8 Application of d.c. motors

Some elementary principles of application alone are dealt with here. The focus is on the mechanical equation of dynamics which is reproduced here once again.

$$T_M - T_L = J\frac{dw}{dt} \tag{43}$$

Here T_M and T_L are the motor torque and the load torques respectively which are expressed as functions of ω. Under steady state operation $d\omega/dt$ will be zero. The application of motors mainly looks at three aspects of operation.

1. Starting
2. Speed control
3. Braking

The speed of the machine has to be increased from zero and brought to the operating speed. This is called starting of the motor. The operating speed itself should be varied as per the requirements of the load. This is called speed control. Finally, the running machine has to be brought to rest, by decelerating the same. This is called braking. The torque speed characteristics of the machine is modified to achieve these as it is assumed that the variation in the characteristics of the load is either not feasible or desirable. Hence the methods that are available for modifying the torque speed characteristics and the actual variations in the performance that these methods bring about are of great importance. When more than one method is available for achieving the same objective then other criteria like, initial cost, running cost, efficiency and ease operation are also applied for the evaluation of the methods. Due to the absence of equipment like transformer, d.c. machine operation in

general is assumed to be off a constant voltage d.c. supply.

The relevant expressions may be written as,

$$n = \frac{E}{K_e\phi} = \frac{V - I_a R_a - V_b}{pZ\phi/b} \quad (44)$$

$$T_M = K_t.\phi.I_a = \frac{1}{2\pi}.\frac{p.Z}{b}.\phi I_a \quad (45)$$

$$T_M - T_L = J\frac{d\omega}{dt} \quad (46)$$

As can be seen, speed is a function of E and ϕ and T is a function of ϕ and I_a. Using these equations, the methods for starting , speed control and braking can be discussed.

8.1 Starting of d.c. machines

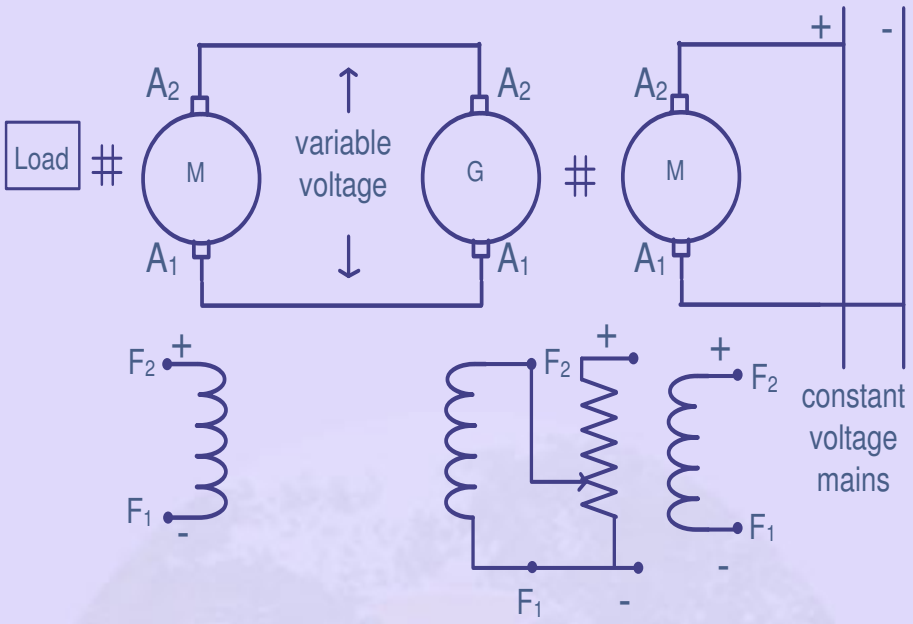
For the machine to start, the torque developed by the motor at zero speed must exceed that demanded by the load. Then $T_M - T_L$ will be positive so also is $d\omega/dt$, and the machine accelerates. The induced emf at starting point is zero as the $\omega = 0$ The armature current with rated applied voltage is given by V/R_a where R_a is armature circuit resistance. Normally the armature resistance of a d.c. machine is such as to cause 1 to 5 percent drop at full load current. Hence the starting current tends to rise to several times the full load current. The same can be told of the torque if full flux is already established. The machine instantly picks up the speed. As the speed increases the induced emf appears across the terminals opposing the applied voltage. The current drawn from the mains thus decreases, so also the torque. This continues till the load torque and the motor torque are equal to each other. Machine tends to run continuously at this speed as the acceleration is zero at this point of operation.

The starting is now discussed with respect to specific machines.

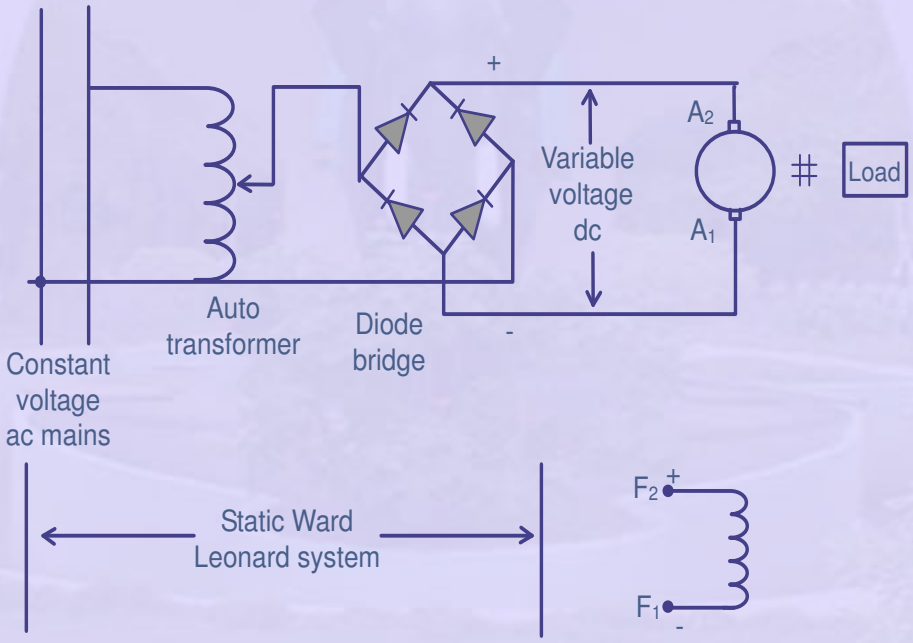
8.1.1 DC shunt motor

If armature and field of d.c. shunt motor are energized together, large current is drawn at start but the torque builds up gradually as the field flux increases gradually. To improve the torque per ampere of line current drawn it is advisable to energize the field first. The starting current is given by V/R_a and hence to reduce the starting current to a safe value, the voltage V can be reduced or armature circuit resistance R_a can be increased. Variable voltage V can be obtained from a motor generator set. This arrangement is called Ward-Leonard arrangement. A schematic diagram of Ward-Leonard arrangement is shown in Fig. 45. By controlling the field of the Ward-Leonard generator one can get a variable voltage at its terminals which is used for starting the motor.

