Unit – IV

CHOPPER CONTROLLED DC MOTOR DRIVES

→ Choppers may be classified according to the no. of quadrants of the $V_a - I_a$ diagram in which they are capable of operating. By various combination of connections it is possible to realize any combination of output voltage and current polarity.

Control of Seperately excited DC Motor :-

(a) Motoring Control :-

→ Generally transistor choppers are preferred over thyristor because they can be operated at a much higher frequency (2.5 to 10 KHz) than thyristors (upto 1 KHz) But because of lower voltage and current ratings of transistors, use of transistors is restricted to 200 KW.

→ For higher ratings, thyristor choppers are used.

→ A transistor chopper controlled seperately excited motor drive is shown in fig. A thyristor chopper is obtained when transistor is replaced by a thyristor with a forced commutation circuit.

→ Transistor Tr is operated periodically with period T and remains on for a duration T_{ON}. Present day choppers operate at a frequency which is high enough to ensure continuous conduction. Waveform for motor terminal voltage V_a and current I_a for continuous conduction as shown below.

→ When $0 \le t \le T_{ON}$, transistor is turned-ON. Hence Motor terminal voltage is 'V', Therefore the operation is described by

$$i_a R_a + L_a\left(\frac{di_a}{dt}\right) + E_b = V, \quad 0 \le t \le T_{ON}$$

In this interval, armature current increases from i_{a1} to i_{a2}. Since motor is connected to the source during this interval, it is called duty interval

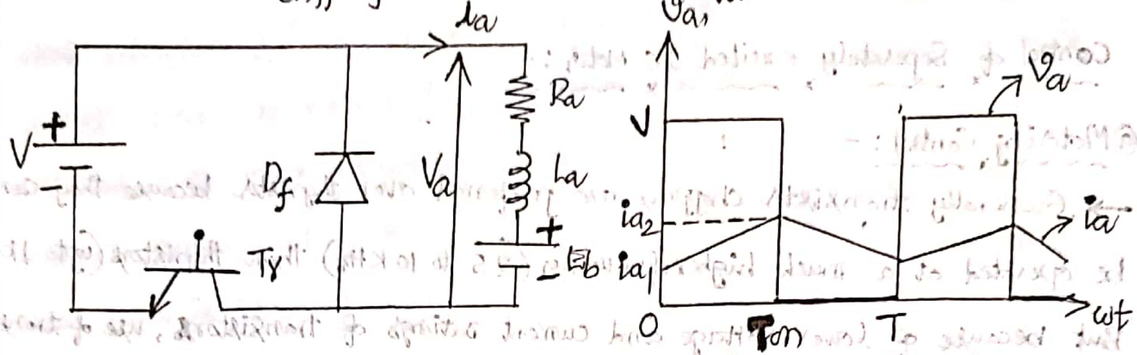
→ At $t = T_{ON}$, Tr is turned-off. Motor current freewheels through the diode D_F and the motor terminal voltage is zero during the interval $T_{ON} \le t \le T$. Motor operation during this interval known as freewheeling interval and is described by

$$i_a R_a + L_a\left(\frac{di_a}{dt}\right) + E_b = 0, \quad T_{ON} \le t \le T$$

Motor current decreases from i_{a2} to i_{a1} during this interval

→ Ratio of duty interval 'T_{ON}' to chopper period 'T' is called duty ratio (or) duty cycle (δ). Thus

$$\delta = \frac{\text{Duty interval}}{\text{Chopper period}} = \frac{T_{ON}}{T}$$



Chopper Control of Seperately excited motor

→ Average output voltage $V_a = \frac{1}{T}\int_0^{T_{ON}} V\,dt = V\left(\frac{T_{ON}}{T}\right) = \delta V$

