UNIT- II

FOUR QUADRANT OPERATION OF DC DRIVES

Braking: The process of reducing the speed of any rotating machine is called braking.

(or)

The process of stopping the motoring action is called braking.

Types of Braking: Braking is calassified into two types:

1. mechanical Braking.
2. Electrical Braking

Four Quadrant Operation of DC Drives:

Four Quadrant operation of any drive means that the machine operates in four quadrants. They are forward motoring, reverse braking, forward braking and reverse motoring.

In motoring mode, machine works as motor and converts electrical energy into mechanical energy.

In Braking mode, machine works as generator and converts mechanical energy into electrical energy

The following figure shows the four-quadrant operation of drives.

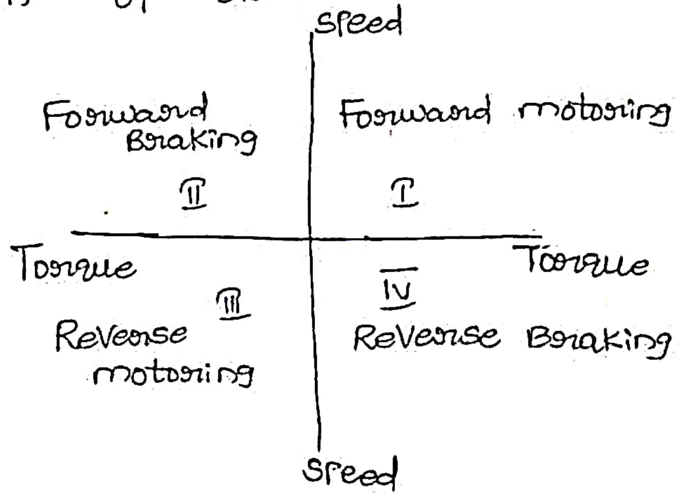


Fig. Four Quadrant operation of DC Drive

The four quadrant operation and its relationship to speed, torque and output power are summarized in following table.

Quadrant	Function	Speed	Torque	Power Output
I	Forward motoring	+	+	+
II	Forward Braking	+	−	−
III	Reverse motoring	−	−	+
IV	Reverse Braking	−	+	−

In first quadrant speed and torque are positive and hence power output is positive. first quadrant corresponds to forward motoring mode.

In second quadrant, speed is positive and torque is negative. Power output is negative. It corresponds to forward braking mode.

In third quadrant, speed and torque are negative and hence power is positive. It corresponds to Reverse motoring mode.

In IV quadrant, speed is negative and torque is positive. output power is negative. It corresponds to Reverse Braking mode.

We know that,

$$\text{Torque } \tau = K_a \phi I_a$$

$$\text{Power} = \text{Torque} \times \text{Speed} = \tau \times \omega_m$$

$$\text{Power} = \frac{\tau . E_b}{K_a \phi}$$

$$P = E_b I_a$$

$$E_b = K_a \phi N$$

$$N = \frac{E_b}{K_a \phi}$$

$$I_a = \frac{\tau}{K_a \phi}$$

Note:
For motoring mode, rotating torque is needed.
For Braking mode, opposing torque is required.

motoring mode → motor → electrical energy into mechanical energy.

Braking mode → Generator → mechanical energy into electrical energy.

Types of Braking:

1. mechanical Braking: It is the type of braking system in which brake force applied on brake pedal is carried to final brake drum or disc rotor by various mechanical linkages like cylindrical rods, fulcrums, springs etc.. in order to stop the vehicle.

It is mechanism of producing opposing torque against rotating torque.

mechanical braking is used in cycles, hydro-plants and trains.

Advantages:

1. Simple in construction and maintenance.
2. Less expensive compare to hydraulic brake.
3. They can be used in any motor.

Dis Advantages:

1. Wear and tear happens at brake surfaces
2. Heat dissipation is not uniform
3. Frequently change braking system.

2. Electrical Braking:

Electrical brakes are devices that use an electrical current or magnetic actuating force to slow or stop the motion of a rotating component.

Electrical Braking is of three types:

1. Regenerative Braking
2. Dynamic Braking

3. Plugging

1. Regenerative Braking:

It is achieved by the condition $E_b > V_s$. Circuit diagram and characteristics for this type of braking is shown below

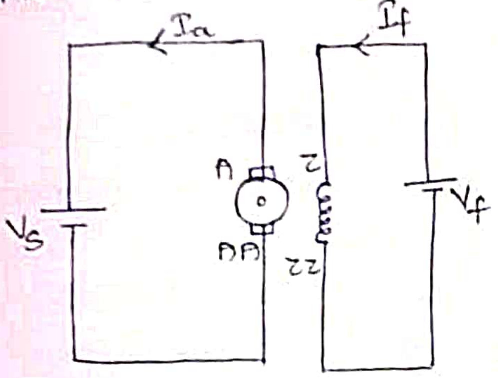


Fig. Circuit Diagram

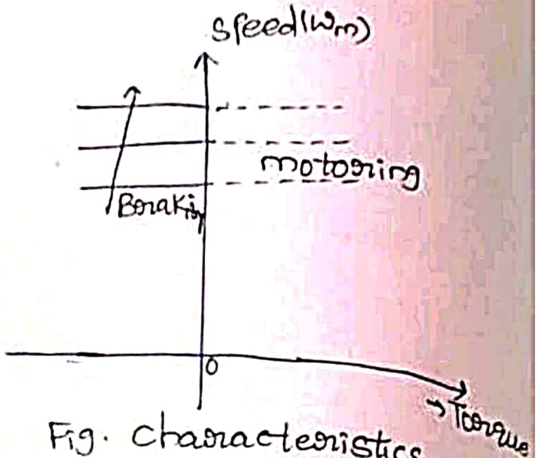


Fig. characteristics

Regenerative braking takes place whenever speed of motor is exceeds the synchronous speed.

