POWER SYSTEMS - I

COURSE FILE

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GEETHANJALI COLLEGE OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF Electrical and Electronics Engineering

Name of the Subject : Power Systems –I **(JNTU CODE – A40214)**

Programme : ***UG***

Branch: EEE **Version No :** ***03***

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4) Date :	**4) Date :**

Approved by : (HOD) 1) Name :

2) Sign :

3) Date :

2. Syllabus

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY, HYDERABAD

	L	T/P/D	C
II Year B.Tech EEE II-Semester	**L**	**T/P/D**	**C**
(A40214) POWER SYSTEMS-I	**3**	**1/-/-**	**3**

UNIT-1: POWER STATIONS

THERMAL POWER STATIONS: Line diagram of Thermal Power Station (TPS) showing paths of coal, steam, water, air, ash and flue gasses- Brief description of TPS components: Economizers, Boilers, Super heaters, Turbines, Condensers, Chimney and Cooling towers.

Nuclear Power Stations: Nuclear Fission and Chain reaction.- Nuclear fuels.- Principle of operation of Nuclear reactor-Reactor Components: Moderators, Control rods, Reflectors and Coolants.- Radiation hazards: Shielding and Safety precautions.- Types of Nuclear reactors and brief description of PWR, BWR and FBR.

Gas Power Stations: Principle of Operation and Components (Block Diagram Approach Only)

UNIT-2: GENERAL ASPECTS OF D.C and A.C DISTRIBUTION SYSTEMS:

Classification of Distribution Systems-Comparison of DC vs AC and Under-Ground vs Over-Head Distribution Systems- Requirements and Design features of Distribution Systems-Voltage Drop Calculations (Numerical Problems) in D.C Distributors for the following cases: Radial D.C Distributor fed one end and at the both the ends (equal/unequal Voltages) and Ring Main Distributor.

Voltage Drop Calculations (Numerical Problems) in A.C. Distributors for the following cases: Power Factors referred to receiving end voltage and with respect to respective load voltages.

UNIT-3 AIR INSULATED AND GAS INSULATED (GIS) SUBSTATIONS:

Classification of substations: Air insulated substations-Indoor & Outdoor substations: Substations layout showing the location of all the substation equipment. Bus bar arrangements in the Sub-Stations: Simple arrangements like single bus bar, sectionalized single bus bar, main and transfer bus bar system with relevant diagrams.

Gas insulated substations (GIS) – Advantages of Gas insulated substations, different types of gas insulated substations, single line diagram of gas insulated substations, bus bar, construction aspects of GIS, Installation and maintenance of GIS, Comparison of Air insulated substations and Gas insulated substations.

UNIT-4 POWER FACTOR AND VOLTAGE CONTROL:

Causes of low p.f -Methods of improving p.f -Phase advancing and generation of reactive KVAR using static Capacitors-Most economical p.f. for constant KW load and constant KVA type loads, Numerical Problems.

Dependency of Voltage on Reactive Power flow. Methods of Voltage Control: Shunt Capacitors, Series Capacitors, Synchronous Capacitors, Tap changing and Booster Transformers

UNIT-5 ECONOMIC ASPECTS OF POWER GENERATION& TARIFF:

Load curve, load duration and integrated load duration curves-load, demand, diversity, capacity, utilization and plant use factors- Numerical Problems. Costs of Generation and their division into Fixed, Semi-fixed and Running Costs. Desirable Characteristics of a Tariff Method.-**Tariff Methods**: Flat Rate, Block-Rate, two-part, three –part, and power factor tariff methods and Numerical Problems.

TEXT BOOKS

1. Principles of Power Systems - V.K Mehta and Rohit Mehta S. Chand& Company Ltd, New Delhi 2004
2. Electrical Power Systems, PSR Murthy, BS Publications.

REFERENCE BOOKS

1. A Text Book on Power System Engineering by R K Rajput, Laxmi Publications (P) New Delhi 2004
2. Electrical Power Generation, Transmission and Distribution by S.N.Singh., PHI, 2003.

3. Electrical Power Systems by C.L.Wadhawa New age International (P) Limited, Publishers 1997.
4. Generation of Electrical Energy, Dr B R Gupta, S. Chand.

About the Department of EEE

Department of Electronics and Electronics Engineering is established in the year 2006 to meet the requirements of the Electrical and Electronic industries such as Vijay electrical, BHEL, BEL and society after the consultation with various stakeholders.

3. Vision of EEE

To provide excellent Electrical and Electronics education by building strong teaching and research environment

4. Mission of EEE

i) *To offer high quality graduate program in Electrical and Electronics education and to prepare students for professional career or higher studies.*
ii) *The department promotes excellence in teaching, research, collaborative activities and positive contributions to society*

5. Program Educational Objectives and Program Outcomes

Program Educational Objectives of the UG Electrical and Electronics Engineering are:

PEO 1. Graduates will excel in professional career and/or higher education by acquiring knowledge in Mathematics, Science, Engineering principles and Computational skills.

PEO 2. Graduates will analyze real life problems, design Electrical systems appropriate to the requirement that are technically sound, economically feasible and socially acceptable.

PEO 3.Graduates will exhibit professionalism, ethical attitude, communication skills, team work in their profession, adapt to current trends by engaging in lifelong learning and participate in Research & Development.

Programme Outcomes:

The Program Outcomes of UG in Electrical and Electronics Engineering are as follows:

PO 1. An ability to apply the knowledge of Mathematics, Science and Engineering in Electrical and Electronics Engineering.

PO 2. An ability to design and conduct experiments pertaining to Electrical and Electronics Engineering.

PO 3. An ability to function in multidisciplinary teams

PO 4. An ability to simulate and determine the parameters such as nominal voltage, current, power and associated attributes.

PO 5. An ability to identify, formulate and solve problems in the areas of Electrical and Electronics Engineering.

PO 6. An ability to use appropriate network theorems to solve electrical engineering problems.

PO 7. An ability to communicate effectively.

PO 8. An ability to visualize the impact of electrical engineering solutions in global, economic and societal context.

PO 9. Recognition of the need and an ability to engage in life-long learning.

PO 10 An ability to understand contemporary issues related to alternate energy sources.

PO 11 An ability to use the techniques, skills and modern engineering tools necessary for Electrical Engineering Practice.

PO 12 An ability to simulate and determine the parameters like voltage profile and current ratings of transmission lines in Power Systems.

PO 13 An ability to understand and determine the performance of electrical machines namely speed, torque, efficiency etc.

PO 14 An ability to apply electrical engineering and management principles to Power Projects.

Mapping of Programme Educational Objectives with Programme Outcomes

A broad relation between the programme objective and the outcomes is given in the following table:

Programme Educational Objectives(PEOs)	Programme Outcomes(POs)													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
I	♦	♦	♦		♦		♦	♦		♦		♦		♦
II	♦		♦	♦			♦	♦			♦	♦		
III			♦			♦			♦				♦	

6. Course Objectives & Outcomes

Course name: Power Systems - I

Faculty name: N SANTHINATH

Year and semester: II B.Tech II Sem

Course objectives:

1. This course is a beginners fundamental of Power systems course.
2. It deals with the generation and distribution of Electric Power.
3. Also this course gives emphasis on the economic aspects of Generating and Distributing Electric Power.

Course outcomes:

1. Ability to understand the Layout of Various Generating Power Stations.
2. Ability to Design Electrical Layout of Various Generating Stations
3. Ability to Determine design parameters required for Distribution systems
4. Ability to understand the features and need of various Compensation Systems
5. Ability to Design Compensation system for a given distribution system

Additional topics:

Signature of the faculty **HOD**

11. CLASS TIME TABLE:

Geethanjali College of Engineering & Technology									
Department of Electrical & Electronics Engineering									
Year/Sem/Sec: II-B. Tech-II Sem(Version-1)				**Room No: LH-14**			**Acad Year 2015-16, WEF:**		
Class Teacher:									
Time	**09.30-10.15**	**10.15-11.00**	**11.00-11.45**	**11.45-12.30**	**12.30-13.10**	**13.10-13.55**	**13.55-14.40**	**14.40-15.25**	**15.25-16.10**
Period	**1**	**2**	**3**	**4**	**LUNCH**	**5**	**6**	**7**	**8**
Monday									
Tuesday									
Wednesday									
Thursday									
Friday									
Saturday									

No	**Subject(T/P)**	**Faculty Name**	**Mobile No**	**Periods/Week**	
1				**4+1*-Periods**	
2				**5+1*-Periods**	
3				**5+1*-Periods**	
4				**5+1*-Periods**	
6				**5+1*-Periods**	
7				**4+4-Periods**	
8				**4+4-Periods**	

12. INDIVIDUAL TIME TABLE:

Faculty Name: N SANTHINATH				Acad Year 2015-16, WEF:				
Time	09.30-10.20	10.20-11.10	11.10-12.00	12.00-12.50	12.50-13.30	13.30-14.20	14.20-15.10	15.10-16.00
Period	1	2	3	4		5	6	7
Monday					LUNCH BREAK			
Tuesday								
Wednesday								
Thursday								
Friday								
Saturday								

No	Subject(T/P)	Periods Per Week		
1	PS-I	5		
2	EM – I LAB (EEE II-II)	6		
3	CS LAB (EEE III-II)	6		

13. Lecture schedule with methodology being adopted:

SL. No	Period No	Unit No	Date	Topic to be covered in One lecture	Regular/ Additional	LCD/ OHP /BB
				Power Stations (TPS, NPS & GPS)		
	1			Line diagram of Thermal Power Station (TPS) showing paths of coal, steam, water, air, ash and flue gasses	Regular	LCD
	2			Line diagram of Thermal Power Station (TPS) showing paths of coal, steam, water, air, ash and flue gasses	Regular	LCD
	3			Brief description of TPS components: Economizers, Boilers	Regular	LCD
	4			Brief description of TPS components: Super heaters, Turbines	Regular	LCD
	5			Brief description of TPS components: Condensers, Chimney and Cooling towers	Regular	LCD
	6			Tutorial	Regular	BB
	7	I		Tutorial	additional	BB
	8			**Nuclear Power Stations:** Nuclear Fission and Chain reaction.- Nuclear fuels	Regular	BB
	9			Principle of operation of Nuclear reactor	Regular	LCD
	10			Reactor Components: Moderators, Control rods	Regular	LCD
	11			Reactor Components: Reflectors and Coolants.	Regular	LCD
	12			Radiation hazards: Shielding and Safety precautions	Regular	LCD
	13			Types of Nuclear reactors and brief description of PWR, BWR and FBR	Regular	LCD
	14			**Gas Power Stations:** Principle of Operation and Components (Block Diagram Approach Only)	Regular	LCD
	15			Tutorial	additional	
	16			**General aspects of DC & AC Distribution Systems:** Introduction to DC & AC Distribution Systems		
	17			Classification of Distribution Systems-Comparison of DC vs AC and Under-Ground vs Over-Head Distribution Systems	Regular	OHP
	18			Requirements and Design features of Distribution Systems	Regular	BB
	19			Voltage Drop Calculations (Numerical Problems) in D.C Distributors for the following cases: Radial D.C Distributor fed one end (equal/unequal Voltages)	Regular	BB
	20			Voltage Drop Calculations (Numerical Problems) in D.C Distributors for the following cases: Radial D.C Distributor fed at the both the ends (equal/unequal Voltages)	Regular	BB

