

Four Quadrant operation of DC motors (Drives)

Braking of Electric Motors

Whenever an electric drive is disconnected from the supply, the speed of the driving motor gradually decreases and becomes zero. Braking is a generic term used to describe a set of operating conditions for electric drive systems.

During the braking process, the energy can change its flow between the source and load. In this period, the machines act as a generator, which pumps the energy back to the electric supply. Generally there are two types of braking methods namely

1. Mechanical braking
2. Electric braking ;)

For both methods of braking, the braking torque is required.

Mechanical Braking.

In mechanical braking, the frictional force between the rotating parts and brake drums provide the required brake. Mechanical Equipments such as brake linings, brake shoes and brake drums are required.

Electric Braking

In Electric braking, the motor is made to work as generator. So it produces a negative slip and negative torque. This is achieved by suitably changing the electrical connections of the motor. Whether mechanical or electric braking, the braking, of the drive should be such as to stop the motor at the specified point of time and locations, for reasons of safety.

1. If a motor running at some speed is disconnected from the input supply, the only opposing torque will be the torque of load.
2. In some important applications such as traction, rapid emergency stops are essential to prevent accidents.

Types of Electric Braking

There are several forms of braking applicable to the usual types of electric motors. Generally, we can group all braking methods into three types.

1. Regenerative braking
2. Dynamic or Rheostatic braking
3. Plugging or reverse current 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 greater than the synchronous speed.

Mechanical energy is converted into electrical energy, part of which is returned to the supply and rest of the energy is lost as heat in the winding and bearings of the electric machine. Most of the electrical machines pass smoothly from motoring region to generating region, when over driven by the load.

Dynamic or Rheostatic Braking

When an electric motor rotates, a kinetic energy is stored in its rotating mass. If the motor is disconnected from the supply it continues to rotate for a period of time until the kinetic energy is totally dissipated in the form of rotational losses. The faster the dissipation of the kinetic energy, the more rapid is the braking.

Plugging

The direction of rotation of an electric motor is dependent on several variables. For ac machines, the phase sequence of the stator windings are one of the variables and for dc machines, the polarities of the field or armature voltage.

For ac machines, the shaft of the machine rotates in the same direction as the magnetic field. If the phase sequence of the stator windings is reversed [RBY],

Dual Converter fed DC Motors Drive

Dual Converter is also called as four quadrant Converter. It means the Output Voltage and Output Current is either positive or negative. Dual Converter Consists of two similar Single phase or three phase fully Controlled Converter which are Connected in parallel at the input side (ac) and are Connected inverse parallel at the Output side.

The electrical Connection diagram of the dual Converter [1 ϕ and 3 ϕ].

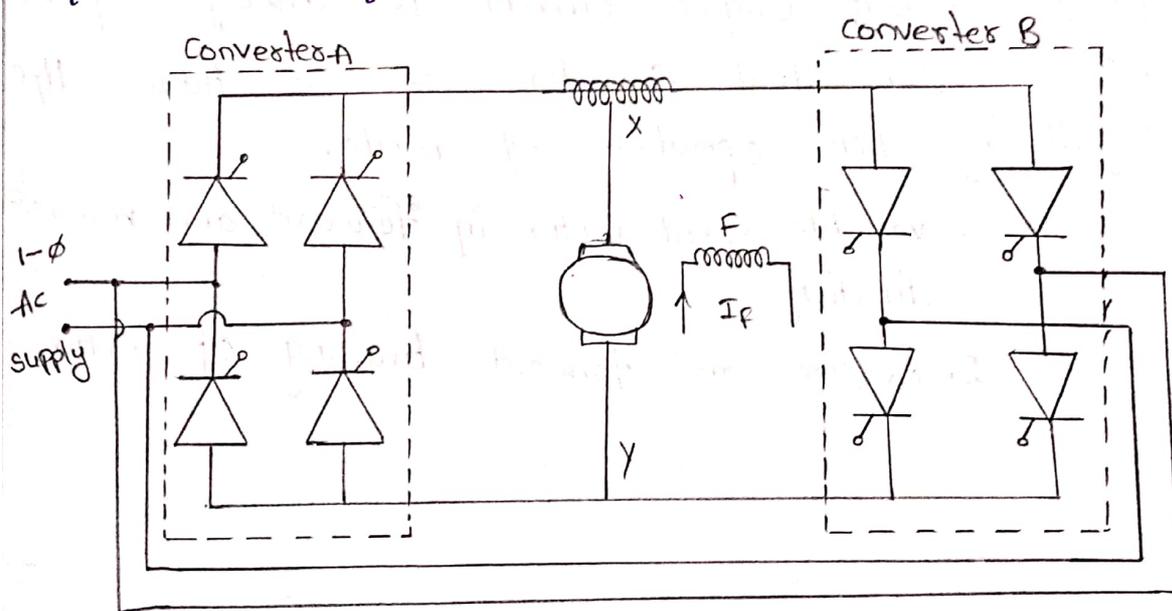


Fig: single-phase dual converter

In Conventional fully Controlled rectifier operation at Continuous Current mode the average Output Voltage is equal to

$$\frac{2\sqrt{2}V}{\pi} \cos \alpha, \text{ For single phase}$$

$$\text{or } \frac{3}{\pi} V_{LM} \cos \alpha, \text{ For three-phase.}$$

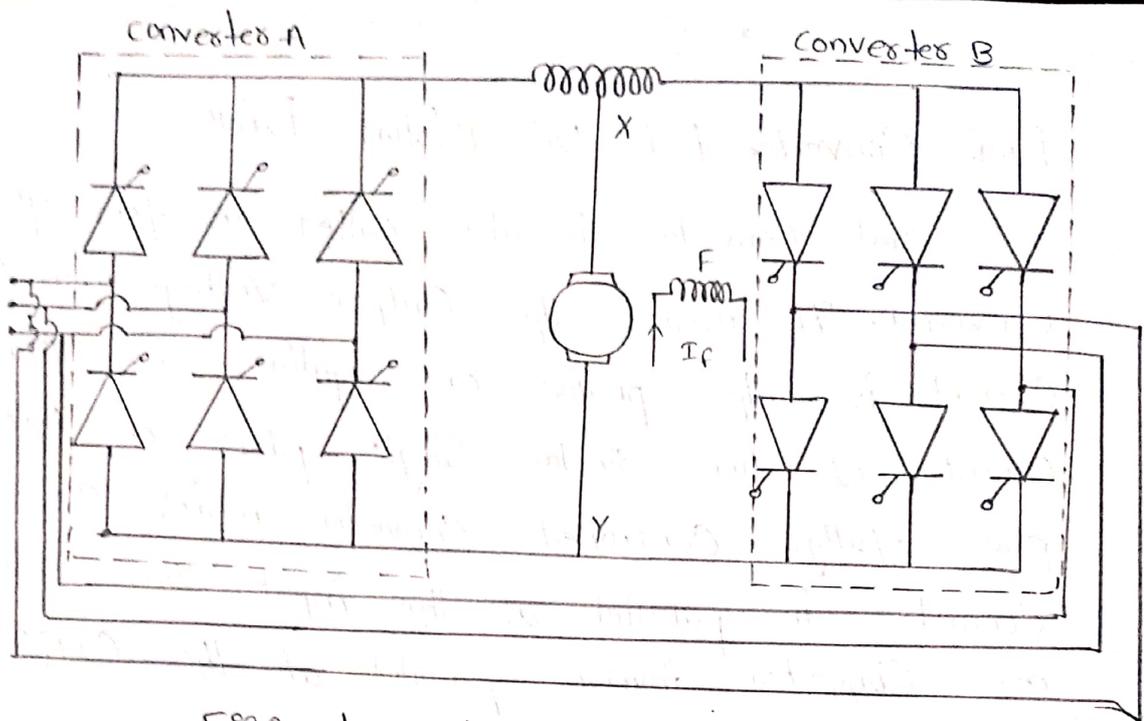


Fig:- Three-phase dual Converter

By Varying delay angle α and it is possible to vary the Output dc Voltage is positive or negative. But Output Current is always positive

Using dual Converter, we can have the following two operations of mode.