Armature current $I_a = \frac{V_a - E_b}{R_a} = \frac{\delta V - E_b}{R_a}$

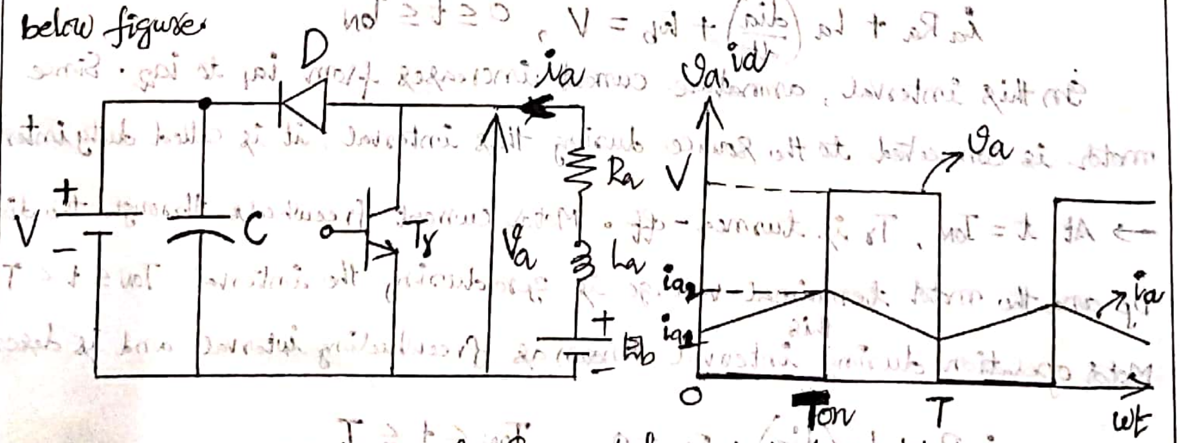
The steady state speed equation is given by

$$\omega = \frac{V_a - I_a R_a}{K} = \frac{V_a}{K} - \frac{R_a}{K}\left(\frac{T}{K}\right)$$

$$\boxed{\omega = \frac{\delta V}{K} - \left(\frac{R_a}{K^2}\right)T}$$

Regenerative Braking :-

→ chopper for regenerative braking and corresponding waveforms as shown in below figure.



Regenerative Braking of Seperately excited motor by chopper control.

→ When T_r is ON, i_a increases from i_{a1} to i_{a2}. The mechanical energy converted into electrical by the motor, now working as a generator, partly increases the stored magnetic energy in armature circuit inductance and remainder is dissipated in armature resistor and transistor.

→ When T_r is OFF, armature current flows through diode 'D' and the source 'V' and the current reduces from i_{a2} to i_{a1}. The stored electromagnetic energy [redacted] and energy supplied by machine is fed to the source.

→ The interval $0 \le t \le T_{ON}$ is called energy storage interval

$T_{ON} \le t \le T$ is called duty interval

→ The duty ratio is given by

$$\delta = \frac{\text{Duty interval}}{\text{Chopper period}} = \frac{-T_{ON} + T}{T} = \frac{T - T_{ON}}{T}$$

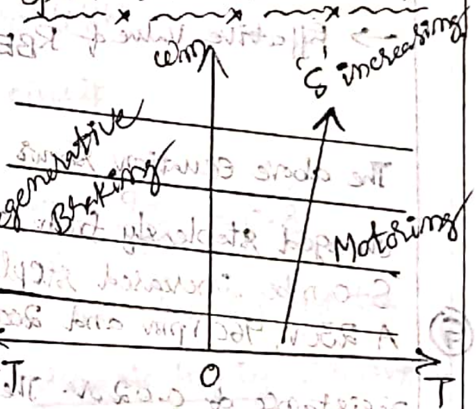
→ $$V_a = \frac{1}{T}\int_{T_{ON}}^{T} V\,dt = \delta V$$

