPPERS

Chopper: Chopper is a static semi conductor device which converts fixed DC into variable DC directly.

It is represented by



Chopper acts as switch i.e., it connects supply to load or disconnects supply to load.

Advantages of choppers:

1. Fast response
2. Smooth control
3. High efficiency
4. Regeneration.

Applications of choppers:

1. Battery operated vehicles
2. Trolley buses.
3. Subway cars
4. Traction-motor control.

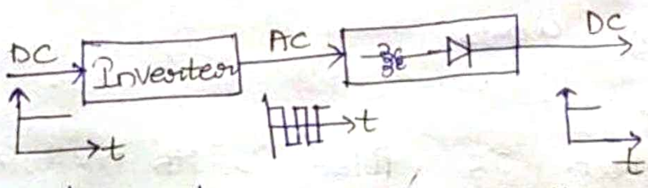
Classification of choppers: [Types]

Choppers are classified into two types. They are:

1. Ac choppers
2. Dc choppers

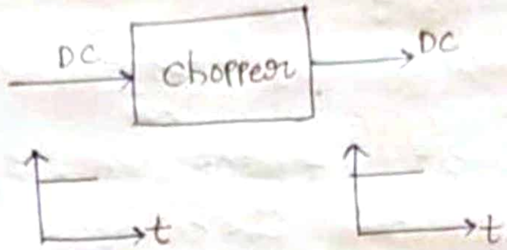
1. Ac choppers:

In case of AC link chopper, first dc is converted to ac with help of inverter. After that AC is stepped up or stepped down by a transformer, which is then converted back to dc by a rectifier.



Ac link chopper is costly, bulky and less efficient as conversion done in two stages.

2. DC chopper: It is a static device that converts fixed dc input voltage to variable dc output voltage directly.



This kind of choppers are more efficient as they involve only one stage conversion.

Control strategies of choppers:

In case of AC, current control otherwise known as firing angle control is involved.

In case of DC, voltage control is involved.

The variable dc voltage is controlled by varying ON and OFF times of converter.

Frequency of operation is given by

$$f_c = \frac{1}{t_{ON}+t_{OFF}} = \frac{1}{T}$$

Duty cycle/ratio is given by $\delta = \frac{t_{ON}}{t_{ON}+t_{OFF}} = \frac{t_{ON}}{T}$

Duty cycle varies from 0 to 1 and it should not vary beyond 1.

There are two control strategies in choppers.

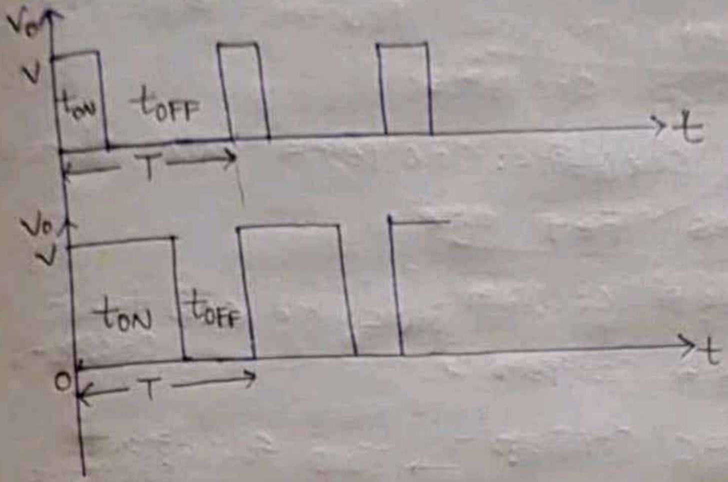
1. Time ratio control strategy. (TRC)
2. Current limit control strategy (CLC)

1. Time ratio control strategy: It can be achieved in two ways

(i) Constant Frequency:

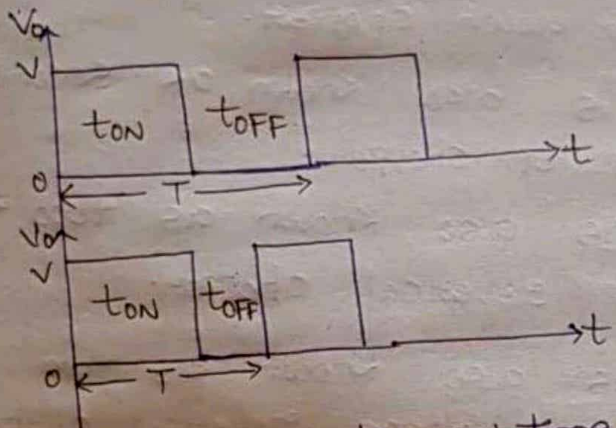
It is also known as Pulse width modulation and is used in inverters.

In this method, either ON time or OFF time can be Varied but total time Period is kept constant.



b) Variable Frequency:

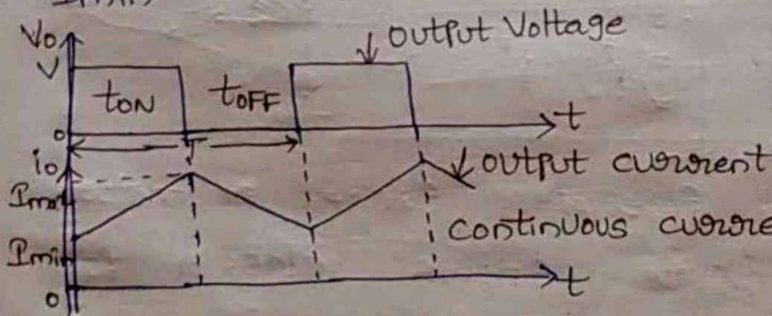
It is also known as frequency modulation and is applicable in radio signals in electronics.



In this method, ON time, OFF time and total time Period can be Varied such that frequency is Varied $(\because f = \frac{1}{T})$

2. Current Limit control strategy:

In this method, current is maintained in between minimum and maximum limits i.e Imin and Imax as shown in figure below



When current is minimum, device is in ON State and when current is maximum device is in off state.

$t_{ON} > t_{OFF}$ ($\alpha < 90$) → continuous mode

$t_{ON} < t_{OFF}$ ($\alpha > 90$) → discontinuous mode.

It is preferred in low power applications and is used in choppers.

Classification of choppers: Choppers are classified into five types. They are

1. Type A (or) class A chopper
2. Type B (or) class B chopper

→ Single Quadrant Choppers

3. Type C (or) class C chopper
4. Type D (or) class D chopper

→ Two Quadrant Choppers

5. Type E (or) class E chopper → Four Quadrant Choppers.

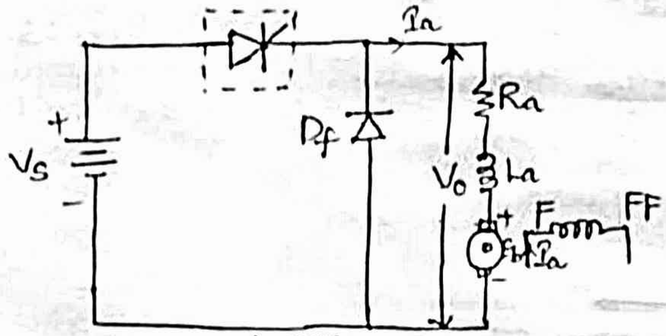
Type A chopper is also known as first Quadrant or step down chopper.