In this, power or energy of driven machinery is returned back to power supply mains

When E_b of motor is greater than V_s, which reverse direction of armature current. The machine now begin to operate as generator and generated energy is supplied to source.

$\therefore$ For motoring, $E_b = V_o - I_a R_a$

For Regenerative braking, $E_b = V_o + I_a R_a$.

From characteristics, for braking

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

where $$I_a = \frac{E_b - V_o}{R_a}$$

$$\therefore T = -K_{af}\left(\frac{E_b - V_o}{R_a}\right)$$

Regenerative braking is not applicable for DC Series motor because in Series motor, as speed of motor increases, armature current increase and hence field flux will decrease and hence back emf will never become greater than supply Voltage.

Advantages:

Proper implementation of regenerative braking has the following benefits

1. Extends driving range
2. Improves Braking efficiency
3. Reduces brake wear and tear
4. Improves energy conservation
5. It is efficient method of braking.

Dis-Advantages:

1. Not applicable for series motors.
2. Cost of components and installation is high.

2. Dynamic or Rheostatic Braking:

It is also known as rheostatic braking. Circuit diagram for dynamic braking is shown below

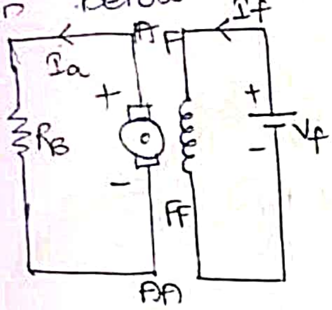


Fig. Seperately excited motor

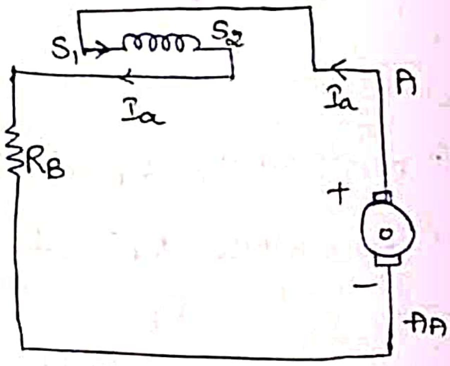


Fig. Series motor.

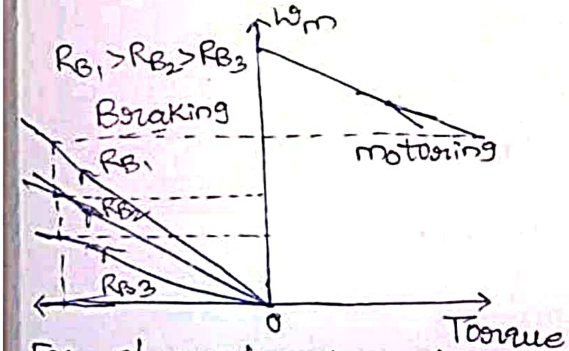


Fig. Characteristics for Seperately excited motor

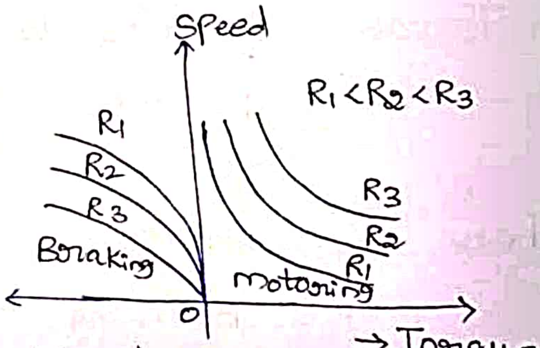


Fig. characteristics for Series motor.

In this type of braking, the motor which is at running condition is disconnected from source and connected across resistance. When motor is disconnected from source the rotor keeps rotating due to inertia and it work as self excited generator. When motor works as generator, flow of current and torque reverses which makes the machine to stop.

During Braking to maintain steady torque, sectional resistances are cut one by one.

From characteristics,

For seperately excited motor,

w.k.T, $E_b = V_0 - I_a(R_a+R_B)$

Since, $V_s = 0 \Rightarrow V_0 = 0$

$\therefore$ For motoring, $E_b = -I_a(R_a+R_B)$

For Braking, $E_b = I_a(R_a+R_B)$

$$I_a = \frac{E_b}{R_a+R_B}$$

$$\tau = -K_{af} \cdot I_a = -K_{af}\left(\frac{E_b}{R_a+R_B}\right)$$

For series motor:

For motoring, $E_b = -I_a(R_a+R_B+R_f)$

For Braking, $E_b = I_a(R_a+R_B+R_f)$

$$I_a = \frac{E_b}{R_a+R_B+R_f}$$

Torque, $\tau = -K_{af} \cdot I_a$

$$\tau = -K_{af} \cdot \frac{E_b}{R_a+R_B+R_f}$$

where R_a = Armature resistance

R_B = Braking resistance

R_f = Field resistance

Advantages:

1. This method was applicable for DC series, shunt, induction motor and synchronous motors.
2. It does not require any external energy from supply for braking the motor.
3. There are no mechanical brake shoes to wear out.

Dis Advantages:

1. Generated energy will be wasted in the form of heat in resistance.

Although dynamic braking is used for both dc and ac motors, principles and methods used for each are very different.

3. Plugging:

It is also known as reverse voltage or counter current braking.