→ $$I_a = \frac{E_b - V_a}{R_a} = \frac{E_b - \delta V}{R_a}$$

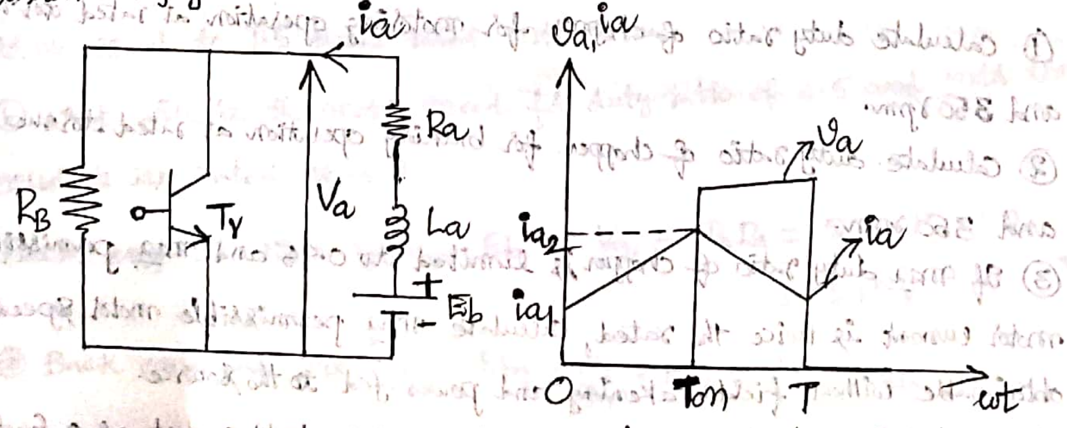
→ $$T = -K I_a$$

→ $$\omega = \frac{\delta V}{K} - \frac{R_a}{K^2} T$$

Speed – Torque characteristics



Dynamic Braking :- Dynamic braking circuit and its waveforms are shown in fig.



Dynamic braking of Seperately excited motor by Chopper Control.

→ During the interval $0 \le t \le T_{ON}$, i_a increases from i_{a1} to i_{a2}. A part of the generated energy is stored in inductance and the rest is dissipated in R_a and T_r.

→ During the interval $T_{ON} \le t \le T$, i_a decreases from i_{a2} to i_{a1}. The energies generated and stored in inductance are dissipated in braking resistance R_B, and therefore controls its effective value.

If i_a is assumed to be rippless DC, then energy consumed by R_B during a cycle of chopper operation is

→ $W = I_a^2 R_B (T - T_{ON})$

→ Average power consumed by R_B

$$P = \frac{W}{T} = \frac{I_a^2 R_B (T - T_{ON})}{T} = I_a^2 R_B (1-\delta)$$

→ Effective value of $R_{BE} = \frac{P}{I_a^2} = R_B(1-\delta)$ where $\delta = \frac{T_{ON}}{T}$

The above equation shows that the effective value of braking resistor can be changed steplessly from 0 to R_B as δ is controlled from 1 to 0. As the speed falls, δ can be increased steplessly to brake the motor at a constant max torque.

(9) A 230V, 960 rpm and 200A seperately excited DC motor has an armature resistance of 0.02 Ω. The motor is fed from a chopper which provides both motoring and braking operations. The source has a voltage of 230V. Assume continuous conduction.

① Calculate duty ratio of chopper for motoring operation at rated torque and 350 rpm.

② Calculate duty ratio of chopper for braking operation at rated torque and 350 rpm.

③ If max duty ratio of chopper is limited to 0.95 and max permissible motor current is twice the rated, calculate max permissible motor speed obtainable without field weakening and power fed to the source.

④ If motor field is also controlled in ③, calculate field current as a fraction of its rated value for a speed of 1200 rpm.

$E_{b_1} = V_a - I_a R_a = 230 - 200 \times 0.02 = 226V$ at 960 rpm.

① $E_{b_2} = \frac{N_2}{N_1} \times E_{b_1} = \frac{350}{960} \times 226 = 82.4V$

$V_{a_2} = E_{b_2} + I_a R_a = 82.4 + 200 \times 0.02 = 86.4V$

$(1/\text{Duty ratio}) = \frac{V}{V_{a_2}} \Rightarrow \delta = \frac{V_{a_2}}{V} = \frac{86.4}{230} = 0.376$

② $V_{a_3} = E_{b_3} - I_a R_a = 82.4 - 200 \times 0.2 = 78.4V$

$\delta = \frac{V_{a_3}}{V} = \frac{78.4}{230} = 0.34$

③ $V_{a_4} = \delta V = 0.95 \times 230 = 218.5V$

$E_{b_4} = V_{a_4} + I_a R_a = 218.5 + (2 \times 200 \times 0.02) = 226.5V$

Max permissible motor speed $= \frac{226.5}{226} \times 960 = 962$ rpm

Neglect the losses in the chopper, power fed to the source.

