UNIT II. ELECTRIC TRACTION

*Obje***ctive:**

The aim of this chapter is to gain knowledge on

- Requirements of an ideal traction system
- Supply systems
- Mechanics oftrain movement – tractive effort
- Specific energy consumption – traction motors andcontrol
- Braking methods - current collection systems
- Recent trends inelectric traction.

INTRODUCTION

By electric traction is meant locomotion in which the driving (or tractive) force is obtained from electric motors. It is used in electric trains, tramcars, trolley buses and diesel-electric vehiclesetc. Electric traction has many advantages as compared to other non-electrical systems of traction includ-ing steam traction.

Traction Systems

a) non-electric traction systems

They do not involve the use of electrical energy at any stage. Examples are : steam engine drive used in railways and internal-combustion-engine drive used for road transport.

(b) electric traction systems

They involve the use of electric energy at some stage or the other.
They may be further subdivided into two groups :

1.First group consists of self-contained vehicles or locomotives. Examples are : battery-elec-tric drive and diesel-electric drive etc.

2. Second group consists of vehicles which receive electric power from a distribution network fed at suitable points from either central power stations or suitably-spaced sub-stations. Examples are : railway electric locomotive fed from overhead ac supply and tramways and trolly buses supplied with dc supply.

Advantages of Electric Traction

1. Cleanliness. Since it does not produce any smoke or corrosive fumes, electric traction is most suited for underground and tube railways. Also, it causes no damage to the buildings and other apparatus due to the absence of smoke and flue gases.

2. Maintenance Cost. The maintenance cost of an electric locomotive is nearly 50% of that for a steam locomotive. Moreover, the maintenance time is also much less.

3. Starting Time. An electric locomotive can be started at a moment's notice whereas a steam locomotive requires about two hours to heat up.

4. High Starting Torque. The motors used in electric traction have a very high starting torque. Hence, it is possible to achieve higher accelerations of 1.5 to 2.5 km/h/s as against 0.6 to 0.8 km/h/s in steam traction. As a result, we are able to get the following additional advantages:

(i) high schedule speed

(ii) increased traffic handling capacity

(iii) because of (i) and (ii) above, less terminal space is required—a factor of great importance in urban areas.

5.Braking. It is possible to use regenerative braking in electric traction system. It leads to thefollowing advantages :

(i) about 80% of the energy taken from the supply during ascent is returned to it during descent.

(ii) goods traffic on gradients becomes safer and speedier.

(iii) since mechanical brakes are used to a very small extent, maintenance of brake shoes, wheels, tyres and track rails is considerably reduced because of less wear and tear.

6. Saving in High Grade Coal. Steam locomotives use costly high-grade coal which is not so abundant. But electric locomotives can be fed either from hydroelectric stations or pit-head thermal power stations which use cheap low-grade coal. In this way, high-grade coal can be save for metal-lurgical purposes.

7. Lower Centre of Gravity. Since height of an electric locomotive is much less than that of a steam locomotive, its centre of gravity is comparatively low. This fact enables an electric locomotive to negotiate curves at higher speeds quite safely.

8. Absence of Unbalanced Forces. Electric traction has higher coefficient of adhesion since there are no unbalanced forces produced by reciprocating masses as is the case in steam traction. It not only reduces the weight/kW ratio of an electric locomotive but also improves its riding quality in addition to reducing the wear and tear of the track rails.

Disadvantages of Electric Traction

1. The most vital factor against electric traction is the initial high cost of laying out overhead electric supply system. Unless the traffic to be handled is heavy, electric traction becomes uneco-nomical.

2. Power failure for few minutes can cause traffic dislocation for hours.

3. Communication lines which usually run parallel to the power supply lines suffer from elec-trical interference. Hence, these communication lines have either to be removed away from the rail track or else underground cables have to be used for the purpose which makes the entire system still more expensive.

4.Electric traction can be used only on those routes which have been electrified. Obviously,this restriction does not apply to steam traction.

5.Provision of a negative booster is essential in the case of electric traction. By avoiding the flow of return currents through earth, it curtails corrosion of underground pipe work and interference with telegraph and telephone circuits.

Systems of Railway Electrification

- Direct current system
- Single-phase ac system
- Three-phase ac system
- Composite system

Direct Current System

Direct current at 600-750 V is universally employed for tramways in urban areas and for many suburban railways while 1500-3000 V dc is used for main line railways. The current collection is from third rail (or conductor rail) up to 750 V, where large currents are involved and from overhead wire for 1500 V and 3000 V, where small currents are involved. Since in majority of cases, track (or running) rails are used as the return conductor, only one conductor rail is required. Both of these contact systems are fed from substations which are spaced 3 to 5 km for heavy suburban traffic and 40-50 km for main lines operating at higher voltages of 1500 V to 3000 V. These sub-stations themselves receive power from 110/132 kV, 3-phase network (or grid). At these substations, this high-voltage 3-phase supply is converted into low-voltage 1-phase supply with the help of Scott-connected or V-connected 3-phase transformers (Art. 31.9). Next,this low ac voltage is converted into the required dc voltage by using suitable rectifiers or converters (like rotary converter, mercury-arc, metal or semiconductor rectifiers). These substations are usually automatic and are remote-controlled.

The dc supply so obtained is fed via suitable contact system to the traction motors which are either dc series motors for electric locomotive or compound motors for tramway and trolley buses where regenerative braking is desired.

It may be noted that for heavy suburban service, low voltage dc system is undoubtedly superior to 1-phase ac system due to the following reasons :

1.dc motors are better suited for frequent and rapid acceleration of heavy trains than ac mo-tors.

2.dc train equipment is lighter, less costly and more efficient than similar ac equipment.

3.when operating under similar service conditions, dc train consumes less energy than a1-phase ac train.

4. the conductor rail for dc distribution system is less costly, both initially and in maintenance than the high-voltage overhead ac distribution system.

5. dc system causes no electrical interference with overhead communication lines.

The only disadvantage of dc system is the necessity of locating ac/dc conversion sub-stations at relatively short distances apart.

Single-Phase Low-frequency AC System

In this system, ac voltages from 11 to 15 kV at16^{23}or 25 Hz are used. If supply is from agenerating station exclusively meant for the traction system, there is no difficulty in getting the elec-tric supply of16^{23}or 25 Hz. If, however, electric supply is taken from the high voltage transmissionlines at 50 Hz, then in addition to step-down transformer, the substation is provided with a frequency converter. The frequency converter equipment consists of a 3-phase synchronous motor which drivesa I-phase alternator having or 25 Hz frequency.The 15 kV16^{23}or 25 Hz supply is fed to the electric locomotor via a single over-head wire(running rail providing the return path).

A step-down transformer carried by the locomotive reduces the 15-kV voltage to 300-400 V for feeding the ac series motors. Speed regulation of ac series motors is achieved by applying variable voltage from the tapped secondary of the above transformer. Low-frequency ac supply is used because apart from improving the commutation properties of ac motors, it increases their efficiency and power factor. Moreover, at low frequency, line reactance is less so that line impedance drop and hence line voltage drop is reduced. Because of this reduced line drop, it is feasible to space the substations 50 to 80 km apart. Another advantage of employing low frequency is that it reduces telephonic interference.

Three-phase Low-frequency AC System

It uses 3-phase induction motors which work on a 3.3 kV,16^{23}Hz supply. Sub-stations receivepower at a very high voltage from 3-phase transmission lines at the usual industrial frequency of50 Hz. This high voltage is stepped down to 3.3 kV by transformers whereas frequency is reducedfrom 50 Hz to 16^{23} Hz by frequency converters installed at the sub-stations. Obviously, this systememploys two overhead contact wires, the track rail forming the third phase (of course, this leads toinsulation difficulties at the junctions).

Induction motors used in the system are quite simple and robust and give trouble-free operation. They possess the merits of high efficiency and of operating as a generator when driven at speeds above the synchronous speed. Hence, they have the property of automatic regenerative braking during the descent on gradients. However, it may be noted that despite all its advantages, this system has not found much favour and has, in fact, become obsolete because of its certain inherent limita-tions given below :

1. the overhead contact wire system becomes complicated at crossings and junctions.