The second method of starting with increased armature circuit resistance can be obtained by adding additional resistances in series with the armature, at start. The current and the torque get reduced. The torque speed curve under these conditions is shown in Fig. 46(a) . It can be readily seen from this graph that the unloaded machine reaches its final speed but a loaded machine may crawl at a speed much below the normal speed. Also, the starting resistance wastes large amount of power. Hence the starting resistance must be reduced to zero at the end of the starting process. This has to be done progressively, making sure that the current does not jump up to large values. Starting of series motor and compound motors are similar to the shunt motor. Better starting torques are obtained for compound motors as the torque per ampere is more. Characteristics for series motors are given in fig. 47.

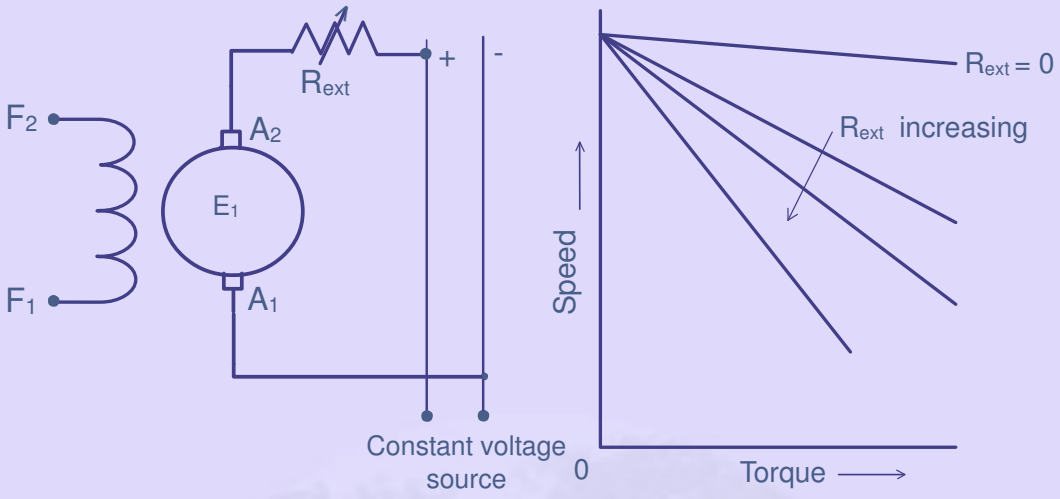


(a)

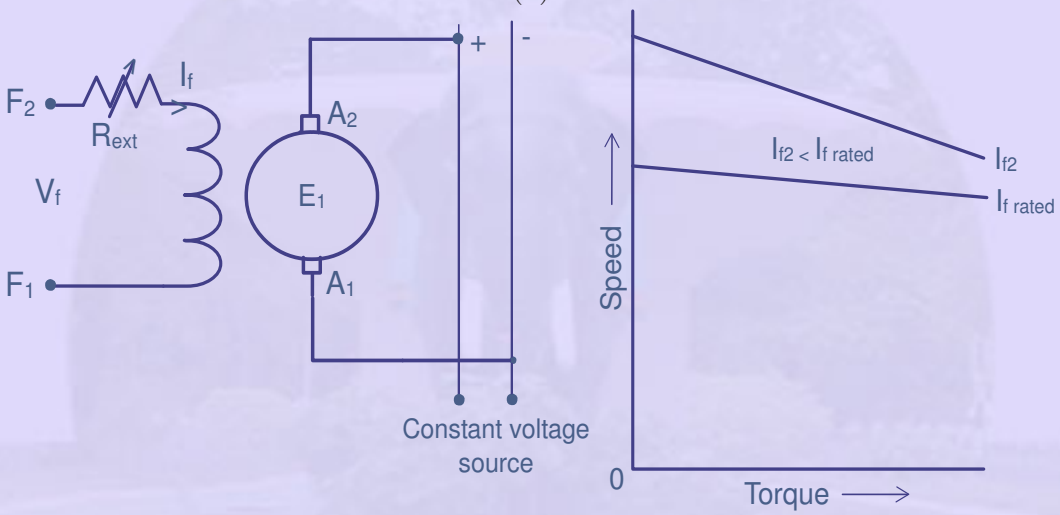


(b)

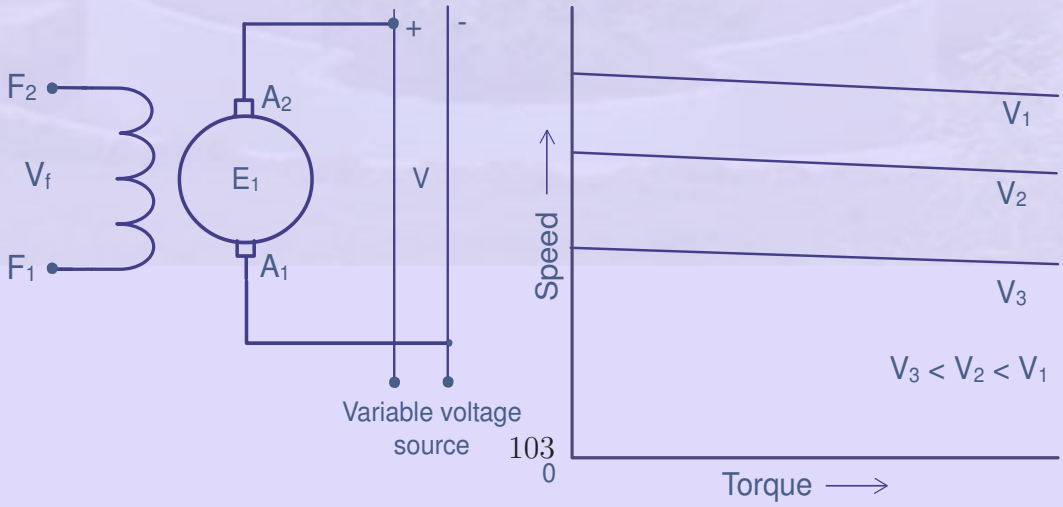
Figure 45: Ward-Leonard arrangement



(a)