Type B chopper is also known as second quadrant or step up chopper.

Type C chopper is also known as two quadrant type A or current reversal chopper.

Type D chopper is also known as two quadrant type B or Voltage reversal chopper.

1. Type A (or) class A (or) step down chopper (or) motoring chopper (or) Buck Converter: Fed seperately Excited DC motor:



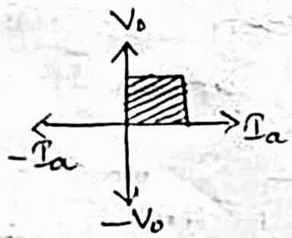


Fig. Class A chopper Fed Seperately Excited DC motor.

The above figure shows class A fed seperately excited DC motor.

When CH_1 is in ON state, current starts flowing through $V_{S+} - CH_1 - R_a - L_a - E_b - V_{S-}$ and voltage will appears across load.

$$V_0 = V_S.$$

It is known as Duty interval.

$$V_0 = I_a R_a + L_a \cdot \frac{dI_a}{dt} + E_b = V_S \quad ; \quad 0 < t < T_{ON}.$$

When CH_1 is in OFF state, current start flowing through $R_a - L_a - E_b - D_f$ and it forms a closed path.

Hence $V_0 = 0$.

It is known as free wheeling interval.

$$\therefore V_0 = 0 = I_a R_a + L_a \cdot \frac{dI_a}{dt} + E_b \quad ; \quad T_{ON} < t < T$$

It was observed that,

when CH_1 is in ON state, $V_0 = V_S$.

CH_1 is in OFF state, $V_0 = 0$.

$$\text{Output Voltage, } V_0 = \frac{1}{T}\left[\int_0^{T_{ON}} V_S \cdot dt + \int_{T_{ON}}^{T} V_0 \cdot dt\right]$$

$$= \frac{V_S}{T}(T_{ON} - 0) + 0$$

$$V_0 = \frac{V_S}{T} \cdot T_{ON}$$

$$V_0 = \delta V_S \quad \text{where } \delta = \frac{T_{ON}}{T}$$

'δ' varies from 0 to 1.

It was observed that power is delivered from source to load. Hence it is known as motoring chopper. (or) step down chopper. Since $V_0 < V_S$

Both voltage and current are positive. Hence class A chopper is also known as first quadrant chopper.

Output waveforms:

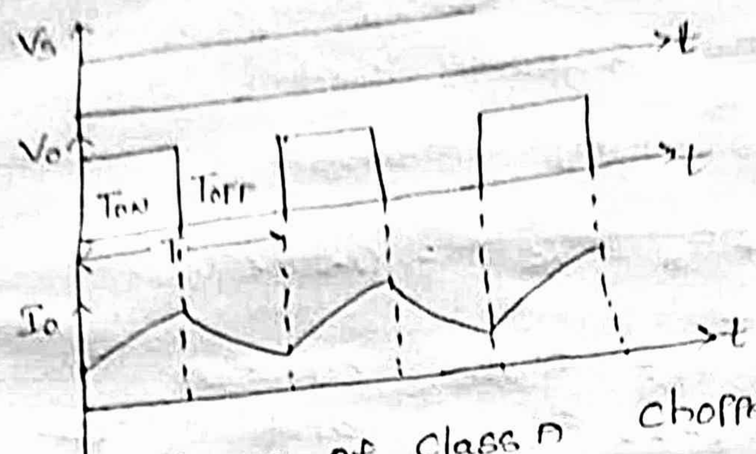


Fig. waveforms of class A chopper fed dc seperately excited DC motor.

Speed - Torque Characteristics:

We know that,

For seperately excited DC motor,

$E_b = V_0 - I_a R_a$

$V_0 = E_b + I_a R_a$

But $E_b = K_m \cdot \omega_m$

Torque $T = K_a \phi I_a$

$\Rightarrow I_a = \dfrac{T}{K_a \phi}$

$V_0 = \delta V_S$

$K_m \omega_m = \delta V_S - \dfrac{T}{K_a \phi} \cdot R_a$

$\Rightarrow \omega_m = \dfrac{\delta V_S}{K_m} - \dfrac{T}{(K_a \phi)^2} \cdot R_a$

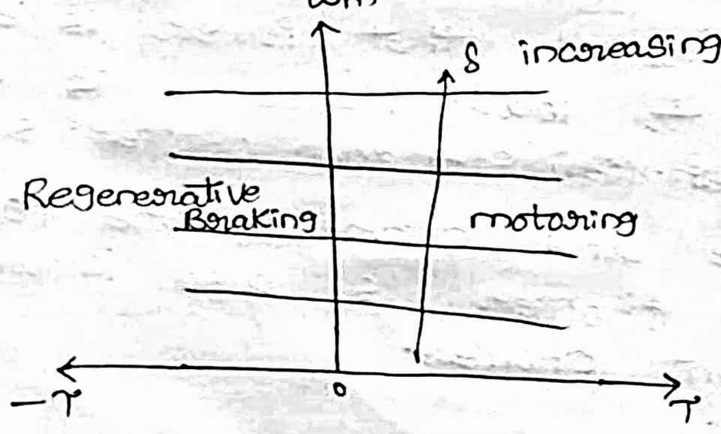
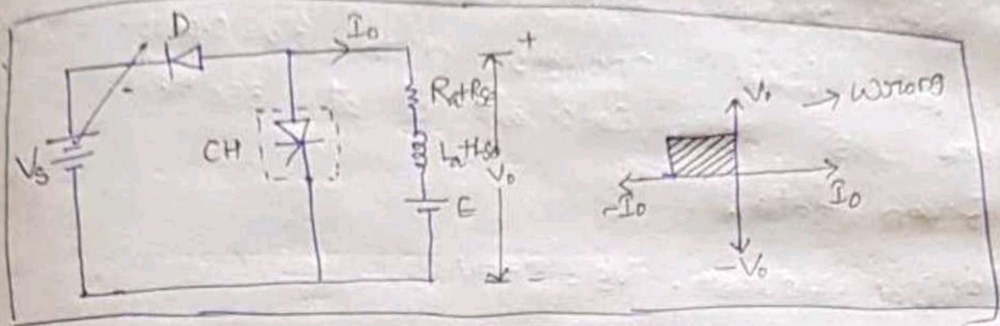


Fig. Torque speed characteristics of class A chopper fed seperately excited DC motor.