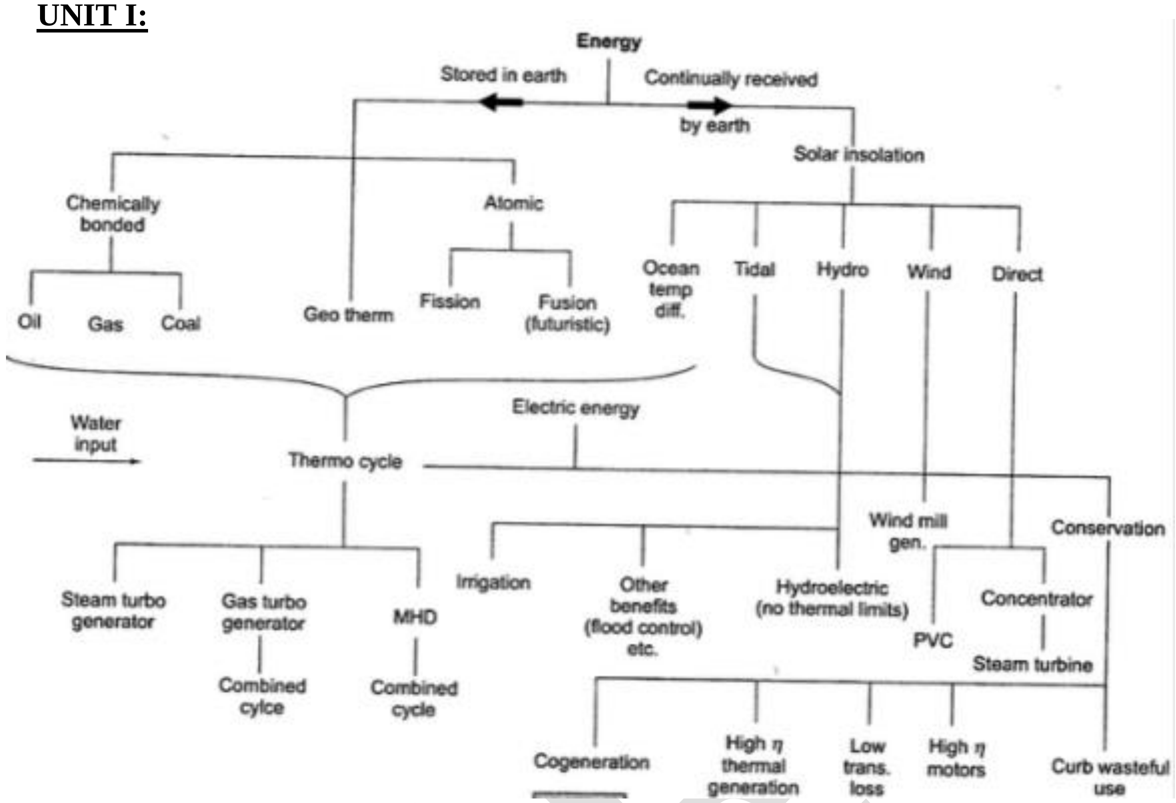
	21			Voltage Drop Calculations (Numerical Problems) in D.C Distributors for the following cases: Ring Main Distributor	Regular	BB
	22			Tutorial	Regular	BB
	23	II		Voltage Drop Calculations (Numerical Problems) in A.C. Distributors for the following cases: Power Factors referred to receiving end voltage.	Regular	BB
	24			Voltage Drop Calculations (Numerical Problems) in A.C. Distributors for the following cases: Power Factors referred to respective load voltages	Regular	
	25			Tutorial	Regular	
	26	III		**Air insulated & Gas insulated substations:-** Classification of substations - Indoor & Outdoor substations:	Regular	BB
				Substations layout showing the location of all the substation equipment		
	27			Bus bar arrangements in the Sub-Stations: Simple arrangements like single bus bar	Regular	BB
	28			Bus bar arrangements in the Sub-Stations: Sectionalized single bus bar	Regular	BB
	29			Bus bar arrangements in the Sub-Stations: Main and Transfer bus bar system with relevant diagrams	Regular	OHP
	30			**Gas insulated substations (GIS)** – Advantages of Gas insulated substations, different types of gas insulated substations	Regular	BB
	31			single line diagram of gas insulated substations, bus bar, construction aspects of GIS	Regular	BB
	32			Installation and maintenance of GIS	Regular	BB
	35				Regular	BB
	36			Comparison of Air insulated substations and Gas insulated substations	Regular	BB
	37			Causes of low p.f -Methods of improving p.f	Regular	OHP
	38			Phase advancing and generation of reactive KVAR using static Capacitors	Regular	BB
	39			Most economical p.f. for constant KW load and constant KVA type loads	Regular	BB
	40			Numerical Problems	Regular	BB
	41			Dependency of Voltage on Reactive Power flow	Regular	BB
	42			**Methods of Voltage Control**: Shunt Capacitors, Series Capacitors,	Regular	BB
	43			Synchronous Capacitors, Tap changing and Booster Transformers	Regular	BB
	44			Load curve, load duration curves	Regular	BB

	45			integrated load duration curves	Regular	BB
	46			Load, demand factors- Numerical Problems	Regular	OHP
	47			diversity, capacity, utilization - Numerical Problems	Regular	LCD
	48			plant use factors - Numerical Problems	Regular	BB
	49			Simple problems	Regular	BB
	50			Tutorial	Regular	BB
	51			**Costs of Generation** and their division into Fixed, Semi-fixed and Running Costs	Regular	BB
	52			Desirable Characteristics of a Tariff Method.-Tariff Methods: Flat Rate, Block-Rate	Regular	BB
	53			Desirable Characteristics of a Tariff Method.-Tariff Methods: two-part, three –part	Regular	BB
	54			Desirable Characteristics of a Tariff Method.-Tariff Methods: power factor tariff methods.	Regular	BB
	55			Numerical Problems	Regular	BB
	56			Tutorial	Regular	BB
	57	1		Tutorial	Regular	BB
	58			Assignment	Regular	BB
	59			Mid Test-2	Regular	BB
	60			Solve university papers	Regular	BB
	61			Solve university papers	Regular	BB
	62			Solve university papers	Regular	BB

Signature of the faculty **HOD**

14. **Detailed Notes:**

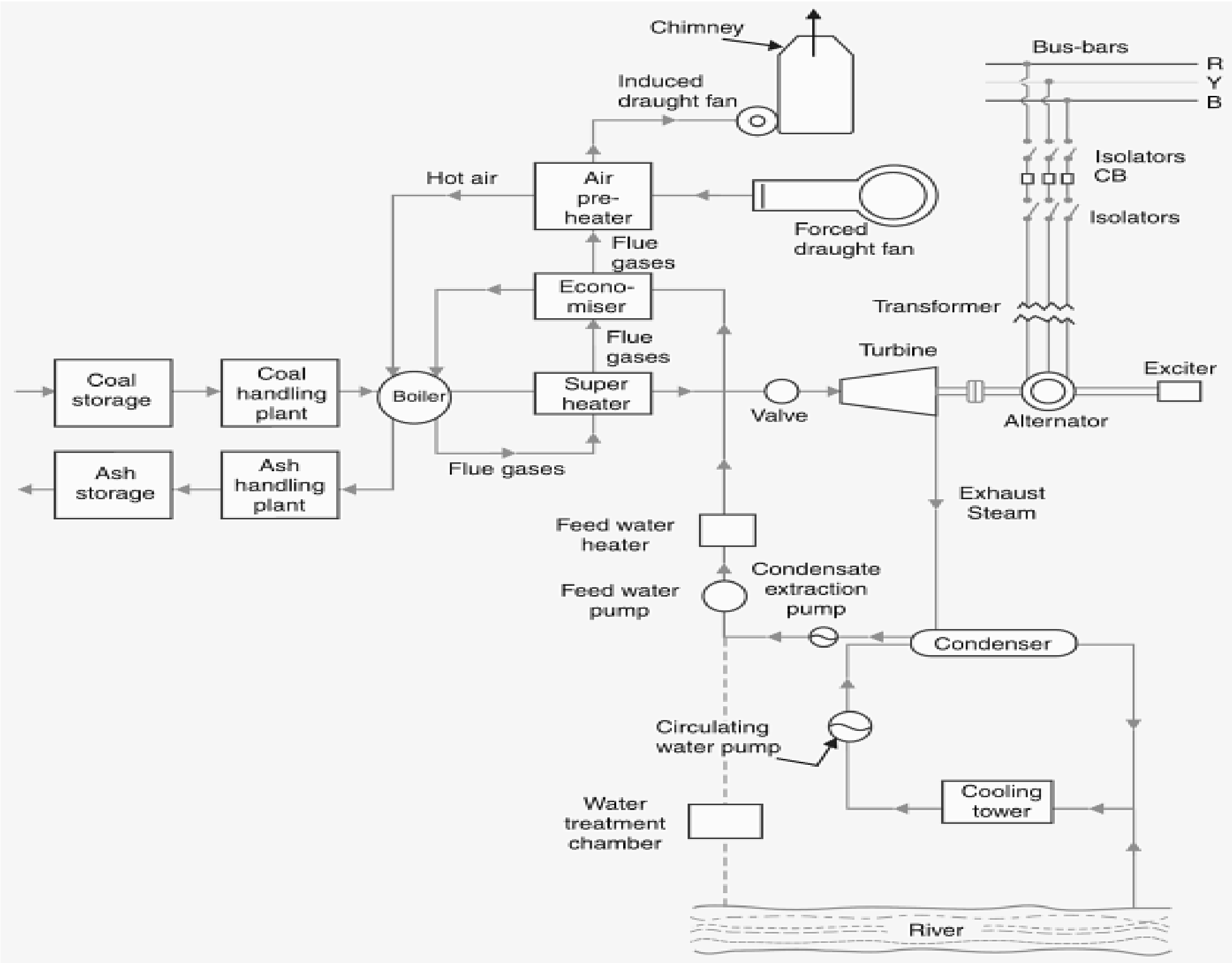
UNIT I:



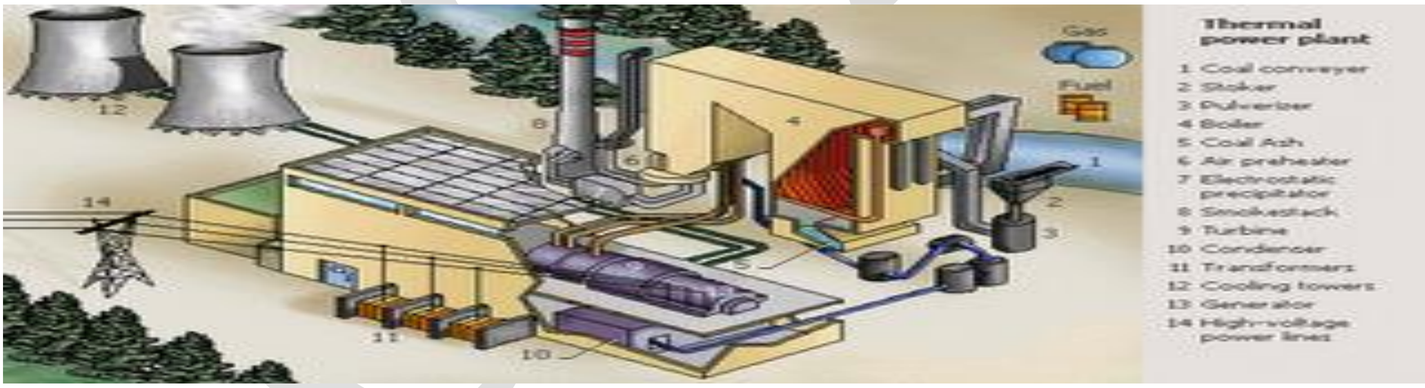
Thermal Power Plant Layout

Thermal Power Plant Layout

The above diagram is the lay out of a simplified thermal power plant and the below is also diagram of a thermal power plant.



The above diagram shows the simplest arrangement of Coal fired (Thermal) power plant.



THERMAL POWER PLANT

Main parts of the plant are

1. Coal conveyor
2. Stoker
3. Pulverizer
4. Boiler
5. Coal ash
6. Air preheater
7. Electrostatic
8. Smoke stack
9. Turbine
10. Condenser
11. Transformers
12.Cooling towers precipitator
13. Generator
14.High-votge power lines

Basic Operation:

A thermal power plant basically works on **Rankline cycle**.

1) Coal conveyor:

This is a belt type of arrangement. With this coal is transported from coal storage place in power plant to the place near by boiler.

2) Stoker:

The coal which is brought near by boiler has to put in boiler furnace for combustion. This stoker is a mechanical device for feeding coal to a furnace.

3) Pulverizer:

The coal is put in the boiler after pulverization. For this pulverizer is used. A pulverizer is a device for grinding coal for combustion in a furnace in a power plant.

3.1) Types of Pulverizes

3.1 a) Ball and Tube Mill

Ball mill is a pulverizer that consists of a horizontal rotating cylinder, up to three diameters in length, containing a charge of tumbling or cascading steel balls, pebbles, or rods.

Tube mill is a revolving cylinder of up to five diameters in length used for fine pulverization of ore, rock, and other such materials; the material, mixed with water, is fed into the chamber from one end, and passes out the other end as slime.

