FOUR QUADRANT OPERATION OF DC DRIVES

Fundamental Torque Equation :-

Consider the fig ①, shows the representation of the motor-load system by an equivalent rotational system.

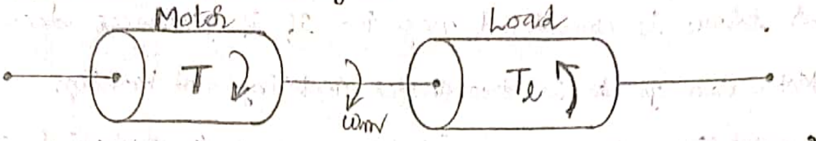


fig ①

Let J = moment of inertia of the motor-load system. $(kg\text{-}m^2)$

ω_m = Instantaneous angular velocity of motor shaft (Rad/sec).

T_e = Instantaneous Torque developed by the motor (N.m)

T_l = Instantaneous load Torque referred to motor shaft (N.m)

The motor-load system in fig① can be described by the following fundamental torque equation :

$$T_e - T_l = \frac{d}{dt}(J\omega_m) = J\left(\frac{d\omega_m}{dt}\right) + \omega_m\left(\frac{dJ}{dt}\right)$$

For drives with constant inertia $\left(\frac{dJ}{dt}\right) = 0$. Hence

$$T_e - T_l = J\left(\frac{d\omega_m}{dt}\right) \Rightarrow T_e = T_l + J\left(\frac{d\omega_m}{dt}\right)$$

The torque component $J\left(\frac{d\omega_m}{dt}\right)$ is known as dynamic torque and is present only during the transient operations.

Drive accelerates (or) decelerates depending on whether T is greater (or) less than T_l. During acceleration $(T_e > T_l)$, motor should supply not only the load torque but also an additional torque component $J\left(\frac{d\omega_m}{dt}\right)$, in order to overcome the drive inertia. During deceleration $(T_e < T_l)$, The dynamic torque $J\left(\frac{d\omega_m}{dt}\right)$ has negative sign. Hence it assists the motor developed torque T_e.

Speed - Torque Conventions :-

For the consideration of four quadrant operation of drives, it is useful to establish suitable conventions of speed and Torque.

→ Motor speed is considered positive when rotating in the forward direction.

→ In loads involving up-and-down motions, The speed of motor which causes upward motion is considered forward motion, and the downward motion is considered as a negative speed.

→ positive motor Torque is defined as the torque which produces acceleration (or) the positive rate of change of speed in forward direction

→ Motor torque is considered negative if it produces deceleration.

→ A Motor can operate in two modes motoring and braking.

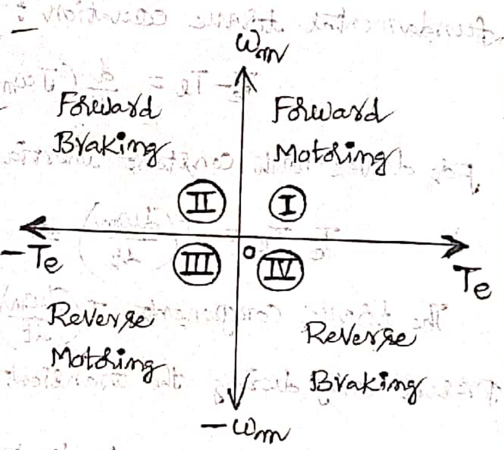
→ In motoring, it converts electrical energy to mechanical energy, which supports its motion.

→ In braking, it converts mechanical energy to electrical energy and hence opposes its motion.

→ Motor can provide motoring & braking both in forward and reverse directions.

Four Quadrant operation of Drives :-

→ fig ⓐ shows the torque and speed coordinates for both forward (+ve) and reverse (−ve) motions.



→ power developed by the motor is given by the product of speed and torque. ($P = T \times \omega$)

→ In Quadrant-(I), developed power is positive. fig ⓐ because both torque & speeds are positive. Hence machine can works as a motor supplying mechanical energy. operation in Quadrant-(I) is thus called forward motoring.

→ In Quadrant-(II), developed power is negative. Because torque is negative and speed is positive. Hence machine works under braking opposes the motion. Therefore, operation in Quadrant-(II) is known as forward braking.

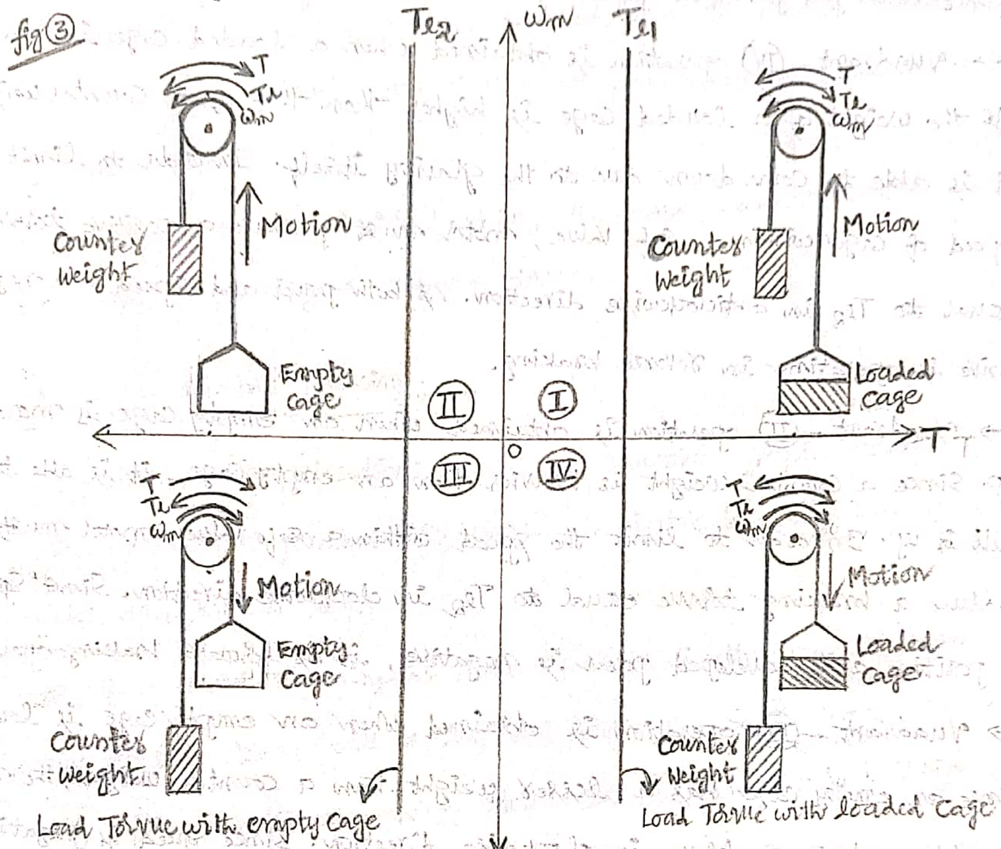
→ In Quadrant-(III), developed power is positive. Because torque is negative and speed is negative. Hence the product is positive. Now machine can works as a motor supplying mech. energy. operation in Quadrant (III) is thus called reverse motoring.