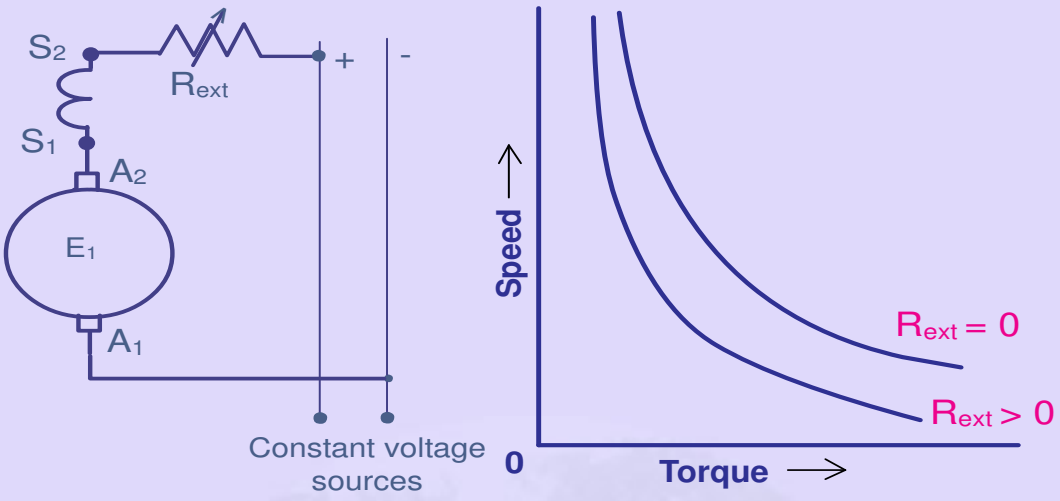


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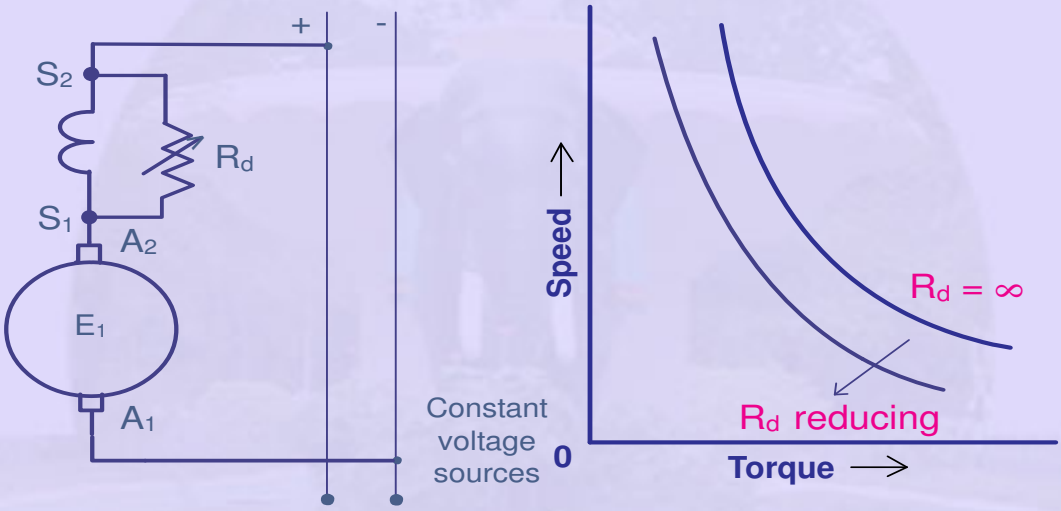


(c)

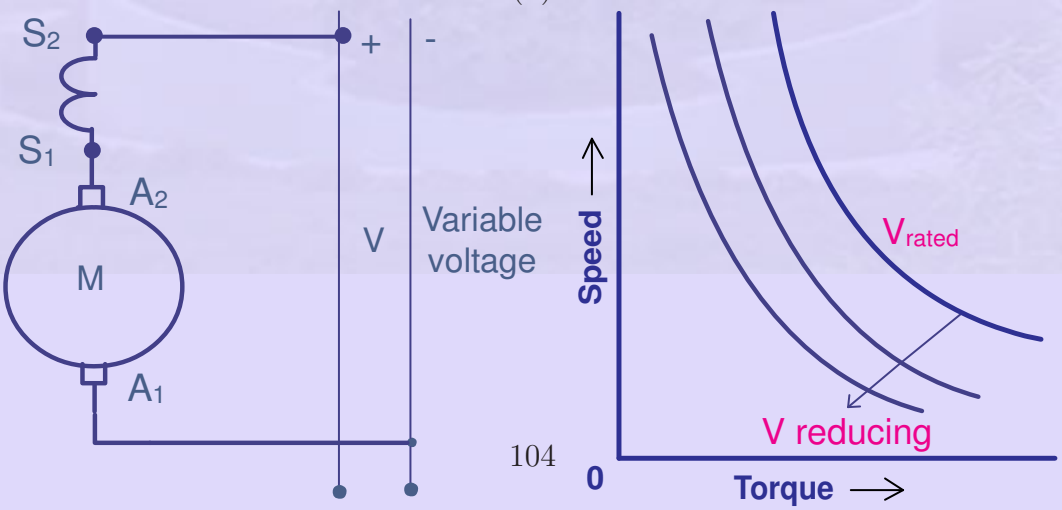
Figure 46: Shunt Motor characteristics



(a)

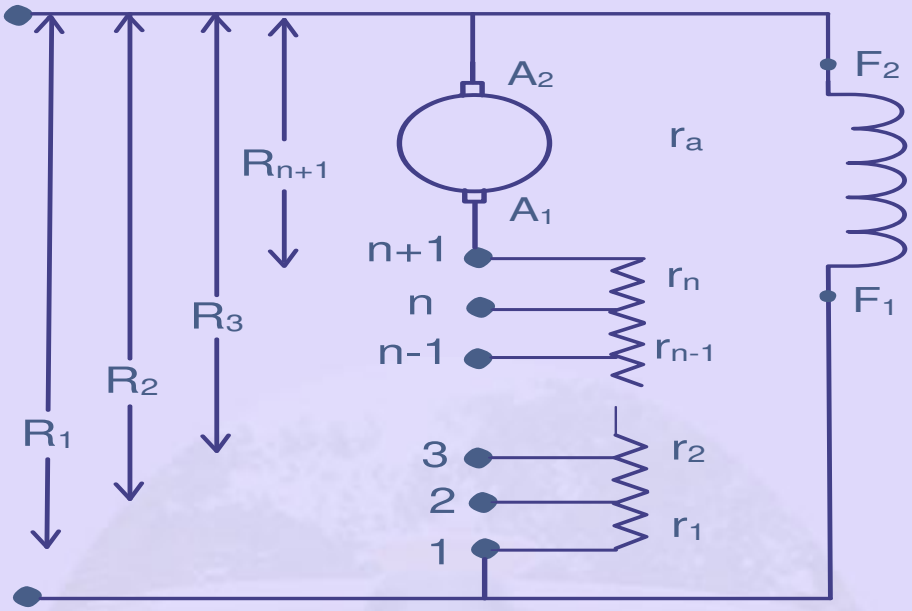


(b)

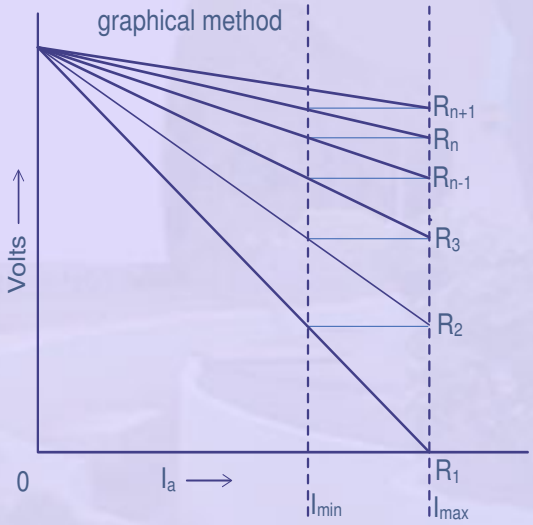


(c)

