

**POWER STATION ENGINEERING**  
**[REL7D005]**  
**LECTURE NOTES**  
**B. TECH IV YEAR–VII SEM (2024-25)**



**DEPARTMENT OF ELECTRICAL  
ENGINEERING  
MODERN ENGINEERING  
&  
MANAGEMENT STUDIES**  
**PREPARED BY-ASST. PROF.BISWAJIT NAYAK**

<b>7<sup>th</sup> Semester</b>	<b>REL7D005</b>	<b>Power Station Engineering</b>	<b>L-T-P 3-0-0</b>	<b>3 Credits</b>
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**Digital Learning Resources:**

Course Name: Facts Devices  
 Course Link: <https://nptel.ac.in/courses/108/107/108107114/>  
 Course Instructor: Prof. Avik Bhattacharya, IIT Roorkee

**Module-I:****(10hours)**

Introduction to different sources of energy and general discussion on their application to generation, Indian Energy Scenario. Prediction of Load: Connected Load, Maximum Load, Demand Factor, Average load, Load Factor, Load duration curves, Diversity Factor, Choice of Type of Generation, Capacity Factor, Reserve Factor, Plant Use Factor, Base Load, Intermediate Load and Peak Load Plants. Economics of power generation: Cost of Electrical Energy, Construction costs, Fixed cost, Costs for Energy, Depreciation of Plant, Fuel cost, Economic scheduling principle, Annual Operating Costs, Effect of Load Factor on cost per kWh, Tariff or Charge to Consumer.

**Module-II:****(8 hours)**

Nuclear power station: Introduction to fission & fusion, Principle of Nuclear Energy, Reactor Construction, Controlled Chain Reaction, Brief study of various Types of Power Reactor, Operational Control of Reactors, Location and layout of nuclear power plant, Economics of Nuclear Power Station.

**Module-III:****(10hours)**

Hydro Electric power station: Selection of site for hydro-electric power plant. Hydrology: Hydrological cycle, precipitation, run-off and its measurement, hydrograph, flow duration and mass curves, Estimation of amount stored by a dam across the river, Storage and Pondage, Elementary idea about Earthen and Concrete Dam. Types of Turbines: Operational principle of Kaplan and Francis Turbine and Pelton wheel, Speed and Pressure Regulation, Work done and Arrangement and location of Hydroelectric Station: Catchment area, Reservoir, Dam, Head Gate, Spillways, Pen stock, Surge Tanks, Scroll case, Draft tubes and Tail Race, Power House, Classification of Hydroelectric Power Plants. Governors, Plant auxiliaries.

**Module-IV:****(10hours)**

Thermal power station: Selection of site for thermal power plant. Main Parts and Working of a Steam Station: Overall Block Diagram indicating the air circuit, coal and ash circuit, water and steam circuit, various types of steam turbines, ash and coal handling system, High Pressure and High-capacity water tube boilers, Economizer, Superheaters, De-Superheater, Re-heater, Air Pre-heater. Draft System: Natural, Induced Forced and Balance Draft, PA fan, FD fan, ID fan, Chimney. Condensers, Feed water heaters, Evaporators, Make-up water, bleeding of steam, cooling water system. Electrostatic Precipitator: Basic working Principle and constructional details. Governors, Plant auxiliaries.

# Theory of Thermal Power Station

The theory of **thermal power station** or **working of thermal power station** is very simple. A **power generation plant** mainly consists of alternator runs with help of steam turbine. The steam is obtained from high pressure boilers. Generally in India, bituminous coal, brown coal and peat are used as fuel of boiler. The bituminous coal is used as boiler fuel has volatile matter from 8 to 33 % and ash content 5 to 16 %. To increase the thermal efficiency, the coal is used in the boiler in powder form.

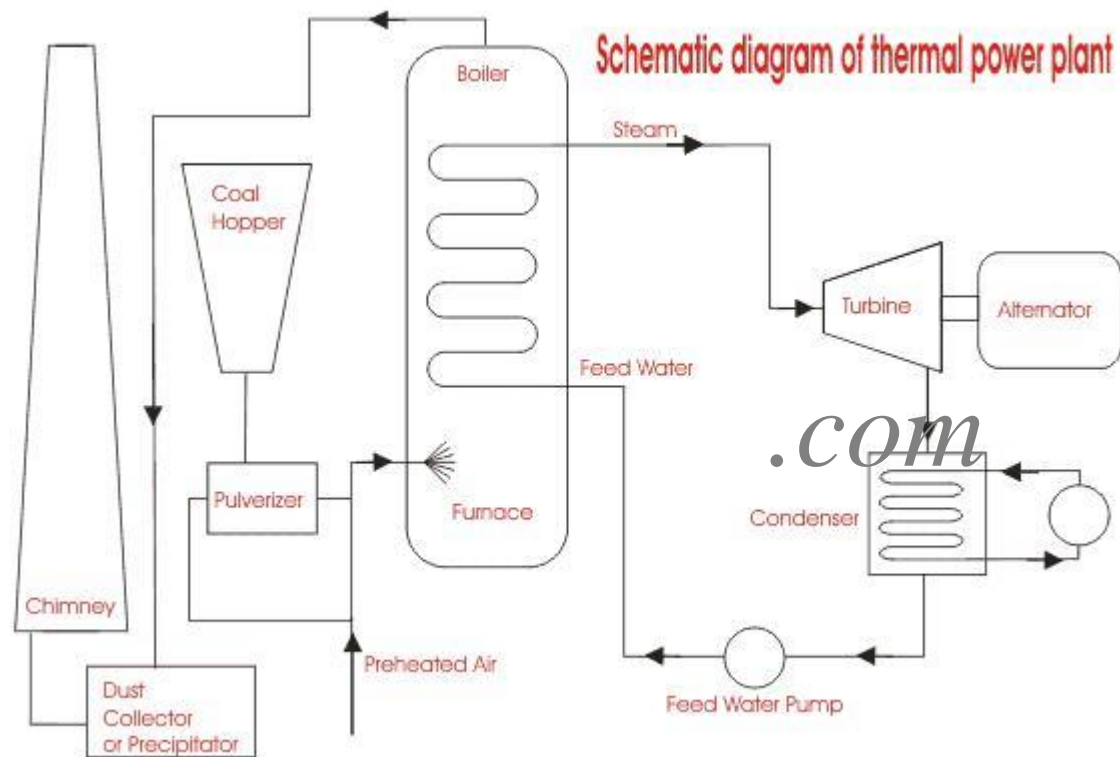
In **coal thermal power plant**, the steam is produced in high pressure in the steam boiler due to burning of fuel (pulverized coal) in boiler furnaces. This steam is further super heated in a super heater. This super heated steam then enters into the turbine and rotates the turbine blades. The turbine is mechanically so coupled with alternator that its rotor will rotate with the rotation of turbine blades. After entering in turbine the steam pressure suddenly falls and corresponding volume of the

condenses the low pressure wet steam. This condensed water is further supplied to low pressure water heater where the low pressure steam increases the temperature of this feed water, it is again heated in high pressure.

For better understanding we furnish every step of function of a thermal power station as follows,

- 1) First the pulverized coal is burnt into the furnace of steam boiler.
- 2) High pressure steam is produced in the boiler.
- 3) This steam is then passed through the super heater, where it further heated up.
- 4) This super heated steam is then entered into a turbine at high speed.
- 5) In turbine this steam force rotates the turbine blades that means here in the turbine the stored potential energy of the high pressured steam is converted into mechanical energy.

### Line Diagram of Power Plant:



6) After rotating the turbine blades, the steam has lost its high pressure, passes out of turbine blades and enters into a condenser.

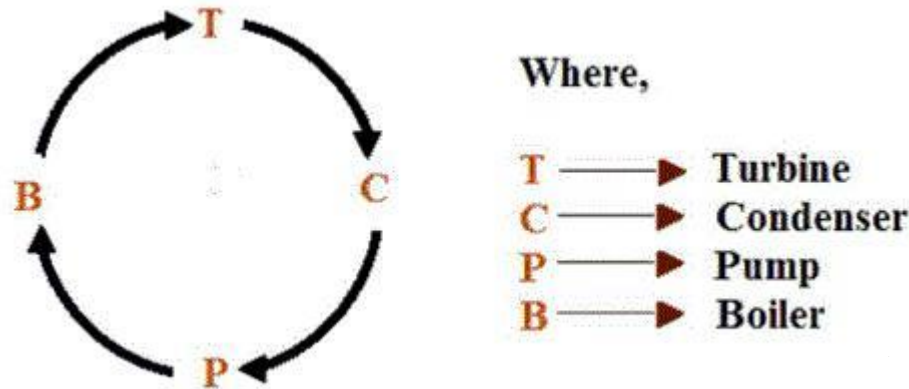
7) In the condenser the cold water is circulated with help of pump which condenses the low pressure wet steam.

8) This condensed water is then further supplied to low pressure water heater where the low pressure steam increases the temperature of this feed water, it is then again heated in a high pressure heater where the high pressure of steam is used for heating.

9) The turbine in thermal power station acts as a prime mover of the [alternator](#).

## Overview of Thermal Power Plant:

A typical Thermal Power Station Operates on a Cycle which is shown below.



In [steam boiler](#) the water is heated up by burning the fuel in air in the furnace & the function of the boiler is to give dry super heated steam at required temperature.

The working fluid is water and steam. This is called feed water and steam cycle. The ideal

Thermodynamic Cycle to which the operation of a Thermal Power Station closely resembles is the

RANKINE CYCLE.

The steam so produced is used in driving the steam Turbines. This turbine is coupled to [synchronous generator](#) (usually three phase synchronous alternator), which generates electrical energy.

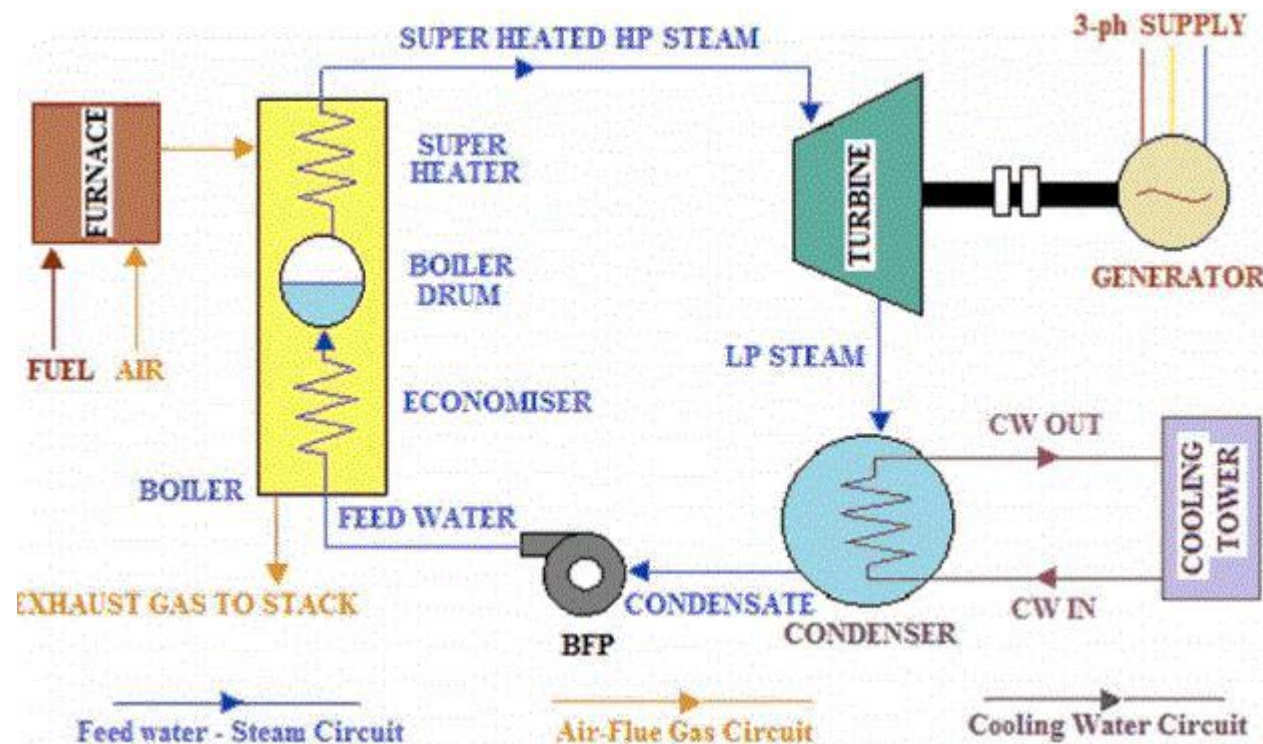
The exhaust steam from the turbine is allowed to condense into water in [steam condenser of turbine](#), which creates suction at very low pressure and allows the expansion of the steam in the turbine to a very low pressure. The principle advantages of condensing operation are the increased amount of energy extracted per kg of steam and thereby increasing efficiency and the condensate which is fed into the boiler again reduces the amount of fresh feed water.

The condensate along with some fresh make up feed water is again fed into the boiler by pump (called the boiler feed pump).

In condenser the steam is condensed by cooling water. Cooling water recycles through cooling tower. This constitutes cooling water circuit.

The ambient air is allowed to enter in the boiler after dust filtration. Also the flue gas comes out of the boiler and exhausted into atmosphere through stacks. These constitute air and flue gas circuit. The flow of air and also the static pressure inside the [steam boiler](#) (called draught) is maintained by two fans called **Forced Draught (FD)** fan and **Induced Draught(ID)** fan.

The total scheme of a typical thermal power station along with different circuits is illustrated below.



Inside the boiler there are various heat exchangers, viz. 'Economiser', 'Evaporator' (not shown in the fig above, it is basically the water tubes, i.e. downcomer riser circuit), 'Super Heater' (sometimes 'Reheater', 'air preheater' are also present).

In Economizer the feed water is heated to considerable amount by the remaining heat of flue gas.

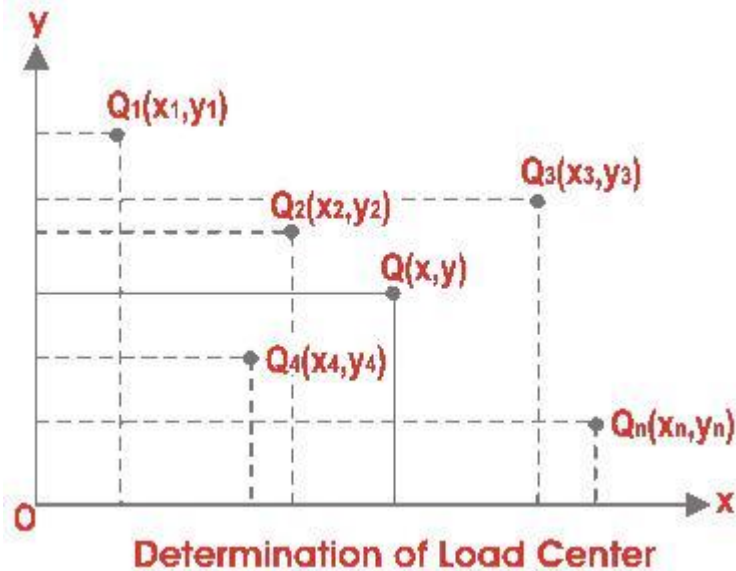
The Boiler Drum actually maintains a head for natural circulation of two phase mixture (steam + water) through the water tubes.

There is also Super Heater which also takes heat from flue gas and raises the temperature of steam as per requirement.

### **Efficiency of Thermal Power Station or Plant**

The overall efficiency of a **thermal power station** or plant varies from **20%** to upon plant capacity. **26%** and it depends

### **Thermal Power Plant Location:**



optimizing the profit, the location of the station is much important factor. **Power generation plant** location plays an optimizing part in the economy of the station.

A thermal power station or thermal power plant has ultimate target to make business profit. Hence for

Let's  $Q_1(x_1, y_1)$ ,  $Q_2(x_2, y_2)$ ,  $Q_3(x_3, y_3)$ ,  $Q_4(x_4, y_4)$ , .....and  $Q_n(x_n, y_n)$

The most economical , location of power plant can be determined by graphical method as described below,

The most economical and ideal power plant location is the center of gravity of the load because for such a power generation plant the length of the power transmission network will be minimum, thus the capital cost to the system is reduced.

Let's explain the graphical method, say, X and Y be two reference axes.

are n numbers of load centers. From the above graph we get, the coordinates of the center of gravity of the load,  $Q(x, y)$  where

$$x = \frac{x_1 Q_1 + x_2 Q_2 + x_3 Q_3 + \dots \dots \dots x_n Q_n}{Q_1 + Q_2 + Q_3 + \dots \dots \dots Q_n} \text{ and } y = \frac{y_1 Q_1 + y_2 Q_2 + y_3 Q_3 + \dots \dots \dots y_n Q_n}{Q_1 + Q_2 + Q_3 + \dots \dots \dots Q_n}$$



Obviously the location of thermal power station is best at the center of gravity of the load, but many times it is not possible to establish a thermal power plant at the CG of the load. Since normally CG point of the load may be at the heart of the city. so other many points to be considered to decide the best optimized location of the power plant.

- 1) The **electric power generation plant** must be constructed at such a place where the cost of land is quite reasonable.
- 2) The land should be such that the acquisition of private property must be minimum.
- 3) A large quantity of cooling water is required for the condensers etc of **thermal power generation plant**, hence the plant should preferably situated beside big source of natural water source such as big river.
- 4) Availability of huge amount of fuel at reasonable cost is one of the major criterion for choosing plant location.
- 5) The plant should be established on plane land.
- 6) The soil should be such that it should provide good and firm foundation of plant and buildings.
- 7) The **thermal power plant** location should not be very nearer to dense locality as there are smoke, noise steam, water vapors etc.
- 8) There must be ample scope of development of future demand.
- 9) Place for ash handling plant for thermal power station should also be available very near by.
- 10) Very tall chimney of power station should not obstruct the traffics of air ships.

### **Advantages & Disadvantages of Thermal Power Station**

#### **Advantages:**

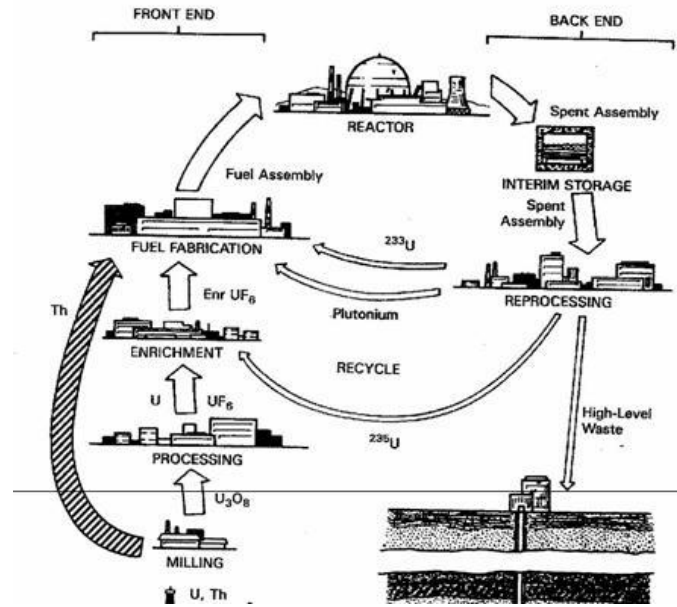
- 1) Economical for low initial cost other than any generating plant.
- 2) Land required less than [hydro power plant](#).
- 3) Since coal is main fuel & its cost is quite cheap than petrol/diesel so generation cost is economical.
- 4) There are easier maintenance.
- 5) Thermal power plant can be installed in any location where transportation & bulk of water are available.

- 1) The running cost for a thermal power station is comparatively high due to fuel, maintenance etc.
- 2) Large amount of smoke causes air pollution. The thermal power station is responsible for Global warming.
- 3) The heated water that comes from thermal power plant has an adverse effect on the lives in the water and disturbs the ecology.

## Overview of Nuclear Reactors:

Learning Objectives:

Gain broad understanding of PWRs, BWRs, HTGRs



# Making Nuclear Fuel

After uranium ore is mined, it must pass through several processing steps before it can be used in a power plant. The ore is milled to remove chemical impurities. Then, the fissionable uranium isotope ( $U^{235}$ ) is concentrated in a process called enrichment. The enriched uranium in powder form is pressed into small pellets and sealed into metal tubes. The tubes are bundled into fuel assemblies and shipped to a nuclear plant and put into the reactor.



## **Objectives to Make Electricity**

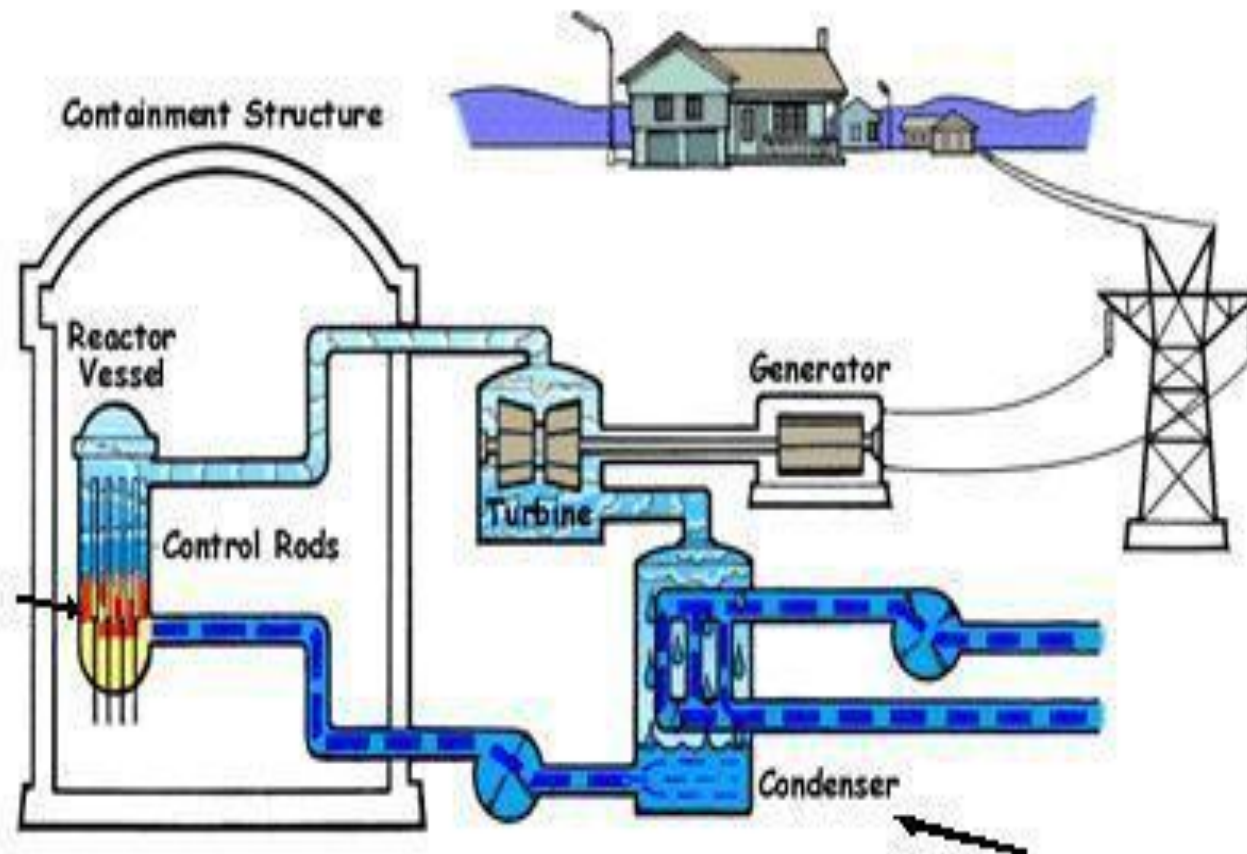
1. Make heat
2. Remove heat using a fluid or gas
3. Pass the fluid or gas through a turbine
4. Turning an electric generator to make Electricity

## **Removing Heat**

- Fluid (water or liquid metal) or gas is pumped through the core to remove heat generated in fuel due to fissioning.
- Pumps needed to circulate coolant
- Transfer directly to turbines or to steam generators (PWRs)
- Condense steam to recirculate back to the core to provide cooling

## Basics of Power Conversion

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## **Power Reactor Types:**

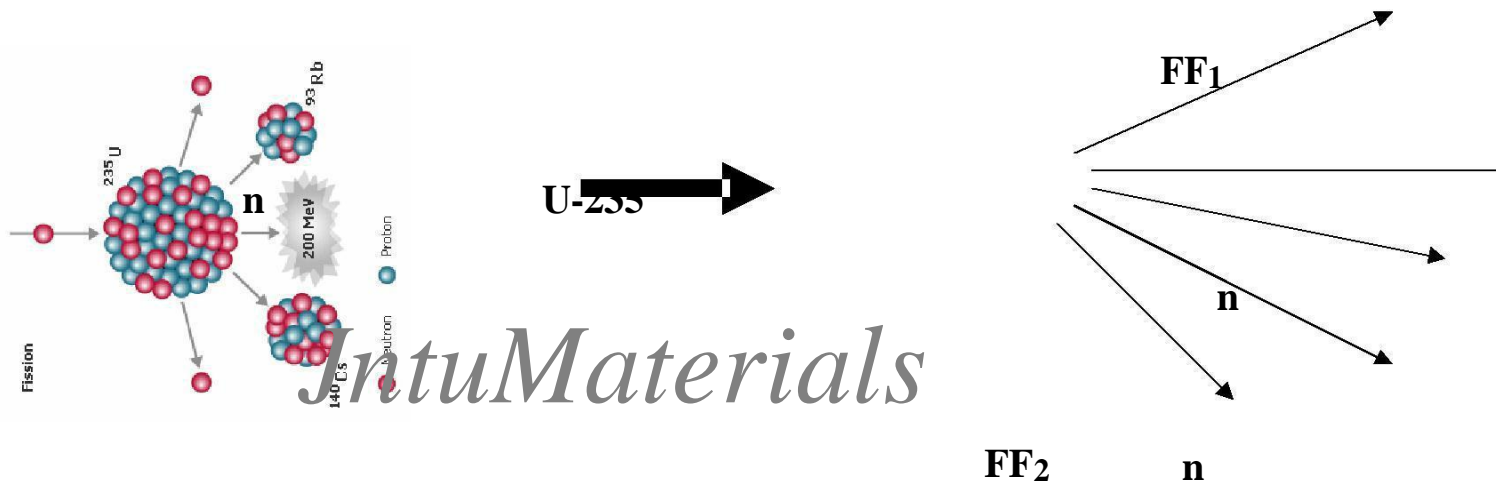
- – Pressurized Water Reactor
- – Boiling Water Reactor
- – Natural Uranium Heavy Water Cooled Reactor (CANDU)
- – RBMK - Russian Chernobyl Like - Water Cooled
- – Fast Reactors - Liquid Metal (Sodium)
- – Gas Reactors (CO<sub>2</sub> or Helium Cooled)
- – Molten Salt Cooled Reactors (Organic Coolants)

## **Making Heat**

- Use the fissioning of uranium atoms (or plutonium) to release 200 Million electron volts per fission.
  - Need to enrich natural uranium to 3 to 4 weight percent U-235 (from 0.7% found in nature.
-

uranium into pellets clad in zirconium assemblies which are placed into the reactor core.

## Fission Event



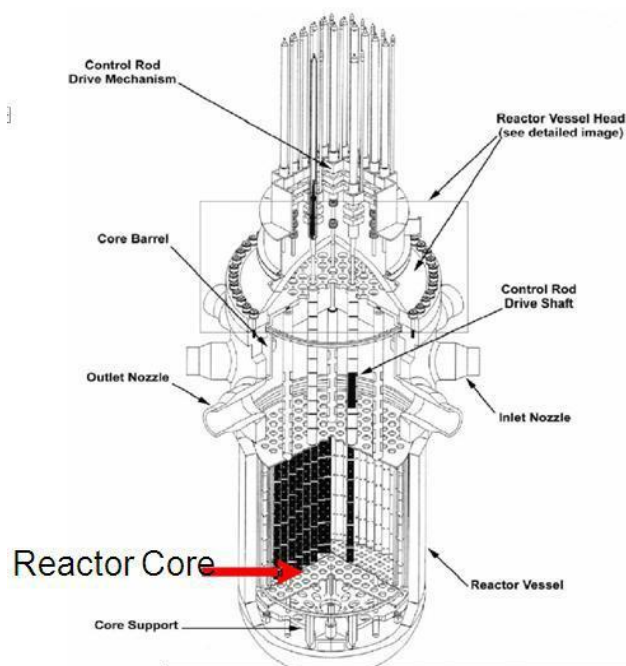
- Release of excess neutrons creates the potential for chain reaction.
- 
- The energy (mostly as kinetic energy of the fission fragments) is substantial.