1. Variable speed motor in forward and reverse direction
2. Reverse and forward braking of motor.

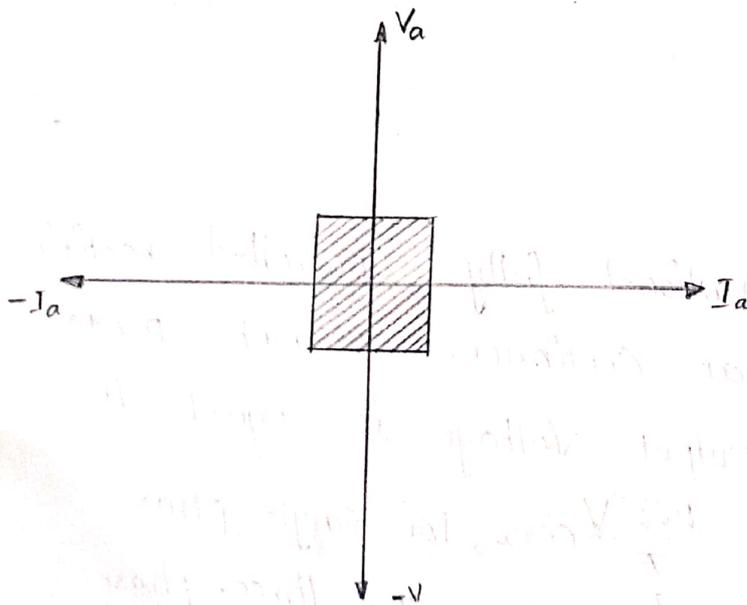


Fig: Quadrant operation unit-2 pg: 6/42

There are two modes of Operation

1. Non Circulating Current mode
2. Circulating Current mode

Non Circulating Current Mode of Operation

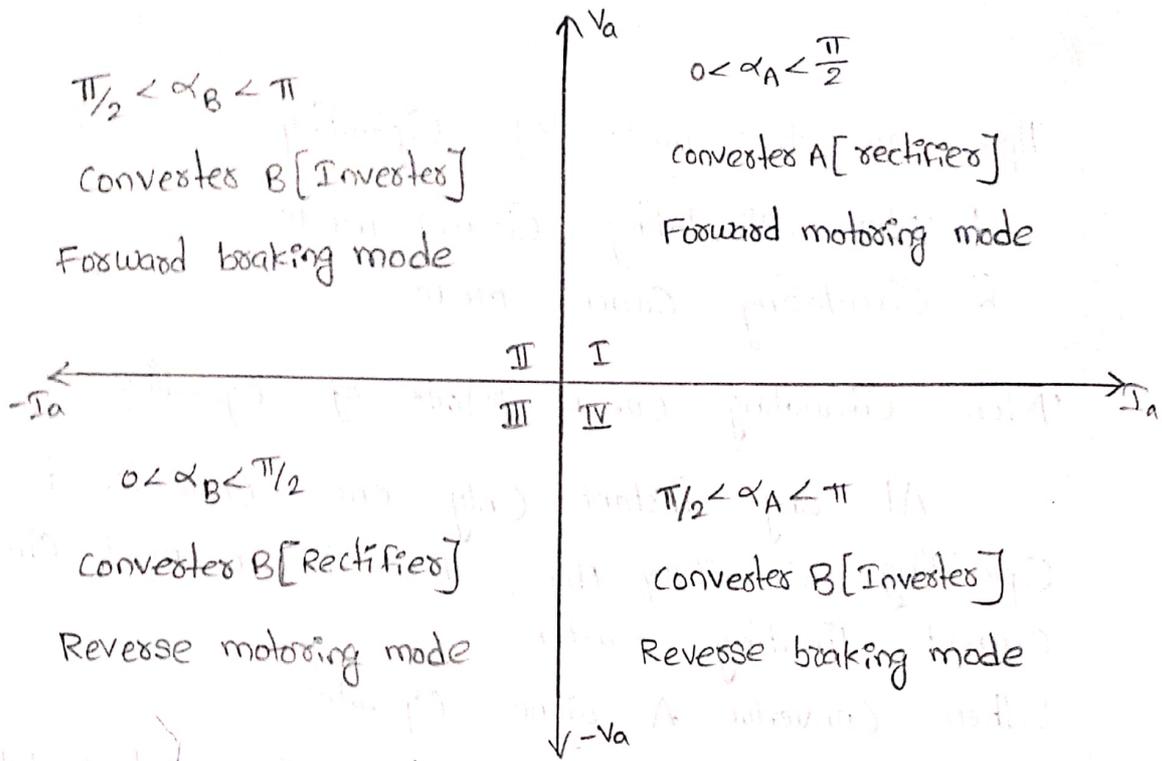
At any instant Only one Converter is in Operating Condition. Here, there is no need Circulating Current limiting reactor.

When Converter A alone Operates

The Current is always flow from x to y. When the firing angle varied from 0 to $\frac{\pi}{2}$ i.e., $[0 < \alpha_A < \frac{\pi}{2}]$, the machine Operates as motor in forward direction and the Converter Operates as rectifier.

When the firing angle varied from $\frac{\pi}{2}$ to π , i.e., $[\frac{\pi}{2} < \alpha_A < \pi]$, the machine Operates in reverse braking mode and the Converter Operates as line commuted inverter. The $V_a - I_a$ plane for non-circulating Current mode.

When the direction of rotation of the Motor is to be reversed, it is required to see that the first Converter is turned off and the motor has attained Zero speed and then Current becomes zero. Afterwards the second Converter is made to operate by giving suitable signals to the gate. To achieve this the current is to be senses also a small time interval is required for the change over of the Converter.



Circulating Current Mode

Both Converter A and B will be in operation through out. At the dc side,

$$\frac{3}{\pi} V_{Lm} \cos \alpha_A = -\frac{3}{\pi} V_{Lm} \cos \alpha_B$$

$$\begin{aligned} \cos \alpha_A &= -\cos \alpha_B \\ &= \cos (\pi - \alpha_B) \end{aligned}$$

$$\alpha_A + \alpha_B = \pi$$

$$\alpha_B = \pi - \alpha_A$$

The firing angles of Converter A and Converter B are controlled such that the average dc output voltages at the terminals x and y due to Converter A and B should have the same value. For achieving this if $\alpha_A = \alpha$, then $\alpha_B = \pi - \alpha$.

Even though the average values are one and the same, instant by instant the output voltages of the converter do not tally.

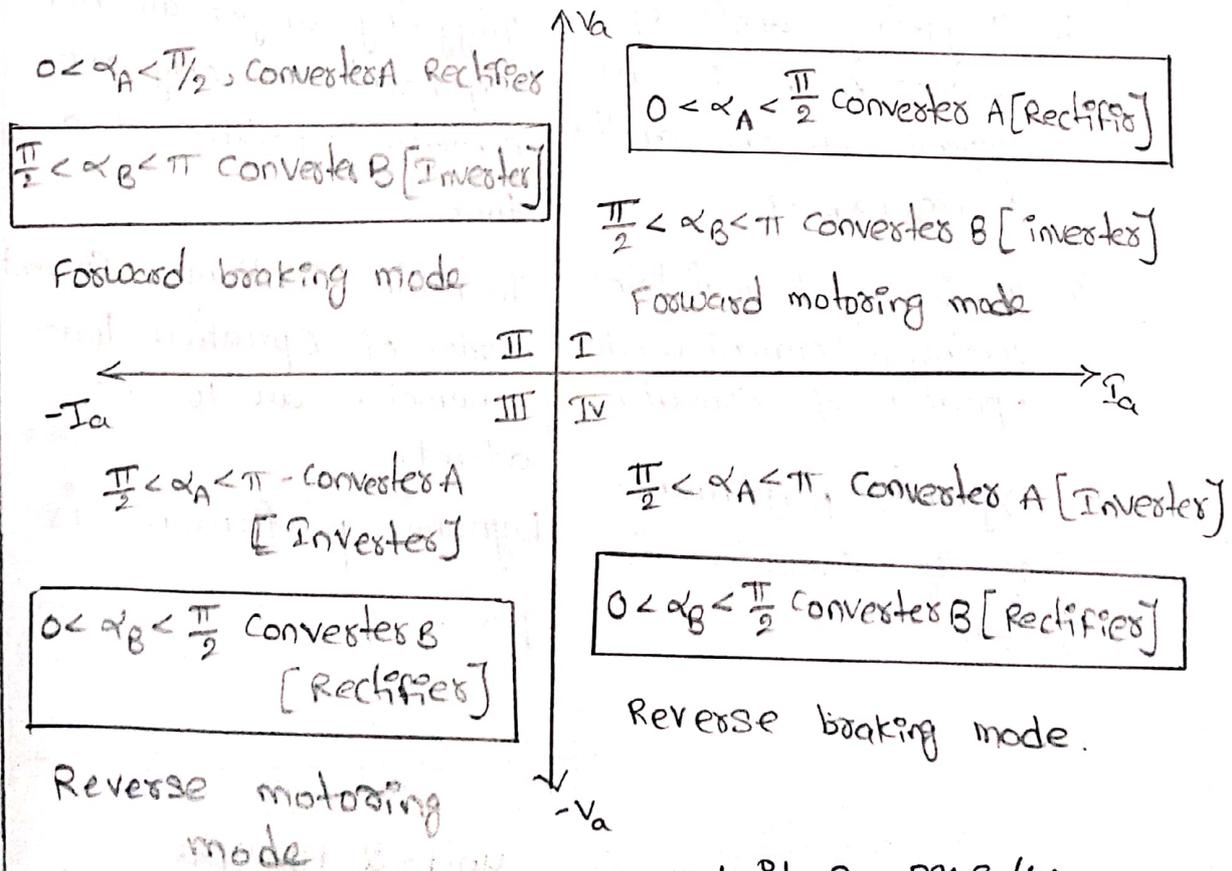
Operation

Case (i) : I, II quadrant Operation

Here, the Converter A firing angle varied from 0 to $\frac{\pi}{2}$ and Converter B firing angle varied from $\frac{\pi}{2}$ to π . Then the Converter A Operated as a rectifier and Converter B operates as an inverter. So the machine acts either as a motor in forward direction fed from Converter A or as a brake in the reverse direction feeding to Supply through Converter B.

Case (ii) : III, IV quadrant Operation.

Here, the Converter B firing angle varied from 0 to $\frac{\pi}{2}$ and Converter A firing angle varied from $\frac{\pi}{2}$ to π . Hence, the Converter B operates as a rectifier and Converter A Operates as a line commutated inverter.



The dc machine Operates either as a motor in reverse direction taking power through Converter B or as a brake in forward direction feeding power to the means through Converter A. This Operation is known as four quadrant Operation. It is indicated in $V_a - I_a$ plane. For this both Converters operate in Continuous mode.

Comparison between Circulating Current mode and non-Circulating Current mode of dual Converter.

	Circulating Current mode of dual Converter	Non-Circulating Current mode of dual Converter
1.	Current limiting reactor is required and to limit the circulating current	Current limiting reactor is not required.
2.	Triggering angles of Converter A and B are depends on one another i.e., $\alpha_A + \alpha_B = \pi$	Triggering angles are not dependent as only one Converter Operates at a time
3.	It is easy to maintain continuous current mode operation of Converter.	To main continuous current mode of operation load parameter are to be altered.
4.	Dynamic performance of the Converter is better	Dynamic performance is poor.

Closed Loop Control of Electric Drive

Feed back loops in an electrical drive may be provided to satisfy one (or) more of the following requirements.

- i. Protection
- ii. Improvement of Speed response
- iii. To improve steady state accuracy.

Block diagram of a closed loop Control System.