$P = V_a I_a = 218.5 \times (2 \times 200) = 87.4$ kW.

④ $\phi \propto \frac{1}{N}$ Assuming linear magnetic circuit

$\frac{\phi_2}{\phi_r} = \frac{N_r}{N_2} \Rightarrow \because \phi \propto I_f \Rightarrow \frac{I_{f2}}{I_{fr}} = \frac{N_r}{N_2} = \frac{960}{1200} = 0.8$

(2008) ⑤ A 230V, 1200 rpm, 15A separately excited motor has an armature resistance of 1.2Ω. Motor is operated under dynamic braking with chopper control. Braking resistance has a value of 20Ω.

ⓐ Calculate duty ratio of chopper for motor speed of 1000 rpm and braking torque equal to 1.5 times rated motor torque.

ⓑ What will be the motor speed for duty ratio of 0.5 and motor torque equal to its rated torque?

Ⓐ Back emf at 1200 rpm, $E_{b_1} = V_{a_1} - I_a R_a = 230 - 15 \times 1.2$

$= 212V$

ⓐ Back emf at 1000 rpm, $E_{b_2} = \frac{N_2}{N_1} \times E_{b_1} = \frac{1000}{1200} \times 212$

$= 176.66V$

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$R_{BE} = R_B(1-\delta)$

$$R_{BE} = \frac{P}{I_a^2} = \frac{V_a I_a}{I_a^2} = \frac{V_a}{I_a} = \frac{E_{b_2} - I_a R_a}{I_a} = \frac{E_{b_2}}{I_a} - R_a$$

$$R_{BE} = \frac{176.66}{1.5 \times 15} - 1.2 = 6.65$$

$$6.65 = 20(1-\delta) \Rightarrow (1-\delta) = 0.3325 \Rightarrow \delta = 0.6675$$

(b) $R_{BE} = \frac{E_b - I_a R_a}{I_a} \Rightarrow E_b = R_{BE} I_a + I_a R_a$

$$E_{b_3} = I_a(R_{BE} + R_a) = I_a[(1-\delta)R_B + R_a]$$

$$E_{b_3} = 15[(1-0.5)20 + 1.2] = 168\text{ V}$$

$$N_3 = \frac{E_{b_3}}{E_{b_1}} \times N_1 = \frac{168}{212} \times 1200 = 950.94 \text{ rpm}$$

(2008) (Q) A 220V, 190 A DC series motor has armature and field resistance of 0.03 and 0.02 ohms respectively. Running on no-load as a generator with field winding connected to a seperate source, it gave following magnetization characteristics at 500 rpm.

Field current (A)	40	80	120	160	200
Terminal Voltage (V)	52	108	148	176	189

Motor is controlled by a chopper in dynamic braking with a braking resistance of 2Ω.

(a) Calculate motor speed for a duty ratio of 0.6 and motor current of 160A (b) what will be the motor speed for a duty ratio of 0.75 and motor torque equal to half of rated torque? Assume the supply voltage be 220V

(A) (a) [illegible]

(9) A 220V, 70A DC Series motor has combined resistance of armature and field of 0.12Ω. Running on load with the field winding connected to a seperate source it gave following magnetization characteristics at 600 rpm:

Field current (A)	10	20	30	40	50	60	70	80
Terminal Voltage (V)	64	118	150	170	184	194	202	210

Motor is controlled by a chopper with a source voltage = 220 V, calculate

① Motor speed for a duty ratio of 0.6 and motor current of 60 A.

② Torque for a speed of 400 rpm and duty ratio of 0.65

(A) ① $V_{a_2} = \delta V = 132\,V$

$E_{b_2} = V_{a_2} - I_{a_2} R = 132 - 60 \times 0.12 = 124.8V$

From Magnetization characteristics for $I_a = 60A$, $E_b = 194V$ at 600 rpm.