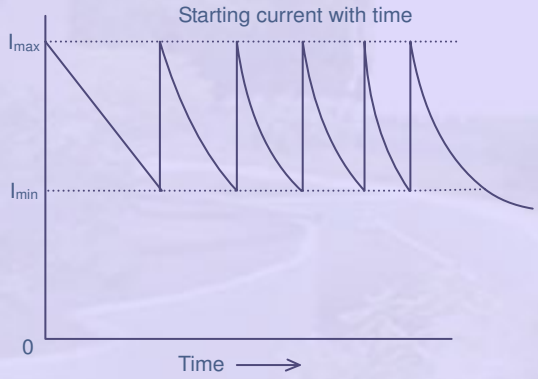
Figure 47: Series motor control



(a)Physical connection



(b) Characteristics



(c) Time-current plot

Figure 48: Calculation of starter resistance steps

8.1.2 Grading of starting resistance for a shunt motor

If the starting resistor is reduced in uniform steps then the current peaks reached as we cut down the resistances progressively increase. To ascertain that at no step does the current jump to a large value non-uniform reduction of resistances must be assorted to. This use of a non-uniform resistance step is called 'grading' of the resistors. The calculations for a starter resistance of a shunt motor are shown below with the help of Fig. 48. In the figure an n element or n+1 step starter is shown. The armature resistance when all the external resistances are cut off is r_a. The total armature circuit resistance at step 1 is $R_1 = (r_1 + r_2 + ... + r_n) + r_a$. The field winding is connected across the supply. The starting current reaches a maximum value I_max when we move on to a step. One resistance element is cut from the circuit when the current falls down to I_min . During the instant when the element is cut the speed and hence the induced emf does not change but the current jumps back to I_max . Thus during the starting the current changes between two limits I_max and I_min. Writing the expression for the current before and after the resistance is changed on step R_i and R_{i+1}, we have

$$I_min = \frac{V-E}{R_i} \quad I_max = \frac{V-E}{R_{i+1}} \quad \text{or} \quad \frac{I_max}{I_min} = \frac{R_i}{R_{i+1}} \tag{47}$$

Proceeding this way for all the steps

$$\frac{I_max}{I_min} = \frac{R_1}{R_2} = \frac{R_2}{R_3} = ... = \frac{R_{n-1}}{R_n} = \frac{R_n}{R_{n+1}} = k(say) \tag{48}$$

$$k^n = \frac{R_1}{R_2} * \frac{R_2}{R_3} * ... * \frac{R_n}{R_{n+1}} = \frac{R_1}{R_{n+1}} = \frac{R_1}{r_a} \quad k = \sqrt[n]{\frac{R_1}{r_a}} \tag{49}$$

Sometimes the ratio k may be required to be fixed. Then the number of steps required can be calculated as

$$n \log k = \log \frac{R_1}{r_a} \quad , n = \frac{\log \frac{R_1}{r_a}}{\log k} \qquad (50)$$

$$\frac{\log R_1 - \log R_n}{\log k}$$

Also,

$$R = \sqrt[n]{\frac{V}{I_1 r_a}} = \sqrt[n]{\frac{V}{R I_2 r_a}} = \sqrt[n+1]{\frac{V}{I_2 r_a}} \qquad (51)$$

From these expressions it is seen that to have the ratio k to be unity, the number of steps should be infinity. Smaller the number of steps larger is the ratio of maximum to minimum current. Also, it is not possible to choose n and k independently. I_max is set by the maximum possible starting current from the point of view of commutation. I_min is found from the minimum torque against which the starting is required to be performed. Similar method exists in the case of series motors and compound motors. In these cases the ratio of currents and the ratio of fluxes are needed. The equation becomes non-linear and a graphical method is normally adopted for the design of the resistances in those cases.

Resistance method of starting is cheaper and simple and hence is used universally. But it wastes energy in the starting resistor. Hence this method is not advised when frequent starting of the motor is required. Ward-Leonard method gives a energy efficient method of starting. With the help of a auto transformer and rectifier set one can get variable voltage d.c. supply from a constant voltage a.c power source. This is some times called a static Ward-Leonard arrangement. This method is becoming more popular over the rotating machine counter part.

8.2 Speed control of d.c. motors

In the case of speed control, armature voltage control and flux control methods are available. The voltage control can be from a variable voltage source like Ward-Leonard arrangement or by the use of series armature resistance. Unlike the starting conditions the series resistance has to be in the circuit throughout in the case of speed control. That means considerable energy is lost in these resistors. Further these resistors must be adequately cooled for continuous operation. The variable voltage source on the other hand gives the motor the voltage just needed by it and the losses in the control gear is a minimum. This method is commonly used when the speed ratio required is large, as also the power rating.

Field control or flux control is also used for speed control purposes. Normally field weakening is used. This causes operation at higher speeds than the nominal speed. Strengthening the field has little scope for speed control as the machines are already in a state of saturation and large field mmf is needed for small increase in the flux. Even though flux weakening gives higher speeds of operation it reduces the torque produced by the machine for a given armature current and hence the power delivered does not increase at any armature current. The machine is said to be in constant power mode under field weakening mode of control. Above the nominal speed of operation, constant flux mode with increased applied voltage can be used; but this is never done as the stress on the commutator insulation increases.

Thus operation below nominal speed is done by voltage control. Above the nominal speed field weakening is adopted. For weakening the field, series resistances are used for shunt as well as compound motors. In the case of series motors however field weakening

is done by the use of 'diverters' . Diverters are resistances that are connected in parallel to the series winding to reduce the field current without affecting the armature current.

8.3 Braking the d.c. motors

When a motor is switched off it 'coasts' to rest under the action of frictional forces. Braking is employed when rapid stopping is required. In many cases mechanical braking is adopted. The electric braking may be done for various reasons such as those mentioned below:

1. To augment the brake power of the mechanical brakes.
2. To save the life of the mechanical brakes.
3. To regenerate the electrical power and improve the energy efficiency.
4. In the case of emergencies to step the machine instantly.
5. To improve the through put in many production process by reducing the stopping time.

In many cases electric braking makes more brake power available to the braking process where mechanical brakes are applied. This reduces the wear and tear of the mechanical brakes and reduces the frequency of the replacement of these parts. By recovering the mechanical energy stored in the rotating parts and pumping it into the supply lines the overall energy efficiency is improved. This is called regeneration. Where the safety of the personnel or the equipment is at stake the machine may be required to stop instantly. Extremely large brake power is needed under those conditions. Electric braking can help in these situations also. In processes where frequent starting and stopping is involved the

process time requirement can be reduced if braking time is reduced. The reduction of the process time improves the throughput.

Basically the electric braking involved is fairly simple. The electric motor can be made to work as a generator by suitable terminal conditions and absorb mechanical energy. This converted mechanical power is dissipated/used on the electrical network suitably. Braking can be broadly classified into:

1. Dynamic
2. Regenerative
3. Reverse voltage braking or plugging

These are now explained briefly with reference to shunt ,series and compound motors.

8.3.1 Dynamic braking

- Shunt machine

  In dynamic braking the motor is disconnected from the supply and connected to a dynamic braking resistance R_{DB}. In and Fig. 49 this is done by changing the switch from position 1 to 2 . The supply to the field should not be removed. Due to the rotation of the armature during motoring mode and due to the inertia, the armature continues to rotate. An emf is induced due to the presence of the field and the rotation. This voltage drives a current through the braking resistance. The direction of this current is opposite to the one which was flowing before change in the connection. Therefore, torque developed also gets reversed. The machine acts like a brake. The

torque speed characteristics separate by excited shunt of the machine under dynamic braking mode is as shown in Fig. 49(b) for a particular value of R_{DB}. The positive torque corresponds to the motoring operation. Fig. 50 shows the dynamic braking of a shunt excited motor and the corresponding torque-speed curve. Here the machine behaves as a self excited generator.