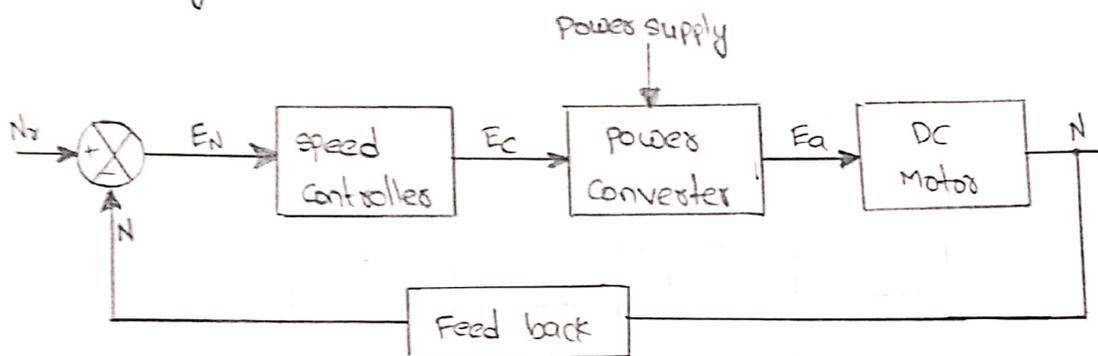
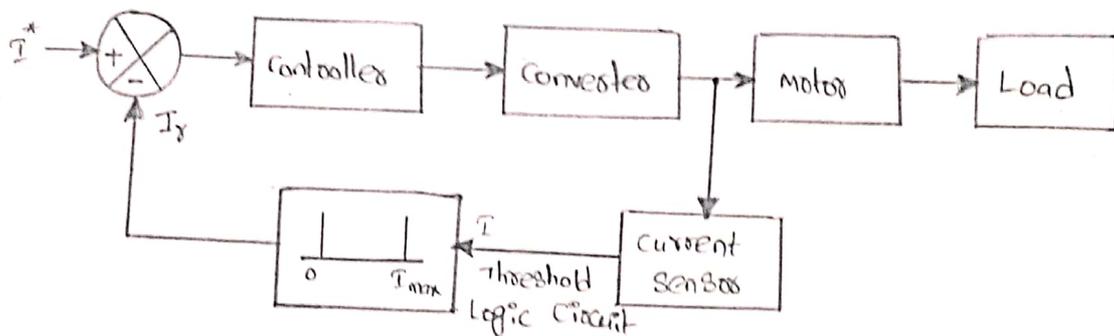


Fig
Above figure shows basic diagram of closed loop control system of dc motor. This system consists of dc motor, power converter feedback path, comparator and speed controller.

Here, the motor speed can be sensed by speed sensor. It is a feedback signal N . i.e., actual speed. Actual speed is compared with reference signal N_r . The section describes various closed loop configurations which find application in electric drives.

Current Limit Control.

Current Limit Control Scheme of given below figure is employed to limit the converter and motor current below a safe limit during transient operations. It has a current feedback loop with a threshold logic circuit. As long as the current is within a set maximum value, which causes the feedback loop to become inactive again.



Closed Loop Torque Control.

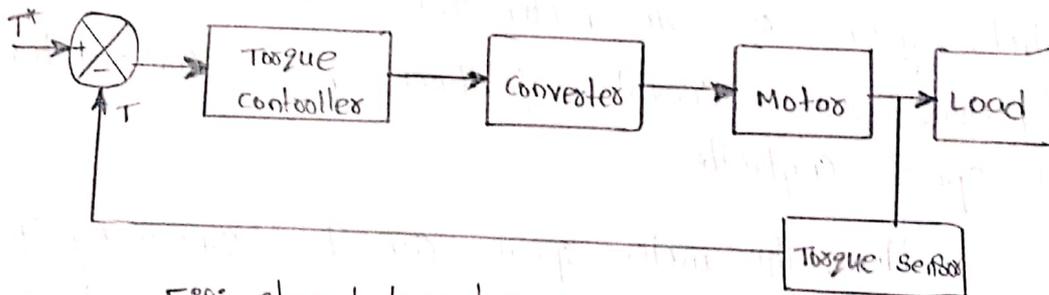
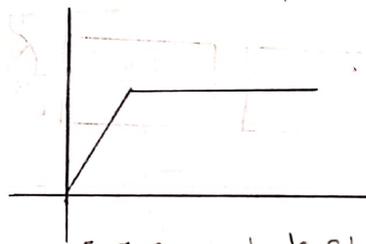
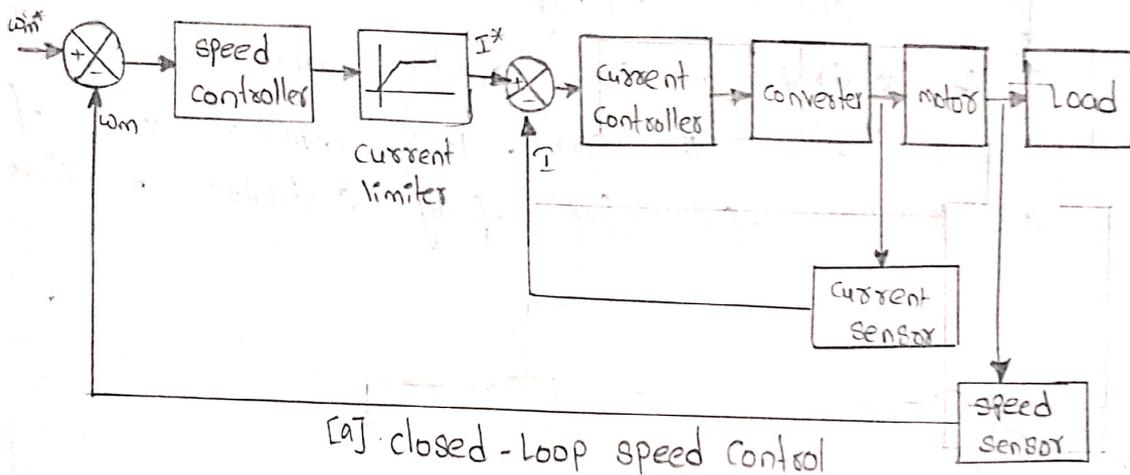


Fig: closed loop torque control

Closed loop torque control scheme of above figure finds application in battery operated vehicles electric trains. Driver presses the accelerator to set torque reference T^* . Through closed loop control of torque, the actual motor torque T follows torque reference T^* .

Closed Loop Speed Control

The below figure shows a closed loop perimeter Control Scheme which is widely used in electrical drives. It employs an inner current control within an outer speed loop. Inner current control loop is provided to limit the converter and motor current or motor torque below a safe limit.



[b] Current limiter

Drive of above figure operates as follows: An increase in reference speed ω_m^* produce a positive error $\Delta\omega_m$. Speed is processed through a speed controller and applied to a current limiter which saturates even for a small speed error. Consequently limiter sets current reference for inner current control loop at a value corresponding to the maximum allowable current.

Closed Loop Speed Control Scheme for Armature Voltage Control and field Weakening Control

This basic approach of closed loop speed control below and above the speed is explained by the drive of figure. The drive employs inner current control loop and outer speed loop. Such a drive will operate at a constant field current and variable armature voltage below the base speed, and at a constant armature voltage and variable field current above the speed. Both armature and field are therefore fed from fully controlled rectifiers.

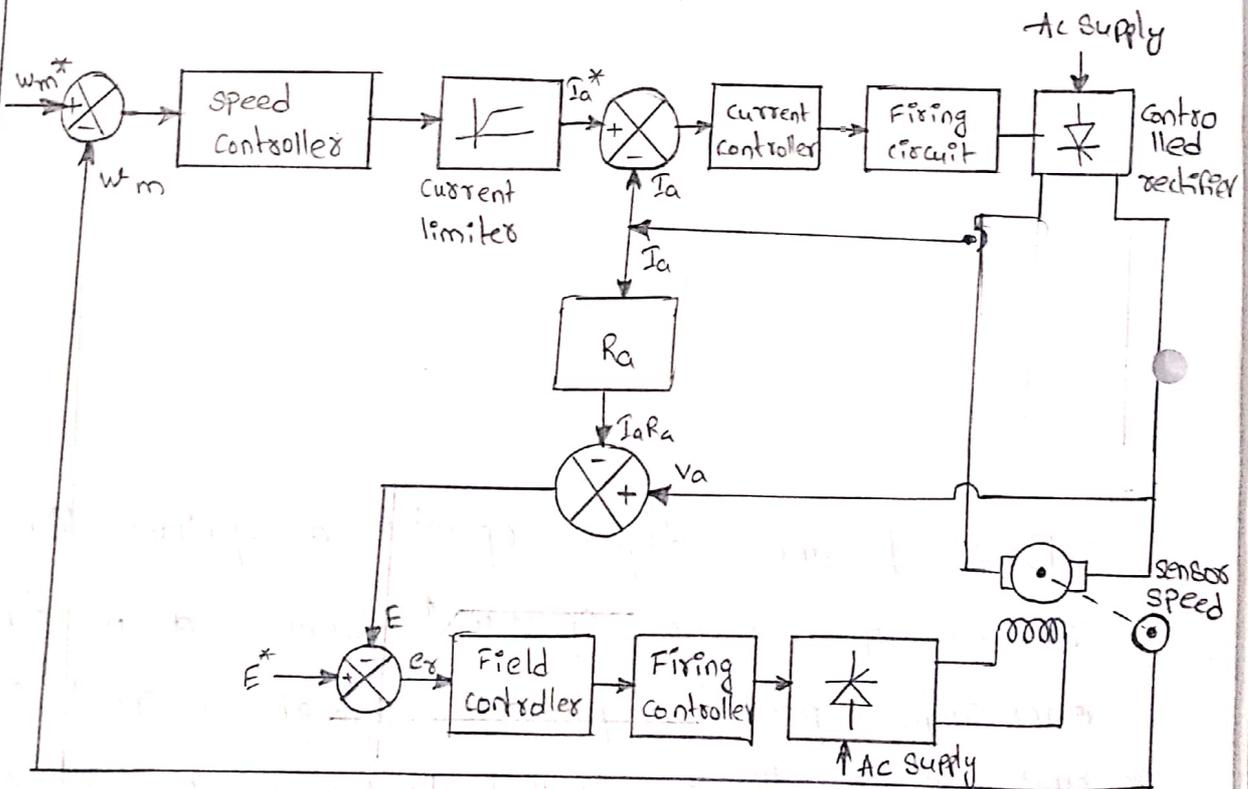


Fig:- closed loop speed control scheme

The higher value is used for motors with low armature circuit resistance. For speeds below base speed, the field controller saturates due to large value of error e_f .

Any positive speed error caused by either an increase in the speed command or an increase in the load torque, produces a higher current reference I_a^* . The motor accelerates due to an increase in I_a^* to correct the speed error and finally settles at a new I_a^* , which makes the motor torque equal to the load torque and the speed error closed to zero.

For any large positive speed error, the current limiter saturates and the current reference I_a^* is limited to a value I_{am} and the drive current is not allowed to exceed the maximum permissible value.