3.1 b) Ring and Ball:

This type consists of two rings separated by a series of large balls. The lower ring rotates, while the upper ring presses down on the balls via a set of spring and adjuster assemblies. Coal is introduced into the center or side of the pulverizer (depending on the design) and is ground as the lower ring rotates causing the balls to orbit between the upper and lower rings. The coal is carried out of the mill by the flow of air moving through it. The size of the coal particles released from the grinding section of the mill is determined by a classifier separator. These mills are typically produced by B&W (Babcock and Wilcox).

4) Boiler:

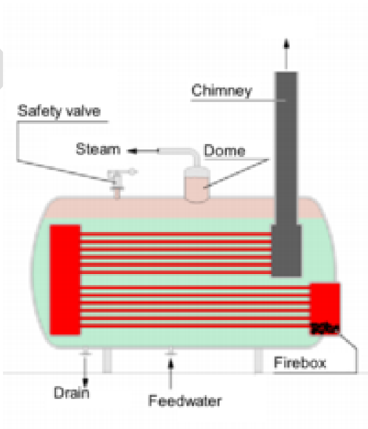
Now that pulverized coal is put in boiler furnace. Boiler is an enclosed vessel in which water is heated and circulated until the water is turned in to steam at the required pressure.

Coal is burned inside the combustion chamber of boiler. The products of combustion are nothing but gases. These gases which are at high temperature vaporize the water inside the boiler to steam. Some times this steam is further heated in a superheater as higher the steam pressure and temperature the greater efficiency the engine will have in converting the heat in steam in to mechanical work. This steam at high pressure and temperature is used directly as a heating medium, or as the working fluid in a prime mover to convert thermal energy to mechanical work, which in turn may be converted to electrical energy. Although other fluids are sometimes used for these purposes, water is by far the most common because of its economy and suitable thermodynamic characteristics.

4.1) Classification of Boilers:

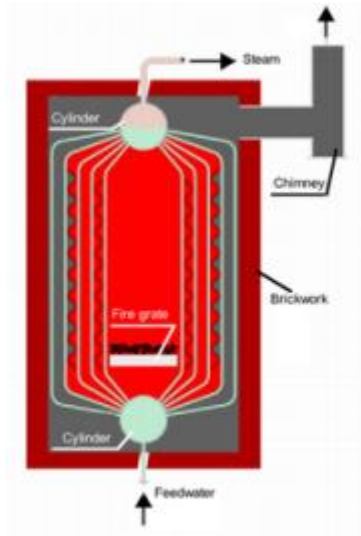
Boilers are classified as

4.1 a) Fire tube boilers :



In fire tube boilers hot gases are passed through the tubes and water surrounds these tubes. These are simple, compact and rugged in construction. Depending on whether the tubes are vertical or horizontal these are further classified as vertical and horizontal tube boilers. In this since the water volume is more, circulation will be poor. So they can't meet quickly the changes in steam demand. High pressures of steam are not possible, maximum pressure that can be attained is about 17.5kg/sq cm. Due to large quantity of water in the drain it requires more time for steam raising. The steam attained is generally wet, economical for low pressures. The output of the boiler is also limited.

4.1 b) Water tube boilers :



In these boilers water is inside the tubes and hot gases are outside the tubes. They consist of drums and tubes. They may contain any number of drums (you can see 2 drums in fig).Feed water enters the boiler to one drum (here it is drum below the boiler).This water circulates through the tubes connected external to drums. Hot gases which surround these tubes will convert the water in tubes in to steam. This steam is passed through tubes and collected at the top of the drum since it is of light weight. So the drums store steam and water (upper drum).The entire steam is collected in one drum and it is taken out from there (see in layout fig).As the movement of water in the water tubes is high, so rate of heat transfer also becomes high resulting in greater efficiency. They produce high pressure, easily accessible and can respond quickly to changes in steam demand. These are also classified as vertical, horizontal and inclined tube depending on the arrangement of the tubes. These are of less weight and less liable to explosion. Large heating surfaces can be obtained by use of large number of tubes. We can attain pressure as high as 125 kg/sq cm and temperatures from 315 to 575 centigrade.

4.1 b) Superheater :

Most of the modern boilers are having superheater and Reheater arrangement. Superheater is a component of a steam-generating unit in which steam, after it has left the boiler drum, is heated above its saturation temperature. The amount of superheat added to the steam is influenced by the location, arrangement, and amount of superheater surface installed, as well as the rating of the boiler. The superheater may consist of one or more stages of tube banks arranged to effectively transfer heat from the products of combustion. Super heaters are classified as convection, radiant or combination of these.

4.1 c) Reheater:

Some of the heat of superheated steam is used to rotate the turbine where it loses some of its energy. Reheater is also steam boiler component in which heat is added to this intermediate-pressure steam, which has given up some of its energy in expansion through the high-pressure turbine. The steam after reheating is used to rotate the second steam turbine (see Layout fig) where the heat is converted to mechanical energy. This mechanical energy is used to run the alternator, which is coupled to turbine, there by generating electrical energy.

5) Condenser:

Steam after rotating steam turbine comes to condenser. Condenser refers here to the shell and tube heat exchanger (or surface condenser) installed at the outlet of every steam turbine in Thermal power stations of utility companies generally. These condensers are heat exchangers which convert steam from its gaseous to its liquid state, also known as phase transition. In so doing, the latent heat of steam is given out inside the condenser. Where water is in short supply an air cooled condenser is often used. An air cooled condenser is however significantly more expensive and cannot achieve as low a steam turbine backpressure (and therefore less efficient) as a surface condenser.

The **purpose** is to condense the outlet (or exhaust) steam from steam turbine to obtain **maximum efficiency** and also to get the condensed steam in the form of pure water, otherwise known as condensate, back to steam generator or (boiler) as boiler feed water.

Why it is required?

The steam turbine itself is a device to convert the heat in steam to mechanical power. The difference between the heat of steam per unit weight at the inlet to turbine and the heat of steam per unit weight at the outlet to turbine represents the heat given out (or heat drop) in the steam turbine which is converted to mechanical power. The heat drop per unit weight of steam is also measured by the word enthalpy drop. Therefore the more the conversion of heat per pound (or kilogram) of steam to mechanical power in the turbine, the better is its performance or otherwise known as efficiency. By condensing the exhaust steam of turbine, the exhaust pressure is brought down below atmospheric pressure from above atmospheric pressure, increasing the steam pressure drop between inlet and exhaust of steam turbine. This further reduction in exhaust pressure gives out more heat per unit weight of steam input to the steam turbine, for conversion to mechanical power. Most of the heat liberated due to condensing, i.e., latent heat of steam, is carried away by the cooling medium. (water inside tubes in a surface condenser, or droplets in a spray condenser (Heller system) or air around tubes in an air-cooled condenser).

Condensers are classified as (i) **Jet condensers or contact condensers** (ii) **Surface condensers**.
In **jet condensers** the steam to be condensed mixes with the cooling water and the temperature of the condensate and the cooling water is same when leaving the condenser; and the condensate can't be recovered for use as feed water to the boiler; heat transfer is by direct conduction.

In **surface condensers** there is no direct contact between the steam to be condensed and the circulating cooling water. There is a wall interposed between them through heat must be convectively transferred. The temperature of the condensate may be higher than the temperature of the cooling water at outlet and the condensate is recovered as feed water to the boiler. Both the cooling water and the condensate are separately with drawn. Because of this advantage surface condensers are used in thermal power plants. Final output of condenser is water at low temperature is passed to high pressure feed water heater; it is heated and again passed as feed water to the boiler. Since we are passing water at high temperature as feed water the temperature inside the boiler does not decrease and boiler efficiency also maintained.

<u>6) .Cooling Towers:</u>

The condensate (water) formed in the condenser after condensation is initially at high temperature. This hot water is passed to cooling towers. It is a tower- or building-like device in which atmospheric air (the heat receiver) circulates in direct or indirect contact with warmer water (the heat source) and the water is thereby cooled (see illustration). A cooling tower may serve as the heat sink in a conventional thermodynamic process, such as refrigeration or steam power generation, and when it is convenient or desirable to make final heat rejection to atmospheric air. Water, acting as the heat-transfer fluid, gives up heat to atmospheric air, and thus cooled, is **re-circulated** through the system, affording economical operation of the process.

Two basic types of cooling towers are commonly used. One transfers the heat from warmer water to cooler air mainly by an evaporation heat-transfer process and is known as the **evaporative or wet cooling tower.**

Evaporative cooling towers are classified according to the means employed for producing air circulation through them: **atmospheric, natural draft, and mechanical draft**. The other transfers the heat from warmer water to cooler air by a sensible heat-transfer process and is known as the non-evaporative or dry cooling tower.

Non-evaporative cooling towers are classified as air-cooled condensers and as air-cooled heat exchangers, and are further classified by the means used for producing air circulation through them. These two basic types are sometimes combined, with the two cooling processes generally used in parallel or separately, and are then known as **wet-dry cooling towers**.

Evaluation of cooling tower performance is based on cooling of a specified quantity of water through a given range and to a specified temperature approach to the wet-bulb or dry-bulb temperature for which the tower is designed. Because exact design conditions are rarely experienced in operation, estimated performance curves are frequently prepared for a specific installation, and provide a means for comparing the measured performance with design conditions.

7) Economiser:

Flue gases coming out of the boiler carry lot of heat. Function of economiser is to recover some of the heat from the heat carried away in the flue gases up the chimney and utilize for heating the feed water to the boiler. It is placed in the passage of flue gases in between the exit from the boiler and the entry to the chimney. The use of economiser results in saving in coal consumption, increase in steaming rate and high boiler efficiency but needs extra investment and increase in maintenance costs and floor area required for the plant. This is used in all modern plants. In this a large number of small diameters thin walled tubes are placed between two headers. Feed water enters the tube through one header and leaves through the other. The flue gases flow out side the tubes usually in counter flow.

8).Air preheater:

The remaining heat of flue gases is utilised by air preheater. It is a device used in steam boilers to transfer heat from the flue gases to the combustion air before the air enters the furnace, also known as air heater, air-heating system. It is not shown in the lay out. But it is kept at a place near by where the air enters in to the boiler.

The purpose of the air preheater is to recover the heat from the flue gas from the boiler to improve boiler efficiency by burning warm air which increases combustion efficiency, and reducing useful heat lost from the flue. As a consequence, the gases are also sent to the chimney or stack at a lower temperature, allowing simplified design of the ducting and stack. It also allows control over the temperature of gases leaving the stack (to meet emissions regulations, for example).After extracting heat flue gases are passed to elctrostatic precipitator.

9).Electrostatic precipitator :

It is a device which removes dust or other finely divided particles from flue gases by charging the particles inductively with an electric field, then attracting them to highly charged collector plates, also known as precipitator. The process depends on two steps. In the first step the suspension passes through an electric discharge (corona discharge) area where ionization of the gas occurs. The ions produced collide with the suspended particles and confer on them an electric charge. The charged particles drift toward an electrode of opposite sign and are deposited on the electrode where their electric charge is neutralized. The phenomenon would be more correctly designated as electro-deposition from the gas phase.

The use of electrostatic precipitators has become common in numerous industrial applications. Among the advantages of the electrostatic precipitator are its ability to handle large volumes of gas, at elevated temperatures if necessary, with a reasonably small pressure drop, and the removal of particles in the micrometer range. Some of the usual applications are: (1) removal of dirt from flue gases in steam plants; (2) cleaning of air to remove fungi and bacteria in establishments producing antibiotics and other drugs, and in operating rooms; (3) cleaning of air in ventilation and air conditioning systems; (4) removal of oil mists in machine shops and acid mists in chemical process plants; (5) cleaning of blast furnace gases; (6) recovery of valuable materials such as oxides of copper, lead, and tin; and (7) separation of rutile from zirconium sand.

10).Smoke stack:

A chimney is a system for venting hot flue gases or smoke from a boiler, stove, furnace or fireplace to the outside atmosphere. They are typically almost vertical to ensure that the hot gases flow smoothly, drawing air into the combustion through the chimney effect (also known as the stack effect). The space inside a chimney is called a flue. Chimneys may be found in buildings, steam locomotives and ships. In the US, the term **smokestack** (colloquially, stack) is also used when referring to locomotive chimneys. The term

funnel is generally used for ship chimneys and sometimes used to refer to locomotive chimneys. Chimneys are tall to increase their draw of air for combustion and to disperse pollutants in the flue gases over a greater area so as to reduce the pollutant concentrations in compliance with regulatory or other limits.

