7.1 Basic definition

(a) Traction System

- Propulsion of vehicle is called the traction.

(b) Electric Traction System

- The system of traction involving the use of electricity is called the electric traction system.

7.2 Ideal traction system

- High starting tractive effort in order to have rapid acceleration.
- Self contained and compact locomotive (train unit) so that it may be able to run on any rout.
- Equipment capable of withstanding large temporary overloads.
- Minimum wear on the track.
- Braking should be such that minimum wear is caused on the brake shoes, and if possible the energy should be regenerated and returned to the supply.
- Equipment required should be minimum, high efficiency, low initial and maintenance cost.
- No interference to the communication line running along the track.
- Easy speed control.
- It should be pollution free.

7.3 Different system of traction

(a) Non-electric Traction System

- Direct Steam Engine Drive
- Direct Internal Combustion Engine Drive

(b) Electric Traction System

- Steam Electric Drive
- Internal Combustion Engine Electric Drive
- Battery Electric Drive
- Electric Traction Drive

7.4 Direct steam engine drive

(a) Advantages

- The reciprocating steam engine is invariably used for getting the necessary motive energy because of its inherent simplicity, operational dependability, simplified maintenance, the simple connections between the cylinders and the driving wheels and easy speed control.
- The locomotive and train unit is self contained; therefore, it is not tied to a route.
- No interference to the communication line.
- The capacity is very high in comparison to direct internal combustion engine drive and battery electric drive.
- Initial investment required is low in comparison to that of electric drive.
- It is cheap for low density traffic areas and in initial stages of communication by rail.

(b) Disadvantages

- Because of difficulty of installing a condenser on a locomotive, the steam engines employed are of non-condensing type, therefore, efficiency is very poor (6 to 8%).
- Adequate supplies of feed water at regular intervals are required.
- The over-load capacity of steam locomotive is limited.
- Steam locomotive has to carry sufficient quantity of coal and water.
- Limited availability and cruising range (160 km) due to water, coal and necessary to clean the ash pan.
- Performance of steam locomotive is governed by the rate of firing coal. (1 man can maintain a firing rate of about 2 tonne/hour for short periods and 2 fire men it may be about 2.7 tonne/hour)
- More number of crew (one driver and two fire men) are required, therefore, wage bill is increased.
- Expensive and costly equipment, such as coaling cranes, ash and fire cleaning pits, water supply plants is required. The maintenance of these facilities also costs money.
- Steam locomotive requires more repair costs.(boiler)
- Larger size of running sheds and workshops are required.
- It is not clean drive.
- Steam locomotive cannot be put into service at any moment as time is required for steam rising.
- Driving wheels are very close; hence more concentrated adhesive weight is required.
- Causes considerable wear due to unbalanced reciprocating parts and corrosion of steel structures by the smoke emitted.
- Speed is limited.
- It cannot be employed for underground railways.
- It is not possible to have acceleration and retardation with steam engine drive as high as with electric drive. Steam engine drive is, therefore, not suitable for urban or suburban services where distance between stations is small.

7.5 Direct internal combustion engine drive

(a) Advantages

- It is widely employed for road transports (buses, trucks, cars etc.).
- The efficiency of internal combustion engine at its normal speed is about 25%.
- It is self contained unit.
- Speed control and braking system employed is very simple.
- It is cheap drive.

(b) Disadvantages

- Its overload capacity is limited and even 10% of overloading may result in stalling of the engine.
- As torque exerted by an internal combustion engine is approximately constant.
- Speed control is possible only by employing a gear box.
- It is not suitable for heavy railway work.
- The life of propulsive equipment is much shorter than that of electrical equipment.

- The maintenance and running costs are higher.
- Since the fuel oil is to be imported in our country.
- The oil engine bus accommodates slightly less passengers than the trolley bus.
- It has no starting torque and must be started by some auxiliary means such as compressed air or electrically.

7.6 Steam electric drive

- A few locomotives employing steam turbine for driving a generator used for supplying current to electric motors have been built for experimental purposes.
- Such locomotives have not been put into general use because of some mechanical difficulties and complications.

7.7 Internal combustion engine electric drive (diesel engine electric traction)

- In this drive the reduction gear and gear box are eliminated as the diesel engine is to drive the dc generator coupled to it at a constant speed.
- This type of drive has found considerable favour for railway work and locomotive of this type are becoming widely used.

(a) Advantages

- No modification of existing track is required for conversion from stem traction to diesel engine electric traction.
- Initial investment required is low as no overhead structure distribution system and equipment is required.
- The diesel engine electric vehicle can accommodate more passengers than the steam engine vehicle and because of its higher acceleration and braking retardation.
- Power loss in speed control is very low because it can carry out by the field control of generator.
- The locomotive and train is a self contained unit.
- The maintenance cost is fairly heavy but the time spent in maintenance and overhaul is very less (only 5 to 10 % of its working day). Hence such a locomotive is available for hauling for almost 6.5 days in a week for 24 hours duty.
- It can be put into service at any moment.
- Overall efficiency is greater than that of steam locomotives (about 25%).

(b) Disadvantages

- Its overload capacity is limited.
- Life of the diesel engine is comparatively shorter.
- Special cooling system required for cooling the diesel engine in addition to motor-generator set.
- The dead weight of such locomotive is more. It requires more axles.
- Running and maintenance costs are high.
- Since the fuel oil is to be imported in our country.
- For the same power output diesel electric locomotive is costlier than steam or electric locomotive.
- Regenerative braking cannot be used.

7.8 Battery electric drive

- In this drive the locomotive carries the secondary batteries which supply power to dc motors employed for driving the vehicle.
- It is used for local delivery of good in large towns with maximum daily run of 50 to 60 km.
- Battery driven vehicle is easy to control, very convenient to use, and absence of fumes.
- Small capacity of the batteries and the necessity for frequent charging, speed range is also limited.

7.9 Electric traction drive

- In this system of traction the vehicle draws electric energy from the distribution system fed at suitable points from either a central power station or substations.

(a) Advantages

- It is cleanest of all other types of systems of traction. Due to this only it is ideally suitable for the underground and tube railways.
- No water and coaling depots are required in electric drive.
- Ancillary equipment, such as coaling cranes, ash and fire cleaning pits, water supply plans, is not required. Size of running sheds and workshops is comparatively smaller.
- The electrical energy required for lights and fans of the train can be drawn from the lines directly and therefore, there is no need of providing generators.
- Batter speed control.
- Rapid acceleration and braking retardation.
- Larger passenger carrying capacity.
- An electric locomotive requires much less time for maintenance and repairs than a steam locomotive and such vehicles can, if desired, be kept in service for 95% or more of the working day.
- Maintenance and repair cost is about 50% of that of steam locomotive.
- The electric locomotive can be put into service immediately whereas steam locomotives takes about two hours to get up steam.
- There is no damage to the plant, equipment and building due to corrosive smoke fumes because of absence of unwanted gases and fire hazards.
- It is most economical in areas of high traffic density particularly if electrical energy is cheap.
- The vibrations in electrically operated vehicles are less as the torque exerted by the electric motors is continuous.
- The coefficient of adhesion is batter in electric traction than the steam traction. Due to this ratio of weight to output kW of locomotive is reduces improvement in riding qualities and reduction in wear and tear of the track.
- Electric equipment can withstand large temporary overloads and can draw relatively large power from the distributing system.
- Electric traction helps in saving of high grade coal which is limited in quantity in our country.
- Power requirement for railway electrification has been of the order of 50 kW/track km.

- Railway electrification encourages rural electrification as no special transmission line has to be run for this purpose.
- Electric braking is superior to mechanical braking because of less wear on brake shoes, wheels and track.
- In case of steam traction break blocks and wheels are likely to overheat on continuous grades and sometimes trains have stopped for allowing these brake blocks and wheels to cool down but in case of electric traction it is not so.

(b) Disadvantages

- It involves a heavy initial cost for the power supply system.
- Statutory regulations, concerning leakage currents from overhead conductors and the voltage drop in the track rails have to be complied with.
- Failure of power supply for a few minutes may paralyse the whole system.
- Steam locomotives can use their steam for heating the compartments in cold weather very cheaply.
- Electric traction system is tied up to only electrified routes.
- In case of ac traction the communication lines running along the track experience considerable interference from the power lines.
- Additional equipment is required for regeneration. In case of dc series motor regeneration is not simple process.
- In cold countries a service locomotive is required to run up and down the line in order to prevent the formation of a layer of ice on the conductor rails.

Table 7.1 Efficiencies of Different Types of Locomotives

S. No.	Traction System	Efficiency
1.	Steam Locomotive	5-7%
2.	Gas Turbine Electric Locomotive	10%
3.	Diesel Electric Locomotive	25-30%
4.	Electric Locomotive with Thermal Power Plant	34-36%
5.	Electric Locomotive with Hydro-Electric Power Plant	40-42%

7.10 Systems of track electrification

(a) The DC System

(b) The Single Phase AC System

(c) The Three Phase AC System

(d) The Composite System

- Single Phase - Three Phase System or Kando System
- Single Phase - DC System

7.11 The DC system

- In this system, D.C. series motors used for getting the necessary motive power, D.C. compound motors are also used for tramways and trolley buses where regenerative braking can be utilized.
- The operating voltage is from 600 V to 750 V for tramway and suburban railways and from 1500 V to 3000 V for mainline service.

Table 7.2 DC System

S. No.	Operating Voltage in Volts	Spacing between Sub-Station in km	Application
1.	600	3 to 5	Tramways, Trolley Bus
2.	1500 to 3000	30 to 40	Main Line Services

- The distribution system consists of one contact wire in case of tramways and two contact wires in case of trolley buses.
- The spacing of sub-stations depends upon the operating voltage and the traffic density of the route.

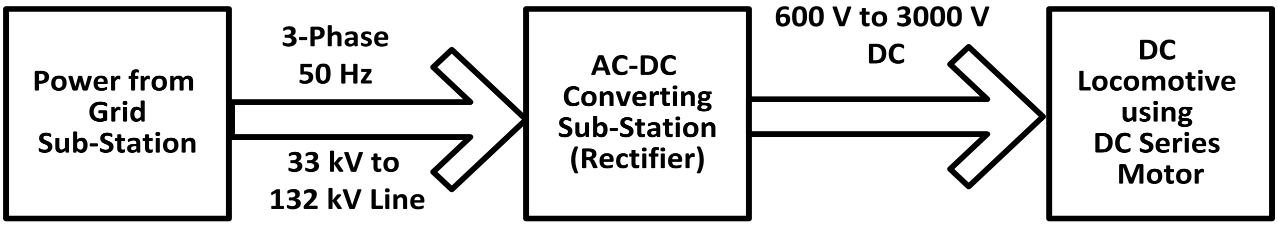

Figure 7.1 DC System

(a) Advantages

- DC series motor has better speed torque characteristics and smooth speed control.
- It offers high starting torque.
- It has low maintenance cost.
- Smaller weight per kW output.
- Batter speed control.
- Efficient braking system.

(b) Disadvantages

- This system has high cost of sub-station due to converting equipments.
- More number of sub-stations is required as they are spaced at shorter distance.
- Additional equipments like negative boosters are also required to maintain return voltage within specified limit.