The speed error is corrected at the maximum permissible armature current until the speed error becomes small and the current limiter comes out of saturation. Now, the speed error is corrected with \dot{I}_a less than the permissible value I_{am} .

For negative speed error, I_a is set at zero because I_a is of no use when reference speed is increased again, making speed error positive, the charged PI controller takes longer time to respond.

Let us now examine the operation above-base speed. When closed to the base speed, V_a is almost near the rated value and the field controller comes out of saturation for a speed command above base speed. The speed error causes a higher value of V_a .

The motor accelerates, E increases, field error decreases, reducing the field current. Thus the motor speed continues to decrease until the motor speed becomes equal to the reference speed. Thus, the speed control above the base speed is obtained by field control with the armature voltage maintained near the rated value.

In the field control region, the drive responds very slowly due to large value of the field time constant.

Problems

A 220V, 200A, 800 rpm dc separately excited motor has an armature resistance of 0.05Ω . The motor armature is fed from a variable voltage source with an internal resistance of 0.03Ω . Calculate the internal voltage of the variable voltage source when the motor is operating in regenerative braking at 80% of the rated motor torque and 600 rpm.

Since torque is proportional to the armature current, motor armature current when regenerating.

$$I_{a2} = 0.8 \times 200 = 160 \text{ A}$$

$$E_{b1} = 220 - 200 \times 0.05 = 210 \text{ V}$$

$$E_{b2} = \frac{N_2}{N_1} \times E_{b1} = \frac{600}{800} \times 210 = 157.5 \text{ V}$$

Internal voltage of the variable voltage source

$$= 157.5 - 160(0.05 + 0.03) = 144.7 \text{ V}$$

A 220V, 970rpm, 100A DC Separately excited motor has an armature resistance of 0.05Ω . It is braked by plugging from an initial speed of 1000 rpm. Calculate:

- Resistance to be placed in armature circuit to limit braking current to twice the full load value,
- Braking torque and
- Torque when the speed has fallen to zero.

At 970 rpm

$$E_{b1} = V - I_a R_a = 220 - 100 \times 0.05 = 215V$$

Back emf at 1000 rpm

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

$$\frac{E_{b2}}{215} = \frac{1000}{970}$$

$$E_{b2} = 221.65V$$

at 1000 rpm.

a) For plugging operation

$$I_a = 2 \times 100 = 200A$$

$$R_B + R_a = \frac{E_{b2} + V}{I_a} = \frac{221.65 + 220}{200} = 2.21\Omega$$

$$R_B = 2.21 - 0.05 = 1.16\Omega$$

$$\boxed{R_B = 1.16\Omega}$$

$$b) \text{ Torque} = \frac{E_{b2} I_a}{\omega_m} = \frac{221.65 \times 200}{1000 \times \frac{2\pi}{60}}$$

$$\boxed{T = 423.4 \text{ N-m}}$$

c) At zero speed $E_b = 0$

$$I_a = \frac{V}{R_B + R_a} = \frac{220}{2.21} = 99.55A.$$

$$T \propto I_a$$

$$\frac{T_2}{T_1} = \frac{I_{a2}}{I_{a1}}$$

$$T_1 = 423.3 \text{ N}\cdot\text{m}, \quad I_{a1} = 200 \text{ A}, \quad I_{a2} = 99.55 \text{ A}$$

$$\frac{T_2}{423.3} = \frac{99.55}{200}$$

$$T_2 = 210.7 \text{ N}\cdot\text{m}$$

A 220 V DC Series motor runs at 1200 rpm and takes an armature current of 100 A when driving a load with a constant torque. Resistance of the armature and field windings are 0.05 Ω each. DC series motor is operated under dynamic braking at twice the rated torque and 1000 rpm. Calculate the value of braking current and resistor. Assume linear magnetic circuit.

Torque $T \propto I_a^2$

$$T_1 = K_f I_{a1}^2$$

$$T_2 = K_f I_{a2}^2$$

$$I_{a2} = I_{a1} \sqrt{\frac{T_2}{T_1}} = 100 \sqrt{\frac{2T_1}{T_1}} = 141.4 \text{ A}$$

$$E_{b1} = K_e I_{a1} N_1$$

$$E_{b2} = V - I_{a2} [R_a + R_f]$$

$$= 220 - 100(0.1) = 237.55 \text{ V}$$

$$\frac{E_{b2}}{E_{b1}} = \frac{N_2}{N_1} \times \frac{I_{a2}}{I_{a1}}$$

$$\frac{E_{b2}}{237.55} = \frac{1000}{1200} \times \frac{141.4}{100}$$

$$E_{b2} = 278 \text{ V}$$

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$$\text{Now, } E_{b2} = I_{ar} (R_B + R_a + R_f)$$

$$278 = 14.1 \cdot 4 (R_B + 0.1) = 14.1 \cdot 4 R_B + 14.14$$

$$\boxed{R_B = 1.86 \Omega}$$

=

* Control of DC Motors by Choppers:

choppers are used to get variable dc voltage from a dc source of fixed voltage. self commutated devices such as MOSFET's power transistors, IGBTs, GTOs and IGCTs are used for building choppers because they can be commutated by a low power control signal and do not need commutation circuit and can be operated at a higher frequency for the same rating.

Advantages of using chopper in speed control of dc motors are: high efficiency, flexibility in control, light weight, small size, quick response and regeneration down to very low speeds.

Types of DC Chopper Drives

1. single quadrant chopper drives
2. Two quadrant chopper drives
3. Four quadrant chopper drives.

chopper control of Separately Excited Dc Motors:

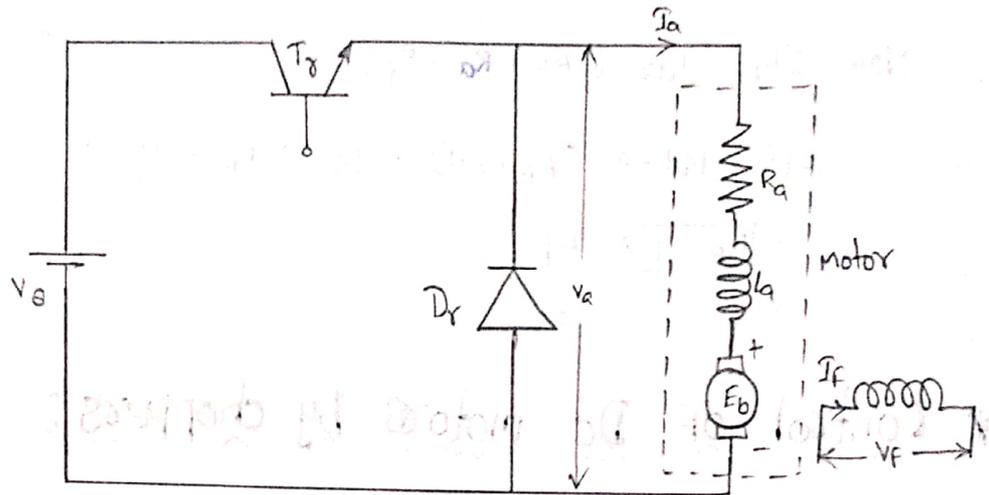


Fig: chopper control of separately excited motor

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 highest 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.

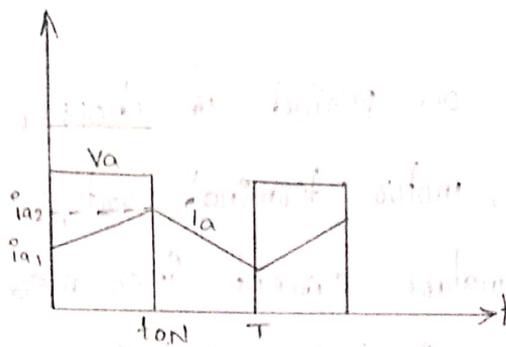


Fig: Waveforms of motor terminal voltage ' V_a ' and armature

current ' i_a ' for continuous conduction.

Motoring Control:

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

Current limit control is used in chopper. In current limit control, the load current is allowed to vary between two given 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 free wheels 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 ' i_a ' and voltage ' V_a ' waveforms are shown above. 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 increase. Discontinuous conduction avoid in this case. The current limit control is superior one

During on-period of chopper (i.e) duty interval, $0 \leq t \leq t_{on}$, motor terminal voltage V_a is source voltage V_s and armature current increases from i_{a1} to i_{a2} . The operation is described by,

$$i_a R_a + L_a \frac{di_a}{dt} + E_b = V_s ; 0 \leq t \leq t_{on}$$

chopper is turned off at $t = t_{on}$. During off-period of chopper (i.e.) free wheeling interval, $t_{on} \leq t \leq T$, motor current free wheels through diode D_f and motor terminal voltage V_a is zero.

this is described by,

$$R_a i_a + L_a \frac{di_a}{dt} + E_b = 0 ; t_{on} \leq t \leq T$$

From output waveform fig 5.2.