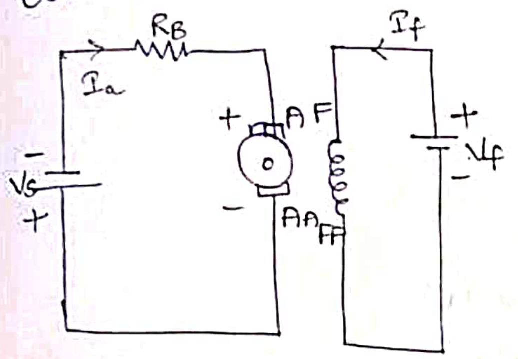


Fig. DC Seperately excited motor

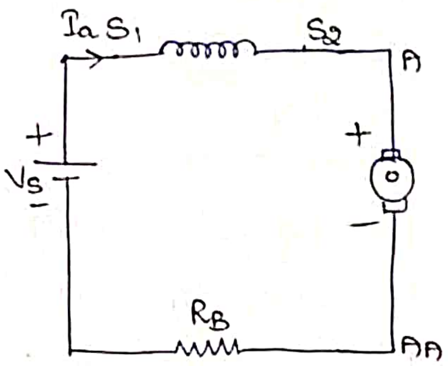


Fig. Series motor

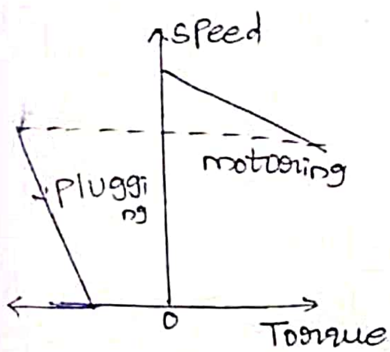


Fig. characteristics for seperately excited motor

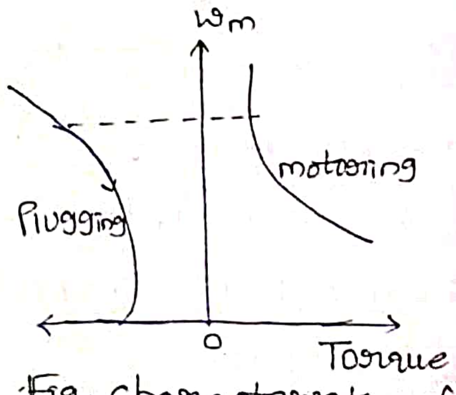


Fig. characteristics for DC series motor.

In this method, the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of motor and as a result speed decreases.

During Plugging, the external resistance is also introduced into circuit to limit the flowing current.

For braking of seperately excited dc motor, reverse Voltage is applied.

For series motor, plugging is achieved by reversing either armature or field terminals but both cannot be reversed together.

The main disadvantage of this method is regenerated Power and supply Power is wasted in form of heat in resistance.

Applications: plugging is commonly used in

1. Controlling Elevators
2. Rolling mills
3. Printing presses
4. machine tools.

From characteristics:

Seperately Excited motor:

For motoring, $E_b = V_0 - I_a(R_a + R_B)$

For Plugging, $E_b = -V_0 + I_a(R_a + R_B)$

$$I_a = \frac{E_b + V_0}{R_a + R_B}$$

$$T = -K_{af} \cdot I_a = -K_{af} \cdot \left(\frac{E_b + V_0}{R_a + R_B}\right)$$

DC series motor:

$E_b = V_0 - I_a(R_a + R_B + R_f)$ → For motoring

$E_b = -V_0 + I_a(R_a + R_B + R_f)$ → For Braking

$$I_a = \frac{E_b + V_0}{R_a + R_B + R_f}$$

$$T = -K_{af} \cdot I_a = -K_{af}\left(\frac{E_b + V_0}{R_a + R_B + R_f}\right)$$

problems:

1. A 220V, 200A, 800 rpm seperately excited DC motor is fed from Variable Voltage source with internal resistance of 0.04Ω. Calculate internal Voltage of Variable Voltage source when motor is operating in regenerative braking at 80% of rated torque and 600 rpm with $R_a = 0.06\Omega$.

Sol For motoring,

$$E_{b1} = V_0 - I_aR_a = 220 - (200 \times 0.06) = 208V.$$

w.K.T, $\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2}$

$$\Rightarrow E_{b2} = \frac{E_{b1} \cdot N_2}{N_1} = \frac{208 \times 600}{800} = 156V$$

For Regenerative Braking,

$$V_0 = E_{b2} - I_aR_a$$

$$= 156 - 200 \times 0.8\,(0.06 + 0.04)$$

$$V_0 = 140$$

[Note: $E_b > V_0$]

2. A 230V, 870 rpm, 100A seperately excited DC motor has $R_a = 0.02\Omega$. motor is connected to a overhalling load with a torque of 400 N-m. Determine speed of motor in Regenerative Braking.

Sol Given data,

Regenerative Braking is applied on motor,

$$E_{b1} = V_0 - I_aR_a = 230 - (100 \times 0.02) = 228V. \text{ (motoring)}$$

w.K.T, $E_{b1} = K_m \cdot \omega_m$

$$K_m = \frac{E_{b1}}{\omega_m} = \frac{228}{870 \times \frac{2\pi}{60}} = 2.5 \text{ Voltsec/Rad}.$$

$$\tau = K_m \cdot I_a \Rightarrow I_a = \frac{\tau}{K_m} = \frac{400}{2.5} = 160A.$$

$$E_{b2} = V_0 + I_aR_a \text{ (Regenerative braking)}$$

$$= 230 + 160 \times 0.02 = 233.2V.$$

w.K.T, $\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2} \Rightarrow N_2 = \frac{E_{b2} \cdot N_1}{E_{b1}} = \frac{233.2 \times 870}{228}$

$$= 889.84 \text{ rpm}$$

$$= 889.84 \times \frac{2\pi}{60}$$

$$\omega_2 = 93.18 \text{ rad}$$

3. A 400V, 750 rpm, 70A seperately excited dc motor has $R_a = 0.3\Omega$, when running under rated condition. The motor is to be braked by dynamic braking. If armature current is limited to 90A, then what external resistance to be connected in armature.