→ In Quadrant-(IV), developed power is negative. Because torque is positive and speed is negative. Hence machine works under braking opposes the motion Therefore, operation in Quadrant-(IV) is known as reverse braking.

Four quadrant operation of a motor driving a hoist load :-

Let us consider the operation of a hoist in four quadrants as shown in fig ③. Directions of motor and load torques, and direction of speed are marked by arrows.

fig ③



→ A hoist consists of a rope wound on a drum coupled to the motor shaft. one end of the rope is tied to a cage which is used to transport man (or) material from one level to another level. other end of the rope has a counter weight. weight of the counter weight is chosen to be higher than the weight of an empty cage but lower than of a fully loaded cage.

→ Load torque line T_{l1} in quadrants Ⅰ and Ⅳ represents speed-torque characteristic for the loaded hoist. This torque is the difference of torques due to loaded hoist and counter weight.

→ Load torque line T_{l2} in quadrants Ⅱ and Ⅲ is the speed-torque characteristic for an empty hoist. This torque is the difference of torques due to counter weight and the empty hoist. Its sign is negative because the weight of a counter weight is always higher than that of an empty cage.

→ The Vuadrant – (I) operation of a hoist requires the movement of the cage upward, which corresponds to the positive motor speed which is in anti clockwise direction. This motion will be obtained if the motor produces positive torque in anticlockwise direction equal to the magnitude of load torque T_{l1}. Since developed power is positive, this is forward motoring operation.

→ Vuadrant – (IV) operation is obtained when a loaded cage is lowered. As the weight of a loaded cage is higher than that of a counter weight it is able to come down due to the gravity itself. In order to limit the speed of cage within a safe value, motor must produce a positive torque T_e equal to T_{l2} in anticlockwise direction. As both power and speed are negative drive is operating in reverse braking.

→ Vuadrant – (II) operation is obtained when an empty cage is moved up. Since a counter weight is heavier than an empty cage, it is able to pull it up. In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{l2} in clockwise direction. Since speed is positive and developed power is negative, it is forward braking operation.

→ Vuadrant – (III) operation is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in clockwise direction. Since speed is negative and developed power is positive, this is reverse motoring operation.

Operating Modes of a DC Machine :-

(I) **Motoring** :- In motoring operation, back emf (E_b) is less than supply Voltage (V_a). Both armature and field currents are positive. The motor develops torque to meet the load demand.

(2008) (II) **Braking** :-

With direction of current shown in fig (4), the machine develops torque in the positive direction and converts electrical energy into mechanical energy which is absorbed by the load.

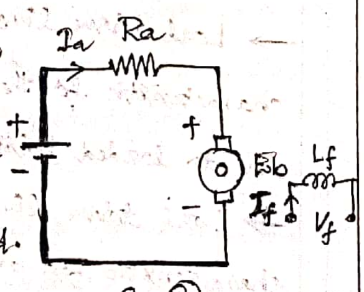


fig (4)

→ If, by some means, the motor armature current is reversed while maintaining the flux in the same direction, the motor torque will reverse and the machine will works as a generator, absorbing mechanical energy from the load and converting it into electrical energy.

→ This mechanical energy is obtained from the energy stored in the inertia of the motor-load system (or) from the active load torque from the motor shaft.

→ In fact, in electric braking, the motor made to work as a generator producing a negative torque.

Need for Electric Braking :-

→ In some applications such as traction, rapid emergency stops are essential to prevent accidents. The electric braking helps in achieving quick and smooth stops.

→ If a motor running at some speed is directly from the supply, the only opposing torque will be the load torque T_L. So the motor will stop only after the kinetic energy stored in its inertia is dissipated.

→ When either the load torque is small (or) the inertia is large, the motor takes a long time to stop. In applications requiring the frequent stops, the stopping time must be reduced by introducing additional opposite torque by the use of electric braking.

→ In applications such as in lifts, machine tools, and the rolling mills, accurate stops are required. Electric braking allows accurate stops without subjecting mechanical parts to large stresses.

→ In certain applications involving active loads, the drive speed will reach dangerous values if the braking force is not provided by the motor. For example, in a hoist application when a loaded hoist is being lowered, the motor should provide a braking force to hold the speed within safelimits. In traction applications, when a train goes down a steepest gladient, a braking force is required to hold the train speed within safe limits.

The braking operation is classified in accordance with the manner in which the generated electrical energy is disposed of. There are three methods of braking a dc motor.

① **Regenerative Braking :-**

In regenerative braking, the energy generated is supplied to the source. Generally, the source will not have the ability to store the energy. The energy supplied is diverted to other loads connected to the source where it is usefully employed and the source is relieved from supplying this much energy.

→ If the source does not have the ability to store energy nor are there other loads connected to the source, regenerative braking cannot be employed

ⓐ **Seperately Excited Motor :-**

Consider the figure ⑤, represents the DC seperately excited motor. If by some means, the back emf E_b made to greater than the supply voltage V_a, the current will reverse. Now the machine will works as a generator thus giving regenerative braking. The induced emf E_b can be made greater than supply voltage V_a, either by increasing E_b (or) decreasing source voltage V_a.

In some applications, the supply voltage V_a cannot be changed. For example, in case of traction application, the same source caters to a number of loads which may be operates simultaneously and may require a constant voltage. In these applications, regenerative braking occurs only when E_b exceeds V_a. This happens when the speed increases beyond the rated no-load speed.

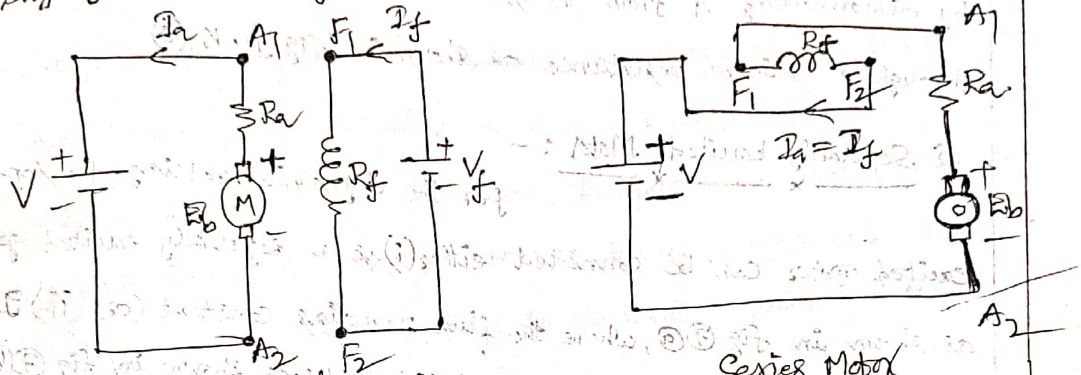
→ For substantially greater speed than the rated no-load speed, the field must be weakend to restrict the braking current and torque.