7.12 The single phase AC system

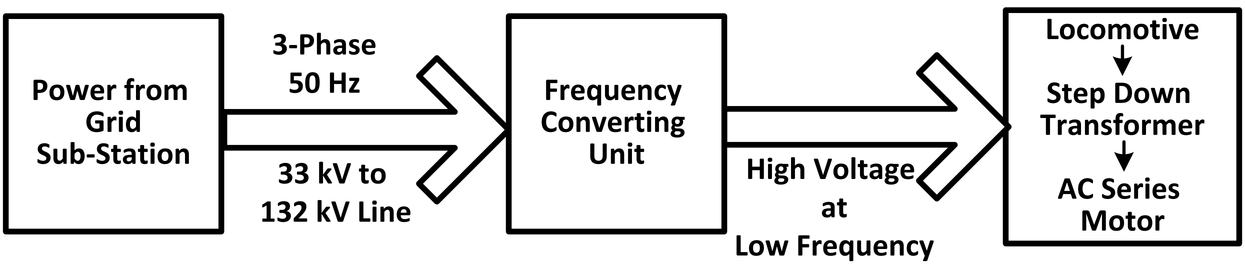

Figure 7.2 Single Phase AC System

- In single phase AC system ac series motors are used for getting necessary motive power.
- The voltage employed for distribution network is 15 to 25 kV at $6\frac{2}{3}$ or 25 Hz, which is stepped down on locomotive to a low voltage suitable for supplying to single ac series motor.

- The spacing of substation is 50 to 80 km.
- The change of supply frequency become necessary because of
  - Batter performance.
  - Improves its commutation properties, power factor and efficiency.
  - Reduces the line reactance and hence the voltage drop.
- AC single phase system is invariably adopted for main line service.

7.13 The three phase AC system

- In this system 3-phase induction motor operating at 300 to 3600 V and low frequency are employed for getting the required motive power.
- The 3-phase induction motor
  - Simple
  - Robust in construction
  - High operating efficiency
  - Automatic regenerative braking without required any additional equipment.

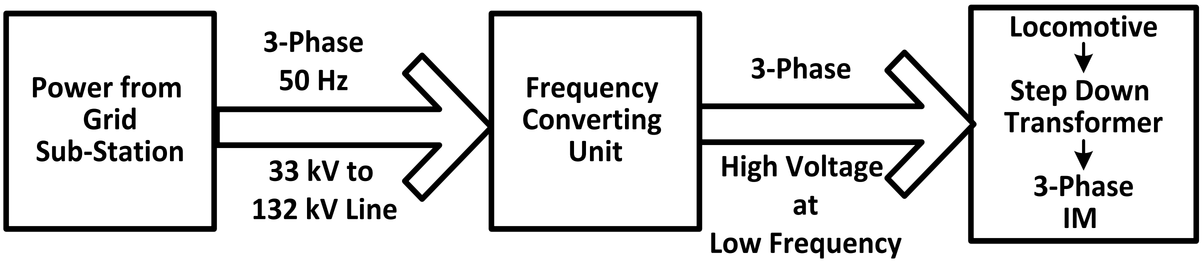

Figure 7.3 Three Phase AC System

- Drawbacks
  - Low starting torque
  - High starting current
  - Two overhead contact wires

7.14 The kando system (single phase to three phase system)

- In this system single phase high voltage (25 kV) at normal supply frequency is used to distribute power.
- The locomotive which carries a phase convertor which converts single phase AC to three-phase AC. The three-phase power is then fed to three-phase induction motors for getting necessary motive force.
- In this system only one contact wire of overhead system which is overcome the disadvantage of 3 phase AC system
- This system was adopted in Hungary in 1932.

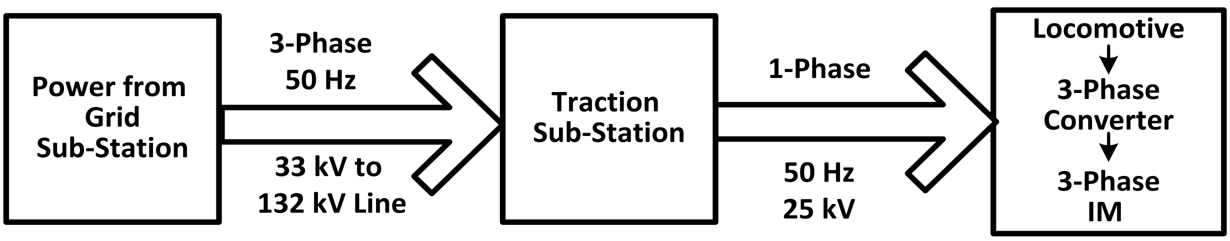

Figure 7.4 Kando System

7.15 The single phase AC to DC system

- In this system of track electrification single phase AC 25 kV at normal frequency is fed to overhead distribution.
- The AC locomotive carries transformer to step down high input voltage and rectifying equipments to convert AC into DC This system is adopted in India for track electrification.
- This system becomes most popular because of various salient advantages over other systems particularly DC system.
- This system has got numerous advantages over dc system
  - The line current for a given demand of power is reduced on account of high system voltage
  - On account of high voltage the substations can be spaced at longer distances (50 to 80 km) whereas the substations are spaced at 12 to 30 km in case of 3000 V DC system and at 5 to 12 km in case of 1500 V DC system.
  - Since the dc series motors having ideal traction characteristics are employed in this system for getting the required propelling power, therefore, this system have got the advantages of the dc system.

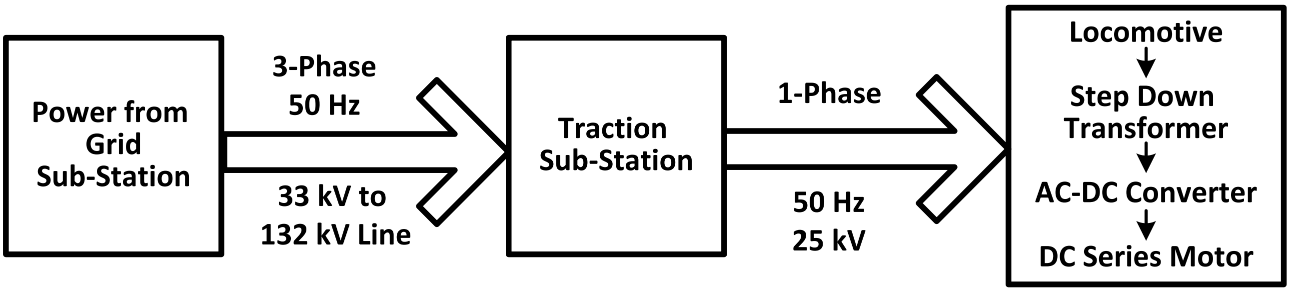

Figure 7.5 Single Phase AC to DC System

7.16 Comparison of DC and AC system of railway electrification from the point of view of main line and suburban line railway service

(a) Main Line Railway Service

- The essential requirements of main line railway service are :
  - Higher maximum speed. (V_m)
  - Minimum cost of track electrification.
- Single phase AC system is preferred for main line service because of following features
  - 25 kV overhead systems reduce conductor section and hence simplified structure design due to high voltage.
  - Higher spacing of sub-station reduces number of sub-station and increases flexibility of selecting cheaper, land Maintenance cost is less due to cheap and efficient equipment of AC system.

(b) Sub-urban Railway Service

- The essential requirements of sub-urban railway service are :
  - Rapid acceleration and retardation rates due to frequent starting and stopping.
  - Motor performance should not affected by voltage fluctuations.
  - Less chances of interference in the telecommunication lines running along the track.

- The above requirements can be fulfill by DC system and hence invariably adopted for sub-urban services considering following facts :
  - For similar conditions the energy consumption in dc system is less as compared with that in AC system.
  - The DC locomotive and motor coach equipments are lighter in weight, cheaper in initial and maintenance cost and efficient.

Table 7.3 Comparison of DC and AC Traction

Factor	DC Traction	AC Traction
Motor	DC series motor.	AC series motor.
Performance	Good performance.	Not as good as that used for DC traction.
Starting torque	More.	Less.
Speed control	The speed control of DC series Motor is limited.	Wide range of speed control is Possible.
Interference	DC system causes less interference with Communication lines.	It will produce more interference with Communication lines.
Overhead distribution	Heavier and more costly Comparatively.	Lighter and less costly.
Substations	The number of substations required for a given track distance on DC traction is More.	The number of substations required in AC traction is less.
Weight of cu	Weight of cu required per track km is more.	Weight of cu required per track km is less.
Application	Tramway, Trolley bus.	Main Line Service.

7.17 Current collectors for overhead system

- Electric current collectors are used by trolleybuses, trams, electric locomotives or EMUs to carry electrical power from overhead lines or electrical third rails to the electrical equipment of the vehicles. Those for overhead wires are roof-mounted devices; those for third rails are mounted on the bogies.
- Typically, they have one or more spring-loaded arms that press a collector or contact shoe against the rail or overhead wire. As the vehicle moves, the contact shoe slides along the wire or rail to draw the electricity needed to run the vehicle's motor.
- The current collector arms are electrically conductive but mounted insulated on the vehicle's roof, side or base. An insulated cable connects the collector with the switch, transformer or motor. The steel rails of the tracks act as the electrical return.
- Electric vehicles that collect their current from an overhead line system use different forms of one- or two-arm pantograph collectors, bow collectors or trolley poles. The current collection device presses against the underside of the lowest wire of an overhead line system, which is called a contact wire.

- Most overhead supply systems are either DC or single phase AC, using a single wire with return through the grounded running rails. Three phase AC systems use a pair of overhead wires, and paired trolley poles.

(a) Trolley Collector

- The trolley collector is universally employed with tramways and trolley buses.
- This consists of grooved gun metal wheel or grooved slider with carbon insert carried at the end of a long pole. The other end of this pole is hinged to a swiveling base fixed to the roof of the vehicle.
- Draw back particularly with trolley wheel collector is that there poor contact between wheel and trolley wire, It can't be operate in either direction of motion.
- The trolley collector is suitable for comparative low speed (say 24 to 32 kmph) beyond this speed there is every possibility of its jumping off the trolley wire.

(b) Bow Collector

- The bow collector is also employed for collecting the current with tramways.
- The bow collector consists of light metal strip or bow 0.6 to 0.9 meter wide pressing against the trolley wire and attached to a framework mounted on the roof of vehicle.
- In order to avoid jumping off the trolley wire at high speeds, it is desired that the wire be accurately located above the track and staggered about 15 cm to each side of center line to avoid the wearing of the groove in the contact strip.