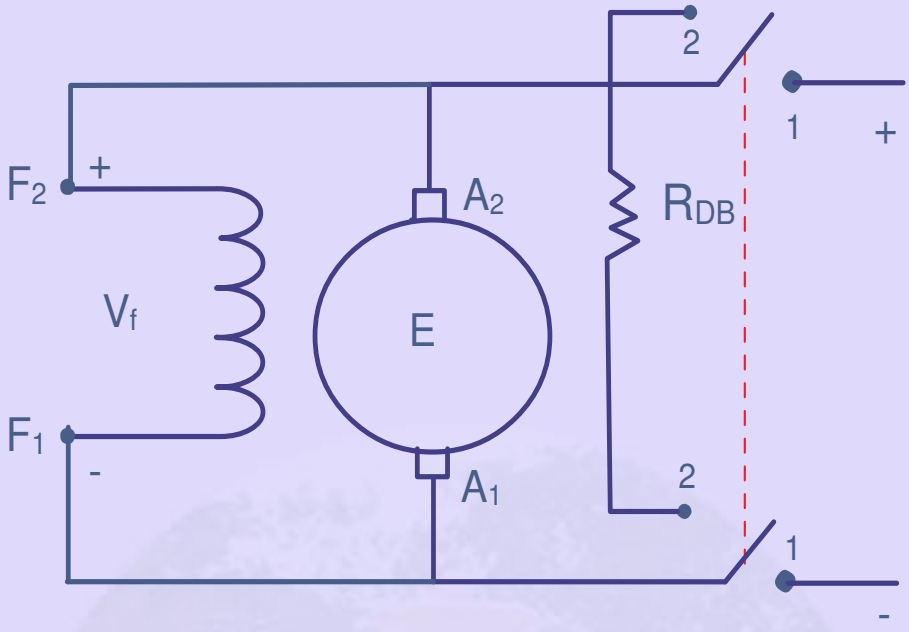
Below a certain speed the self-excitation collapses and the braking action becomes Zero.

- Series machine

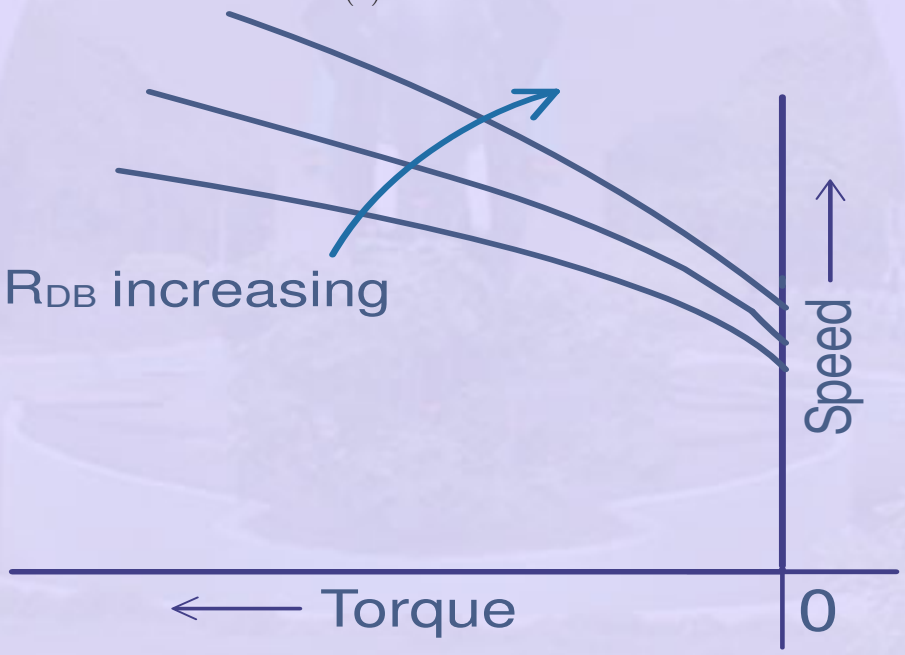
  In the case of a series machine the excitation current becomes zero as soon as the armature is disconnected from the mains and hence the induced emf also vanishes. In order to achieve dynamic braking the series field must be isolated and connected to a low voltage high current source to provide the field. Rather, the motor is made to work like a separately excited machine. When several machines are available at any spot, as in railway locomotives, dynamic braking is feasible. Series connection of all the series fields with parallel connection of all the armatures connected across a single dynamic braking resistor is used in that case.

- Compound generators

  In the case of compound machine, the situation is like in a shunt machine. A separately excited shunt field and the armature connected across the braking resistance are used. A cumulatively connected motor becomes differentially compounded generator and the braking torque generated comes down. It is therefore necessary to reverse the series field if large braking torques are desired.

