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 supper heated in a super heater. This supper 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 steam increases. After imparting energy to the turbine rotor the steam passes out of the turbine blades into the condenser. In the condenser the cold water is circulated with the help of pump which 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 supper 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.
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.

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.

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 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 26% and it depends upon plant capacity.

**Thermal Power Plant Location:**

A thermal power station or thermal power plant has ultimate target to make business profit. Hence for 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.
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. Let’s Q₁(x₁, y₁), Q₂(x₂, y₂), Q₃(x₃, y₃), Q₄(x₄, y₄), ………………………………………….and Qₙ(xₙ, yₙ) 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

\[
\begin{align*}
x &= \frac{x₁Q₁ + x₂Q₂ + x₃Q₃ + \cdots + xₙQₙ}{Q₁ + Q₂ + Q₃ + \cdots + Qₙ} \quad \text{and} \quad y = \frac{y₁Q₁ + y₂Q₂ + y₃Q₃ + \cdots + yₙQₙ}{Q₁ + Q₂ + Q₃ + \cdots + Qₙ}
\end{align*}
\]

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.
**Disadvantages:**

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.
4) Overall efficiency of thermal power plant is low like less 30%.

**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
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 (CO₂ 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.
• Need to fabricate uranium into pellets clad in zirconium fuel 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

Schematic Arrangement of a BWR
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 NOx.

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.

Distribution Systems – General

Introduction:

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 trans-mission system may be compared with arteries in the human body and distribution system with cap-illaries. They serve the same purpose of supply-ing 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 ± 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.

12.2. Classification 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 line losses.

There is no definite line between transmission and distribution 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.

(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-301
Principles of Power System:

To depend 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, 6.6kV 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 obtaining 3-wire system are discussed in the following article.
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 ± 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 (± 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 internetwork 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:**

**Based ON Nature Of Duties:**

**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 (400kV or 230kV). 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.

Converting Substation:
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 equipment 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)
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 SF6 gas modules. The modules are assembled in accordance with the required Configuration. The various Live parts are enclosed in the metal enclosures (modules) containing SF6 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 creates the electromagnetic field. The three types of power relate to each other in a trigonometric form as seen in Figure 5 below. [2]

![The "Power Triangle"](image)

**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). (3)

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. These losses can be modeled as \[ \text{Loss} = I^2 \times R \], where \( R \) is the resistance. 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. [3]

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. [2]

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 unity power factor 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.
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 drawbacks to this method are utility restrictions and future inductive loads that change the maximum operational inductive loading. [2]

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. [2]

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 drawbacks 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. [2]

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...
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 the size, configuration, and operation of the power system. Typically, the 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.

**Conclusions and Future Plans**

Since this is the project’s first semester, there is a lot more in store. Our future plans include learning Siemens Power System Simulator for Engineering (PSS/E) and helping the fall EE461 students learn and use PSS/E. In order to learn PSS/E we will be utilizing the labs
created by the WAPA System Study Senior Design Group. In addition to the learning PSS/E our plans include a system impact study of the proposed Colorado State University Windfarm.

Projects are given $50 per person per semester. Since this first semester was mostly spent doing research, we came in extremely under budget. The only real expenses were group members’ time.

**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 safeguard the interest of the consumers, the government has enacted a law in this regard. The statutory limit of voltage variation is ± 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, (ii) transmission line, (iii) transformer impedance, (iv) feeders and (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. ± 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 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 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 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 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 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 time considered, to the rating of the machine.

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 chargers 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 ever 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.