→ For speeds lower than the rated no-load speed, E_b can exceed V_a only by strengthening the field.

→ As the motor field is normally designed to operate at the knee point of the magnetization characteristics under rated conditions, the flux can be increased only by a small amount by increasing the field current.

→ The heating of field winding also does not permit the field current to be increased beyond a certain value.

→ In fact, when the machine is fed by a constant voltage source, regenerative braking can be employed only for speeds above and slightly below base speed.



Seperately Excited Motor

Series Motor

ⓑ Series Motor :-

→ The regenerative braking operation of DC series motor cannot be achieved as simple way as the seperately excited motor.

→ As we know, the regenerative braking to takes place, the motor induced emf must exceed the supply voltage and armature current should reverse.

→ The reversal of armature current will reverse the current through the field and therefore, the induced emf will also reverse, setting up a short circuit condition.

→ It is possible to maintain the field current in the same direction by connecting the field through a bridge rectifier.

→ However, a switch over from motoring to regeneration will involve a change in the magnitude of the current and therefore in the induced voltage. Because of this the machine will not be able to self-excite against the supply voltage.

→ One commonly used method of regenerating braking of the series motor is to connect it as a shunt motor. Since the resistance of the field winding is low, a series resistance is connected in the field circuit to limit the current within the safe value.

→ The main advantage of regenerative braking is that the generated electrical energy is usefully employed instead of wasting in rheostats as in case of dynamic and plugging brakings.

② Dynamic Braking :- (Rheostatic Braking)

The dynamic braking of a DC motor is obtained by disconnecting it from the source and closing the armature circuit through a suitable resistance as shown in fig ⑦. & ⑧

ⓐ Seperately Excited Motor :-

For the dynamic braking, the seperately excited motor can be connected either (i) as a seperately excited generator as shown in fig ⑦ⓐ, where the flux remains constant (or) (ii) It can be connected as a self excited shunt generator as shown in fig ⑦ⓑ.

→ when the motor is runs at rated speed, the induced emf (E_b) is nearly equal to the supply voltage. If the braking is initiated now, a resistance equal to the starting resistance is required to limit the braking current within the safe limit.

→ The speed - torque characteristics of a seperately excited motor under the dynamic braking with seperate & shunt excitations are shown in fig ⑦ⓒ for two values of the braking resistance.

→ In both cases, the torque decreases with speed.

→ In the self excitation case, the induced voltage (E_b) and hence armature and field currents decreases with speed. Thus decrease in torque for a given change in speed is more compared to that of seperate excitation.

→ Moreover, In the case of self excitation, the torque becomes zero at a finite speed. This is due to the fact that, for a given value of resistance, there is a critical value of speed ω_c below

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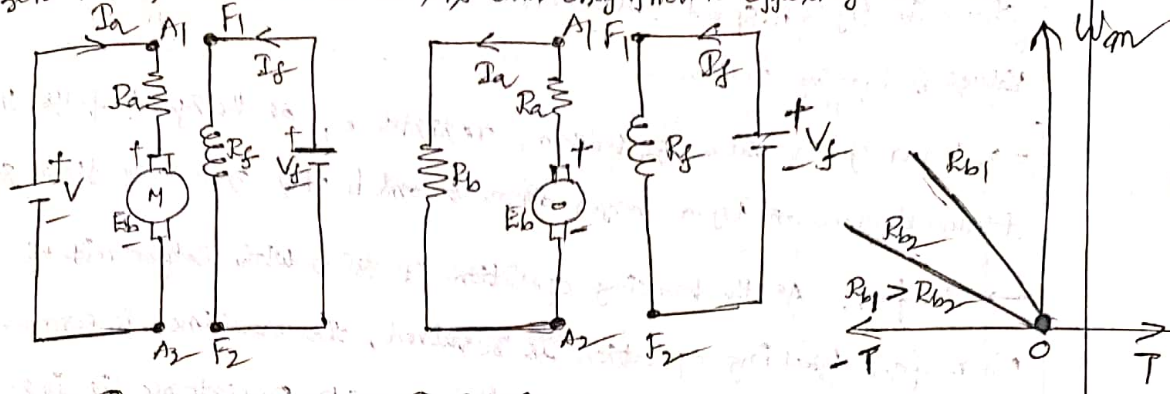
which the machine fails to excite. After the braking torque falls to zero value, the machine coasts with only friction opposing the motion.



(a) Motoring (b) Braking.

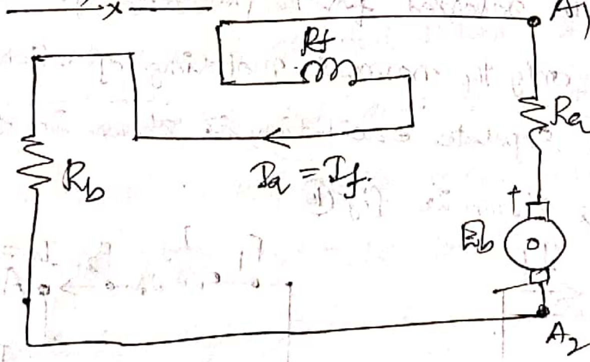
→ Due to all these factors, the braking time corresponds to self excitation is considerably larger compared to that of seperate excitation.

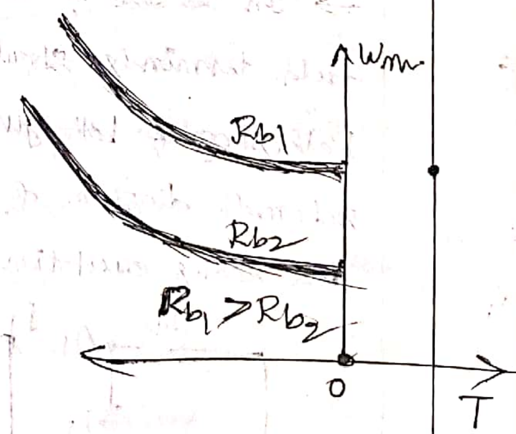
→ When used to hold an active load, the operation at lower speeds is not possible due to the absence of braking torque. Therefore self excitation is used only for emergency stops in the event of power failure.

→ Variable resistance is usually employed when quick braking is required. The max value of the resistance is so chosen that the current at the initiation of braking at the highest speed will have the max permissible value.

→ The Resistance is reduced with the speed to maintain the braking torque at the highest value until $R_B = 0$.

(b) Series Motor :-





→ The series motor is usually connected as a self - excited series generator for dynamic braking.

→ It can be noted that, the current forced through the field winding by the induced emf aids the residual flux for the self excitation. This can be achieved by either reversing the armature (or) field terminals as shown in fig (8a). speed – torque characteristics are shown in fig (8b) for two values of braking resistance

→ For a given value of braking resistance, as the speed falls the torque decreases by a larger amount and becomes zero at a finite speed.