## Energy Release:

- 1 fission = 200 Mev
- 1 gram U-235 fissioned =  $8.6 \times 10^{10}$  joules = 24,000 kwh  
(Equivalent to lighting a small city for overnight)  
24,000 kwh requires 3.2 tons of coal
- 12.6 bbls oil Energy Density  
(energy / mass)
- Energy Density of U-235 = 28,000 times energy density of coal

## Creating the Reactor Core:

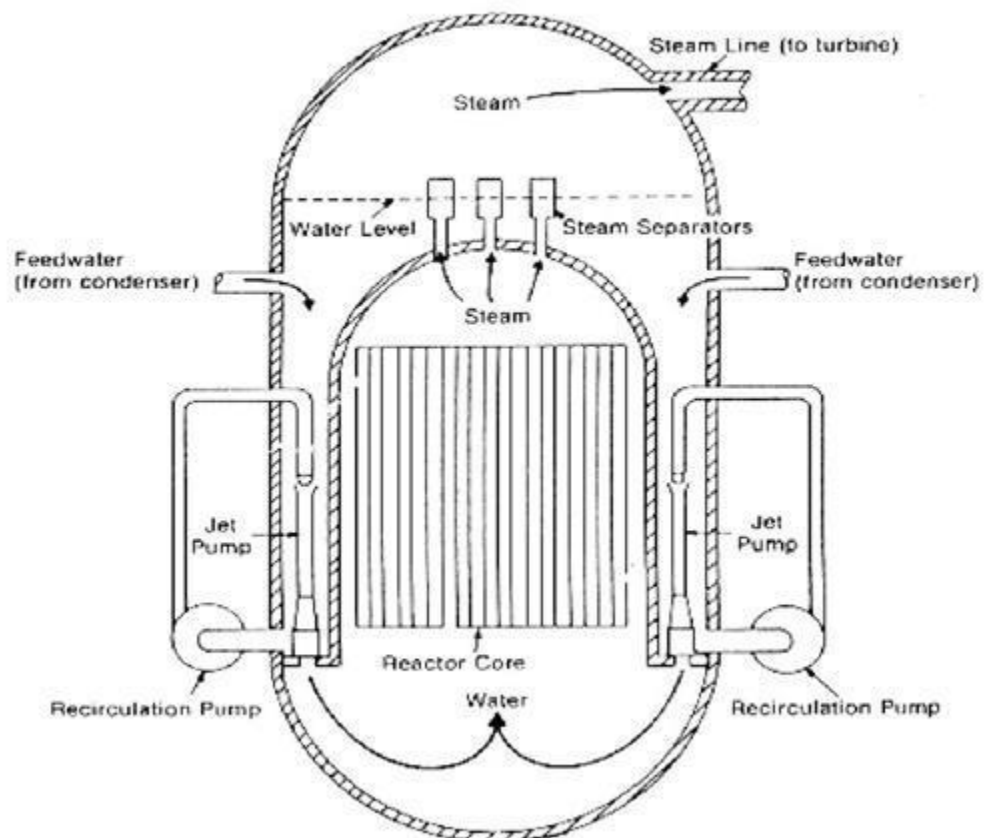
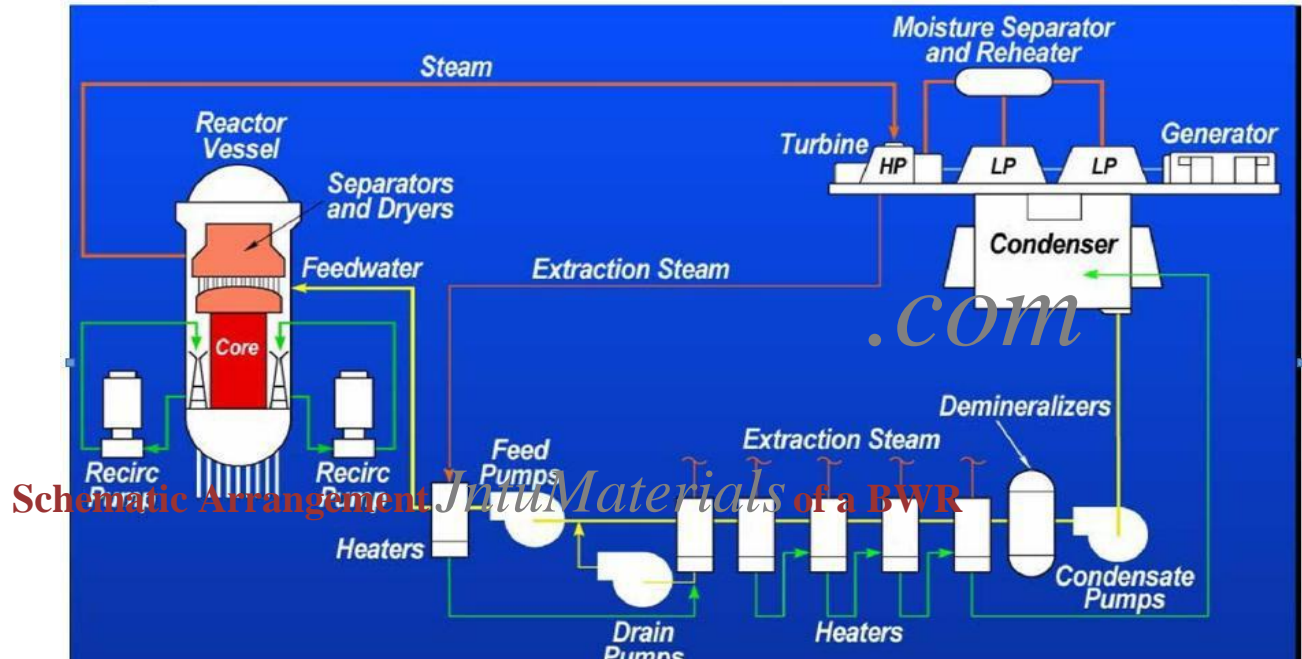


- Need to model uranium fuel
- Reactor internals
- Coolant flow
- Apply Reactor Physics
- Develop neutron flux solutions
- Yields power distributions
- Creates heat that must be removed

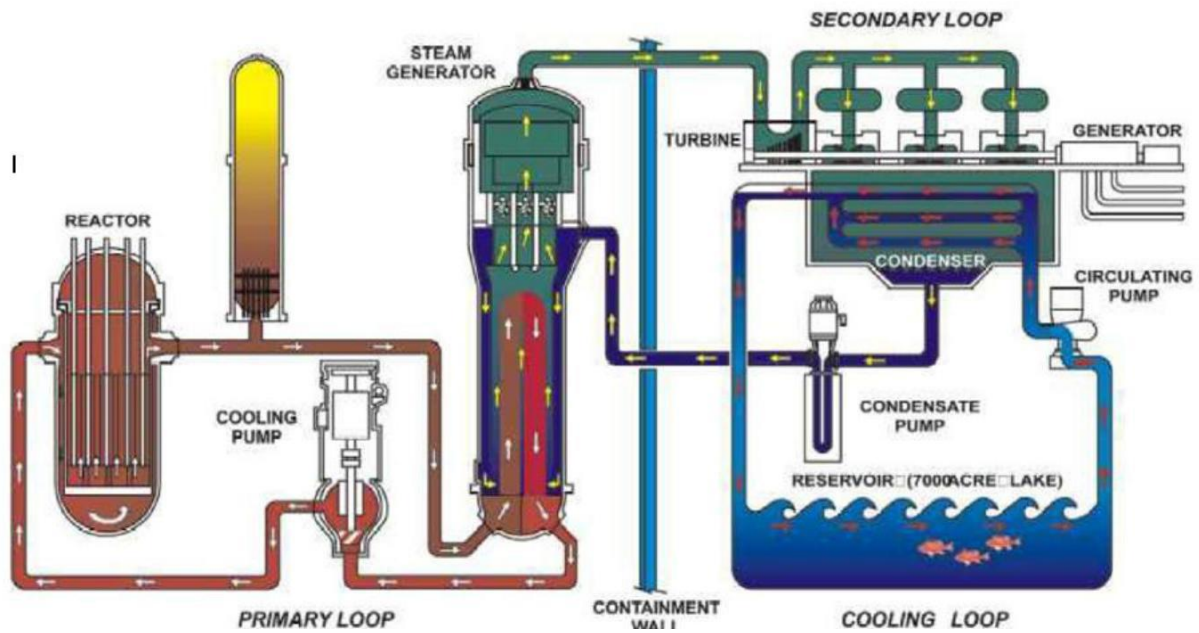
## Important Factors in Design

- Reactor Core Design
  - Fuel Design
  - Reactor Physics - Core Power Distribution
  - Reactivity Control - Ability to shutdown plant •
- Safety Analysis - no fuel failure or melting
- Core Heat Removal
  - Coolant - Heat Transfer
  - Safety Systems (Emergency)

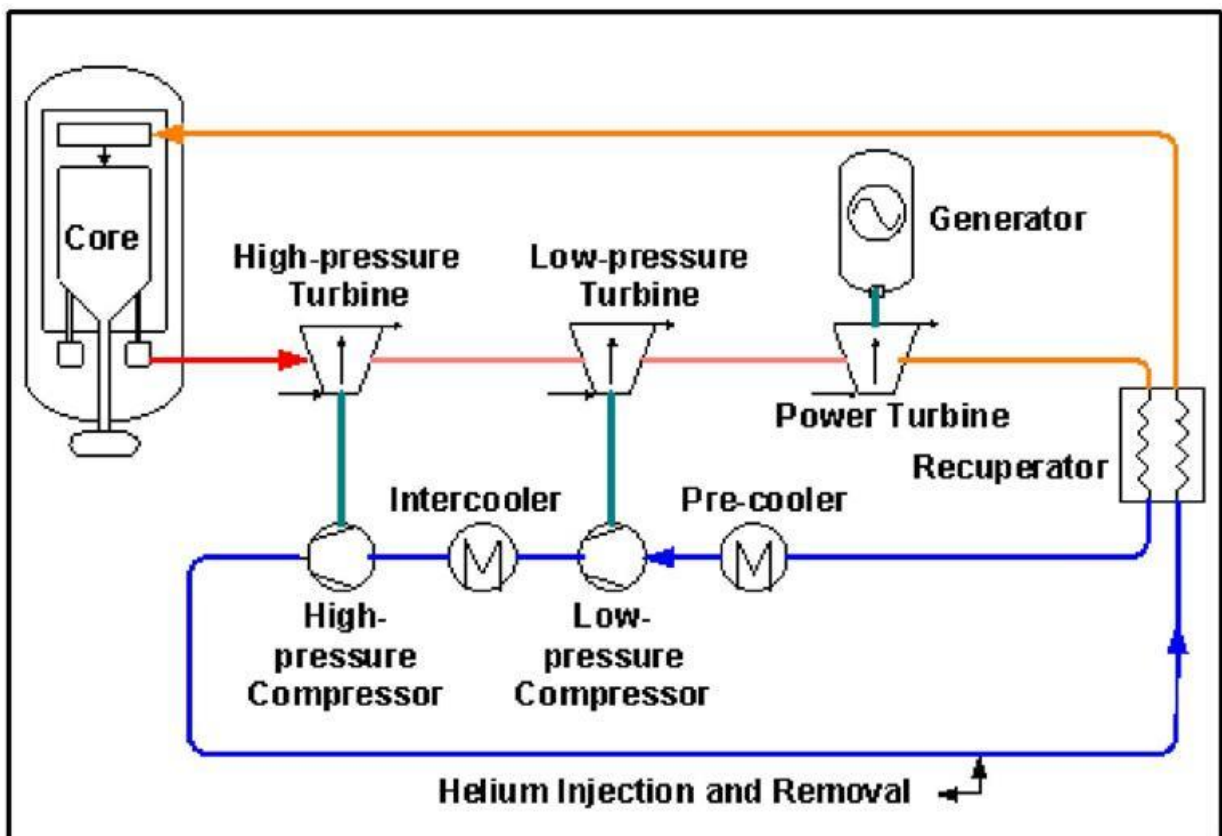
- Confinement of Radioactivity
- Electricity Production
- **BWR Power Cycle**



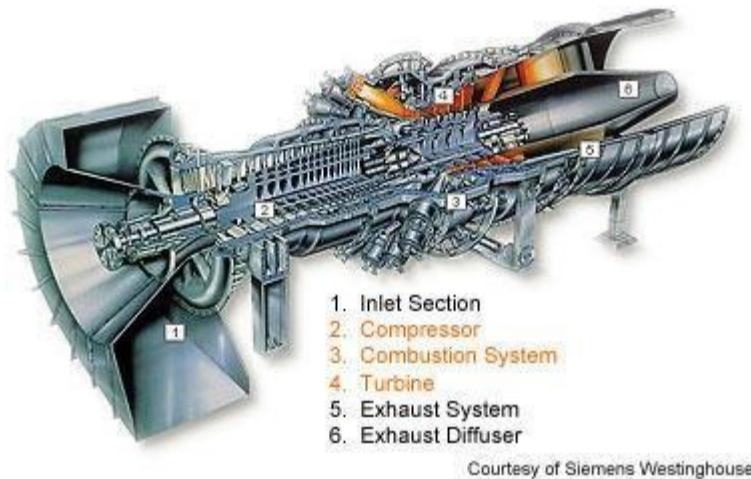
## Pressurized Water Reactors



## Power Cycle –Brayton



## How Gas Turbine Power Plants Work:



The combustion (gas) turbines being installed in many of today's natural-gas-fueled power plants are complex machines, but they basically involve three main sections:

**The compressor:**, which draws air into the engine, pressurizes it, and feeds it to the combustion chamber at speeds of hundreds of miles per hour.

**The combustion system:** typically made up of a ring of fuel injectors that

inject a steady stream of fuel into combustion chambers where it mixes with the air. The mixture is burned at temperatures of more than 2000 degrees F. The combustion produces a high temperature, high pressure gas stream that enters and expands through the turbine section.

**The turbine:** is an intricate array of alternate stationary and rotating aerofoil-section blades. As hot combustion gas expands through the turbine, it spins the rotating blades. The rotating blades perform a dual function: they drive the compressor to draw more pressurized air into the combustion section, and they spin a generator to produce electricity.

**Land based gas turbines are of two types:**(1) heavy frame engines and (2) aeroderivative engines. Heavy frame engines are characterized by lower pressure ratios (typically below 20) and tend to be physically large. Pressure ratio is the ratio of the compressor discharge pressure and the inlet air pressure. Aeroderivative engines are derived from jet engines, as the name implies, and operate at very high compression ratios (typically in excess of 30). Aeroderivative engines tend to be very compact and are useful where smaller power outputs are needed. As large frame turbines have higher

power outputs, they can produce larger amounts of emissions, and must be designed to achieve low emissions of pollutants, such as NO<sub>x</sub>.

One key to a turbine's fuel-to-power efficiency is the temperature at which it operates. Higher temperatures generally mean higher efficiencies, which in turn, can lead to more economical operation. Gas flowing through a typical power plant turbine can be as hot as 2300 degrees F, but some of the critical metals in the turbine can withstand temperatures only as hot as 1500 to 1700 degrees F. Therefore, air from the compressor might be used for cooling key turbine components, reducing ultimate thermal efficiency.



## **Introduction:**

### **Distribution Systems—General**

The electrical energy produced at the generating station is conveyed to the consumers through a network of transmission and distribution systems. It is often difficult to draw line between the transmission and distribution systems of a large power system. It is impossible to distinguish the two merely by their voltage because what was considered as a high voltage a few years ago is now considered as a low voltage. In general, distribution system is that part of power system which distributes power to the consumers for utilization. The transmission and distribution systems are similar to man's circulatory system. The transmission system may be compared with arteries in the human body and distribution system with capillaries. They serve the same purpose of supplying the ultimate consumer in the city with the life-giving blood of civilization—electricity. In this chapter, we shall confine our attention to the general introduction to distribution system.

## 12.1.Distribution System:

That part of power system which distributes electric power for local use is known as **distribution system**.

In general, the distribution system is the electrical system between the sub-station fed by the transmission system and the consumers meters. It generally consists of *feeders*, *distributors* and the *service mains*. Fig. 12.1 shows the single line diagram of a typical low tension distribution system.

(i)**Feeders**: A feeder is a conductor which connects the sub-station (or localised generating station) to the area where power is to be distributed. Generally, no tappings are taken from the feeder so that current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.

(ii)**Distributor**: A distributor is a conductor from which tappings are taken for supply to the consumers. In Fig. 12.1, *AB*, *BC*, *CD* and *DA* are the distributors. The current through a distributor is not constant because tappings are taken at various places along its length. While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variations is  $\pm 6\%$  of rated value at the consumers' terminals.

(iii)*Service mains*. A service mains is generally a small cable which connects the distributor to the consumers' terminals.



## of Distribution Systems

A distribution system may be classified according to ;

i)*Nature of current.* According to nature of current, distribution system may be classified as (a) d.c. distribution system (b) a.c. distribution system. Now-a-days, a.c. system is universally adopted for distribution of electric power as it is simpler and more economical than direct current method.

(ii)*Type of construction.* According to type of construction, distribution system may be classified as (a) overhead system (b) underground system. The overhead system is generally employed for distribution as it is 5 to 10 times cheaper than the equivalent underground system. In general, the underground system is used at places where overhead construction is impracticable or prohibited by the local laws.

(iii) **Scheme of connection:** According to scheme of connection, the distribution system may be classified as (a) radial system (b) ring main system (c) inter-connected system.

Each scheme has its own advantages and disadvantages and those are discussed in Art.12.7.

### 12.3 A.C. Distribution:

Now-a-days electrical energy is generated, transmitted and distributed in the form of alternating current. One important reason for the widespread use of alternating current in preference to direct current is the fact that alternating voltage can be conveniently changed in magnitude by means of a transformer. Transformer has made it possible to transmit a.c. power at high voltage and utilize it at a safe potential. High transmission and distribution voltages have greatly reduced the current in the conductors and the resulting

according to voltage or bulk capacity. However, in general, the a.c. distribution system is the electrical system between the step-down substation fed by the transmission system and the consumers' meters. The a.c. distribution system is classified into (i) primary distribution system and (ii) secondary distribution system. line losses.



There is no definite line between transmission and distribution

**(i) Primary distribution system.** It is that part of a.c. distribution system which operates at voltages somewhat higher than general utilisation and handles large blocks of electrical energy than the average low-voltage consumer uses. The voltage used for primary distribu



## Principles of Power System:

To depends upon the amount of power to be conveyed and the distance of the substation required to be fed. The most commonly used primary distribution voltages are 11 kV, 6.6 kV and 3.3 kV. Due to economic considerations, primary distribution is carried out by 3-phase, 3-wire system.

Fig. 12.2 shows a typical primary distribution system. Electric power from the generating station is transmitted at high voltage to the substation located in or near the city. At this substation, voltage is stepped down to 11 kV with the help of step-down transformer. Power is supplied to various substations for distribution or to big consumers at this voltage. This forms the high voltage distribution or primary distribution.

**(ii) Secondary distribution system:** It is that part of a.c. distribution system which includes the range of voltages at which the ultimate consumer utilises the electrical energy delivered to him. The secondary distribution employs 400/230 V, 3-phase, 4-wire system.

Fig. 12.3 shows a typical secondary distribution system. The primary distribution circuit delivers power to various substations, called distribution sub-stations. The substations are

situated near the consumers' localities and contain step-down transformers. At each distribution substation, the voltage is stepped down to 400V and power is delivered by 3-phase, 4-wire a.c. system. The voltage between any two phases is 400 V and between any phase and neutral is 230V. The single phase domestic loads are connected between any one phase and then neutral, whereas 3-phase 400 V motor Power transformer loads are connected across 3-phase lines directly.

## D.C. Distribution:

It is a common knowledge that electric power is almost exclusively generated, transmitted and distributed as a.c. However, for certain applications, d.c. supply is absolutely necessary. For instance, d.c. supply is required for the operation of variable speed machinery ( *i.e.*, d.c. motors), for electro-chemical work and for congested areas where storage battery reserves are necessary. For this purpose, a.c. power is converted into d.c. power at the substation by using converting machinery *e.g.*, mercury arc rectifiers, rotary converters and motor-generator sets. The d.c. supply from the substation may be obtained in the form of ( *i* ) 2-wire or ( *ii* ) 3-wire for distribution.

(i) 2-wire d.c. system: As the name implies, this system of distribution

consists of two wires.

One is the outgoing or positive wire and the other is the return or negative wire. The loads such as lamps, motors etc. are connected in parallel between the two wires as shown in Fig. 12.4. This system is never used for transmission purposes due to low efficiency but may be employed for distribution of d.c. power.

## Principles of Power System:

(ii) **3-wire d.c. system**:. It consists of two outers and a middle or neutral wire which is earthed at the substation. The voltage between the outers is twice the voltage between either outer and neutral wire as shown in Fig. 12.5. The principal advantage of this system is that it makes available two voltages at the consumer terminals *viz.*,  $V$  between any outer and the neutral and  $2V$  between the outers. Loads requiring high voltage ( *e.g.*, motors) are connected across the outers, whereas lamps and heating circuits requiring less voltage are connected between either outer and the neutral. The methods of

## Methods of Obtaining 3-wire D.C. System:

There are several methods of obtaining 3-wire d.c. system. However, the most important ones are: ( *i* ) *Two generator method*. In this method, two shunt wound d.c. generators  $G_1$  and  $G_2$  connected in series and the neutral is obtained from the common point between generators as shown in Fig. 12.6 ( *i* ). Each generator supplies the load on its own side. Thus generator  $G_1$

supplies a load current of  $I_1$ , whereas generator  $G_2$  supplies a load current of  $I_2$ . The difference of load currents on the two sides, known as out of balance current ( $I_1 - I_2$ ) flows through the neutral wire. The principal disadvantage of this method is that two separate generators are required.

(ii) **3-wire d.c. generator:** The above method is costly on account of the necessity of two generators. For this reason, 3-wire d.c. generator was developed as shown in Fig. 12.6 (ii). It consists of a standard 2-wire machine with one or two coils of high reactance and low resistance, connected permanently to diametrically opposite points of the armature winding. The neutral wire is obtained from the common point as shown.

(iii) **Balancer set.** The 3-wire system can be obtained from 2-wire d.c. system by the use of balancer set as shown in Fig. 12.7.  $G$  is the main 2-wire d.c. generator and supplies power to the whole system. The balancer set consists of two identical d.c shunt machines  $A$  and  $B$  coupled mechanically with their armatures and field windings joined in series across the outers. The junction of their armatures is earthed and neutral wire is taken out from here. The balancer set has the additional advantage that it maintains the potential difference on two sides of neutral equal to each other. This method is discussed in detail in the next chapter.

## 12.6 Overhead Versus Underground System:

The distribution system can be overhead or underground. Overhead lines are generally mounted on wooden, concrete or steel poles which are arranged to carry distribution transformers in addition to the conductors. The underground system uses conduits, cables and manholes under the surface of streets and sidewalks. The choice between overhead and underground system depends upon a number of widely differing factors. Therefore, it is desirable to make a comparison between the two.

(i) **Public safety:** The underground system is more safe than overhead system because all distribution wiring is placed underground and there are little chances of any hazard.

(ii) **Initial cost:** The underground system is more expensive due to the high cost of trenching, conduits, cables, manholes and other special equipment. The initial cost of an underground system may be five to ten times than that of an overhead system.

(iii) **Flexibility:** The overhead system is much more flexible than the underground system. In the latter case, manholes, duct lines etc., are permanently placed once installed and the load expansion can only be met by laying new lines. However, on an overhead system, poles, wires, transformers etc., can be easily shifted to meet the changes in load conditions.

(iv) **Faults:** The chances of faults in underground system are very rare as the cables are laid underground and are generally provided with better insulation.

(v) **Appearance:** The general appearance of an underground system is better as all the distribution lines are invisible. This factor is exerting considerable public pressure on electric supply companies to switch over to underground system.

(vi) **Fault location and repairs:** In general, there are little chances of faults in an underground system. However, if a fault does occur, it is difficult to locate and repair on this system. On an overhead system, the conductors are visible and easily accessible so that fault locations and repairs can be easily made.

(vii) **Current carrying capacity and voltage drop:** An overhead distribution conductor has a considerably higher current carrying capacity than an underground cable conductor of the same material and cross-section. On the other hand, underground cable conductor has much lower inductive reactance than that of an overhead conductor because of closer spacing of conductors.

(viii) **Useful life:** The useful life of underground system is much longer than that of an overhead system. An overhead system may have a useful life

of 25 years, whereas an underground system may have a useful life of more than 50 years.

(ix) **Maintenance cost:** The maintenance cost of underground system is very low as compared with that of overhead system because of less chances of faults and service interruptions from wind, ice, lightning as well as from traffic hazards.

(x) **Interference with communication circuits:** An overhead system causes electromagnetic interference with the telephone lines. The power line currents are superimposed on speech currents, resulting in the potential of the communication channel being raised to an undesirable level. However, there is no such interference with the underground system.

It is clear from the above comparison that each system has its own advantages and disadvantages. However, comparative economics ( i.e., annual cost of operation) is the most powerful factor influencing the choice between underground and overhead system. The greater capital cost of underground system prohibits its use for distribution. But sometimes non-economic factors ( e.g., general appearance, public safety etc.) exert considerable influence on choosing underground system. In general, overhead system is adopted for distribution and the use of underground system is made only where overhead construction is impracticable or prohibited by local laws.

## 12.7 Connection Schemes of Distribution System

All distribution of electrical energy is done by constant voltage system. In practice, the following distribution circuits are generally used :

**i) Radial System:** In this system, separate feeders radiate from a single substation and feed the distributors at one end only. Fig. 12.8 ( i) shows a single line diagram of a radial system for d.c. distribution where a feeder OC supplies a distributor A B at point A . Obviously, the distributor is fed at one end only i.e., point A is this case. Fig. 12.8 ( ii) shows a single line diagram of radial system for a.c. distribution. The radial system is employed only when power is generated at low voltage and the substation is located at the centre of the load.

This is the simplest distribution circuit and has the lowest initial cost. However, it suffers from the following drawbacks :

- a) The end of the distributor nearest to the feeding point will be heavily loaded.
- b) The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the consumers who are on the side of the fault away from the substation.
- c) The consumers at the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes.

Due to these limitations, this system is used for short distances only.

**ii) Ring main system.** In this system, the primaries of distribution transformers form a loop.

The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation. Fig. 12.9 shows the single line diagram of ring main system for a.c. distribution where substation supplies to the closed feeder LMNOPQRS.

The distributors are tapped from different points M, O and Q of the feeder through distribution transformers. The ring main system has the following advantages :

- a) There are less voltage fluctuations at consumer's terminals.
- b) The system is very reliable as each distributor is fed via two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained. For example, suppose that fault occurs at any point F of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers via the feeder SRQPONM.

**iii) Interconnected system:** When the feeder ring is energised by two or more than two generating stations or substations, it is called inter-connected system. Fig. 12.10 shows the single line diagram of interconnected system where the closed feeder ring ABCD is supplied by two substations S and S at points D and C respectively. Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers. The interconnected system has the following advantages :

- a) It increases the service reliability.
- b) Any area fed from one generating station during peak load hours can be fed from the other generating station. This reduces reserve power capacity and increases efficiency of the system.

## 12.8 Requirements of a Distribution System

A considerable amount of effort is necessary to maintain an electric power supply within the requirements of various types of consumers. Some of the requirements of a good distribution system are : proper voltage, availability of power on demand and reliability.

**i) Proper voltage.** One important requirement of a distribution system is that voltage variations at consumer's terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system. Low voltage causes loss of revenue, inefficient lighting and possible burning out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system should ensure that the voltage variations at consumers terminals are within permissible limits. The statutory limit of voltage variations is  $\pm 6\%$  of the rated value at the consumer's terminals. Thus, if the declared voltage is 230 V, then the highest voltage of the consumer should not exceed 244 V while the lowest voltage of the consumer should not be less than 216 V.

**ii) Availability of power on demand.** Power must be available to the consumers in any amount that they may require from time to time. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric supply company. As electrical energy cannot be stored, therefore, the distribution system must be capable of supplying load demands of the consumers. This necessitates that operating staff must continuously study load patterns to predict in advance those major load changes that follow the known schedules.

**iii) Reliability.** Modern industry is almost dependent on electric power for its operation. Homes and office buildings are lighted, heated, cooled and ventilated by electric power. This calls for reliable service. Unfortunately, electric power, like everything else that is man-made, can never be absolutely reliable. However, the reliability can be improved to a considerable extent by



( a) interconnected system ( b) reliable automatic control system ( c) providing additional reserve facilities.

## 12.9 Design Considerations in Distribution System

Good voltage regulation of a distribution network is probably the most important factor responsible for delivering good service to the consumers. For this purpose, design of feeders and distributors requires careful consideration.

i) Feeders. A feeder is designed from the point of view of its current carrying capacity while the voltage drop consideration is relatively unimportant. It is because voltage drop in a feeder can be compensated by means of voltage regulating equipment at the substation.

ii) Distributors. A distributor is designed from the point of view of the voltage drop in it. It is because a distributor supplies power to the consumers and there is a statutory limit of voltage variations at the consumer's terminals ( $\pm 6\%$  of rated value). The size and length of the distributor should be such that voltage at the consumer's terminals is within the permissible limits.

## **Power Substation Types:**

### **Power Substation:**

An Electrical Power Substation receives electric power from generating station via transmission lines and delivers power via the outgoing transmission lines. Substations are integral parts of a power system and form important links between the generating stations, transmission systems, distribution systems and the load points. Various power substations located in generating stations, transmission and distribution systems have similar layout and similar electrical components. Electrical power substation basically consists of number of incoming circuit connections and number of outgoing circuit connections connected to the busbars. Busbars are conducting bars to which number of circuit connections is connected. Each circuit has certain number of electrical components such as circuit breakers, Isolators, earth switches, current transformers, voltage transformers, etc.

In a Power Substation there are various indoor and outdoor switchgear and equipment. Transformers are necessary in a substation for stepping up and stepping down of a.c voltage. Besides the transformers, the several other equipment include busbars, circuit breakers, isolators, surge arresters, Substation Earthing System, Shunt reactors, Shunt Capacitors etc. Each equipment has certain functional requirement. The equipment are either indoor or outdoor depending upon the voltage rating and local conditions.

In a large power system large number of Generating stations, Electrical Power Substations and load centers are interconnected. This large internet-work is controlled from load dispatch center. Digital and voice signals are transmitted over the transmission lines via the Power substations. The substations are interlinked with the load control centers via Power Line Carrier Systems (PLCC). Modern Power System is controlled with the help of several automatic, semi - automatic equipment. Digital Computers and microprocessors are installed in the control rooms of large substations, generating stations and load control centers for data collection, data monitoring, automatic protection and control.

### **Functions of Electrical Power Substations are:**

- Supply electric power to the consumers continuously
- Supply of electric power within specified voltage limits and frequency limits
- Shortest possible fault duration.
- Optimum efficiency of plants and the network
- Supply of electrical energy to the consumers at lowest cost

## Types of Electrical Power Substations:

### Step up or primary Electrical Power substation:

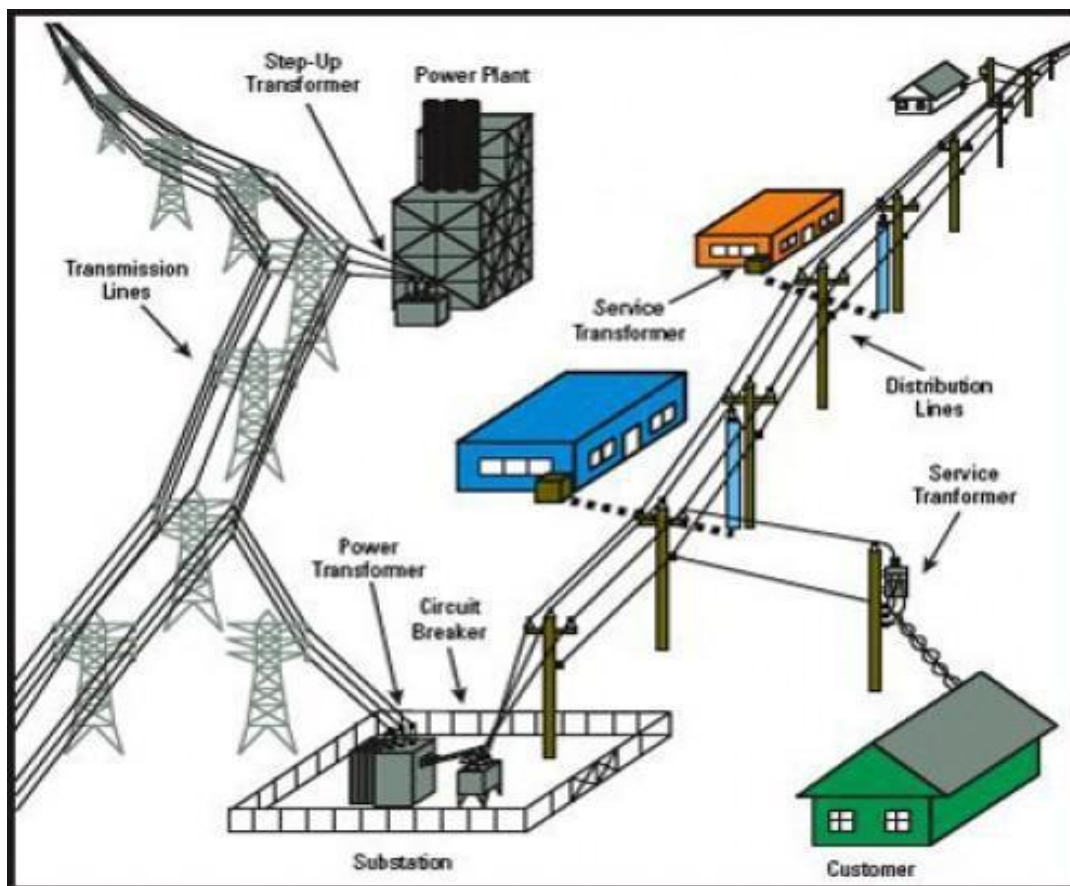
Primary substations are associated with the power generating plants where the voltage is stepped up from low voltage (3.3, 6.6, 11, 33kV) to 220kV or 400kV for transmitting the power so that huge amount of power can be transmitted over a large distance to load centers.

### Primary Grid Electrical Power Substation:

Such substations are located at suitable load centers along with the primary transmission lines. At primary Grid Power Substations the primary transmission voltage (220kV or 400kV) is stepped down to secondary transmission voltages (110kV). This Secondary transmission lines are carried over to Secondary Power Substations situated at the load centers where the voltage is further stepped down to Sub transmission Voltage or Primary Distribution Voltages (11kV or 33kV).

### Step Down or Distribution Electrical Power Substations:

Such Power Substations are located at the load centers. Here the Sub transmission Voltages of Distribution Voltages (11kV or 33kV) are stepped down to Secondary Distribution Voltages (400V or 230V). From these Substations power will be fed to the consumers to their terminals.



## **Basis of Service Rendered:**

### **Transformer Substation:**

Transformers are installed on such Substations to transform the power from one voltage level to other voltage level.

### **Switching Substation:**

Switching substations are meant for switching operation of power lines without transforming the voltages. At these Substations different connections are made between various transmission lines. Different Switching Schemes are employed depends on the application to transmit the power in more reliable manner in a network.