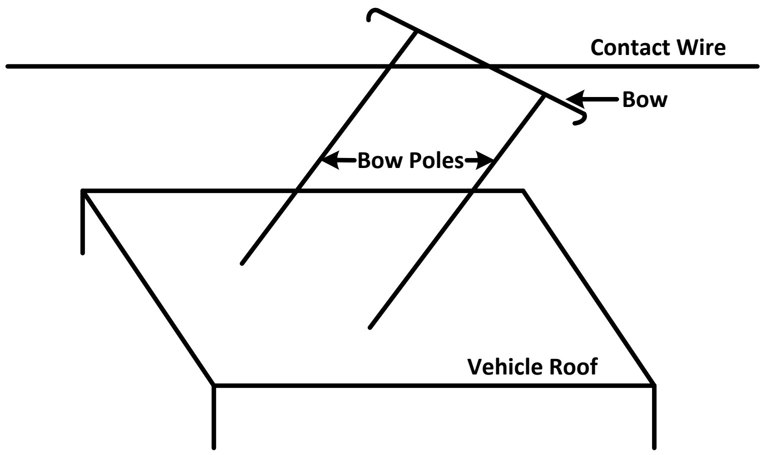

Figure 7.6 Bow Collector

(c) Pantograph Collector

- The pantograph is employed in railways for collection of current where the operating speed is as high as 100 or 130 kmph and the currents to be collected are as large as 2000 or 3000 A.
- Pantographs are mounted on the roof of the vehicles and usually carry sliding shoe for contact with the overhead trolley wire.
- The contact shoes are usually about 1.2 meter long. There may be a single shoe or two shoes on each pantograph.
- Material used for pantograph is often steel with sometimes, wearing used plates of copper or bronze inserted.

- The pressure varies from 5 to 15 kg. The pantograph is raised or lowered from the driver cab by one of the following methods or with some modification of it.
- Advantages over other types of the collectors. (i) It can operate in either direction of motion. (ii) There is no risk of leaving wire junction etc. (iii) The erection of the overhead network is very simple due to absence of points and grooved crossings required for bows. (iv) Its height can be varied from the drivers cabin by carrying out simple operations.

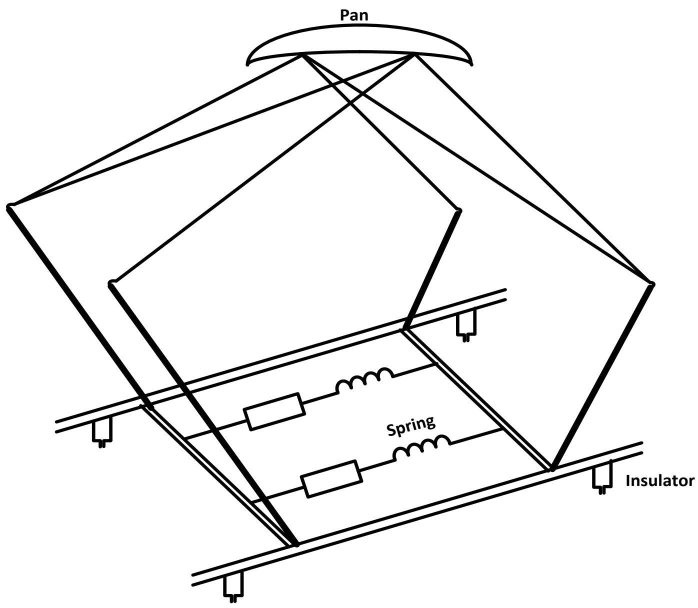

Figure 7.7 Pantograph Collector

7.18 Typical speed-time curve for main line service

- The Curve drawn between Speed and Time, taking Speed in km/hr on Y-axis and Time in Sec or min on X-axis is known as speed-time curve.
- It's give complete information of the motion of the train. (*Distance=Speed × Time*)
- Speed time curve mainly consists of
  - Acceleration.
  - Free Run or Constant Speed Run.
  - Coasting.
  - Retardation or Braking.

(a) Acceleration

- Constant Acceleration of Acceleration During Notching up
  - Nothing up period. (0 to t_1)
  - Current will remain constant.
  - Supply voltage will be increase. (By cutting out the starting resistance)
  - Tractive effort will remain constant.
  - Acceleration will be constant.
- Speed curve Running or Acceleration on speed curve
  - Speed curve running period. (t_1 to t_2)
  - Voltage will be constant. (Approx.)
  - Current will be decreasing and become constant.

- o Acceleration will be decreases and finally become zero.
- o Tractive effort is equal to resistance to motion of train.

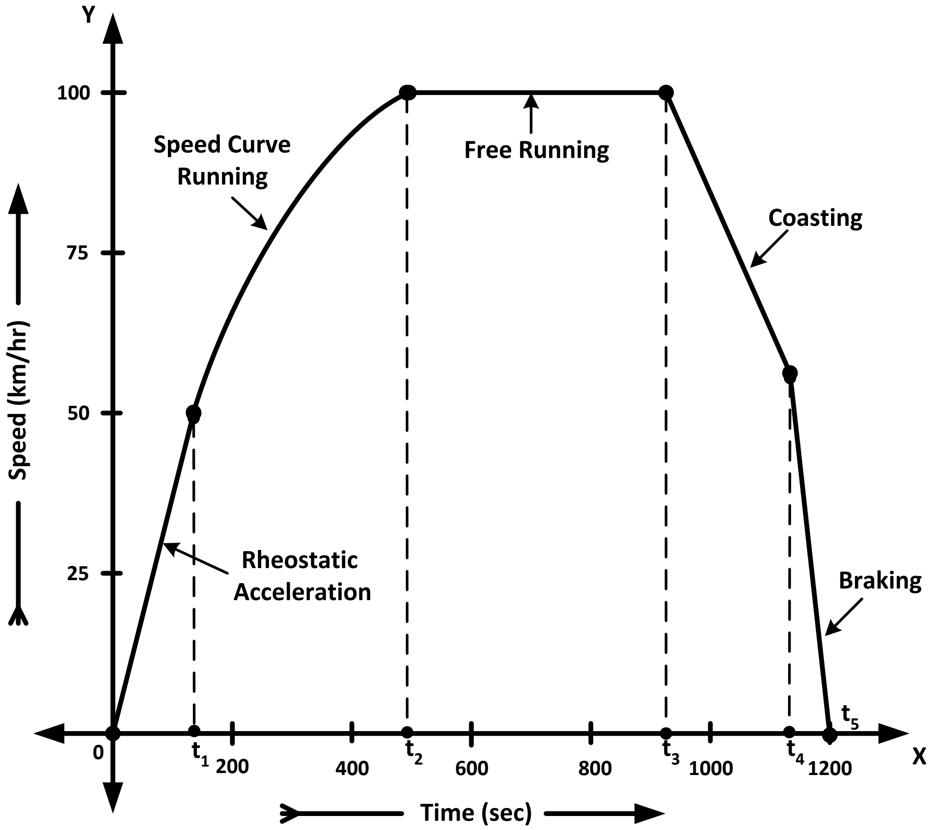

Figure 7.8 Typical Speed-Time curve for Main Line Service

(b) Free Run or Constant Speed Run

- Free run period. (t_2 to t_3)
- The train attains the maximum speed.
- During this period the train runs with constant speed and constant power is drawn.

(c) Coasting

- At the end of free running period (t_3 to t_4), power supply is cut off and the train is allowed to run under its own momentum.
- The speed of train starts decreasing on account of resistance to the motion of train.
- The rate of decrease of speed during coasting period is known as coasting retardation.

(d) Retardation or Braking Period

- At the end of coasting period (t_4 to t_5), the brakes are applied to bring the train to rest.
- During this period speed decreases rapidly and finally reduces to zero.

7.19 Typical speed-time curve for suburban and urban service

(a) Suburban Service

- In this service the distance between the stops is little longer than urban service but smaller than main line service (between 1 to 8 km).
- Free run is not possible.
- Coasting is for comparatively longer period.
- Acceleration and retardation required are as high as for urban service.

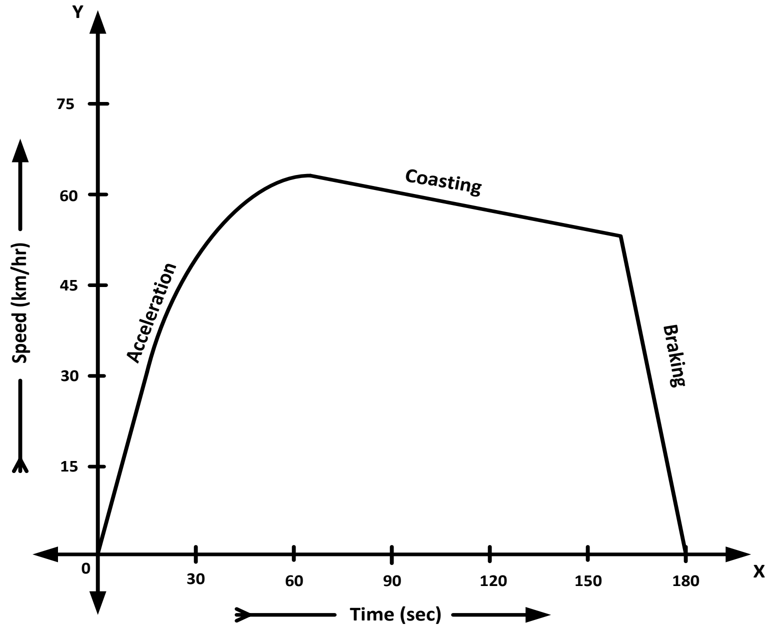

Figure 7.9 Typical Speed-Time curve for Suburban Service

(b) Urban Service or City Service

- In this service the distance between the stops is comparatively very short. (say 1 km or so)
- Time required for this run is very small.
- The acceleration as well as retardation is required to be high so that high average speed and short time run is obtained.
- Free run is not possible.
- Coasting period is also small.

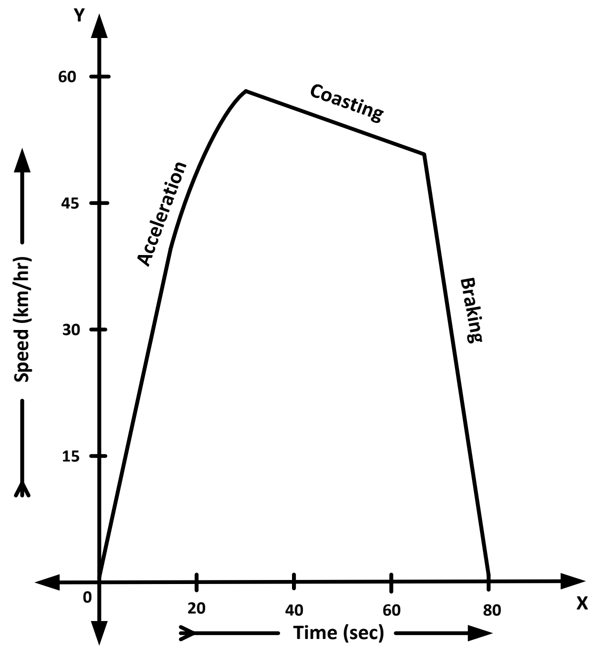

Figure 7.10 Typical Speed-Time curve for Urban Service

Table 7.4 Characteristics of Various type of Services

S. No.	Type of Service	Acceleration in kmphps	Retardation in kmphps	Maximum Speed in kmph	Distance between Stations in km
1.	Urban	1.5 to 4.00	3 to 4	60	1
2.	Suburban	1.5 to 4.00	3 to 4	75	1 to 8
3.	Main Line	0.6 to 0.8	1.5	110	More than 10

7.20 Crest speed, average speed and schedule speed

(a) Crest Speed

- The maximum speed attained by the vehicle during the run is known as crest speed.

(b) Average Speed

- The distance covered between two stops divided by the actual time of run is known as average speed.

$$Average\ Speed = \frac{Distance\ between\ Stops}{Actual\ Time\ of\ run, T}$$

(c) Schedule Speed

- The ratio of distance covered between two stops and total time of run including time of stop is known as schedule speed.

$$Schedule\ Speed = \frac{Distance\ between\ Stops}{Actual\ Time\ of\ run + Stop\ Time}$$

- Schedule Speed < Average Speed
- Difference is large in case of urban & sub-urban, negligibly small in case of main line service.