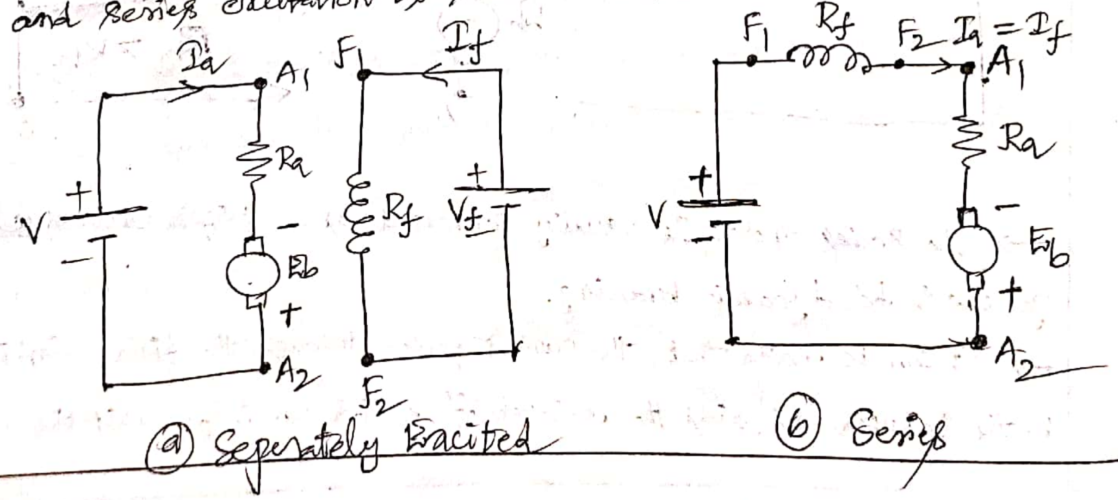
→ In fact, As the braking operation is slow with self excitation, when fast braking operation is required, the machine is connected as a seperate-excitation and an appropriate resistance is inserted in series with the field to limit the current within safe limit.

→ It can be noted here that, Dynamic Braking is an inefficient method of braking because all the generated energy is dissipated in form of heat in resistances.

(3) **plugging** :– (Counter current Braking)

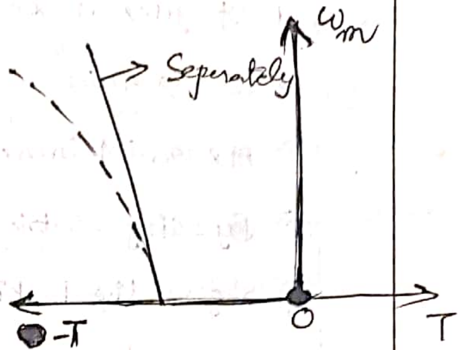
→ If the armature terminals of a seperately excited motor when running are reversed, the supply voltage and induced emf will act in the same direction and the motor current will reverse, producing braking torque. This type of braking is called plugging.

→ In the case of series motor, either the armature terminals (or) field terminals should be reversed for the plugging operation. Reversing of both gives only the normal motoring operation. The schematic diagram of the seperate excitation is shown in fig (9) and series excitation is shown in fig (10)



→ When running at the rated speed, the induced emf is nearly equal to the supply voltage. Therefore, at the initiation of braking, the total voltage drop in the armature circuit will be nearly 2V. Hence a resistance equal to twice the starting resistance will be required to limit the current within the safe value.

→ Speed—Torque characteristics of DC Motors under plugging operation as shown in fig (11) for both separate and series excitations.



→ The change in armature circuit resistance during braking is not necessary as the braking torque remains sufficiently large from rated to zero speed. Moreover, the braking torque is not zero at zero speed.

→ When used for stopping, an additional arrangement is required to disconnect the motor from the supply at (or) near zero speed, otherwise it will speed up in the reverse direction.

→ The main disadvantage of plugging is power line disturbance, especially by large drives, and also not only the power supplied by the load, but also the power taken from the source is wasted in resistances.

Advantages of Electrical Braking over Mechanical Braking:—

→ In the case of electrical Drives, If the supply is cut-off, then speed is decreases and comes to standstill gradually. This inherent property of an electric drive to come back to rest may not be very quick and so it has to be combined with a mechanical brake.

The Various disadvantages of Mechanical braking Method are:—

① Large amount of wear on the brake, which requires frequent and costly replacement.

② Constant attention is required to compensate for wear.

③ If appropriate adjustment of the brake is not made it might endanger the lives of men and equipments.

→ The advantage of mechanical braking is that no-electric power is consumed.

Advantages of Electric Braking :-

① It gives a smooth stoppage (Braking) of the drive.

② It is quick.

③ Its maintainance cost is low.

④ By using electric braking, we may also save energy, as in the case of regenerative braking.

⑤ We can have good control of speed.

⑥ Quick stoppage and quick starting of the motor.

⑦ Heat produced in electric braking method is not harmful to the equipment.

→ The disadvantage of electric braking is that greater expenditure in initial cost.

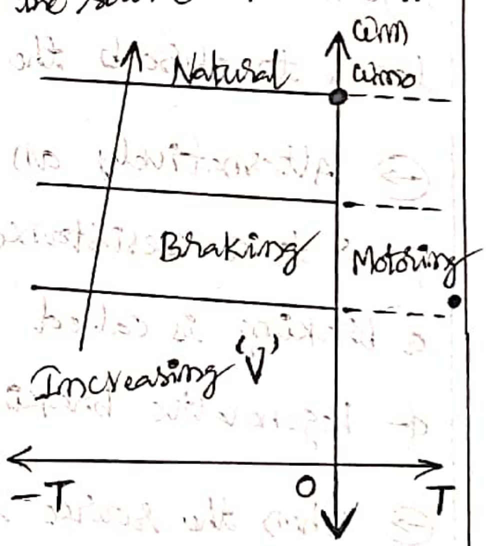
Braking :- (DC Motors)

→ In braking, the motor works as a generator developing a negative torque which opposes the motion.

(a) Regenerative Braking :-

→ In which, generated energy is supplied to the source. This to happen, the following condition should be satisfied.

$E_b > V$ and negative I_a



→ Since field flux cannot be increased beyond rated because of saturation. Therefore, for a source of fixed voltage of rated value Regenerative braking is possible only for speeds higher than rated and with a variable voltage source it is also possible below rated speeds.

→ Fig shows the speed-torque characteristics of seperately excited DC motor.

→ In case of DC series motor, as motor speed increases, armature current and hence flux decreases. Consequently, the above condition cannot be achieved. Thus regenerative braking is not possible.

→ In actual supply system when the machine regenerates its terminal voltage rises. Consequently the regenerated power flows into the loads connected to the supply and the source relieved from supplying this much amount of power.

→ The Regenerative braking is possible only when there are loads connected to the line and they are in need of power more or equal to the regenerative power.

→ When the capacity of loads is less than the regenerated power, all the regenerated power will not be absorbed by the loads. The remaining power will be supplied to capacitors (including stray capacitances) in line and the line voltage will rise to dangerous value leading to break down of insulation. Hence regenerative braking should only be used when there are enough loads to absorb the regenerated power.