Such Substations are located where AC to DC conversion is required. In HVDC transmission Converting Substations are employed on both sides of HVDC link for converting AC to DC and again converting back from DC to AC. Converting Power Substations are also employed where frequency is to be converted from higher to lower and lower to higher. This type of frequency conversion is required in connecting to Grid Systems.

## **Based on Operation Voltage:**

### **High Voltage Electrical Power Substation:**

This type of Substation associated with operating voltages between 11kV and 66kV.

### **Extra High Voltage Electrical Power Substation:**

This type of Substation is associated where the operating voltage is between 132kV and 400kV.

### **Ultra High Voltage Electrical Power Substation:**

Substations where Operating Voltages are above 400kV is called Ultra High Voltage Substation

## **Based on Substation Design:**

### **Outdoor Electrical Power Substations:**

In Outdoor Power Substations, the various electrical equipments are installed in the switchyard below the sky. Electrical equipments are mounted on support structures to obtain sufficient ground clearance.

### **Indoor Electrical Power Substation:**

In Indoor Power Substations the apparatus is installed within the substation building. Such substations are usually for the rating of 66kV. Indoor Substations are preferred in heavily polluted areas and Power Substations situated near the seas (saline atmosphere causes Insulator Failures results in Flashovers)

Indoor Substation

### **Based on Design Configuration:**



### **Air Insulated Electrical Power Substation:**

In Air Insulated Power Substations busbars and connectors are visible. In this Power Substations Circuit Breakers and Isolators, Transformers, Current Transformers, Potential Transformers etc are installed in the outdoor. Busbars are supported on the post Insulators or Strain Insulators. Substations have galvanized Steel Structures for Supporting the equipment, insulators and incoming and outgoing lines. Clearances are the primary criteria for these substations and occupy a large area for installation.

### **Gas Insulated Electrical Power Substation:**

In Gas Insulated Substation Various Power Substation equipments like Circuit Breakers, Current Transformers, Voltage Transformers, Busbars, Earth Switches, Surge Arresters, Isolators etc are in the form of metal enclosed SF<sub>6</sub> gas modules. The modules are assembled in accordance with the required Configuration. The various Live parts are enclosed in the metal enclosures (modules) containing SF<sub>6</sub> gas at high pressure. Thus the size of Power Substation reduces to 8% to 10% of the Air Insulated Power Substation.

### **Hybrid Electrical Power Substation:**

Hybrid Substations are the combination of both Conventional Substation and Gas Insulated Substation. Some bays in a Power Substation are Gas Insulated type and some are Air Insulated Type. The design is based on convenience, Local Conditions available, area available and Cost.



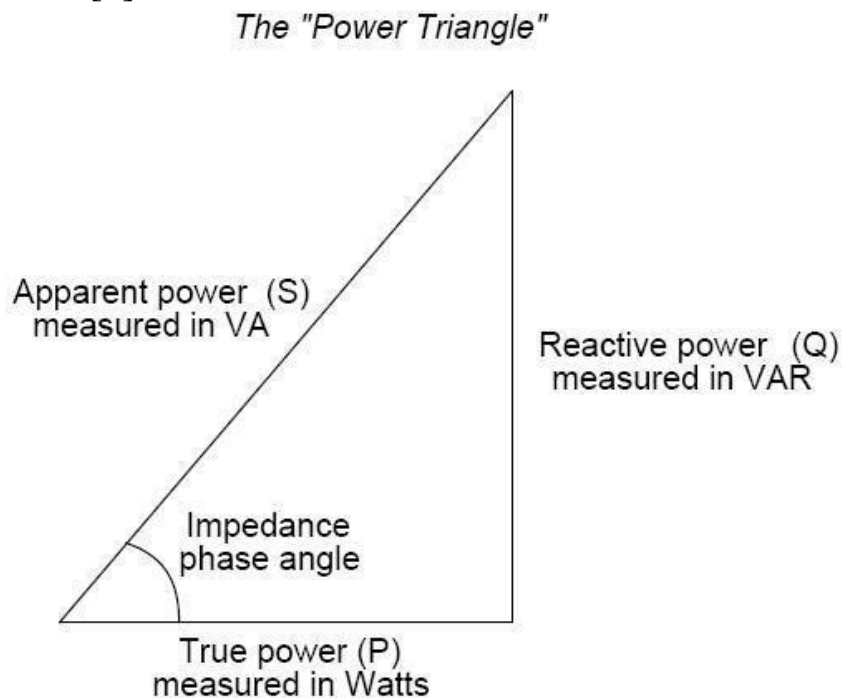
Gas Insulated Substation



### Power Factor Defined:

In power systems, wasted energy capacity, also known as poor power factor, is often overlooked. It can result in poor reliability, safety problems and higher energy costs. The lower your power factor, the less economically your system operates.

Power factor is the ratio between the real power and the apparent power drawn by an electrical load. Like all ratio measurements it is a unit-less quantity and can be represented power that actually does the work, KVA is the apparent power and KVAR (not included in the equation) is the reactive power. In an inductive load, such as a motor, active power performs the work and reactive power other in a trigonometric form as seen in Figure 5 below. [2]



**Figure 5: The Power Triangle**

For the purely resistive circuit, the power factor is 1 (perfect), because the reactive power equals zero. Here, the power triangle would look like a horizontal line, because the opposite (reactive power) side would have zero length.

For the purely inductive circuit, the power factor is zero, because true power equals zero. Here, the power triangle would look like a vertical line, because the adjacent (true power) side would have zero length.

The same could be said for a purely capacitive circuit. If there are no dissipative (resistive) components in the circuit, then the true power must be equal to zero, making any power in the circuit purely reactive. The

power triangle for a purely capacitive circuit would again be a vertical line (pointing down instead of up as it was for the purely inductive circuit).

Power factor can be an important aspect to consider in an AC circuit; because any power factor less than 1 means that the circuit's wiring has to carry more current than what would be necessary with zero reactance in the circuit to deliver the same amount of (true) power to the resistive load. The poor power factor makes for an inefficient power delivery system.

Poor power factor can be corrected, paradoxically, by adding another load to the circuit drawing an equal and opposite amount of reactive power, to cancel out the effects of the load's inductive reactance. Inductive reactance can only be canceled by capacitive reactance, so we have to add a capacitor in parallel to our example circuit as the additional load. The effect of these two opposing reactance's in parallel is to bring the circuit's total impedance equal to its total resistance (to make the impedance phase angle equal, or at least closer, to zero).

Power factor measures how efficiently the current is being converted into real work— with a low power factor, more electrical current is required to provide the same amount of real power. All current causes dissipation in a distribution system. A power factor of 1 will result in the most efficient loading of the supply; a load with a power factor of 0.5 will result in higher losses in the distribution system.

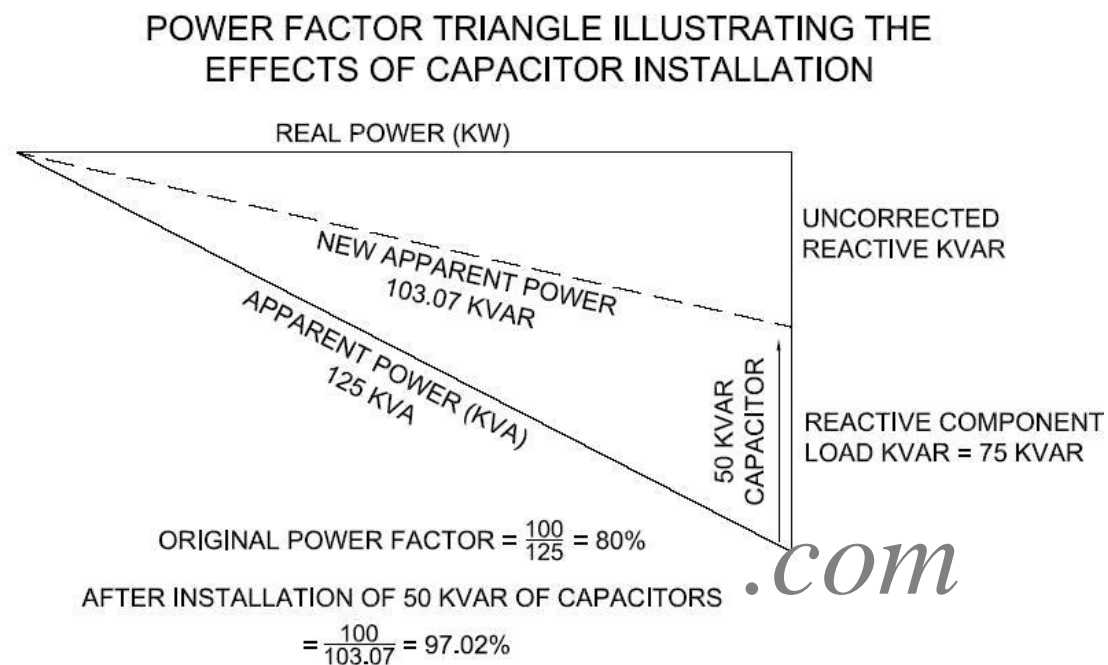
The reactive load of an industrial power system typically consists of a large number of AC induction motors. This can cause the total load to be up to 50% inductive. Large inductive loads cause the apparent power to be 25% to 41% higher than the real power. If the utility billing is based on real power (KW) only, the utility must provide up to 41% more capacity than they are billing for. Since it takes more capacity and is more expensive to serve a customer with a low power factor, that customer has to pick up the tab. Most electrical rate tariffs contain provisions that include a minimum power factor. Customers who fall short of the minimum power factor level receive a power factor charge. Power factor charges may range from \$5 to thousands of dollars per month.

Overall there are several consequences of a low power factor; these consequences include decreased system capacity, increased system losses, and extra cost. Benefits of increasing a low power factor include eliminated or reduced power factor charges on utility bills, more efficient operations with increased capacity and reduced current draw.



## Methods of Power Factor Correction:

In the real world, utilities normally only require a power factor of 0.9. Although a unity power factor provides the most efficient power system, a UPF leaves the power system susceptible to harmonic problems. Harmonic problems cause excessive heating in motors, nuisance tripping, and premature failure of solid state components. Power factor correction (PFC) is usually achieved by adding capacitive load to offset the inductive load present in the power system. The power factor of the power system is constantly changing due to variations in the size and number of the motors being used at one time. This makes it difficult to balance the inductive and capacitive loads continuously. In addition, harmonic problems can be introduced if the capacitors are not sized with the specific power system characteristics in mind. The utility company may also restrict or deny the introduction of KVARs into their power system. These are all considerations that need to be addressed prior to making any decisions about the size or type of power factor correction.



**Figure 6: Power Triangle illustrating effects of capacitor PFC**

The most inexpensive and widely used method of correcting the power factor is through the use of one fixed capacitor bank connected to the incoming transformer or switchgear bus. The fixed capacitor bank is sized to regulate a 0.9 power factor during maximum operational inductive loading. This means that during periods of operation where less than maximum inductive loading is utilized, extra KVAR capacity will be introduced into the utility power system. The only draw backs to this method are utility restrictions and future inductive loads that change the maximum operational inductive loading.

A variation of the above method can be used only if a discrete number of motors are causing the power factor problems. Individual capacitors can be connected in parallel with each motor. When the motor is energized, the capacitor bank is also energized to provide power factor correction while the motor is being used (as seen in Figures 3 and 4 located on the next page). The benefit of this method is that the amount of capacitive load is regulated with the amount of inductive load. The drawbacks to this method are that it may not be feasible physically or economically to have an individual capacitor for each motor, and maintenance of multiple units may be costly and difficult.

Another method of power factor correction is the use of a variable capacitor bank. This bank would be connected just like the fixed bank. The advantage of the variable capacitor bank is that the bank monitors the system power factor and automatically regulates the amount of capacitive load connected to the system to offset the inductive load. Since the capacitive load is regulated, there would be no conflict with the utility. The variable capacitor banks normally come with internal protection, provide space for additional banks, and provide a centrally located easily maintained unit. The draw backs to the variable capacitor bank are an increased chance of harmonic problems due to the variations in capacitance, initial cost, and maintenance costs of internal parts used for capacitor switching.

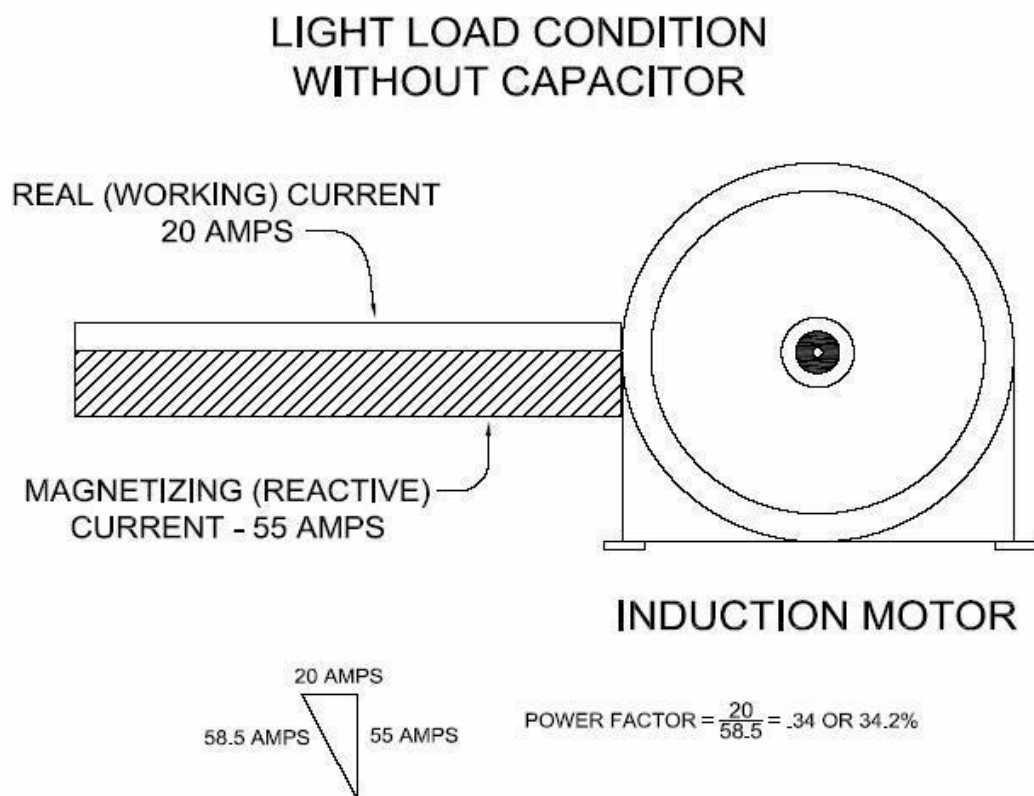
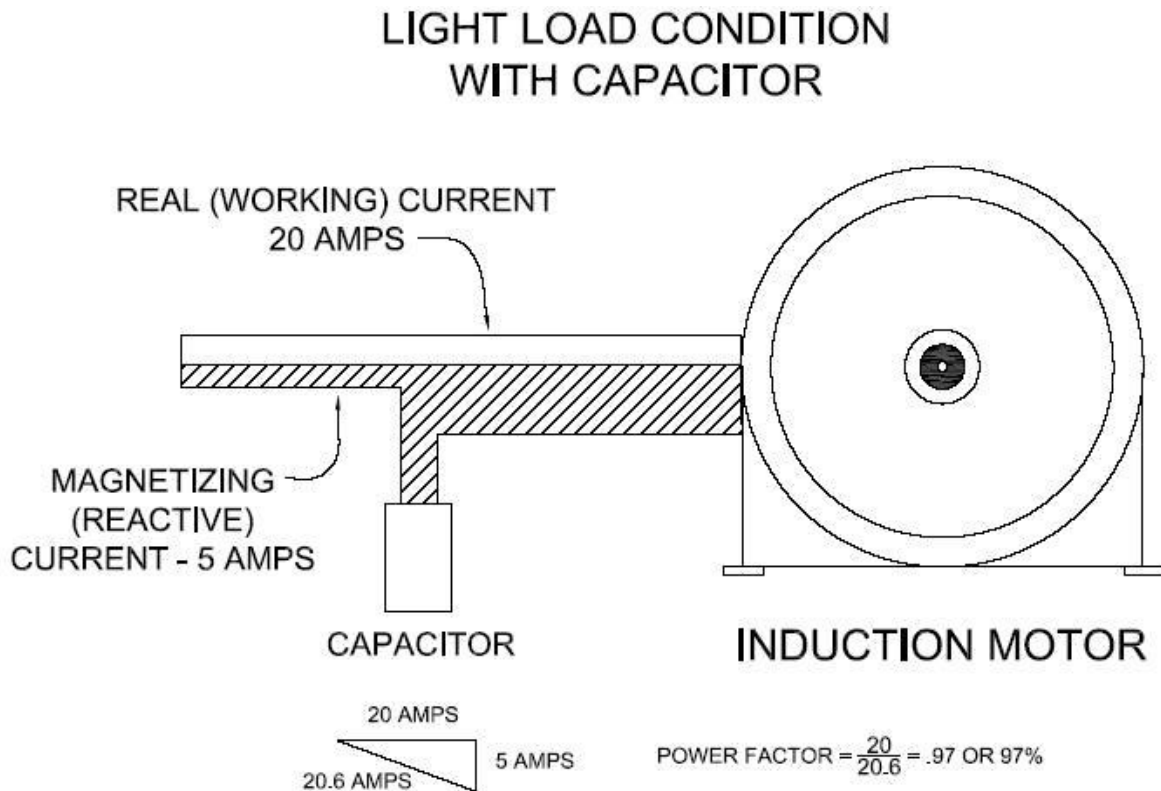


Figure 7: Induction motor without a capacitor in parallel

A combination of the previously mentioned methods seems to be the normal configuration that is used once correction is decided upon. Normally, capacitors are connected to the largest motors to provide correction while they are running. In addition, a variable or fixed capacitor bank is connected to the main transformer or switchgear. The advantage of this is regulation of the capacitive load and a reduction in the size of the capacitor bank connected to the main transformer or switchgear. [2]

It should be noted that too much capacitance in an AC circuit will result in a low power factor just as well as too much inductance. You must be careful not to over-correct when adding capacitance to an AC circuit. You must also be very careful to use the proper capacitors for the job (rated adequately for power system voltages and the occasional voltage spike from lightning strikes, for continuous AC service, and capable of handling the expected





## **Figure 8: Induction motor with a capacitor in**

levels of current). If a circuit is predominantly inductive, we say that its power factor is lagging (because the current wave for the circuit lags behind the applied voltage wave). Conversely, if a circuit is predominantly capacitive, we say that its power factor is leading. Thus, our example circuit started out with a power factor of 0.705 lagging, and was corrected to a power factor of 0.999 lagging. [1]

All in all poor power factor in an AC circuit can be corrected to a value close to unity (1), by adding a parallel reactance opposite to the effect of the load's reactance. If the load's reactance is inductive in nature (which is almost always will be), parallel capacitance is what is needed to correct poor power factor.

### **Benefits of Power Factor Correction**

The primary benefit of power factor correction is the elimination of charges related to reactive power-consumption. If the utility is adding a power factor penalty or billing for apparent power (KVA), reduction in reactive power will net savings. The amount of savings seen will depend on costs for correction are paid back inside of one year, and after that, the savings will reduce operating costs. In addition, power factor correction will improve the overall performance of the power system which can increase switchgear, starter, and motor life. The bottom line is protection, efficiency, and savings.

### **Introduction of Voltage Control:**

In a modern power system, electrical energy from the generating station is delivered to the ultimate consumers through a network of transmission and distribution. For satisfactory operation of motors, lamps and other loads, it is desirable that consumers are supplied with substantially constant voltage. Too wide variations of voltage may cause erratic operation or even malfunctioning of consumers' appliances. To safe-guard the interest of the consumers, the government has enacted a law in this regard. The statutory limit of voltage variation is  $\pm 6\%$  of declared voltage at consumers' terminals. The principal cause of voltage variation at consumer's premises is the change in load on the supply system. When the load on the system increases, the voltage at the consumer's terminals falls due to the increased

voltage drop in (i) Induction Regulators alternator synchronous impedance (ii) transmission line (iii) transformer impedance (iv) feeders and condenser (v) distributors. The reverse would happen should the load on the system decrease. These voltage variations are undesirable and must be kept within the prescribed limits ( *i.e.*  $\pm 6\%$  of the declared voltage). This is achieved by installing voltage regulating equipment at suitable places in the power system. The purpose of this chapter is to deal with important voltage control equipment and its increasing utility in this fast developing power system.

## **Importance of Voltage Control**

When the load on the supply system changes, the voltage at the consumer's terminals also changes. The variations of voltage at the consumer's terminals are undesirable and must be kept within prescribed limits for the following reasons: i) In case of lighting load, the lamp characteristics are very sensitive to changes of voltage. For instance, if the supply voltage to an incandescent lamp decreases by 6% of rated value, then illuminating power may decrease by 20%. On the other hand, if the supply voltage is 6% above the rated value, the life of the lamp may be reduced by 50% due to rapid deterioration of the filament. (ii) In case of power load consisting of induction motors, the voltage variations may cause erratic operation. If the supply voltage is above the normal, the motor may operate with a saturated magnetic circuit, with consequent large magnetising current, heating and low power factor. On the other hand, if the voltage is too low, it will reduce the starting torque of the motor considerably. (iii) Too wide variations of voltage cause excessive heating of distribution transformers. This may reduce their ratings to a considerable extent. It is clear from the above discussion that voltage variations in a power system must be kept to minimum level in order to deliver good service to the consumers. With the trend towards larger and larger interconnected system, it has become necessary to employ appropriate methods of voltage control.

## **Location of Voltage Control Equipment**

In a modern power system, there are several elements between the generating station and the consumers. The voltage control equipment is used at more than one point in the system for two reasons.

Firstly, the power network is very extensive and there is a considerable drop in transmission and distribution systems. Secondly, the various circuits of the power system have dissimilar load characteristics. For these reasons, it is necessary to provide individual means of voltage control for

each circuit or group of circuits. In practice, voltage control equipment is used at :

- i) generating stations
- ii) transformer stations
- iii) the feeders if the drop exceeds the permissible limits 15.3

### **Methods of Voltage Control:**

There are several methods of voltage control. In each method, the system voltage is changed in accordance with the load to obtain a fairly constant voltage at the consumer's end of the system. The following are the methods of voltage control in an a.c. power system:

- i) By excitation control
- ii) By using tap changing transformers
- iii) Auto-transformer tap changing
- iv) Booster transformers v) Induction regulators vi) By synchronous condenser

Method ( i ) is used at the generating station only whereas methods ( ii ) to ( v ) can be used for Since the modern power system is a.c., voltage control for this system will be discussed. However, for a d.c. system, voltage control can be effected by ( i ) overcompounded generators and ( ii ) boosters.

### **Introduction to Economics of Power Generation:**

The function of a power station is to deliver power at the lowest possible cost per kilo watt hour. This total cost is made up of fixed charges consisting of interest on the capital, taxes, insurance, depreciation and salary of managerial staff, the operating expenses such as cost of fuels, water, oil, labor, repairs and maintenance etc.

### **The cost of power generation can be minimized by :**

1. Choosing equipment that is available for operation during the largest possible % of time in a year.
2. Reducing the amount of investment in the plant.
3. Operation through fewer men.
4. Having uniform design
5. Selecting the station as to reduce cost of fuel, labor, etc.

All the electrical energy generated in a power station must be consumed immediately as it cannot be stored. So the electrical energy



generated in a power station must be regulated according to the demand. The demand of electrical energy or load will also vary with the time and a power

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station must be capable of meeting the maximum load at any time. Certain definitions related to power station practice are given below:

**Load curve:**

Load curve is plot of load in kilowatts versus time usually for a day or a year.

**Load duration curve:**

Load duration curve is the plot of load in kilowatts versus time duration for which it occurs.

**Maximum demand:**

Maximum demand is the greatest of all demands which have occurred during a given period of time.

**Average load:**

Average load is the average load on the power station in a given period (day/month or year)

**Base load:**

Base load is the minimum load over a given period of time.

**Connected load:**

Connected load of a system is the sum of the continuous ratings of the load consuming apparatus connected to the system.

**Peak load :**

Peak load is the maximum load consumed or produced by a unit or group of units in a stated period of time. It may be the maximum instantaneous load or the maximum average load over a designated interval of time.

**Demand factor :**

Demand factor is the ratio of maximum demand to the connected load of a consumer.

**Diversity factor :**

Diversity factor is the ratio of sum of individual maximum demands to the combined maximum demand on power stations

**Load factor :**

Load factor is the ratio of average load during a specified period to the  
time considered, to the rating of the machine.

maximum load occurring during the period.

**Load factor = Average Load / Maximum demand**

**Station load factor:**

Station load factor is the ratio of net power generated to the net maximum demand on a power station.

**Plant factor:**

Plant factor is the ratio of the average load on the plant for the period of time considered, to the aggregate rating of the generating equipment installed in the plant.

**Capacity factor:**

Capacity factor is the ratio of the average load on the machine for a period of

**Demand factor:**

Demand factor is the ratio of maximum demand of system or part of system, to the total connected load of the system, or part of system, under consideration.

## **Economics of Power Generation:**

### **(B) Variable Cost :**

These costs vary in some proportion of the power generated in a plant.

These costs consist of

#### **i) Cost of fuel :**

Cost of fuel is directly related with the amount of power generated. For generating more power, more fuel is required. Cost of fuel may be 10% to 25% of the total cost of production. In case of hydroelectric plants the cost of fuel is zero.

#### **ii) Maintenance and Repair Charges:**

In order to keep the plant in running condition, certain repairs are always needed. Stock of some consumable and non- consumable items has got to be maintained. All charges for such staff are considered as operating costs.

#### **iii) Wages:**

Salaries including allowances bonus, benefits etc., for the workers are considered as operating costs.

Total cost of production is thus sum of the fixed charges and the operating charges. As the plant load factor improves, the cost per kWh decreases. The sum of the charges for various factors will give an optimum load factor where such charges will be least.

### **Tariff :**

A tariff is the rate of charge per kilowatt hour of energy supplied to a consumer. The cost of generation of electrical energy may be conveniently split into two parts e.g. fixed charges plus the operating charges. So a tariff should be adjusted in such a way that the total receipts balance the total expenditure involved in generating the energy. There are several solutions to this problem, some of which are given below:

#### **1. Uniform Rate Tariff:**

In this case there is a fixed rate per unit amount of energy consumed. The consumption of energy is measured by the energy meter installed at the premises of the consumer. This type of tariff accounts for all the costs involved in the generation of power. This is the simplest tariff easily understood by consumers. However, this type of tariff does not distinguish

between small power domestic consumer and bulk power industrial consumers.

## **2. Two Part Tariff:**

In this the total charges are split into two parts - fixed charges based on maximum demand (in kW) plus the charges based on energy consumption (in kWh). This method suffers from the drawback that an additional provision is to be incorporated for the measurement of maximum demand. Under such tariff, the consumers having 'peaked' demand for short duration are discouraged.

## **3. Block Rate Tariff:**

In this the fixed charges are merged into the unit charges for one or two blocks of consumption, all units in excess being charged at low or high unit rate. Lower rates for higher blocks are fixed in order to encourage the consumers for more and more consumptions. This is done in case the plant has got larger spare capacity. Wherever the plant capacity is inadequate, higher blocks are charged at higher rate in order to discourage the consumers for higher than minimum consumption.

## **4. Three Part Tariff:**

It is an extension of the two part tariff in that it adds to the consumer some fixed charges irrespective of the energy consumption or maximum demand. In this even if the consumer has got zero power consumption, he has to pay some charges merely because a connection has been provided to him.

## **5. Power Factor Tariff:**

In ac power supply size of the plant is determined by the kVA rating. In case the power factor of a consumer installation is low, the energy consumption in terms of kW will be low. In order to discharge such consumers, power factor tariff is introduced, which may be of the following types.

### **(a) Maximum kVA demand Tariff:**

In this instead of kW the kVA consumption is measured and the charge are Based partly or fully on this demand.

**(b) Sliding Scale tariff:**

In this case the average power factor is fixed say at 0.8 lagging. Now if the power factor of a consumer falls below by 0.01 or multiples there of, some additional charges are imposed. A discount may be allowed in case the power factor is above 0.8.

The depreciation on the plant is charged by any of the following methods

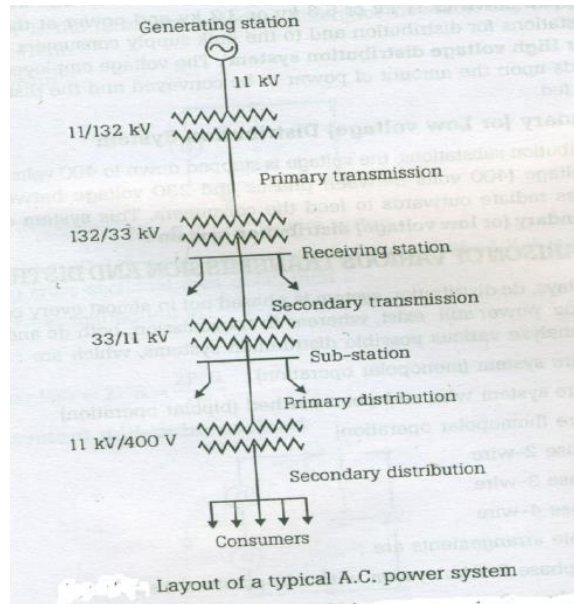
1. Straight Line method
2. Sinking fund method
3. Diminishing value method.

## UNIT-II

### ELECTRICAL DISTRIBUTION SYSTEMS

An electric power system has three important components.

i) Generation system    ii) Transmission system    iii) Distribution system



The electrical energy produced at generating station is conveyed to the consumers through the network of transmission and distribution systems at different voltages.

The part of power system which distributes electrical energy for local use is known as distribution system. In general it lies between substation fed by the transmission system (or a local generating plant) and consumer meters.

#### Elements of distribution system:

A distribution system can be subdivided into i) Feeders ii) Distributors iii) Service mains

##### i) Feeders:

It is a conductor which connects the substation (or localized generation station) to the area where the power is to be distributed. **Generally no tapings are taken from this feeder.**

- Current in the feeders remains same throughout the feeder as no tapings are taken from it.
- **Feeders are designed based on its current carrying capacity.**

##### ii) Distributors:

It is a conductor from which tapings are taken to supply consumers.

- So the distributor does not carry same current throughout its length.
- **Distributors are designed based on its voltage drop along its length.**

iii) Service mains:

It is a small conductor/ cable which connect the distributor to the consumer terminals.

**Classification of distribution systems:**

**1) According to nature of current:**

- a) DC distribution system: Types: i) 2-wire dc system ii) 3-wire dc system
- b) AC distribution system.

Generally Ac distribution is used. Where as in some applications dc supply is absolutely necessary like for the operation of variable speed machinery (i.e. dc motors), for electro chemical work and for congested areas where storage battery reserves are necessary.