7.21 Factor affecting on schedule speed

- The Schedule speed of a given is affected by the following factors:

(a) Effect of acceleration and Braking Retardation

- For a given run and with fixed crest speed the increase in acceleration will result in decrease in actual time of run and therefore increase in schedule speed.
- Similarly increase in braking retardation will affect the schedule speed.
- Variation in acceleration and retardation will have more effect on schedule speed in case of shorter distance run in comparison to longer distance run.

(b) Effect on maximum speed

- For constant distance run and with fixed acceleration and retardation the actual time of run will decrease, and therefore schedule speed will increase with the increase in crest speed.
- The effect of variation in crest speed on schedule speed in considerable in case of long distance run.

(c) Effect on duration of stop

- For a given average speed the schedule will increase by reducing the duration of stop.
- The variation in duration of stop will affect the schedule speed more in case of shorter distance run as compared to longer distance run.

7.22 Simplified speed-time curve

- "Convert or Replace typical speed-time curve to simple geometric shaped curve is known as simplified speed-time curve."
- From these simplified curves, the relationships between acceleration, retardation, average speed and distance can be easily workout.
- Trapezoidal curve can be used for main line service and quadrilateral curve can be used for urban and sub-urban service.

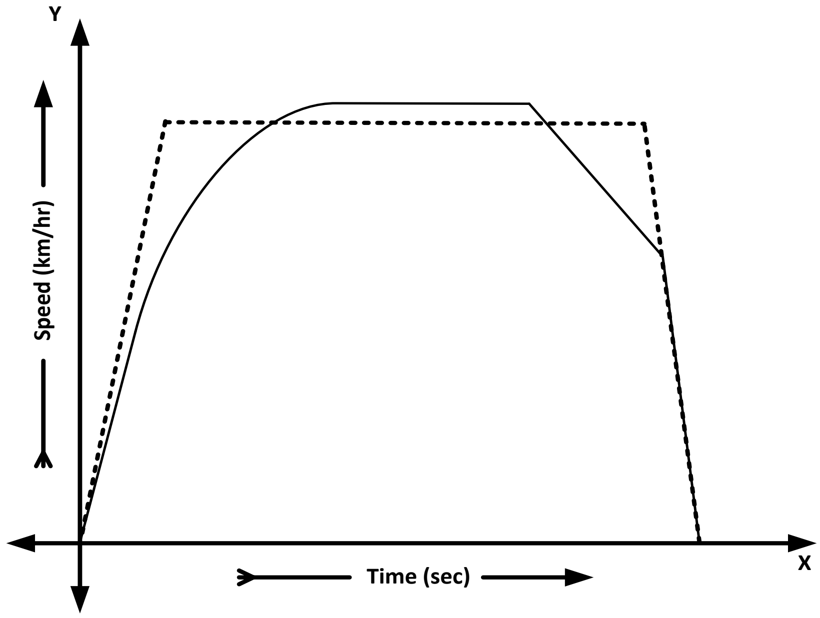

Figure 7.11 Approximate Trapezoidal Speed-Time Curves

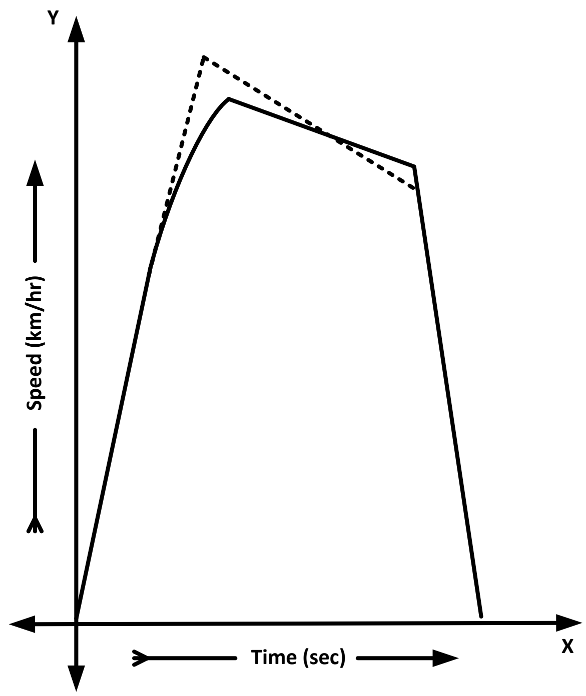

Figure 7.12 Approximate Quadrilateral Speed-Time Curves

7.23 Calculation by trapezoidal speed-time curve

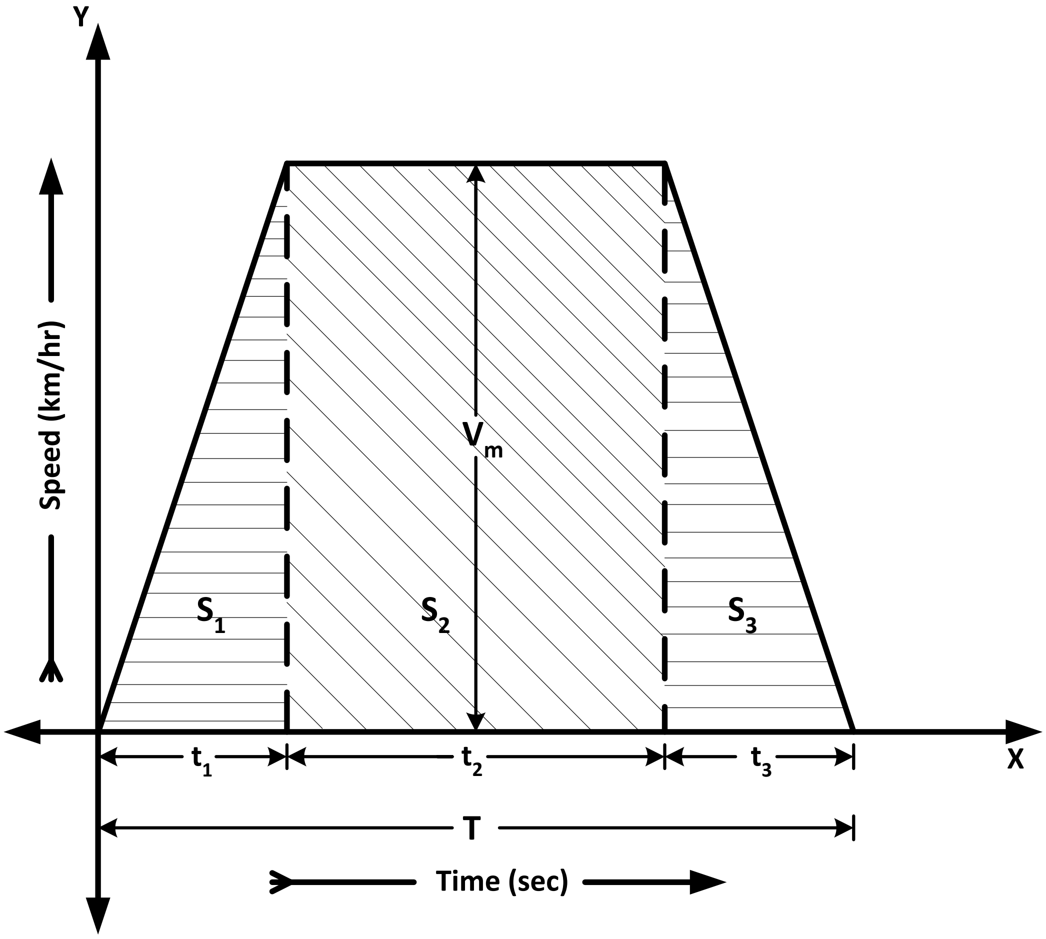

Figure 7.13 Trapezoidal Speed-Time Curves

$\alpha = Acceleration\ in\ kmphps$

$\beta = Retardation\ in\ kmphps$

$V_m = Crest\ speed\ in\ kmph$

$T = Total\ time\ of\ run\ in\ \sec$

$$Time\ for\ Acceleration\ in\ \sec,\ t_1 = \frac{V_m}{\alpha}$$

$$Time\ for\ Retardation\ in\ \sec,\ t_3 = \frac{V_m}{\beta}$$

$$Time\ for\ Free\ Run\ in\ \sec,\ t_2 = T - (t_1 + t_3)$$

$$= T - \left[\frac{V_m}{\alpha} + \frac{V_m}{\beta}\right]$$

Total Distance of Run, in km(S) = Distance travelled during acceleration +
Distance travelled during free run +
Distance travelled during retardation

$$S = S_1 + S_2 + S_3$$

$$S_1 = \frac{1}{2}\frac{V_m t_1}{3600}$$
$$put,\ t_1 = \frac{V_m}{\alpha}$$
$$S_1 = \frac{V_m^2}{7200\alpha}$$

$$S_2 = \frac{V_m t_2}{3600}$$
$$put,\ t_2 = T - \left[\frac{V_m}{\alpha} + \frac{V_m}{\beta}\right]$$
$$S_2 = \frac{V_m}{3600}\left[T - \left(\frac{V_m}{\alpha} + \frac{V_m}{\beta}\right)\right]$$
$$S_2 = \frac{V_m T}{3600} - \frac{V_m^2}{3600\alpha} - \frac{V_m^2}{3600\beta}$$

$$S_3 = \frac{1}{2}\frac{V_m t_3}{3600}$$
$$put,\ t_3 = \frac{V_m}{\beta}$$
$$S_3 = \frac{V_m^2}{7200\beta}$$

Now,

$$S = S_1 + S_2 + S_3$$
$$= \frac{V_m^2}{7200\alpha} + \frac{V_m T}{3600} - \frac{V_m^2}{3600\alpha} - \frac{V_m^2}{3600\beta} + \frac{V_m^2}{7200\beta}$$
$$= \frac{V_m^2}{\alpha}\left[\frac{1}{7200} - \frac{1}{3600}\right] + \frac{V_m^2}{\beta}\left[\frac{1}{7200} - \frac{1}{3600}\right] + \frac{V_m T}{3600}$$
$$= \frac{V_m^2}{\alpha}\left[\frac{1-2}{7200}\right] + \frac{V_m^2}{\beta}\left[\frac{1-2}{7200}\right] + \frac{V_m T}{3600}$$
$$S = \frac{V_m T}{3600} - \frac{V_m^2}{7200\alpha} - \frac{V_m^2}{7200\beta}$$
$$\therefore \frac{V_m^2}{3600}\left[\frac{1}{2\alpha} + \frac{1}{2\beta}\right] - \frac{V_m T}{3600} + S = 0$$
$$\therefore V_m^2\left[\frac{1}{2\alpha} + \frac{1}{2\beta}\right] - V_m T + 3600S = 0$$
$$take,\ K = \left[\frac{1}{2\alpha} + \frac{1}{2\beta}\right]$$
$$\therefore V_m^2 K - V_m T + 3600S = 0$$