Sol Given data,

Dynamic braking is applied on motor,

w.K.T, $E_b = V_0 - I_a R_a$

$= 400 - 70 \times 0.3$

$E_b = 379V$

$$I_a = \frac{E_b}{R_a + R_B}$$

$$90 = \frac{379}{0.3 + R_B}$$

$$90(0.3 + R_B) = 379$$

$$27 + 90R_B = 379$$

$$90R_B = 379 - 27$$

$$90R_B = 352$$

$$R_B = \frac{352}{90} = 3.91\Omega$$

4. A 400V, 750 rpm, 70A seperately excited dc motor has $R_a = 0.3\Omega$ when running under rated condition. The motor is to be braked by plugging. If armature current is limited to 90A what external resistance is to be connected in series with armature when speed has fallen to 300 rpm. Calculate Initial torque.

Sol Given data,

Plugging is applied on motor,

w.K.T, $E_{b1} = V_0 - I_a R_a = 400 - 70 \times 0.3 = 379V$.

we know that,

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

$$\rightarrow E_{b2} = \frac{E_{b1} \cdot N_2}{N_1} = \frac{379 \times 300}{750} = 151.6V$$

w.K.T, $I_a = \frac{E_b + V_0}{R_a + R_B}$

$$70 = \frac{379 + 400}{0.3 + R_B}$$

$$21 + 70R_B = 779$$

$$70R_B = 758$$

$$R_B =$$

$$\text{Torque} = \frac{E_{b1} \times I_a}{\omega} = \frac{379 \times 70}{750 \times \frac{2\pi}{60}} = 337.9 \text{ N-m.}$$

$$\text{Braking Torque} = \frac{E_{b2} \times I_a}{\omega} = \frac{151.6 \times 70}{300} = 35.37 \text{ N-m}$$

5. A 970 rpm, 100A, 220V seperately excited DC motor has $R_a = 0.05\Omega$, it is braked by Plugging at an initial speed of 1000 rpm. Calculate

(a) Braking resistance to be connected in series with armature.

(b) Torque at rated value.

(c) Torque when speed has fallen to zero with current twice the rated value.

Sol Given data,

$N_1 = 970$ rpm

$I_a = 100A$

$V_0 = 220V$

$R_a = 0.05\Omega$

$N_2 = 1000$ rpm

(i) · $R_B = ?$

we Know that,

For Plugging

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

Now,

Before Plugging, it was in motoring state

$\therefore E_{b1} = V_0 - I_a R_a$

$= 220 - 100 \times 0.05$

$E_{b1} = 215 V$

We know that,

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

$$E_{b2} = \frac{E_{b1} \cdot N_2}{N_1} = \frac{215 \times 1000}{970} = 221.649 V$$

W.K.T, For Plugging

$E_{b2} = -V_0 + I_a(R_a + R_B)$

$\Rightarrow 221.649 = -220 + I_a R_a + I_a R_B$

$221.649 = -220 + 100 \times 0.05 + I_a R_B$

$221.649 + 215 = 100 R_B$

$$R_B = \frac{221.649 + 215}{100} = 4.366 \Omega$$

(ii) Torque at rated Value,

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

$= -K_{af} \cdot \left(\frac{E_{b2} + V_0}{R_a + R_B}\right)$

Assume $K_{af} = 1$

$$\therefore T = -1 \left(\frac{221.649 + 220}{0.05 + 4.366}\right)$$

$T = 100.01$ N-m

(iii) When speed has fallen to zero i.e.,

$E_{b2} = 0.$

$$\therefore T = -K_{af}\left(\frac{V_0}{R_a + R_B}\right)$$

$$= -1\left(\frac{220}{4.366 + 0.05}\right)$$

$T = 49.818$ N-m

Four Quadrant operation of DC motors by dual converter:

Dual converter is nothing but two fully controlled rectifiers connected in anti-parallel