$$V_a = \frac{1}{T} \int_0^{t_{on}} V_s dt = \frac{V_s}{T} \int_0^{t_{on}} dt$$

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

$$V_a = \delta V_s$$

where, $\delta \rightarrow$ duty cycle = $\frac{\text{ON period}}{\text{total time}} = \frac{t_{on}}{T} = \alpha$

$$V_a = E_b + I_a R_a$$

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

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

$$E_b = k_m \omega_m$$

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

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

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

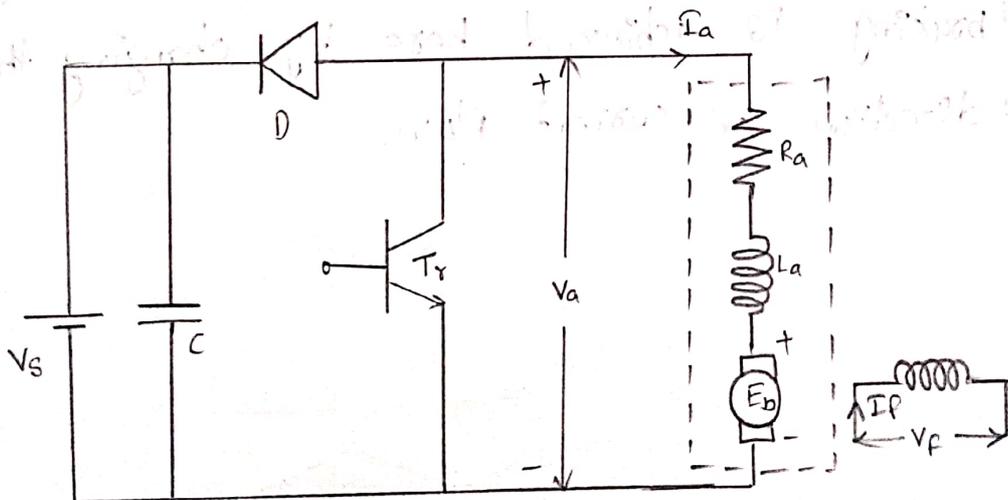
$$\omega_m = \frac{V_a}{k_m} - \frac{T}{k_m^2} R_a$$

$$\omega_m = \frac{\delta V}{k_m} - \frac{R_a}{k_m^2} T$$

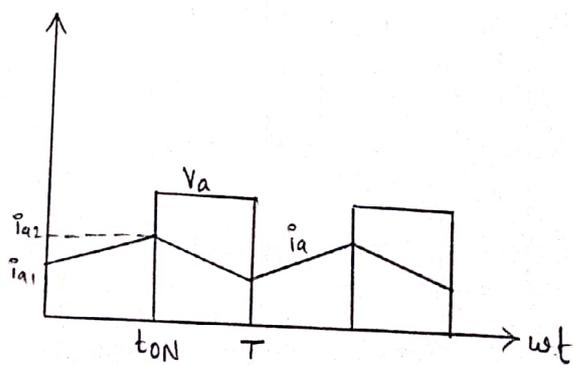
The nature of speed-torque characteristics shown in fig 5.5.

Regenerative braking:-

Regenerative braking of a separately excited motor is fairly simple and can be carried out down to very low speeds.



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 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 the chopper is switched off, a large voltage occurs across the load terminals. This voltage is greater than supply voltage V_s and the energy stored in the inductance and energy supplied by the machine is fed back to the supply system. Very effective braking of the motor is possible upto extreme small speeds. Regenerative braking is achieved here by changing the direction of current flow.



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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} .

$$V_a = \frac{1}{T} \int_{t_{ON}}^T v_s dt = \frac{v_s}{T} \int_{t_{ON}}^T dt = \frac{v_s}{T} [t]_0^{t_{ON}} = \frac{v_s}{T} [T - t_{ON}]$$

$$= v_s \left[\frac{T - t_{ON}}{T} \right] = v_s \left[1 - \frac{t_{ON}}{T} \right]$$

$$V_a = (1 - \delta) v_s$$

$$E_b = k_m \omega_m$$

$$T = -k_m I_a \quad [(\because I_a \text{ reversed})]$$

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

$$\omega_m = \frac{V_a}{k_m} - \frac{\left[\frac{-T}{k_m} \right] R_a}{k_m}$$

$$\omega_m = \frac{(1 - \delta) v_s}{k_m} + \frac{R_a}{k_m^2} \cdot T$$

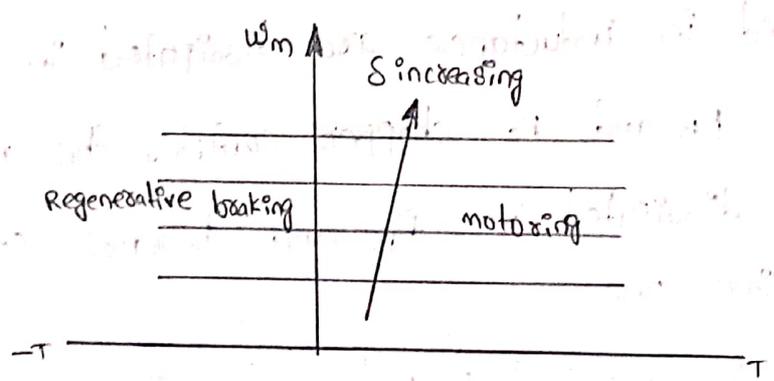
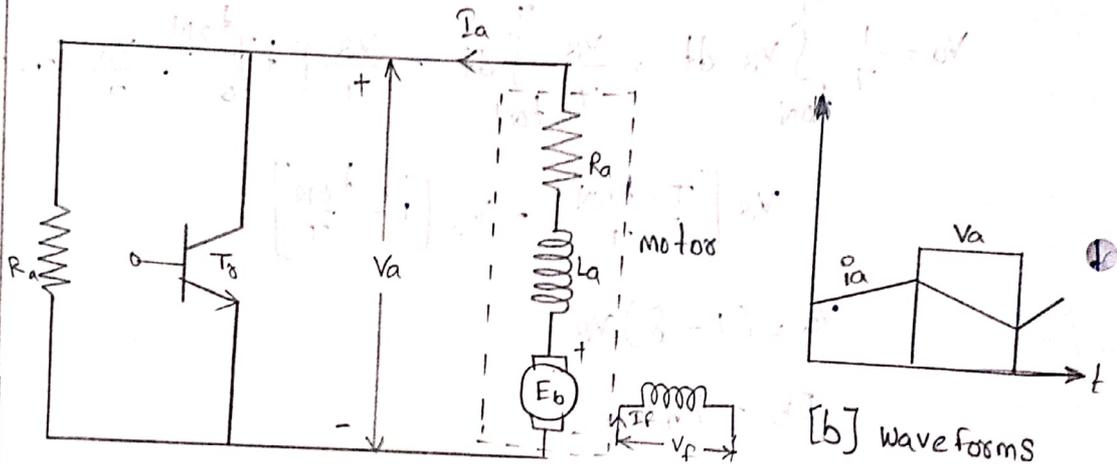


Fig:- speed - torque curves of chopper controlled separately excited motor

Dynamic braking:

In dynamic braking, motor armature is disconnected from the source and connected across a resistor R_B . The generated energy is dissipated in R_B and R_a .



[a] Dynamic braking

During $0 \leq t \leq t_{on}$, i_a increases from i_{a1} to i_{a2} , a part of energy is stored in inductance and rest is dissipated in R_a and chopper. During $t_{on} \leq t \leq \tau$, i_a decreases from i_{a2} to i_{a1} , the energies generated and stored in inductance are dissipated in braking resistance R_B and R_a . Chopper controls the magnitude of energy dissipated in R_B and therefore control is effective one.

If i_a is assumed to be rippleless dc, then energy consumed by R_B during chopper operation [OFF - period] is,

$$I_a^2 R_B (T - t_{ON})$$

Average power consumed by R_B is,

$$P = \frac{I_a^2 R_B (T - t_{ON})}{T} = I_a^2 R_B \left(1 - \frac{t_{ON}}{T}\right)$$

$$P = I_a^2 R_B (1 - \delta)$$

Effective value of R_B is

$$R_{BE} = \frac{I_a^2 R_B (1 - \delta)}{I_a^2}$$

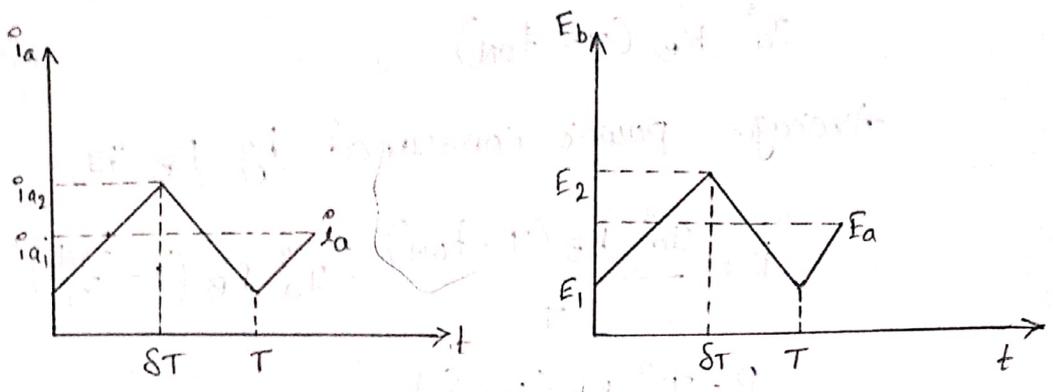
$$R_{BE} = R_B (1 - \delta)$$

The effective value of braking resistor can be changed steplessly from 0 to R_B as duty cycle is controlled from 1 to 0.

Chopper control of series motor

Motoring control of series motor:

The main problem in the analysis of a chopper controlled series motor arises due to the nonlinear relationship between the induced voltage E and armature current I_a , because of the saturation in the magnetization characteristic. At a given motor speed, the instantaneous back emf E_b changes between E_1 and E_2 as I_a changes between I_{a1} and I_{a2} as shown in below figure.



Regenerative Braking of DC Series Motor:

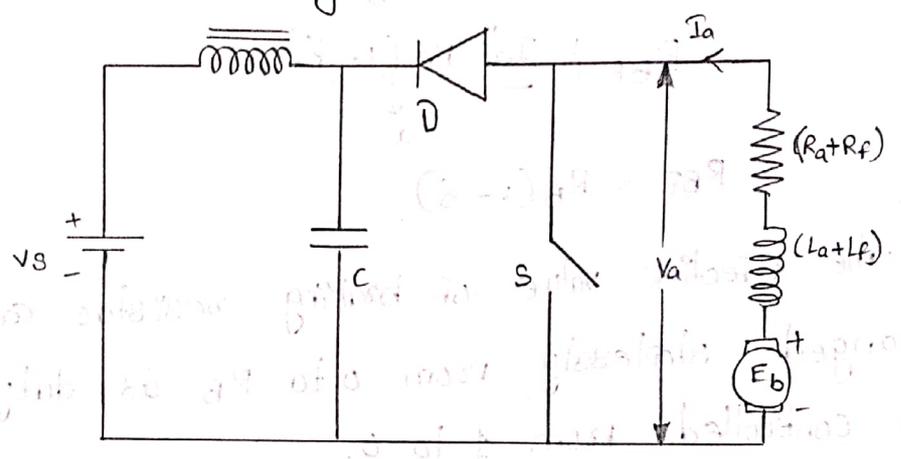


Fig:- Regenerative braking of dc series motor

when the chopper control is absent, a series motor cannot be braked by regenerative braking. with chopper control it is possible to brake a series motor using regenerative braking. However regenerative braking of dc series motor is not so simple and effective as that of separately excited motor. The circuit employed for regenerative braking of series motor is shown above fig.