Class A chopper fed DC series motor:



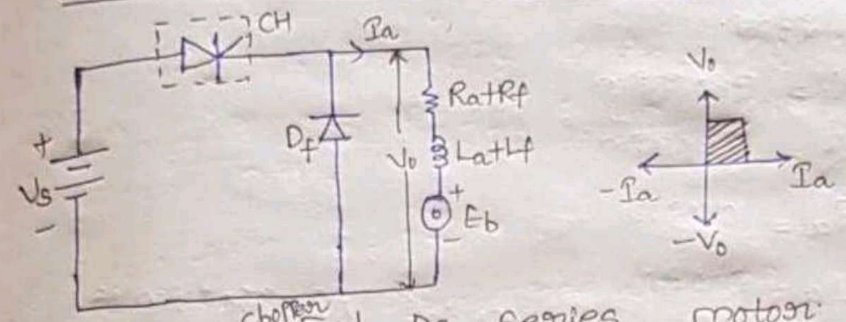
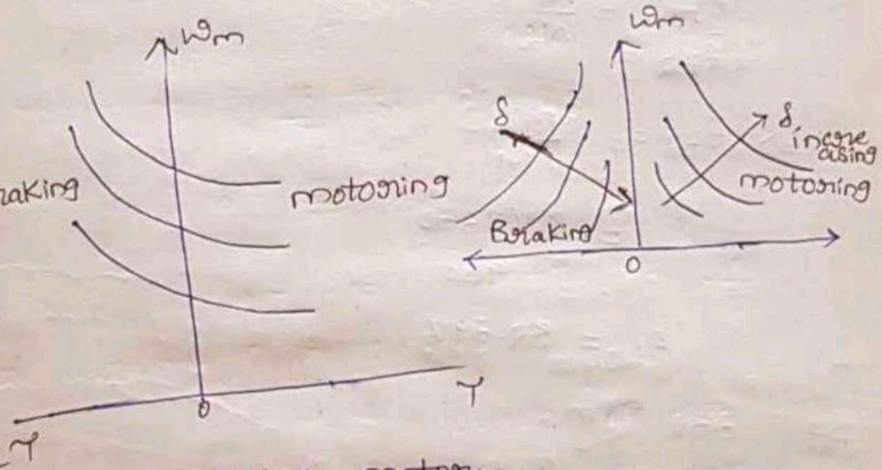


Fig. class A chopper Fed DC series motor.

All explanation and output voltage expression, waveforms are as same as seperately excited DC motor. But only change in speed torque characteristics as follows.

Speed-Torque characteristics:



W.K.T, For DC series motor,

$$E_b = V_0 - I_a(R_a+R_f)$$

$$E_b = K_{af} \cdot I_a \cdot N + K_{res} \cdot N$$

$$\tau = K_{af} \cdot I_a^2 \quad ; \quad N = \frac{V_0 - I_a(R_a+R_f)}{K_{af} \cdot I_a + K_{res}}$$

$$I_a = \sqrt{\frac{\tau}{K_{af}}}$$

$$\Rightarrow K_{af} \cdot I_a N + K_{res} \cdot N = \delta V_s - \sqrt{\frac{\tau}{K_{af}}} \cdot (R_a+R_f)$$

Problems:

1. A 230V, 960rpm, 200A seperately excited dc motor is fed from chopper with $R_a = 0.02\Omega$. Supply voltage is 230V. Calculate 'δ' at 350 rpm.

Sol Given data,

supply voltage, $V_S = 230V$

$V_0 = 230V$.

Speed $N_1 = 960$ rpm

$N_2 = 350$ rpm

$R_a = 0.02\Omega$

$I_a = 200A$.

Back emf at rated speed $N = 960$rpm is

$E_{b1} = V_0 - I_a R_a$

$= 230 - 200 \times 0.02$

$E_{b1} = 226V$

we know that,

$$\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2}$$

$$\Rightarrow E_{b2} = \frac{E_{b1} \cdot N_2}{N_1}$$

$$= \frac{226 \times 350}{960}$$

$E_{b2} = 82.39V$

At 350 rpm,

$E_{b2} = V_0 - I_a R_a$

$\Rightarrow E_{b2} = V_0 - I_a R_a$

$V_0 = E_{b2} + I_a R_a$

$= 82.39 + 200 \times 0.02$

$V_0 = 86.39V$

where $V_0 = \delta \cdot V_S$

$$\delta = \frac{V_0}{V_S} = \frac{86.39}{230} = 0.37$$

2. A 230V, 24A, 1000rpm seperately excited dc motor with $R_a = 2\Omega$ is controlled by chopper at 500Hz, $V_{ac} = 230V$. Calculate duty ratio for 1.2 times rated motor torque at 500rpm

Sol Given data,

$V_0 = 230V$

$I_a = 24A$

$N_1 = 1000rpm$

$R_a = 2\Omega$

$F = 500Hz$

$V_{ac} = 230V$

we know that,

$F = \frac{1}{T} = \frac{1}{500} = 0.002 = 2\times10^{-3}$ sec

$E_{b1} = V_0 - I_aR_a$

$= 230 - (24\times2)$

$E_{b1} = 182V$

we know that,

$\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2}$

$\Rightarrow E_{b2} = \frac{E_{b1}.N_2}{N_1} = \frac{182\times500}{1000} = 91$ V

$E_{b2} = V_0 - I_aR_a$

$V_0 = E_{b2} + I_aR_a = 91 + 1.2\times24\times2$

$V_0 = $ ~~139V~~ $148.6V$

$\delta = \frac{V_0}{V_S} = \frac{148.6}{230} = 0.6416$

3. A chopper is used to ON or OFF seperately excited dc motor with $V_S = 230V$, $T_{ON} = 10ms$, $T_{OFF} = 15ms$. Calculate average load current when motor speed is 1500rpm and $K_m = 0.5$ Vs/rad

Sol Given data,

$V_S = 230V$

$T_{ON} = 10ms$.

$T_{OFF} = 15\,ms$.

Speed = 1500 rpm.

$K_m = 0.5\ V\,sec/rad$

we know that,

$E_b = K_m \cdot \omega_m$

$= 1500 \times 0.5 \times \frac{2\pi N}{60}$

$E_b = 0.5 \times \frac{2\pi \times 1500}{60} = 78.539V$

$\delta = \frac{T_{ON}}{T} = \frac{10}{10+15} = \frac{10}{25}$

$\delta = 0.4$

$V_0 = \delta \cdot V_s = 230 \times 0.4 = 92V$

$E_b = V_0 - I_a R_a$

Assume $R_a = 1$

$E_b = V_0 - I_a$

$78.53 = 92 - I_a$

$-I_a = 78.53 - 92$

$-I_a = -13.47A$

$I_a = 13.47A$.

Type-B Chopper Fed Seperately Excited DC motor:

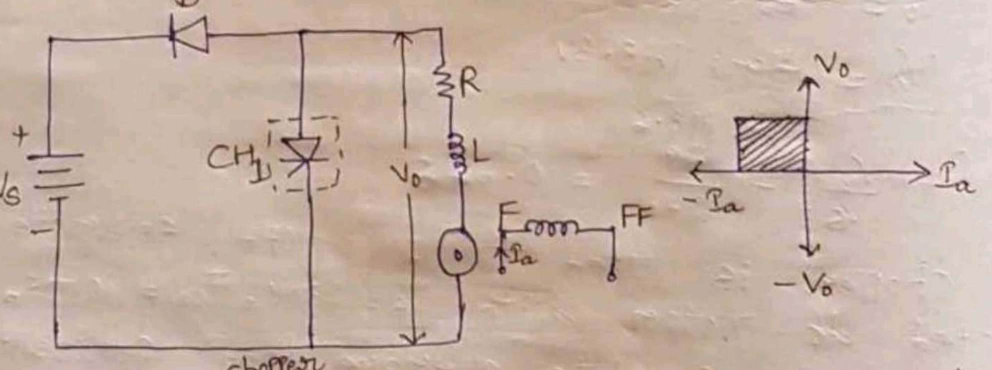


Fig. Class B chopper Fed Seperately excited DC motor.