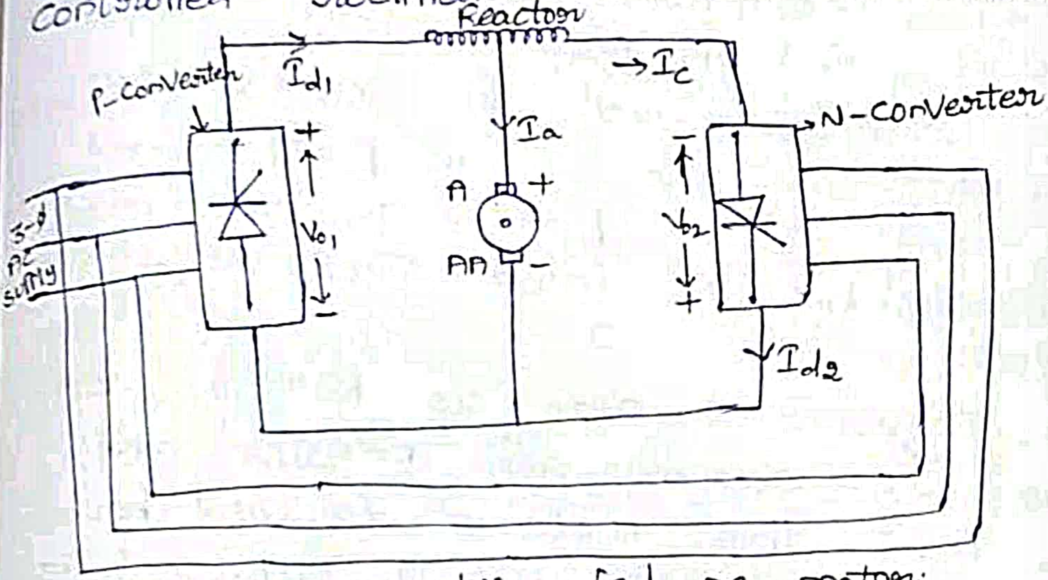
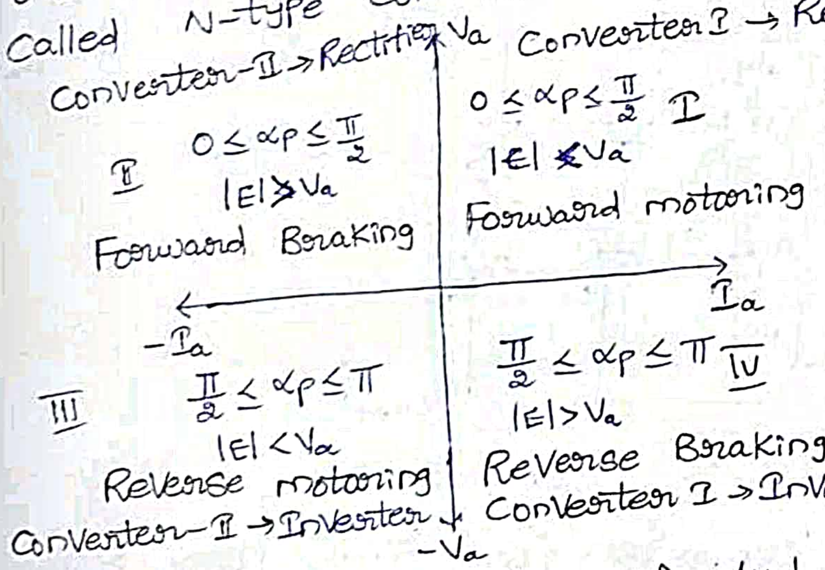


Fig. Dual converter fed DC motor

Dual converter works in four quadrants in circulating current mode.

The four modes of operation in dual converter are Forward motoring, Forward Braking, Reverse motoring and reverse Braking.

In the circuit, the converter operating as rectifier is called P-type converter and other converter operating as inverter is called N-type converter.



Parameter	+ve	-ve
Speed	I, II	III, IV

Fig. Quadrant operation of dual converter.

Four quadrant operation of Dual converter is shown in above figure.

when Converter-I acts as rectifier, both Voltage and current are Positive and $|E| < V_a$. It is act in forward motoring mode. Hence operation of first quadrant is obtained.

when Converter-I acts as inverter, Voltage is negative and current is positive and $|E| > V_a$ and it is Reverse braking mode. Hence operation of fourth quadrant is obtained.

when Converter-II acts as Rectifier, both Voltage is +ve and current ~~are~~ is negative and $|E| > V_a$ and this mode is forward braking. Hence operation of second quadrant is obtained.

when Converter-II acts as inverter, both are negative and Voltage and current are negative and $|E| < V_a$ and this mode is reverse motoring mode. Hence operation of third quadrant is obtained.

In this manner four quadrant operation is achieved by using dual converter.

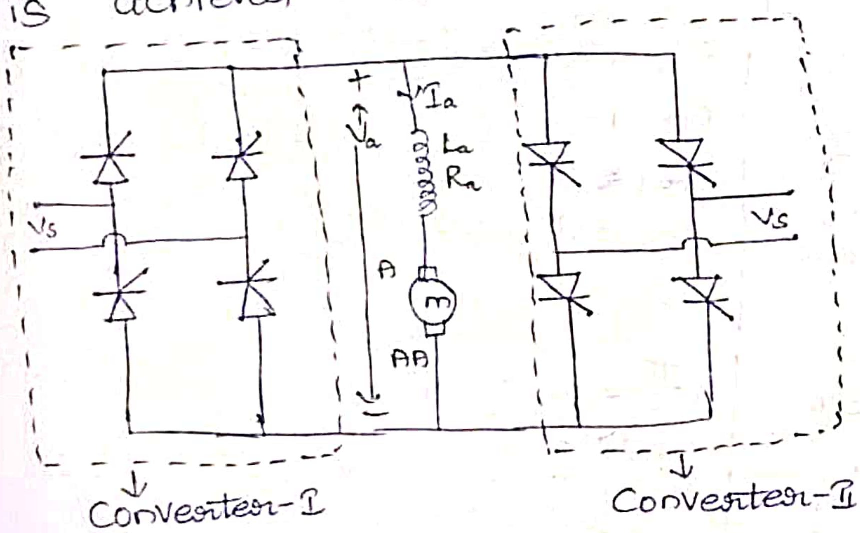


Fig. Dual Converter for Single Phase supply.

Note: For operation, represent circuit with reactor, otherwise not necessary.