2. constant-speed characteristics of induction motors are not suitable for traction work.

3. induction motors have speed/torque characteristics similar to dc shunt motors.

Hence, theyare not suitable for parallel operation because, even with little difference in rotationalspeeds caused by unequal diameters of the wheels, motors will becomes loaded very unevenly.

Composite System

Such a system incorporates good points of two systems while ignoring their bad points. Two such composite systems presently in use are :

1. 1-phase to 3-phase system also called Kando system

2. 1-phase to dc system.

Kando System

In this system, single-phase 16-kV, 50 Hz supply from the sub-station is picked up by the locomotive through the single overhead contact wire. It is then converted into 3-phase ac supply at the same frequency by means of phase converter equipment carried on the locomotives. This 3-phase supply is then fed to the 3-phase induction motors.As seen, the complicated overhead two contact wire arrangement of ordinary 3-phase system is replaced by a single wire system. By using silicon controlled rectifier as inverter, it is possible to get variable-frequency 3-phase supply at 1/2 to 9 Hz frequency. At this low frequency, 3-phase motors develop high starting torque without taking excessive current. In view of the above, Kando system is likely to be developed further.

Single-phase AC to DC System

This system combines the advantages of high-voltage ac distribution at industrial frequency with the dc series motors traction. It employs overhead 25-kV, 50-Hz supply which is stepped down by the transformer installed in the locomotive itself. The low-voltage ac supply is then converted into dc supply by the rectifier which is also carried on the locomotive. This dc supply is finally fed to dc series traction motor fitted between the wheels. The system of traction employing 25-kV, 50-Hz, 1-phase ac supply has been adopted for all future track electrification in India.

Types of Railway Services

There are three types of passenger services offered by the railways :

1. **City or Urban Service.** In this case, there are frequent stops, the distance between stopsbeing nearly 1 km or less. Hence, high acceleration and retardation are essential to achieve moderately high schedule speed between the stations.

2. **Suburban Service.** In this case, the distance between stops averages from 3 to 5 km over a distance of 25 to 30 km from the city terminus. Here, also, high rates of acceleration and retardation are necessary.

3. **Main Line Service.** It involves operation over long routes where stops are infrequent. Here, operating speed is high and accelerating and braking periods are relatively unimportant.

On goods traffic side also, there are three types of services (i) main-line freight service (ii) local or pick-up freight service and (iii) shunting service.

Train Movement

The movement of trains and their energy consumption can be conveniently studied by means of speed/time and speed/distance curves. As their names indicate, former gives speed of the train at various times after the start of the run and the later gives speed at various distances from the starting point. Out of the two, speed/time curve is more important because

1. its slope gives acceleration or retardation as the case may be.

2. area between it and the horizontal (i.e. time) axis represents the distance travelled.

3. energy required for propulsion can be calculated if resistance to the motion of train is known.

Typical Speed/Time Curve

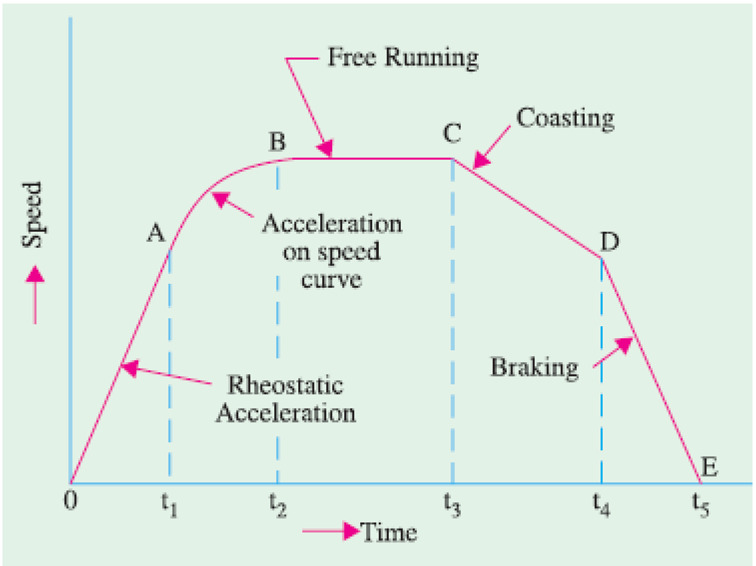

Fig. 43.8

1. Constant Acceleration Period (0 to t_1)

It is also called notching-up or starting period because during this period, starting resistance of the motors is gradually cut out so that the motor current (and hence, tractive effort) ismaintained nearly constant which produces constant acceleration alternatively called ‘rheostatic acceleration’ or ‘acceleration while notching.

2.Acceleration on Speed Curve(t_1 to t_2)

This acceleration commences after the starting resistance has been all cut-out at point t_1 and full supply voltagehas been applied to the motors. During this period, the motor current and torque de-crease as train speed increases. Hence, acceleration gradually decreases till torque developed by motors exactly bal-ances that due to resistance to the train motion. The shape of the portion AB of the speed/time curve depends primarily on the torque/speed characteristics of the traction motors.

3.Free-running Period (t_2 to t_3)

The train continues to run at the speed reached at point t_2. It is represented by portion BC in Fig. 43.8 and is a constant-speed period which occurs on level tracks.

4.Coasting (t_3 to t_4)

Power to the motors is cut off at point t_3 so that the train runs under its momentum,thespeed gradually falling due to friction, windage etc. (portion CD). During this period, retardation remains practically constant. Coasting is desirable because it utilizes some of the kinetic energy ofthetrain which would, otherwise, be wasted during braking. Hence, it helps to reduce the energy consumption of the train.

5.Braking (t_4 to t_5)

At point t_4, brakes are applied and the train is brought to rest at point t_5. It may be noted that coasting and braking are governed by train resistance and allowable retardation respectively.

Speed/Time Curves for Different Service

Fig. 43.9 (a) is representative of city service where relative values of acceleration and retarda-tion are high in order to achieve moderately high average speed between stops. Due to shortdistances between stops, there is no possibility of free-running period though a short coasting period is included to save on energy consumption.

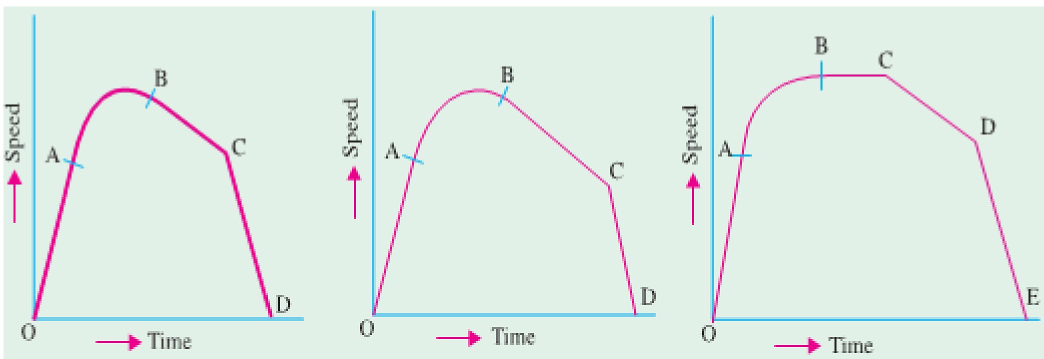

Fig. 43.9

In suburban services [Fig. 43.9 (b)], again there is no free-running period but there is compara-tively longer coasting period because of longer distances between stops. In this case also, relatively high values of acceleration and retardation are required in order to make the service as attractiveas possible. For main-line service [Fig. 43.9 (c)], there are long periods of free-running at high speeds. The accelerating and retardation periods are relatively unimportant.