11) Generator:

An alternator is an electromechanical device that converts mechanical energy to alternating current electrical energy. Most alternators use a rotating magnetic field. Different geometries - such as a linear alternator for use with sterling engines - are also occasionally used. In principle, any AC generator can be called an alternator, but usually the word refers to small rotating machines driven by automotive and other internal combustion engines.

12) Transformers:

It is a device that transfers electric energy from one alternating-current circuit to one or more other circuits, either increasing (stepping up) or reducing (stepping down) the voltage. Uses for transformers include reducing the line voltage to operate low-voltage devices (doorbells or toy electric trains) and **raising the voltage from electric generators so that electric power can be transmitted over long distances.** Transformers act through electromagnetic induction; current in the primary coil induces current in the secondary coil. The secondary voltage is calculated by multiplying the primary voltage by the ratio of the number of turns in the secondary coil to that in the primary.

UNIT-II: NUCLEAR POWER PLANT

Nuclear power plants provide about 17% of the world's electricity. Nuclear power technology in India has reached a state of maturity and the Department of Atomic Energy (DAE) continues to take steps to develop it further. These steps are aimed at improving the safety and availability of operating stations, reducing the gestation period of plants under construction by using innovative management techniques, cost optimization and development of mew reactor systems. At present in India 15 reactors are functioning at 6 sites (Tarapur, Rawatbhata, Kalpakkam, Narora, Kakrapar and kaiga)

Nuclear Fuel

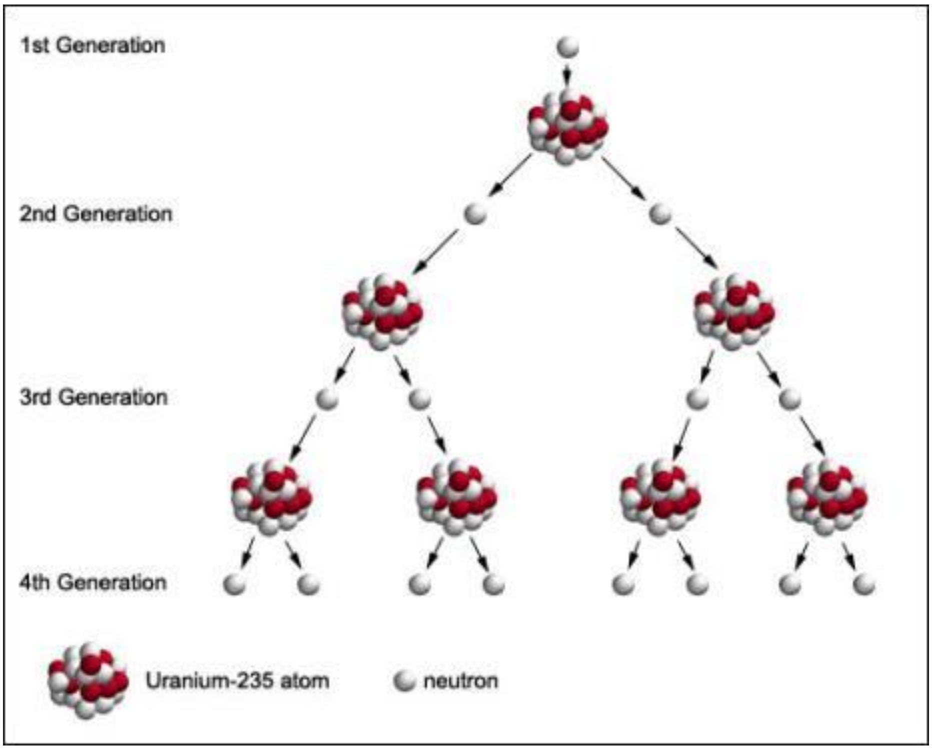
Nuclear fuel is any material that can be consumed to derive nuclear energy. The most common type of nuclear fuel is fissile elements that can be made to undergo nuclear fission chain reactions in a nuclear reactor the most common nuclear fuels are ^{235}U and ^{239}Pu. Not all nuclear fuels are used in fission chain reactions

Nuclear Fission

When a neutron strikes an atom of uranium, the uranium splits into two lighter atoms and releases heat simultaneously. Fission of heavy elements is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments

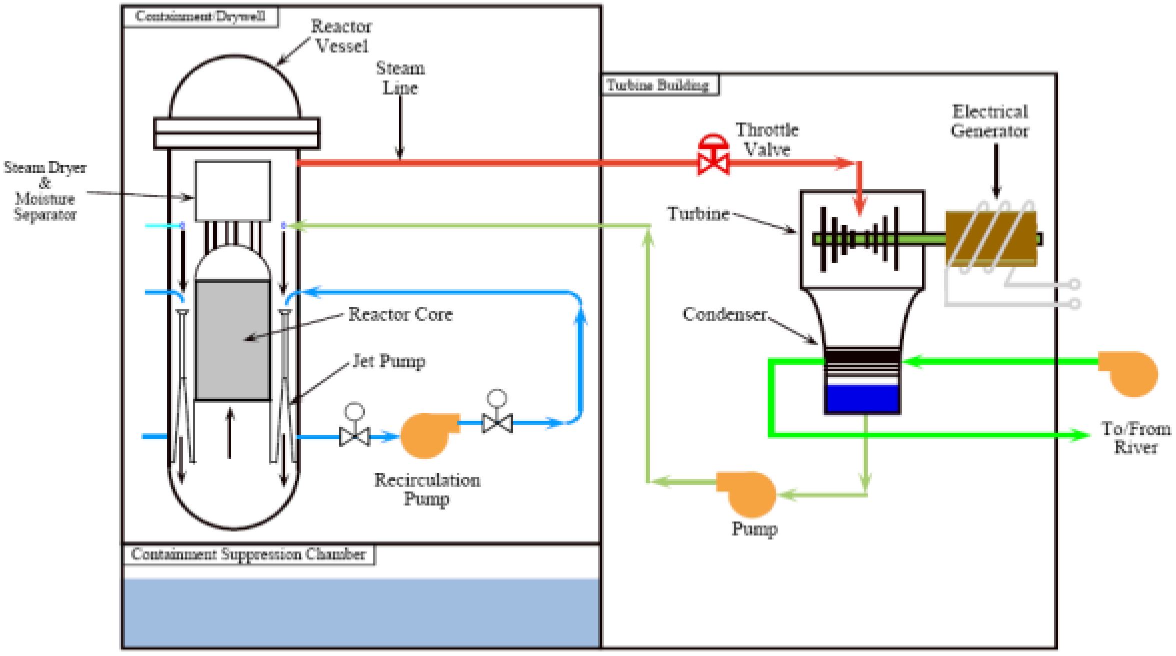
NUCLEAR CHAIN REACTIONS

A chain reaction refers to a process in which neutrons released in fission produce an additional fission in at least one further nucleus. This nucleus in turn produces neutrons, and the process repeats. If the process is controlled it is used for nuclear power or if uncontrolled it is used for nuclear weapons



U^{235} + n ⟶ fission + 2 or 3 n + 200 MeV

If each neutron releases two more neutrons, then the number of fissions doubles each generation. In that case, in 10 generations there are 1,024 fissions and in 80 generations about 6 x 10^{23} (a mole) fissions.



NUCLEAR REACTOR:

Main Parts of Nuclear Reactor:

1). control rod
2). steam generator
3). steam turbine
4). coolant pump
5). Feed pump
6). Condenser
7). Coolant tower

A **nuclear reactor** is a device in which nuclear chain reactions are initiated, controlled, and sustained at a steady rate, as opposed to a nuclear bomb, in which the chain reaction occurs in a fraction of a second and is uncontrolled causing an explosion. The most significant use of nuclear reactors is as an energy source for the generation of electrical power for the power in some ships. This is usually accomplished by methods that involve using heat from the nuclear reaction to power steam turbines

1).Control Rods:

Control rods made of a material that absorbs neutrons are inserted into the bundle using a mechanism that can rise or lower the control rods. Raising and lowering the control rods allow operators to control the rate of nuclear reaction. When an operator wants the less heat, the rods are lowered into the uranium bundle. The rods can also be lowered completely into the uranium bundle to shut the reactor down in the case of an accident or to change the fuel. The control rods essentially contain neutron absorbers like, boron, cadmium or indium.

2).Steam Generators:

Steam generators are heat exchangers used to convert water into steam from heat produced in a nuclear reactor core. One or two steam generators can also be used depending upon the reactor used. The coolant is maintained at a pressure of the order of 150 bar. Either ordinary water or heavy water is used as the coolant.

3).Steam Turbine:

A steam turbine is a mechanical device that extracts thermal energy from pressurized steam, and converts it into useful mechanical work. The operation of the turbine is similar to the one used in thermal power plants. Various high-performance alloys and super-alloys have been used for steam generator tubing.

4).Coolant pump:

The coolant pump pressurizes the coolant to pressures of the order of 155bar. The pressure of the coolant loop is maintained almost constant with the help of the pump and a pressurizer unit.

5).Feed pump

Steam coming out of the turbine, flows through the condenser for condensation and re-circulated for the next cycle of operation. The feed pump circulates the condensed water in the working fluid loop.

6).Condenser

Condenser is a device or unit which is used to condense vapor into liquid. The objective of the condenser are to reduce the turbine exhaust pressure to increase the efficiency and to recover high quality feed water in the form of condensate & feed back it to the steam generator without any further treatment.

Cooling Tower

Large quantities of water are required to condensate working fluid. Cooling towers are heat removal devices used to transfer process waste heat to the atmosphere. Water circulating through the condenser is taken to the cooling tower for cooling and reuse.

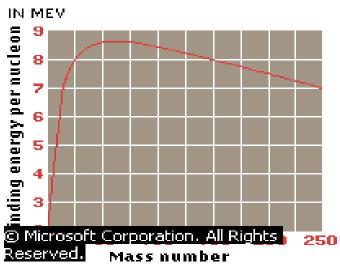
ADVANTAGES OF NUCLEAR POWER GENERATION:

- Nuclear power generation does emit relatively low amounts of carbon dioxide (CO_2). The emissions of green house gases and therefore the contribution of nuclear power plants to global warming is therefore relatively little.
- This technology is readily available; it does not have to be developed first.
- It is possible to generate a high amount of electrical energy in one single plant.

DISADVANTAGES OF NUCLEAR POWER GENERATION:

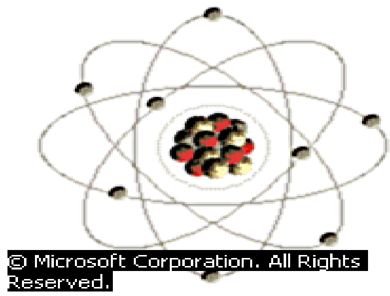
- The problem of radioactive waste is still an unsolved one. The waste from nuclear energy is extremely dangerous and it has to be carefully looked after for several thousand years (10'000 years according to United States Environmental Protection Agency standards).
- High risks: Despite a generally high security standard, accidents can still happen. It is technically impossible to build a plant with 100% security. A small probability of failure will always last. The consequences of an accident would be absolutely devastating both for human being as for the nature. The more nuclear power plants (and nuclear waste storage shelters) are built, the higher is the probability of a disastrous failure somewhere in the world.
- Nuclear power plants as well as nuclear waste could be preferred targets for terrorist attacks. No atomic energy plant in the world could withstand an attack similar to 9/11 in Yew York. Such a terrorist act would have catastrophic effects for the whole world.
- During the operation of nuclear power plants, radioactive waste is produced, which in turn can be used for the production of nuclear weapons. In addition, the same know-how used to design nuclear power plants can to a certain extent be used to build nuclear weapons (nuclear proliferation).
- The energy source for nuclear energy is Uranium. Uranium is a scarce resource; its supply is estimated to last only for the next 30 to 60 years depending on the actual demand.
- The time frame needed for formalities, planning and building of a new nuclear power generation plant is in the range of 20 to 30 years in the western democracies. In other words: It is an illusion to build new nuclear power plants in a short time

THE BASICS OF NUCLEAR POWER



Nuclear power plants generate electricity from fission, usually of uranium-235 (U-235), the nucleus of which has 92 protons and 143 neutrons. When it absorbs an extra neutron, the nucleus becomes unstable and splits into smaller pieces (“fission products”) and more neutrons. The fission products and neutrons have a smaller total mass than the U-235 and the first neutron; the mass difference has been converted into energy, mostly in the form of heat, which produces steam and in turn drives a turbine generator to produce electricity.