The above figure shows the class B Chopper fed seperately excited DC motor.

when CH_1 is in ON state, E_b will act as source. Current flows through E_{b+} $- L_a - R_a - CH_1 - E_{b-}$ and it forms a closed path. Hence $V_0 = 0$. Energy is stored in inductor. This interval is known as Energy storage interval.

Hence $V_0 = 0$

$$V_0 = I_aR_a + L_a\frac{dI_a}{dt} + E_b = 0 \; ; \; 0 < t < T_{ON}.$$

when CH_1 is in OFF state, Df is in forward bias and energy is dissipated from inductor through $E_b - L_a - R_a - D_f - V_{S+} - V_{S-}$

Hence $V_0 = V_s$.

It is known as Duty interval.

$$V_0 = I_aR_a + L_a\frac{dI_a}{dt} + E_b = V_s \; ; \; T_{ON} < t < T_{OFF}$$

It was observed that,

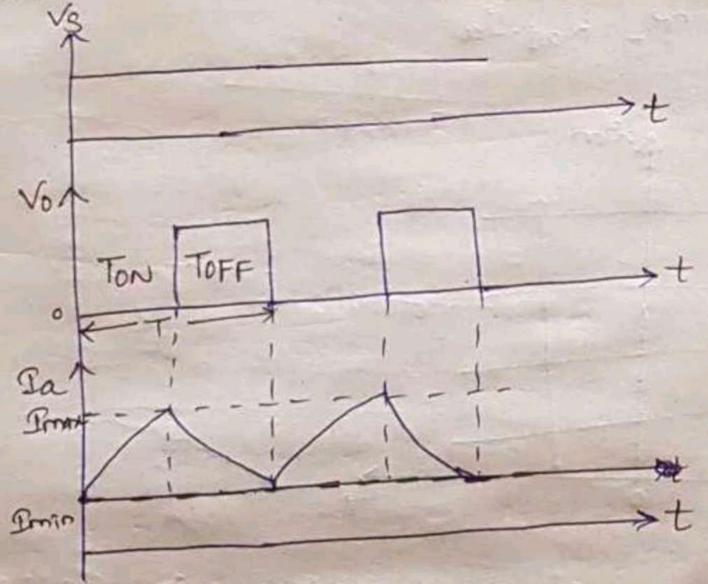
when CH_1 is in ON state, $V_0 = 0$

CH_1 is in OFF state, $V_0 = V_s$.

Class B chopper is also known as step-up chopper (or) Boost converter. Since $V_0 > V_s$

It was observed that power is delivered from load to source. Hence class B chopper is also known as Regenerative Braking chopper.

Output waveforms:



Average output Voltage,

$$V_0 = \frac{1}{T}\left[\int_{T_{ON}}^{T} V_s \cdot dt + \int_{0}^{T_{ON}} V_s \cdot dt\right]$$

$$\therefore V_o = \frac{V_s}{T}\left[T - T_{ON}\right]$$

$$= V_s\left[\frac{T - T_{ON}}{T}\right]$$

$$= V_s\left[1 - \frac{T_{ON}}{T}\right]$$

$$V_s = V_o(1-\delta)$$

$$V_o = \frac{V_s}{1-\delta}$$

$$V_o > V_s.$$

where 'δ' Varies from '0' to '1'

Speed - Torque characteristics:

At starting, only motoring action takes pl

$$\therefore E_b = V_o + I_aR_a$$

But Due to regenerative braking, back emf becomes.

$$E_b = V_o + I_aR_a$$

$$\text{where } V_o = \frac{V_s}{1-\delta}$$

$$E_b = K_m\omega_m$$

$$N = \frac{V_o + I_aR_a}{K_m}$$

$$\tau = K_a\phi \cdot I_a$$

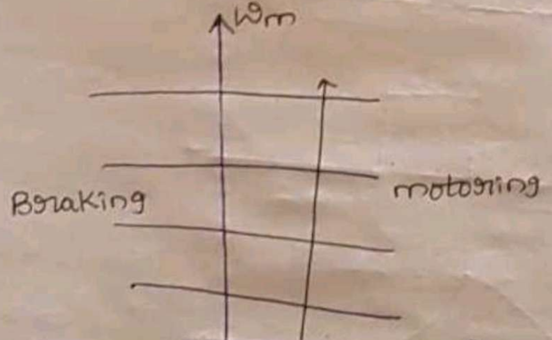
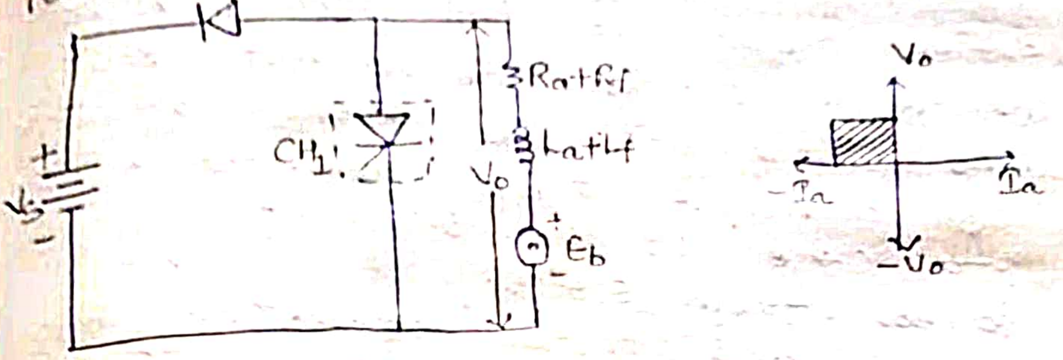


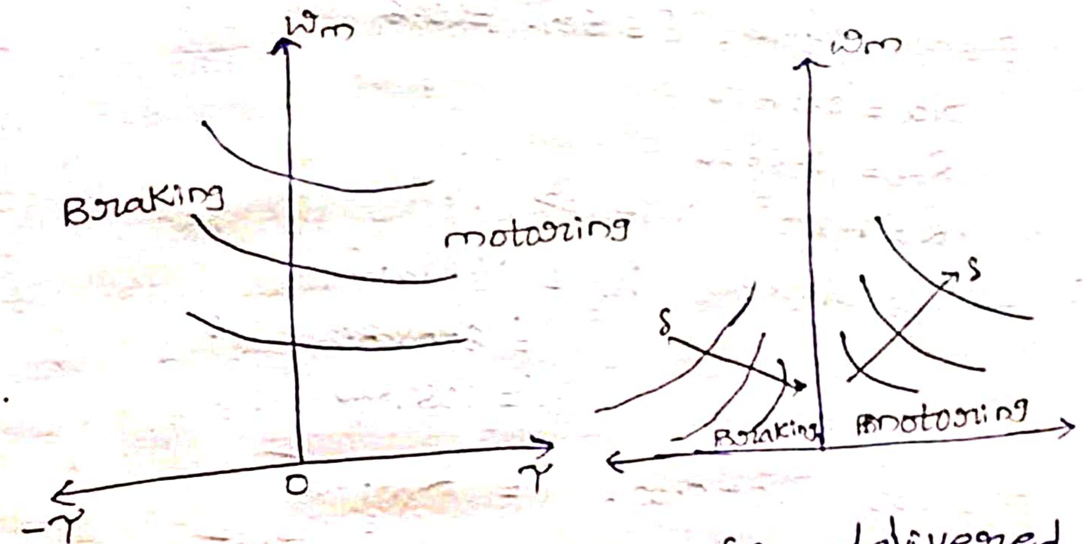
Fig. Torque speed characteristics of class B fed seperately excited DC motor.