Systems of Railway Electrification

Presently, following four types of track electrification systems are available :

1.Direct current system

2.Single-phase ac system

3.Three-phase ac system

4.Composite system—involving conversion of single-phase ac into 3-phase ac or dc

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Quantities Involved in Traction Mechanics

Following principal quantities are involved in train movement

D = distance between stops
M_e = effective mass of the train

We = effective weight of the train
β_c = retardation during coasting

Va = average speed
t = total time for the run

t_2 = time of free running = $t - (t_1 + t_3)$ F_t = tractive effort

M=deadmassofthetrain
W = dead weight of the train

α = accelaration during starting period β = retardation during braking

V_m = maximum (or crest) speed.

t_1 = time of acceleration t_3 = time of braking

T = torque

Relationship Between Principal Quantities in Trapezoidal Diagram

$\alpha = V_m / t_1$ or $t_1 = V_m / \alpha$

$\beta = V_m / t_3$ or $t_3 = V_m / \beta$

As we know, total distance D between the two stops is given by the area of trapezium OABC.

□D = area OABC

= area OAD + area ABED + area BCE

$$= \frac{1}{2} V_m t_1 + V_m t_2 + \frac{1}{2} V_m t_3$$

$$= \frac{1}{2} V_m t_1 + V_m [t - (t_1 + t_3)] + \frac{1}{2} V_m t_3$$

$$= V_m \left[\frac{t_1}{2} + t - t_1 - t_3 + \frac{t_3}{2} \right]$$

$$= V_m \left[t - \frac{1}{2}(t_1 + t_3) \right]$$

$$= V_m \left[t - \frac{V_m}{2} \left(\frac{1}{\alpha} + \frac{1}{\beta} \right) \right]$$

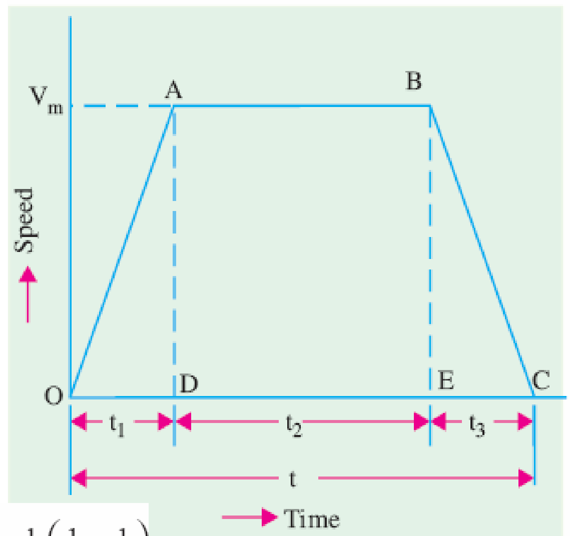


Fig. 43.11

Let, $K = \frac{1}{2} \left(\frac{1}{\alpha} + \frac{1}{\beta} \right)$

$D = V_m (t - KV_m)$

or $KV^{2} - V_m t + D = 0$

$$\therefore \quad V_m = \frac{t \pm \sqrt{t^2 - 4KD}}{2K}$$

Rejecting the positive sign which gives impracticable value, we get

$$V_m = \frac{t \pm \sqrt{t^2 - 4KD}}{2K}$$

From Eq. (*i*) above, we get

$$KV_m^2 = V_m t - D \quad \text{or} \quad K = \frac{t}{V_m} - \frac{D}{V_m^2} = \frac{D}{V_m^2} \left(V_m \cdot \frac{t}{D} - 1 \right)$$

Now, $V_a = \frac{D}{t}$ $\quad \therefore \quad K = \frac{D}{V_m^2} \left(\frac{V_m}{V_a} - 1 \right)$

Obviously, if V_m, V_a and D are given, then value of K and hence of α and β can be found.

Relationship Between Principal Quantities in Quadrilateral Diagram

Let β_c represent the retardation during coasting period. As before,

$$t_1 = V_1/\alpha,\ t_2 = (V_2 - V_1)/\beta_c \text{ and } t_3 = V_2/\beta$$

$$\begin{aligned}
D &= \text{area } OABC \\
&= \text{area } OAD + \text{area } ABED + \text{area } BCE \\
&= \frac{1}{2}V_1 t_1 + t_2\left(\frac{V_1 + V_2}{2}\right) + \frac{1}{2}V_2 t_3 \\
&= \frac{1}{2}V_1(t_1 + t_2) + \frac{1}{2}V_2(t_2 + t_3) \\
&= \frac{1}{2}V_1(t - t_3) + \frac{1}{2}V_2(t - t_1) \\
&= \frac{1}{2}t(V_1 + V_2) - \frac{V_1 t_1}{2} - \frac{V_1 t_3}{2} \\
&= \frac{1}{2}t(V_1 + V_2) - \frac{1}{2}V_1 V_2\left(\frac{1}{\alpha} + \frac{1}{\beta}\right) \\
&= \frac{1}{2}t(V_1 + V_2) - KV_1 V_2
\end{aligned}$$

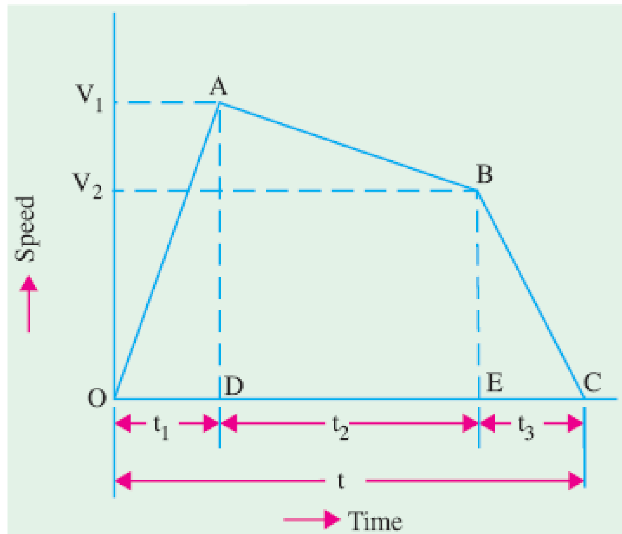


Fig. 43.12

where $K = \frac{1}{2}\left(\frac{1}{\alpha} + \frac{1}{\beta}\right) = \frac{\alpha + \beta}{2\alpha\beta}$ Also, $\beta_c = \frac{(V_1 - V_2)}{t_2}$

$$\therefore\quad V_2 = V_1 - \beta_c t_2 = V_1 - \beta_c(t - t_1 - t_3)$$

$$= V_1 - \beta_c\left(t - \frac{V_1}{\alpha} - \frac{V_2}{\beta}\right) = V_1 \beta_c\left(t - \frac{V_1}{\alpha}\right) + \beta_c \frac{V_2}{\beta}$$

or $V_2\left(1 - \frac{\beta_c}{\beta}\right) = V_1 - \beta_c\left(t - \frac{V_1}{\alpha}\right)$ $\therefore\ V_2 = \frac{V_1 - \beta_c(t - V_1/\alpha)}{(1 - \beta_c/\beta)}$

Tractive Effort for Propulsion of a Train

The tractive effort (F_t) is the force developed by the traction unit at the rim of the driving wheels for moving the unit itself and its train (trailing load). The tractive effort required for train propulsion on a level track is

$$Ft = F_a + F_r$$

If gradients are involved, the above expression becomes

$$Ft = F_a + F_g + F_r \text{ — for ascending gradient}$$

$$= F_a - F_g + F_r \text{ — for descending gradient}$$

where F_a = force required for giving linear acceleration to the train

F_g= force required to overcome the effect of gravity

F_r= force required to overcome resistance to train motion.

(a) Value of F_a

If M is the dead (or stationary) mass of the train and a its linear acceleration, then

$$F_a = Ma$$

Since a train has rotating parts like wheels, axles, motor armatures and gearing etc., its effective (or accelerating) mass M_e is more (about 8 – 15%) than its stationary mass. These parts have to be given angular acceleration at the same time as the whole train is acceleratedinthelineardirection.