Using quadratic equation,
$a = K, b = -T, c = 3600S$

$$V_m = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$
$$V_m = \frac{T \pm \sqrt{T^2 - 4K3600S}}{2K}$$
$$V_m = \frac{T}{2K} \pm \sqrt{\frac{T^2}{4K^2} - \frac{3600S}{K}}$$

for +Ve sign will be much higher value than that is possible in practical value.
so, take -Ve sign for calculation

$$\boxed{V_m = \frac{T}{2K} - \sqrt{\frac{T^2}{4K^2} - \frac{3600S}{K}}}$$

7.24 Calculation by quadrilateral speed-time curve

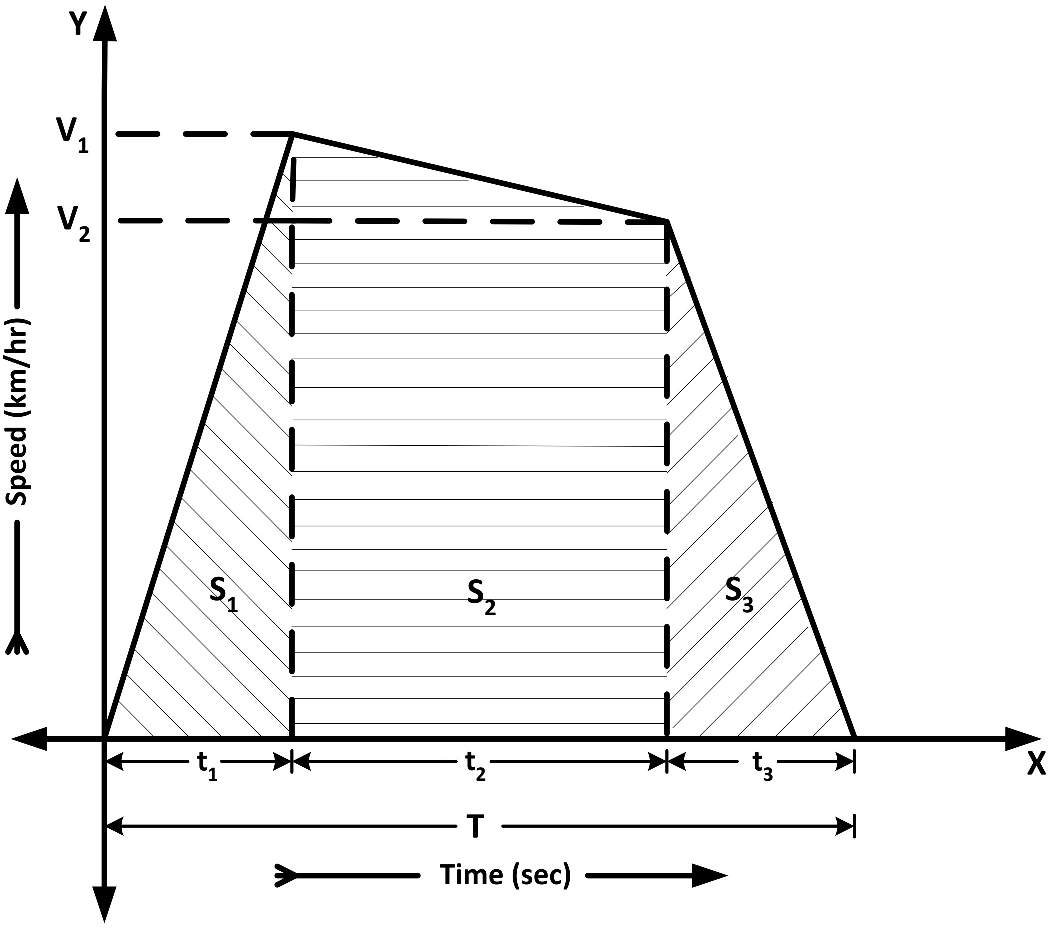

Figure 7.14 Quadrilateral Speed-Time Curves

α = Acceleration in kmphps
β_c = Coasting Retardation in kmphps
β = Braking Retardation in kmphps
V_1 = Maximum speed at the end of acceleration in kmph
V_2 = Maximum speed at the end of Coasting in kmph
T = Total time of run in sec

$$\text{Time for Acceleration in sec, } t_1 = \frac{V_1}{\alpha}$$

$$\text{Time for Retardation in sec, } t_3 = \frac{V_2}{\beta}$$

$$\text{Time for Free Run in sec, } t_2 = \frac{V_1 - V_2}{\beta_c}$$

Total Distance of Run, in km(S) = Distance travelled during acceleration + Distance travelled during coasting + Distance travelled during braking

$$S = S_1 + S_2 + S_3$$

$$S_1=\frac{1}{2}\frac{V_1t_1}{3600}$$

$$S_2=\frac{V_2t_2}{3600}+\frac{1}{2}\frac{(V_1-V_2)t_2}{3600}=\left(\frac{V_1+V_2}{2}\right)\frac{t_2}{3600}$$

$$S_3=\frac{1}{2}\frac{V_2t_3}{3600}$$

Now,

$$S=S_1+S_2+S_3$$

$$S=\frac{1}{2}\frac{V_1t_1}{3600}+\left(\frac{V_1+V_2}{2}\right)\frac{t_2}{3600}+\frac{1}{2}\frac{V_2t_3}{3600}$$

$$=\frac{V_1t_1}{7200}+\frac{V_1t_2}{7200}+\frac{V_2t_2}{7200}+\frac{V_2t_3}{7200}$$

$$S=\frac{V_1}{7200}(t_1+t_2)+\frac{V_2}{7200}(t_2+t_3)$$

$Put\ t_1+t_2+t_3=T$

$$S=\frac{V_1}{7200}(T-t_3)+\frac{V_2}{7200}(T-t_1)$$

$$=\frac{T}{7200}(V_1+V_2)-\frac{V_1t_3}{7200}-\frac{V_2t_1}{7200}$$

$$Put,\ t_1=\frac{V_1}{\alpha}\ \ \&\ \ t_3=\frac{V_2}{\beta}$$

$$S=\frac{T}{7200}(V_1+V_2)-\frac{V_1}{7200}\frac{V_2}{\beta}-\frac{V_2}{7200}\frac{V_1}{\alpha}$$

$$\boxed{7200S=T(V_1+V_2)-V_1V_2\left[\frac{1}{\alpha}+\frac{1}{\beta}\right]}$$

Now,

$$t_2=\frac{V_1-V_2}{\beta_c}$$

$$V_2=V_1-t_2\beta_c$$

$$V_2=V_1-\beta_c\,(T-t_1-t_3)$$

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

$$\left[V_2-\frac{\beta_c}{\beta}V_2\right]=V_1-\beta_c\,(T-\frac{V_1}{\alpha})$$

$$\boxed{V_2=\frac{V_1-\beta_c\,\mathrm{T}+\frac{\beta_c}{\alpha}V_1}{1-\frac{\beta_c}{\beta}}}$$

7.25 Mechanics of train movement

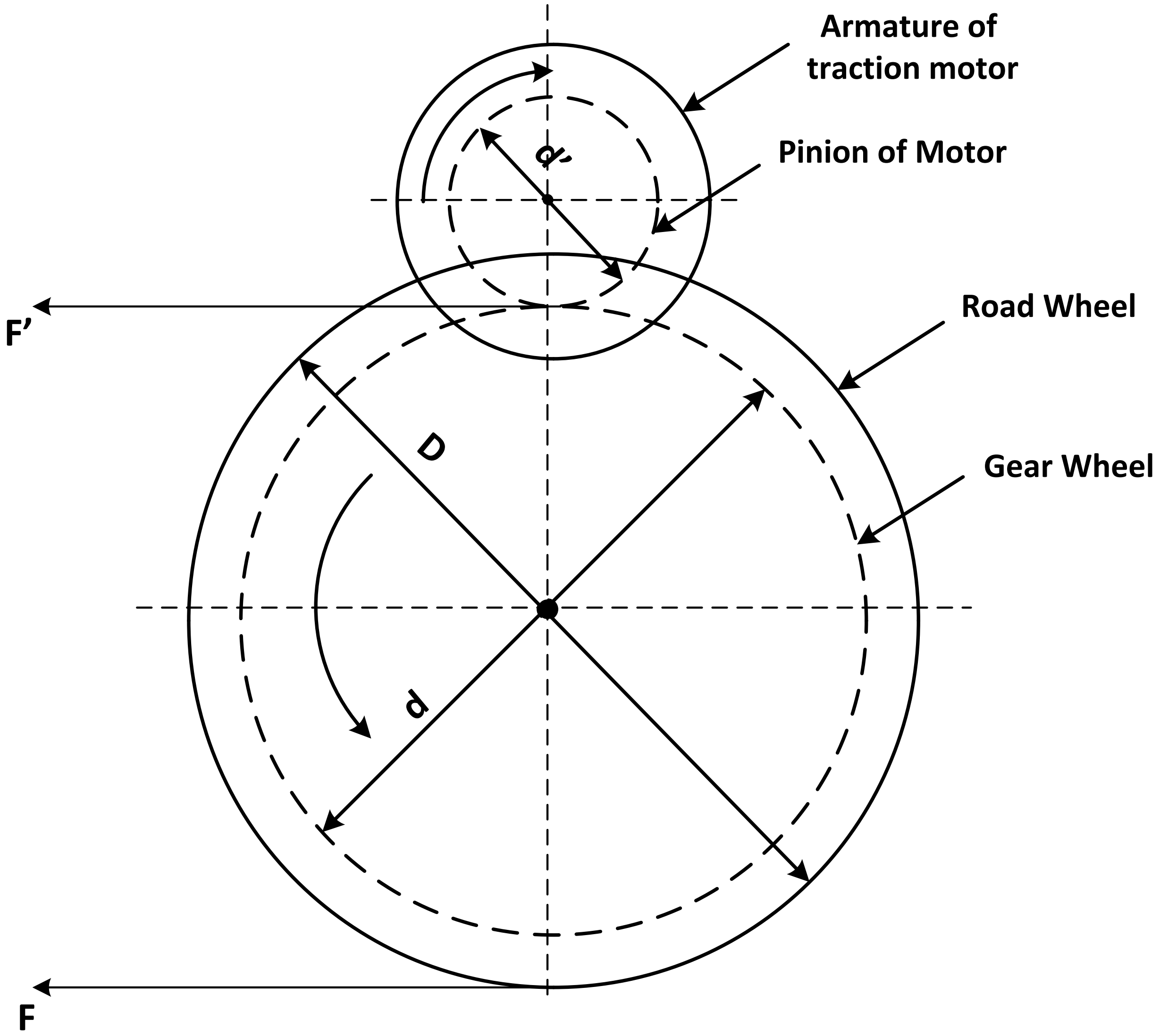

Figure 7.15 Transmission of Tractive Effort

$T = \text{Torque exerted by Motor}$
$F' = \text{Tractive effort at Pinion}$
$F = \text{Tractive effort at Wheel}$
$d' = \text{Diameter of Pinion}$
$d = \text{Diameter of gear Wheel}$
$D = \text{Diameter of Road Wheel}$
$\gamma = \text{gear ratio} = \frac{d}{d'}$
$\eta = \text{Efficiency of Transmission}$

Let, driving Motor exert a torque T in Nm
Tractive Effort at edge of pinion is given by

$$T = F'\frac{d'}{2} \text{ or } \boxed{F' = \frac{2T}{d'}}$$

Tractive effort transferred the driving wheel

$$F = \eta F'\left(\frac{d}{D}\right)$$

$$F = \eta \frac{2T}{d'}\left(\frac{d}{D}\right)$$

$$\boxed{F = \eta T \frac{2\gamma}{D}}$$

7.26 Co-efficient of adhesion(μ)

- Maximum friction force between driving wheel and track=μW
  Where, μ=co-efficient of adhesion between driving wheel and track
  W=Weight of train on driving axles
- Motion of train without slipping

$$\boxed{F \leq \mu W}$$

- Co-efficient of adhesion (μ)

$$\mu = \frac{Tractive\ effort\ to\ slip\ the\ wheels}{Adhesive\ Weight}$$

Table 7.5 Co-efficient of Adhesion

Speed in kmph	0	15	30	45	60	75
$\boldsymbol{\mu}$	0.25	0.18	0.14	0.12	0.10	0.09

- For clean dry rails μ=0.25
- For wet or greasy rails μ=0.08
- Depends upon
  - Friction between wheels and the rail track.
  - Series-Parallel connection of Motor.
  - Speed of Response of drive.
  - Smoothness with which torque can be controlled.
  - Nature of motor torque-speed characteristics.