During regenerative braking, series motor functions as self excited series generator. For self excitation current flowing through the winding [field] should assist residual magnetism.

Therefore when changing from motoring to braking connection, when armature current reverses field current should flow in the same direction. This is achieved by reversing the field with respect to armature when changing from motoring to braking operation. ω_m can be found out from the following equations.

$$E = V_a + I_a [R_a + R_f]$$

But $V_a = \delta V$

$\therefore E = \delta V + I_a [R_a + R_f]$

$$K_m \omega_m = \delta V + I_a [R_a + R_f]$$

$$\omega_m = \frac{\delta V + I_a [R_a + R_f]}{K_m}$$

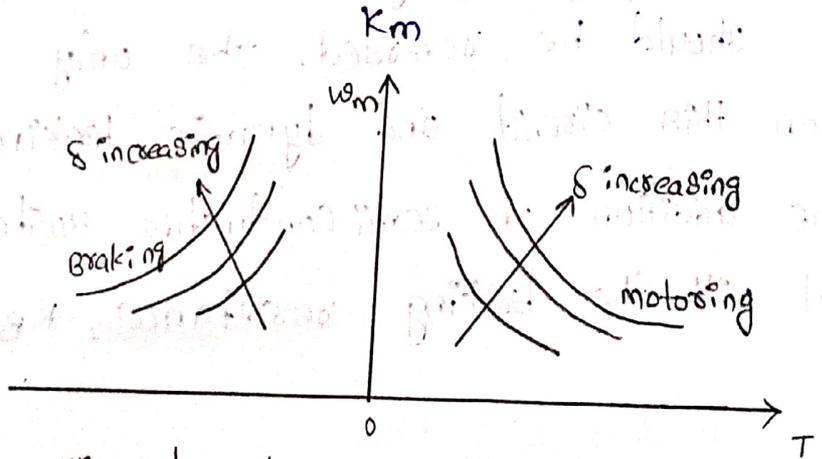


Fig: characteristics of braking

The nature of speed-torque characteristics shown in above fig. such characteristics give unstable operation with most loads. Therefore regenerative braking of series motor is difficult. The main problems are the difficulty in initial build up

of the back emf and poor stability.

Dynamic Braking of Dc series motor:

The circuit diagram for dynamic braking of dc series motor is shown in the below figure.

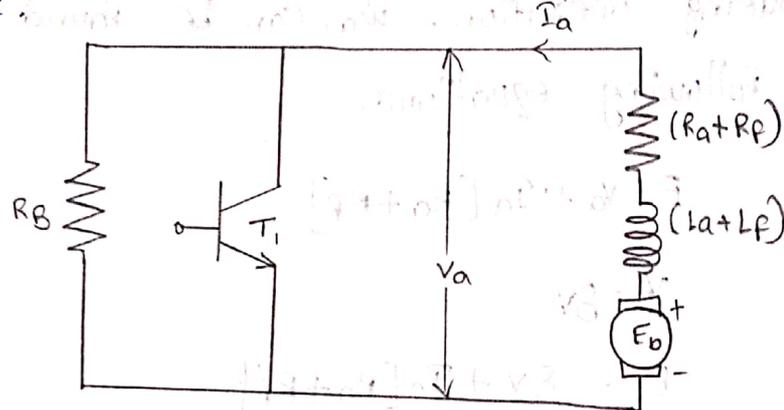


Fig:- Dynamic braking of dc series motor since motor works as a self excited generator when changing from motoring to braking field should be reversed. The only difference between this circuit and dynamic braking circuit is the addition of semi conductor switch S in parallel with the braking resistance, R_B .

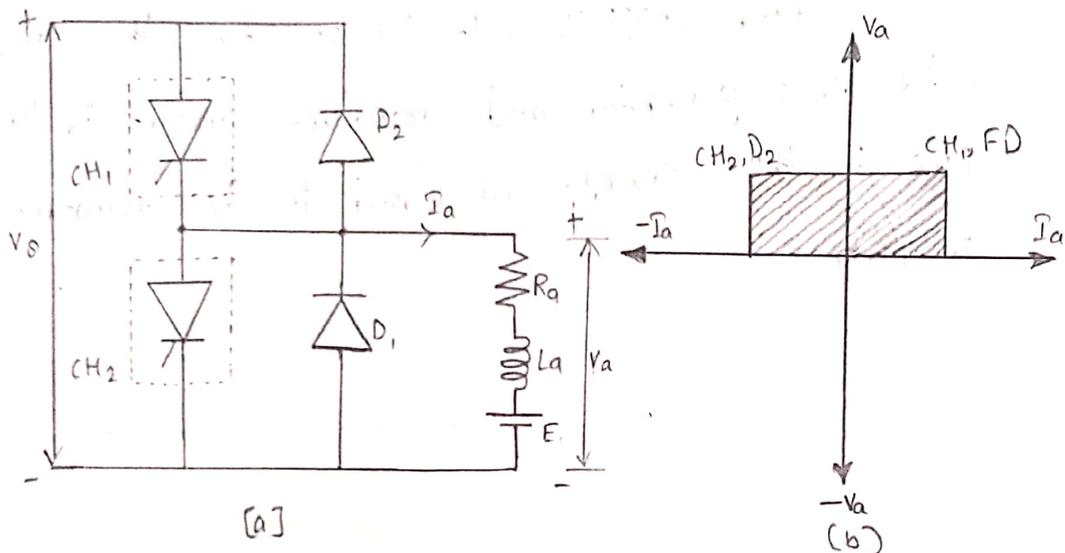
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Two quadrant chopper drives

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 drives:



This type of chopper drive provides forward motoring mode and forward braking mode. It consists of two choppers, CH_1 and CH_2 , and two diodes D_1 and D_2 , and a DC motor.

Forward motoring mode:

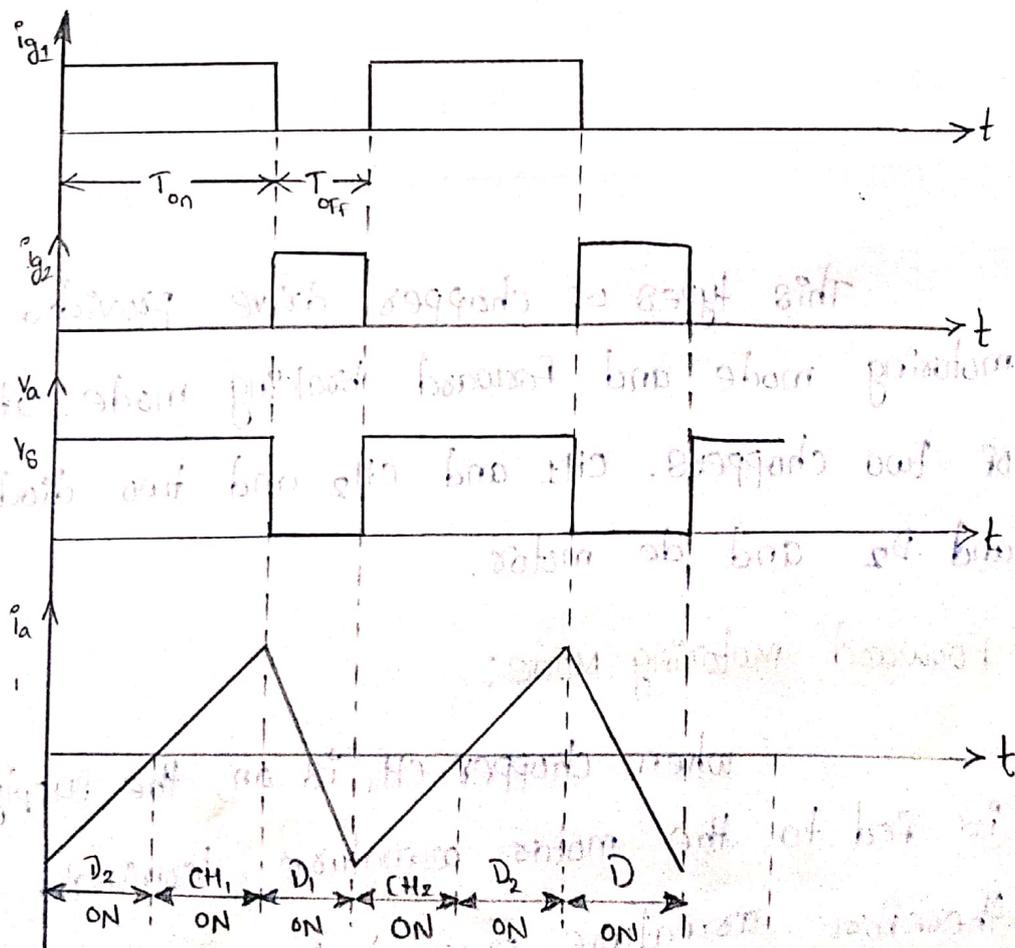
When chopper CH_1 is on, the supply voltage is fed to the motor armature terminals and therefore armature current increases.

Here voltage and current is always positive. Therefore the motor rotates in forward direction.

When CH_1 is off state, i_a free wheels through diode D_1 and therefore i_a decreases. It is the forward motoring mode. It is first quadrant operation.

Forward Braking mode:

When chopper CH_2 is on state, the motor acts as a generator and armature current i_a increases. Due to this energy is stored in the armature inductance.