Type B chopper Fed DC Series motor:



Explanation, output voltage expressions and waveforms are same as Type B chopper fed seperately excited DC motor.

Speed - Torque characteristics:



In Type B, chopper power is delivered from load to source. Hence it is also known as regenerative braking chopper.

$$\therefore\ E_b = V_o + I_a(R_a+R_f)$$

$$E_b = K_{af}\cdot I_a\cdot N + K_{res}\cdot N$$

$$\tau = K_{af}\cdot I_a^2$$

where $V_o = \dfrac{V_s}{1-\delta}$

$$N = \frac{V_o - I_a(R_a+R_f)}{K_{af}\cdot I_a + K_{res}}$$

Problems:

1. A DC series motor is fed from 600V DC source through a chopper. The DC motor has the following parameters: The average armature current of 300A is ripple free. For a chopper duty cycle of 60%, determine

(i) Input Power from source

(ii) motor speed and motor torque

$R_a = 0.04\Omega$, $R_s = 0.06\Omega$, $K = 4\times10^{-3}$ Nm/amp^2

Sol Given data,

$V_S = 600V$

$I_a = 300A$

Duty cycle, $\delta = 60\% = 0.6$

$R_a = 0.04\Omega$

$R_{se} = 0.06\Omega$

$K = 4\times10^{-3}$ Nm/amp^2

(i) Input Power $P_{in} = V_S \cdot I_a \cdot \delta$

$= 600\times300\times0.6$

$P_{in} = 108$ kW

(ii) motor Torque, $T = K_m \cdot I_a^2$

$= 4\times10^{-3}\times300^2$

$= 360$ N-m

$$N = \frac{V_o - I_a(R_a+R_f)}{K_{af}\cdot I_a}$$

$V_o = \delta V_S$

$= 0.6\times600$

$V_o = 360V$

$$N = \frac{360 - 300(0.04+0.06)}{4\times10^{-3}\times300}$$

$N = 275$ rad/sec

$= 28.79$ rpm

Class C chopper (Two- Quadrant Type-A chopper) fed separately excited DC motor:

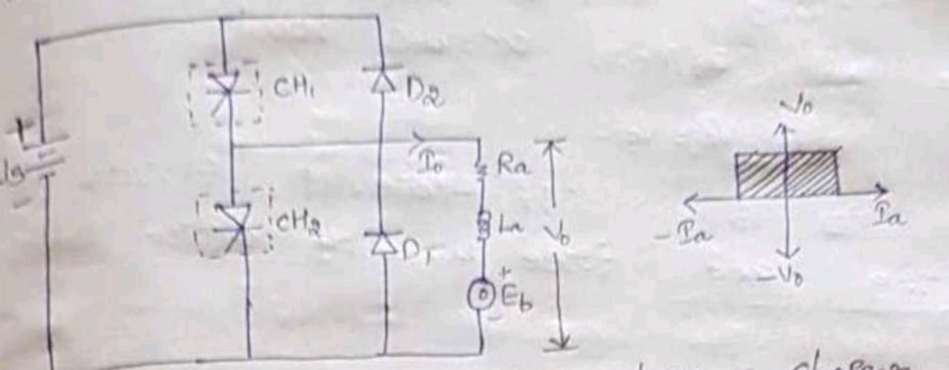


Fig. circuit Diagram for class c chopper fed separately excited DC motor.

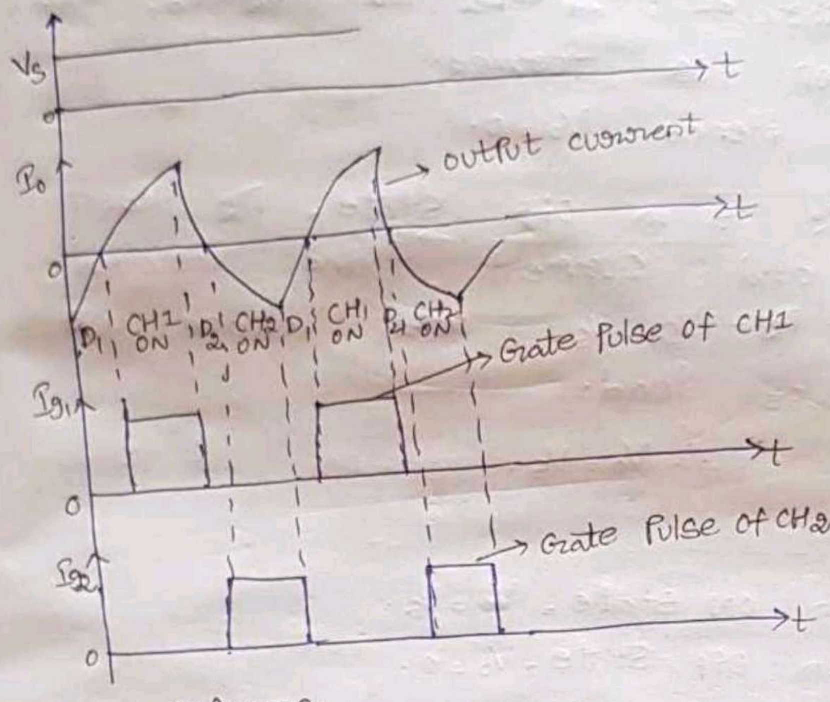


Fig. waveforms.

Above figure shows circuit diagram and waveforms of class B chopper fed seperately excited DC motor.

It is a two Quadrant chopper also Known as two Quadrant Type A chopper.

It is the combination of class A and class B choppers.

CH1 and D1 constitutes the class A chopper.

CH2 and D2 constitutes class B chopper

when CH_1 is in ON state, current start flowing through $V_{S+} - CH_1 - R_a - L_a - E_b - V$ across load. Voltage will appear

$\therefore V_0 = V_S$.

when CH_1 is in OFF state, D_1 Starts Conducting and free wheeling action takes Place.

Hence $V_0 = 0$.

when CH_2 is in ON state, current starts flowing through $E_{b+} - L_a - R_a - CH_2 - E_{b-}$ and closed loop is formed.

Hence $V_0 = 0$.

when CH_2 is in OFF state, D_2 Start Conducting and current flows through $E_b - L_a - R_a - D_2 - V_{S+} - V_{S-}$ and Voltage will appear across load.

$\therefore V_0 = V_S$.

when,

CH_1 is in ON state, $V_0 = V_S$.

CH_1 is in OFF state, $V_0 = 0$.

CH_2 is in ON state, $V_0 = 0$.

CH_2 is in OFF state, $V_0 = V_S$.

It was observed that Voltage remains Same and current becomes reversed.

Hence class c chopper is also known as current reversal chopper.