**Difference between AC and DC distribution systems:**

<b><u>DC transmission/Distribution</u></b>	<b><u>AC transmission/distribution</u></b>
Required less number of conductors. So less cost	Required more number of conductors. So more cost
No L & C effect $\Rightarrow$ no phase displacement	Construction of line is difficult
Less voltage drop. So better voltage regulation	More voltage drop.
No skin effect	Skin effect exists
No corona loss	Corona loss exists
No charging capacitance $\Rightarrow$ No power loss due to charging capacitor	Power loss due to charging capacitor exists.
No dielectric losses	
No stability problems.	
Less insulation stress	
No step up / step down of voltage is possible with transformers	Step up / step down of voltage is possible with transformers
DC switches and Circuit breakers are complex equipment and have less efficiency.	Easy and cheap maintenance is possible

**2) According to type of construction:**

- a) Overhead system    b) Underground system

The choice between these two systems depends on various factors like,

- i) Public safety, ii) Initial cost, iii) Flexibility, iv) Faults occurrence, repairs, v) Appearance,
- vi) Current carrying capacity & voltage drop, vii) Useful life, viii) Maintenance cost,
- ix) Interference with communication circuits

### 3) According to scheme of connection:

- a) Radial system   b) Ring main system   c) Interconnected system

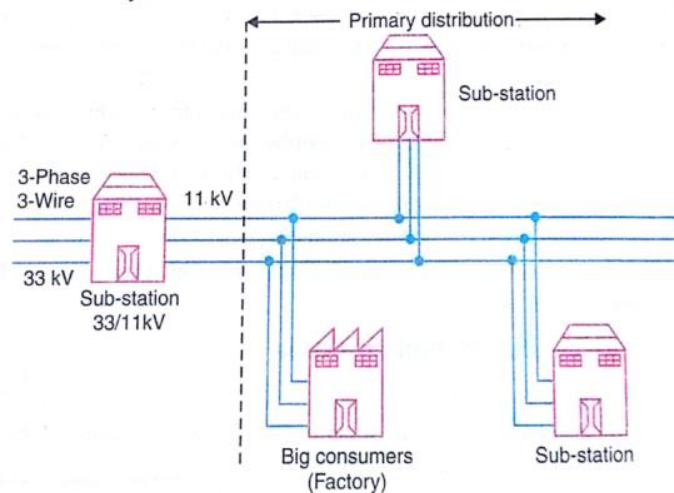
### 4) According to number of wires:

- a) Two wire system   b) Three wire system   c) Four wire system

The AC distribution system is divided into two parts.

#### i) Primary or High voltage distribution system:

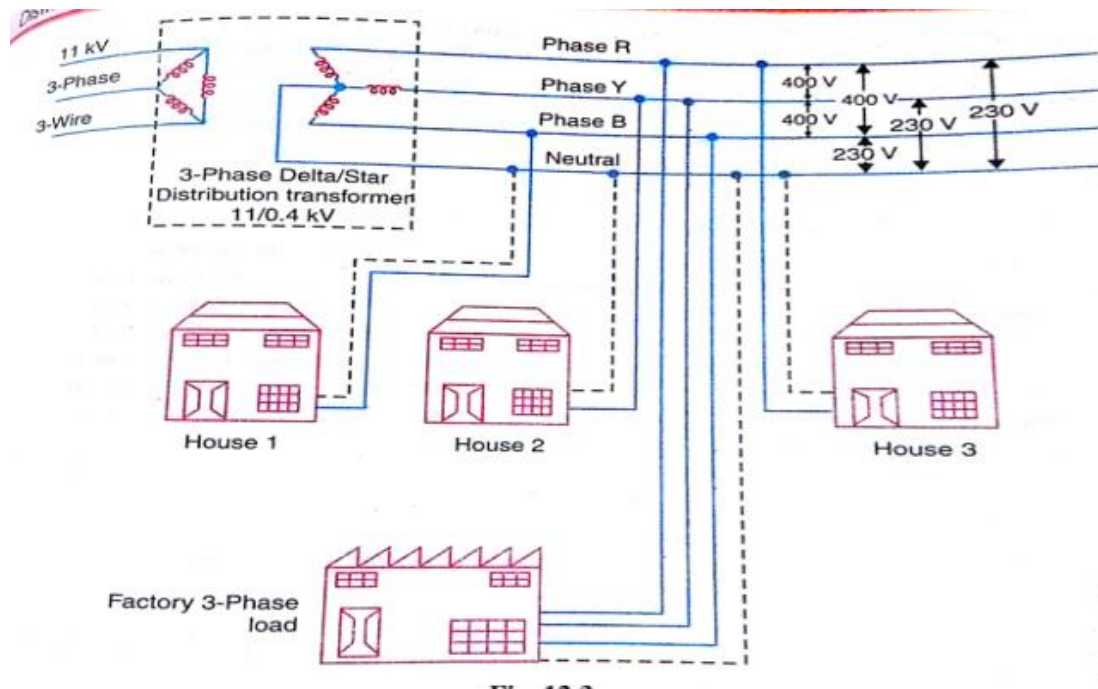
The system which conveys electrical energy to various distribution substations and to the bulk power consumers (at the voltage rating of 11KV or 6.6KV or 3.3KV) is called primary or high voltage distribution system. **This system operates at voltages somewhat higher than general utilization** and handles large block of electrical energy. The voltage for primary distribution depends upon the amount of power to be conveyed and the distance of substation required to be fed. **Generally primary distribution is carried out by 3-phase, 3- wire system.**



#### ii) Secondary or Low voltage distribution system:

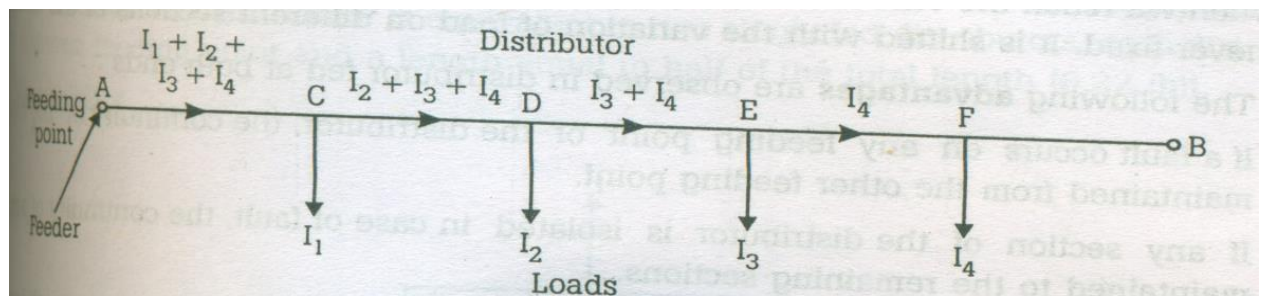
The system which **feeds electrical energy** to various consumers **at low voltages** (400V **between phases or 230 V** between phase and neutral) from distribution substation is called secondary or low voltage distribution system. At each distribution substation the voltage is stepped down to 400V and power is delivered to the consumer through **3-phase, 4-wire system**. The single phase domestic loads are connected between any one phase and the neutral, where as 3-phase, 400V motor loads are connected across 3-phase lines directly. Ex: Rice mills





### Calculation of voltage drops in distributors:

1) DC distributor fed at one end with concentrated load:



Distributor fed at one end with concentrated loading

Consider the single line diagram of two wire DC distributor AB fed at one end A and having concentrated loads  $I_1$ ,  $I_2$ ,  $I_3$ ,  $I_4$  tapped at points C, D, E, F respectively as shown in above figure.

Let  $R_{AC}$ ,  $R_{CD}$ ,  $R_{DE}$ ,  $R_{EF}$  are the resistances of distributor sections AB, BC, CD, DE and EF respectively.

Then,

Voltage drop in section FE,  $V_{EF} = I_4 R_{EF}$

Voltage drop in section DE,  $V_{DE} = (I_3 + I_4) R_{DE}$

Voltage drop in section CD,  $V_{CD} = (I_2 + I_3 + I_4) R_{CD}$

Voltage drop in section AC,  $V_{AC} = (I_1 + I_2 + I_3 + I_4) R_{AC}$

Total voltage drop in the distributor =  $V_{AC} + V_{CD} + V_{DE} + V_{EF}$

$$= (I_1 + I_2 + I_3 + I_4) R_{AC} + (I_2 + I_3 + I_4) R_{CD} + (I_3 + I_4) R_{DE} + I_4 R_{EF}$$

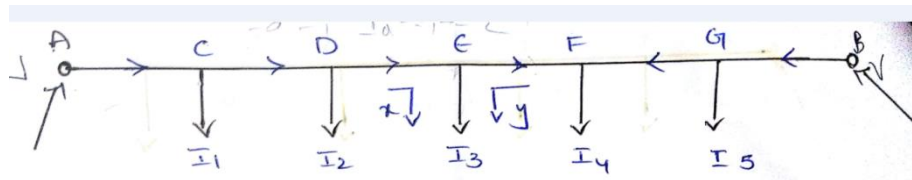
The minimum potential occur at point F, which is farthest from feeding point A,  $V_F$

$$= V_A - \text{Voltage drops in sections AC, CD, DE, EF}$$

$$= V_A - [(I_1 + I_2 + I_3 + I_4) R_{AC} + (I_2 + I_3 + I_4) R_{CD} + (I_3 + I_4) R_{DE} + I_4 R_{EF}],$$

In two wire DC distribution systems, two wires (go and return wire) are employed and hence the voltage drop will be voltage drop in both the wires.

## 2) DC distributor fed at both the ends with equal voltages and concentrated loading:



Consider a distributor AB fed at both the ends with equal voltages 'V' volts & having concentrated loads  $I_1, I_2, I_3, I_4, I_5$  at points C, D, E, F, G respectively.

Let  $R_{AC}, R_{CD}, R_{DE}, R_{EF}, R_{FG}, R_{GB}$  are the resistances of distribution sections AC, CD, DE, EF, FG, GB respectively.

As we move away from one of the feeding points A, the potential goes on decreasing till it reaches minimum at some load point and then again rises and becomes volts as we reach the other feeding point B. The point of minimum potential depends on the variation of load on the distribution sections.

- Let E be the minimum potential point in the above distributor, Then the loads between A and E are supplied from feeding point A, and in between B and E are supplied from feeding point B.
- The load at minimum potential is supplied from both the ends.

Let  $I_A$  amperes current is flowing from feeding point A then the currents in various section of the distributors are given below.

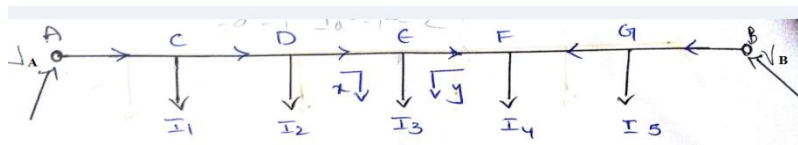
Section	Current in section	Voltage drop in section
AC	$I_A$	$I_A R_{AC}$
CD	$I_A - I_1$	$(I_A - I_1) R_{CD}$

DE	$I_A - (I_1 + I_2)$	$(I_A - I_1 - I_2) R_{DE}$
EF	$I_A - (I_1 + I_2 + I_3)$	$(I_A - I_1 - I_2 - I_3) R_{EF}$
FG	$I_A - (I_1 + I_2 + I_3 + I_4)$	$(I_A - I_1 - I_2 - I_3 - I_4) R_{FG}$
GB	$I_A - (I_1 + I_2 + I_3 + I_4 + I_5)$	$(I_A - I_1 - I_2 - I_3 - I_4 - I_5) R_{GB}$

Total voltage drop in distributor =  $I_A R_{AC} + (I_A - I_1) R_{CD} + (I_A - I_1 - I_2) R_{DE} + (I_A - I_1 - I_2 - I_3) R_{EF} + (I_A - I_1 - I_2 - I_3 - I_4) R_{FG} + (I_A - I_1 - I_2 - I_3 - I_4 - I_5) R_{GB} = V_A - V_B = 0$

From the above equation  $I_A$  can be calculated and the minimum potential point can be found by observing the load point which is supplying from both the ends.

3) DC distributor fed at both the ends with unequal voltages and concentrated loading:



Consider a distributor fed AB fed at both the ends A and B with unequal voltages  $V_A$  and  $V_B$  respectively and having the concentrated loads  $I_1, I_2, I_3, I_4$  and  $I_5$  at C, D, E, F and G points respectively.

Let  $R_{AC}, R_{CD}, R_{DE}, R_{EF}, R_{FG}, R_{GB}$  are the resistances of distribution sections AC, CD, DE, EF, FG, GB respectively.

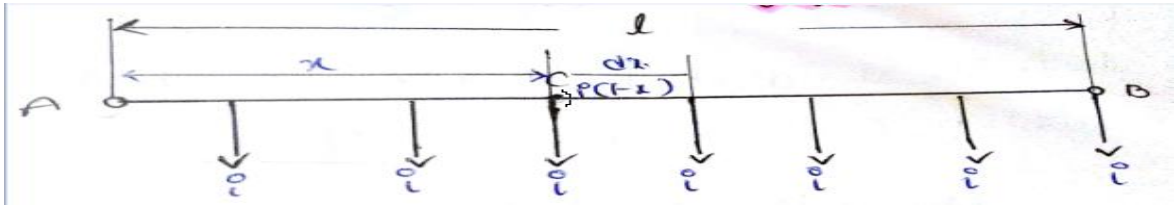
Let E be the minimum potential point at which the load is fed from both the ends. Let  $I_A$  amperes current is flowing from feeding point A then the currents in various sections of the distributors are given below.

Section	Current in section	Voltage drop in section
AC	$I_A$	$I_A R_{AC}$
CD	$I_A - I_1$	$(I_A - I_1) R_{CD}$
DE	$I_A - (I_1 + I_2)$	$(I_A - I_1 - I_2) R_{DE}$
EF	$I_A - (I_1 + I_2 + I_3)$	$(I_A - I_1 - I_2 - I_3) R_{EF}$
FG	$I_A - (I_1 + I_2 + I_3 + I_4)$	$(I_A - I_1 - I_2 - I_3 - I_4) R_{FG}$
GB	$I_A - (I_1 + I_2 + I_3 + I_4 + I_5)$	$(I_A - I_1 - I_2 - I_3 - I_4 - I_5) R_{GB}$

Total voltage drop in distributor =  $I_A R_{AC} + (I_A - I_1) R_{CD} + (I_A - I_1 - I_2) R_{DE} + (I_A - I_1 - I_2 - I_3) R_{EF} + (I_A - I_1 - I_2 - I_3 - I_4) R_{FG} + (I_A - I_1 - I_2 - I_3 - I_4 - I_5) R_{GB} = V_A - V_B$

From the above equation  $I_A$  can be calculated and the minimum potential point can be found by observing the load point which is supplying from both the ends.

4) DC distributor fed at one end with uniform loading:



Consider a DC distributor fed at one end A and load uniformly with  $i$  A/m as shown in figure.

Let

Length of the distributor = ' $l$ ' m

Resistance of the distributor =  $r \Omega/\text{m}$  (both for go and return conductors)

Current rating of the distributor =  $i$  A/m

Total current fed at point A =  $il$  A

Consider a point C at a distance of  $x$  m from point A.

The current flowing at point C =  $i(l-x)$  A

Consider a small length  $dx$  at point C.

Resistance of small length of the distributor =  $rdx \Omega$

Voltage drop over the length  $dx$ ,  $dV = i(l-x)rdx$

Total voltage drop in the distributor from A up to point C,  $V_{AC} =$

$$\int_0^x dV = \int_0^x i(l-x) r dx$$

$$= ir \int_0^x l dx - ir \int_0^x x dx$$

$$= irlx - \frac{irx^2}{2} = ir \left[ lx - \frac{x^2}{2} \right]$$

$$\text{The total voltage drop in a distributor, } V_{AB} = ir \left[ lx - \frac{x^2}{2} \right]_{x=l}$$

$$= \frac{irl^2}{2} \quad V = 1/2 (il) (rl) = 1/2 IR (V)$$

Where  $I$  is the total current entering the distributor

R is the total resistance of the distributor

(From the above equation it can be seen that in a uniformly loaded distributor fed at one end, the total voltage drop is equal to the voltage drop produced by the whole of the load assumed to be concentrated at the midpoint.)

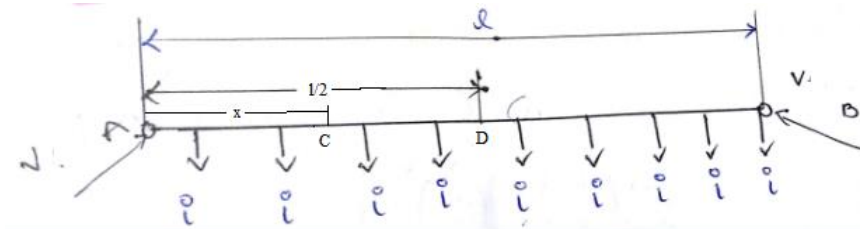
Power loss in element dx,  $dP = i^2 (l - x)^2 r dx$

Total power loss in distributor,  $P = i^2 r \int_0^l (l - x)^2 dx$

$$= -i^2 r \left[ \frac{(l - x)^3}{3} \right]_0^l$$

$$= -i^2 r \left( 0 - \frac{l^3}{3} \right) = \frac{i^2 r l^3}{3} W$$

#### 4) DC distributor fed at both ends with uniform loading with equal voltages:



Consider a DC distributor fed at both ends with equal voltages and is uniformly loaded with  $i$  A/m as shown in fig.

As the distributor fed with equal voltages at both ends (i.e.  $V_A = V_B$ ), and is uniformly loaded, the minimum potential point occurs at the midpoint of the distributor and the total current is supplied from both the feeders equally.

⇒ Current supplied from feeding point A =  $il/2$  A

Current supplied from feeding point B =  $il/2$  A

Consider a point C at a distance of ' $x$ ' m from A

Current flowing at point C =  $i \left( \frac{l}{2} - x \right)$

Consider a small length  $dx$  of the distributor at point C, then

Voltage drop in the small section,  $dv = i \left( \frac{l}{2} - x \right) r dx$

Where  $r$  is the resistance of distributor per meter

$$\Rightarrow V_{AC} = \int_0^x i \left( \frac{l}{2} - x \right) r dx = \int_0^x \frac{ir l}{2} dx - \int_0^x i r x dx$$

$$= \frac{ir l x}{2} - i r \frac{x^2}{2} = \frac{ir}{2} [l x - x^2]$$

Let D be the minimum potential point (i.e midpoint of the distributor) which is at a distance of  $x/2$  m from point A.

$$\Rightarrow V_{AD} = \frac{ir l^2}{8} \text{ V}$$

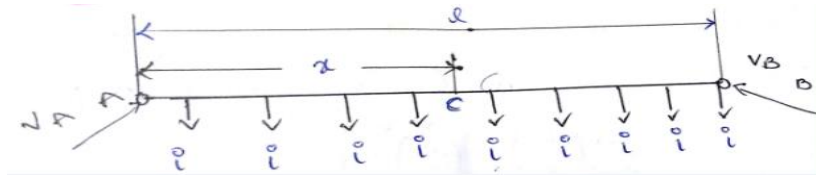
$$\text{Minimum potential, } V_D = V_A - V_{AD} = V - \frac{ir l^2}{8}$$

$$\text{Power loss in element } dx, dP = \left[ i \left( \frac{l}{2} - x \right) \right]^2 r dx$$

$$\text{Total power loss in distributor, } P = \int_0^l \left[ i \left( \frac{l}{2} - x \right) \right]^2 r dx = i^2 r \int_0^l \left( \frac{l}{2} - x \right)^2 dx = -\frac{i^2 r}{3} \left[ \left( \frac{l}{2} - x \right)^3 \right]_0^l$$

$$= -\frac{i^2 r}{3} \left[ -\frac{l^3}{8} - \frac{l^3}{8} \right] = \frac{1}{12} i^2 r l^3 \text{ W}$$

5) DC distributor fed at both ends with uniform loading with un equal voltages:



Consider a DC distributor fed at both ends with un equal voltages and is uniformly loaded with  $i$  A/m as shown in fig.

Let length of the distributor =  $l$  meter

Resistance of the distributor =  $r \Omega / \text{m}$

Let C be the minimum potential point where current enters from both ends of the distributor i.e it is the minimum potential point of the distributor.

Current supplied from feeding point A =  $ix$  A

Current supplied from feeding point B =  $i(l-x)$  A

Voltage drop in section AC =  $\frac{1}{2} i r x^2$  V

Voltage drop in section BC =  $\frac{1}{2} i r (l-x)^2$  V

Voltage at point C,  $V_C = V_A - \text{Voltage drop in section AC}$

And also Voltage at point C,  $V_C = V_B - \text{Voltage drop in section BC}$

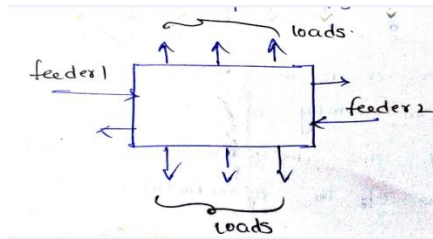
$$\Rightarrow V_A - \frac{1}{2}irx^2 = V_B - \frac{1}{2}ir(1-x)^2$$

$$\Rightarrow V_A - V_B = \frac{1}{2}ir[x^2 - (1-x)^2] = \frac{1}{2}ir[2lx - 1^2]$$

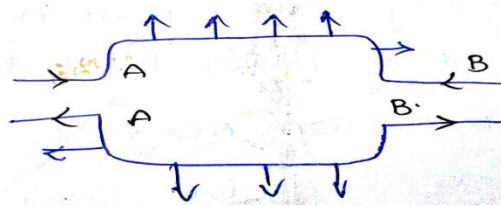
$$\Rightarrow \text{Distance of minimum potential point from feeding point A, } x = \frac{V_A - V_B}{irl} + \frac{l}{2}$$

### Ring distributor:

A distributor arranged to form a closed loop and fed at one or more points is called a ring distributor.



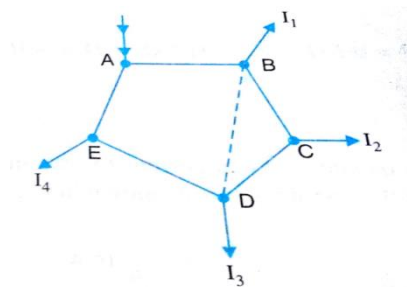
It is considered as a series of open distributors fed at both the ends. The equivalent circuit of above distributor is given as,



The principle advantage of ring distributor is that by proper choice in number of feeding points, great economy in copper can be achieved.

### Ring distributor with interconnections:

In order to reduce the voltage drops in various sections of the ring distributor's (which serves a large area) distant points, the distributors are joined through a conductor called interconnector.



There are several methods for solving these type of problems. One of the methods is to apply Thevenin's theorem. The steps involved in this method are:

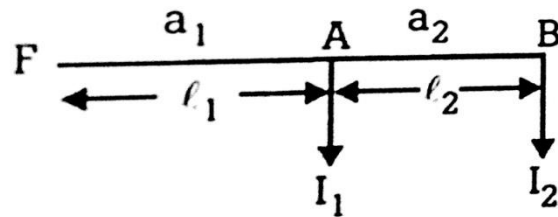
- i) Consider the interconnector to be disconnected. And find the potential difference between the two feeding points. Let this be  $E_0$ .
- ii) Calculate the resistance viewed from the two feeding points (across which interconnector is connected) and let it be  $R_0$
- iii) Then Current in interconnector is given by,  $\frac{E_0}{R_0 + R_{interconnector}}$

Therefore the current distribution in each section and voltage of load points can be calculated.

### **Stepped and tapered mains:**

A distributor whose cross sectional area at different parts is selected such that the total volume of copper utilized for a given constant voltage drop is called stepped distributor.

Consider a distributor feeding two loads  $I_1$ ,  $I_2$  tapped of at points A and B as shown in figure.



Let  $a_1$ ,  $l_1$  and  $a_2$ ,  $l_2$  be the area of cross section and lengths of sections FA and AB respectively.

Let  $\rho$  be the resistivity of distributor then,

$$\text{Resistance for section FA (both go and return)} = \frac{2\rho l_1}{a_1}$$

$$\text{Resistance for section AB (both go and return)} = \frac{2\rho l_2}{a_2}$$

$$\text{Voltage drop in section FA} = \frac{2\rho l_1}{a_1} (I_1 + I_2) = v(\text{let}) \Rightarrow a_1 = \frac{2\rho l_1}{v} (I_1 + I_2)$$



$$\text{Voltage drop in section AB} = \frac{2\rho l_2}{a_2} I_2 = v_t - v \Rightarrow a_2 = \frac{2\rho l_2}{v_t - v} I_2$$

Where  $v_t$  is the total voltage drop in the distributor which is constant

$$\text{Total voltage drop in the distributor, } v_t = \frac{2\rho l_1}{a_1} (I_1 + I_2) + \frac{2\rho l_2}{a_2} I_2$$

$$\text{Total volume of the copper} = 2a_1 l_1 + 2a_2 l_2 = \frac{4\rho l_1^2}{v} (I_1 + I_2) + \frac{4\rho l_2^2}{v_t - v} I_2$$

For minimum volume of copper,  $\frac{d(\text{volume})}{dv} = 0$

$$\Rightarrow -\frac{4\rho l_1^2}{v^2} (I_1 + I_2) + \frac{4\rho l_2^2}{(v_t - v)^2} I_2 = 0$$

Simplifying the above equation, we get,

$$\frac{a_1}{a_2} = \sqrt{\frac{I_1 + I_2}{I_2}}$$

i.e for minimum volume of copper, the area of cross section of the distributor should be proportional to the square root of the current carried by that part of the distributor which is practically not feasible because more joints are involved which is technically undesirable. One more objection of this method is that future additions to the system may completely alter the distribution of current in sections, and sometimes it is useless to use stepped distributor though it is economical.

### A.C. Distribution:

Now a days, electrical energy is generated, transmitted and distributed in the form of alternating current. The energy is transmitted with 3-phase and 3-wire system where as the distribution system is divided into two parts.

1. Primary distribution system: It is 3-phase and 3 wire system which operates at high voltages (3.3, 6.6 or 11KV) than the normal utilization levels. It delivers power to secondary distribution circuit through distribution transformer.

2. Secondary distribution system: Delivers power to various consumers at 400V supply. It consists of 3-phase and 4-wire system for unbalanced load or single phase, 2- wire system for small power appliances.

While doing voltage drop calculations in AC distribution system, the following factors to be considered.

i) All the operations (ex: summing or subtracting currents) should be done vectorially but not arithmetically.

ii) Power factor of loads should be considered.

There are two ways in referring power factors.

a) Referred to supply or receiving end voltage,

b) Referred to voltage at the load point itself.

## Power Substation:

### Sub-Station

The assembly of apparatus used to change some characteristic (e.g. voltage, a.c. to d.c., frequency, p.f. etc.) of electric supply is called a **sub-station**.

Sub-stations are important part of power system. The continuity of supply depends to a considerable extent upon the successful operation of sub-stations. It is, therefore, essential to exercise utmost care while designing and building a sub-station. The following are the important points which must be kept in view while laying out a sub-station:

- (i) It should be located at a proper site. As far as possible, it should be located at the centre of gravity of load.
- (ii) It should provide safe and reliable arrangement. For safety, consideration must be given to the maintenance of regulation clearances, facilities for carrying out repairs and maintenance, abnormal occurrences such as possibility of explosion or fire etc. For reliability, consideration must be given for good design and construction, the provision of suitable protective gear *etc.*
- (iii) It should be easily operated and maintained.
- (iv) It should involve minimum capital cost.

In a large power system large number of Generating stations, Electrical Power Substations and load centers are interconnected. This large internet-work is controlled from load dispatch center. Digital and voice signals are transmitted over the transmission lines via the Power substations. The substations are interlinked with the load control centers via Power Line Carrier Systems (PLCC). Modern Power System is controlled with the help of several automatic, semi - automatic equipment. Digital Computers and microprocessors are installed in the control rooms of large substations, generating stations and load control centers for data collection, data monitoring, automatic protection and control.

### Functions of Electrical Power Substations are:

- Supply electric power to the consumers continuously
- Supply of electric power within specified voltage limits and frequency limits
- Shortest possible fault duration.
- Optimum efficiency of plants and the network
- Supply of electrical energy to the consumers at lowest cost

### Classification of Sub-Stations

There are several ways of classifying sub-stations. However, the two most important ways of classifying them are according to (1) service requirement and (2) constructional features.

**According to service requirement.** A sub-station may be called upon to change voltage level or improve power factor or convert a.c. power into d.c. power etc. According to the service requirement, sub-stations may be classified into:

(i) **Transformer sub-stations.** Those sub-stations which change the voltage level of electric supply are called transformer sub-stations. These sub-stations receive power at some voltage and deliver it at some other voltage. Obviously, transformer will be the main component in such sub-stations. Most of the sub-stations in the power system are of this type.

(ii) **Switching sub-stations.** These sub-stations do not change the voltage level *i.e.* incoming and outgoing lines have the same voltage. However, they simply perform the switching operations of power lines.

(iii) **Power factor correction sub-stations.** Those sub-stations which improve the power factor of the system are called power factor correction sub-stations. Such sub-stations are

generally located at the receiving end of transmission lines. These sub-stations generally use synchronous condensers as the power factor improvement equipment.

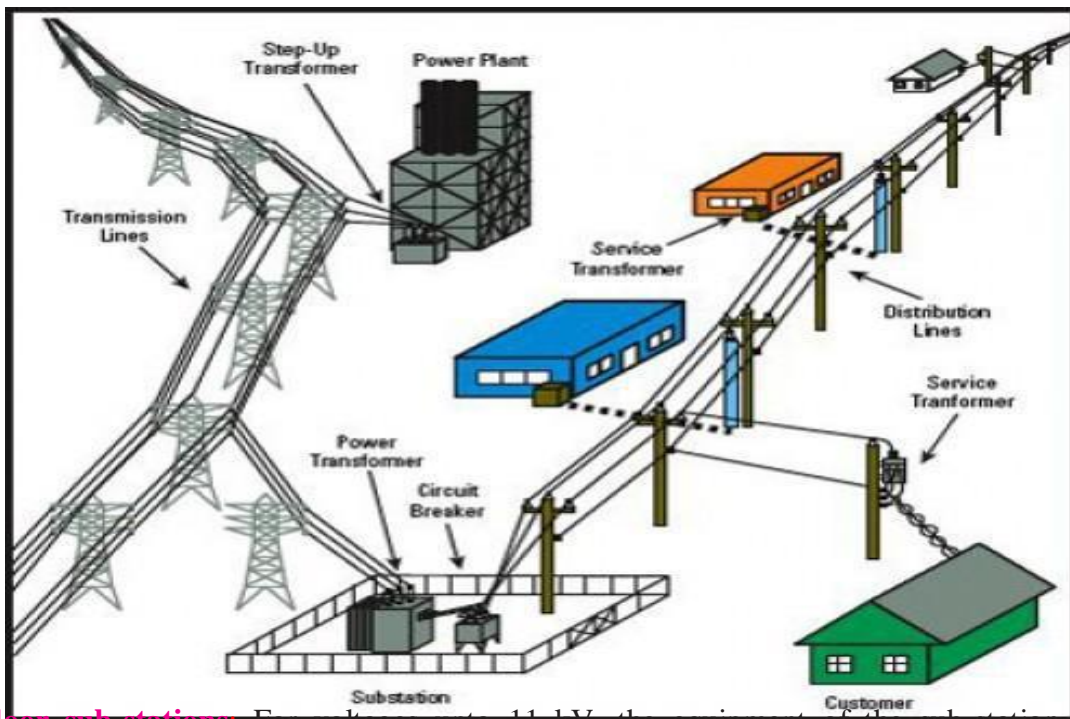
**(iv) Frequency changer sub-stations.** Those sub-stations which change the supply frequency are known as frequency changer sub-stations. Such a frequency change may be required for industrial utilisation.

**(v) Converting sub-stations.** Those sub-stations which change a.c. power into d.c. power are called converting sub-stations. These sub-stations receive a.c. power and convert it into d.c. power with suitable apparatus (*e.g.* ignitron) to supply for such purposes as traction, electroplating, electric welding etc.

**(vi) Industrial sub-stations.** Those sub-stations which supply power to individual industrial concerns are known as industrial sub-stations.

**According to constructional features.** A sub-station has many components (*e.g.* circuit breakers, switches, fuses, instruments etc.) which must be housed properly to ensure continuous and reliable service. According to constructional features, the sub-stations are classified as:

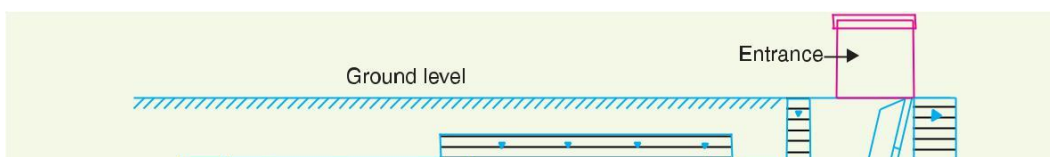
- Indoor sub-station
- Outdoor sub-station
- Underground sub-station
- Pole-mounted sub-station



**(i) Indoor sub-stations.** For voltages upto 11 kV, the equipment of the sub station is installed indoor because of economic considerations. However, when the atmosphere is contaminated with impurities, these sub-stations can be erected for voltages upto 66 kV.