For $194V \longrightarrow 600$ rpm
$124.8V \longrightarrow N$ rpm $\Big\} \Rightarrow N = \frac{600 \times 124.8}{194} = 386$ rpm.

② $V_a = E_b + I_a R_a = \delta V_s$

$E_b + I_a(0.12) = 0.65 \times 220 = 143$

$0.12 I_a = 143 - E_b$ — ①

The above equation is a non-linear equation and can be solved by Trial and error. From Magnetization characteristics

For $I_a = 70A$, $E_b = 202V$ for 600 rpm

600 rpm $\longrightarrow$ 202 V
400 rpm $\longrightarrow E_b$ $\Big\} \Rightarrow E_b = \frac{400 \times 202}{600} = 134.66V$

put $E_b = 134.66V$ and $I_a = 70A$ in equation ①

$0.12 I_a = 8.4$, $143 - E_b = 8.34$, $\therefore$ L.H.S ≈ R.H.S

These values balances the equation Hence $E_b = 134.66$ holds good

$$\tau = \frac{E_b I_a}{\omega} = \frac{134.66 \times 70}{\left(\frac{2\pi \times 400}{60}\right)} = 225\ Nm.$$

Q) A DC series motor of above example is now controlled in regenerative braking by a chopper with a source voltage of 220V.

(a) Calculate motor speed for a duty ratio of 0.5 and motor braking torque equal to the rated motor torque.

(b) Calculate maximum allowable motor speed for a max. permissible current of 70A and max. permissible duty ratio of 0.95

(c) What resistance must be inserted in armature circuit for the drive to run at 1000 rpm without exceeding armature current beyond 70A? The chopper duty ratio is ranges from 0.05 to 0.95.

(d) To what extent the no. of turns in field winding should be reduced to run the motor at 1000 rpm without exceeding the armature current beyond 70A.

A) (a) $V_a = \delta V_s = 0.5 \times 220 = 110V$

$E_b = V_a + I_a R_a = 110 + 70 \times 0.12 = 118.4V$

For $I_a = 70A$, $E_b = 202V$ for 600 rpm

$202 \rightarrow 600$ rpm
$118.4 \rightarrow N$
$\Rightarrow N = \frac{118.4}{202} \times 600 = 351.7$ rpm

(b) $V_a = \delta V_s = 0.95 \times 220 = 209V$

$E_b = V_a + I_a R_a = 217.4V$

For $I_a = 70A$, $E_b = 202V$ for 600 rpm

$202 \rightarrow 600$ rpm
$217.4 \rightarrow N$
$\Rightarrow N = \frac{217.4}{202} \times 600 = 645.7$ rpm

(c) For $I_a = 70A$, $E_b = 202V$ for 600 rpm

600 rpm $\rightarrow 202V$
1000 rpm $\rightarrow E_b$
$\Rightarrow E_b = \frac{1000}{600} \times 202 = 336.67V$

$E_b = V_a + (R_a + R_{ext}) I_a \Rightarrow 336.67 = 0.95 \times 220 + (0.12 + R_{ext})70$

$0.12 + R_{ext} = 1.82 \Rightarrow R_{ext} = 1.7\Omega$

(d) It is assume that even after changing field turns $R_a = 0.12\Omega$

$E_b = \delta V_s + I_a R_a = 0.95 \times 220 + 70 \times 0.12 = 217.4$ for 1000 rpm

$1000\ rpm \rightarrow 217.4V$
$600\ rpm \rightarrow E_b$ } $E_{b_2} = \frac{600}{1000} \times 217.4 = 130.44V$

Fraction to which the no. of turns in the field are reduced $= \frac{E_{b2}}{E_{b1}}$

$= \frac{130.44}{202} = 0.646$

(Q) A DC Series motor of above example is now controlled in dynamic braking. Available chopper provides a variation in duty ratio from 0.1 to 0.9

(a) Calculate braking resistor so that max braking speed at the armature current of 70A will be 800 rpm.