7.27 Tractive effort for propulsion of train

- "The effective force necessary to propel the train at the wheel of locomotive is called the tractive effort." It measured in N.
- Total tractive effort required to run a train on track = Tractive effort required for linear and angular acceleration + Tractive effort to overcome the effort of gravity + Tractive effort to overcome the train resistance.
- $Ft=F_a \pm F_g + F_r$

(a) Tractive effort for Acceleration

- According to laws of dynamics,

$$Force = mass(kg) \times Acceleration(m/s^2)$$

$$F = m\,\alpha\ (N\ or\ kg{\cdot}m/s^2)$$

m=W (tones) (weight of train)
m=1000W kg-- (1)
Acceleration = α (km/h/s)
= α×1000/3600 (m/s²)
=0.2778 α (m/s²)---------------------- (2)

- So, tractive effort required for linear acceleration
  $F_a = m\ \alpha = 1000W \times 0.2778\ \alpha$
  $F_a = 277.8\ W\alpha\ (N)$
- Rotating parts of train such as wheels & motor also accelerate in angular direction.
- Tractive effort required is equal to tractive effort required to have angular acceleration of rotating parts and tractive effort required to have the linear acceleration.
- Angular acceleration depends on individual weight and radius of gyration of the rotating parts of train,
  W_e*=Equivalent or acceleration weight of train*
  $W_e > W$ *(8 to 15%)*
- Tractive effort required for acceleration
  $F_a = 277.8\ W_e\ \alpha\ (N)$

(b) Tractive effort to overcoming the effect of gravity

"When a train is on a slope, a force of gravity equal to the component of the dead weight along the slope acts on the train and tends to cause its motion down the gradient or slope."

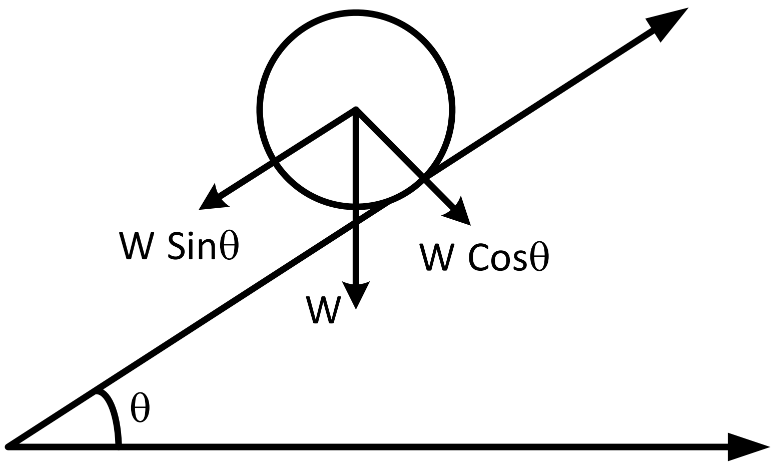

Figure 7.16 Effect of Gravity

- *Force due to gradient,* $F_g = 1000W\sin\theta$ *(kg).*
- *Percentage gradient (G%)*
  $G = \sin\theta$
  $G\% = 100 * \sin\theta$
  $\sin\theta = (G\%)/100$
  $F_g = 10WG\%\ (kg)$
  $= 10WG\% * 9.81\ (N)$
  $F_g = 98.1WG\%\ (N)$

(c) Tractive effort to overcome train resistance

- Train Resistance consists of all the forces resisting the motion of a train when it is running at uniform speed on a straight and level track.
- Train resistance
  - The friction at the various parts of the rolling stock.
  - The friction between the track and wheel.
  - Air resistance.
- The general equation for the train resistance is given as

  $R=K_1+K_2V+K_3V^2$

  Where, K_1, K_2, K_3 are constant and depends upon type of train and track

  R is resistance in N

  V is speed in km/hr
- Tractive effort required to overcome the train resistance

  $F_r=W*r$ (N)

  Where, r=Specific train Resistance, N/tonne of dead weight

Total Tractive Effort:-

$F_t=F_a \pm F_g F_r$

$F_t=277.8\ W_e\alpha \pm 98.1WG\%+W*r$

+ve sign for the motion up the gradient

-ve sign for the motion down the gradient

7.28 AC electric locomotive

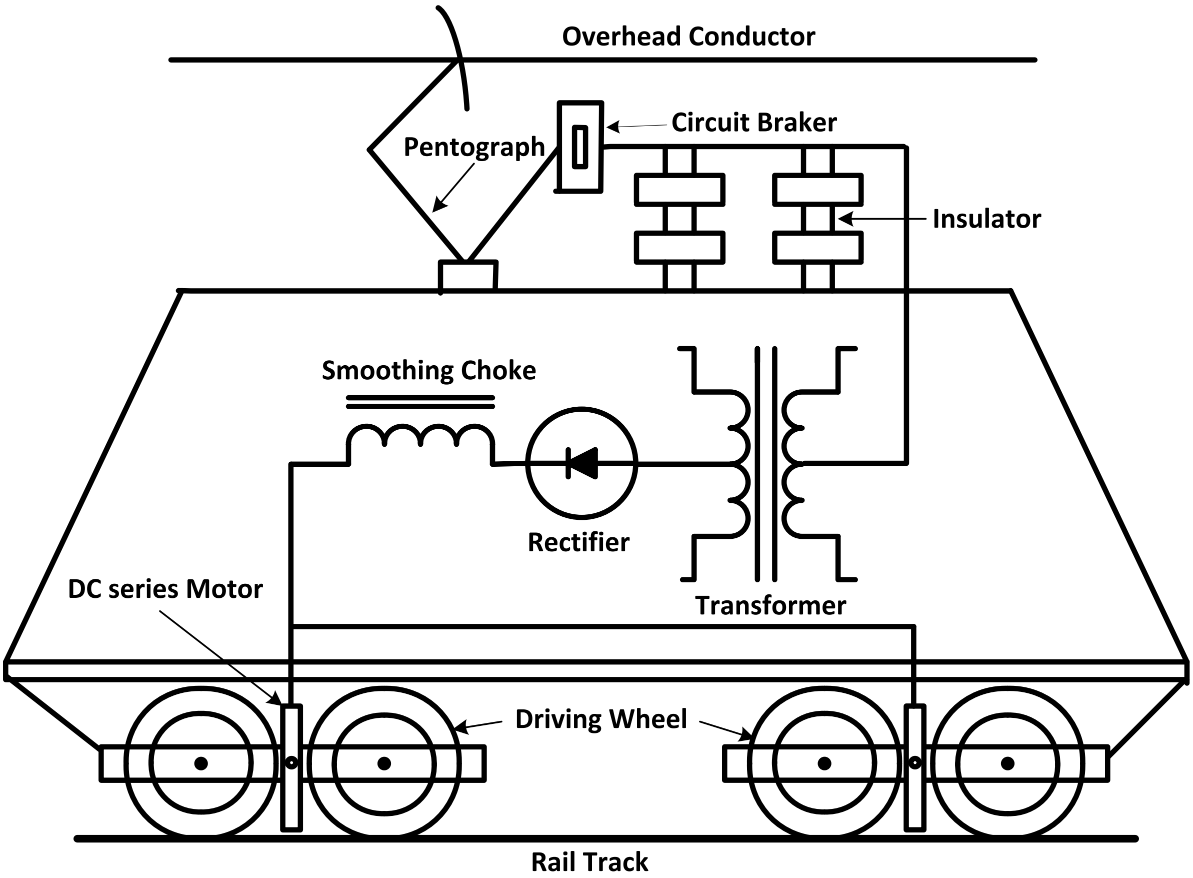

Figure 7.17 AC Electric Locomotive

(a) Overhead conductor

- This is the overhead conductor running along the track through which high voltage AC (22 to 25 kV) is supplied from traction substation and fed to the locomotive.

(b) Pantograph

- It is a current collecting device mounted on the roof of locomotive. It collects the required power from overhead conductor and feds to locomotive.

(c) Circuit Breaker

- The circuit breaker is a protective device for locomotive equipments. It is mounted on the roof of locomotive. The function of circuit breaker is to make the supply ON and OFF both in normal and faulty condition.

(d) On load Tap changer

- The on-load tap changer is a speed regulating devices of motors. It regulates motor speed by varying voltage from input side of the transformer.

(e) Transformer

- The transformer is used to step down the line voltage from 25 kV to 1500 V or required voltage to run the traction motor.

7.29 General features of traction motor

(a) Mechanical Features

- A traction motor must be robust and capable to withstand continues vibrations since service conditions are extremely severe.
- The weight of the traction motor should be minimum in order to increase the pay load capacity of the vehicle.
- The traction motor is located underneath a motor coach, therefore must be small in overall dimensions specially in its overall diameter.
- The traction motor must be totally enclosed type, particularly when mounted beneath the locomotive or motor coach, to provide protection against ingress of dirt, dust, water, mud etc.

  (Thus, for magnetic circuit of traction motor cast iron, which cannot withstand continuous vibrations, is not suitable. Use of cast steel or fabricated steel, which gives more mechanical strength, is made in place of cast iron. Those parts of the motor, which are not highly stressed; must be made of pressed or fabricated steel plates and light alloys.)

(b) Electrical Features

- <u>High Starting Torque:-</u> A traction motor must be capable of developing high starting torque, specially when train is to be accelerated at a reasonably high rate such as in case of urban or suburban services.
- <u>Simple Speed Control:-</u> The traction motor should be amenable to simple speed control methods as an electric train has to be started and stopped very often.
- <u>Self-relieving Property:-</u> The speed-torque characteristics of the motor should be such that the speed may fall with the increase in load. The motors having such speed-torque characteristics are self protective against excessive overloading as power output of a motor is proportional to the product of torque and speed.