Hence, $F_e = M_e a$

(i) If M_e is in kg and α in m/s^2, then $F_a = M_e$ a newton

(ii) If M_e is in tonne and α in km/h/s, then converting them into absolute units, we have

$$F_a = (1000\ M_e) \times (1000/3600)\ a = 277.8\ M_e \text{ a newton}$$

(b) Value of F_g

As seen from Fig. 43.13, $F_g = W \sin\theta = Mg \sin\theta$

In railway practice, gradient is expressed as the rise (in metres) a track distance of 100 m and is called percentage gradient.

$$\therefore \quad \%\,G = \frac{BC}{AC/100} = 100\frac{BC}{AC} = 100 \sin\theta$$

Substituting the value of sin θ in the above equation, we get

$$F_g = Mg\,G/100 = 9.8 \times 10^{-2}\,MG$$

(*i*) When *M* is in kg, $F_g = 9.8 \times 10^{-2}\,MG$ newton

(*ii*) When *M* is given in tonne, then

$$F_g = 9.8 \times 10^{-2}\,(1000\,M)\,G = 98\,MG \text{ newton}$$

(c) Value of F_r

Train resistance comprises all those forces which oppose its motion. It consists of mechanical resistance and wind resistance. Mechanical resistance itself is made up of internal and external resistances. The internal resistance comprises friction at journals, axles, guides and buffers etc. The external resistance consists of friction between wheels and rails and flange friction etc. Mechanical resistance is almost independent of train speed but depends on its weight. The wind friction varies directly as the square of the train speed.

If r is specific resistance of the train i.e. resistance offered per unit mass of the train, then

$$F_r = M.r.$$

(i) If r is in newton per kg of train mass and M is the train mass in kg, then

F_r= M.r newton

(ii) If r is in newton per tonne train mass (N/t) and M is in tonne (t), then

F_r= M tonne × r = M_r newton*

Hence, expression for total tractive effort becomes

$$F_t = F_a \pm F_g + F_r = (277.8\ \alpha\ M_e \pm 98\ MG + Mr)\ \text{newton}$$

Please remember that here M is in tonne, α in km/h/s, G is in metres per 100 m of track length (i.e. % G) and r is in newton/tonne (N/t) of train mass. The positive sign for F_g is taken when motion is along an ascending gradient and negative sign when motion is along a descending gradient.

Power Output from Driving Axles

If F_t is the tractive effort and v is the train velocity, then

output power = F_t × v

(i) If F_t is in newton and v in m/s, then

output power= F_t × v watt

(ii) If F_t is in newton and v is in km/h , then converting v into m/s, we have

$$\text{output power} = F_t \times \left(\frac{1000}{3600}\right) v \text{ watt} = \frac{F_t\, v}{3600} \text{ kW}$$

If η is the efficiency of transmission gear, then power output of motors is

$$= F_t \,.\, v/\eta \text{ watt} \qquad \text{— v in m/s}$$

$$= \frac{F_t\, v}{3600\, \eta} \text{ kW} \qquad \text{— v in km/h}$$

Energy Output from Driving Axles

Energy (like work) is given by the product of power and time.

E = (F_t × v) × t = F_t × (v × t) = F_t × D

As seen from Fig. 43.11

$$E = F_t \times \text{area } OAD + F_t' \times \text{area } ABED = F_t \times \frac{1}{2}\, V_m t_1 + F_t' \times \frac{1}{2}\, V_m t_2$$

where D is the distance travelled in the direction of tractive effort.

Total energy output from driving axles for the run is

E =energy during acceleration + energy during free run

where F_t is the tractive effort during accelerating period and F_t' that during free-running period. Incidentally, F_t will consist of all the three components given in Art. 43.37 whereas F_t' will consist of (98 MG + Mr) provided there is an ascending gradient.

Evaluation of Specific Energy Output

We will first calculate the total energy output of the driving axles and then divide it by train mass in tonne and route length in km to find the specific energy output. It will be presumed that :

(i) there is a gradient of G throughout the run and

(ii) power remains ON upto the end of free run in the case of trapezoidal curve (Fig. 43.11) and upto the accelerating period in the case of quadrilateral curve (Fig. 43.12).

Now, output of the driving axles is used for the following purposes :

1. for accelerating the train

2. for overcoming the gradient

3. for overcoming train resistance.

(i) Energy output during accelerating period

Ea = F_t × distance travelled during accelerating period

= F_t × area OAD

$$= F_t \times \frac{1}{2} V_m t_1 = \frac{1}{2} F_t . V_m . \frac{V_m}{\alpha}$$

$$= \frac{1}{2} . F_t \left(\frac{1000}{3600} . V_m \right) . \frac{V_m}{\alpha} \text{ joules}$$

$$= \frac{1}{2} . F_t \left(\frac{1000}{3600} . V_m \right) . \frac{V_m}{\alpha} . \frac{1}{3600} \text{ Wh}$$

Substituting the value of F_t , we get

$$E_a = \frac{1000}{(3600)^2} . \frac{V_m^2}{2\alpha} (277.8 \alpha M_e + 98 MG + Mr) \text{ Wh}$$

(ii) Energy output during free-running period

Here, work is required only against two forces i.e. gravity and resistance (as mentioned earlier)

Energy $E_{fr} = F_t' \times$ area ABED

$$= F_t' \times (V_m \times t_2) = F_t' \times \left(\frac{1000}{3600} V_m \right) . t_2 \text{ joules}$$

$$= F_t' \times \left(\frac{1000}{3600} V_m \right) \times t_2 \times \frac{1}{3600} \text{ Wh} = \left(\frac{1000}{3600} \right) F_t' \times V_m t_2 . \frac{1}{3600} \text{ Wh}$$

$$= \left(\frac{1000}{3600} \right) . F_t' \times D_{fr} \text{ Wh} = \left(\frac{1000}{3600} \right) (98 MG + Mr) D_{fr} \text{ Wh}$$

where D_{fr} is the distance in km travelled during the free-running period
Total energy required is the sum of the above two energies

$$\therefore E = E_a + E_{fr}$$

$$= \frac{1000}{(3600)^2}\frac{V_m^2}{2\,\alpha}(277.8\,\alpha\,.\,M_e + 98\,MG + Mr) + \frac{1000}{3600}(98\,MG + Mr)\,D_{fr}\ \text{Wh}$$

$$= \frac{1000}{(3600)^2}\frac{V_m^2}{2\,\alpha}\,277.8\,\alpha\,M_e + \frac{1000}{(3600)^2}\cdot\frac{V_m^2}{2\,\alpha}(98\,MG + Mr) + \frac{1000}{3600}(98\,MG + Mr)\,.\,D_{fr}\ \text{Wh}$$

$$= 0.01072\,V_m^2\,.\,M_e + \frac{1000}{3600}(98\,MG + Mr)\left(\frac{V_m^2}{2\alpha \times 3600} + D_{fr}\right)\text{Wh}$$

Now, $$\frac{V_m^2}{2\alpha \times 3600} = \frac{1}{2}\left(\frac{V_m}{3600}\right)\cdot\frac{V_m}{\alpha} = \frac{1}{2}\left(\frac{V_m}{3600}\right)\cdot t_1$$

= distance travelled during accelerating period *i.e.* D_a

$$\therefore \quad E = 0.01072\,V_m^2\,.\,M_e + \frac{1000}{3600}(98\,MG + Mr)\,(D_a + D_{fr})\ \text{Wh}$$

$$= 0.01072\,V_m^2\,.\,M_e + (27.25\,MG + 0.2778\,Mr)\,D'\ \text{Wh}$$

Energy Consumption

It equals the total energy input to the traction motors from the supply. It is usually expressed in Wh which equals 3600J. It can be found by dividing the energy output of the driving wheels with the combined efficiency of transmission gear and motor

$$\therefore \quad \text{energy consumption} = \frac{\text{output of driving axles}}{\eta_{motor} \times \eta_{gear}}$$

Specific Energy Consumption

It is the energy consumed (in Wh) per tonne mass of the train per km length of the run,

$$E_{spc} = \frac{\text{total energy consumed in Wh}}{\text{train mass in tonne} \times \text{run length in km}} = \frac{\text{specific energy output}}{\eta}$$

where η = overall efficiency of transmission gear and motor = $\eta_{gear} \times \eta_{motor}$

As seen from Art. 43.41, specific energy consumption is

$$E_{spc} = \left(0.01072\,.\,\frac{V_{m^2}}{\eta D}\,.\,\frac{M_e}{M} + 27.25\,\frac{G}{\eta}\,.\,\frac{D'}{D} + 0.2778\,\frac{r}{\eta}\,.\,\frac{D'}{D}\right)\text{Wh/t-km}$$

If no gradient is involved, then specific enrgy consumption is

$$E_{spc} = \left(0.01072\,.\,\frac{V_{m^2}}{\eta D}\,.\,\frac{M_e}{M} + 0.2778\,\frac{r}{\eta}\,.\,\frac{D'}{D}\right)\text{Wh/t-km}$$

The specific energy consumption of a train running at a given schedule speed is influenced by

1.Distance between stops 2. Acceleration 3. Retardation 4. Maximum speed

5. Type f train and equipment 6. Track configuration.

Adhesive Weight

It is given by the total weight carried on the driving wheels. Its value is W_a = x W, where W is dead weight and x is a fraction varying from 0.6 to 0.8.