Torque - speed characteristics:

w.k.T,

For seperately excited DC motor

$$E_b = V_0 - I_a R_a$$

$$V_0 = E_b + I_a R_a$$

$$T = K_{af} \cdot I_a$$

$$N = \frac{V_0 - I_a R_a}{K_a \phi}$$

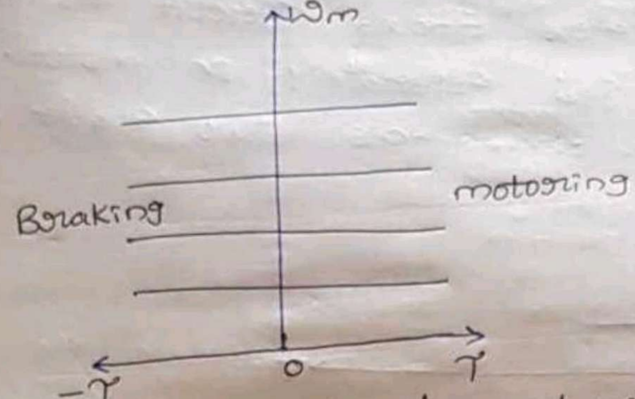


Fig. Torque speed characteristics for class c fed seperately excited DC motor.

For DC series motor,

$$E_b = V_0 - I_a(R_a + R_f)$$

$$E_b = K_{af} \cdot I_a \cdot N + K_{res} \cdot N$$

$$T = K_{af} \cdot I_a^2$$

$$N = \frac{V_0 - I_a(R_a + R_f)}{K_{af} \cdot I_a + K_{res}}$$

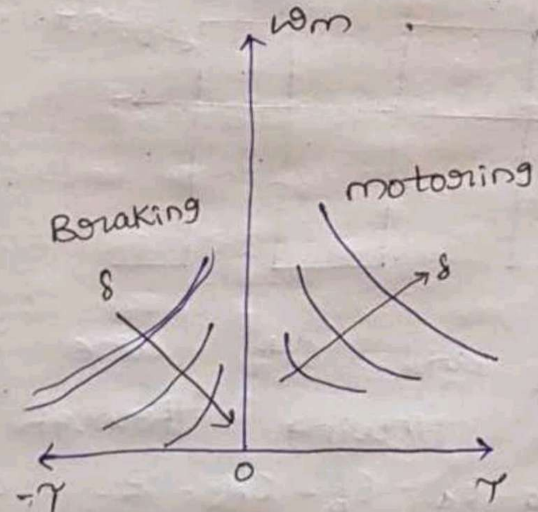


Fig. N-T characteristics for class c fed DC series motor.

Class D Chopper Fed Seperately Excited DC motor:

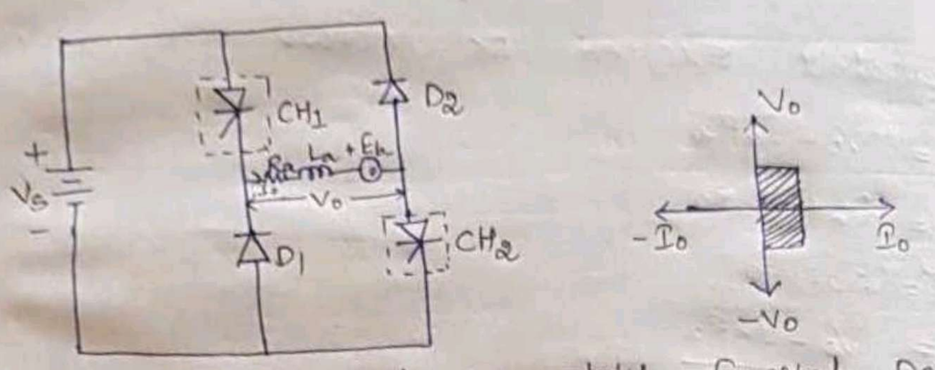
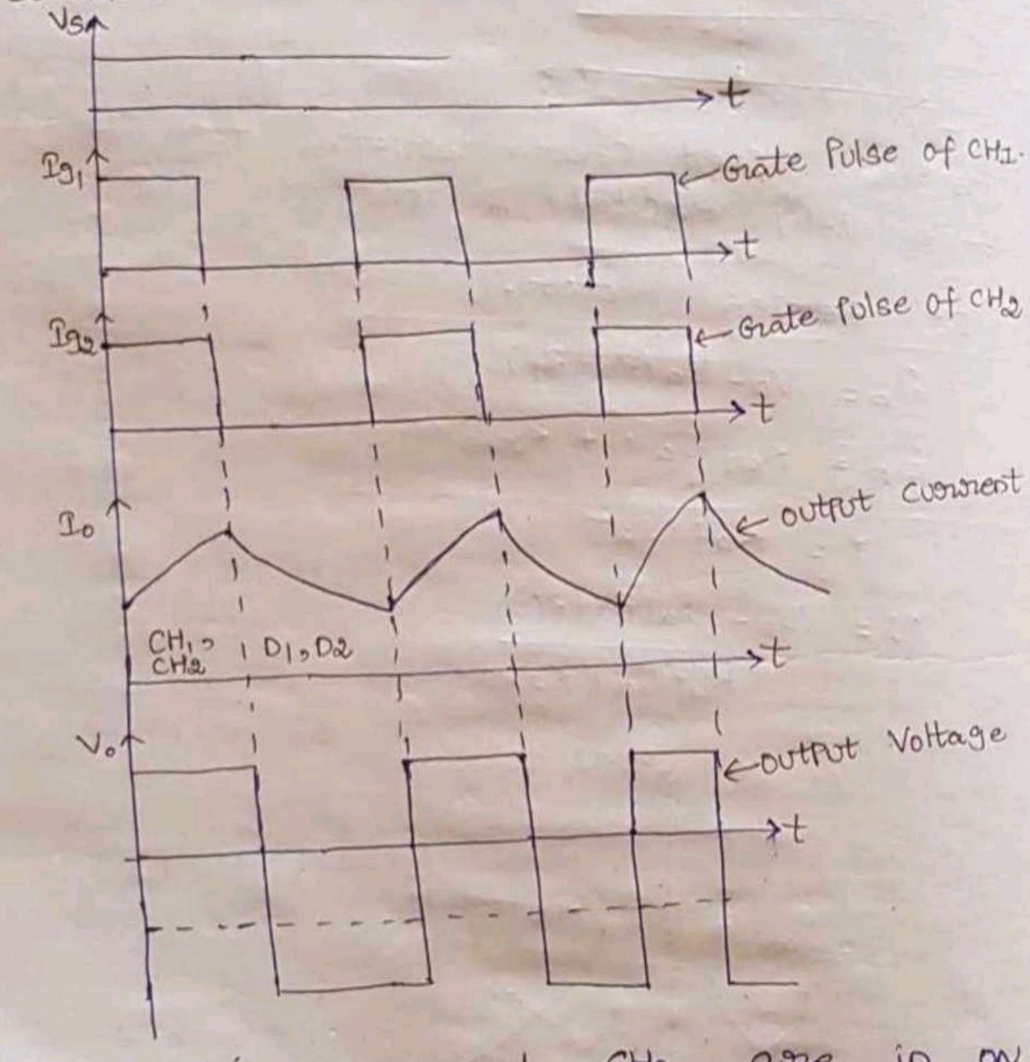


Fig. class D Fed seperately Excited DC motor

The above figure shows circuit diagram from class D Fed Seperately DC motor. It is also known as two quadrant type-B chopper.