Natural uranium is a mixture of two isotopes, fissionable U-235 (0.7 per cent) and non-fissionable U-238. However, U-238 can absorb neutrons to form plutonium-239 (P-239), which is fissionable, and up to half the energy produced by a reactor can in fact come from fission of P-239. Some types of reactor require the amount of U-235 to be increased above the natural level, which is called enrichment. Pressurized water reactors (PWRs), the most common type of reactor, require fuel enriched to about 3 per cent U-235.



Reactor fuel is made up of fuel pellets or pins enclosed in a tubular cladding of steel, zircaloy, or aluminium. Several of these fuel rods make up each fuel assembly. The fast neutrons released in the fission reaction need to be slowed down before they will induce further fissions and give a sustained chain reaction. This is done by a moderator, usually water or graphite, which surrounds the fuel in the reactor. However, in "fast reactors" there is no moderator and the fast neutrons sustain the fission reaction.

A coolant is circulated through the reactor to remove heat from the fuel. Ordinary water (which is usually also the moderator) is most commonly used but heavy water (deuterium oxide), air, carbon dioxide, helium, liquid sodium, liquid sodium-potassium alloy, molten salts, or hydrocarbon liquids may be used in different types of reactor.

The chain reaction is controlled by using neutron absorbers such as boron, either by moving boron-containing control rods in and out of the reactor core, or by varying the boron concentration in the cooling water. These can also be used to shut down the reactor. The power level of the reactor is monitored by temperature, flow, and radiation instruments and used to determine control settings so that the chain reaction is just self-sustaining.

The main components of a nuclear reactor are: the pressure vessel (containing the core); the fuel rods, moderator, and primary cooling system (making up the core); the control system; and the containment building. This last element is required in the event of an accident, to prevent any radioactive material being released to the environment, and is usually cylindrical with a hemispherical dome on top.

During operation, and also after it is shut down, a nuclear reactor will contain a very large amount of radioactive material. The radiation emitted by this material is absorbed in thick concrete shields surrounding the reactor core and primary cooling system. An important safety feature is the emergency core cooling system, which will prevent overheating and "meltdown" of the reactor core if the primary cooling system fails. *See also* Nuclear Fission.

II HISTORICAL OVERVIEW

Radioactivity was discovered by Antoine Henri Becquerel in 1896, although not called this until two years later when Pierre and Marie Curie discovered the radioactive elements polonium and radium, which occur naturally with uranium. In 1932 the neutron was discovered by British scientist James Chadwick. Enrico Fermi and colleagues in Italy then discovered that bombarding uranium with neutrons slowed by means of paraffin produced at least four different radioactive products. Six years later, German scientists Otto Hahn and Fritz Strassman demonstrated that the uranium atom was actually being split. The Austrian-born Swedish physicist Lise Meitner continued the work with her nephew Otto Frisch and defined nuclear fission for the first time.

In 1939, Fermi travelled to the United States to escape the Fascist regime in Italy, and was followed by physicist Niels Bohr, who fled the German occupation of Denmark. Collaborating at Columbia University, they developed the concept of a chain reaction as a source of power. With the outbreak of World War II concerns arose among refugee European physicists in France, the United Kingdom, and the United

States that Nazi Germany might develop an atomic bomb. The focus of research then changed to military applications.

The Manhattan Project began in the United States in 1940, with the aim to develop nuclear weapons. In 1942, Fermi constructed the first experimental nuclear reactor at the University of Chicago. One year later, a prototype plutonium production reactor was demonstrated at Oak Ridge and by 1945 three full-scale reactors were in operation at Hanford. The first nuclear bomb was tested at Alamogordo Air Base in New Mexico in July 1945. Two bombs were then dropped on Japan in August, the first at Hiroshima and the second at Nagasaki.

With the end of World War II in 1945, the Cold War and the East-West arms race took over. The Union of Soviet Socialist Republics (USSR) mounted a crash development programme and soon began plutonium production. The United States continued with plutonium production and also developed different types of reactor, as did the USSR, United Kingdom, France, and Canada. Both sides developed a range of technologies that was also applicable to nuclear power generation. Reliable energy supplies were important to national recovery, and nuclear power was seen as an essential element of national power programmes.

The first purpose-built reactor for electrical power generation was started up in 1954 at Obninsk, near Moscow, in the USSR. In 1956 the first large-scale commercial reactor generating electrical power (as well as producing plutonium) began operating at Calder Hall, England. In the United States three types of reactor were being developed for commercial use, namely the pressurized water reactor (PWR), boiling water reactor (BWR), and the fast breeder reactor (FBR). In 1957 the first commercial power unit, a BWR, was started up in the United States.

There have been some major incidents in nuclear power plants. In 1957 a plutonium production reactor caught fire at Wind scale (modern-day Sellafield) in Cumbria, England, spreading large amounts of radioactivity across Britain and northern Europe. It was the worst nuclear accident in the history of the UK. In 1979, in the worst nuclear accident in US history, a core meltdown occurred at Three Mile Island power plant near Harrisburg, Pennsylvania. The worst nuclear accident to date occurred in 1986, when a runaway nuclear reaction at Chernobyl power plant near Kiev, USSR (modern-day CIS), led to a series of explosions that dispersed massive amounts of radioactive material throughout the Northern hemisphere. In 1999 a “criticality incident” occurred at the Tokai-Mura plant in Japan, causing the worst nuclear damage in that country. (See also section on Nuclear Accidents.)

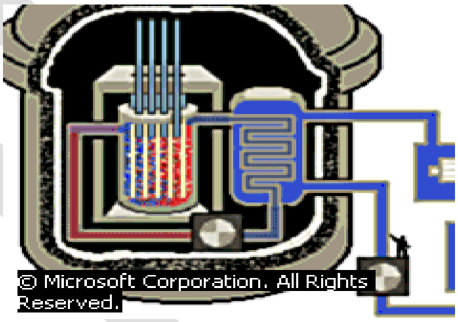
The number of nuclear reactors in the world has grown steadily. By 1964 there were 14 reactors connected to electricity distribution systems worldwide. In 1970 there were 81; this number grew to 167 by 1975, to 365 by 1985, to 435 by 1995, and then decreased to 428 by 1999.


Photo Researchers, Inc./US Dept. of Energy

V TYPES OF REACTOR

Most of the world’s reactors are located in nuclear power plants, the rest are research reactors, or reactors used for propulsion of submarines and ships. Some designs can be re-fuelled while in operation, others need to be shut down to refuel. Several advanced reactor designs, which are simpler, more efficient, and inherently safer, are also under development. There are two basic types of fission reactors: thermal reactors and fast reactors. In thermal reactors, the neutrons created in the fission reaction lose energy by colliding with the light atoms of the moderator until they can sustain the fission reaction. In fast reactors, “fast” neutrons sustain the fission reaction and a moderator is not needed. They require enriched fuel, but the fast neutrons can be used to convert U-238 into fissile material (plutonium), creating more nuclear fuel than the amount consumed. They can also be used to “burn” plutonium as a means of reducing the amount that is stockpiled.

For the purpose of electricity generation there are five main categories of reactors, each comprising one or more types. Light Water Reactors include Pressurized Water Reactors (PWRs), together with the Russian VVER design, and Boiling Water Reactors (BWRs). Gas Cooled Reactors comprise Magnox reactors and Advanced Gas-Cooled Reactors (AGR), developed in the United Kingdom, as well as High Temperature Gas-Cooled Reactors (HTGR). Pressurized Heavy Water Reactors include the CANDU reactor developed in Canada. Light Water Graphite Reactors comprise the RBMK reactors, developed in the USSR. Lastly, Fast Breeder Reactors include Liquid Metal Fast Breeder Reactors (LMFBR).



In the early 1950s enriched uranium was only available in the United States and the USSR. For this reason, reactor development in the United Kingdom (Magnox), Canada (CANDU), and France was based on natural uranium fuel. The Russian RBMK design also used natural uranium fuel.

In natural uranium reactors ordinary water cannot be used as the moderator, because it absorbs too many neutrons. In the successful CANDU design this was overcome by using heavy water (deuterium oxide) for the moderator and coolant. Nearly all reactors in the United Kingdom have used a graphite moderator and carbon dioxide as the coolant.

In the United Kingdom, the Magnox reactors of the 1960s were followed by the AGRs, which used enriched fuel and were able to operate at higher temperatures and with greater efficiency. The Steam Generating Heavy Water Reactor (SGHWR) design was intended as the next technological step but this policy was changed in favour of the more established PWR design, of which many were already in operation. However, only one PWR was subsequently constructed in the United Kingdom, at Sizewell. Nuclear power generates about 25 per cent of the country’s electricity.

Comparison of Main Types of Reactor			
THERMAL			
EFFICIENCY (MW)	**REACTOR**	**COOLANT MODERATOR**	**ELECTRICAL OUTPUT**
32%	PWR	water	160 to 1380
32%	BWR	water	75 to 1300
27%	Magnox	carbon dioxide	50 to 420
41%	AGR	carbon dioxide	600 to 625
31%	RBMK	water	1000 & 1500
34%	CANDU	heavy water	220 to 935

French researchers abandoned the design they had initially developed and embarked in the early 1970s on a nuclear power programme based totally on PWRs when French-produced enriched uranium became available. These now supply almost 80 per cent of France’s electricity.

Worldwide 56 per cent of power reactors are PWRs, 22 per cent are BWRs, 6 per cent are pressurized heavy water reactors (mostly CANDUs), 3 per cent are AGRs, and 23 per cent are other types. Eighty-eight per cent are fuelled by enriched uranium oxide, the rest by natural uranium, with a few light water reactors also using mixed oxide fuel (MOX), which contains plutonium as well as uranium. Light water is the coolant/moderator for 80 per cent to 85 per cent of all reactors.

The most important factors to be considered for any type of nuclear reactor are: safety; cost per kilowatt of generating capacity to construct; cost per kilowatt delivered (to include fuel, operation, and downtime costs); operating lifetime; and decommissioning costs.

Pressurized Water Reactor (PWR)

PWRs are normally fuelled with uranium oxide pellets in a zirconium cladding, although in recent years some mixed oxide fuel (MOX), which contains plutonium, has been used. The fuel is enriched to 3 per cent U-235. The moderator is the ordinary water coolant, which is kept pressurized at about 150 bar to stop it boiling. It is pumped through the reactor core, where it is heated to about 325° C (about 620° F). The superheated water is pumped through a steam generator, where, through heat exchangers, a secondary loop of water is heated and converted to steam. This steam drives one or more turbine generators, is condensed, and pumped back to the steam generator. The secondary loop is isolated from the reactor core water and is therefore not radioactive. A third stream of water from a lake, river, the sea, or cooling tower is used to condense the steam. A typical reactor pressure vessel is 15 m (49 ft) high and 5 m (16 ft) in diameter, with walls 25 cm (10 in) thick. The core contains about 90 tonnes of fuel.

The PWR was originally designed by Westinghouse Bettis Atomic Power Laboratory for military ship applications, then by Westinghouse Nuclear Power Division for commercial applications. The Soviet-designed VVER (Veda-Vodyanoi Energetichesky Reaktor) design is similar to Western PWRs but has different steam generators and safety features.

Boiling Water Reactor (BWR)

The BWR is simpler than the PWR but less efficient in its fuel use and has a lower power density. Like the PWR, it is fuelled by uranium oxide pellets in a zirconium cladding, but slightly less enriched. The moderator is the ordinary water coolant, which is kept at lower pressure (70 bar) so that it boils within the core at about 300° C. The steam produced in the reactor pressure vessel is piped directly to the turbine generator, condensed, and then pumped back to the reactor. Although the steam is radioactive, there is no intermediate heat exchanger between the reactor and turbine to decrease efficiency. As in the PWR, the condenser cooling water has a separate source, such as a lake or river.

The BWR was originally designed by Allis-Chambers and General Electric (GE) of the United States. The GE design has survived, and other versions are available from ASEA-Atom, Kraftwerk Union, and Hitachi.

Gas-Cooled Reactors

Magnox reactors take their name from the magnesium-based alloy used as cladding for the natural uranium metal fuel. The moderator is graphite and the carbon dioxide coolant is circulated through the core at a pressure of about 27 bar, exiting at about 360° C. The heat is transferred to the secondary water loop, in which steam is raised to drive the turbine generators. Early units had a steel pressure vessel with the steam generators outside the containment. Later versions had a concrete pressure vessel containing the core and the steam generators. Magnox reactors are a British design but were also built in Tokai-Mura (Japan) and Latina (Italy).