**(ii) Outdoor sub-stations.** For voltages beyond 66 kV, equipment is invariably installed outdoor. It is because for such voltages, the clearances between conductors and the space required for switches, circuit breakers and other equipment becomes so great that it is not economical to install the equipment indoor.

**(iii) Underground sub-stations.** In thickly populated cities, there is scarcity of land as well as the prices of land are very high. This has led to the development of underground sub-station. In such sub-stations, the equipment is placed underground.



The design of underground sub-station requires more careful consideration than other types of sub-stations. While laying out an underground sub-station, the following points must be kept in view:

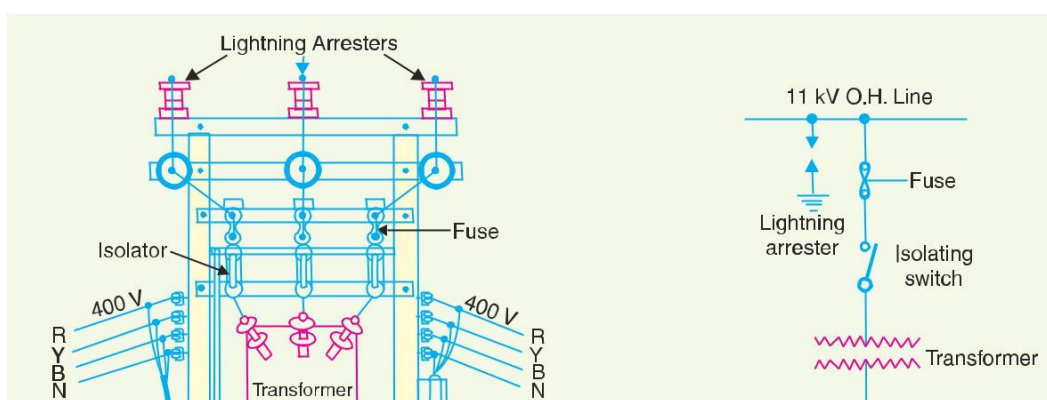
- (i) The size of the station should be as minimum as possible.
- (ii) There should be reasonable access for both equipment and personnel.
- (iii) There should be provision for emergency lighting and protection against fire.
- (iv) There should be good ventilation.
- (v) There should be provision for remote indication of excessive rise in temperature so that H.V. supply can be disconnected.
- (vi) The transformers, switches and fuses should be air cooled to avoid bringing oil into the premises.

**(iv) Pole-mounted sub-stations.** This is an outdoor sub-station with equipment installed overhead on *H*-pole or 4-pole structure. It is the cheapest form of sub-station for voltages not exceeding 11kV (or 33 kV in some cases). Electric power is almost distributed in localities through such sub-stations.

### Pole-Mounted Sub-Station

It is a distribution sub-station placed overhead on a pole. It is the cheapest form of sub-station as it does not involve any building work. Fig (i) shows the layout of pole-mounted sub-station whereas Fig. (ii) shows the schematic connections. The transformer and other equipment are mounted on H-type pole (or 4-pole structure).

The 11 kV line is connected to the transformer (11kV / 400 V) through gang isolator and fuses. The lightning arresters are installed on the H.T. side to protect the sub-station from lightning strokes. The transformer steps down the voltage to 400V, 3-phase, 4-wire supply. The voltage between any two lines is 400V whereas the voltage between any line and neutral is 230 V. The oil circuit breaker (O.C.B.) installed on the L.T. side automatically isolates the transformer from the consumers in the event of any fault.



### Comparison between Outdoor and Indoor Sub-Stations

The comparison between outdoor and indoor sub-stations is given below in the tabular form:

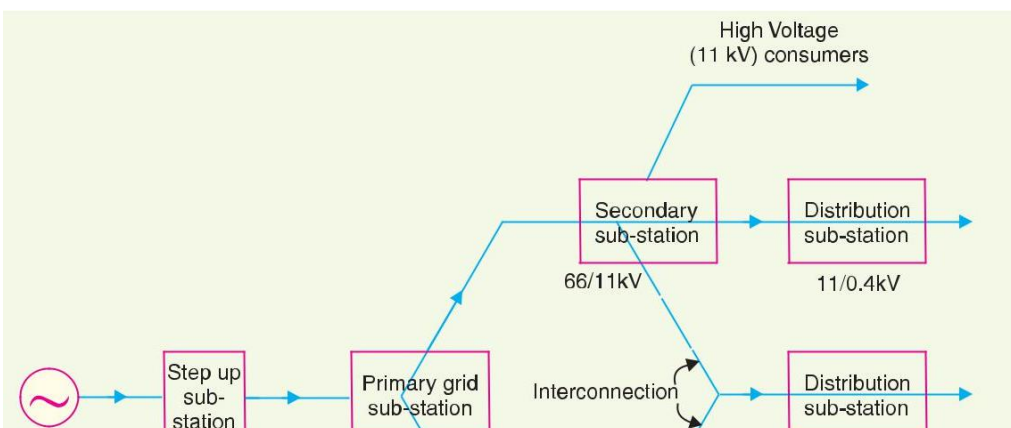
S.No.	Particular	Outdoor Sub-station	Indoor Sub-station
1	Space required	More	Less
2	Time required for erection	Less	More
3	Future extension	Easy	Difficult
4	Fault location	Easier because the equipment is in full view	Difficult because the equipment is enclosed
5	Capital cost	Low	High
6	Operation	Difficult	Easier
7	Possibility of fault escalation	Less because greater clearances can be provided	More

From the above comparison, it is clear that each type has its own advantages and disadvantages. However, comparative economics (i.e. annual cost of operation) is the most powerful factor influencing the choice between indoor and outdoor sub-stations. The greater cost of indoor sub-station prohibits its use. But sometimes non-economic factors (e.g. public safety) exert considerable influence in choosing indoor sub-station. In general, most of the sub-stations are of outdoor type and the indoor sub-stations are erected only where outdoor construction is impracticable or prohibited by the local laws.

### Transformer Sub-Stations

The majority of the sub-stations in the power system are concerned with the changing of voltage level of electric supply. These are known as transformer sub-stations because transformer is the main component employed to change the voltage level. Depending upon the purpose served, transformer sub-stations may be classified into:

- (i) Step-up sub-station      (ii) Primary grid sub-station
- (iii) Secondary sub-station      (iv) Distribution sub-station



It may be noted that it is not necessary that all electric supply schemes include all the stages shown in the figure. For example, in a certain supply scheme there may not be secondary sub-stations and in another case, the scheme may be so small that there are only distribution sub-stations.

**(i) Step-up sub-station.** The generation voltage (11 kV in this case) is stepped up to high voltage (220 kV) to affect economy in transmission of electric power. The sub-stations which accomplish this job are called step-up sub-stations. These are generally located in the power houses and are of outdoor type.

**(ii) Primary grid sub-station.** From the step-up sub-station, electric power at 220 kV is transmitted by 3-phase, 3-wire overhead system to the outskirts of the city. Here, electric power is received by the primary grid sub-station which reduces the voltage level to 66 kV for secondary transmission. The primary grid sub-station is generally of outdoor type.

**(iii) Secondary sub-station.** From the primary grid sub-station, electric power is transmitted at 66kV by 3-phase, 3-wire system to various secondary sub-stations located at the strategic points in the city. At a secondary sub-station, the voltage is further stepped down to 11 kV. The 11 kV lines run along the important road sides of the city. It may be noted that big consumers (having demand more than 50 kW) are generally supplied power at 11 kV for further handling with their own sub-stations. The secondary sub-stations are also generally of outdoor type.

**(iv) Distribution sub-station.** The electric power from 11 kV lines is delivered to distribution sub-stations. These sub-stations are located near the consumers localities and step down the voltage to 400 V, 3-phase, 4-wire for supplying to the consumers. The voltage between any two phases is 400V and between any phase and neutral it is 230 V. The single phase residential lighting load is connected between any one phase and neutral whereas 3-phase, 400V motor load is connected across 3-phase lines directly. It may be worthwhile to mention here that majority of the distribution sub-stations are of pole-mounted type.

#### **Components of Sub-Stations:**

Besides the transformers, the several other equipment include

- busbars
- circuit breakers
- isolators
- surge arresters
- Substation Earthing System
- current transformers
- voltage transformers
- Shunt reactors
- Shunt Capacitors etc.

Each equipment has certain functional requirement.



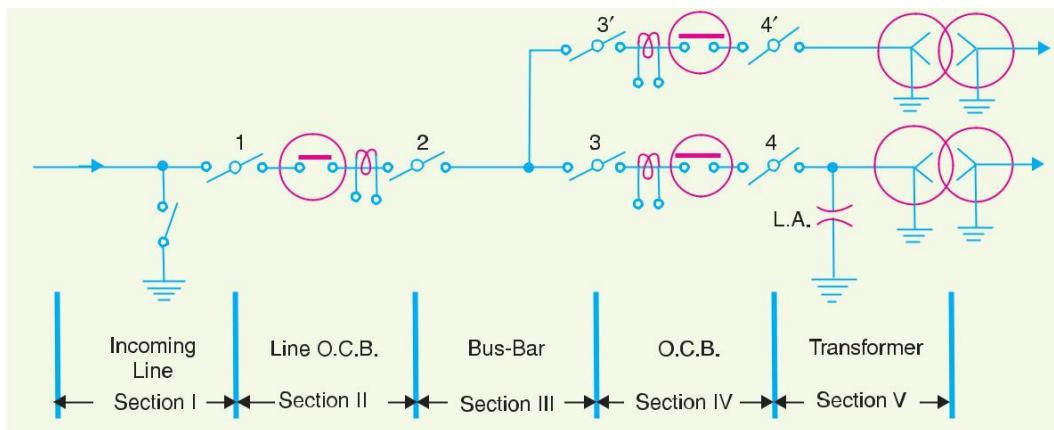
## Busbars

Busbars are conducting bars to which number of circuit connections is connected. Bus-bars are copper or aluminium bars (generally of rectangular x-section) and operate at constant voltage. The incoming and outgoing lines in a sub-station are connected to the bus-bars. The most commonly used bus-bar arrangements in sub-stations are :

- (i) Single bus-bar arrangement
- (ii) Single bus-bar system with sectionalisation
- (iii) Double bus-bar arrangement

**Insulators.** The insulators serve two purposes. They support the conductors (or bus-bars) and confine the current to the conductors. The most commonly used material for the manufacture of insulators is porcelain. There are several types of insulators (*e.g.* pin type, suspension type, post insulator etc.) and their use in the sub-station will depend upon the service requirement. For example, post insulator is used for bus-bars. A post insulator consists of a porcelain body, cast iron cap and flanged cast iron base. The hole in the cap is threaded so that bus-bars can be directly bolted to the cap.

**Isolating switches.** In sub-stations, it is often desired to disconnect a part of the system for general maintenance and repairs. This is accomplished by an isolating switch or isolator. An isolator is essentially a knife switch and is designed to open a circuit under *no load*. In other words, isolator switches are operated only when the lines in which they are connected carry *\*no* current.



The entire sub-station has been divided into V sections. Each section can be disconnected with the help of isolators for repair and maintenance. For instance, if it is desired to repair section No. II, the procedure of disconnecting this section will be as follows. First of all, open the circuit breaker in this section and then open the isolators 1 and 2. This procedure will disconnect section II for repairs. After the repair has been done, close the isolators 1 and 2 first and then the circuit breaker.

**Circuit breaker.** A circuit breaker is an equipment which can open or close a circuit under normal as well as fault conditions. It is so designed that it can be operated manually (or by remote control) under normal conditions and automatically under fault conditions. For the latter operation, a relay circuit is used with a circuit breaker. Generally, bulk oil circuit breakers are used for voltages upto 66kV while for high (>66 kV) voltages, low oil circuit breakers are used. For still higher voltages, air-blast, vacuum or  $SF_6$  circuit breakers are used.

**Power Transformers:** A power transformer is used in sub-station to step-up or step-down the voltage. Except at the power station, all the subsequent sub-stations use step-down transformers to gradually reduce the voltage of electric supply and finally deliver it at utilisation voltage. The modern practice is to use 3-phase transformers in sub-stations ; although 3 single phase bank of



transformers can also be used. The use of 3-phase transformer (instead of 3 single phase bank of transformers) permits two advantages. Firstly, only one 3-phase load-tap changing mechanism can be used. Secondly, its installation is much simpler than the three single phase transformers.

The power transformer is generally installed upon lengths of rails fixed on concrete slabs having foundations 1 to 1.5 m deep. For ratings upto 10 MVA, naturally cooled, oil immersed transformers are used. For higher ratings, the transformers are generally air blast cooled.

**Instrument transformers.** The lines in sub-stations operate at high voltages and carry current of thousands of amperes. The measuring instruments and protective devices are designed for low voltages (generally 110 V) and currents (about 5 A). Therefore, they will not work satisfactorily if mounted directly on the power lines. This difficulty is overcome by installing *instrument transformers* on the power lines. The function of these instrument transformers is to transfer voltages or currents in the power lines to values which are convenient for the operation of measuring instruments and relays. There are two types of instrument transformers viz.

(i) Current transformer (C.T.)

(ii) Potential transformer (P.T.)

**(i) Current transformer (C.T.).** A current transformer is essentially a step-down transformer which steps down the current to a known ratio. The primary of this transformer consists of one or more turns of thick wire connected in series with the line. The secondary consists of a large number of turns of fine wire and provides for the measuring instruments and relays a current which is a constant fraction of the current in the line. Suppose a current transformer rated at 100/5 A is connected in the line to measure current. If the current in the line is 100 A, then current in the secondary will be 5 A. Similarly, if current in the line is 50 A, then secondary of C.T. will have a current of 2.5 A. Thus the C.T. under consideration will step down the line current by a factor of 20.

**(ii) Voltage transformer.** It is essentially a step-down transformer and steps down the voltage to a known ratio. The primary of this transformer consists of a large number of turns of fine wire connected across the line. The secondary winding consists of a few turns and provides for measuring instruments and relays a voltage which is a known fraction of the line voltage. Suppose a potential transformer rated at 66kV/110V is connected to a power line. If line voltage is 66kV, then voltage across the secondary will be 110 V.

**Metering and Indicating Instruments.** There are several metering and indicating instruments (*e.g.* ammeters, voltmeters, energy meters etc.) installed in a sub-station to maintain watch over the circuit quantities. The instrument transformers are invariably used with them for satisfactory operation.

**Miscellaneous equipment.** In addition to above, there may be following equipment in a sub-station :

- Fuses
- carrier-current equipment
- sub-station auxiliary supplies

### **Bus-Bar Arrangements in Sub-Stations**

Bus-bars are the important components in a sub-station. There are several bus-bar arrangements that can be used in a sub-station. The choice of a particular arrangement depends upon various factors such as system voltage, position of sub-station, degree of reliability, cost etc. The following are the important bus-bar arrangements used in sub-stations :

**(i) Single bus-bar system.** As the name suggests, it consists of a single bus-bar and all the incoming and outgoing lines are connected to it. The chief advantages of this type of arrangement are low initial cost, less maintenance and simple operation. However, the principal disadvantage of single bus-bar system is that if repair is to be done on the bus-bar or a fault occurs on the bus, there is a complete interruption of the supply. This arrangement is not used for voltages exceeding 33kV.

The indoor 11kV sub-stations often use single bus-bar arrangement.

There are two 11 kV incoming lines connected to the bus-bar through circuit breakers and isolators. The two 400V outgoing lines are connected to the bus bars through transformers (11kV/400 V) and circuit breakers.

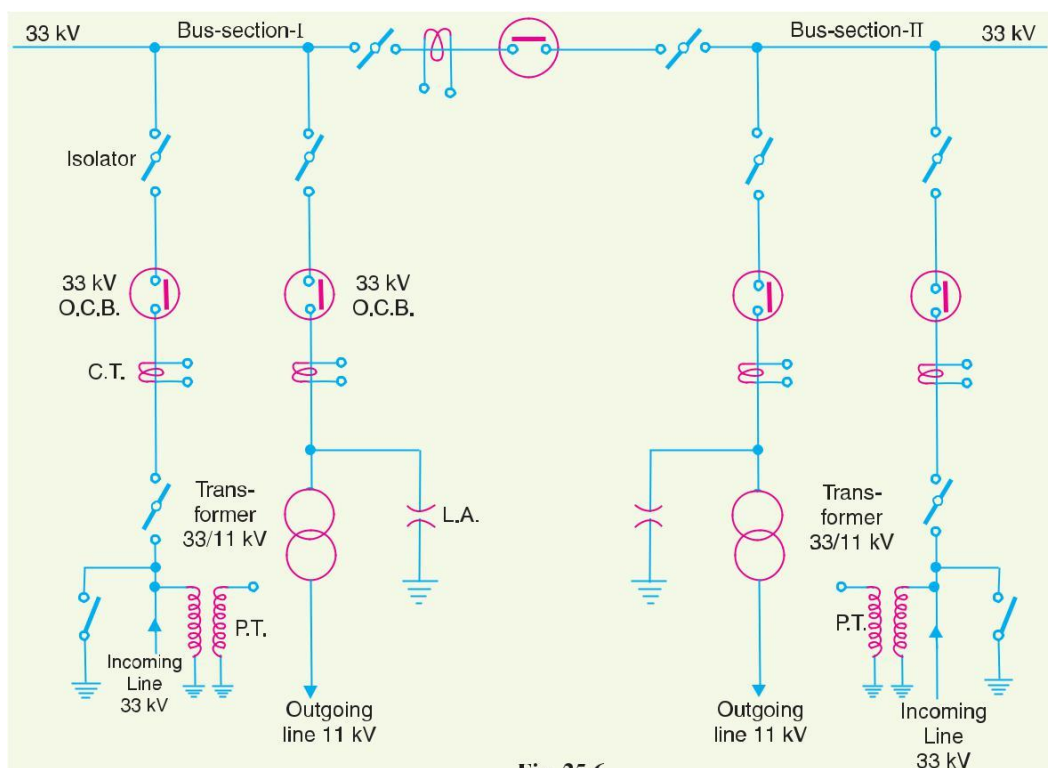


Fig. 25.6

**(ii) Single bus-bar system with sectionalisation.** In this arrangement, the single bus-bar is divided into sections and load is equally distributed on all the sections. Any two sections of the bus-bar are connected by a circuit breaker and isolators. Two principal advantages are claimed for this arrangement. Firstly, if a fault occurs on any section of the bus, that section can be isolated without affecting the supply from other sections. Secondly, repairs and maintenance of any section of the bus-bar can be carried out by de-energising that section only, eliminating the possibility of complete shut down. This arrangement is used for voltages upto 33 kV.

Fig. 25.6 shows bus-bar with sectionalisation where the bus has been divided into two sections. There are two 33 kV incoming lines connected to sections I and II as shown through circuit breaker and isolators. Each 11 kV outgoing line is connected to one section through transformer (33/11 kV) and circuit breaker. It is easy to see that each bus-section behaves as a separate bus-bar.

**(iii) Duplicate bus-bar system.** This system consists of two bus-bars, a “main” bus-bar and a “spare” bus-bar. Each bus-bar has the capacity to take up the entire sub-station load. The incoming and outgoing lines can be connected to either bus-bar with the help of a bus-bar coupler which consists of a circuit breaker and isolators. Ordinarily, the incoming and outgoing

lines remain connected to the main bus-bar. However, in case of repair of main bus-bar or fault occurring on it, the continuity of supply to the circuit can be maintained by transferring it to the spare bus-bar. For voltages exceeding 33kV, duplicate bus-bar system is frequently used.

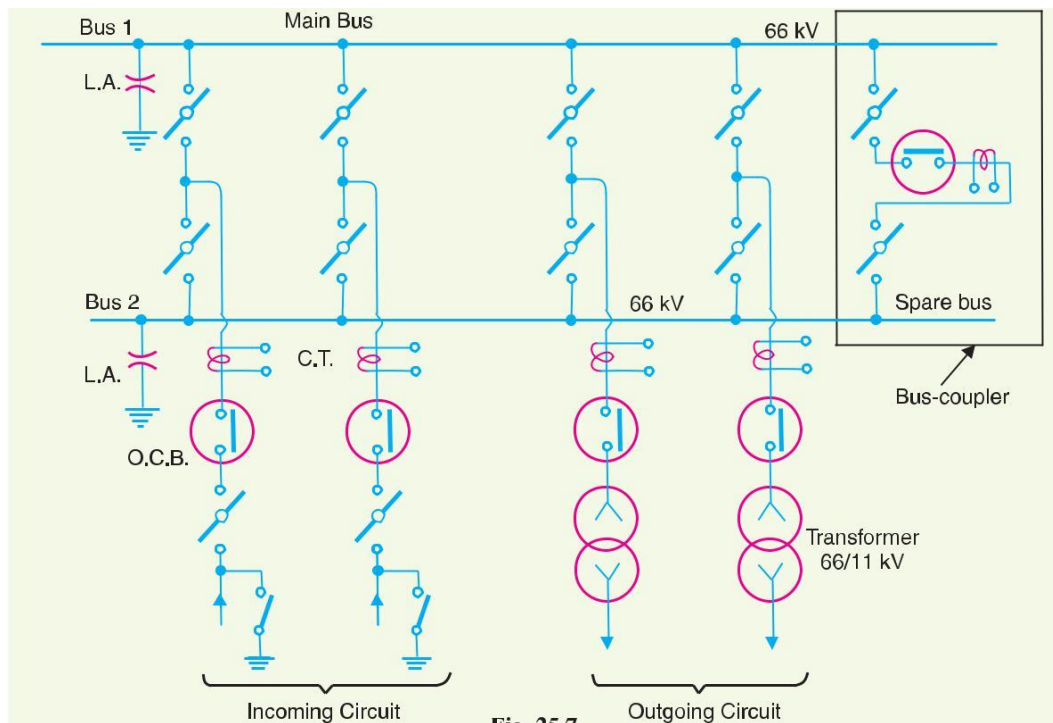


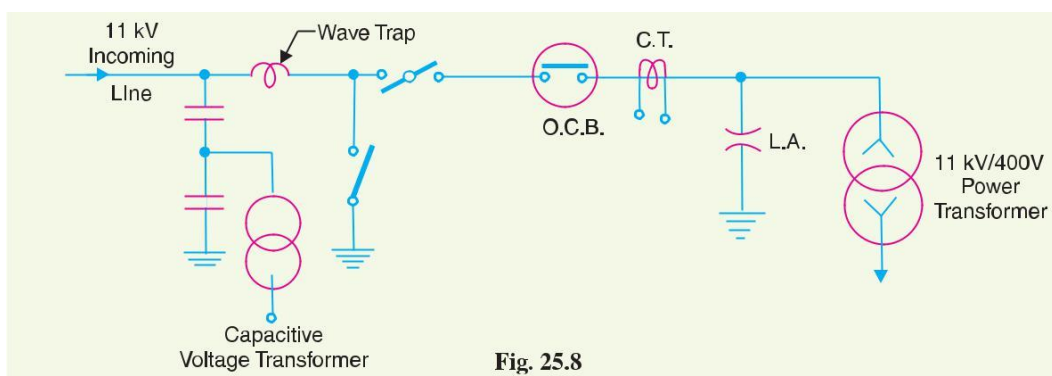
Fig. 7 shows the arrangement of duplicate bus-bar system in a typical sub-station. The two 66kV incoming lines can be connected to either bus-bar by a bus-bar coupler. The two 11 kV outgoing lines are connected to the bus-bars through transformers (66/11 kV) and circuit breakers.

### Terminal and Through Sub-Stations

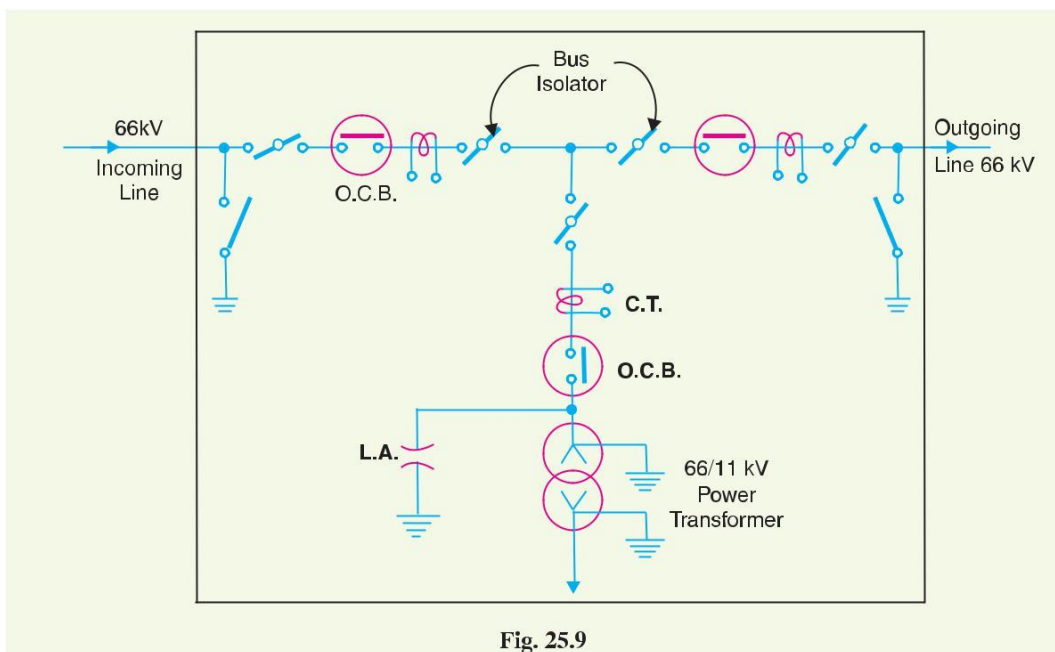
All the transformer sub-stations in the line of power system handle incoming and outgoing lines. Depending upon the manner of incoming lines, the sub-stations are classified as:

(i) Terminal sub-station (ii) Through sub-station

**(i) Terminal sub-station.** A terminal sub-station is one in which the line supplying to the substation terminates or ends. It may be located at the end of the main line or it may be situated at a point away from main line route. In the latter case, a tapping is taken from the main line to supply to the sub-station. Fig. 25.8 shows the schematic connections of a terminal sub-station. It is clear that incoming 11 kV main line terminates at the sub-station. Most of the distribution sub-stations are of this type.

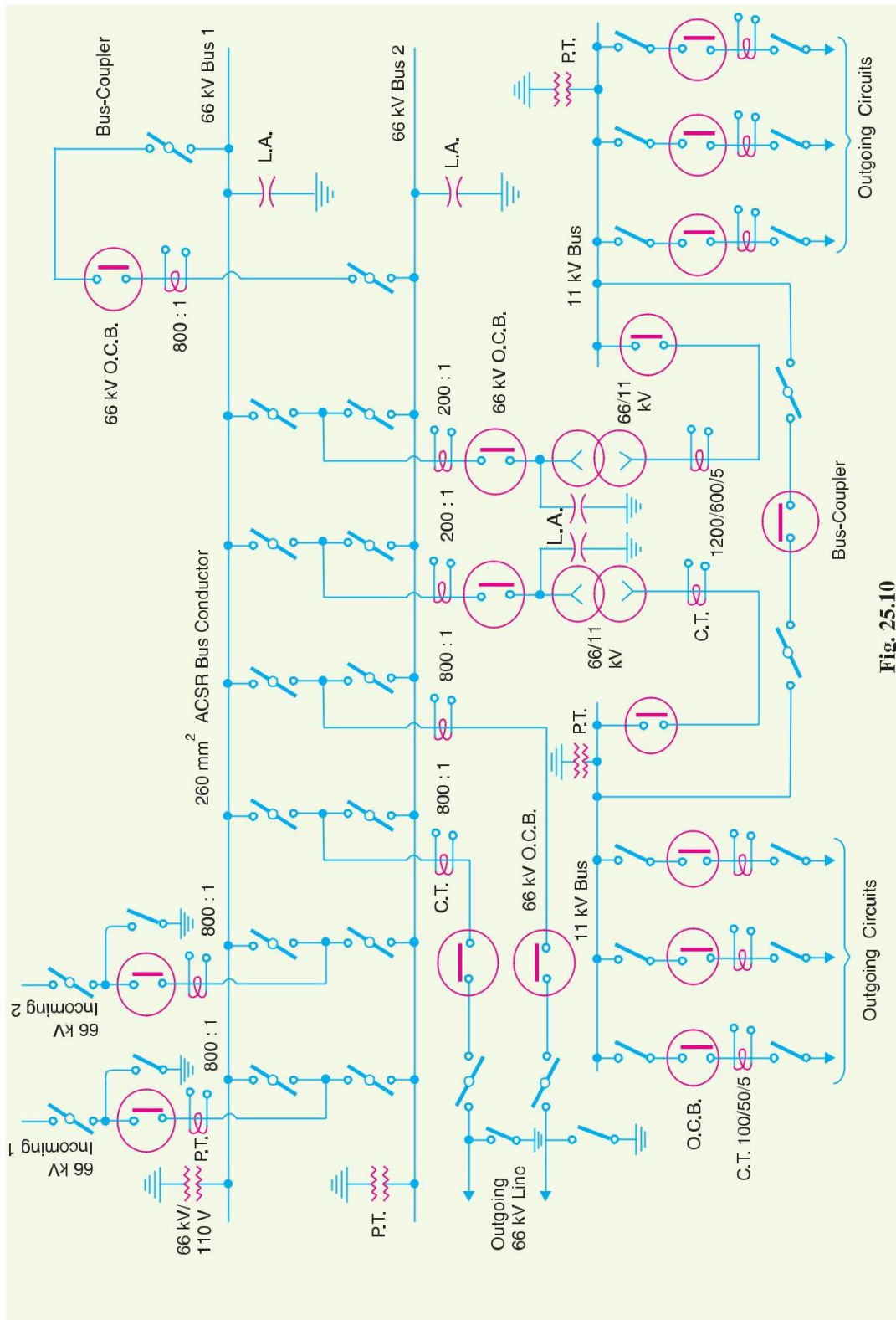


**(ii) Through sub-station.** A through sub-station is one in which the incoming line passes 'through' at the same voltage. A tapping is generally taken from the line to feed to the transformer to reduce the voltage to the desired level. Fig. 25.9 shows the schematic connections of a through sub-station. The incoming 66 kV line passes through the sub-station as 66 kV outgoing line. At the same time, the incoming line is tapped in the sub-station to reduce the voltage to 11 kV for secondary distribution.