Waveforms:



When both CH1 and CH2 are in ON state current starts flowing through the path V_{S+} – CH_1 – R_a – L_a – E_b – CH_2 – V_{S-} and voltage will appear across load.

$\therefore V_o = V_S$.

When both CH_1 and CH_2 are in OFF state current starts flowing through the path E_b+ − D_2 − V_{S+} − V_{S-} − D_1 − R_a − L_a and negative voltage will appear across load.

Hence $V_0 = -V_S$

It was observed that reversal of voltage takes place.

Hence type D chopper is also known as voltage reversal chopper.

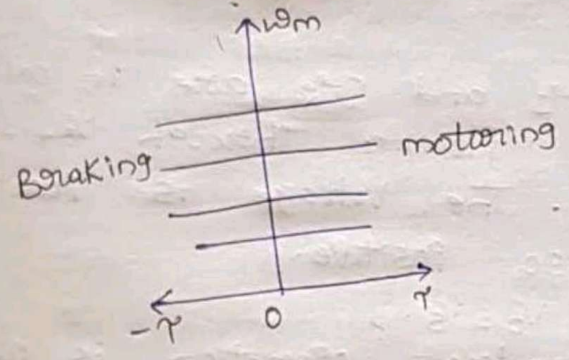
Speed- Torque characteristics:

For seperately excited DC motor,

$$E_b = V_0 - I_a R_a$$

$$\tau = K_a \phi \cdot I_a$$

$$N = \frac{V_0 - I_a R_a}{K_a \phi}$$

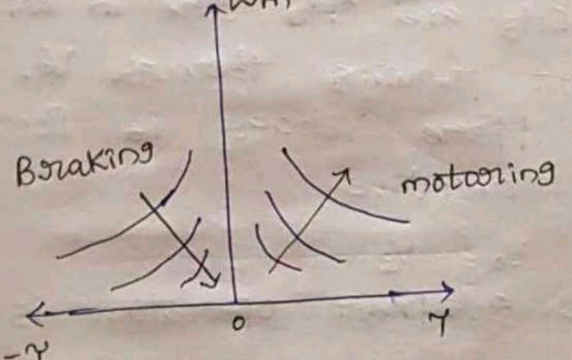


For DC series motor,

$$E_b = V_0 - I_a(R_a + R_f) = K_{af} \cdot I_a N + K_{res} \cdot N$$

$$\tau = K_{af} \cdot I_a^2$$

$$N = \frac{V_0 - I_a(R_a + R_f)}{K_{af} \cdot I_a + K_{res}}$$



Type E chopper Fed seperately Excited Dc motor

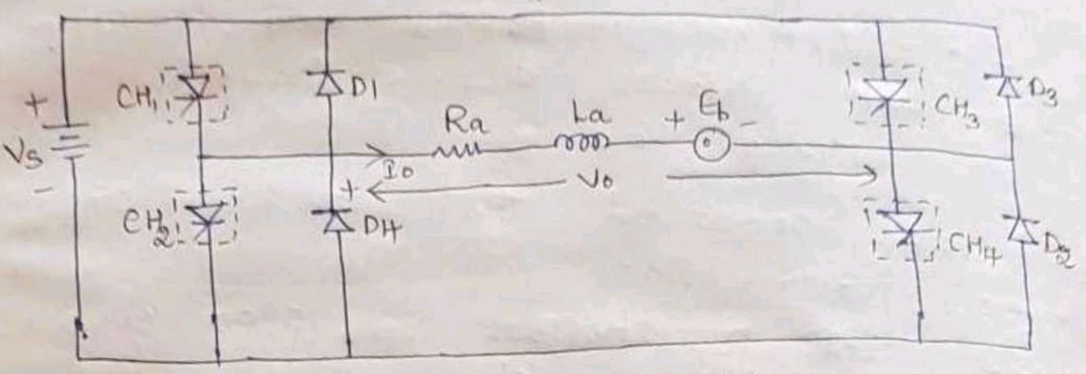
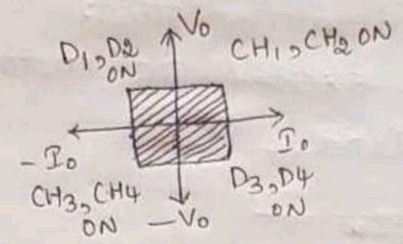


Fig. Type E chopper fed seperately Excited DC motor



The above figure shows circuit diagram of class E chopper fed seperately excited DC motor.

when both CH_1 and CH_2 are in ON state current starts flowing through $V_{S+} - CH_1 - R_a - L_a - E_b - CH_2 - V_{S-}$. The voltage is positive and current is also positive.

$$\therefore V_0 = V_S.$$

Hence first Quadrant operation is obtained.

when both CH_1 and CH_2 are in OFF state then current start flowing through $E_b - D_3 - V_{S+} - V_{S-} - D_4 - R_a - L_a$.

$\therefore$ Voltage is negative and current is positive

$$V_0 = -V_S.$$

Hence fourth Quadrant operation is obtained.

when both CH_3 and CH_4 are in ON state, current start flowing through $V_{S+} - CH_3 - E_b - L_a - R_a - CH_4 - V_{S-}$. Here voltage is positive and current is negative

$$\therefore V_0 = -V_S.$$

Hence third Quadrant operation is obtained.

When both CH_3 and CH_4 are in OFF state, current start flowing through E_b - L_a - R_a - D_1 - V_s = D_2. Current direction is reversed but voltage is positive.

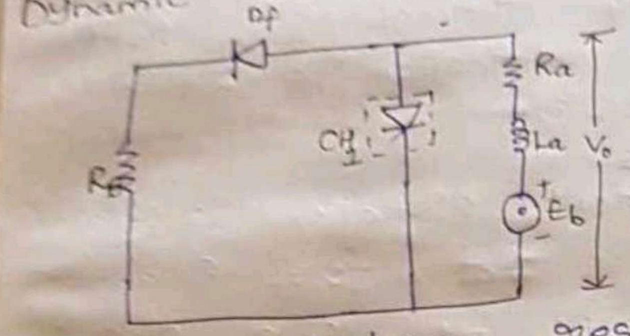
∴ $V_0 = V_s$

Hence second quadrant operation is obtained.

It was observed that four quadrant operation is obtained by using class E chopper.

Hence it is also known as four quadrant chopper.

Dynamic Braking of choppers:



when armature resistance is disconnected from source and is connected across a resistance then it is known as Dynamic braking.