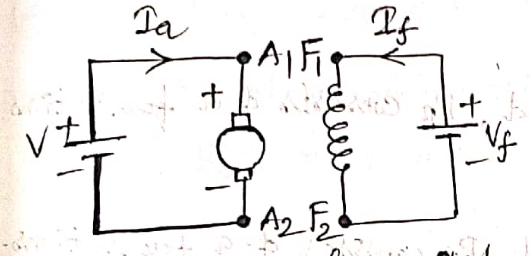
→ Alternatively an arrangement is made to divert the excess power to a resistance bank where it is dissipated as heat. Such a braking is called composite braking because it is a combination of Regenerative braking and dynamic braking.

→ When the source is a battery, the regenerated energy can be stored in the battery.

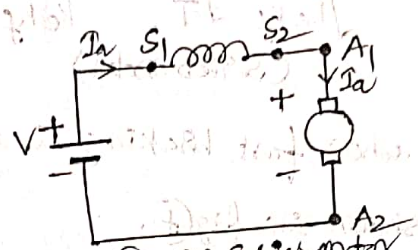
Dynamic Braking (Rheostatic braking) :-

→ In dynamic braking, motor armature is disconnected from the source and connected across a resistance R_B.

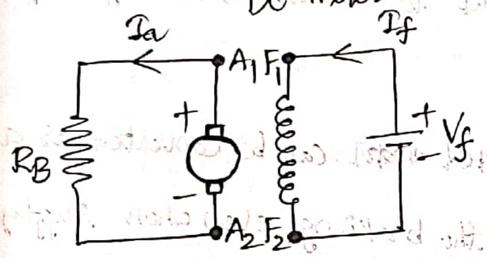
→ The generated energy is dissipated in R_B and R_a.



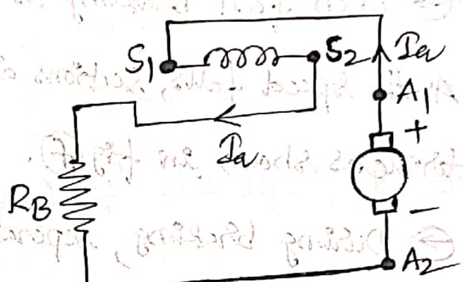
ⓐ Seperately Excited DC motor



ⓑ DC Series motor



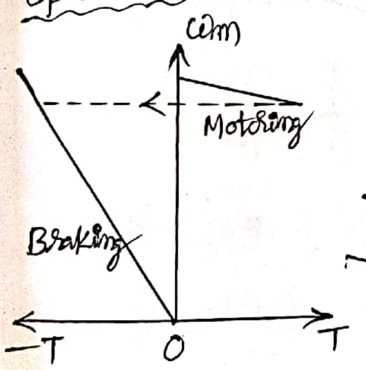
ⓒ Dynamic Braking of Seperately Excited DC motor

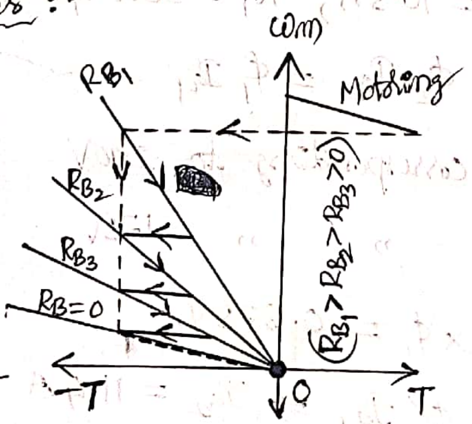


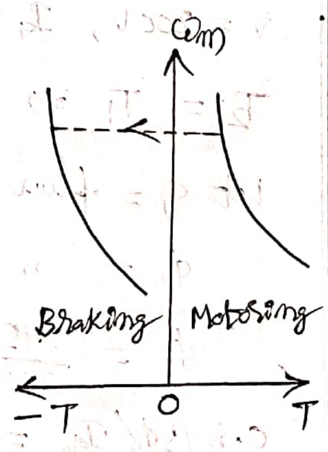
ⓓ Dynamic Braking of DC Series motor.

→ For motoring connections of Figs ⓐ & ⓑ, the braking connections are shown in figs ⓒ, ⓓ. Since series machine works as a self excited generator, the connection is reversed, so that field assists the residual magnetism as shown in fig ⓓ.

Speed-Torque curves :-







—— with few sections of R_B

- - - Stepless Variation of R_B

ⓔ Seperately Excited DC motor

ⓕ Seperately Excited motor with Variable armature resistance

ⓖ Series Motor.

Figs (e), (g) shows speed torque curves for seperately excited and DC series motor. It also shows the transition from motoring to braking.

⊖ These characteristics are obtained from $\omega_m = \frac{V}{K} - \frac{R_a}{K^2} T$ and (seperately)

$$\omega_m = \frac{V}{\sqrt{K_e K_f}} \frac{1}{\sqrt{T}} - \frac{R_a}{K_e K_f}$$ by putting $V = 0$

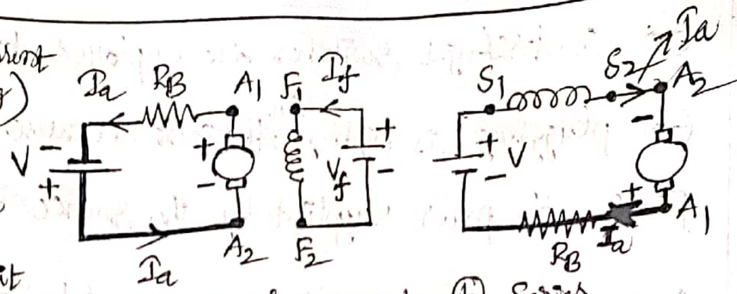
(series motor)

⊖ when fast braking is desired, R_B consists of a few sections as shown in fig (f).

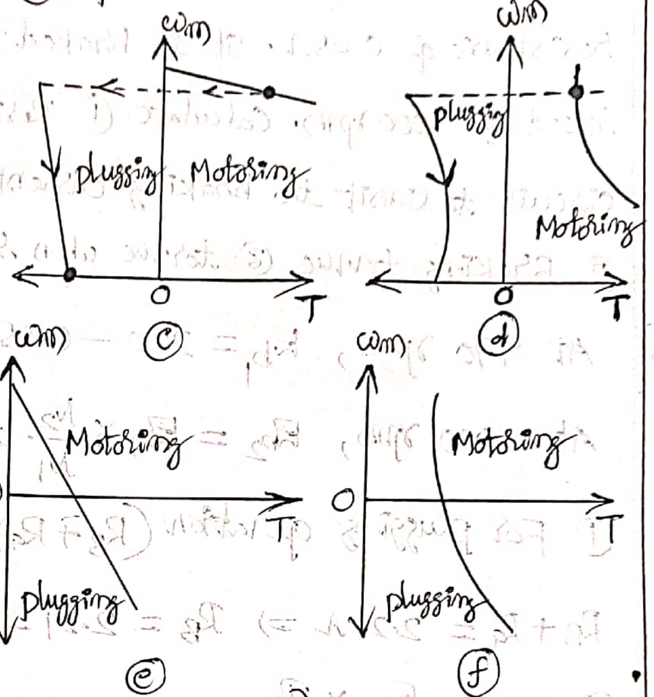
⊖ when fast braking is desired, R_B consists of a few sections. As the speed falls, sections are cut-out to maintain a high avg. torque as shown in fig (f).