- Possibility of dynamic or regenerative braking:- The traction motor should be amenable to easy and simple methods of rheostatic and/or regenerative braking,
- Capability of withstanding voltage fluctuations:- Traction motor should be capable of withstanding rapid fluctuations in supply voltage without undue effect on its performance since in traction work rapid voltage fluctuation owing to heavy current inrush at start, is common feature.
- Capability of withstanding temporary interruption of supply:- Traction motor should be capable of withstanding temporary interruptions of supply without undue rush of current, since it occurs at the instant of crossing over the cross-over and section insulators.
- Overload capacity:- Traction motor should be capable of taking excessive load as it is subjected to very arduous duty.
- Parallel running:- In traction work, usually more than one motor (two or four motors per motor car) are required. Traction motors, therefore, should be of such speed-torque and current-torque characteristics that when they are operated in parallel and mechanically coupled, they share the load almost equally.

  (No motor meets all the requirement mentioned above. Most suitable motor for dc systems are the series and compound motors whereas for ac systems the single phase series motors and 3-phase induction motors are employed.)

7.30 Starting and speed control of DC traction motors

- Various methods used for starting and controlling of speed of dc series motors are discussed below.

(a) Rheostatic Control

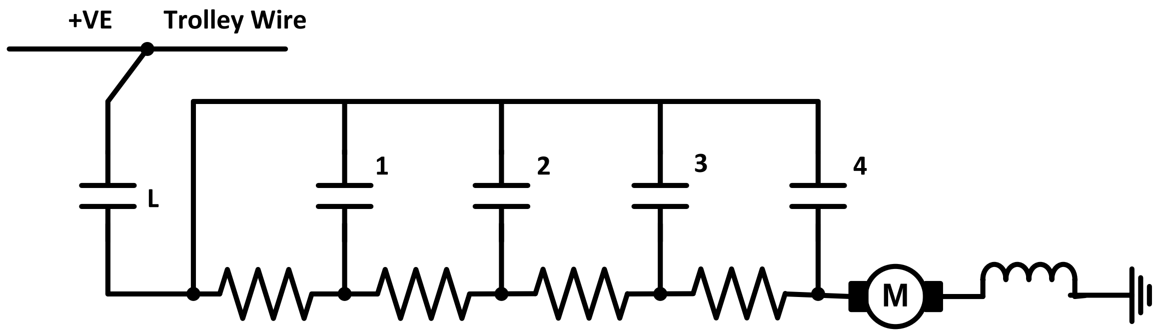

Figure 7.18 Rheostatic Control

- A series motor can be started by connecting as external resistance in series with the main circuit of motor. At the starting instant, since the back emf developed by the motor is zero, therefore, the resistance connected in series with the motor is maximum and is of such a value that the voltage drop across it with full load rated current is equal to line voltage.
- As motor speeds up, the back emf developed by the motor increases, therefore, the external resistance is gradually reduced in order to maintain the current constant throughout the starting or accelerating period.
- Basic traction motor circuit with rheostatic starting is shown in Figure 7.18.
- In this method there is a considerable loss of energy in the external circuit.

- The resistors employed are designed for short-time rating and not for continuous rating as they are required to carry current only during starting of motors. The motor can, therefore, have only one speed characteristics.

(b) Series-Parallel Control

- The main disadvantage of wastage of electrical energy in rheostatic control is partly overcome in this method when there are two or more motors.
- In case of two motors, the motors are first connected in series with each other and starting and control resistance as illustrated in Figure 7.19(a).

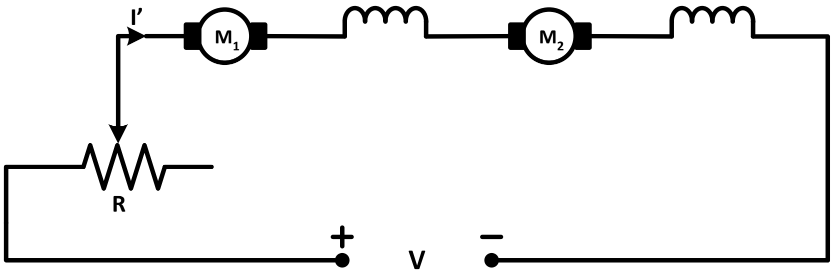

Figure 7.19(a)

- The additional resistance is gradually cut-out by controller as the motor attain speeds and finally the control resistance is totally removed, then each motor has one half of the line voltage across it, as shown in Figure 7.19(b).

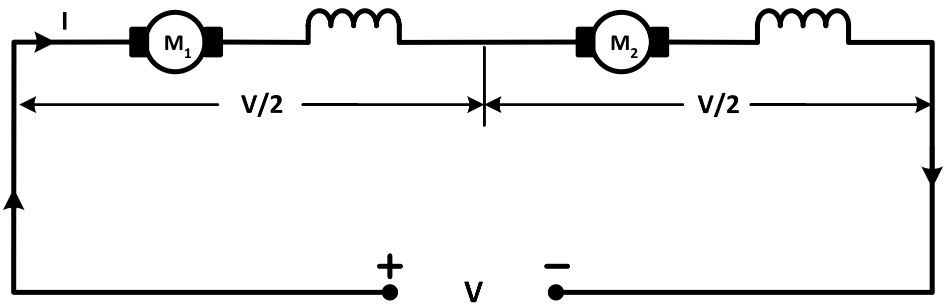

Figure 7.19(b)

- This is the first running position. In this position for any given value of armature current, each motor will run at half of its normal speed.
- In the next step the two motors are connected in parallel and in series with a variable resistance R, as shown in Figure 7.19(c).

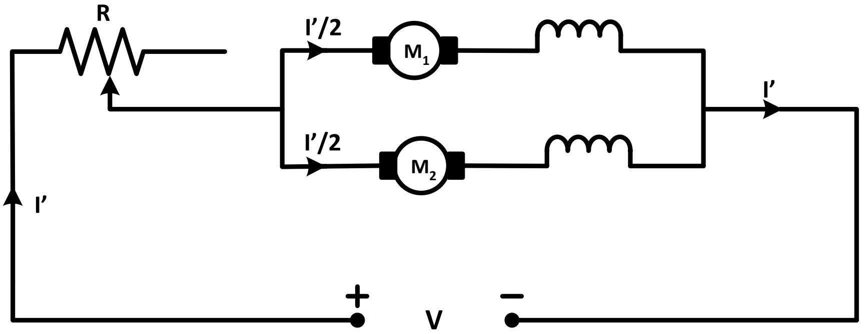

Figure 7.19(c)

- This resistance is gradually cut out as the motors attain the speed and finally when this resistance is totally removed from the circuit, as illustrated in Figure 7.19(d), the second position is obtained.

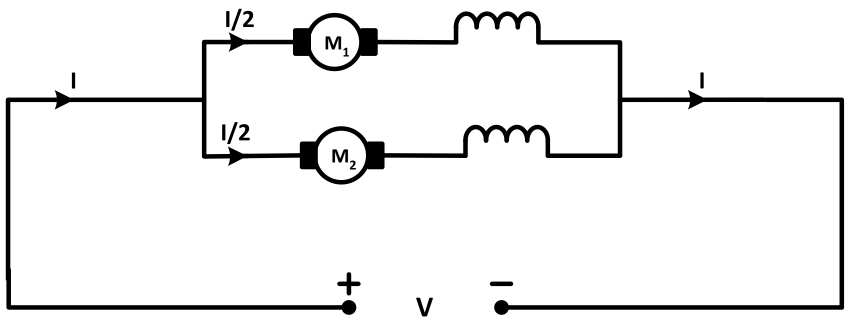

Figure 7.19(d)

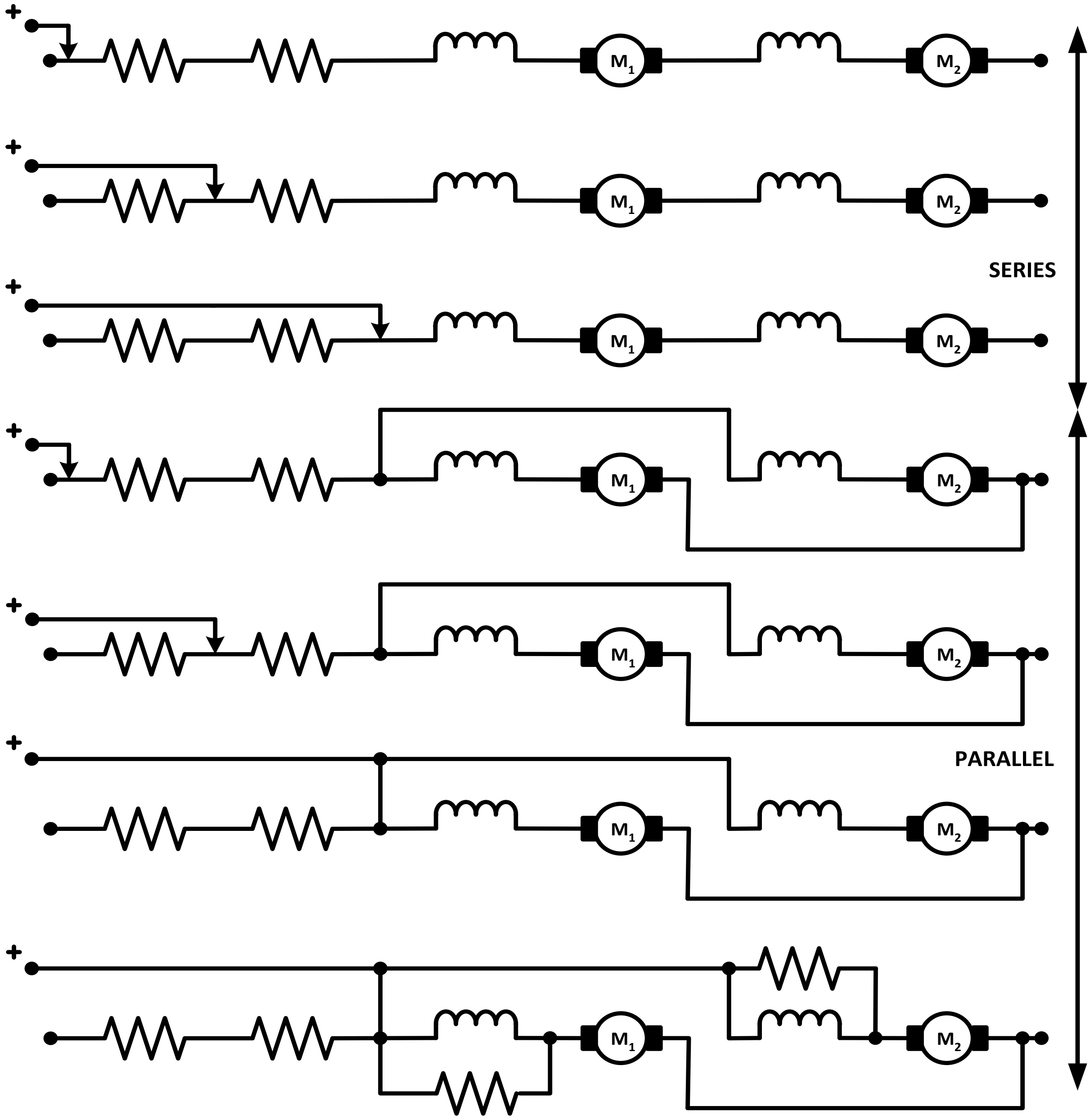

Figure 7.20 Combination of Series-Parallel and Resistance Control of DC Series Motors

- In this position each motor is connected across the full line voltage. A diagram of connections illustrating the switching sequence is given in Figure 7.20.