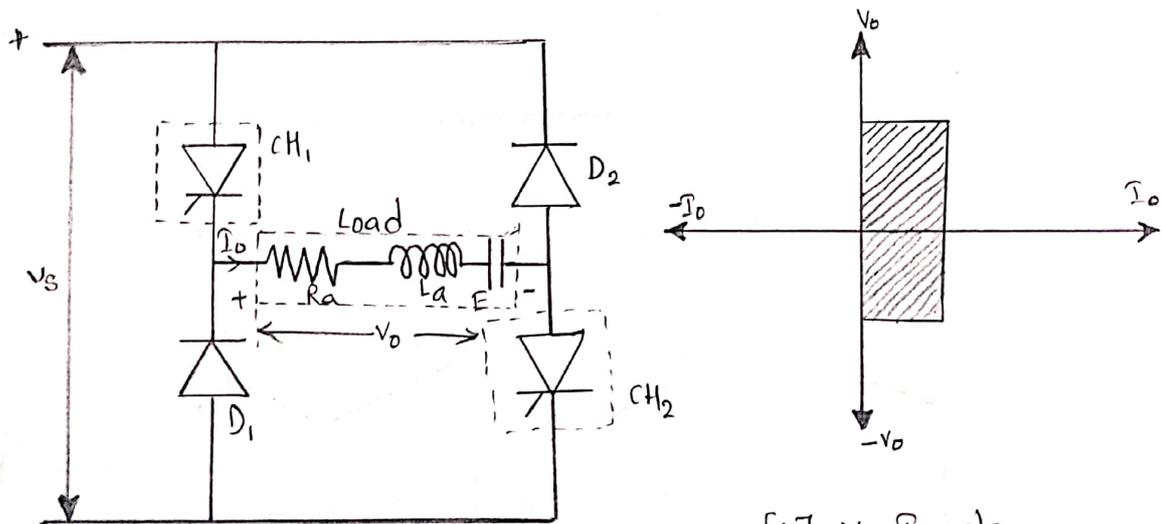


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When CH_2 is off state, diode D_2 gets turned on and therefore armature current i_a is reversed. It is the second quadrant operation. In this mode output voltage is positive and output current is negative. It is forward regenerative braking mode.

Two Quadrant Type B Chopper Drives

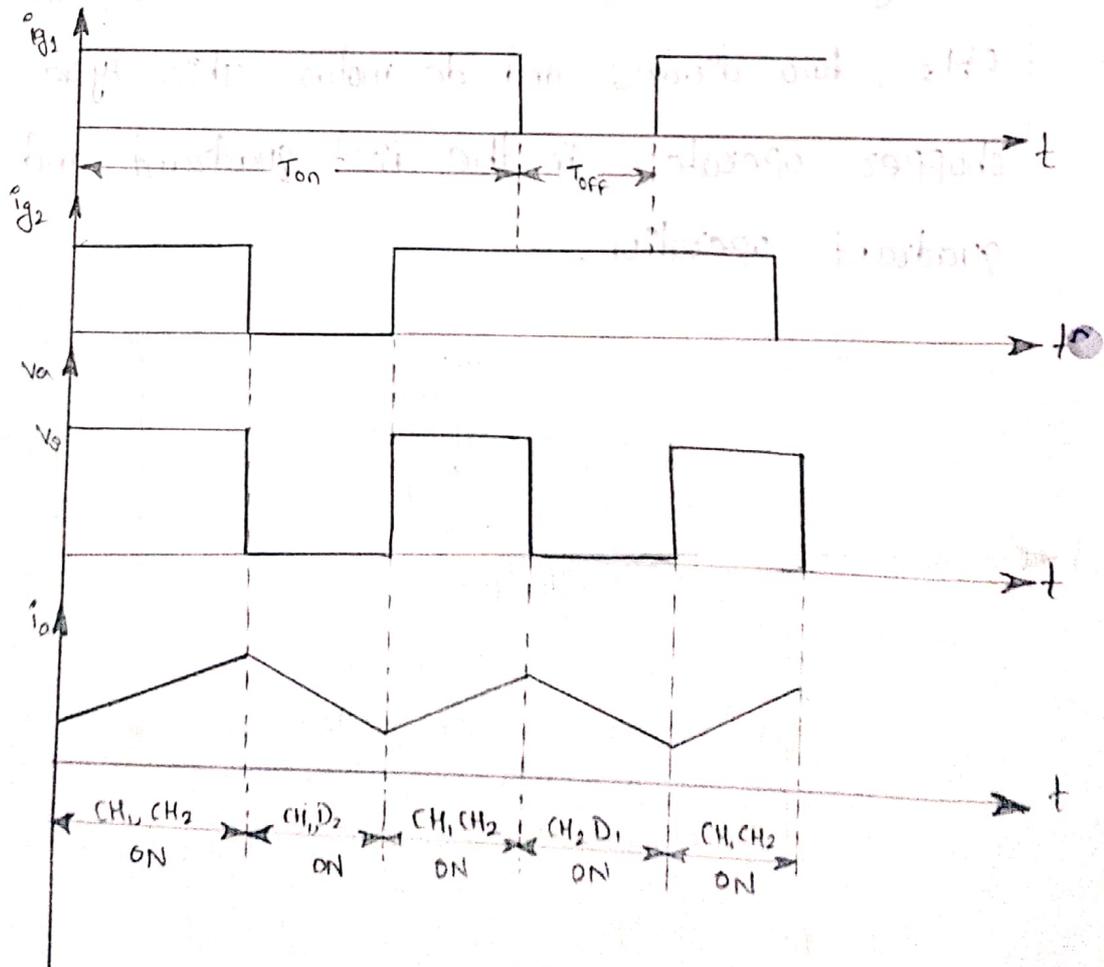
This type of chopper drive provides forward motoring mode and reverse regenerative braking mode. It consists of two choppers CH_1 and CH_2 , two diodes and dc motor. This type of chopper operates in the first quadrant and fourth quadrant operation.



Forward motoring mode:

When chopper CH_1 and CH_2 on, the motor rotates in the forward direction and i_a increases. When CH_1 is off state, now the current flows through CH_2 and diode D_1 . Hence output voltage and output current is always positive. It gives forward motoring mode operation.

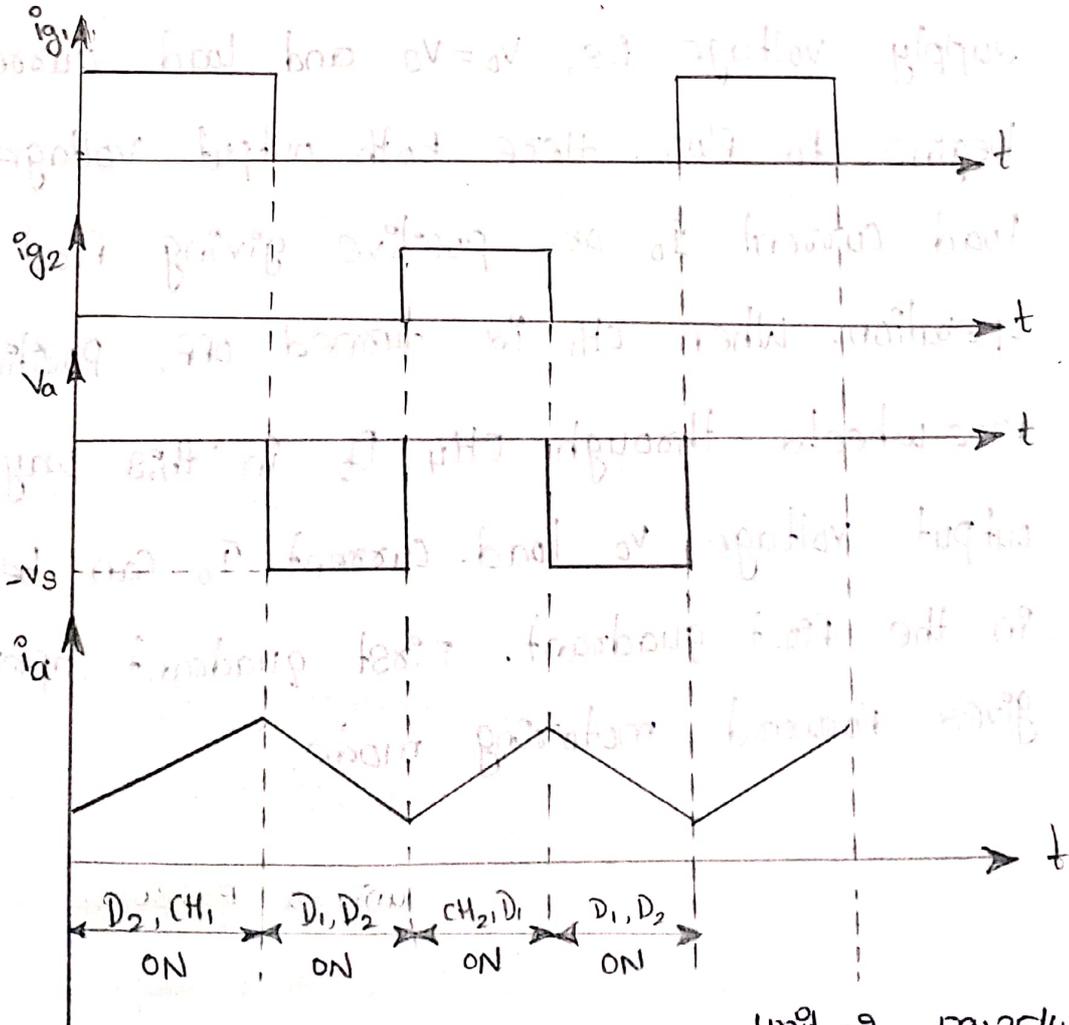
Below figure shows forward motoring mode $[0.5 < \delta < 1]$ of two quadrant type B chopper.



Reverse Braking mode

When both choppers CH_1 and CH_2 are off, now the current flows through diode D_1 and D_2 . Here output current is positive and output voltage is negative. i.e., power flows from load to source. Here we can achieve reverse braking mode. It is the fourth quadrant operation. It is shown in figure. Here the motor speed can be controlled by changing the duty cycle of the choppers.