Coefficient of Adhesion

Adhesion between two bodies is due to interlocking of the irregularities of their surfaces in contact. The adhesive weight of a train is equal to the total weight to be carried on the driving.wheels. It is less than the dead weight by about 20 to 40%.

If $x = \dfrac{\text{adhesive weight, } W_a}{\text{dead weight } W}$, then, $W_a = x\,W$

Let, F_t = tractive effort to slip the wheels

or

= maximum tractive effort possible without wheel slip

Coefficient of adhesion, $\mu_a = F_t / W_a$

$\therefore \quad F_t = \mu_a W_a = \mu_a x W = \mu_a x Mg$

If M is in tonne, then

$$F_t = 1000 \times 9.8\, x\, \mu_a M = 9800\, \mu_a\, x\, M \text{ newton}$$

It has been found that tractive effort can be increased by increasing the motor torque but only upto a certain point. Beyond this point, any increase in motor torque does not increase the tractive effort but merely causes the driving wheels to slip. It is seen from the above relation that for increasing F_t, it is not enough to increase the kW rating of the traction motors alone but the weight on the driving wheels has also to be increased. Adhesion also plays an important role in braking. If braking effort exceeds the adhesive weight of the vehicle, skidding takes place.

Mechanism of Train Movement

The essentials of driving mechanism in an electric vehicle are illustrated in Fig. 43.14. The armature of the driving motor has a pinion which meshes with the gear wheel keyed to the axle of the driving wheel. In this way, motor torque is transferred to the wheel through the gear.

Let,T = torque exerted by the motor

F_1= tractive effort at the pinion

Ft= tractive effort at the wheel

γ= gear ratio

Here,d_1, d_2= diameters of the pinion and gear wheel respectively

D = diameter of the driving wheel

η = efficiency of power transmission from the motor to driving axle

Now, $T = F_1 \times d_1/2$ or $F_1 = 2T/d_1$

Tractive effort transferred to the driving wheel is

$$F_t = \eta F_1\left(\frac{d_2}{D}\right) = \eta \cdot \frac{2T}{d_1}\left(\frac{d_2}{D}\right) = \eta T\left(\frac{2}{D}\right)\left(\frac{d_2}{d_1}\right) = 2\,\gamma\eta\frac{T}{D}$$

For obtaining motion of the train without slipping, $F_t \le \mu_a W_a$ where μ_a is the coefficient of adhesion (Art. 43.45) and W_a is the adhesive weight.

Control of D.C. Motors

The starting current of motor is limited to its normal rated current by starter during starting. At the instant of switching on the motor, back e.m.f. $E_b = 0$

□ Supply voltage = V = IR + Voltage drop across The starting current of motor is limited to its normal rated current by starter during starting. At the instant of switching on the motor, back e.m.f. $E_b = 0$

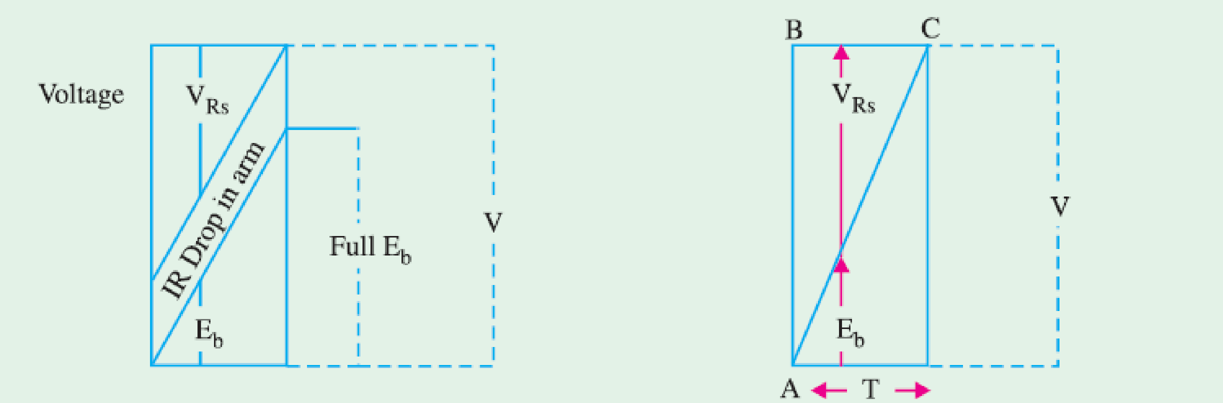
□ Supply voltage = V = IR + Voltage drop across R_s

At any other instant during starting

$V = IR + \text{Voltage across } R_s + E_b$

At the end of accelerating period, whentotal R_s is cut-off

$V = E_b + IR$



(*a*) Voltage during starting of D.C. motor (*b*) Voltage during starting neglecting IR drop

Fig. 43.28

If T is the time in sec. for starting and neglecting IR drop, total energy supplied = V.I.T. watt-sec From Fig. 43.28 (b) Energy wasted in R_s = Area of triangle ABC × I = ½. T.V.I. watt -sec. = ½ VIT watt - sec.

But total energy supplied = V.I.T watt - sec.

□ Half the energy is wasted in starting

□ $\eta_{starting} = 50\%$

Series - Parallel Starting

With a 2 motor equipment ½ the normal voltage will be applied to each motor at starting as shown in Fig. 43.29 (a) (Series connection) and they will run upto approximate ½ speed, at which instant they are switched on to parallel and full voltage is applied to each motor. R_s is gradually cutout, with motors in series connection and then reinserted when the motors are connected in parallel, and again gradually cut-out.

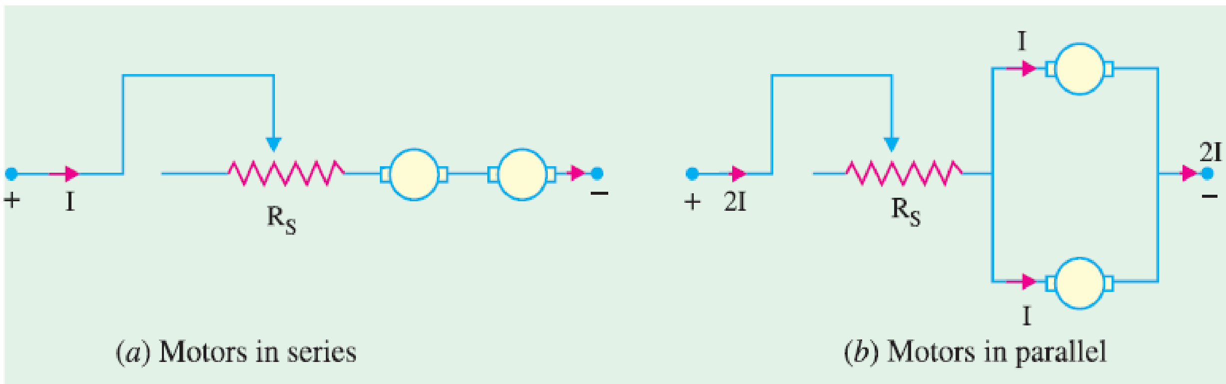


Fig. 43.29

In traction work, 2 or more similar motors are employed. Consider 2 series motors started by series parallel method, which results in saving of energy.