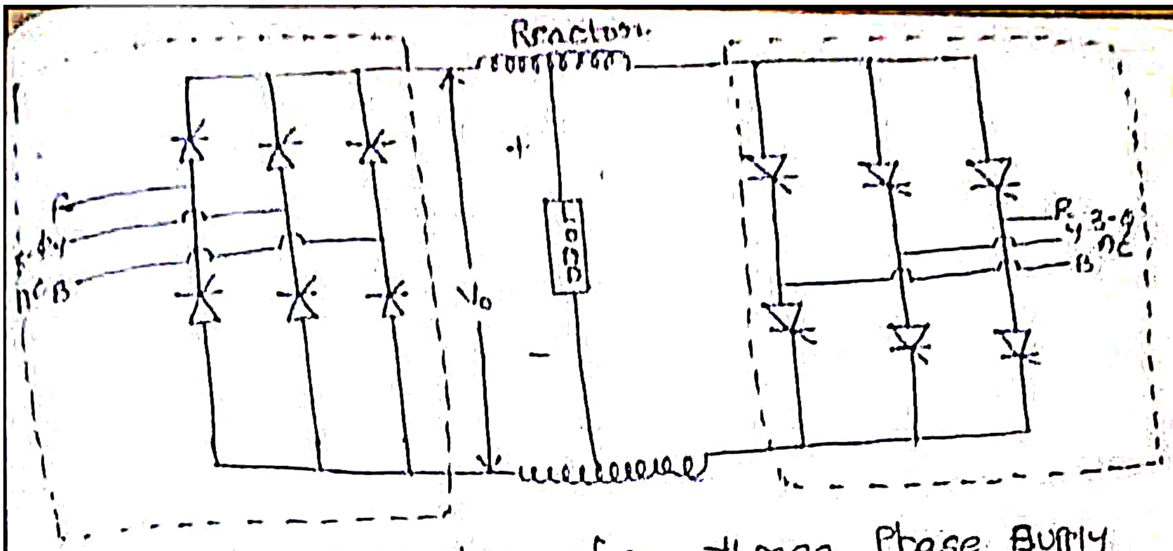


Fig. Dual Converter for three Phase Supply Operation

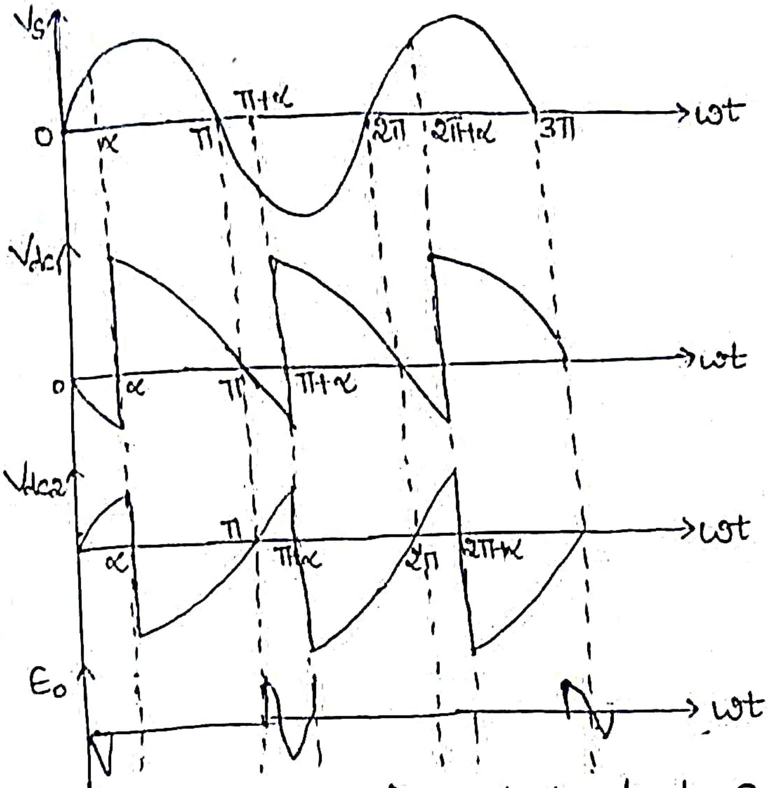


Fig. waveform for 1-φ dual Converter fed dc motor

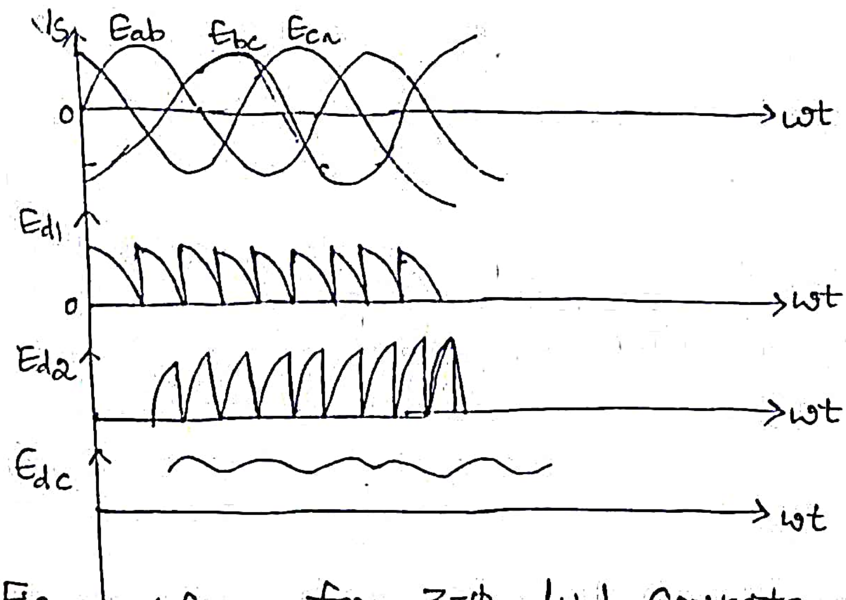


Fig. waveform for 3-φ dual Converter fed dc motor

Dual Converter Operates in two modes.