⊖ During braking, seperately excited motor can be converted as a self excited generator. This permits the braking even when supply fails.

Plugging :- (Counter current Braking)



ⓐ Seperately Excited ⓑ Series



⊖ For plugging, the supply voltage of a seperately excited motor is reversed so that it assists the back emf in forcing armature current in reverse direction.

⊖ A resistance RB also connected in series with armature to limit the current.

⊖ For a plugging of series motor armature alone is reversed.

⊖ $$\omega_m = \left(\frac{-V}{K}\right) - \frac{R_a}{K^2} T \quad \text{(Seperately excited)}$$

$$\omega_m = \frac{(-V)}{\sqrt{K_e K_f}} \frac{1}{\sqrt{T}} - \frac{R_a}{K_e K_f} \quad \text{(Series)}$$

⊖ plugging for motor rotation in reverse direction arises, when a motor is connected for forward motoring, is driven by an active load in the reverse direction. Here again back emf and applied voltage act in the same direction. However, the direction of torque remains positive. This type of situation arises in cranes, and hoist application and the braking is then called Counter-Torque braking.

⊖ plugging gives fast braking due to high avg. torque, even with one section of braking resistance RB.

⊖ Since torque is not zero at zero speed, when used for stopping a load, the supply must be disconnected when close to zero speed.

→ Centrifugal switches are employed to disconnect the supply.

→ plugging is highly in efficient because in addition to generated power, the power supplied by the source also wasted in resistances.

Regenerative Braking of a DC Shunt Motor :-

→ When a DC shunt motor (or seperately excited motor) used in a hoist applications, when the loaded hoist is lowered the torque developed by the motor and the load torque are additive and makes the motor accelerate.

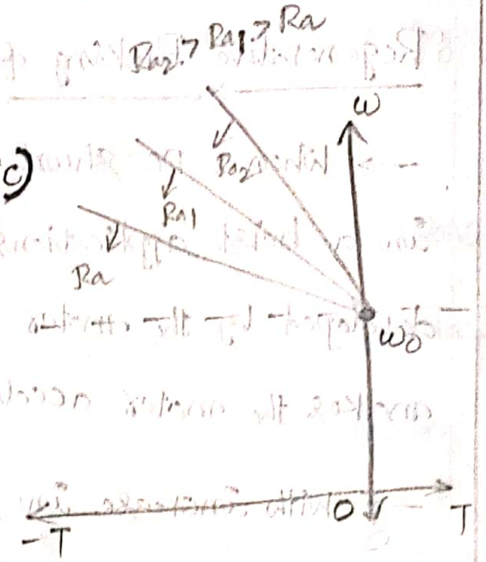
→ With increase in speed, the emf induced in the armature also increases and attains a value equal to the applied voltage when the speed becomes the ideal no-load speed. As a result, the armature current and hence the electromagnetic torque becomes zero.

→ When the speed becomes greater than the ideal no-load speed the $E_b > V$, and therefore the armature current becomes negative. The drive then acts as a generator and provides the braking torque.

→ The drive attains a steady state speed when the braking torque developed by the motor is equal to the load torque. During this operation, the emf induced in the armature is directed against the applied voltage as it happens during motoring operation.

→ The speed-torque characteristics of the motor during braking as shown in figure ①. There are three characteristics - one being the inherent one, with no additional resistance in the ar circuit, and the other two being the modified ones, corresponding to increased values of resistances in the ar circuit. It is clear that, braking can occur only at speeds greater than the ideal no-load speed of the motor.

At speeds lower than the ideal no-load speed, retarding torque can be provided only by means of rheostatic Braking (Dynamic)



$$\rightarrow \omega = \frac{V_a + I_a R_a}{K_v \phi} = \frac{V_a}{K_v\phi} + \left(\frac{R_a}{K_v\phi}\right) I_a$$

$$I_a = \frac{T}{-K_v\phi} \quad (\because T = -K_v \phi I_a)$$

$$\omega = \left(\frac{V_a}{K_v\phi}\right) + \frac{R_a}{(K_v\phi)^2}(-T)$$

$$\omega = \left(\frac{V_a}{K_v\phi}\right) + \frac{R_a}{(K_v\phi)^2} T_b \quad (\because T_b = -T) \Rightarrow \omega = \omega_0 + \frac{R_a}{(K_a\phi)^2} T_b$$

which represents the straight line with the slope equal to $\frac{R_a}{(K_v\phi)^2}$

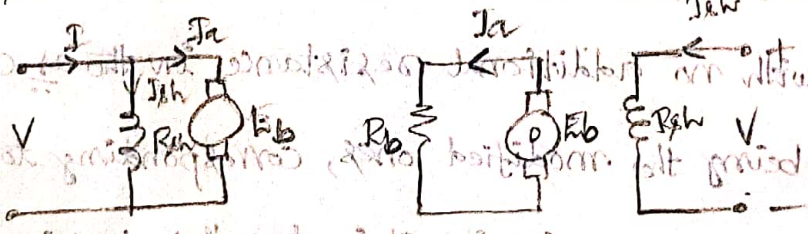
The term in the above equation shows that at $T=0$, the characteristics passes through the point corresponding to the ideal no-load speed.

It is clear that from the figure, the higher the resistance of the ar. circuit, to produce a particular braking torque, higher is the speed required.

→ It is not possible to obtain regenerative braking at very low speed by this method as a sufficient increase in field current cannot be obtained.

Dynamic (or) Rheostatic Braking :- (DC Shunt Motor)

→ During this type of braking the motor acts as a generator, where armature terminals are short circuited through an external Res.



→ The Voltage and speed equation corresponding to this operation are:

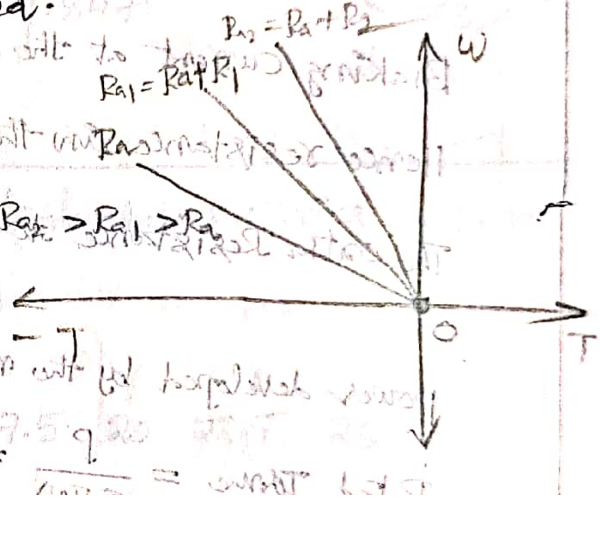
$$E_b = -I_a (R_a + R_{ext})$$

$$\omega = -T \frac{(R_a + R_{ext})}{(K_v \phi)^2} \quad (\because V_a = 0)$$

→ The speed - torque characteristics during rheostatic braking are as shown in fig ②. They approximate to straight lines passing through the origin. The slope of the characteristics depends on the total resistance in the armature circuit.