(a) **Series operation.** The 2 motors, are started in series with the help of R_s. The current during starting is limited to normal rated current 'I' per motor. During series operation, current 'I' is drawn from supply. At the instant of starting OA = AB = IR drop in each motor. OK = Supply voltage 'V'. The back e.m.fs. of 2 motors jointly develop along OM as shown in Fig. 43.30 (a). At point. E, supply voltage V = Back e.m.fs of 2 motors + IR drops of 2 motor. Any point on the line BC represents the sum of Back e.m.fs. of 2 motors + IR drops of 2 motors + Voltage across resistance R_s of 2 motors OE = time taken for series running.

At pt 'E' at the end of series running period, each motor has developed a back e.m.f.

$$= \frac{V}{2} - IR$$

$$EL = ED - LD$$

(b) **Parallel operation.** The motors are switched on in parallel at the instant 'E', with R_s reinserted as shown in Fig. 43.29 (b). Current drawn is 2I from supply. Back e.m.f. across each motor = EL. So the back e.m.f. now develops along LG. At point 'H' when the motors are in full parallel,(R_s = 0 and both the motors are running at rated speed)

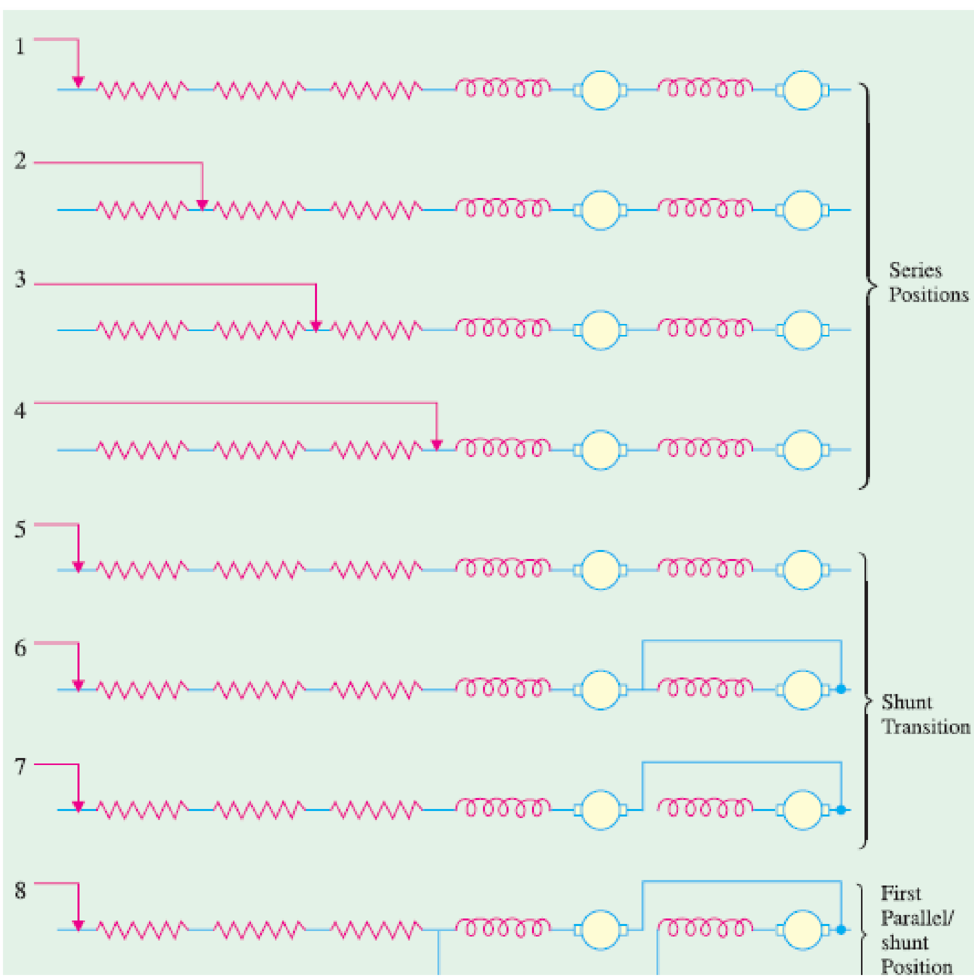
Supply voltage= V = HF = HG + GF

= Normal Back e.m.f. of each motor + IR drop in each motor

Series Parallel Control by Shunt Transition Method

The various stages involved in this method of series - parallel control are shown in Fig. 43.31 In steps 1, 2, 3, 4 the motors are in series and are accelerated by cutting out the R_s in steps. In step 4, motors are in full series. During transition from series to parallel, R_s is reinserted in circuit- step 5. One of the motors is bypassed -step 6 and disconnected from main circuit - step 7. It is then con-nected in parallel with other motor -step 8, giving 1st parallel position. R_s is again cut-out in steps completely and the motors are placed in full parallel.

The main difficulty with series parallel control is to obtain a satisfactory method of transition from series to parallel without interrupting the torque or allowing any heavy rushes of current.



In shunt transition method, one motor is short circuited and the total torque is reduced by about 50% during transition period, causing a noticeable jerk in the motion of vehicle.

The Bridge transition is more complicated, but the resistances which are connected in parallel with or ‘bridged’ across the motors are of such a value that current through the motors is not altered in magnitude and the total torque is therefore held constant and hence it is normally used for railways. So in this method it is seen that, both motors remain in circuit through-out the transition. Thus the jerks will not be experienced if this method is employed.

Series Parallel Control by Bridge Transition

(a) At starting, motors are in series with R_s i.e. link P in position = AA′

(b) Motors in full series with link P in position = BB′ (No R_s in the circuit)

The motor and R_s are connected in the form of Wheatstone Bridge. Initially motors are in series with full R_s as shown in Fig. 43.32 (a). A and A′ are moved in direction of arrow heads. In position BB′ motors are in full series, as shown in Fig. 43.32 (b), with no R_s present in the circuit.