The Advanced Gas-Cooled Reactor (AGR) is a development of the Magnox design using uranium oxide fuel enriched to 2-3 per cent U-235 and clad in stainless steel or zircaloy. The moderator is graphite and the carbon dioxide coolant circulates at about 40 bar, exiting the core at 640° C. The heat is transferred to the secondary water loop, in which steam is raised to drive the turbine generators. A concrete pressure vessel is used, with walls about 6 m (20 ft) thick. AGRs are unique to the UK.

High Temperature Gas-Cooled Reactors (HTGRs) are largely experimental. The fuel elements are spheres made from a mixture of graphite and nuclear fuel. The German version has the fuel loaded in a silo, the US version loads the fuel into hexagonal graphite prisms. The coolant is helium, pressurized to about 100 bar, circulated through the interstices between the spheres or through holes in the graphite prisms. An example of this type is described in the Advanced Reactors section later in this article.

Pressurized Heavy Water Reactor

The most widely used reactor of this type is the Canadian CANDU (Canadian Deuterium Uranium Reactor). The moderator and coolant is heavy water (deuterium oxide) and the fuel consists of natural uranium oxide pellets in zircaloy tubes. These are contained in pressure tubes mounted horizontally through a tank of heavy water called the “calandria”, which acts as the moderator. This feature avoids the need for a pressure vessel and facilitates on-load refuelling. The heavy water coolant is pumped through the pressure tubes at 110 bar and exits at about 320° C. The heat is transferred to the secondary water loop, in which steam is raised to drive the turbine generators.

The CANDU was designed by Atomic Energy of Canada Limited (AECL) to make the best use of Canada’s natural resources of uranium without needing enrichment technology, although requiring heavy water production facilities. In total, 21 CANDUs have been built, 5 of them outside Canada.

Light Water Graphite Reactor

The Soviet-designed Reaktor Bolshoi Moshchnosty Kanalyny (RBMK) is a pressurized water reactor with individual fuel channels. The moderator is graphite, the coolant—ordinary water, and the fuel—enriched uranium oxide. The fuel tubes and coolant tubes pass vertically through a massive graphite moderator block. This is contained in a pressure vessel and filled with helium-nitrogen mixture to improve heat transfer and prevent oxidation of the graphite. The coolant is maintained at 75 bar and exits at up to 350° C. The water is permitted to boil and the steam, after removal of water, is fed to the turbine generators.

Following the 1986 Chernobyl disaster, the design weaknesses of the RBMK were recognized and modifications made to help overcome them. The last operating reactor at the Chernobyl site was closed down in December 2000, and others will eventually be phased out.

Fast Breeder Reactor

The Liquid Metal Fast Breeder (LMFBR) uses molten sodium as the coolant and runs on fuel enriched with U-235. Instead of a moderator being employed, the core is surrounded by a reflector, which bounces neutrons back into the core to help sustain the chain reaction. A blanket of “fertile” material (U-238) is included above and below the fuel, to be converted into fissile plutonium by capture of fast neutrons. The core is compact, with a high power density. The molten sodium primary coolant transfers its heat to a secondary sodium loop, which heats water in a third loop to raise steam and drive the turbine generators.

Development of fast reactors proceeds only in France, India, Japan, and Russia. The only commercial power reactors of this type are in Kazakhstan and Russia. The British fast reactor, which generated 240 megawatts, was closed down in the 1990s and is being decommissioned

THE NUCLEAR FUEL CYCLE

Nuclear power is based on uranium, a slightly radioactive metal that is relatively abundant (about as common as tin and 500 times as abundant as gold). Thorium is also usable as a nuclear fuel, but there is no economic incentive to exploit it at present. Economically extractable reserves at current low world prices amount to just 4.4 million tonnes, from the richer ores. At the current world usage rate of 50,000 tonnes per annum this would last only another 80 years. But if prices were to rise significantly, the usable reserves would increase to the order of 100 million tonnes. And if prices were to rise to several hundred dollars per kilogram, it may become economic to extract uranium from seawater, in which it is present at about 3 mg per tonne. This would be a sufficient supply for a greatly enlarged industry for several centuries.

Uranium Production

The world's uranium reserves are mostly located in Australia (35 per cent), countries of the former USSR (29 per cent), Canada (13 per cent), Africa (8 per cent), and South America (8 per cent). In terms of production, Canada (33 per cent) is followed by Australia (15 per cent) and Nigeria (10 per cent). Other producers are Kazakhstan, Namibia, Russia, South Africa, the US, and Uzbekistan.

Uranium ore contains about 1 per cent uranium. It is mined either by open-pit or deep-mining techniques and milled (crushed and ground) to release the uranium minerals from the surrounding rock. The uranium is then dissolved, extracted, precipitated, filtered, and dewatered to produce a uranium ore concentrate called "yellowcake" which contains about 60 per cent uranium. This has a much smaller volume than the ore, and hence is less expensive to transport. It is either shipped to the fuel enrichment plant or, alternatively, to the fuel fabrication plant if it is not to be enriched.

Enrichment

The yellowcake is converted to uranium hexafluoride (UF_6), which is a gas above 50° C and is used as the feedstock for the enrichment process. Because most reactors require more than the 0.7 per cent natural concentration of U-235, some of the U-238 needs to be removed to give a concentration of 3 per cent U-235 or thereabouts.Enrichment is carried out using either the gaseous diffusion process or the newer gas centrifuge process. A laser process is also under development. The gas centrifuge process requires only 5 per cent of the energy to separate the same amount of U-235 as the diffusion process, although diffusion plants are still dominant worldwide.

Fuel Fabrication

The enriched UF_6 is converted to uranium dioxide in the form of a ceramic powder. This is pressed and then sintered in a furnace to produce a dense ceramic pellet. Pellets are welded into fuel rods and combined into fuel assemblies, which are then transported to the nuclear power station for loading into the reactor.

Plutonium oxide may also be mixed with the uranium oxide to make mixed oxide fuel (MOX), as a means of reducing the amount of stockpiled plutonium (although not the total amount in circulation) and avoiding the need to enrich the uranium. MOX fuel is manufactured at the reprocessing plant where the plutonium is held and is increasingly being used in light water reactors, up to a maximum of about 30 per cent of the fuel in a PWR. Because spent MOX fuel is highly radioactive, the plutonium is unlikely to be illegally diverted into manufacture of nuclear weapons.

Power Generation

The fuel assemblies are loaded into the reactor in a planned cycle to "burn" the fuel most efficiently. The "burn-up" is expressed as gigawatt-days per tonne (GWd/te) of uranium. The early Magnox stations achieved 5 GWd/te but by the late 1980s PWRs and BWRs were achieving 33 GWd/te. Figures of 50 GWd/te are now being achieved, and this is forecast to increase.

Spent Fuel

The fuel elements are removed from the reactor when they have reached the design burnup level, typically after four years. At this point they are intensely radioactive and generate a lot of heat, so the spent fuel is placed in a cooling pond adjacent to the reactor. The water (which is dosed with boric acid to absorb neutrons and prevent a chain reaction) acts as a radiation shield and coolant. The fuel elements remain there for at least five months until the radioactivity has decayed enough to permit them to be transported.

Where the fuel is to be reprocessed, it is transported in shielded flasks by rail or road to the reprocessing plant. Where this is not the case, it will remain in the cooling pond. Older ponds were designed to accommodate up to ten years' worth of spent fuel but may be able to accommodate more by removing older fuel into dry storage facilities. But ultimately the spent fuel will need to be sent for permanent disposal if it is not to be reprocessed.

Reprocessing

The spent fuel is typically made up of non-fissile U-238 (about 95 per cent), fissile U-235 (about 0.9 per cent), various highly radioactive fission products, and a mixture of plutonium isotopes (more than half of which are fissile). Reprocessing separates the uranium and plutonium from the waste, and was historically carried out to recover plutonium for manufacture of nuclear weapons. In the UK this was also carried out to deal with the magnesium alloy Magnox fuel casings, which are eventually corroded by the water in the cooling pond and are not suitable for dry storage. The recovered U-235 is used for the manufacture of new fuel, and the plutonium can be used for manufacture of MOX fuel (see Fuel Fabrication above), although the majority is stockpiled at present.

The spent fuel received from the nuclear power station is stored in a cooling pond and then mechanically cut up. In the commonly used Purex process the fuel is dissolved in nitric acid and then the uranium, plutonium, and fission products are separated by solvent extraction using a mixture of tributyl phosphate and kerosene. The uranium goes to fuel fabrication and the plutonium is either stored or used for MOX fuel production. The fission products are separated into a liquid stream, which is processed with glass-making materials into a vitrified high level waste (HLW) product. Other liquid and solid waste streams are also generated, and these are discussed in the section on radioactive waste management later in the article.

Reprocessing in the civil nuclear industry is a contentious and complex issue. Between 1976 and 1981 it was not carried out in the United States due to concerns that plutonium could be illegally diverted into the manufacture of nuclear weapons (although now permitted, it has not been resumed). Instead, a "once through" policy for nuclear fuel is followed, with spent fuel regarded as waste destined for permanent disposal.

The UK, France, Japan, and Russia have reprocessing plants and all are busy reducing their stock of nuclear weapons (apart from Japan, which has none), so the amounts of stored plutonium are increasing.

Options for handling plutonium include "burning" it in a fast reactor, or using it up as MOX fuel followed by disposal of the spent fuel. As well as the plutonium issue, decision-making factors include the economics of the process and national perceptions of future energy needs.

Transport

Uranium concentrate, new nuclear fuel, spent fuel, and radioactive waste are transported by rail, road, ship, and air in packages designed to prevent release of radioactive material under all foreseeable accident scenarios. The most radioactive items such as spent fuel or vitrified high level waste are transported in extremely rugged "flasks" or "casks", which will typically have undergone high-speed impact tests and fire tests to demonstrate their integrity.

I RADIOACTIVE WASTE MANAGEMENT

Nuclear power stations, reprocessing plants, fuel fabrication plants, uranium mines, and all other nuclear facilities produce solid and liquid wastes of varying characteristics and amounts. These are internationally classified as high level waste (HLW), intermediate level waste (ILW), and low level waste (LLW).

A typical 1000 MW nuclear power station produces about 300 cu m of LLW and ILW waste each year, of which 95 per cent would be classified as LLW. It also produces about 30 tonnes of spent fuel, classified as HLW. In comparison, a coal-fired power station of the same capacity would produce 300,000 tonnes of ash per year, containing a very large amount of radioactivity and toxic heavy metals, which would be dispersed into landfill sites and the atmosphere. Worldwide, about 200,000 cu m of low and intermediate waste are produced from nuclear power stations each year, together with 10,000 cu m of HLW (primarily spent fuel).

Wastes of lower activity are also produced, including very low level waste from most nuclear facilities which can be disposed of in normal municipal waste disposal sites without special precautions. Uranium mines and mills produce large volumes of waste containing low concentrations of radioactive and toxic materials, which are handled by normal mining techniques such as tailings dams. The enrichment process produces depleted uranium, primarily consisting of U-238, which is slightly radioactive and requires some precautions for safe disposal.

II NUCLEAR SAFETY

Before discussing the safety issues surrounding nuclear power it is necessary to understand the basics of radiation.

Introduction to Radiation

Average Annual Radiation Exposure Dose in the United Kingdom

SOURCE OF EXPOSURE	PERECENTAGE OF RADIATION RECEIVED
Natural radon gas in the home	50%
Gamma rays from rocks and soil	14%
Medical (mostly from X-rays)	14%
Internal (from eating, drinking & breathing)	11.5%
Cosmic rays from outer space	10%
Occupational (medical and industrial)	0.3%
Nuclear weapons fallout and effects of Chernobyl	0.2%
Discharges from the nuclear industry less than	0.1%
Consumer products (such as smoke alarms) less than	0.1%

Heat and light are types of radiation that people can feel or see, but we cannot detect ionizing radiation in this way (although it can be measured very accurately by various types of instrument). Ionizing radiation passes through matter and causes atoms to become electrically charged (ionized), which can adversely affect the biological processes in living tissue.