1. Circulating current mode:

In this mode reactor is present and current is continuous. Both converters operate at a time in this mode i.e., one act as rectifier and other acts as inverter. This mode is also known as continuous or simultaneous mode.

2. Non-circulating current mode:

This mode is also known as discontinuous or non-simultaneous mode.

In this mode reactor is not present and current is discontinuous. Only one converter operate at a time either as rectifier or inverter.

In case of dual converter,

$$V_{01} + V_{02} = 0$$

$$\Rightarrow V_{01} = -V_{02}$$

$$\frac{2V_m}{\pi} \cos\alpha_1 = -\frac{2V_m}{\pi} \cos\alpha_2$$

$$\cos\alpha_1 = -\cos\alpha_2$$

Applying inverse on both sides

$$\alpha_1 = -\alpha_2$$

$$\alpha_1 + \alpha_2 = 180^\circ.$$

Note:

1. Four Quadrant Operation of dual converter
2. modes of operation of dual converter.

Difference between Circulating and Non-circulating mode:

Non-Circulating mode	Circulating mode
1. In this mode, load current is discontinuous.	1. In this mode, load current is continuous.
2. This mode is also known as discontinuous or non-simultaneous mode.	2. This mode is also known as continuous or simultaneous mode.
3. In this mode both converters operate at a time i.e., one as inverter and other as rectifier.	3. In this mode only one converter operate at a time i.e., either as rectifier or inverter.
4. In this mode the reactor is not present.	4. In this mode, the reactor is ~~not~~ Present
5. Due to non-existance of reactor, it is efficient and losses are less.	5. Due to existance of reactor, it is less efficient and losses are more.
6. Cost is Low.	6. Cost is High.
7.	7.

Problems:

1. A 220V, 750rpm, 200A Seperately excited DC motor has an armature resistance of 0.05Ω. Armature is fed from a three phase non-circulating current mode dual converter. Consist of fully controlled rectifiers A and B. Rectifier A provides motoring operation in forward direction and Rectifier-B in reverse direction. Line voltage of AC source is 400V, Calculate firing angle of rectifier for motoring operation at rated torque at 600 rpm assuming continuous conduction.

Sol Given Data,

3-ϕ fully controlled converter fed DC motor

Converter in non-circulating mode, 3-ϕ dual converter α = ? at rated torque, $I_a = 200A$, $N = 600rpm$.

We know that,

For 3-φ fully controlled converter.

$$V_o = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha \; ; \; V_m = \sqrt{2}V_s \; , \; V_s = \frac{V_L}{\sqrt{3}}$$

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

$$E_{b1} = V_o - I_aR_a$$

$$= 220 - (200 \times 0.05)$$

$$E_{b1} = 210V$$

$$\Rightarrow E_{b2} = \frac{E_{b1}.N_2}{N_1} = \frac{210 \times 600}{750} = 168V.$$

$$E_{b2} = V_o - I_aR_a$$

$$\Rightarrow V_o = E_{b2} + I_aR_a = 168 + (200 \times 0.05) \doteq 178V.$$

But $V_o = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$

$$V_s = \frac{400}{\sqrt{3}} = 230.94V$$

$$V_m = \sqrt{2} \times 230.94 = 326.59V$$

$$\Rightarrow 178 = \frac{3\sqrt{3} \times 326.59}{\pi}\cos\alpha$$

$$178 = 540.17\cos\alpha$$

$$\alpha = \cos^{-1}\left(\frac{178}{540.17}\right) = 70.75°.$$

(ii) For same problem apply braking at rated torque at 600 rpm.

Sol Given that

$$E_{b1} = 210V$$

$$E_{b2} = ~~178V~~ ~~=178V~~ = 168V$$

$E_{b2} = V_0 + I_a R_a$ (Braking)

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

$= 168 - 200(0.05)$

$V_0 = 158\,V$

w.k.T,

$V_0 = \frac{3\sqrt{3} V_m}{\pi} \cos\alpha$

$V_m = 326.59\,V$

$158 = \frac{3\sqrt{3} \times 326.59}{\pi} \cos\alpha \Rightarrow 158 = 540.175 \cos\alpha$

$\Rightarrow \cos\alpha = \frac{158}{540.175}$

$\cos\alpha = 0.292$

$\Rightarrow \alpha_1 = \cos^{-1}(0.292) = 73.022^\circ$.

$\alpha_1 + \alpha_2 = 180^\circ \Rightarrow \alpha_2 = 180 - 73.022$

$\alpha_2 = 106.97^\circ$

(iii) Regenerative braking operation at rated torque at -600 rpm.

$E_{b1} = 210V$; $N_1 = 750$ rpm, $N_2 = -600$ rpm

w.k.T. $\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2} \Rightarrow E_{b2} = \frac{E_{b1} \cdot N_2}{N_1} = \frac{210 \times -600}{750}$

$E_{b2} = -168V$.