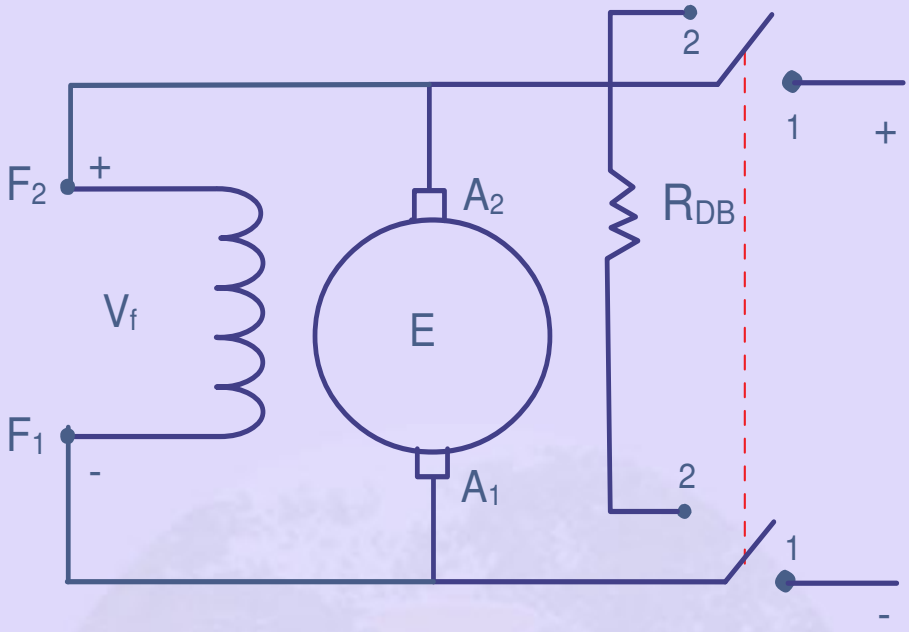


(a)Connections

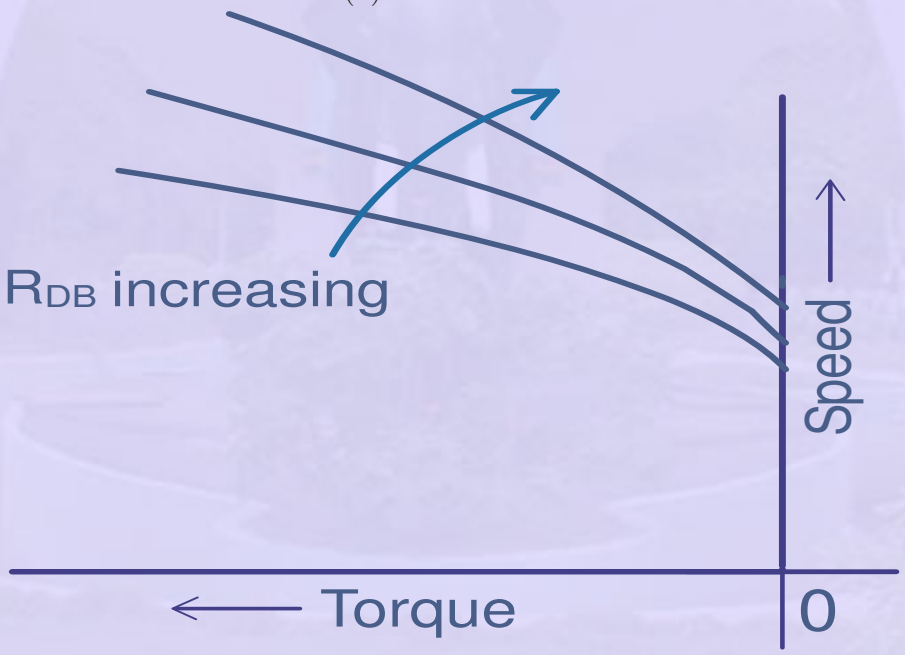


(b)Characteristics

Figure 49: Dynamic Braking of a shunt motor



(a)Connections



(b)Characteristics

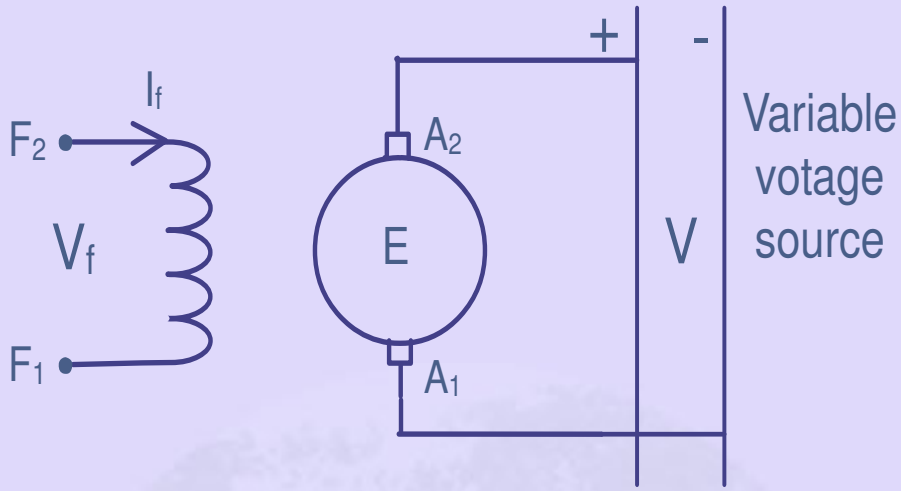
Figure 50: Dynamic braking of shunt excited shunt machine

8.3.2 Regenerative braking

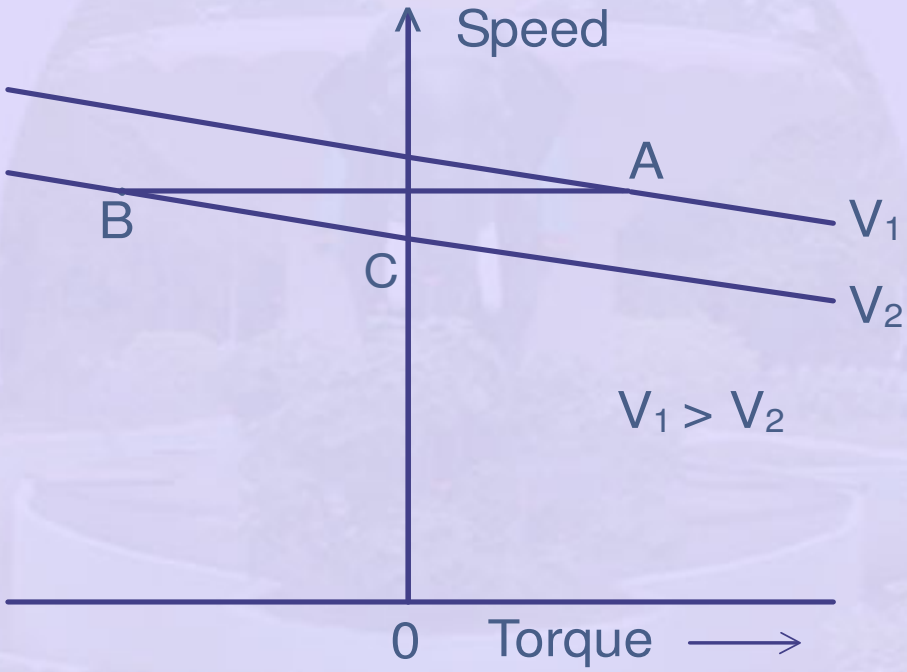
In regenerative braking as the name suggests the energy recovered from the rotating masses is fed back into the d.c. power source. Thus this type of braking improves the energy efficiency of the machine. The armature current can be made to reverse for a constant voltage operation by increase in speed/excitation only. Increase in speed does not result in braking and the increase in excitation is feasible only over a small range, which may be of the order of 10 to 15%. Hence the best method for obtaining the regenerative braking is to operate, the machine on a variable voltage supply. As the voltage is continuously pulled below the value of the induced emf the speed steadily comes down. The field current is held constant by means of separate excitation. The variable d.c. supply voltage can be obtained by Ward-Leonard arrangement, shown schematically in Fig. 51. Braking torque can be obtained right up to zero speed. In modern times static Ward-Leonard scheme is used for getting the variable d.c. voltage. This has many advantages over its rotating machine counter part. Static set is compact, has higher efficiency, requires lesser space, and silent in operation; however it suffers from drawbacks like large ripple at low voltage levels, unidirectional power flow and low over load capacity. Bidirectional power flow capacity is a must if regenerative braking is required. Series motors cannot be regeneratively braked as the characteristics do not extend to the second quadrant.

8.3.3 Plugging

The third method for braking is by plugging.Fig. 52 shows the method of connection for the plugging of a shunt motor. Initially the machine is connected to the supply with the switch S in position number 1. If now the switch is moved to position 2, then a reverse voltage is applied across the armature. The induced armature voltage E and supply voltage