Dynamic braking is also known as rheostatic braking

Here motor armature is disconnected from source and braking resistance is connected in series with armature.

when CH_1 is in ON state armature is short circuited and resistance across terminals is zero.

when CH_1 is in OFF state, the resistance across terminals is R_B.

$$R = R_B\left[\frac{T}{T} - \frac{T_{ON}}{T}\right]$$

$$= R_B\left[\frac{T - T_{ON}}{T}\right]$$

$$R_{eff} = R_B[1-\delta] \quad ; \text{ '}\delta\text{' varies from '0' to '1'}$$

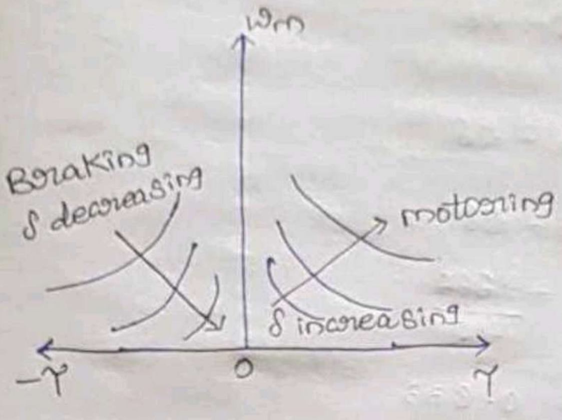
Above equation shows that the effective value of braking resistor can be changed steplessly from 0 to R_B as 'δ' is controlled from 0 to 1.

i.e $R = R_B$ when $\delta = 0$

$R = 0$ when $\delta = 1$.

Back emf expression is given by

$$E_b = I_a[R_a + R_B(1-\delta)]$$



problems:

1. A 230V, 960 rpm, 200A seperately excited DC motor has $R_a = 0.02\Omega$. Motor is operated in dynamic braking with braking resistance of 2Ω.
(i). calculate Duty cycle ratio for motor speed of 600 rpm when braking torque is equal to twice the rated torque.
(ii). what will be motor speed of duty cycle 0.6 when braking torque is equal to twice the rated torque.

Sol Given data,

$V_0 = 230V$

$N_1 = 960 rpm$

$I_a = 200A$.

$R_a = 0.02\Omega$

$R_B = 2\Omega$

(i) $N_2 = 600 rpm$

$I_a = 2I_a$

$E_{b1} = V_0 - I_a R_a$

$= 230 - 200 \times 0.02$

$=$ ~~22.6V~~ $226 V$

w.k.T,

$$\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2}$$

$$E_{b2} = \frac{E_{b1} \cdot N_2}{N_1} = \frac{226 \times 600}{960} = 141.25V.$$

$$E_{b2} = I_a \left[R_a + R_B(1-\delta)\right]$$

$$\Rightarrow 141.25 = 400 \left[0.02 + 2(1-\delta)\right]$$

$$\frac{141.25}{400} = 0.02 + 2 - 2\delta$$

$$\frac{141.25}{400} - 2.02 = -2\delta$$

$$-1.666 = -2\delta$$

$$\delta = \frac{-1.666}{-2}$$

$$\delta = 0.833$$

(ii) $E_{b2} = I_a \left[R_a + R_B(1-\delta)\right]$

$$= 400\left[0.02 + 2(1-0.6)\right]$$

$$= 328V.$$

w.k.T,

$$\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2} \Rightarrow N_2 = \frac{N_1 \cdot E_{b2}}{E_{b1}}$$

$$= \frac{960 \times 328}{226}$$

$$N_2 = 1393 \text{ rpm}$$

Closed loop operation of DC motor using chopper:

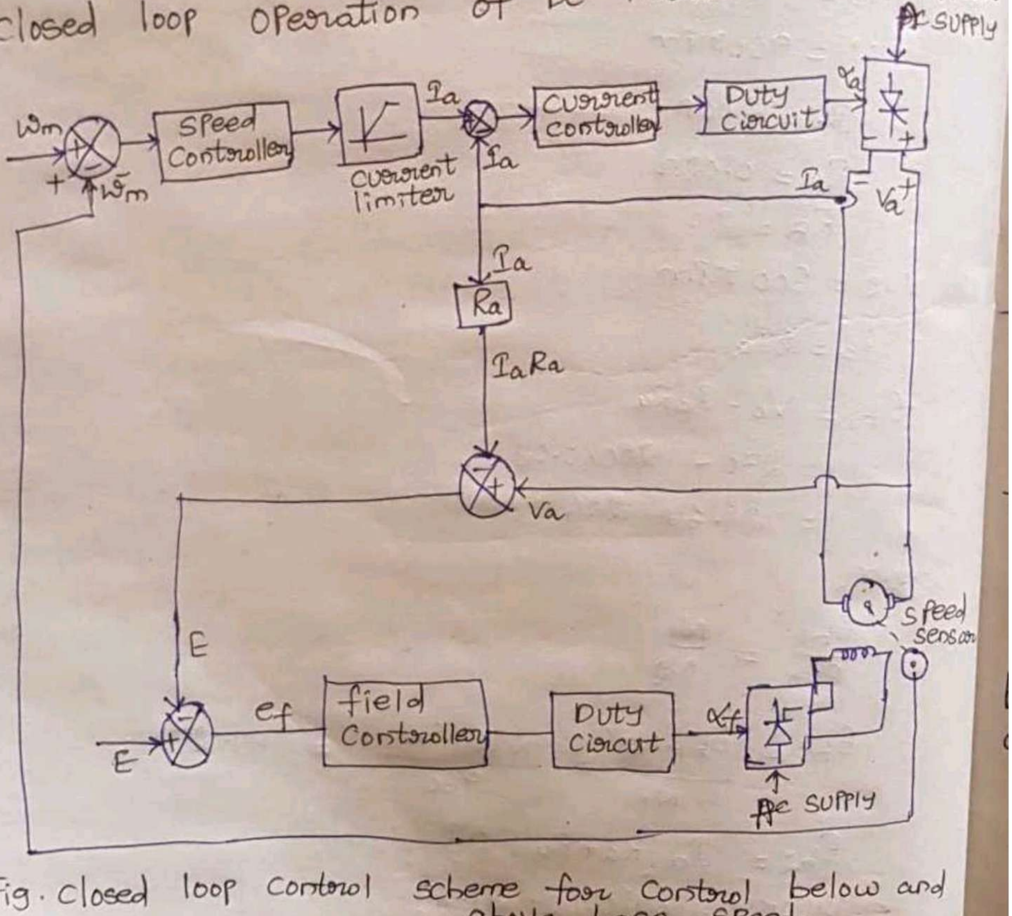


Fig. Closed loop control scheme for control below and above base speed.

The closed loop operation of DC motor by using choppers is shown in figure.
It consists of two loops namely
1. Inner current control loop
2. Outer speed control loop.

The main purpose of closed loop operation is:
1. Protection
2. Enhancement of speed
3. Steady state accuracy.

Whenever there is increase in reference speed ω_m, it produces positive speed error and it is passed through speed controller and output of speed controller is applied to current limiter, it saturates for even small speed error. It set the value of current of maximum allowable value inorder to vary duty cycle/ratio. It should be in the range of 0 to 1.
If it is not set, by default more current will apply to duty circuit and entire there is a chance of damage.
This method of action is known as motoring.

When reference speed ω_m is decreased which produces negative speed error, it is passed through speed controller, then it is passed to current limiter, it saturates for even small speed error. It was passed through current controller and it will set maximum allowable current for Duty circuit in order to own circuit in safer mode.
'δ' should be in range of 0 to 1
This method of action is known as braking.
In this manner both motoring and braking actions were achieved by using closed loop operation of choppers.
The type of controllers used were P, PI and PID controllers.