(b) Also calculate the max available motor torque for a speed of 87 rpm with braking resistance as calculated in (a)

(A) (a) For 70A, $E_b = 202V$ for 600 rpm

$600\ rpm \rightarrow 202V$
$800\ rpm \rightarrow E_b$ } $E_b = \frac{800}{600} \times 202 = 269.33V$

$R_{BE} = \frac{E_b}{I_a} - R_a = \frac{269.33}{70} - 0.12 = 3.73\Omega$

For a given value of R_B, max value of R_{BE} is obtained at min value of 'δ'

$R_{BE} = R_B(1 - \delta_{min})$

$3.73 = R_B(1 - 0.1) \Rightarrow R_B = 4.14\Omega$

(b) For a given speed, torque will be maximum when duty ratio is maximum

Total Armature circuit resistance at max duty ratio δ_{max}

$R_T = R_B(1 - \delta_{max}) + R_a = 4.14(1 - 0.9) + 0.12 = 0.534\Omega$

$E_b = I_a R_T$ — (1)

Equation (1) must be satisfied for a speed of 87 rpm. (*)

(Q) A 230V, 960 rpm, 200A seperately excited DC motor has an armature resistance of 0.02Ω. The Source Voltage = 230V. It is operated in dynamic braking with chopper control with a braking resistor of 2Ω

(1) calculate duty ratio of chopper for a motor speed of 600 rpm and braking torque of twice the rated value.

② What will be the motor speed for a duty ratio of 0.6 and motor torque equal to twice its rated torque.

Ⓐ ① E_b at 600 rpm $= \frac{600}{960} \times 226 = 141.25V$ $E_{b1} = 230 - 200 \times 0.02 = 226$

$R_{BE} = (1-\delta)R_B = \frac{E}{I_a} - R_a$

$(1-\delta)\times 2 = \frac{141.25}{2\times 200} - 0.02 \Rightarrow \delta = 0.83$

② $E = I_a[(1-\delta)R_B + R_a] = 2\times 200[(1-0.6)\times 2 + 0.02] = 328V$

$\text{Speed} = \frac{328}{226} \times 960 = 1393.3$ rpm.

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⊛ Trying various values of I_a and the value of corresponding E (at 87 rpm = 26.68V) obtained from magnetization characteristics gave a approximate solution of $I_a = 50A$

At 50A, $K_a\phi = \frac{184}{600\times\left(\frac{2\pi}{60}\right)} = 2.928$

$T = (K_a\phi)I_a = 2.928 \times 50 = 146.4$ Nm

Ⓠ A dc shunt motor takes a current of 50A on a 440V supply runs at a speed of 1000 rpm with $R_a = 0.5\Omega$ & $R_{sh} = 100\Omega$. A chopper is used to control the speed of the motor in the range of 400–800 rpm having a constant torque. The onperiod of the chopper is 2ms with its field supply voltage from 440V. Determine the range of frequencies of the chopper.

Ⓐ E_b at 1000 rpm $= 440 - 45.6\times 0.5 = 417.2V$, $I_f = \frac{440}{100} = 4.4A$

① E_b at 400 rpm $= \frac{400}{1000} \times 415 = 166.88$ rpm $\quad I_a = 50 - 4.4 = 45.6A$

$V = 166.88 + 45.6\times 0.5 = 189.68V$, $\delta = \frac{V_0}{V} = \frac{189.68}{440} = 0.431 = \frac{T_{ON}}{T} = T_{ON}f_1$

$f_1 = \frac{0.431}{T_{ON}} = \frac{0.431}{2\times 10^{-3}} = 215.5 Hz$

② E_b at 800 rpm $= 333.76V$

$V = 333.76 + 45.6\times 0.5 = 356.56V$

$\delta = \frac{356.56}{440} = 0.81 = T_{ON}f_2 \Rightarrow f_2 = \frac{0.81}{2\times 10^{-3}} = 405 Hz$

Range of freq is $215.5 Hz \le f \le 405 Hz$