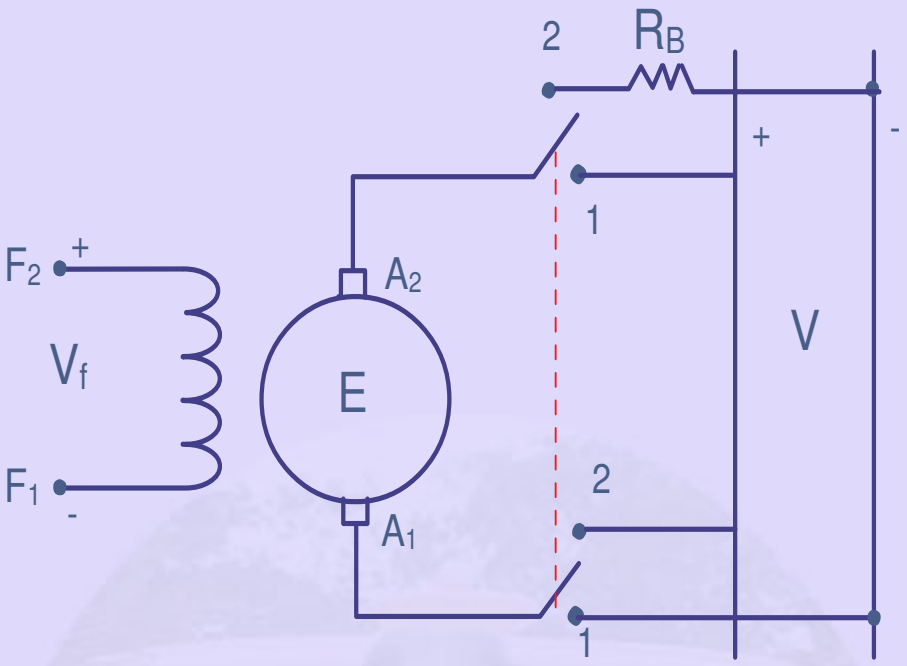


(a)Physical connection

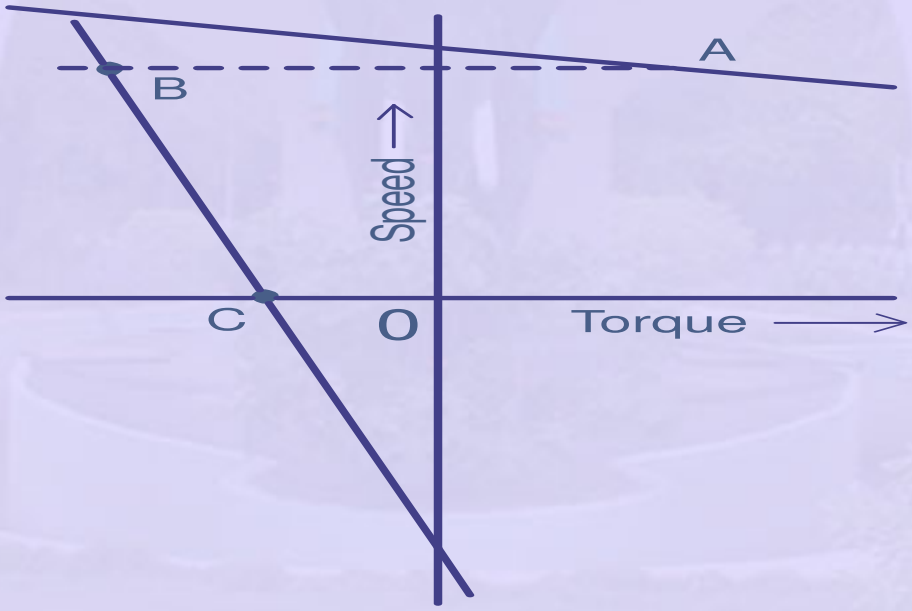


(b)Characteristics

Figure 51: Regenerative braking of a shunt machine



(a)Physical connection



(b)Characteristics

Figure 52: Plugging or reverse voltage braking of a shunt motor

V aid each other and a large reverse current flows through the armature. This produces a large negative torque or braking torque. Hence plugging is also termed as reverse voltage braking. The machine instantly comes to rest. If the motor is not switched off at this instant the direction of rotation reverses and the motor starts rotating the reverse direction. This type of braking therefore has two modes viz. 1) plug to reverse and 2) plug to stop. If we need the plugging only for bringing the speed to zero, then we have to open the switch S at zero speed. If nothing is done it is plug to reverse mode. Plugging is a convenient mode for quick reversal of direction of rotation in reversible drives. Just as in starting, during plugging also it is necessary to limit the current and thus the torque, to reduce the stress on the mechanical system and the commutator. This is done by adding additional resistance in series with the armature during plugging.

- Series motors

  In the case of series motors plugging cannot be employed as the field current too gets reversed when reverse voltage is applied across the machine. This keeps the direction of the torque produced unchanged. This fact is used with advantage, in operating a d.c. series motor on d.c. or a.c. supply. Series motors thus qualify to be called as 'Universal motors'.

- Compound motors

  Plugging of compound motors proceeds on similar lines as the shunt motors. However some precautions have to be observed due to the presence of series field winding. A cumulatively compounded motor becomes differentially compounded on plugging. The mmf due to the series field can 'over power' the shunt field forcing the flux to low values or even reverse the net field. This decreases the braking torque, and increases the duration of the large braking current. To avoid this it may be advisable to deactivate

the series field at the time of braking by short circuiting the same. In such cases the braking proceeds just as in a shunt motor. If plugging is done to operate the motor in the negative direction of rotation as well, then the series field has to be reversed and connected for getting the proper mmf. Unlike dynamic braking and regenerative braking where the motor is made to work as a generator during braking period, plugging makes the motor work on reverse motoring mode.

8.4 Application of d.c motors and generators

It is seen from the earlier sections that the d.c.machine is capable of having variety of torque-speed characteristics depending on the circuit conditions. The need for generating these characteristics will be clear only when they are seen along with the characteristics of the loads that they operate with. Even though a detailed treatment of motor load systems is outside the scope here, it may be useful to look into the typical torque-speed characteristics of some of the common loads.

Loads are broadly divided into,

(a) Passive loads

(b) Active loads

They may be unidirectional in operation or work in either direction (Reversible loads).

Passive loads absorb the mechanical energy developed by the motors while active loads are capable of working as both sinks and sources for mechanical energy. The direction of rotation may be taken to be clockwise/counter clockwise rotation. Normally the

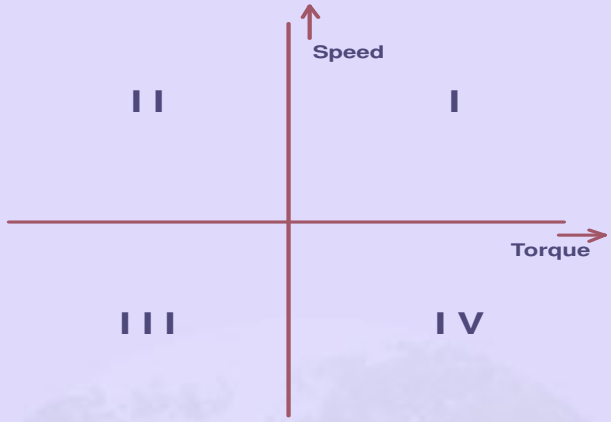
direction in which the load operates most of the time, is taken as the positive direction of rotation. Any torque which accelerates the motor load system in the positive direction of rotation is termed as a positive toque. With this rotation torques of motors, generators or loads can be represented graphically on a four quadrantal diagram. The torque being taken as an independent variable, is represented along the x-axis. Y-axis represents the speed. Quadrants. I and III in Fig. 53(a) represent 'forward motoring' and 'reverse motoring' operation respectively. Quadrants II and IV similarly represent generating/braking quadrants as they absorb mechanical power and cause braking action.

Fig. 53(b) shows a few typical load characteristics on a four quadrantal diagram.