### Key Diagram of 66/11 kV Sub-Station

Fig. 25.10 shows the key diagram of a typical 66/11 kV sub-station. The key diagram of this sub-station can be explained as under:



**Fig. 25.10**

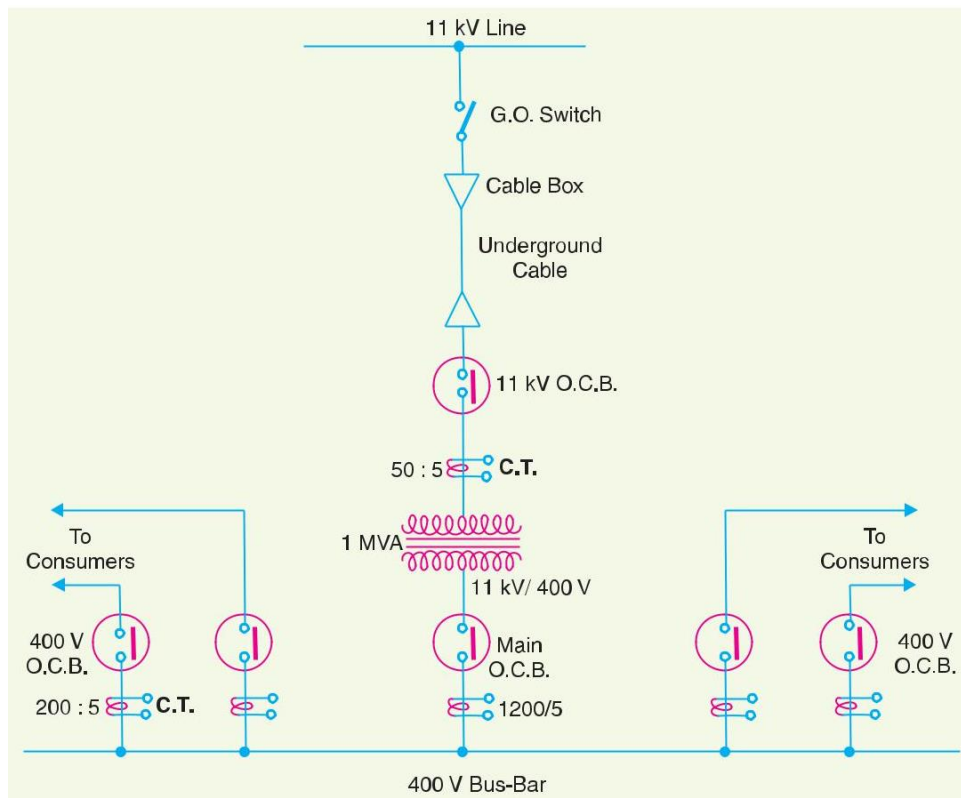


- (i) There are two 66 kV incoming lines marked 'incoming 1' and 'incoming 2' connected to the bus-bars. Such an arrangement of two incoming lines is called a double circuit. Each incoming line is capable of supplying the rated sub-station load. Both these lines can be loaded simultaneously to share the sub-station load or any one line can be called upon to meet the entire load. The double circuit arrangement increases the reliability of the system. In case there is a breakdown of one incoming line, the continuity of supply can be maintained by the other line.
- (ii) The sub-station has duplicate bus-bar system; one 'main bus-bar' and the other spare bus-bar. The incoming lines can be connected to either bus-bar with the help of a bus-coupler which consists of a circuit breaker and isolators. The advantage of double bus-bar system is that if repair is to be carried on one bus-bar, the supply need not be interrupted as the entire load can be transferred to the other bus.
- (iii) There is an arrangement in the sub-station by which the same 66 kV double circuit supply is going out *i.e.* 66 kV double circuit supply is passing through the sub-station. The outgoing 66 kV double circuit line can be made to act as incoming line.
- (iv) There is also an arrangement to step down the incoming 66 kV supply to 11 kV by two units of 3-phase transformers; each transformer supplying to a separate bus-bar. Generally, one transformer supplies the entire sub-station load while the other transformer acts as a standby unit. If need arises, both the transformers can be called upon to share the sub-station load. The 11 kV outgoing lines feed to the distribution sub-stations located near consumers localities.
- (v) Both incoming and outgoing lines are connected through circuit breakers having isolators on their either end. Whenever repair is to be carried over the line towers, the line is first switched off and then earthed.
- (vi) The potential transformers (P.T.) and current transformers (C.T.) are suitably located for supply to metering and indicating instruments and relay circuits (not shown in the figure). The P.T. is connected right on the point where the line is terminated. The CTs are connected at the terminals of each circuit breaker.
- (vii) The lightning arresters are connected near the transformer terminals (on H.T. side) to protect them from lightning strokes.
- (viii) There are other auxiliary components in the sub-station such as capacitor bank for power factor improvement, earth connections, local supply connections, d.c. supply connections etc. However, these have been omitted in the key diagram for the sake of simplicity.

#### **Key Diagram of 11 kV/400 V Indoor Sub-Station**

Fig. 25.11 shows the key diagram of a typical 11 kV/400 V indoor sub-station. The key diagram of this sub-station can be explained as under :

- (i) The 3-phase, 3-wire 11 kV line is tapped and brought to the gang operating switch installed near the sub-station. The G.O. switch consists of isolators connected in each phase of the 3-phase line.
- (ii) From the G.O. switch, the 11 kV line is brought to the indoor sub-station as underground cable. It is fed to the H.T. side of the transformer (11 kV/400 V) *via* the 11 kV O.C.B. The transformer steps down the voltage to 400 V, 3-phase, 4-wire.
- (iii) The secondary of transformer supplies to the bus-bars *via* the main O.C.B. From the bus-bars, 400 V, 3-phase, 4-wire supply is given to the various consumers *via* 400 V O.C.B. The voltage between any two phases is 400 V and between any phase and neutral it is 230 V. The single phase residential load is connected between any one phase and neutral whereas 3-phase, 400 V motor load is connected across 3-phase lines directly.
- (iv) The CTs are located at suitable places in the sub-station circuit and supply for the metering and indicating instruments and relay circuits.



**Air Insulated Electrical Power Substation:**

In Air Insulated Power Substations busbars and connectors are visible. In this Power Substations Circuit Breakers and Isolators, Transformers, Current Transformers, Potential Transformers etc are installed in the outdoor. Busbars are supported on the post Insulators or Strain Insulators. Substations have galvanized Steel Structures for Supporting the equipment, insulators and incoming and outgoing lines. Clearances are the primary criteria for these substations and occupy a large area for installation.

**Gas Insulated Electrical Power Substation:**

In Gas Insulated Substation Various Power Substation equipments like Circuit Breakers, Current Transformers, Voltage Transformers, Busbars, Earth Switches, Surge Arresters, Isolators etc are in the form of metal enclosed SF<sub>6</sub> gas modules. The modules are assembled in accordance with the required Configuration. The various Live parts are enclosed in the metal enclosures (modules) containing SF<sub>6</sub> gas at high pressure. Thus the size of Power Substation reduces to 8% to 10% of the Air Insulated Power Substation.

**Hybrid Electrical Power Substation:**

Hybrid Substations are the combination of both Conventional Substation and Gas Insulated Substation. Some bays in a Power Substation are Gas Insulated type and some are Air Insulated Type. The design is based on convenience, Local Conditions available, area available and Cost.

**Advantages of GIS Substation:**

- It occupies very less space (1/10th) compared to ordinary substations. Hence these Gas Insulated Substations (GIS) are most preferred where area for substation is small (eg: Cities)
- Most reliable compared to Air Insulated Substations, number of outages due to the fault is less
- Maintenance Free
- Can be assembled at the shop and modules can be commissioned in the plant easily

**Disadvantages of GIS Substation:**

- Cost is higher compared to Ordinary Conventional Substations
- Care should be taken that no dust particles enter into the live compartments which results in flash overs
- When fault occurs internally, diagnosis of the fault and rectifying this takes very long time (outage time is high)



- SF6 gas pressure must be monitored in each compartment, reduction in the pressure of the SF6 gas in any module results in flashovers and fault

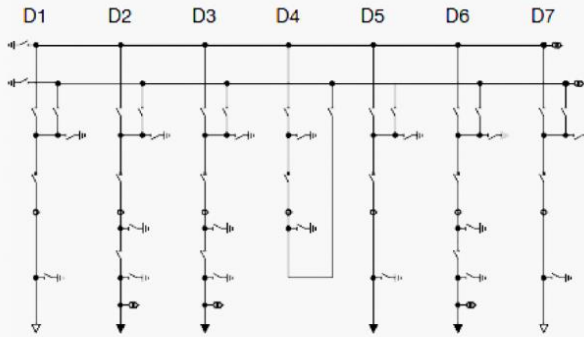


Figure 1 – Single line diagram of double busbar

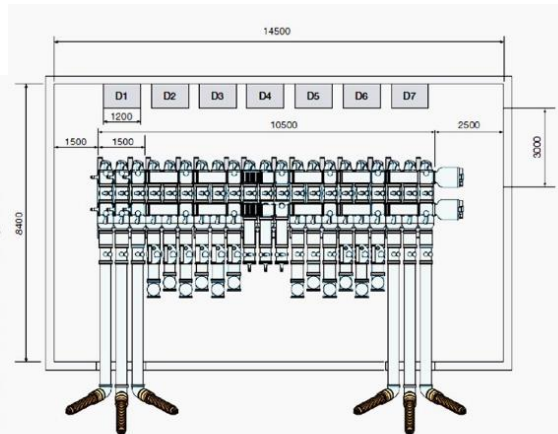


Figure 2 – Layout of double busbar GIS

The Gas insulated substation comprises the following components:

- 1 Circuit breaker
- 2 Disconnect switch
- 3 Earthing switch
- 4 Current transformer
- 5 Voltage transformer
- 6 Bus bar & connectors
- 7 Power transformer
- 8 Surge arrester
- 9 Cable termination
- 10 SF6 / air or SF6 / oil bushing

### **Advantages of GIS over the conventional open air substation**

The application of GIS during the last fifteen years has been very rapid. The rapid growth in GIS application is due to the following special advantages:

1. Area and volume saving in construction for over or underground applications. Therefore they offer saving in land area and construction costs.
2. Insensitivity to external influences because of grounded metal enclosures.
3. Greatly improved safety and reliability due to earthed metal housing of all high voltage parts and much higher intrinsic strength of SF6 gas as insulation.
4. Short on site erection times, based on large factory assembled and tested shipping units
5. Fulfillment of aesthetic requirements with indoor applications
6. High service reliability due to non-exposure of the use of high voltage parts to atmosphere influences
7. Reduction in radio interference with the use of earthed metal enclosures.
8. Use as mobile substations for transportation to load centers on standard tracks. These substations can be located closer to load centers thereby reducing transmission losses and expenditure in the distribution network.
9. More optimal life cycle costs because of lesser maintenance, down time and repair costs.
10. It is not necessary that high voltage or extra high voltage switchgear has to be installed outdoors.

### **Disadvantages of GIS**

Although GIS has been in operation for several years, a lot of problems encountered in practice need fuller understanding. Some of the problems being studied are:

1. Switching operation generate Very Fast Transients Over Voltages (VFTOS).
2. VFTOS may cause secondary breakdown inside a GIS and Transient Enclosure Voltages (TEV) outside the GIS.
3. Field non-uniformities reduce withstanding levels of a GIS.
4. Prolonged arcing may produce corrosive/toxic by-products.
5. Support spacers can be weak points when arc by-products and metallic particles are present.

## UNIT-IV

### Power Factor and Voltage Control

#### Power Factor

*The cosine of angle between voltage and current in an a.c. circuit is known as **power factor**.*

In an a.c. circuit, there is generally a phase difference  $\phi$  between voltage and current. The term  $\cos \phi$  is called the power factor of the circuit. If the circuit is inductive, the current lags behind the voltage and the power factor is referred to as lagging. However, in a capacitive circuit, current leads the voltage and power factor is said to be leading. Consider an inductive circuit taking a lagging current  $I$  from supply voltage  $V$ ; the angle of lag being  $\phi$ . The phasor diagram of the circuit is shown in Fig. 6.1. The circuit current  $I$  can be resolved into two perpendicular components, namely;

- (i)  $I \cos \phi$  - in phase with  $V$
- (ii)  $I \sin \phi$  -  $90^\circ$  out of phase with  $V$

The component  $I \cos \phi$  is known as active or wattful component, whereas component  $I \sin \phi$  is called the reactive or wattless component. The reactive component is a measure of the power factor. If the reactive component is small, the phase angle  $\phi$  is small and hence power factor  $\cos \phi$  will be high. Therefore, a circuit having small reactive current (i.e.,  $I \sin \phi$ ) will have high power factor and vice-versa. It may be noted that value of power factor can never be more than unity.

(i) It is a usual practice to attach the word 'lagging' or 'leading' with the numerical value of power factor to signify whether the current lags or leads the voltage. Thus if the circuit has a p.f. of 0.5 and the current lags the voltage, we generally write p.f. as 0.5 lagging.

(ii) Sometimes power factor is expressed as a percentage. Thus 0.8 lagging power factor may be expressed as 80% lagging.

#### Power Triangle:

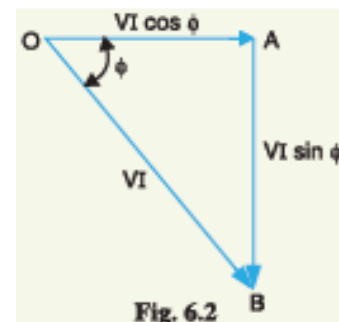
The analysis of power factor can also be made in terms of power drawn by the ac circuit. If each side of the current triangle  $oab$  is multiplied by voltage  $V$ , then we get the power triangle.

$OA = VI \cos \phi$  and represents the active power in watts or kW

$AB = VI \sin \phi$  and represents the reactive power in VAR or kVAR

$OB = VI$  and represents the apparent power in VA or kVA

The following points may be noted from the power triangle:



The following points may be noted from the power triangle :

- (i) The apparent power in an a.c. circuit has two components viz., active and reactive power at right angles to each other.

$$OB^2 = OA^2 + AB^2$$

or  $(\text{apparent power})^2 = (\text{active power})^2 + (\text{reactive power})^2$

or  $(\text{kVA})^2 = (\text{kW})^2 + (\text{kVAR})^2$

(ii) Power factor,  $\cos \phi = \frac{OA}{OB} = \frac{\text{active power}}{\text{apparent power}} = \frac{\text{kW}}{\text{kVA}}$

Thus the power factor of a circuit may also be defined as the ratio of active power to the apparent power. This is a perfectly general definition and can be applied to all cases, whatever be the waveform.

- (iii) The lagging\* reactive power is responsible for the low power factor. It is clear from the power triangle that smaller the reactive power component, the higher is the power factor of the circuit.

$$\text{kVAR} = \text{kVA} \sin \phi = \frac{\text{kW}}{\cos \phi} \sin \phi$$

$$\therefore \text{kVAR} = \text{kW} \tan \phi$$

- (iv) For leading currents, the power triangle becomes reversed. This fact provides a key to the power factor improvement. If a device taking leading reactive power (e.g. capacitor) is connected in parallel with the load, then the lagging reactive power of the load will be partly neutralised, thus improving the power factor of the load.

- (v) The power factor of a circuit can be defined in one of the following three ways :

(a) Power factor =  $\cos \phi$  = cosine of angle between  $V$  and  $I$

(b) Power factor =  $\frac{R}{Z} = \frac{\text{Resistance}}{\text{Impedance}}$

(c) Power factor =  $\frac{VI \cos \phi}{VI} = \frac{\text{Active power}}{\text{Apparent Power}}$

- (vi) The reactive power is neither consumed in the circuit nor it does any useful work. It merely flows back and forth in both directions in the circuit. A wattmeter does not measure reactive power.

**Illustration.** Let us illustrate the power relations in an a.c. circuit with an example. Suppose a circuit draws a current of 10 A at a voltage of 200 V and its p.f. is 0.8 lagging. Then,

$$\text{Apparent power} = VI = 200 \times 10 = 2000 \text{ VA}$$

$$\text{Active power} = VI \cos \phi = 200 \times 10 \times 0.8 = 1600 \text{ W}$$

$$\text{Reactive power} = VI \sin \phi = 200 \times 10 \times 0.6 = 1200 \text{ VAR}$$

The circuit receives an apparent power of 2000 VA and is able to convert only 1600 watts into active power. The reactive power is 1200 VAR and does no useful work. It merely flows into and out of the circuit periodically. In fact, reactive power is a liability on the source because the source has to supply the additional current (i.e.,  $I \sin \phi$ ).

## Disadvantages of Low Power Factor

The power factor plays an importance role in a.c. circuits since power consumed depends upon the power factor.

$$\begin{aligned} P &= V_L I_L \cos \phi && \text{(For single phase supply)} \\ \therefore I_L &= \frac{P}{V_L \cos \phi} && \dots(i) \end{aligned}$$

$$\begin{aligned} P &= \sqrt{3} V_L I_L \cos \phi && \text{(For 3 phase supply)} \\ \therefore I_L &= \frac{P}{\sqrt{3} V_L \cos \phi} && \dots(ii) \end{aligned}$$

It is clear from above that for fixed power and voltage, the load current is inversely proportional to the power factor. Lower the power factor, higher is the load current and *vice-versa*. A power factor less than unity results in the following disadvantages :

(i) **Large kVA rating of equipment.** The electrical machinery (e.g., alternators, transformers, switchgear) is always rated in **kVA**.

$$\text{Now,} \quad \text{kVA} = \frac{\text{kW}}{\cos \phi}$$

It is clear that **kVA** rating of the equipment is inversely proportional to power factor. The smaller the power factor, the larger is the **kVA** rating. Therefore, at low power factor, the **kVA** rating of the equipment has to be made more, making the equipment larger and expensive.

(ii) **Greater Conductor size:** To transmit or distribute a fixed amount of power at constant voltage, the conductor will have to carry more current at low power factor. This necessitates large conductor size. For example, take the case of a single phase a.c. motor having an input of 10 kW on full load, the terminal voltage being 250 V. At unity p.f., the input full load current would be  $10,000/250 = 40$  A. At 0.8 p.f.; the kVA input would be  $10/0.8 = 12.5$  and the current input  $12,500/250 = 50$  A. If the motor is worked at a low power factor of 0.8, the cross-sectional area of the supply cables and motor conductors would have to be based upon a current of 50 A instead of 40 A which would be required at unity power factor.

(iii) **Large copper losses.** The large current at low power factor causes more  $I^2R$  losses in all the elements of the supply system. This results in poor efficiency.

(iv) **Poor voltage regulation.** The large current at low lagging power factor causes greater voltage drops in alternators, transformers, transmission lines and distributors. This results in the decreased voltage available at the supply end, thus impairing the performance of utilisation devices. In order to keep the receiving end voltage within permissible limits, extra equipment (*i.e.*, voltage regulators) is required.

(v) **Reduced handling capacity of system.** The lagging power factor reduces the handling capacity of all the elements of the system. It is because the reactive component of current prevents the full utilisation of installed capacity.

The above discussion leads to the conclusion that low power factor is an objectionable feature in the supply system

## Causes of Low Power Factor

Low power factor is undesirable from economic point of view. Normally, the power factor of the whole load on the supply system is lower than 0.8. The following are the causes of low power factor:

(i) Most of the a.c. motors are of induction type (1 $\phi$  and 3 $\phi$  induction motors) which have low lagging power factor. These motors work at a power factor which is extremely small on light load (0.2 to 0.3) and rises to 0.8 or 0.9 at full load.

(ii) Arc lamps, electric discharge lamps and industrial heating furnaces operate at low lagging power factor.

(iii) The load on the power system is varying ; being high during morning and evening and low at other times. During low load period, supply voltage is increased which increases the magnetisation current. This results in the decreased power factor.

## Power Factor Improvement

The low power factor is mainly due to the fact that most of the power loads are inductive and, therefore, take lagging currents. In order to improve the power factor, some device taking leading power should be connected in parallel with the load. One of such devices can be a capacitor. The capacitor draws a leading current and partly or completely neutralises the lagging reactive component of load current. This raises the power factor of the load.

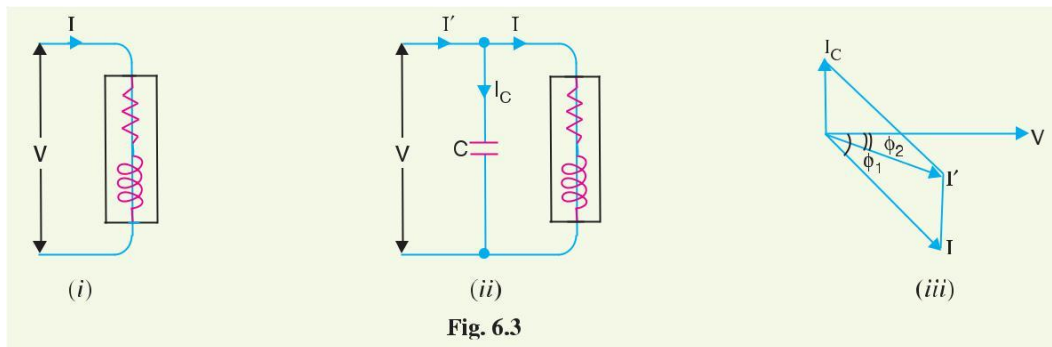


Fig. 6.3

**Illustration.** To illustrate the power factor improvement by a capacitor, consider a single phase load taking lagging current  $I$  at a power factor  $\cos \phi_1$ .

The capacitor  $C$  is connected in parallel with the load. The capacitor draws current  $I_C$  which leads the supply voltage by  $90^\circ$ . The resulting line current  $I'$  is the phasor sum of  $I$  and  $I_C$  and its angle of lag is  $\phi_2$  as shown in the phasor diagram of Fig. 6.3. (iii). It is clear that  $\phi_2$  is less than  $\phi_1$ , so that  $\cos \phi_2$  is greater than  $\cos \phi_1$ . Hence, the power factor of the load is improved. The following points are worth noting:

(i) The circuit current  $I'$  after p.f. correction is less than the original circuit current  $I$ .

The active or wattful component remains the same before and after p.f. correction because only the lagging reactive component is reduced by the capacitor.

(ii)  $\therefore I \cos \phi_1 = I' \cos \phi_2$

The lagging reactive component is reduced after p.f. improvement and is equal to the difference between lagging reactive component of load ( $I \sin \phi_1$ ) and capacitor current ( $I_C$ ) i.e.,  $I' \sin \phi_2 = I \sin \phi_1 - I_C$

(iv) As  $I \cos \phi_1 = I' \cos \phi_2$

$$\therefore VI \cos \phi_1 = VI' \cos \phi_2 \quad [\text{Multiplying by } V]$$

Therefore, active power (kW) remains unchanged due to power factor improvement.

(v)  $I' \sin \phi_2 = I \sin \phi_1 - I_C$

$$\therefore VI' \sin \phi = VI \sin \phi - VI_C \quad [\text{Multiplying by } V]$$

i.e., Net kVAR after p.f. correction = Lagging kVAR before p.f. correction – leading kVAR of equipment

### Power Factor Improvement Equipment

Normally, the power factor of the whole load on a large generating station is in the region of 0.8 to 0.9. However, sometimes it is lower and in such cases it is generally desirable to take special steps to improve the power factor. This can be achieved by the following equipment:

1. Static capacitors.
2. Synchronous condenser.
3. Phase advancers.

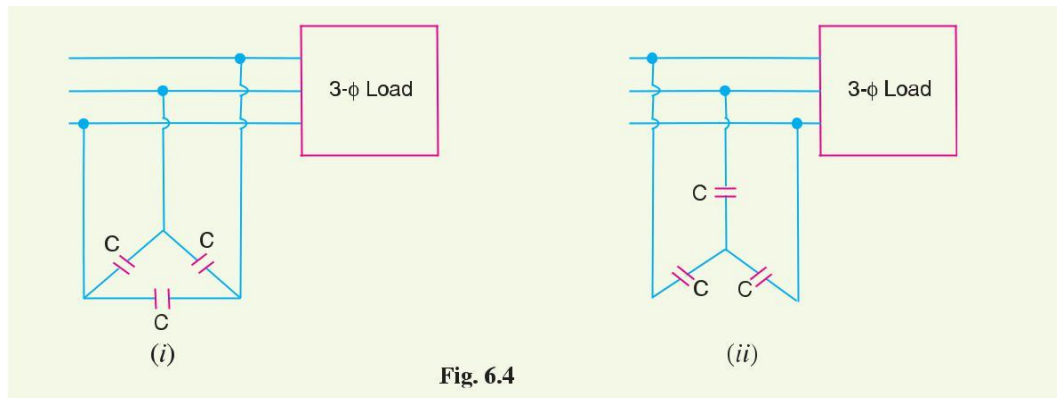


Fig. 6.4

**1. Static capacitor.** The power factor can be improved by connecting capacitors in parallel with the equipment operating at lagging power factor. The capacitor (generally known as static capacitor) draws a leading current and partly or completely neutralises the lagging reactive component of load current. This raises the power factor of the load. For three-phase loads, the capacitors can be connected in delta or star as shown in Fig. 6.4. Static capacitors are invariably used for power factor improvement in factories.

#### Advantages

- (i) They have low losses.
- (ii) They require little maintenance as there are no rotating parts.
- (iii) They can be easily installed as they are light and require no foundation.
- (iv) They can work under ordinary atmospheric conditions.

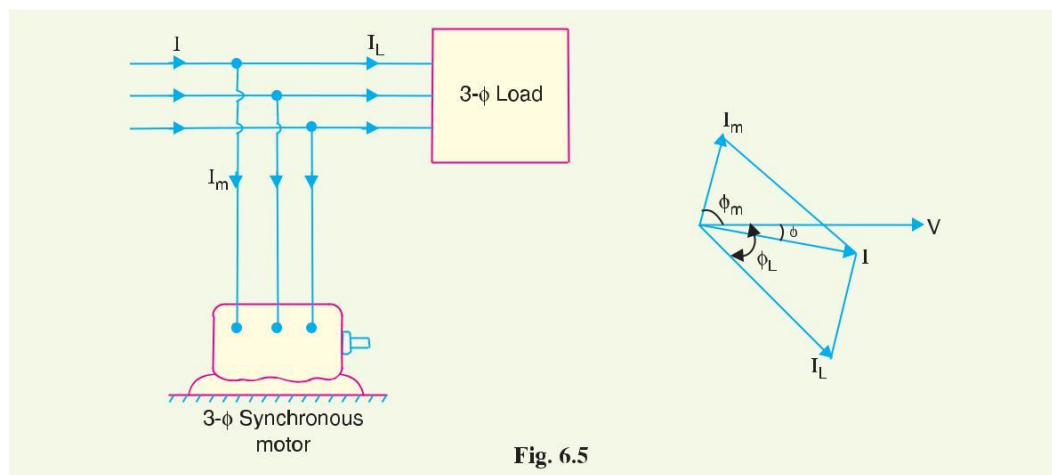


## Disadvantages

- (i) They have short service life ranging from 8 to 10 years.
- (ii) They are easily damaged if the voltage exceeds the rated value.
- (iii) Once the capacitors are damaged, their repair is uneconomical.

**2. Synchronous condenser.** A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor. An over-excited synchronous motor running on no load is known as *synchronous condenser*. When such a machine is connected in parallel with the supply, it takes a leading current which partly neutralises the lagging reactive component of the load. Thus the power factor is improved.

Fig 6.5 shows the power factor improvement by synchronous condenser method. The 3 $\phi$  load takes current  $I_L$  at low lagging power factor  $\cos \phi_L$ . The synchronous condenser takes a current  $I_m$  which leads the voltage by an angle  $\phi_m^*$ . The resultant current  $I$  is the phasor sum of  $I_m$  and  $I_L$  and lags behind the voltage by an angle  $\phi$ . It is clear that  $\phi$  is less than  $\phi_L$  so that  $\cos \phi$  is greater than  $\cos \phi_L$ . Thus the power factor is increased from  $\cos \phi_L$  to  $\cos \phi$ . Synchronous condensers are generally used at major bulk supply substations for power factor improvement.



## Advantages

- (i) By varying the field excitation, the magnitude of current drawn by the motor can be changed by any amount. This helps in achieving stepless  $\uparrow$  control of power factor.
- (ii) The motor windings have high thermal stability to short circuit currents.
- (iii) The faults can be removed easily.

## Disadvantages

- (i) There are considerable losses in the motor.
- (ii) The maintenance cost is high.
- (iii) It produces noise.
- (iv) Except in sizes above 500 kVA, the cost is greater than that of static capacitors of the same rating.
- (v) As a synchronous motor has no self-starting torque, therefore, an auxiliary equipment has to be provided for this purpose.

**3. Phase advancers.** Phase advancers are used to improve the power factor of induction motors. The low power factor of an induction motor is due to the fact that its stator winding draws exciting current which lags behind the supply voltage by  $90^\circ$ . If the exciting ampere turns can be

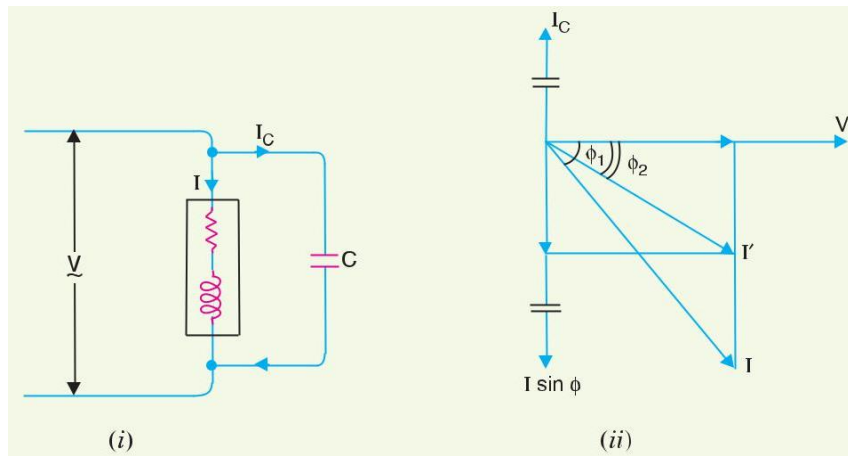


provided from some other a.c. source, then the stator winding will be relieved of exciting current and the power factor of the motor can be improved. This job is accomplished by the phase advancer which is simply an a.c. exciter. The phase advancer is mounted on the same shaft as the main motor and is connected in the rotor circuit of the motor. It provides exciting ampere turns to the rotor circuit at slip frequency. By providing more ampere turns than required, the induction motor can be made to operate on leading power factor like an over-excited synchronous motor.

Phase advancers have two principal advantages. Firstly, as the exciting ampere turns are supplied at slip frequency, therefore, lagging kVAR drawn by the motor are considerably reduced. Secondly, phase advancer can be conveniently used where the use of synchronous motors is unadmissible. However, the major disadvantage of phase advancers is that they are not economical for motors below 200 H.P.

### Calculations of Power Factor Correction

Consider an inductive load taking a lagging current  $I$  at a power factor  $\cos \phi_1$ . In order to improve the power factor of this circuit, the remedy is to connect such an equipment in parallel with the load which takes a leading reactive component and partly cancels the lagging reactive component of the load. Fig. 6.6 (i) shows a capacitor connected across the load. The capacitor takes a current  $I_C$  which leads the supply voltage  $V$  by  $90^\circ$ . The current  $I_C$  partly cancels the lagging reactive component of the load current as shown in the phasor diagram in Fig. 6.6 (ii). The resultant circuit current becomes  $I'$  and its angle of lag is  $\phi_2$ . It is clear that  $\phi_2$  is less than  $\phi_1$  so that new p.f.  $\cos \phi_2$  is more than the previous p.f.  $\cos \phi_1$ .



From the phasor diagram, it is clear that after p.f. correction, the lagging reactive component of the load is reduced to  $I' \sin \phi_2$ .

$$\text{Obviously, } I' \sin \phi_2 = I \sin \phi_1 - I_C$$

$$\text{Or } I_C = I \sin \phi_1 - I' \sin \phi_2$$

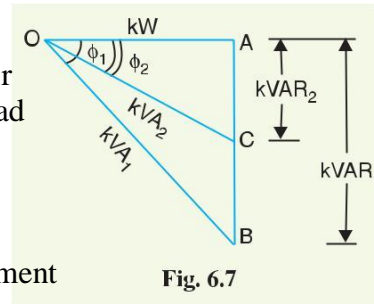
$\therefore$  Capacitance of capacitor to improve p.f. from  $\cos \phi_1$  to  $\cos \phi_2$

$$= \frac{I_C}{\omega V}$$

**Power triangle.** The power factor correction can also be illustrated from power triangle. Thus referring to Fig. 6.7, the power triangle  $OAB$  is for the power factor

$\cos \phi_1$ , whereas power triangle  $OAC$  is for the improved power factor  $\cos \phi_2$ . It may be seen that

active power ( $OA$ ) does not change with power factor improvement. However, the lagging kVAR of the load is reduced by the p.f. correction equipment, thus improving the p.f. to  $\cos \phi_2$ .



Leading kVAR supplied by p.f. correction equipment

$$\begin{aligned} &= BC = AB - AC \\ &= \text{kVAR}_1 - \text{kVAR}_2 \\ &= OA (\tan \phi_1 - \tan \phi_2) \\ &= \text{kW} (\tan \phi_1 - \tan \phi_2) \end{aligned}$$

Knowing the leading kVAR supplied by the p.f. correction equipment, the desired results can be obtained.