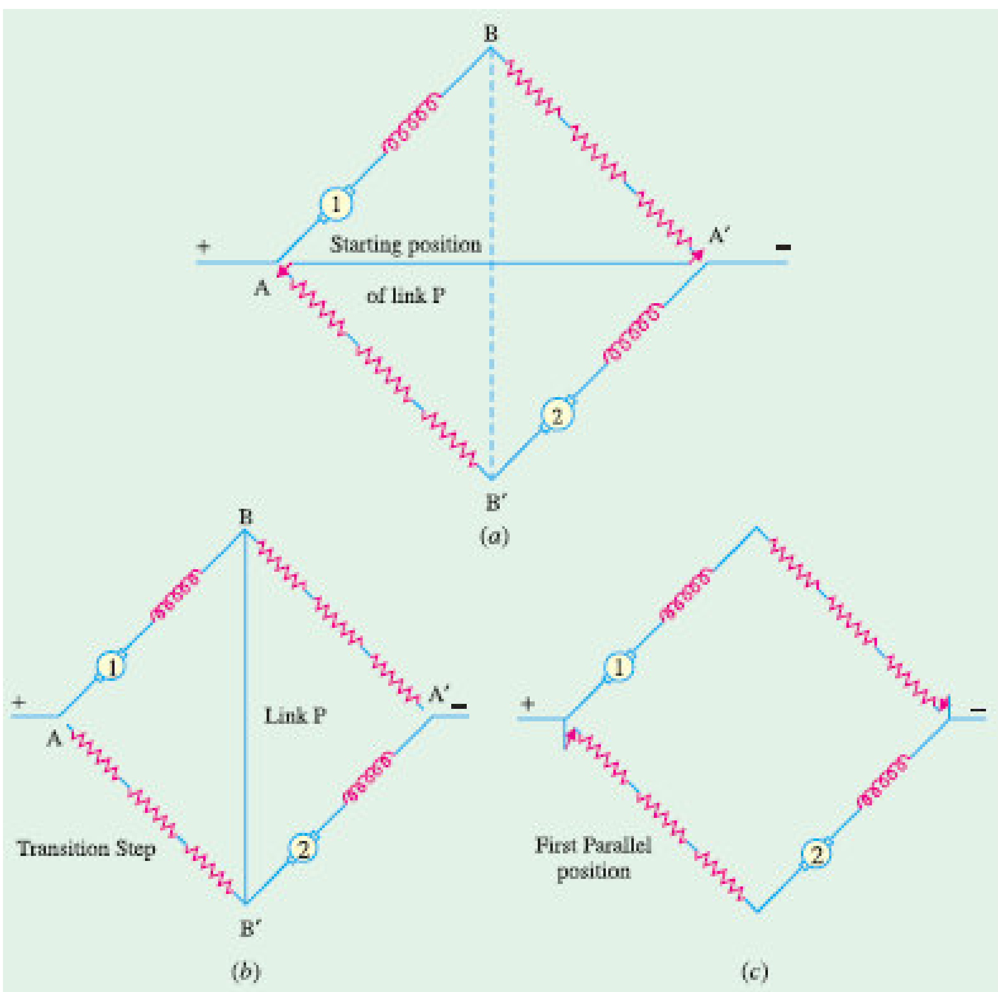


Fig. 43.32

In transition step the R_s is reinserted. In I^st parallel step, link P is removed and motors are connected in parallel with full R_s as shown in Fig. 43.32 (c). Advantage of this method is that the normal acceleration torque is available from both the motors, through - out starting period. Therefore acceleration is smoother, without any jerks, which is very much desirable for traction motors

Braking in Traction

Both electrical and mechanical braking is used. Mechanical braking provides holding torque. Electric Braking reduces wear on mechanical brakes, provides higher retardation, thus bringing a vehicle quickly to rest. Different types of electrical braking used in traction are discussed.

Rheostatic Braking

(a) Equalizer Connection (b) Cross Connection

(a) Equalizer Connection

For traction work, where 2 or more motors are employed, these are connected in parallel for braking, because series connection would produce too high voltage. K.E. of the vehicle is utilized in driving the machines as generators, which is dissipated in braking resistance in the form of heat. To ensure that the 2 machines share the load equally, an equalizer connection is used as shown in Fig. 43.33 (a). If it is not used, the machine whose acceleration builts-up first would send a current through the 2^nd machine in opposite direction, causing it to excite with reverse voltage. So that the 2 machines would be short circuited on themselves. The current would be dangerously high. Equalizer prevents such conditions. Hence Equalizer connection is important during braking in traction.

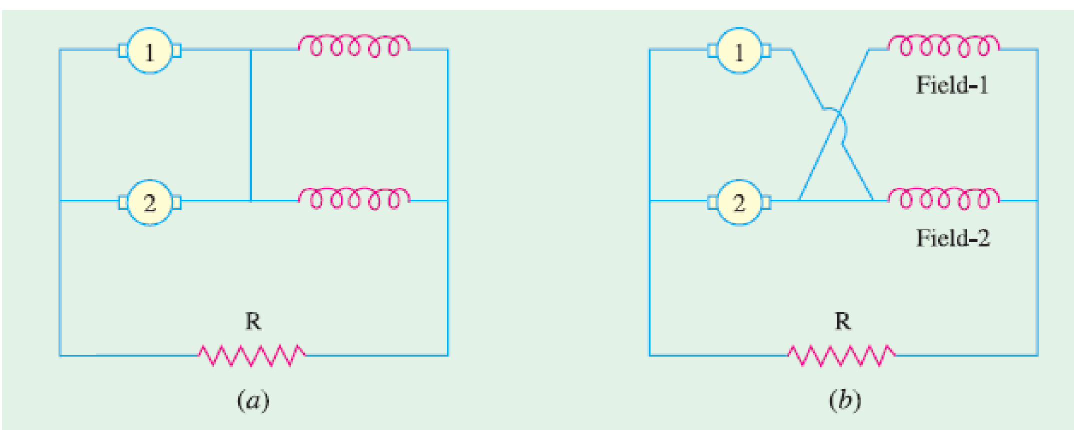


Fig. 43.33

(b) Cross Connection

In cross connection the field of machine 2 is connected in series with armature of machine 1 and the field of machine 1 is connected in series with armature of machine 2 as shown in Fig. 43.33 (b). Suppose the voltage of machine 1 is greater than that of 2. So it will send greater current through field of machine 2, causing it to excite to higher voltage. At the same time machine 1 excitation is low, because of lower voltage of machine 2. Hence machine 2 will produce more voltage and machine 1 voltage will be reduced. Thus automatic compensation is provided and the 2 machines operate satisfactorily.

Because of cross - connection during braking of traction motors, current in any of the motor will not go to a very high value.

Regenerative Braking with D.C. Motors

In order to achieve the regenerative braking, it is essential that (i) the voltage generated by the machine should exceed the supply voltage and (ii) the voltage should bez kept at this value, irrespective of machine speed. Fig. 43.34 (a) shows the case of 4 series motors connected in parallel during normal running i.e. motoring.

One method of connection during regenerative barking, is to arrange the machines as shunt machines, with series fields of 3 machines connected across the supply in series withsuitableresistance. One of the field winding is still kept in series across the 4 parallel armatures as shown in figure 43.34 (b). The machine acts as a compound generator. (with slight differential compounding) Such an arrangement is quiet stable; any change in line voltage produces a change in excitation which produces corresponding change in e.m.f. of motors, so that inherent compensation is provided e.g. let the line voltage tends to increase beyond the e.m.f. of generators. The increased voltage across the shunt circuit increases the excitation thereby increasing the generated voltage. Vice-versa is also true. The arrangement is therefore self compensating.

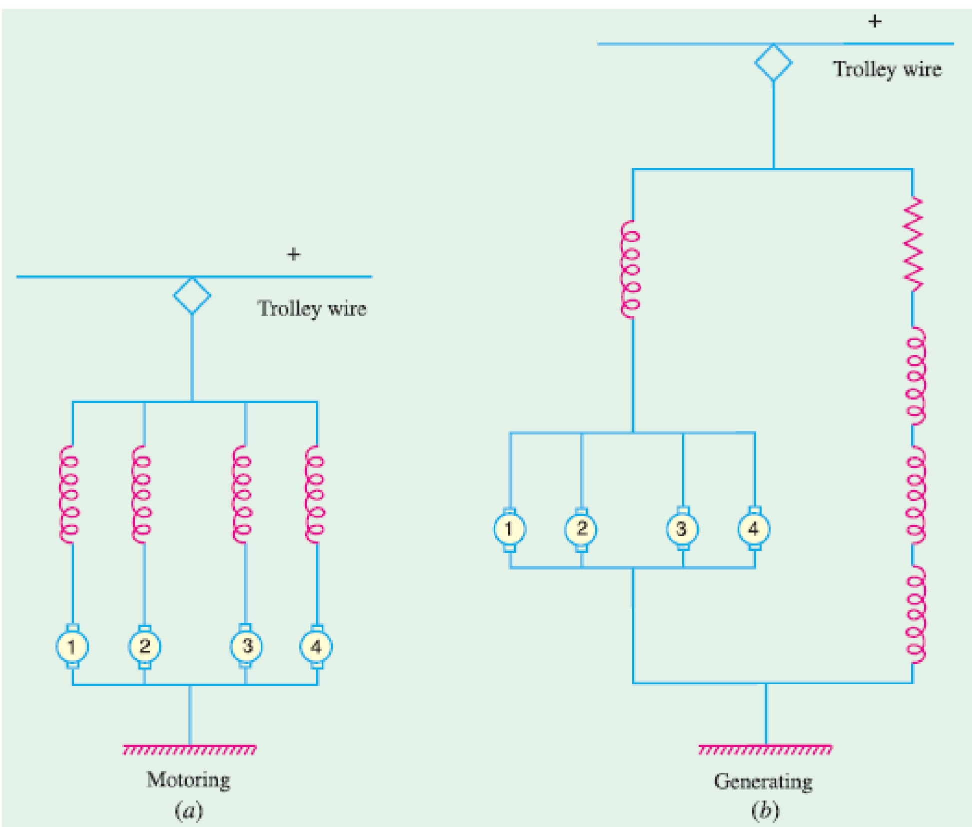


Fig. 43.34

D.C. series motor can't be used for regenerative braking without modification for obvious reasons. During regeneration current through armature reverses; and excitation has to be maintained. Hence field connection must be reversed.