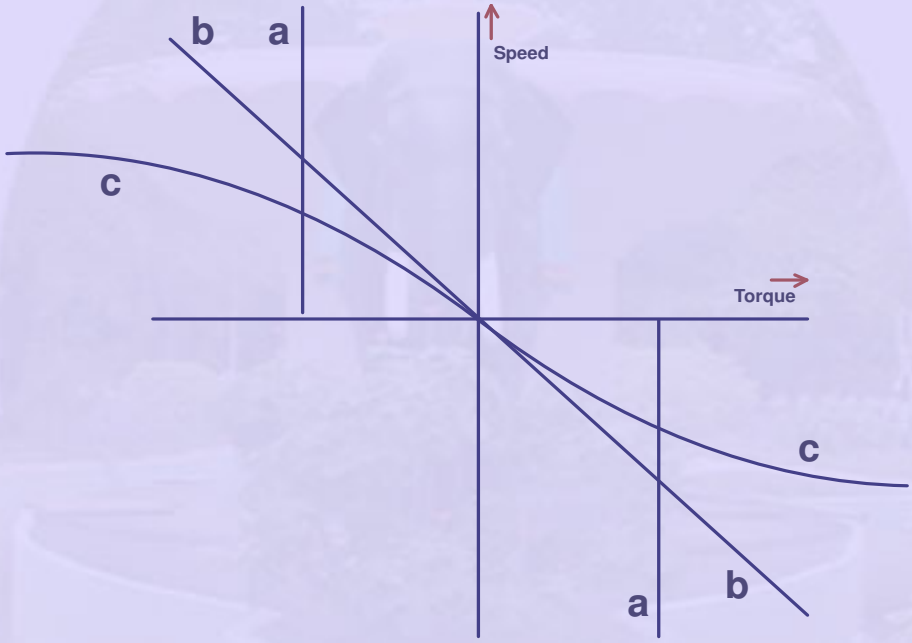
The characteristics a, b,and c correspond to frictional torque, cutting torque and fan torque respectively. While the frictional torque is not a function of speed, the cutting toque is proportional to the speed and the fan torque varies as the square of the speed. These can only absorb mechanical power and hence are represented in quadrantal II for positive direction of rotation. Similar loads produce characteristics in quadrant IV for negative direction of rotation.

Fig. 54 shows a typical behaviour of an active load. Here an elevator is taken as an example. Here the counter weight is assumed to be heavier than the cage and similarly the loaded cage in assumed to be heavier than the counter weight. As seen from the Fig. 54 the torque is constant and depends on the difference in the weight of the case and the counter weight, and the radius of the drum. The characteristics of the load exists in all the four quadrants and is capable of delivering as well as absorbing mechanical power. Hence it is called as an active load. The governing equation when the motor and a load are connected together is

$$T_M(w) - T_L(w) = J\frac{dw}{dt} \tag{52}$$



(a)



(b)

Figure 53: Typical load characteristics on a four quadrantal diagram

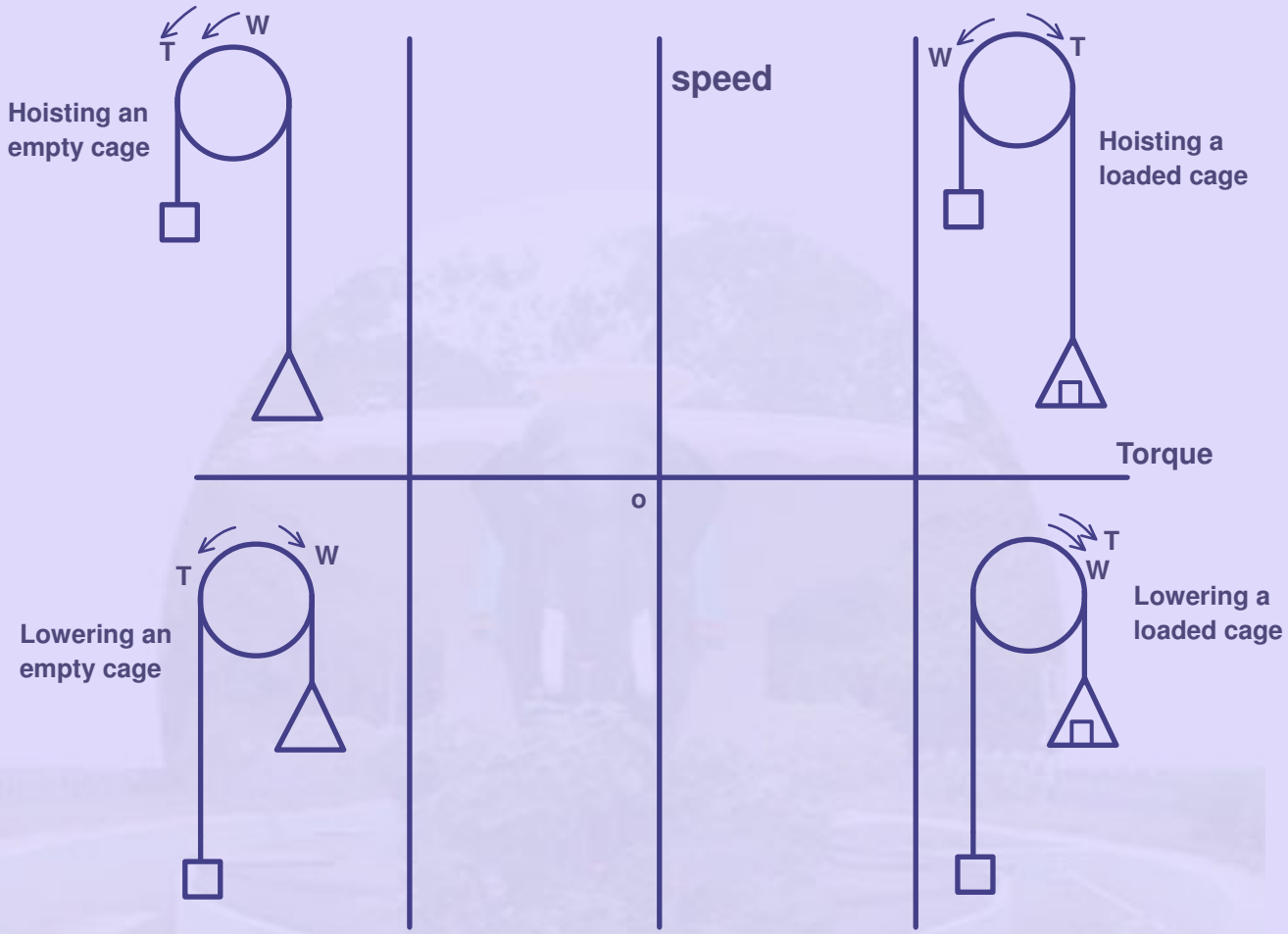


Figure 54: Four quadrantal diagram

where $T_M(w)$ and $T_M(w)$ are motor and load torques respectively. J is the polar moment of inertia of the motor and load put together at the motor shaft. $\frac{dw}{dt}$ is made positive when the speed has to be increased in the positive direction and negative when reducing the speed. Under steady operation $T_M(w) - T_L(W) = 0$. Both motor and load torques are expressed as functions of the speed. The speed at which motor and load torques are equal and opposite is the steady state operating speed. By varying the characteristics of the motor (or the load), this speed can be changed to suit our requirements. Normally the torque speed characteristics of a load cannot be changed easily. Thus most speed control methods adopt, varying the motor characteristics to achieve speed control. Some typical loads and the motors commonly used to drive the same are tabulated in Table.

d.c. shunt motor	lathes,fans,pumps disc and band saw drive requiring moderate torques.
d.c. series motor	Electric traction, high speed tools
d.c. compound motor	Rolling mills and other loads requiring large momentary toques.