### Importance of Power Factor Improvement

The improvement of power factor is very important for both consumers and generating stations as discussed below:

(i) *For consumers* A consumer has to pay electricity charges for his maximum demand in kVA plus the units consumed. If the consumer improves the power factor, then there is a reduction† in his maximum kVA demand and consequently there will be annual saving due to maximum demand charges. Although power factor improvement involves extra annual expenditure on account of pf correction equipment, yet improvement of pf to a *proper value* results in the net annual saving for the consumer.

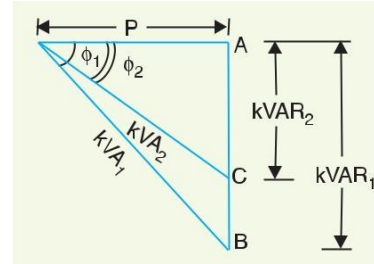
(ii) *For generating stations* A generating station is as much concerned with power factor improvement as the consumer. The generators in a power station are rated in kVA but the useful output depends upon kW output. As station output is  $\text{kW} = \text{kVA} \times \cos \phi$ , therefore, number of units supplied by it depends upon the power factor. The greater the power factor of the generating station, the higher is the kWh it delivers to the system. This leads to the conclusion that improved power factor increases the earning capacity of the power station.

### Most Economical Power Factor

If a consumer improves the power factor, there is reduction in his maximum kVA demand and hence there will be annual saving over the maximum demand charges. However, when power factor is improved, it involves capital investment on the power factor correction equipment. The consumer will incur expenditure every year in the shape of annual interest and depreciation on the investment made over the pf correction equipment. Therefore, the net annual saving will be equal to the annual saving in maximum demand charges minus annual expenditure incurred on pf correction equipment.

The value to which the power factor should be improved so as to have maximum net annual saving is known as the **most economical power factor**.

Consider a consumer taking a peak load of  $P$  kW at a power factor of  $\cos \phi_1$  and charged at a rate of  $Rs\ x$  per kVA of maximum demand per annum. Suppose the consumer improves the power factor to  $\cos \phi_2$  by installing pf correction equipment. Let expenditure incurred on the pf correction equipment be  $Rs\ y$  per kVAR per annum. The power triangle at the original pf  $\cos \phi_1$  is OAB and for the improved pf  $\cos \phi_2$ , it is OAC.



$$\text{kVA max demand at } \cos \phi_1, \text{ kVA}_1 = P / \cos \phi_1 = P \sec \phi_1$$

$$\text{kVA max demand at } \cos \phi_2, \text{ kVA}_2 = P / \cos \phi_2 = P \sec \phi_2$$

Annual saving in maximum demand charges

$$\begin{aligned} &Rs \times (\text{kVA}_1 - \text{kVA}_2) \\ &Rs \times (P \sec \phi_1 - P \sec \phi_2) \end{aligned}$$

$$= Rs \times P (\sec \phi_1 - \sec \phi_2) \quad (i)$$

Reactive power at  $\cos \phi_1$ ,  $\text{kVAR}_1 = P \tan \phi_1$

Reactive power at  $\cos \phi_2$ ,  $\text{kVAR}_2 = P \tan \phi_2$

Leading kVAR taken by pf correction equipment

$$P (\tan \phi_1 - \tan \phi_2)$$

Annual cost of pf correction equipment

$$= Rs \ P y (\tan \phi_1 - \tan \phi_2) \quad (ii)$$

Net annual saving,  $S$

$$= \text{exp (i)} - \text{exp (ii)}$$

$$= xP (\sec \phi_1 - \sec \phi_2) - yP (\tan \phi_1 - \tan \phi_2)$$

In this expression, only  $\phi_2$  is variable while all other quantities are fixed. Therefore, the net annual saving will be maximum if differentiation of above expression wrt  $\phi_2$  is zero

$$\text{ie } \frac{d}{d\phi_2}(S) = 0$$

$$\text{or } \frac{d}{d\phi_2} [xP (\sec \phi_1 - \sec \phi_2) - yP (\tan \phi_1 - \tan \phi_2)] = 0$$

$$\text{or } \frac{d}{d\phi_2} [xP (\sec \phi_1 - \sec \phi_2) - yP (\tan \phi_1 - \tan \phi_2)] = 0$$

$$\text{or } \frac{d}{d\phi_2} (xP \sec \phi_1) - \frac{d}{d\phi_2} (xP \sec \phi_2) - \frac{d}{d\phi_2} (yP \tan \phi_1) + yP \frac{d}{d\phi_2} (\tan \phi_2) = 0$$

$$\text{or } 0 - xP \sec \phi_2 \tan \phi_2 - 0 + yP \sec^2 \phi_2 = 0$$

$$\text{or } -x \tan \phi_2 + y \sec \phi_2 = 0$$

$$\text{or } \tan \phi_2 = \frac{y}{x} \sec \phi_2$$

$$\text{or } \sin \phi_2 = y/x$$

$$\therefore \text{ Most economical power factor, } \cos \phi_2 = \sqrt{1 - \sin^2 \phi_2} = \sqrt{1 - (y/x)^2}$$

It may be noted that the most economical power factor ( $\cos \phi_2$ ) depends upon the relative costs of supply and pf correction equipment but is independent of the original pf  $\cos \phi_1$ .

### **Importance of Voltage Control**

When the load on the supply system changes, the voltage at the consumer's terminals also changes. The variations of voltage at the consumer's terminals are undesirable and must be kept within pre-scribed limits for the following reasons:

(i) In case of lighting load, the lamp characteristics are very sensitive to changes of voltage. For instance, if the supply voltage to an incandescent lamp decreases by 6% of rated value, then illuminating power may decrease by 20%. On the other hand, if the supply voltage is 6% above the rated value, the life of the lamp may be reduced by 50% due to rapid deterioration of the filament.

(ii) In case of power load consisting of induction motors, the voltage variations may cause erratic operation. If the supply voltage is above the normal, the motor may operate with a saturated magnetic circuit, with consequent large magnetising current, heating and low power factor. On the other hand, if the voltage is too low, it will reduce the starting torque of the motor considerably.

(iii) Too wide variations of voltage cause excessive heating of distribution transformers. This may reduce their ratings to a considerable extent.

It is clear from the above discussion that voltage variations in a power system must be kept to minimum level in order to deliver good service to the consumers. With the trend towards larger and larger interconnected system, it has become necessary to employ appropriate methods of voltage control.

### **Location of Voltage Control Equipment**

In a modern power system, there are several elements between the generating station and the consumers. The voltage control equipment is used at more than one point in the system for two reasons. Firstly, the power network is very extensive and there is a considerable voltage drop in transmission and distribution systems. Secondly, the various circuits of the power system have dissimilar load characteristics. For these reasons, it is necessary to provide individual means of voltage control for each circuit or group of circuits. In practice, voltage control equipment is used at:

- (i) generating stations
- (ii) transformer stations
- (iii) the feeders if the drop exceeds the permissible limits

### **Methods of Voltage Control**

There are several methods of voltage control. In each method, the system voltage is changed in accordance with the load to obtain a fairly constant voltage at the consumer's end of the system. The following are the methods of voltage control in an ac power system:

- (i) By excitation control
- (ii) By using tap changing transformers
- (iii) Auto-transformer tap changing
- (iv) Booster transformers
- (v) Induction regulators
- (vi) By synchronous condenser

Method (i) is used at the generating station only whereas methods (ii) to (v) can be used for transmission as well as primary distribution systems. However, method (vi) is reserved for the voltage control of a transmission line. We shall discuss each method separately in the next sections.

### **Excitation Control**

When the load on the supply system changes, the terminal voltage of the alternator also varies due to the changed voltage drop in the synchronous reactance of the armature. The voltage of the alternator can be kept constant by changing the field current of the alternator in accordance with the load. This is known as excitation control method. The excitation of alternator can be controlled by the use of automatic or hand operated regulator acting in the field circuit of the alternator. The first method is preferred in modern practice. There are two main types of automatic voltage regulators viz

- (i) Tirril Regulator
- (ii) Brown-Boveri Regulator

These regulators are based on the “overshooting the mark” principle to enable them to respond quickly to the rapid fluctuations of load. When the load on the alternator increases, the regulator produces an increase in excitation more than is ultimately necessary. Before the voltage has the time to increase to the value corresponding to the increased excitation, the regulator reduces the excitation to the proper value.

### **Tirril Regulator**

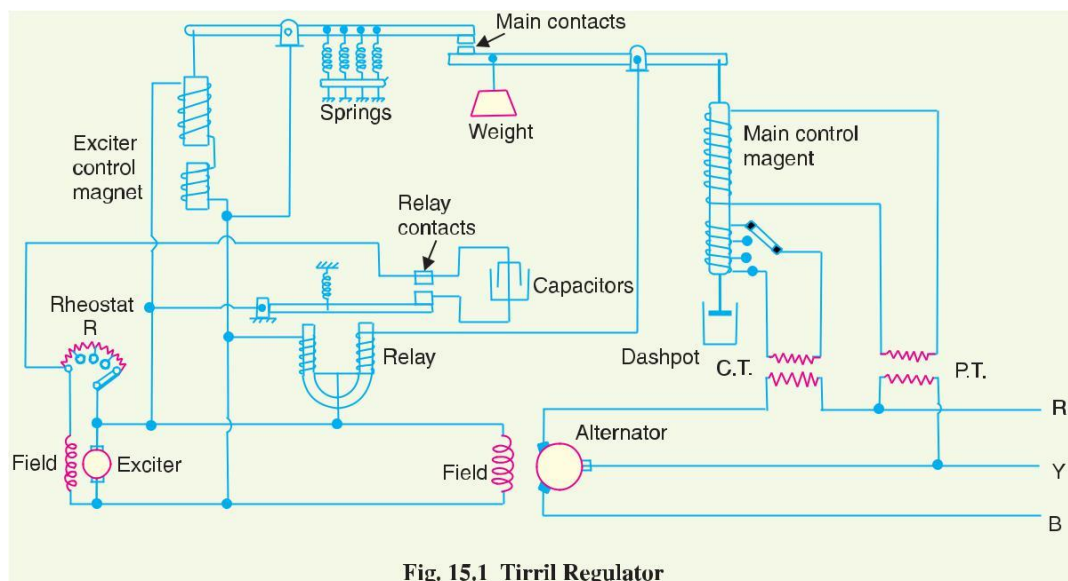
In this type of regulator, a fixed resistance is cut in and cut out of the exciter field circuit of the alternator. This is achieved by rapidly opening and closing a shunt circuit across the exciter rheostat. For this reason, it is also known as vibrating type voltage regulator.

Construction Fig. shows the essential parts of a Tirril voltage regulator. A rheostat R is provided in the exciter circuit and its value is set to give the required excitation. This rheostat is put in and out of the exciter circuit by the regulator, thus varying the exciter voltage to maintain the desired voltage of the alternator.

**(i) Main contact** There are two levers at the top which carry the main contacts at the facing ends. The left-hand lever is controlled by the exciter magnet whereas the right-hand lever is controlled by an ac magnet known as main control magnet.

**(ii) Exciter magnet** This magnet is of the ordinary solenoid type and is connected across the exciter mains. Its exciting current is, therefore, proportional to the exciter voltage. The counterbalancing force for the exciter magnet is provided by four coil springs.

**(iii) A C magnet** It is also of solenoid type and is energised from ac bus-bars. It carries series as well as shunt excitation. This magnet is so adjusted that with normal load and voltage at the alternator, the pulls of the two coils are equal and opposite, thus keeping the right-hand lever in the horizontal position.



(iv) *Differential relay* It essentially consists of a U-shaped relay magnet which operates the relay contacts. The relay magnet has two identical windings wound differentially on both the limbs. These windings are connected across the exciter mains—the left hand one permanently while the right hand one has its circuit completed only when the main contacts are closed. The relay contacts are arranged to shunt the exciter-field rheostat  $R$ . A capacitor is provided across the relay contacts to reduce the sparking at the time the relay contacts are opened.

**Operation** The two control magnets (*ie* exciter magnet and ac magnet) are so adjusted that with normal load and voltage at the alternator, their pulls are equal, thus keeping the main contacts open. In this position of main contacts, the relay magnet remains energised and pulls down the armature carrying one relay contact. Consequently, relay contacts remain open and the exciter field rheostat is in the field circuit.

When the load on the alternator increases, its terminal voltage tends to fall. This causes the series excitation to predominate and the ac magnet pulls down the right-hand lever to close the main contacts. Consequently, the relay magnet is de-energised and releases the armature carrying the relay contact. The relay contacts are closed and the rheostat  $R$  in the field circuit is short circuited. This increases the exciter-voltage and hence the excitation of the alternator. The increased excitation causes the alternator voltage to rise quickly. At the same time, the excitation of the exciter magnet is increased due to the increase in exciter voltage. Therefore, the left-hand lever is pulled down, opening the main contacts, energising the relay magnet and putting the rheostat  $R$  again in the field circuit before the alternator voltage has time to increase too far. The reverse would happen should the load on the alternator decrease.

It is worthwhile to mention here that exciter voltage is controlled by the rapid opening and closing of the relay contacts. As the regulator is worked on the overshooting the mark principle, therefore, the terminal voltage does not remain absolutely constant but oscillates between the maximum and minimum values. In fact, the regulator is so quick acting that voltage variations never exceed  $\pm 1\%$ .

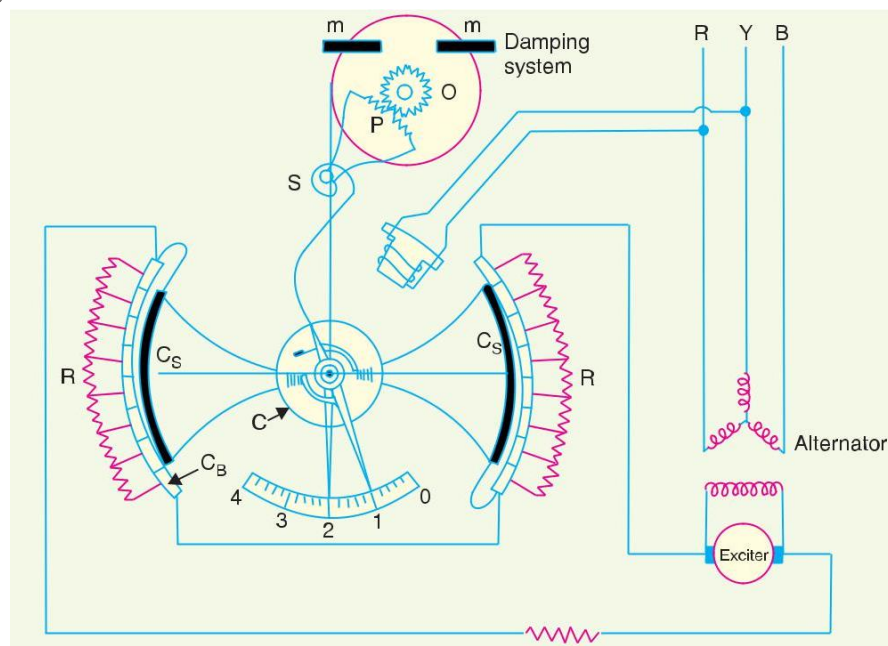
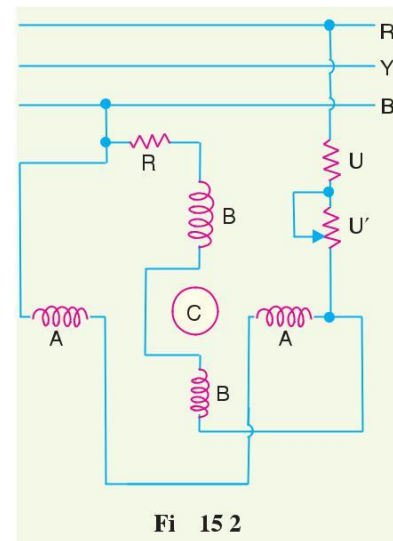


## Brown-Boveri Regulator

In this type of regulator, exciter field rheostat is varied continuously or in small steps instead of being first completely cut in and then completely cut out as in Tirril regulator. For this purpose, a regulating resistance is connected in series with the field circuit of the exciter. Fluctuations in the alternator voltage are detected by a control device which actuates a motor. The motor drives the regulating rheostat and cuts out or cuts in some resistance from the rheostat, thus changing the exciter and hence the alternator voltage.

**Construction** Fig. shows the schematic diagram of a Brown-Boveri voltage regulator. It also works on the “overshooting the mark principle” and has the following four important parts:

(i) **Control system** The control system is built on the principle of induction motor. It consists of two windings  $A$  and  $B$  on an annular core of laminated sheet steel. The winding  $A$  is excited from two of the generator terminals through resistances  $U$  and  $U'$  while a resistance  $R$  is inserted in the circuit of winding  $B$ . The ratio of resistance to reactance of the two windings are suitably adjusted so as to create a phase difference of currents in the two windings. Due to the phase difference of currents in the two windings, rotating magnetic field is set up. This produces electromagnetic torque on the thin aluminium drum  $C$  carried by steel spindle; the latter being supported at both ends by jewel bearings. The torque on drum  $C$  varies with the terminal voltage of the alternator. The variable resistance  $U'$  can also vary the torque on the drum. If the resistance is increased, the torque is decreased and vice-versa. Therefore, the variable resistance  $U'$  provides a means by which the regulator may be set to operate at the desired voltage



(ii) **Mechanical control torque** The electric torque produced by the current in the split phase winding is opposed by a combination of two springs (main spring and auxiliary spring) which produce a constant mechanical torque irrespective of the position of the drum. Under steady deflected state, mechanical torque is equal and opposite to the electric torque.

(iii) **Operating system** It consists of a field rheostat with contact device. The rheostat consists of a pair of resistance elements connected to the stationary contact blocks  $C_B$ . These two resistance sectors  $R$  are connected in series with each other and then in series with the field circuit of the exciter. On the inside surface of the contact blocks roll the contact sectors  $C_S$ . When the terminal voltage of the alternator changes, the electric torque acts on the drum. This causes the contact sectors to roll over the contact blocks, cutting in or cutting out rheostat resistance in the exciter field circuit.

(iv) **Damping torque** The regulator is made stable by damping mechanism which consists of an aluminium disc  $O$  rotating between two permanent magnets  $m$ . The disc is geared to the rack of an aluminium sector  $P$  and is fastened to the aluminium drum  $C$  by means of a flexible spring  $S$  acting as the recall spring. If there is a change in the alternator voltage, the eddy currents induced in the disc  $O$  produce the necessary damping torque to resist quick response of the moving system.

**Operation** Suppose that resistances  $U$  and  $U'$  are so adjusted that terminal voltage of the alternator is normal at position 1. In this position, the electrical torque is counterbalanced by the mechanical torque and the moving system is in equilibrium. It is assumed that electrical torque rotates the shaft in a clockwise direction.

Now imagine that the terminal voltage of the alternator rises due to decrease in load on the supply system. The increase in the alternator voltage will cause an increase in electrical torque which becomes greater than the mechanical torque. This causes the drum to rotate in clockwise direction, say to position 3. As a result, more resistance is inserted in the exciter circuit, thereby decreasing the field current and hence the terminal voltage of the alternator. Meanwhile, the recall spring  $S$  is tightened and provides a counter torque forcing the contact roller back to position 2 which is the equilibrium position. The damping system prevents the oscillations of the system about the equilibrium position.

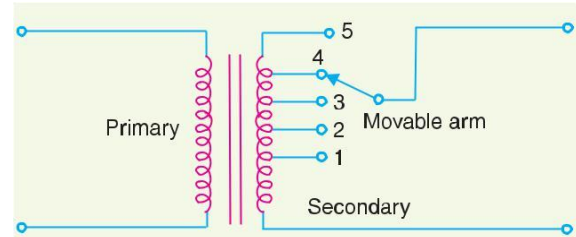
### Tap-Changing Transformers

The excitation control method is satisfactory only for relatively short lines. However, it is not suitable for long lines as the voltage at the alternator terminals will have to be varied too much in order that the voltage at the far end of the line may be constant. Under such situations, the problem of voltage control can be solved by employing other methods. One important method is to use tap-changing transformer and is commonly employed where main transformer is necessary. In this method, a number of tappings are provided on the secondary of the transformer. The voltage drop in the line is supplied by changing the secondary emf of the transformer through the adjustment of its number of turns.



### (i) Off load tap-changing transformer

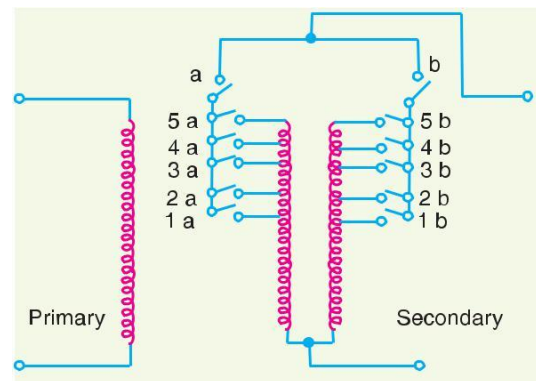
Fig shows the arrangement where a number of tapings have been provided on the secondary. As the position of the tap is varied, the effective number of secondary turns is varied and hence the output voltage of the secondary can be changed. Thus referring to Fig., when the movable arm makes contact with stud 1, the secondary voltage is minimum and when with stud 5, it is maximum. During the period of light load, the voltage across the primary is not much below the alternator voltage and the movable arm is placed on stud 1. When the load increases, the voltage across the primary drops, but the secondary voltage can be kept at the previous value by placing the movable arm on to a higher stud. Whenever a tapping is to be changed in this type of transformer, the load is kept off and hence the name off load tap-changing transformer.



The principal disadvantage of the circuit arrangement is that it cannot be used for tap-changing on load. Suppose for a moment that tapping is changed from position 1 to position 2 when the transformer is supplying load. If contact with stud 1 is broken before contact with stud 2 is made, there is break in the circuit and arcing results. On the other hand, if contact with stud 2 is made before contact with stud 1 is broken, the coils connected between these two tapings are short-circuited and carry damaging heavy currents. For this reason, the above circuit arrangement cannot be used for tap-changing on load.

### (ii) On-load tap-changing transformer

In supply system, tap-changing has normally to be performed on load so that there is no interruption to supply. Fig. shows diagrammatically one type of on-load tap-changing transformer. The secondary consists of two equal parallel windings which have similar tapings 1a- 5a and 1b- 5b. In the normal working conditions, switches *a*, *b* and tapings with the same number remain closed and each secondary winding carries one-half of the total current. Referring to Fig., the secondary voltage will be maximum when switches *a*, *b* and 5a, 5b are closed. However, the secondary voltage will be minimum when switches *a*, *b* and 1a, 1b are closed. Suppose that the transformer is working with tapping position at 4a, 4b and it is desired to alter its position to 5a, 5b. For this purpose, one of the switches *a* and *b*, say *a*, is opened. This takes the secondary winding controlled by switch *a* out of the circuit. Now, the secondary winding controlled by switch *b* carries the total current which is twice its rated capacity. Then the tapping on the disconnected winding is changed to 5a and switch *a* is closed. After this, switch *b* is opened to disconnect its winding, tapping position on this winding is changed to 5b and then switch *b* is closed. In this way, tapping position is changed without interrupting the supply.

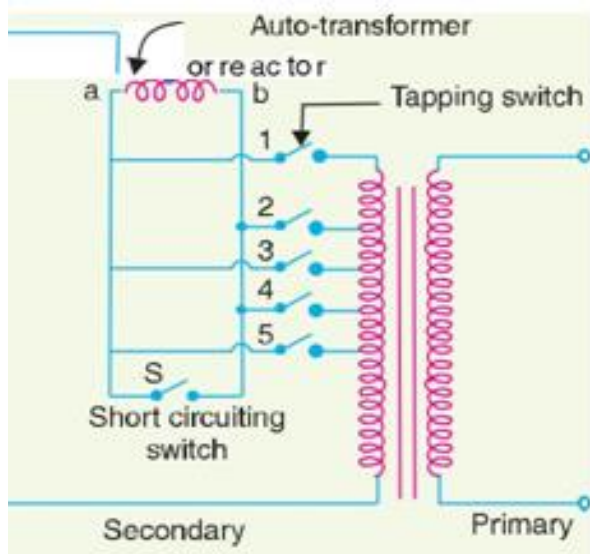


This method has the following disadvantages:

- (i) During switching, the impedance of transformer is increased and there will be a voltage surge
- (ii) There are twice as many tapings as the voltage steps

### Auto-Transformer Tap-changing:

Fig. shows diagrammatically auto-transformer tap changing. Here, a mid-tapped autotransformer or reactor is used. One of the lines is connected to its mid-tapping. One end, say  $a$  of this transformer is connected to a series of switches across the odd tapings and the other end  $b$  is connected to switches across even tapings. A short-circuiting switch  $S$  is connected across the auto-transformer and remains in the closed position under normal operation. In the normal



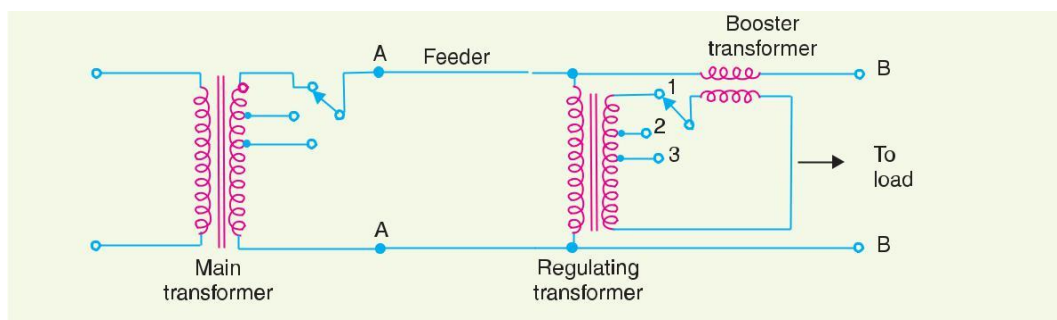
operation, there is no inductive voltage drop across the auto-transformer.

From Fig., it is clear that with switch 5 closed, minimum secondary turns are in the circuit and hence the output voltage will be the lowest. On the other hand, the output voltage will be maximum when switch 1 is closed. Suppose now it is desired to alter the tapping point from position 5 to position 4 in order to raise the output voltage. For this purpose, short-circuiting switch  $S$  is opened, switch 4 is closed, then switch 5 is opened and finally short-circuiting switch is closed. In this way, tapping can be changed without interrupting the supply.

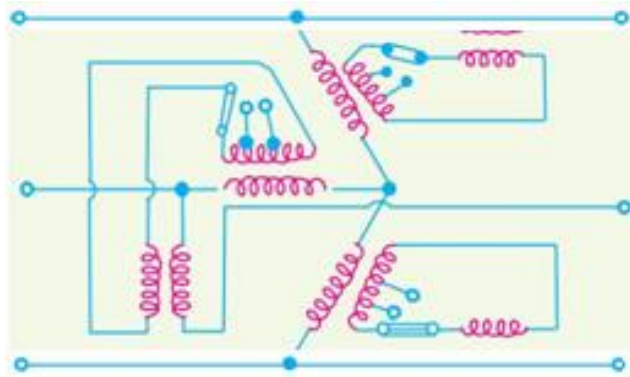
It is worthwhile to describe the electrical phenomenon occurring during the tap changing. When the short-circuiting switch is opened, the load current flows through one-half of the reactor coil so that there is a voltage drop across the reactor. When switch 4 is closed, the turns between points 4 and 5 are connected through the whole reactor winding. A circulating current flows through this local circuit but it is limited to a low value due to high reactance of the reactor.

### Booster Transformer

Sometimes it is desired to control the voltage of a transmission line at a point far away from the main transformer. This can be conveniently achieved by the use of a booster transformer as shown in Fig. The secondary of the booster transformer is connected in series with the line whose voltage is to be controlled. The primary of this transformer is supplied from a regulating transformer fitted with on-load tap-changing gear. The booster transformer is connected in such a way that its secondary injects a voltage in phase with the line voltage.



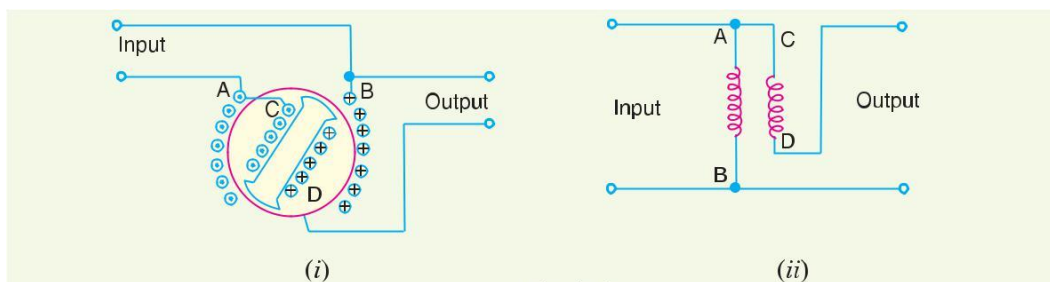
The voltage at  $AA$  is maintained constant by tap-changing gear in the main transformer. However, there may be considerable voltage drop between  $AA$  and  $BB$  due to fairly long feeder and tapping of loads. The voltage at  $BB$  is controlled by the use of regulating transformer and booster transformer. By changing the tapping on the regulating transformer, the magnitude of the voltage injected into the line can be varied. This permits to keep the voltage at  $BB$  to the desired value. This method of voltage control has three disadvantages. Firstly, it is more expensive than the on-load tap-changing transformer. Secondly, it is less efficient owing to losses in the booster and thirdly more floor space is required. Fig. shows a three-phase booster transformer.



## Induction Regulators

An induction regulator is essentially a constant voltage transformer, one winding of which can be moved *wrt* the other, thereby obtaining a variable secondary voltage. The primary winding is connected across the supply while the secondary winding is connected in series with the line whose voltage is to be controlled. When the position of one winding is changed *wrt* the other, the secondary voltage injected into the line also changes. There are two types of induction regulators *viz* single phase and 3-phase.

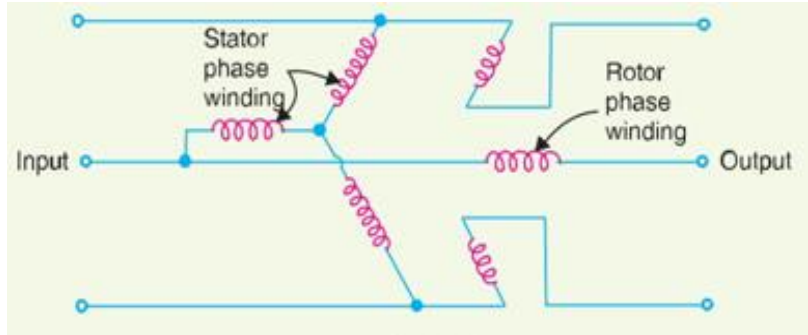
**(i) Single-phase induction regulator** A single phase induction regulator is illustrated in Fig. In construction, it is similar to a single phase induction motor except that the rotor is not allowed to rotate continuously but can be adjusted in any position either manually or by a small motor. The primary winding  $AB$  is wound on the stator and is connected across the supply line. The secondary winding  $CD$  is wound on the rotor and is connected in series with the line whose voltage is to be controlled.



The primary exciting current produces an alternating flux that induces an alternating voltage in the secondary winding  $CD$ . The magnitude of voltage induced in the secondary depends upon its position *wrt* the primary winding. By adjusting the rotor to a suitable position, the secondary

voltage can be varied from a maximum positive to a maximum negative value. In this way, the regulator can add or subtract from the circuit voltage according to the relative positions of the two windings. Owing to their greater flexibility, single phase regulators are frequently used for voltage control of distribution primary feeders.