→ In this braking, braking torque can be obtained at very low speeds, ie 0.1 to 0.07 of the rated speed.

→ A major disadvantage of the method is that the braking torque is zero when the excitation fails. This difficulty can be overcome by connecting a series field in the armature circuit during braking only.



Dual Converter fed DC Motor Drive :-

→ The fully controlled converter can produce a reversible direct output Voltage with output current in one direction, and is said to be capable of operation in two quadrants, the first and forth.

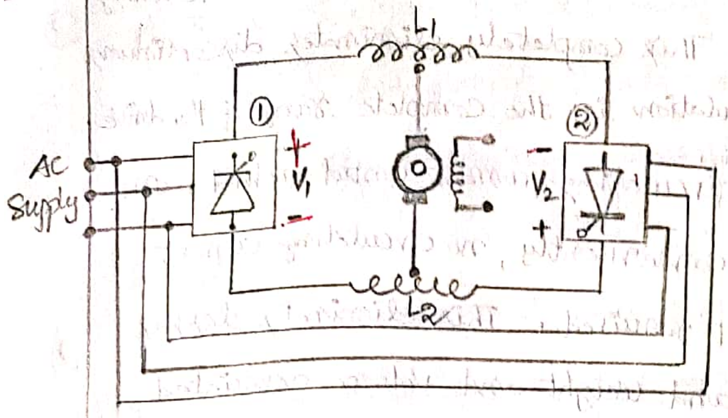
→ Such a range of operation is useful for some purposes ① like a motor is used to provide unidirectional torque with reversible rotation ② a DC transmission link between two ac systems in which power can be transmitted in either direction according to the polarity of the Voltage, and current flows in one direction.

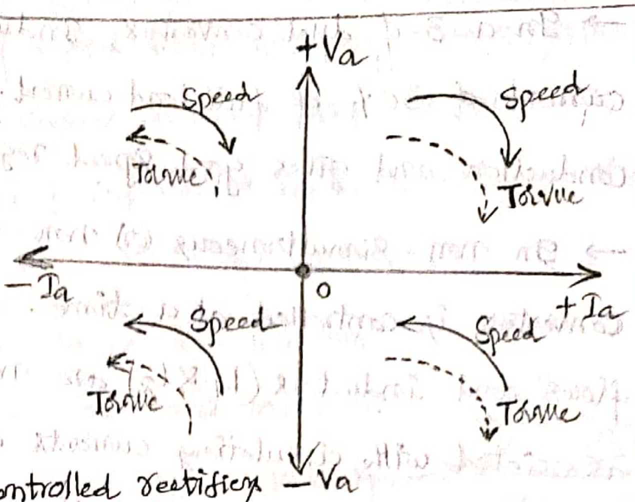
→ If four quadrant operation of a DC motor is required ie reversible rotation and reversible torque is obtained by connecting two fully controlled converters back to back across the load circuit. Such a system is known as a Dual converter.

→ Since both Voltage and current of either polarity are obtained with a dual converter, therefore the system will provide the four-quadrant operation.

→ A dual converter consisting of two fully controlled rectifiers connected in anti-parallel across the armature.

→ For power ratings upto 10 KW, 1-ϕ fully controlled rectifiers can be used.





→ For higher ratings, 3-φ fully controlled rectifiers are employed.

→ In the above figure, Converter-① provides positive motor current and voltage in either direction, allows motor control in quadrants (I) & (IV)

→ Converter-② provides negative motor currents and voltage in either direction, allows motor control in quadrants (II) & (III).

→ There are two methods of control for the Dual Converter.

① Simultaneous control (or) circulating current control.

② Non-Simultaneous control (or) non-circulating current control.

→ In simultaneous control both converters are controlled together. In order to avoid dc circulating current between converters, they are operated to produce same DC voltage across the motor terminals. Thus,

$$V_1 + V_2 = 0$$

where $V_1 = \left(\frac{3\sqrt{3}V_m}{\pi}\right)\cos\alpha_1 = V_{max}\cos\alpha_1$

$V_2 = \left(\frac{3\sqrt{3}V_m}{\pi}\right)\cos\alpha_2 = V_{max}\cos\alpha_2$

$$V_{max}\cos\alpha_1 + V_{max}\cos\alpha_2 = 0$$

$$\cos\alpha_1 + \cos\alpha_2 = 0 \Rightarrow \alpha_1 + \alpha_2 = 180^\circ.$$

→ Even though DC circulating currents are prevented by the above method, ac currents circulating due to difference between instantaneous output voltages of two rectifiers. Inductors are (L_1 & L_2) added to reduce the ac circulating current. Because of the flow of ac circulating current, simultaneous control is also known as circulating current control.

→ In a 3-ϕ dual converter, Inductors are chosen to allow a circulating current of 30% of full load current. This completely eliminates discontinuous conduction and gives good speed regulation in the complete range of the drive.

→ In non-simultaneous (or) non-circulating current control method, one converter is controlled at a time. consequently, no circulating current flows and inductors (L_1 & L_2) are not required. This eliminates losses associated with circulating currents and weight and volume associated with inductors. But then discontinuous conduction occurs at light loads and the control is rather complex.

→ When a speed control above base is also required, the field is controlled by feeding it from a controlled rectifier

Advantages of circulating current Mode :-

① The circulating current keeps both converters in virtually continuous conduction independent of whether the external load current is continuous (or) discontinuous.

② The reversal of load current is inherently a natural and smooth proceedure due to the natural freedom provided in the power circuit for the load current to flow in either direction at any time.

③ Since the converters are in continuous conduction, the time response of the scheme is very fast.

④ Linear transfer characteristics are obtained.

Disadvantages of circulating current Mode :-

① Since the current limiting reactor is required, the size and cost of the reactor may quite significant at high power levels.

② Since converters have to handle load (or) circulating currents, the thyristors with high current ratings are required for these converters.

③ The efficiency and power factor are low because of circular current which increases losses.

Closed-Loop Control of DC Drives :- (M.D. Singh)

→ In drive applications, where the speed and position control is needed, a power electronic control converter is required as an interface between the input power and the motor.