Alpha radiation consists of positively charged particles made up of two protons and two neutrons. It is stopped completely by a sheet of paper or the thin surface layer of the skin; however, if alpha-emitters are ingested by breathing, eating, or drinking they can expose internal tissues directly and may lead to cancer. Beta radiation consists of electrons, which are negatively charged and more penetrating than alpha particles. They will pass through 1 or 2 centimeters of water but are stopped by a sheet of aluminium a few millimeters thick.

X-rays are electromagnetic radiation of the same type as light, but of much shorter wavelength. They will pass through the human body but are stopped by lead shielding. Gamma rays are electromagnetic radiation of shorter wavelength than X-rays. Depending on their energy, they can pass through the human body but are stopped by thick walls of concrete or lead.

Neutrons are uncharged particles and do not produce ionization directly. However, their interaction with the nuclei of atoms can give rise to alpha, beta, gamma, or X-rays, which produce ionization. Neutrons are penetrating and can be stopped only by large thicknesses of concrete, water, or paraffin. Radiation exposure is a complex issue. We are constantly exposed to naturally occurring ionizing radiation from radioactive material in the rocks making up the Earth, the floors and walls of the buildings we use, the air we breathe, the food we eat or drink, and in our own bodies. We also receive radiation from outer space in the form of cosmic rays.

We are also exposed to artificial radiation from historic nuclear weapons tests, the Chernobyl disaster, emissions from coal-fired power stations, nuclear power plants, nuclear reprocessing plants, medical X-rays, and from radiation used to diagnose diseases and treat cancer. The annual exposure from artificial sources is far lower than from natural sources. The dose profile for an "average" member of the UK population is shown in the table above, although there will be differences between individuals depending on where they live and what they do (for example, airline pilots would have a higher dose from cosmic rays and radiation workers would have a higher occupational dose).

Radiation Effects and Dose Limits

Large doses of ionizing radiation in short periods of time can damage human tissues, leading to death or injury within a few days. Moderate doses can lead to cancer after some years. And it is generally accepted that low doses will still cause some damage, despite the difficulty in detecting it (although there is a body of opinion that there exists a "threshold" below which there is no significant damage). There is still no definite conclusion as to whether exposure to the natural level of background radiation is harmful, although damaging effects have been demonstrated at levels a few times higher.

Absorbed radiation dose is measured in sieverts (Sv), although doses are usually expressed in millisieverts (mSv). One chest X-ray gives a dose of about 0.2 mSv. The natural background radiation dose in the UK is about 2.5 mSv per annum, although it doubles in some areas, and in certain parts of the world it may reach several hundred mSv. A dose of 5 Sv (that is, 5,000 mSv) is likely to be fatal.

Basic principles and recommendations on radiation protection are issued by the International Commission on Radiological Protection (ICRP) and used to develop international standards and national regulations to protect radiation workers and the general public. The basic approach is consistent all over the world. Over and above the natural background level, the dose limit for a radiation worker is set at 100 mSv per year averaged over five years, and 1mSv per year over five years for a member of the general public. Doses should always be kept as low as reasonably achievable, and the limits should not be exceeded.

In the UK the recommended maximum annual dose for a radiation worker is set at 20 mSv (although higher limits may apply elsewhere in the world) and the typical annual dose for a radiation worker would be controlled to less than 1.5 mSv. However, some may receive more than 10 mSv, and a few may approach the annual limit.

Ensuring Nuclear Safety

In common with all hazardous industrial activities, the risk of major nuclear accidents is minimized at power stations and reprocessing plants by means of multiple levels of protection. In order of importance, engineered systems are provided for prevention, detection, and control of any release of radioactive material. Escape and evacuation of people on site and nearby is available as the last resort. Sophisticated analysis is carried out to evaluate the effect of the protective systems in all foreseeable accident scenarios and to demonstrate that the risk of failure is sufficiently low.

For example, for a major release of radioactivity from a modern nuclear power station there would have to be a whole series of failures. The primary cooling system would have to fail, followed by the emergency cooling system, then the control rods, then the pressure vessel, and finally the malfunction of the containment building before significant amounts of radioactivity could be released.

The safety record of the nuclear industry worldwide over the last 45 years has been generally good, with the exception of the Windscale (Sellafield) fire in 1957 (which actually happened with a military plutonium production reactor rather than a power reactor), the Three Mile Island accident in 1979, the Chernobyl disaster of 1986, and the most recent accident, at Tokai-Mura in Japan in 1999, all of which are discussed in more detail in the next section. However, there have also been a number of incidents at nuclear power stations and reprocessing plants over the years, which resulted in severe damage and/or had the potential to escalate into major accidents, and should therefore be classified as "near misses".

Nuclear Accidents

There have been four particularly severe nuclear accidents in the last 45 years, which released, or almost released, large amounts of radioactivity.

The 1957 Windscale fire was the worst nuclear accident in UK history. It happened when an early plutonium production reactor (with few safety systems) caught fire, and is not representative of modern nuclear power reactors.

The 1979 core meltdown at the Three Mile Island PWR was the worst nuclear accident in US history. The disaster was largely contained, but happened because of deficiencies in the control system and incorrect responses by the operators when abnormal circumstances arose initially, which then escalated into a far worse situation.

The 1986 Chernobyl disaster was the worst nuclear accident in history. It was caused by the operators carrying out an unauthorized and previously untried procedure on an RBMK reactor that involved them disabling a number of safety devices. This led to the reactor becoming unstable and eventually exploding.

In the years following the accident over 30 people (mainly firefighters) died from radiation exposure. A further 300 workers and firefighters suffered radiation sickness (those who were sent in to clean up the plant following the explosion were later found to have been at a significantly increased risk of lung cancer) and almost 2,000 people in the surrounding area who were children at the time have developed thyroid cancer (which is fortunately treatable, and so few have died), with more cases expected. Massive amounts of radioactive material were dispersed throughout the Northern hemisphere.

The 1999 accident at the Tokai-Mura nuclear plant in Japan was the worst nuclear accident in Japanese history. It was a "criticality incident", in which there was a sustained burst of neutrons due to a chain reaction starting up. It was caused by operators carrying out a prohibited procedure while manufacturing highly enriched fuel (15 per cent to 20 per cent U-235) for an experimental fast reactor. There were a small number of fatalities (those closest to the incident, which is typical of criticality accidents) and people living in the surrounding area were irradiated with neutrons for some hours.

III NUCLEAR POWER TODAY AND TOMORROW

Today

Worldwide, there are about 430 power reactors operating in 25 countries, providing about 17 per cent of the world's electricity. Of these 56 per cent are PWRs, 22 per cent are BWRs, 6 per cent are pressurized heavy water reactors (mostly CANDUs), 3 per cent are AGRs, and 23 per cent are other types. In all, 88 per cent are fuelled by enriched uranium oxide, the rest by natural uranium. A few light water reactors also use mixed oxide fuel (MOX) and this is likely to increase, partly as a way to dispose of the growing stocks of military plutonium. The number of fast breeder reactors (FBRs) has reduced with the closure of FBR programmes in several countries.

Nuclear power and hydro-electric power together provide 36 per cent of world electricity: neither put carbon dioxide into the atmosphere. In both cases the technology is mature. The new renewable technologies hardly appear in the statistics but, with financial support, they are starting to make their presence felt. It is unlikely, however, that renewables will ever provide more than 20 per cent of world energy. In a world greedy for energy, where oil is already beginning to be supply-constrained and gas will follow by 2010, concerns for the security of energy supply are now being voiced. In the US, where power blackouts are prevalent in some states, life extension of nuclear stations is being implemented urgently to ensure supply despite pressures from the environmental movement to phase out nuclear power.

Life extension of nuclear reactors in the UK has been very successful but current policy appears to be to retire stations at the end of their useful lives and replace them with gas-fired stations. However, replacement by gas brings a huge carbon dioxide penalty which will derail the UK’s Kyoto Protocol’s obligations. The much more stringent post-2010 requirements that have been called for by the Royal Commission on Environmental Pollution require a 60 per cent carbon dioxide reduction by 2050, but have virtually no chance of success without a nuclear input. Sweden and Germany are following a similar nuclear closure route.

Nuclear power construction is on the plateau or in decline in some developed countries and consequently the teams of experienced nuclear engineers have been dispersed (despite the 38 new nuclear power plants currently under construction). Some countries, such as the UK, have lost the capacity to build a nuclear power station. University departments teaching nuclear technology have all but disappeared, which could be a limiting factor on new nuclear construction and will take time to change.

Nuclear power is generally not discussed by politicians with the exception of France, some Far Eastern countries, China, and Russia. The EU energy commissioner Loyola de Palacio said, on November 7, 2000: “From the environmental point of view nuclear energy cannot be rejected if you want to maintain our Kyoto commitments.” She went on to imply she wanted nuclear power to be part of the Kyoto Protocol’s Clean Development Mechanism.

The Short-Term Future

Attention is beginning to move towards building new nuclear power stations. Looking ahead to a doubling of energy demand by 2050, and with the world now trying to reduce its use of fossil fuels in order to contain carbon dioxide emissions, it is difficult to see how this can be achieved without a substantial increase in nuclear power. Nevertheless, the public perception of the industry in many countries is that it is more dangerous than other forms of energy and the problems of storing nuclear waste have not been fully solved (though there is considerable evidence to counter this argument).

A new generation of advanced reactors is being developed, which are more fuel efficient and inherently safer, with passive safety systems. The new designs are based on accumulated experience derived from operating PWRs and BWRs. Advanced boiling water and pressurized water reactors are already operating and the smaller AP 600 Westinghouse design has been certificated (as already mentioned, global certification, as with new aircraft, will be essential to get new designs into production). The European pressurized water reactor is available for construction, a number of liquid and gas cooled fast reactor systems have been designed, and some prototypes constructed. These new designs will produce electricity more cheaply than coal-fired stations and than gas-generated electricity (if gas prices continued to increase), and probably also more cheaply than renewable electricity (and with better availability).

Interest in high-temperature gas-cooled reactors (HTGRs) using helium at 950º C has been revived, particularly in Japan and China, and a Pebble Bed Modular Reactor (PBMR) with direct cycle gas turbine generator is being developed in South Africa.

The use of nuclear reactors to generate process heat is an important development, particularly if the heat is used for desalination. An integrated nuclear reactor producing electricity and clean water could produce water at between 0.7 dollars and 1.1 dollars per cubic metre. There is considerable interest in this technology from North Africa, the Arabian Peninsula states, Turkey, and northern China.

Further Ahead

The existing types of nuclear reactor are not particularly efficient in their use of uranium. An alternative is the fast breeder reactor (FBR), which uses uranium some 60 times more efficiently than today's PWRs and BWRs, although it is more expensive and is not yet a mature technology. Russian scientists have successfully operated the BS 600 fast reactor for 18 years with over 75 per cent availability. FBRs in other countries have been less successful and they eventually closed down because it was thought that the technology would not be required for 30 years and uranium and plutonium are readily available at the present time. In the long term, fast reactor technology could effectively increase world energy resources by a factor of ten and its time will no doubt come, unless nuclear fusion can be engineered into a power station. Research on fusion continues, with the time horizon constantly receding, but it is expected that the prize will be worth the effort.

UNIT-III

GENERAL ASPECTS OF DISTRIBUTION SYSTEMS AND D.C. DISTRIBUTION SYSTEMS:

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, *A B*, *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.

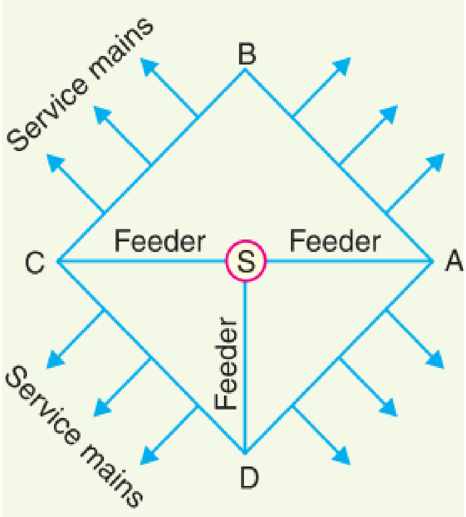


Fig. 12.1

(*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.

7.3 Comparison of D.C. and A.C. Transmission

The electric power can be transmitted either by means of d.c. or a.c. Each system has its own merits and demerits. It is, therefore, desirable to discuss the technical advantages and disadvantages of the two systems for transmission of electric power.

1. D.C. transmission. For some years past, the transmission of electric power by d.c. has been receiving the active consideration of engineers due to its numerous advantages.