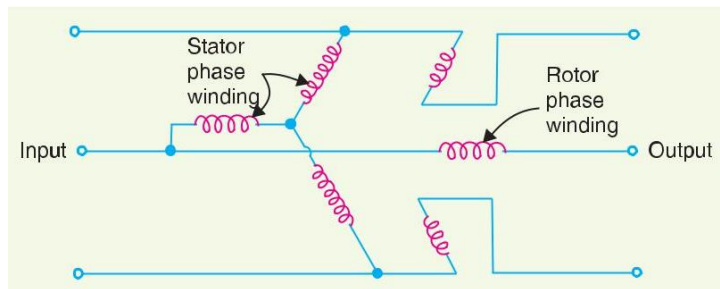
(ii) **Three-phase induction regulator** In construction, a 3-phase induction regulator is similar to a 3-phase induction motor with wound rotor except that the rotor is not allowed to rotate continuously but can be held in any position by means of a worm gear. The primary windings either in star or delta are wound on the stator and are connected across the supply. The secondary windings are wound on the rotor and the six terminals are brought out since these windings are to be connected in series with the line whose voltage is to be controlled.



When polyphase currents flow through the primary windings, a rotating field is set up, this induces an emf in each phase of rotor winding. As the rotor is turned, the magnitude of the rotating flux is not changed; hence the rotor emf per phase remains constant. However, the variation of the position of the rotor will affect the phase of the rotor emf wrt the applied voltage as shown in Fig. The input primary voltage per phase is  $V_p$  and the boost introduced by the regulator is  $V_r$ . The output voltage  $V$  is the vector sum of  $V_p$  and  $V_r$ . Three phase induction regulators are used to regulate the voltage of feeders and in connection with high voltage oil testing transformers.

### Voltage Control by Synchronous Condenser

The voltage at the receiving end of a transmission line can be controlled by installing specially designed synchronous motors called synchronous condensers at the receiving end of the line. The synchronous condenser supplies wattless leading kVA to the line depending upon the excitation of the motor. This wattless leading kVA partly or fully cancels the wattless lagging kVA of the line, thus controlling the voltage drop in the line. In this way, voltage at the receiving end of a transmission line can be kept constant as the load on the system changes.

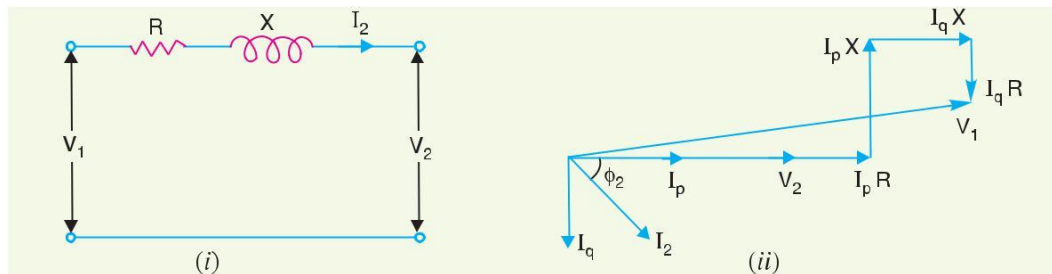


For simplicity, consider a short transmission line where the effects of capacitance are neglected. Therefore, the line has only resistance and inductance.

Let  $V_1$  and  $V_2$  be the per phase sending end and receiving end voltages respectively.

Let  $I_2$  be the load current at a lagging power factor of  $\cos \phi_2$

**(i) Without synchronous condenser** Fig. (i) shows the transmission line with resistance  $R$  and inductive reactance  $X$  per phase. The load current  $I_2$  can be resolved into two rectangular components viz  $I_p$  in phase with  $V_2$  and  $I_q$  at right angles to  $V_2$  [See Fig. (ii)] Each component will produce resistive and reactive drops; the resistive drops being in phase with and the reactive drops in quadrature leading with the corresponding currents. The vector addition of these voltage drops to  $V_2$  gives the sending end voltage  $V_1$



**(ii) With synchronous condenser** Now suppose that a synchronous condenser taking a leading current  $I_m$  is connected at the receiving end of the line. The vector diagram of the circuit becomes as shown in Fig. Note that since  $I_m$  and  $I_q$  are in direct opposition and that  $I_m$  must be greater than  $I_q$ , the four drops due to these two currents simplify to:

$$(I_m - I_q) R \text{ in phase with } I_m$$

$$\text{and } (I_m - I_q) X \text{ in quadrature leading with } I_m$$

From the vector diagram, the relation between  $V_1$  and  $V_2$  is given by ;

$$OE^2 = (OA + AB - DE)^2 + (BC + CD)^2$$

$$\text{or } V_1^2 = [V_2 + I_p R - (I_m - I_q) X]^2 + [I_q X + (I_m - I_q) R]^2$$

From this equation, the value of  $I_m$  can be calculated to obtain any desired ratio of  $V_1/V_2$  for a given load current and power factor

$$\text{kVAR capacity of condenser} = \frac{3 V_2 I_m}{1000}$$



## UNIT-V

### Economic Aspects of Power Generation and Tariff Methods

#### Load Curves

The curve showing the variation of load on the power station with respect to (wrt) time is known as **load curve**.

The load on a power station is never constant; it varies from time to time. These load variations during the whole day (ie, 24 hours) are recorded half-hourly or hourly and are plotted against time on the graph. The curve thus obtained is known as daily load curve as it shows the variations of load wrt time during the day. Fig. shows a typical daily load curve of a power station. It is clear that load on the power station is varying, being maximum at 6 PM in this case. It may be seen that load curve indicates at a glance the general character of the load that is being imposed on the plant. Such a clear representation cannot be obtained from tabulated figures.

The monthly load curve can be obtained from the daily load curves of that month. For this purpose, average values of power over a month at different times of the day are calculated and then plotted on the graph. **The monthly load curve is generally used to fix the rates of energy.** The yearly load curve is obtained by considering the monthly load curves of that particular year. **The yearly load curve is generally used to determine the annual load factor.**



**Importance** The daily load curves have attained a great importance in generation as they supply the following information readily:

- (i) The daily load curve shows the variations of load on the power station during different hours of the day
- (ii) The area under the daily load curve gives the number of units generated in the day  
Units generated/day = Area (in kWh) under daily load curve
- (iii) The highest point on the daily load curve represents the maximum demand on the station on that day
- (iv) The area under the daily load curve divided by the total number of hours gives the average load on the station in the day

$$\text{Average load} = \frac{\text{Area (in kWh) under daily load curve}}{24 \text{ hours}}$$

- (v) The ratio of the area under the load curve to the total area of rectangle in which it is contained gives the load factor

$$\text{Load factor} = \frac{\text{Average load}}{\text{Max demand}} = \frac{\text{Average load} \times 24}{\text{Max demand} \times 24}$$

$$= \frac{\text{Area (in kWh) under daily load curve}}{\text{Total area of rectangle in which the load curve is contained}}$$

(vi) The load curve helps in selecting the size and number of generating units

(vii) The load curve helps in preparing the operation schedule of the station

### Important Terms and Factors

The variable load problem has introduced the following terms and factors in power plant engineering:

**(i) Connected load** It is the sum of continuous ratings of all the equipments connected to supply system

A power station supplies load to thousands of consumers. Each consumer has certain equipment installed in his premises. The sum of the continuous ratings of all the equipments in the consumer's premises is the "connected load" of the consumer. For instance, if a consumer has connections of five 100-watt lamps and a power point of 500 watts, then connected load of the consumer is  $5 \times 100 + 500 = 1000$  watts. The sum of the connected loads of all the consumers is the connected load to the power station.

**(ii) Maximum demand:** It is the greatest demand of load on the power station during a given period.

The load on the power station varies from time to time. The maximum of all the demands that have occurred during a given period (say a day) is the maximum demand. Thus referring back to the load curve of Fig., the maximum demand on the power station during the day is 6 MW and it occurs at 6 PM. Maximum demand is generally less than the connected load because all the consumers do not switch on their connected load to the system at a time. The knowledge of maximum demand is very important as it helps in determining the installed capacity of the station. The station must be capable of meeting the maximum demand.

**(iii) Demand factor** It is the ratio of maximum demand on the power station to its connected load.

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}}$$

The value of demand factor is usually less than 1. It is expected because maximum demand on the power station is generally less than the connected load. If the maximum demand on the power station is 80 MW and the connected load is 100 MW, then demand factor =  $80/100 = 0.8$ . The knowledge of demand factor is vital in determining the capacity of the plant equipment.

**(iv) Average load** The average of loads occurring on the power station in a given period (day or month or year) is known as **average load** or **average demand**.

$$\text{Daily average load} = \frac{\text{No of units (kWh) generated in a day}}{24 \text{ hours}}$$

$$\text{Monthly average load} = \frac{\text{No of units (kWh) generated in a day}}{\text{Number of hours in a month}}$$

$$\text{Yearly average load} = \frac{\text{No of units (kWh) generated in a day}}{8760 \text{ hours}}$$

**(v) Load factor** The ratio of average load to the maximum demand during a given period is known as **load factor**,

$$\text{Load factor} = \frac{\text{Average load}}{\text{Max demand}}$$

The load factor may be daily load factor, monthly load factor or annual load factor if the time period considered is a day or month or year Load factor is always less than 1 because average load is smaller than the maximum demand The load factor plays key role in determining the overall cost per unit generated Higher the load factor of the power station, lesser\* will be the cost per unit generated

**(vi) Diversity factor** The ratio of the sum of individual maximum demands to the maximum demand on power station is known as **diversity factor**

$$\text{Diversity factor} = \frac{\text{Sum of individual max demands}}{\text{Maximum demand on power station}}$$

A power station supplies load to various types of consumers whose maximum demands generally do not occur at the same time Therefore, the maximum demand on the power station is always less than the sum of individual maximum demands of the consumers Obviously, diversity† factor will always be greater than 1 The greater the diversity factor, the lesser‡ is the cost of generation of power

**(vii) Plant capacity factor** It is the ratio of actual energy produced to the maximum possible energy that could have been produced during a given period

$$\text{Plant capacity factor} = \frac{\text{Actual energy produced}}{\text{Max energy that could have been produced}} = \frac{\text{Average demand} \times T}{\text{Plant capacity} \times T}$$

Thus if the considered period is one year,

$$\text{Annual plant capacity factor} = \frac{\text{Annual kWh output}}{\text{Plant capacity} \times 8760}$$

The plant capacity factor is an indication of the reserve capacity of the plant A power station is so designed that it has some reserve capacity for meeting the increased load demand in future Therefore, the installed capacity of the plant is always somewhat greater than the maximum demand on the plant.

Reserve capacity = Plant capacity – Max demand

It is interesting to note that difference between load factor and plant capacity factor is an indication of reserve capacity If the maximum demand on the plant is equal to the plant capacity, then load factor and plant capacity factor will have the same value In such a case, the plant will have no reserve capacity.

**(viii) Plant use factor** It is ratio of kWh generated to the product of plant capacity and the number of hours for which the plant was in operation ie

$$\text{Plant use factor} = \frac{\text{Station output in kWh}}{\text{Plant capacity} \times \text{Hours of use}}$$

### Units Generated per Annum

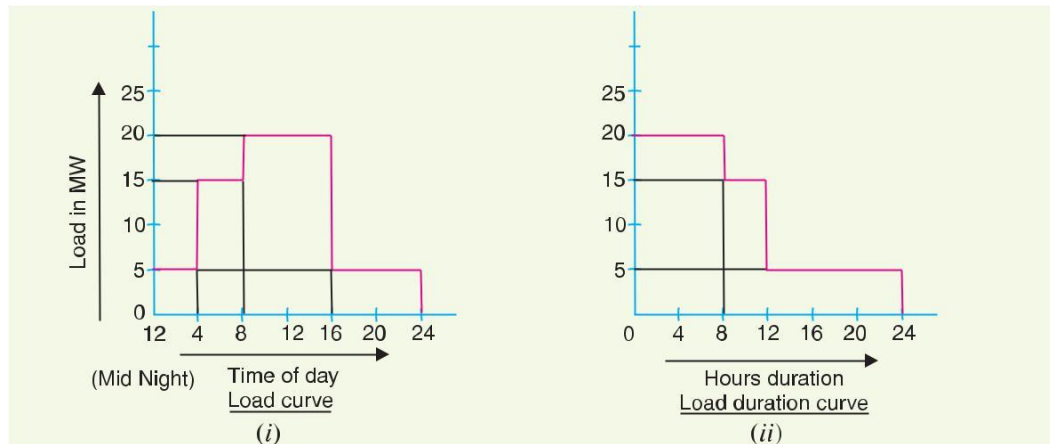
It is often required to find the kWh generated per annum from maximum demand and load factor The procedure is as follows:

$$\text{Load factor} = \frac{\text{Average load}}{\text{Max demand}}$$



## Load Duration Curve

When the load elements of a load curve are arranged in the order of descending magnitudes, the curve thus obtained is called a **load duration curve**



The load duration curve is obtained from the same data as the load curve but the ordinates are arranged in the order of descending magnitudes. In other words, the maximum load is represented to the left and decreasing loads are represented to the right in the descending order. Hence the area under the load duration curve and the area under the load curve are equal.

Fig. shows the daily load curve. The daily load duration curve can be readily obtained from it. It is clear from daily load curve, that load elements in order of descending magnitude are: 20 MW for 8 hours; 15 MW for 4 hours and 5 MW for 12 hours.

The following points may be noted about load duration curve:

- (i) The load duration curve gives the data in a more presentable form. In other words, it readily shows the number of hours during which the given load has prevailed
- (ii) The area under the load duration curve is equal to that of the corresponding load curve. Obviously, area under daily load duration curve (in kWh) will give the units generated on that day
- (iii) The load duration curve can be extended to include any period of time. By laying out the abscissa from 0 hour to 8760 hours, the variation and distribution of demand for an entire year can be summarised in one curve. The curve thus obtained is called the **annual load duration curve**

## Types of Loads

A device which taps electrical energy from the electric power system is called a load on the system. The load may be resistive (eg, electric lamp), inductive (eg, induction motor), capacitive or some combination of them. The various types of loads on the power system are:

- (i) **Domestic load** Domestic load consists of lights, fans, refrigerators, heaters, television, small motors for pumping water etc. Most of the residential load occurs only for some hours during the day (ie, 24 hours) eg, lighting load occurs during night time and domestic appliance load occurs for only a few hours. For this reason, the load factor is low (10% to 12%)

**(ii) Commercial load** Commercial load consists of lighting for shops, fans and electric appliances used in restaurants etc. This class of load occurs for more hours during the day as compared to the domestic load. The commercial load has seasonal variations due to the extensive use of air-conditioners and space heaters.

**(iii) Industrial load** Industrial load consists of load demand by industries. The magnitude of industrial load depends upon the type of industry. Thus small scale industry requires load upto 25 kW, medium scale industry between 25kW and 100 kW and large-scale industry requires load above 500 kW Industrial loads are generally not weather dependent.

**(iv) Municipal load** Municipal load consists of street lighting, power required for water supply and drainage purposes. Street lighting load is practically constant throughout the hours of the night. For water supply, water is pumped to overhead tanks by pumps driven by electric motors. Pumping is carried out during the off-peak period, usually occurring during the night. This helps to improve the load factor of the power system.

**(v) Irrigation load** This type of load is the electric power needed for pumps driven by motors to supply water to fields. Generally this type of load is supplied for 12 hours during night.

**(vi) Traction load** This type of load includes tram cars, trolley buses, railways etc. This class of load has wide variation. During the morning hour, it reaches peak value because people have to go to their work place. After morning hours, the load starts decreasing and again rises during evening since the people start coming to their homes.

### **Load Curves and Selection of Generating Units**

The load on a power station is seldom constant; it varies from time to time Obviously, a single generating unit (ie, alternator) will not be an economical proposition to meet this varying load It is because a single unit will have very poor efficiency during the periods of light loads on the power station Therefore, in actual practice, a number of generating units of different sizes are installed in a power station The selection of the number and sizes of the units is decided from the annual load curve of the station. **The number and size of the units are selected in such a way that they correctly fit the station load curve.** Once this underlying principle is adhered to, it becomes possible to operate the generating units at or near the point of maximum efficiency.

### **Important Points in the Selection of Units**

While making the selection of number and sizes of the generating units, the following points should be kept in view:

- (i) The number and sizes of the units should be so selected that they approximately fit the annual load curve of the station.
- (ii) The units should be preferably of different capacities to meet the load requirements. Although use of identical units (i.e., having same capacity) ensures saving\* in cost, they often do not meet the load requirement.
- (iii) The capacity of the plant should be made 15% to 20% more than the maximum demand to meet the future load requirements.
- (iv) There should be a spare generating unit so that repairs and overhauling of the working units

can be carried out.

(v) The tendency to select a large number of units of smaller capacity in order to fit the load curve very accurately should be avoided. It is because the investment cost per kW of capacity increases as the size of the units decreases.

### Base Load and Peak Load on Power Station

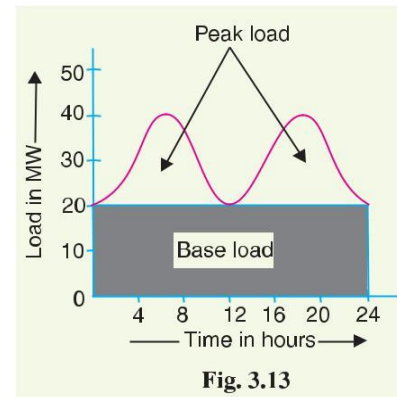
The changing load on the power station makes its load curve of variable nature Fig. shows the typical load curve of a power station. It is clear that load on the power station varies from time to time. However, a close look at the load curve reveals that load on the power station can be considered in two parts, namely;

(i) Base load

(ii) Peak load

**(i) Base load.** The unvarying load which occurs almost the whole day on the station is known as base load.

Referring to the load curve of Fig., it is clear that 20 MW of load has to be supplied by the station at all times of day and night i.e. throughout 24 hours. Therefore, 20 MW is the base load of the station. As base load on the station is almost of constant nature, therefore, it can be suitably supplied (as discussed in the next Article) without facing the problems of variable load.

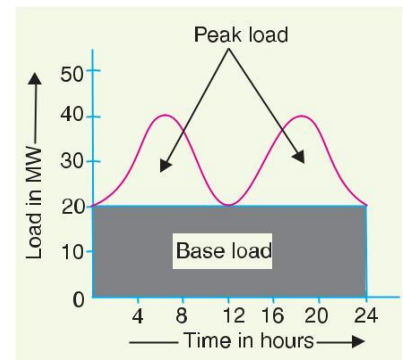


**(ii) Peak load** The various peak demands of load over and above the base load of the station is known as **peak load**.

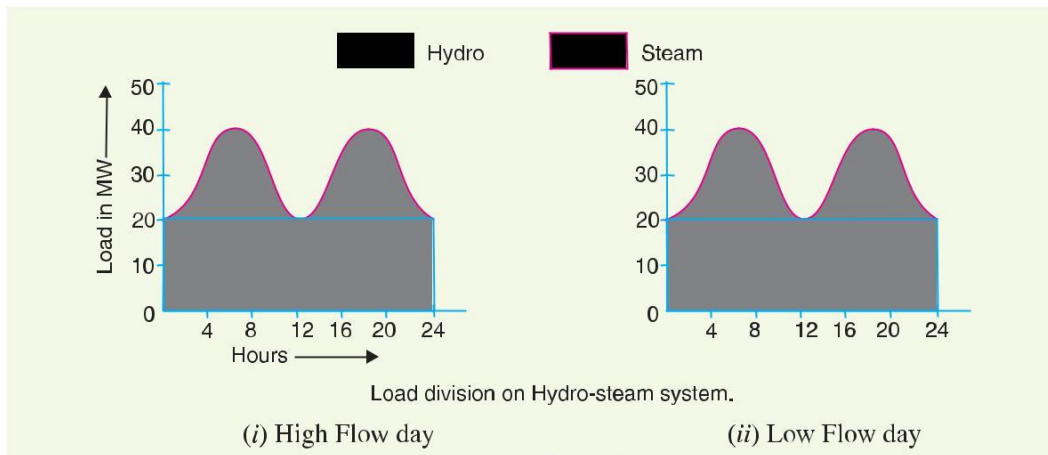
Referring to the load curve of Fig., it is clear that there are peak demands of load excluding base load. These peak demands of the station generally form a small part of the total load and may occur throughout the day.

### Method of Meeting the Load

The total load on a power station consists of two parts viz, base load and peak load. In order to achieve overall economy, the best method to meet load is to interconnect two different power stations. The more efficient plant is used to supply the base load and is known as **base load power station**. The less efficient plant is used to supply the peak loads and is known as **peak load power station**. There is no hard and fast rule for selection of base load and peak load stations as it would depend upon the particular situation. For example, both hydro-electric and steam power stations are quite efficient and can be used as base load as well as peak load station to meet a particular load requirement.



**Illustration** The interconnection of steam and hydro plants is a beautiful illustration to meet the load. When water is available in sufficient quantity as in summer and rainy season, the hydro-electric plant is used to carry the base load and the steam plant supplies the peak load as shown in Fig. (i).



However, when the water is not available in sufficient quantity as in winter, the steam plant carries the base load, whereas the hydro-electric plant carries the peak load as shown in Fig. (ii).

## Interconnected Grid System

The connection of several generating stations in parallel is known as **interconnected grid system**. The various problems facing the power engineers are considerably reduced by interconnecting different power stations in parallel. Although interconnection of station involves extra cost, yet considering the benefits derived from such an arrangement, it is gaining much favour these days.

Some of the advantages of interconnected system are listed below:

**(i) Exchange of peak loads:** An important advantage of interconnected system is that the peak load of the power station can be exchanged. If the load curve of a power station shows a peak demand that is greater than the rated capacity of the plant, then the excess load can be shared by other stations interconnected with it.

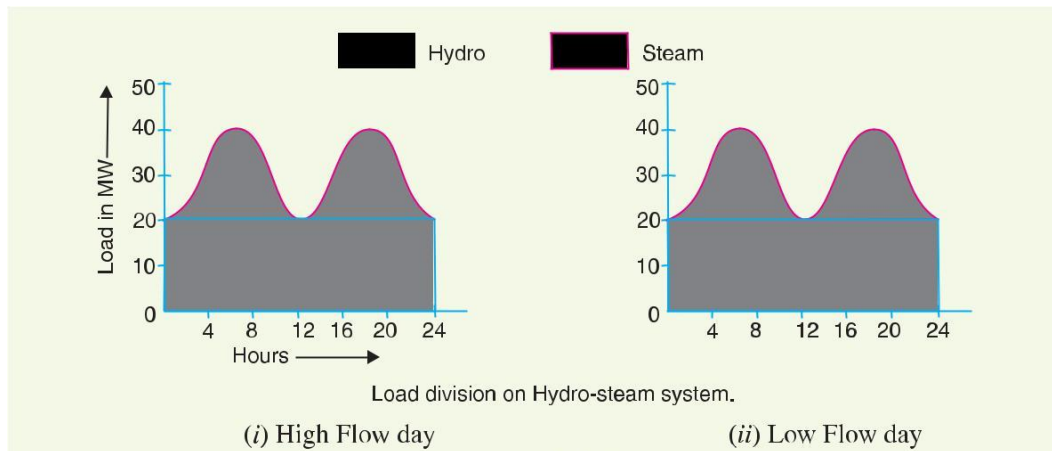
**(ii) Use of older plants:** The interconnected system makes it possible to use the older and less efficient plants to carry peak loads of short durations. Although such plants may be inadequate when used alone, yet they have sufficient capacity to carry short peaks of loads when interconnected with other modern plants. Therefore, interconnected system gives a direct key to the use of obsolete plants.

**(iii) Ensures economical operation:** The interconnected system makes the operation of concerned power stations quite economical. It is because sharing of load among the stations is arranged in such a way that more efficient stations work continuously throughout the year at a high load factor and the less efficient plants work for peak load hours only.

**(iv) Increases diversity factor:** The load curves of different interconnected stations are generally different. The result is that the maximum demand on the system is much reduced as compared to the sum of individual maximum demands on different stations. In other words, the diversity factor of the system is improved, thereby increasing the effective capacity of the system.

**(v) Reduces plant reserve capacity:** Every power station is required to have a standby unit for emergencies. However, when several power stations are connected in parallel, the reserve capacity of the system is much reduced. This increases the efficiency of the system.

**(iv) Increases reliability of supply:** The interconnected system increases the reliability of supply. If a major breakdown occurs in one station, continuity of supply can be maintained by other healthy stations.



## Tariff

The rate at which electrical energy is supplied to a consumer is known as **tariff**.

Although tariff should include the total cost of producing and supplying electrical energy plus the profit, yet it cannot be the same for all types of consumers. It is because the cost of producing electrical energy depends to a considerable extent upon the magnitude of electrical energy consumed by the user and his load conditions. Therefore, in all fairness, due consideration has to be given to different types of consumers (eg, industrial, domestic and commercial) while fixing the tariff. This makes the problem of suitable rate making highly complicated.

**Objectives of tariff** Like other commodities, electrical energy is also sold at such a rate so that it not only returns the cost but also earns reasonable profit. Therefore, a tariff should include the following items:

- (i)** Recovery of cost of producing electrical energy at the power station
- (ii)** Recovery of cost on the capital investment in transmission and distribution systems
- (iii)** Recovery of cost of operation and maintenance of supply of electrical energy eg, metering equipment, billing etc
- (iv)** A suitable profit on the capital investment

## Desirable Characteristics of a Tariff

A tariff must have the following desirable characteristics:

**(i) Proper return:** The tariff should be such that it ensures the proper return from each consumer. In other words, the total receipts from the consumers must be equal to the cost of producing and supplying electrical energy plus reasonable profit. This will enable the electric supply company to ensure continuous and reliable service to the consumers.

**(ii) Fairness:** The tariff must be fair so that different types of consumers are satisfied with the rate of charge of electrical energy. Thus a big consumer should be charged at a lower rate than a small consumer. It is because increased energy consumption spreads the fixed charges over a greater number of units, thus reducing the overall cost of producing electrical energy. Similarly, a consumer whose load conditions do not deviate much from the ideal (ie, non-variable) should be charged at a lower rate than the one whose load conditions change appreciably from the ideal.

**(iii) Simplicity:** The tariff should be simple so that an ordinary consumer can easily understand it. A complicated tariff may cause an opposition from the public which is generally distrustful of supply companies.

**(iv) Reasonable profit:** The profit element in the tariff should be reasonable. An electric supply company is a public utility company and generally enjoys the benefits of monopoly. Therefore, the investment is relatively safe due to non-competition in the market. This calls for the profit to be restricted to 8% or so per annum.

**(v) Attractive:** The tariff should be attractive so that a large number of consumers are encouraged to use electrical energy. Efforts should be made to fix the tariff in such a way so that consumers can pay easily.

## Types of Tariff

There are several types of tariff. However, the following are the commonly used types of tariff:

**Simple tariff** When there is a fixed rate per unit of energy consumed, it is called a **simple tariff** or **uniform rate tariff**.

In this type of tariff, the price charged per unit is constant ie, it does not vary with increase or decrease in number of units consumed. The consumption of electrical energy at the consumer's terminals is recorded by means of an energy meter. This is the simplest of all tariffs and is readily understood by the consumers.

### Disadvantages

- (i) There is no discrimination between different types of consumers since every consumer has to pay equitably for the fixed charges.
- (ii) The cost per unit delivered is high.
- (iii) It does not encourage the use of electricity.



**Flat rate tariff:** When different types of consumers are charged at different uniform per unit rates, it is called a **flat rate tariff**.

In this type of tariff, the consumers are grouped into different classes and each class of consumers is charged at a different uniform rate. For instance, the flat rate per kWh for lighting load may be 60 paise, whereas it may be slightly less (say 55 paise per kWh) for power load. The different classes of consumers are made taking into account their diversity and load factors. The advantage of such a tariff is that it is more fair to different types of consumers and is quite simple in calculations.

**Disadvantages**

(i) Since the flat rate tariff varies according to the way the supply is used, separate meters are required for lighting load, power load etc. This makes the application of such a tariff expensive and complicated.

(ii) A particular class of consumers is charged at the same rate irrespective of the magnitude of energy consumed. However, a big consumer should be charged at a lower rate as in his case the fixed charges per unit are reduced.

**Block rate tariff:** When a given block of energy is charged at a specified rate and the succeeding blocks of energy are charged at progressively reduced rates, it is called a **block rate tariff**.

In block rate tariff, the energy consumption is divided into blocks and the price per unit is fixed in each block. The price per unit in the first block is the highest and it is progressively reduced for the succeeding blocks of energy. For example, the first 30 units may be charged at the rate of 60 paise per unit; the next 25 units at the rate of 55 paise per unit and the remaining additional units may be charged at the rate of 30 paise per unit.

The advantage of such a tariff is that the consumer gets an incentive to consume more electrical energy. This increases the load factor of the system and hence the cost of generation is reduced. However, its principal defect is that it lacks a measure of the consumer's demand. This type of tariff is being used for majority of residential and small commercial consumers.

**Two-part tariff:** When the rate of electrical energy is charged on the basis of maximum demand of the consumer and the units consumed, it is called a **two-part tariff**.

In two-part tariff, the total charge to be made from the consumer is split into two components. viz, fixed charges and running charges. The fixed charges depend upon the maximum demand of the consumer while the running charges depend upon the number of units consumed by the consumer. Thus, the consumer is charged at a certain amount per kW of maximum demand plus a certain amount per kWh of energy consumed.

Total charges = Rs ( $b \times kW + c \times kWh$ )

where,  $b$  = charge per kW of maximum demand and  $c$  = charge per kWh of energy consumed

This type of tariff is mostly applicable to industrial consumers who have appreciable maximum Demand.

### Advantages

- It is easily understood by the consumers.
- It recovers the fixed charges which depend upon the maximum demand of the consumer but are independent of the units consumed

### Disadvantages

- (i) The consumer has to pay the fixed charges irrespective of the fact whether he has consumed or not consumed the electrical energy
- (ii) There is always error in assessing the maximum demand of the consumer

**Maximum demand tariff:** It is similar to two-part tariff with the only difference that the maximum demand is actually measured by installing maximum demand meter in the premises of the consumer. This removes the objection of two-part tariff where the maximum demand is assessed merely on the basis of the rateable value. This type of tariff is mostly applied to big consumers. However, it is not suitable for a small consumer (eg, residential consumer) as a separate maximum demand meter is required.

**Power factor tariff:** The tariff in which power factor of the consumer's load is taken into consideration is known as **power factor tariff**.

In an ac system, power factor plays an important role. A low power factor increases the rating of station equipment and line losses. Therefore, a consumer having low power factor must be penalized. The following are the important types of power factor tariff:

- (i) **k VA maximum demand tariff:** It is a modified form of two-part tariff. In this case, the fixed charges are made on the basis of maximum demand in kVA and not in kW. As kVA is inversely proportional to power factor, therefore, a consumer having low power factor has to contribute more towards the fixed charges. This type of tariff has the advantage that it encourages the consumers to operate their appliances and machinery at improved power factor.
- (ii) **Sliding scale tariff:** This is also known as average power factor tariff. In this case, an average power factor, say 0.8 lagging, is taken as the reference. If the power factor of the consumer falls below this factor, suitable additional charges are made. On the other hand, if the power factor is above the reference, a discount is allowed to the consumer.
- (iii) **kW and kVAR tariff:** In this type, both active power (kW) and reactive power (kVAR) supplied are charged separately. A consumer having low power factor will draw more reactive power and hence shall have to pay more charges.

**Three-part tariff:** When the total charge to be made from the consumer is split into three parts viz, fixed charge, semi-fixed charge and running charge, it is known as a **three-part tariff**.

Total charge = Rs  $(a + b \times \text{kW} + c \times \text{kWh})$

Where, a= fixed charge made during each billing period. It includes interest and depreciation on the cost of secondary distribution and labour cost of collecting revenues,

b= charge per kW of maximum demand,

c= charge per kWh of energy consumed.

It may be seen that by adding fixed charge or consumer's charge (ie, a) to two-part tariff, it becomes three-part tariff. The principal objection of this type of tariff is that the charges are split into three components. This type of tariff is generally applied to big consumers.