For regenerative braking,

$E_{b2} = V_0 + I_a R_a$

$V_0 = E_{b2} - I_a R_a$

$= -168 - 200(0.05)$

$V_0 = -178\,V$

w.k.T, $V_0 = \frac{3\sqrt{3} V_m}{\pi} \cos\alpha$

$-178 = \frac{3\sqrt{3} \times 326.59}{\pi} \cos\alpha$

$\Rightarrow -178 = 540.175 \cos\alpha$

$\Rightarrow \alpha = \cos^{-1}\left(\frac{-178}{540.175}\right) = 109.239°.$

(iv) motoring action at -600 rpm

Given

$E_{b1} = 210V$

~~E_{b2}~~ $N_1 = 750$ rpm

$N_2 = -600$ rpm

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

$$E_{b2} = \frac{E_{b1} \cdot N_2}{N_1} = \frac{210 \times -600}{750} = -168V$$

W.K.T. $E_{b2} = V_0 - I_a R_a$

$V_0 = E_{b2} + I_a R_a$

$V_0 = -168 + 200 \times 0.05$

$V_0 = -158V$

$$V_0 = \frac{3\sqrt{3}V_m}{\pi} \cos\alpha$$

$$-158 = \frac{3\sqrt{3} \times 326.59}{\pi} \cos\alpha$$

$-158 = 540.175 \cos\alpha$

$\alpha = \cos^{-1}\left(\frac{-158}{540.175}\right)$

$\alpha = \cos^{-1}(-0.292)$

$\alpha = 106.977°$

Block Diagram of Closed-loop speed control of DC motor for below and above base speed for seperately excited DC motor:

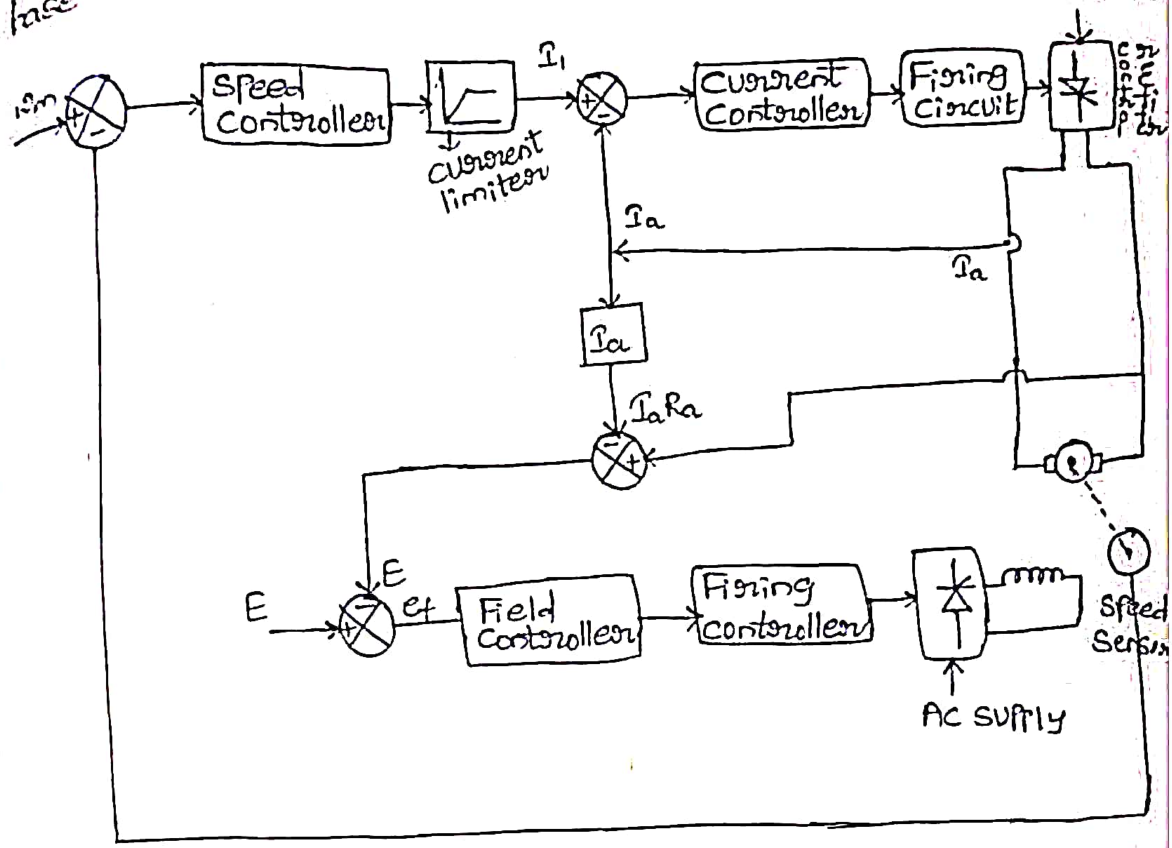


Fig. closed loop Speed Control Scheme.

The block diagram for closed loop control scheme of seperately excited DC motor is shown in above figure.

The main objective of closed loop control is.

1. Protection
2. Enhancement of speed
3. Steady state Accuracy.

It consists of inner current control loop and outer speed control loop.

When reference speed is more than actual speed, positive speed error will be produced. It was applied to speed controller and then passed through current limiter which will saturates even for smaller values of speed error and then the value from current limiter is ~~cost~~ applied to current controller. Current controller will set maximum allowable current in order to vary the firing angles for safer operation of circuit. This method of action is known as motoring.

When reference speed is less than actual speed, negative speed error will be produced. It was applied to speed controller and then passed through current limiter, it saturates even for small values of speed and then value from current limiter is applied to current controller.

Current controller will set maximum allowable value of current in order to operate circuit in safer operation for different firing angles.

This method of action is known as braking.

In this method, motoring and braking actions were achieved by using closed loop operation of seperately excited dc motor.

Different types of controllers used were P, PI and PID controllers.

Questions:

1. Four Quadrant operation of DC drives

2. Types of Braking
(i) Regenerative Braking
(ii) Dynamic or rheostatic Braking
(iii) Plugging

3. Dual Converter
(i) Four Quadrant operation
(ii) modes of operation
(a) circulating current mode
(b) Non-circulating mode

4. Difference between circulating and non-circulating modes of dual converter.

5. Closed loop operation of seperately excited DC motor