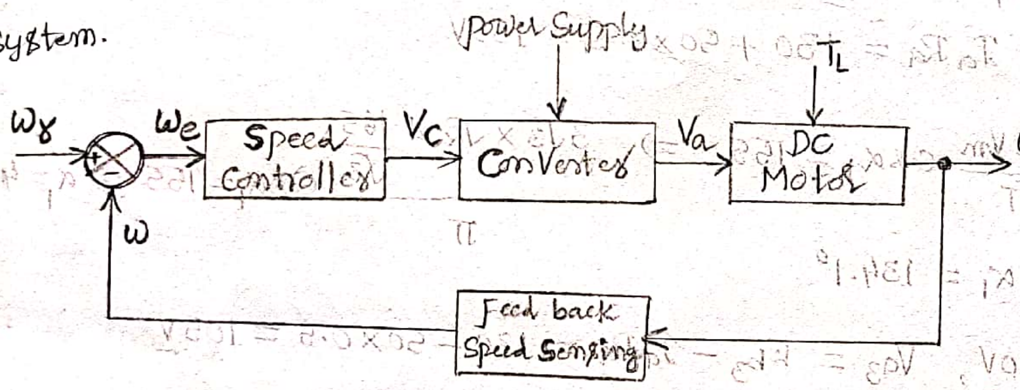
→ In many applications, open-loop operation of dc motors may not be satisfactory because speed changes if the firing angle is kept constant and the torque applied to the dc motor is increased.

→ However, if the drive requires constant-speed operation, the firing angle has to change to maintain a constant speed. This can be achieved in a closed-loop control system.

→ The closed loop system has the following advantages

1. Improved accuracy
2. Fast dynamic response
3. Reduced effects of load disturbances and system non-linearities.

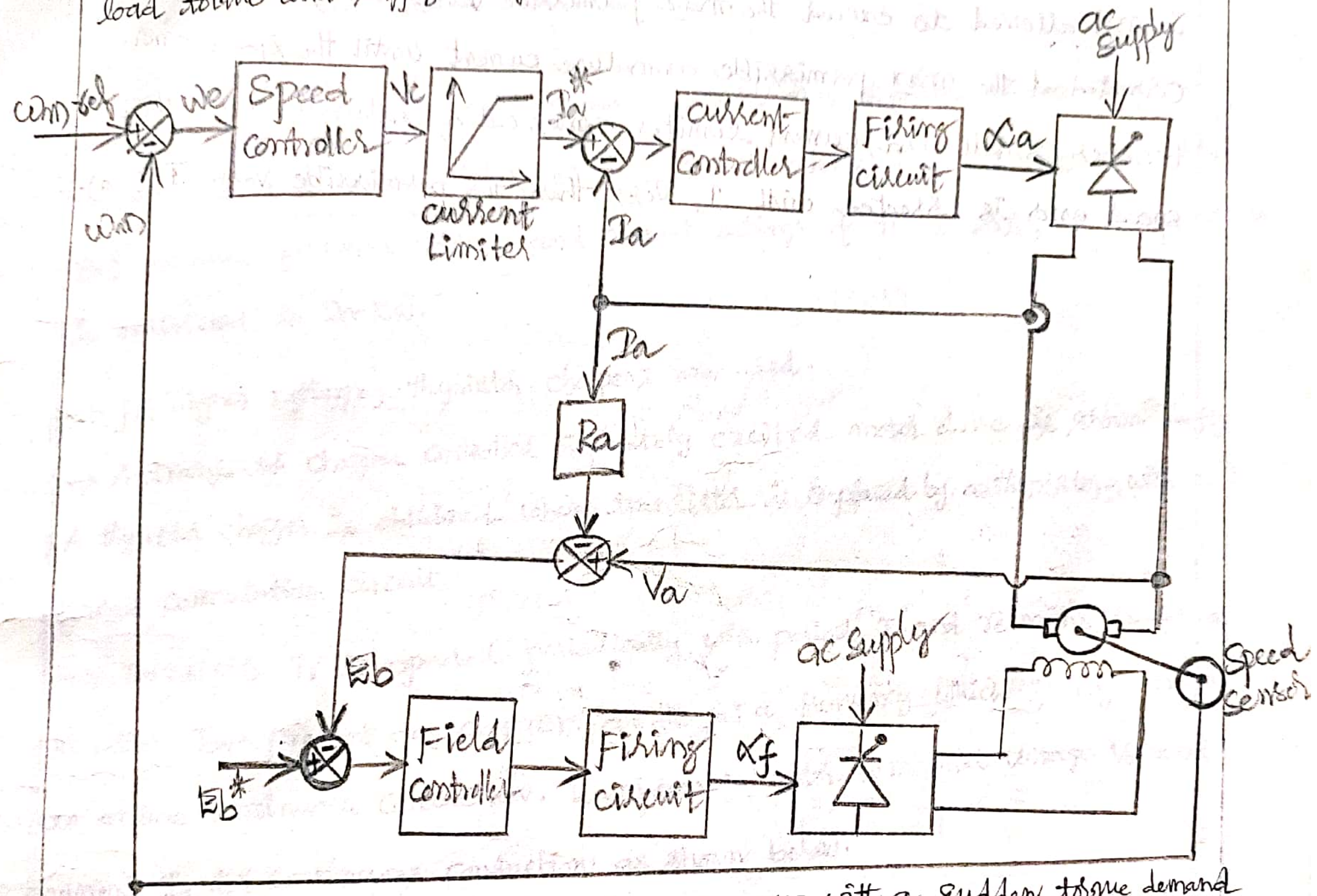
→ When the drive requirement includes rapid acceleration and deceleration closed-loop control is necessary. The system can be made to operate at constant torque (or) constant power over a certain range of speed. In practice, most industrial drive system operates on closed-loop feedback system.



→ The above figure shows the basic block diagram of a closed loop control system. If motor speed decreases due to the application of the additional load torque, the speed error (ω_e) increases which increases the control voltage (V_c). This in turn changes the firing angle of the converter, and thus increases the motor armature voltage (V_a). An increase in the motor voltage develops motor torque to restore the speed of the drive system. The system thus passes through a transient period until the developed torque matches the applied torque.

→ The above closed loop system uses a speed feedback only. In practice the motor is required to operate at a desired speed, but it has to meet the load torque which depends on the armature current.

→ When the motor is operating at a particular speed and if a load is applied suddenly, the speed will fall and the motor will take time to come-up to the desired speed. A speed feedback with an inner current loop as shown below provides faster response to any disturbances in speed command load torque and supply voltage.



→ The purpose of the current loop is to cope up with a sudden torque demand under transient operations such as starting, braking, speed reversal etc. The output of the speed controller V_c is applied to the current limiter which sets the current reference I_a^* for the current loop. The armature current I_a is sensed by a current sensor, filtered normally by an active filter to remove ripple and compared with the current reference I_a^*. The current error processed through a current controller whose output V_c adjusts the firing angle of the converter and brings the motor speed to the desired value.

→ Any positive speed error caused by either an increase in the speed command (or) an increase in 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 close to zero.

→ For large positive speed error, the current limiter saturates and the current reference I_a^* is limited to a value $I_{a(max)}$ and the drive current is not allowed to exceed the max. permissible value. The speed error is corrected at the max. permissible armature current until the speed error becomes small and current limiter comes out of saturation. Now the speed error is corrected with I_a less than the permissible value $I_{a(max)}$.