(c) Field Control

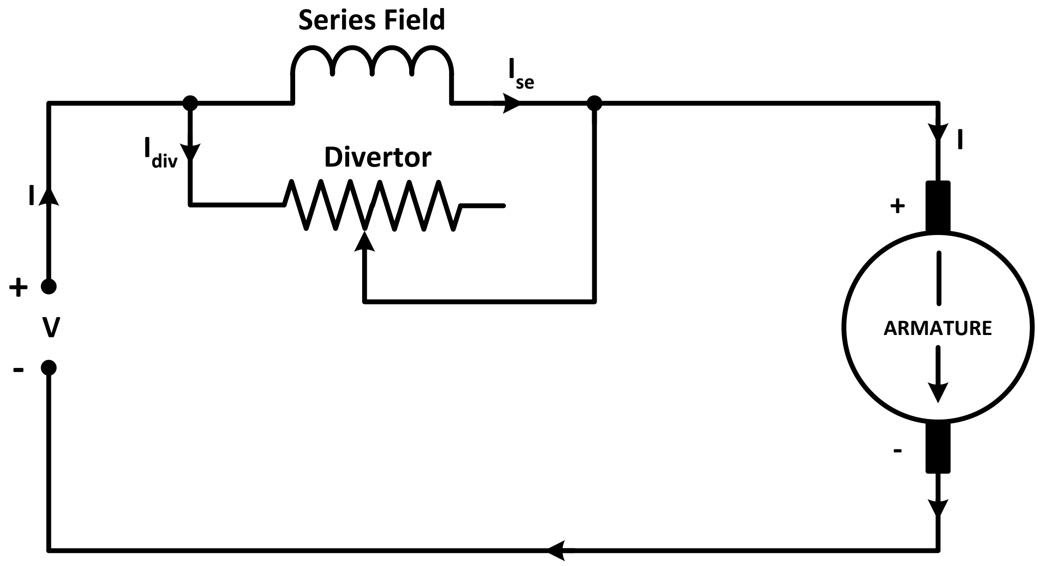

Figure 7.21 Field Divertor Method of Speed Control for DC Series Motors

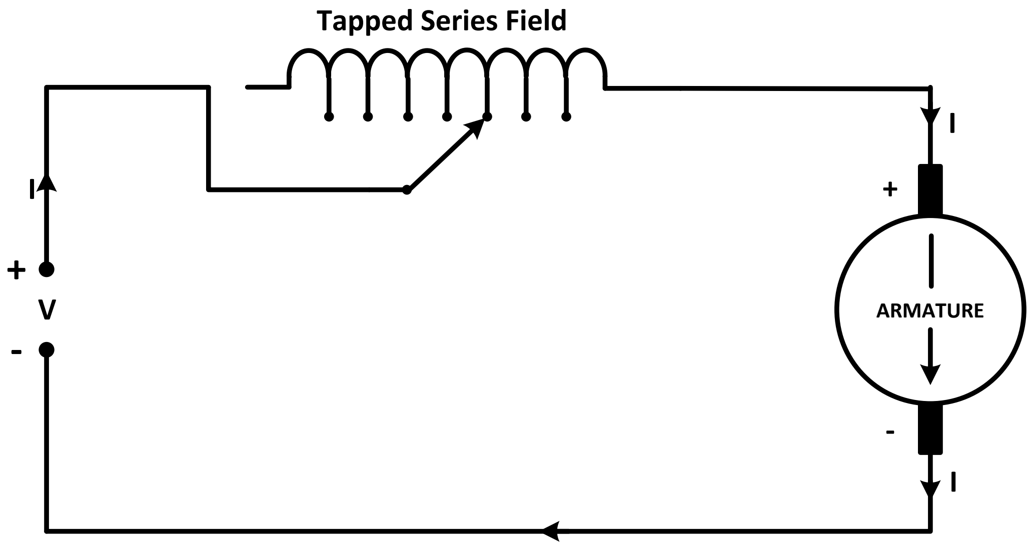

Figure 7.22 Tapped Field Control for DC Series Motors

- As the speed of the motor is inversely proportional to the flux (constant voltage), therefore the speed can be varied by varying the flux.
- It can be varied either (i) by connecting a variable resistance known as diverter in parallel with the field winding or (ii) by cutting out some of the field turns.
- In both case flux can be only reduced, therefore, this method is known as field weakening method and speed above normal can be obtained.
- By this method speed can be raised to the extent of 15 to 30 percent of normal speed owing the design difficulties arising with traction motor.
- This method is no use for starting purpose and by using field weakening method of speed control the necessity of changing the gear ratio can be eliminated.

7.31 Chopper control (DC EMU and AC EMU)

(a) DC EMU(DC Electrical Multiple Unit)

- Figure 7.23 shows arrangement of DC EMU. DC supply from overhead conductor is collected by pantograph and given to converter.
- Inverter is a device which converters DC to AC one inverter gives 3-phase AC output to 3-phase traction motor.
- Other inverter gives 3-phase output to a 3-phase transformer. The 3-phase supply can be used for air-conditioning, fans and compressors.
- The transformer output is converted to DC by means of a rectifier and this DC is used for battery charging control.
- Figure 7.23 shows that general block diagram of electronic power and auxiliary services on DC EMU.

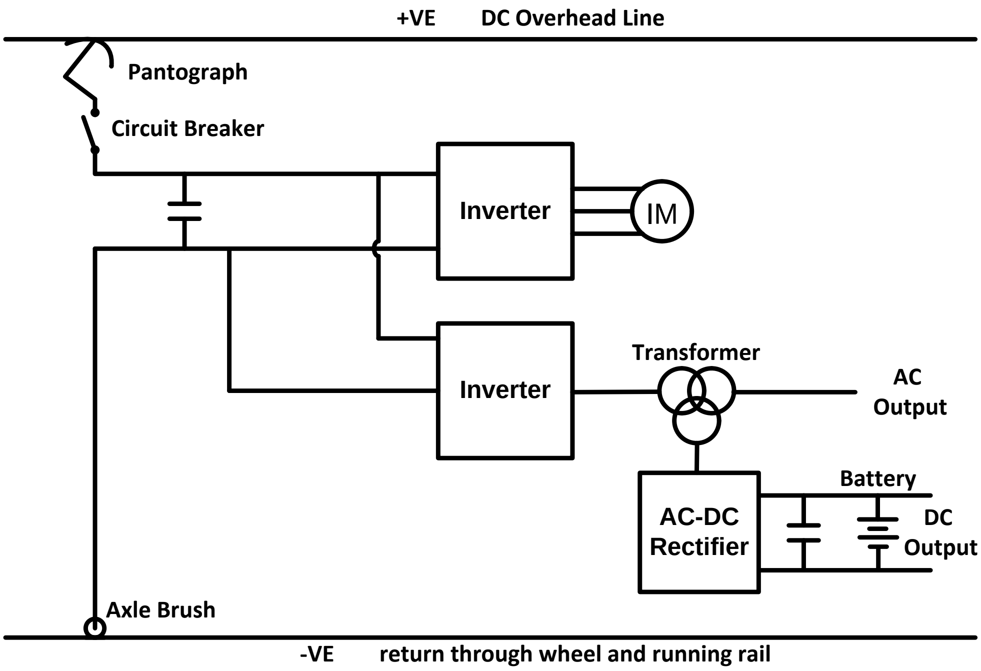

Figure 7.23 Block diagram of electronic power and auxiliary services on DC EMU

(b) AC EMU

- Figure 7.24 shows arrangement of AC EMU. Single phase AC supply is collected from overhead conductor by means of pantograph and it is given to the step down transformer. The output of transformer is converted to DC by a rectifier and then given to inverter.
- Figure 7.24 shows that general block diagram of electronic power and auxiliary services on AC EMU. The function of remaining components is same as that of DC EMU.

7.32 Metro system

- Metro system is underground railway system. It runs with electric power. The metro system is best suited for densely populated cities where local transport is crucial.
- The signaling activities are to be tightly coordinated. The headway distance is also crucial if more than one train works on single track.

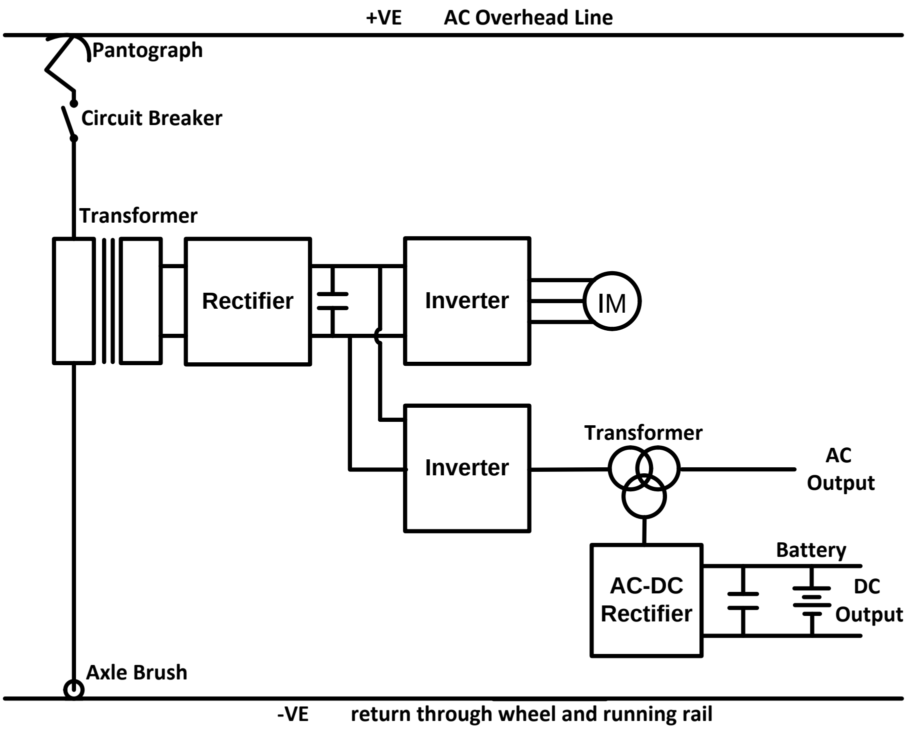

Figure 7.24 Block diagram of electronic power and auxiliary services on AC EMU

- The distance of travel of metro train is comparatively less as compared to normal train. It is meant for transport within metropolitan cities. The distance between stops is also less.
- The technology used in comparatively superior compared to normal train. The metro system is mainly used by people for transport and not used as goods carrier.

Table 7.6 Metro Rail in India

System	City	State	No. of Station	Traction
Kolkata Metro (1984)	Kolkata	West Bengal	24	750 V DC Third rail
Delhi Metro (2002)	Delhi NCR	Delhi, Haryana, Uttar Pardesh	160	25kV AC OHE
Namma Metro (2011)	Bengaluru	Karnataka	41	750 V DC Third rail
Rapid Metro (2013)	Gurgaon	Haryana	11	750 V DC Third rail
Mumbai Metro (2014)	Mumbai	Maharashtra	12	25kV AC OHE
Jaipur Metro (2015)	Jaipur	Rajasthan	9	25kV AC OHE
Chennai Metro (2015)	Chennai	Tamil Nadu	20	25kV AC OHE
Lucknow Metro (2017)	Lucknow	Uttar Pradesh	33	25kV AC OHE