Overhead Equipment (OHE)

Broadly speaking, there are two systems of current col-lection by a traction unit

(i) third rail system and (ii) overhead wire system.

It has been found that current collection from overhead wire is far superior to that from the third rail. Moreover, insulation of third rail at high voltage becomes an impracticable proposition and endangers the safety of the working personnel.

The simplest type of OHE consists of a single contact wire of hard drawn copper or
ket or an overhead span. To facilitate connection to
shown in Fig. 43.2. Because there is appreciable
limits the speed of the traction unit to about 30 km/h.
suitable for tramways and in complicated yards and
v and simplicity of layout is desirable.

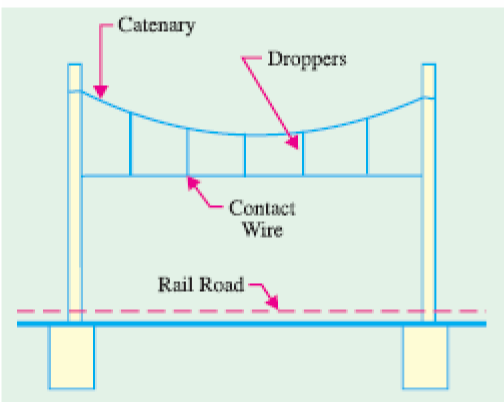


Fig. 43.3

h-speed trains, the contact (or trolley) wire has to be
s in its height between the supporting structures. It
atenary system which consists of one catenary or
ag and the trolley (or contact) wire supported from
s clipped to both wires as shown in Fig. 43.3.

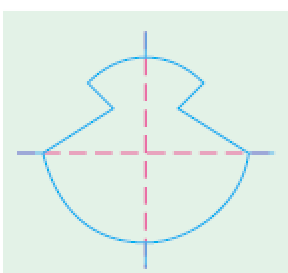


Fig. 43.2

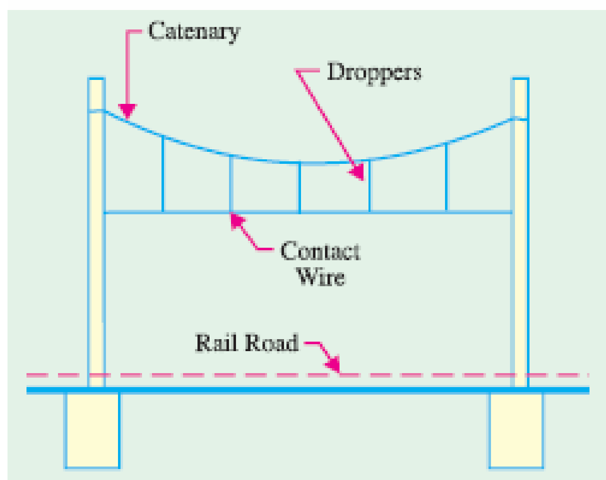


Fig. 43.3

Collector Gear for OHE

The most essential requirement of a collector is that it should keep continuous contact with trolley wire at all speeds. Three types of gear are in common use :

1. trolley collector
2. bow collector
3. pantograph collector.

To ensure even pressure on OHE, the gear equipment must, be flexible in order to follow variations in the sag of the contact wire. Also, reason-able precautions must be taken to prevent the col-lector from leaving the overhead wire at points and crossings.

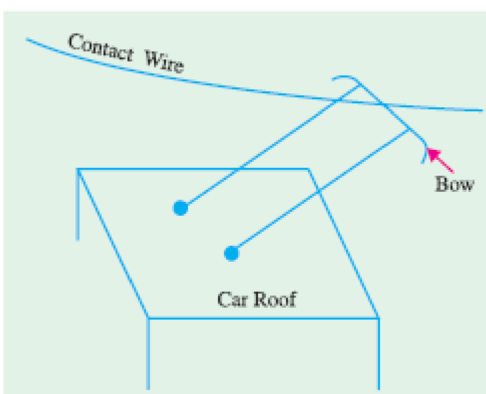
The Trolley Collector

This collector is employed on tramways and trolley buses and is mounted on the roof of the vehicle. Contact with the OH wire is made by means of either a grooved wheel or a sliding shoe carried at the end of a light trolley pole attached to the top of the vehicle and held in contact with OH wire by means of a spring. The pole is hinged to a swivelling base so that it may be reversed for reverse running thereby making it unnecessary for the trolley wire to be accurately maintained above the centre of the track. Trolley collectors always operate in the trailing position.

The trolley collector is suitable for low speeds upto 32 km/h beyond which there is a risk of its jumping off the OH contact wire particularly at points and crossing.

The Bow Collector

It can be used for higher speeds. As shown in Fig. 43.4, it consists of two roof-mounted trolley poles at the ends of which is placed a light metal strip (or bow) about one metre long for current collection. The collection strip is purposely made of soft material (copper, aluminium or carbon) in order that most of the wear may occur on it rather than on the trolley wire. The bow collector also operates in the trailing position. Hence, it requiresprovision of either duplicate bows or an arrangement for reversing the bow for running in the reverse di-rection. Bow collector is not suitable for railway work where speeds up to 120 km/h and currents up to 3000 A are encountered. It is so because the inertia of the bow collector is too high to ensure satisfactory current collection.



d Fig. 43.4

The Pantograph Collector

Its function is to maintain link between overhead contact wire and power circuit of the electric loco-motive at different speeds under all wind conditions andstiffness of OHE. It means that positive pressure has to be maintained at all times to avoid loss of contact and sparking but the pressure must be as low as possible in order to mini-mize wear of OH contact wire.A ‘diamond’ type single-pan pantograph is shown in Fig.43.5.

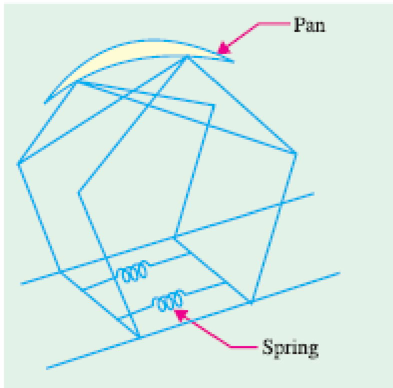


Fig. 43.5

It consists of a pentagonal framework of high-tensile alloy-steel tubing. The contact portion consists of a pressed steel pan fitted with renewable copper wearing strips which are forced against the OH contact wire by the upward action of pantograph springs. The pantograph can be raised or lowered from cabin by air cylinders.

TWO MARKS QUESTIONS

1. What are various traction systems you know of?
2. Discuss merits and demerits of steam engine drive.
3. What are the different systems of railway electrification?
4. What are the merits and demerits of D.C system of track electrification?
5. What are the functions of a D.C. sub station?
6. What are the factors affecting the schedule speed of a train?
7. What is the difference between dead weight and accelerating weight of a locomotive?
8. What do you meant by tractive effort?
9. What are the advantages of electric braking?
10. Why three phase traction system employing induction motors is now obsolete give reasons?
11. What are the various types of braking methods?
12. Discuss the current trends in AC traction systems?
13. What are the advantages of pantographs?
14. What are various current collection systems?

BIG QUESTINONS

1. Sketch the typical speed-time curve for (1) Main line service and to sub – urban services in electric Traction.
2. Explain the mechanics of train movement?
3. What is multiple unit control in electric train and explain in details each one of them?
4. What are different braking systems and explain them in details?
5. What is the speed controls of different system of motors used in electric train?
6. Define co-efficient of adhesion " and explain the factors on which it depends?
7. Discuss the various arrangement of current collection used in electric traction.
8. Write short notes on the recent trends in electric traction.

9. State the principle of regenerative braking. Explain regenerative braking in respect of DC motors, b) Induction motors.
10. What are the various methods of speed control of series motors and their scope of speed range?
11. Discuss the merits and demerits of the induction motor for traction duties?
12. What is the main advantage of series parallel control of motors over rheostatic method of starting and speed control?
13. What is multiple unit control and for what application will you suggest this?