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

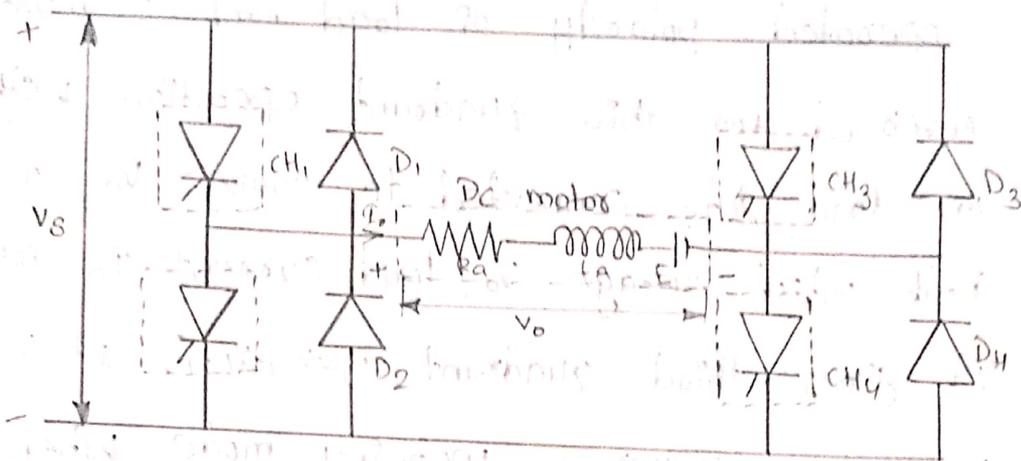


Four Quadrant operation of Dc Motor:-

Below figure shows the power circuit diagram for a four quadrant chopper or type-E chopper. It consists of four power semiconductor switches CH_1 to CH_4 and four power diodes D_1 to D_4 in antiparallel. Working of this chopper in the four quadrants is explained as under:

Forward Motoring Mode:

For first quadrant operation of below figure, CH_4 is kept on, CH_3 is kept off and CH_1 is operated. With CH_1 , CH_4 on, load voltage is equal to supply voltage i.e, $V_o = V_s$ and load current I_o begins to flow. Here both output voltage V_o and load current I_o are positive giving first quadrant operation. When CH_1 is turned off, positive current free wheels through CH_4 , D_2 in this way, both output voltage V_o , load current I_o can be controlled in the first quadrant. First quadrant operation gives forward motoring mode.



Four quadrant operation

Forward Braking mode:

Here CH_2 is operated and CH_1 , CH_3 and CH_4 are kept off. With CH_2 on, reverse (or negative) current flows through L , CH_2 , D_4 and E . During the on time of CH_2 the inductor L stores energy. When CH_2 is turned off, current is fed back to source through diodes D_1 , D_4 . Note that these $[E + L di/dt]$ is greater than the source voltage V_s . As the load voltage V_o is positive and load current I_o is negative, it is second quadrant operation of chopper. Also power is flows # from load to source. second quadrant operation gives forward braking mode.

Reverse Motoring mode

For third quadrant operation of figure, CH_1 is kept off, CH_2 is kept on and CH_3 is

operated. polarity of load emf E must be reversed for this quadrant operation. With CH_3 on, load gets connected to source V_s so that both output voltage V_o , load current I_o are negative. It gives third quadrant operation. It is also known as reverse motoring mode. When CH_3 is turned off, negative current free wheels through CH_2, D_4 . In this way, output voltage V_o and load current I_o can be controlled in the third quadrant.

Reverse Braking Mode:

Here CH_4 is operated and other devices are kept off. Load emf E must have its polarity reversed to that shown in below figure. For operation in the fourth quadrant.

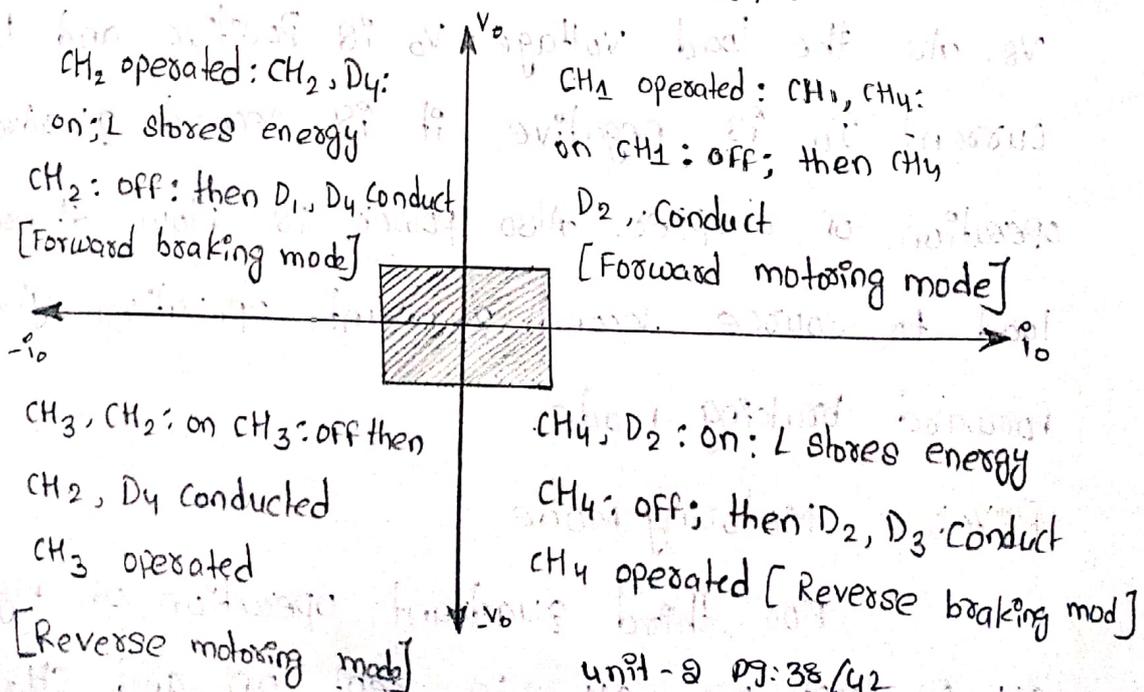


Fig:- operation of conducting devices

With CH_4 on, positive current flows through CH_4 , D_2 , L and E . During the on time of CH_4 inductor L stores energy. When CH_4 is turned off, current is fed back to source through diodes D_2 , D_3 . Here load voltage is negative, but load current is positive leading to the choppers operation in the fourth quadrant.

Also power is flows from load to source. The fourth quadrant operation gives reverse braking mode. The devices conducting in the four quadrants are indicated in above figure.

problems:

The speed of a separately excited dc motor is controlled by a PWM chopper. The dc supply voltage is 100V, the armature resistance is 0.5Ω , the armature circuit inductance is 10mH and the motor constant $K_a\phi$ is 0.03 V/rpm. The motor drives a constant torque load requiring an average armature current of 20A. Assuming the motor current to be continuous, determine
i) the range of speed control, ii) range of duty cycle.

Given data:

$$V = 100V; \quad R_a = 0.5\Omega; \quad L_a = 10\text{mH};$$

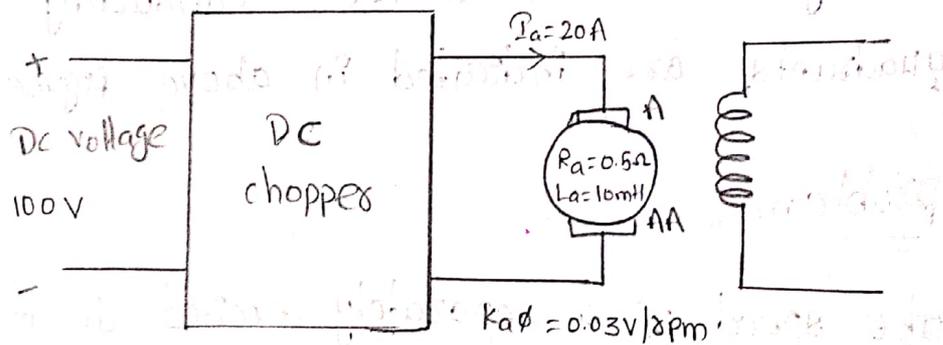
$$k_a\phi = 0.03 \text{ V/rpm}; \quad I_a = 20 \text{ A}$$

To find

- i) The range of speed control
- ii) The range of duty cycle.

Sol:-

Figure shows chopper controlled separately excited dc motor.



Average output voltage of the motor

$$V_a = \alpha V_s = E_b + I_a R_a$$

As motor drives a constant load, motor torque T is constant and therefore, armature current of 20A, minimum possible motor speed is $N=0$, these fore

$$\alpha \times 100 = k_a\phi N + I_a R_a$$

$$\alpha \times 100 = 0.03 \times 0 + 20 \times 0.5$$

$$\alpha = \frac{10}{100} = 0.1$$

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(2)
 Maximum possible motor speed corresponds to $\alpha = 1$. i.e., when 100V is directly applied to the motor. Therefore the range of duty cycle is

$$0.1 < \alpha < 1$$

ii] The range of speed

$$\alpha V_s = K_a \phi N + I_a R_a$$

$$1 \times 100 = 0.03 \times N + 20 \times 0.5$$

$$N = 3000 \text{ rpm}$$

The range of speed control

$$0 < N < 3000 \text{ rpm}$$

(2) A DC series motor, fed from 400V DC source through a chopper, has the following parameters

$$R_a = 0.05 \Omega, \quad R_s = 0.07 \Omega, \quad K = 5 \times 10^{-3} \text{ Nm/amp}^2$$

The average armature current of 200 A ripple free. For a chopper duty cycle of 50%. Determine i] input power from the source (ii) motor speed and (iii) motor torque.

Given data:

$$V_s = 400 \text{ V}, \quad R_a = 0.05 \Omega$$

$$R_s = 0.07 \Omega, \quad K = 5 \times 10^{-3} \text{ Nm/amp}^2$$

$$\alpha = 50\% \text{ (or) } 0.5 \quad I_a = 200 \text{ A} \quad \text{unit - a Pg: 41/42}$$

Sol: i) Input power to the motor

$$= V_t I_a = \alpha V_s I_a$$

$$= 0.5 \times 400 \times 200 = 40,000 \text{ W}$$

Input power = 40 kW.

ii) Motor speed

For a dc series motor

$$\alpha \cdot V_s = E_a + I_a R_a = k I_a \omega_m + I_a R_a$$

$$\alpha \cdot V_s = k I_a \omega_m + I_a (R_a + R_s)$$

$$0.5 \times 400 = 5 \times 10^{-3} \times 200 \times \omega_m + 200 (0.05 + 0.07)$$

$$200 = 1 \omega_m + 24$$

$$\omega_m = 176 \text{ rad/sec}$$

$$\omega_m = \frac{2\pi N}{60} \Rightarrow \frac{2\pi \times N}{60} = 176$$

$$N = 1680.68 \text{ rpm}$$

iii) Motor torque

$$T_e = k I_a^2 = 5 \times 10^{-3} \times (200)^2$$

$$T_e = 200 \text{ N-m}$$

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