Advantages. The high voltage d.c. transmission has the following advantages over high voltage a.c. transmission :

(*i*) It requires only two conductors as compared to three for a.c. transmission.

(*ii*) There is no inductance, capacitance, phase displacement and surge problems in d.c. transmission.

(*iii*) Due to the absence of inductance, the voltage drop in a d.c. transmission line is less than the a.c. line for the same load and sending end voltage. For this reason, a d.c. transmission line has better voltage regulation.

(*iv*) There is no skin effect in a d.c. system. Therefore, entire cross-section of the line conductor is utilised.

(*v*) For the same working voltage, the potential stress on the insulation is less in case of d.c. system than that in a.c. system. Therefore, a d.c. line requires less insulation.

(*vi*) A d.c. line has less corona loss and reduced interference with communication circuits.

(*vii*) The high voltage d.c. transmission is free from the dielectric losses, particularly in the case of cables.

(*viii*) In d.c. transmission, there are no stability problems and synchronising difficulties.

Disadvantages

(*i*) Electric power cannot be generated at high d.c. voltage due to commutation problems.

(*ii*) The d.c. voltage cannot be stepped up for transmission of power at high voltages.

(*iii*) The d.c. switches and circuit breakers have their own limitations.

2. A.C. transmission. Now-a-days, electrical energy is almost exclusively generated, transmitted and distributed in the form of a.c.

Advantages

(*i*) The power can be generated at high voltages.

(*ii*) The maintenance of a.c. sub-stations is easy and cheaper.

(*iii*) The a.c. voltage can be stepped up or stepped down by transformers with ease and efficiency. This permits to transmit power at high voltages and distribute it at safe potentials.

Disadvantages

(*i*) An a.c. line requires more copper than a d.c. line.

(*ii*) The construction of a.c. transmission line is more complicated than a d.c. transmission line.

(*iii*) Due to skin effect in the a.c. system, the effective resistance of the line is increased.

(*iv*) An a.c. line has capacitance. Therefore, there is a continuous loss of power due to charging current even when the line is open.

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.

12.4 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.

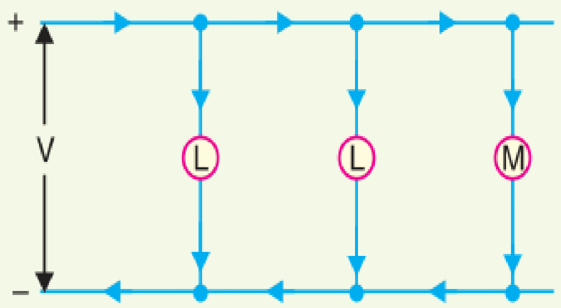


Fig. 12.4

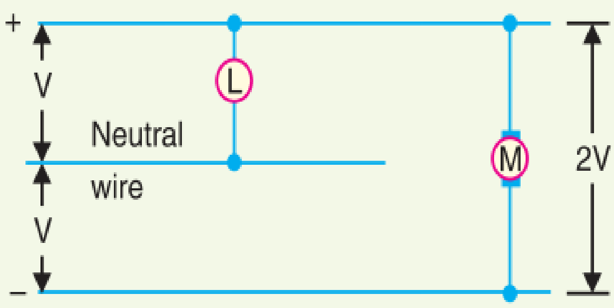


Fig. 12.5

(*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.

12.5 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 are 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.

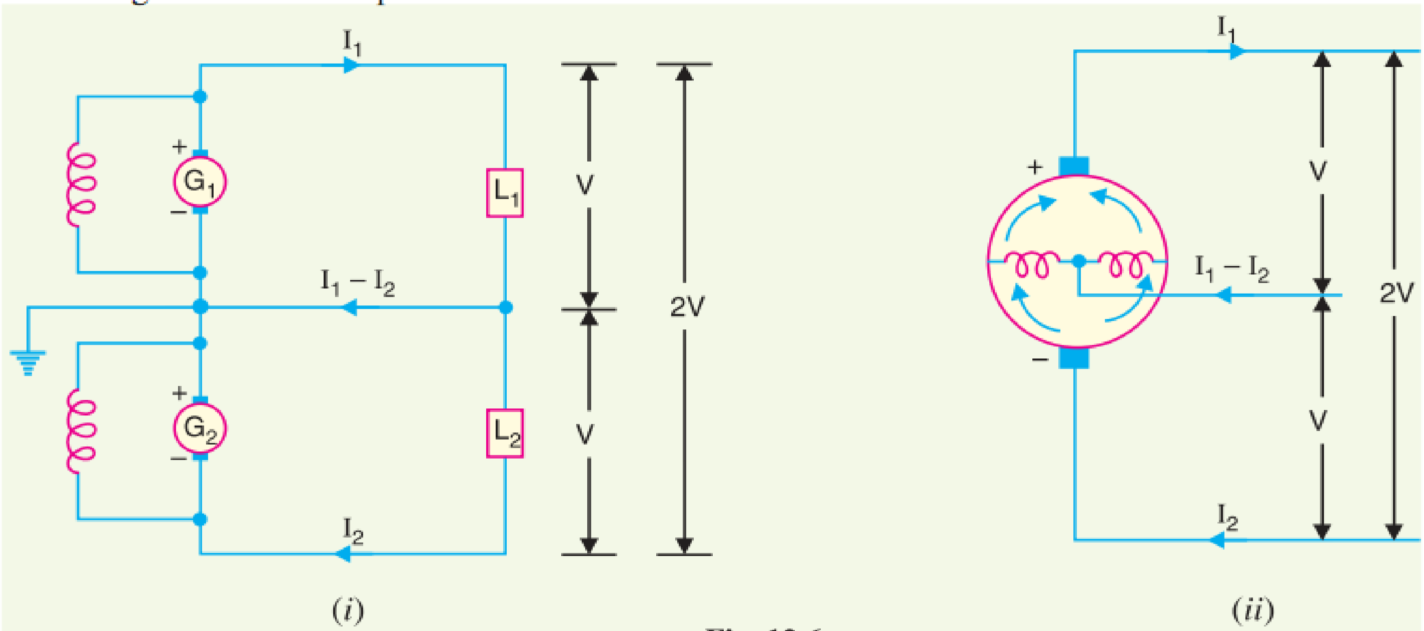


Fig. 12.6

(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.

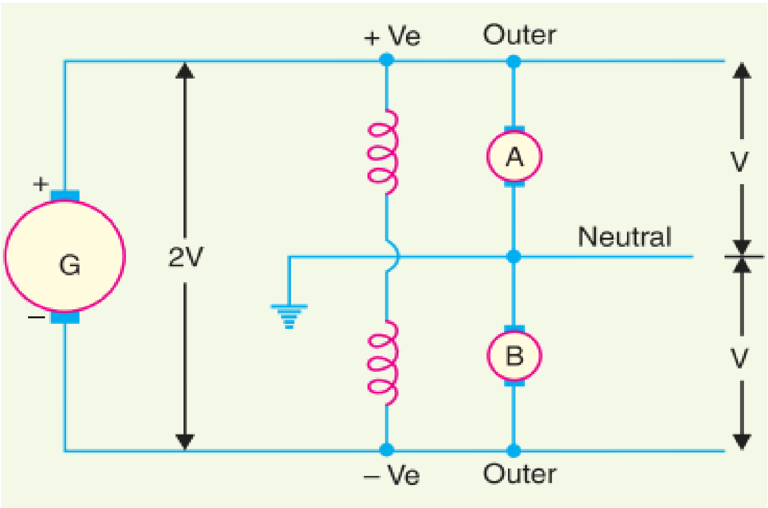


Fig. 12.7

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.

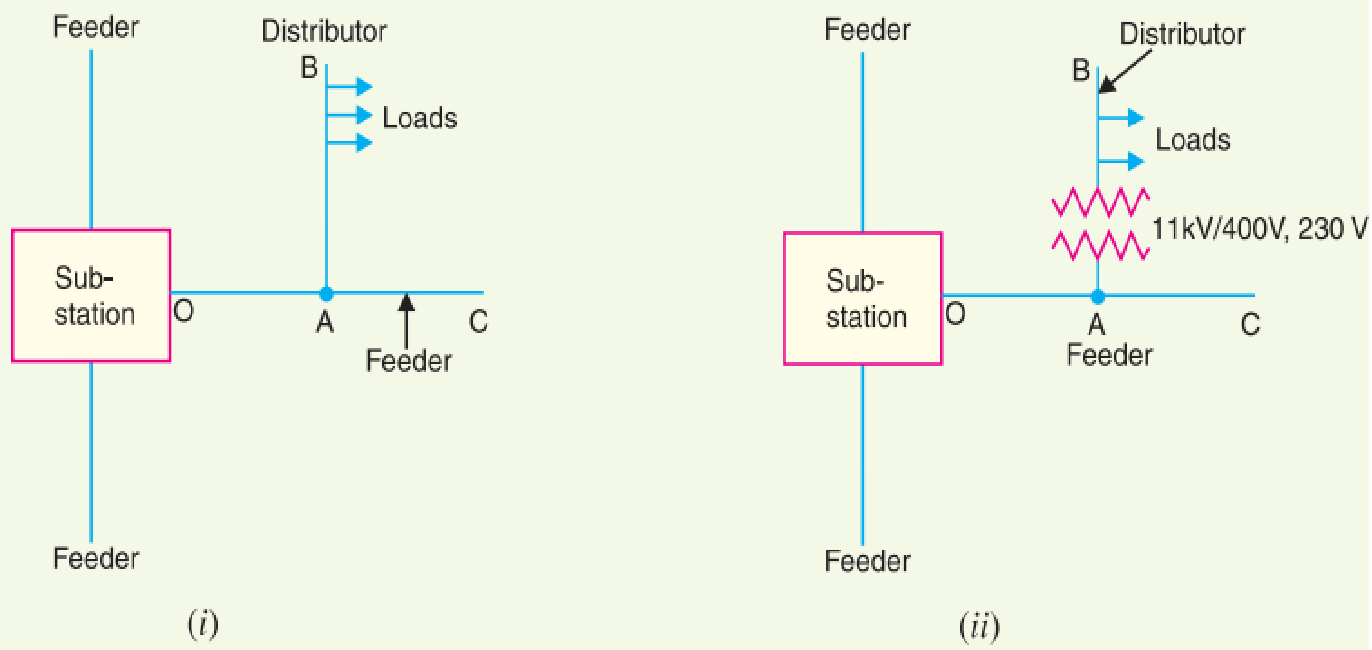


Fig. 12.8

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*.

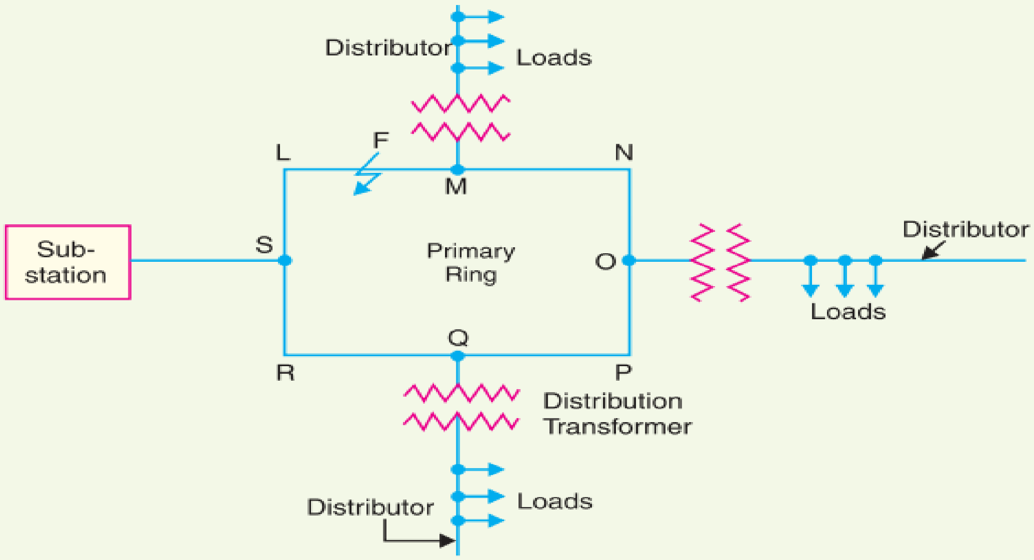


Fig. 12.9

(*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_1 and S_2 at points *D* and *C* respectively. Distributors are connected to

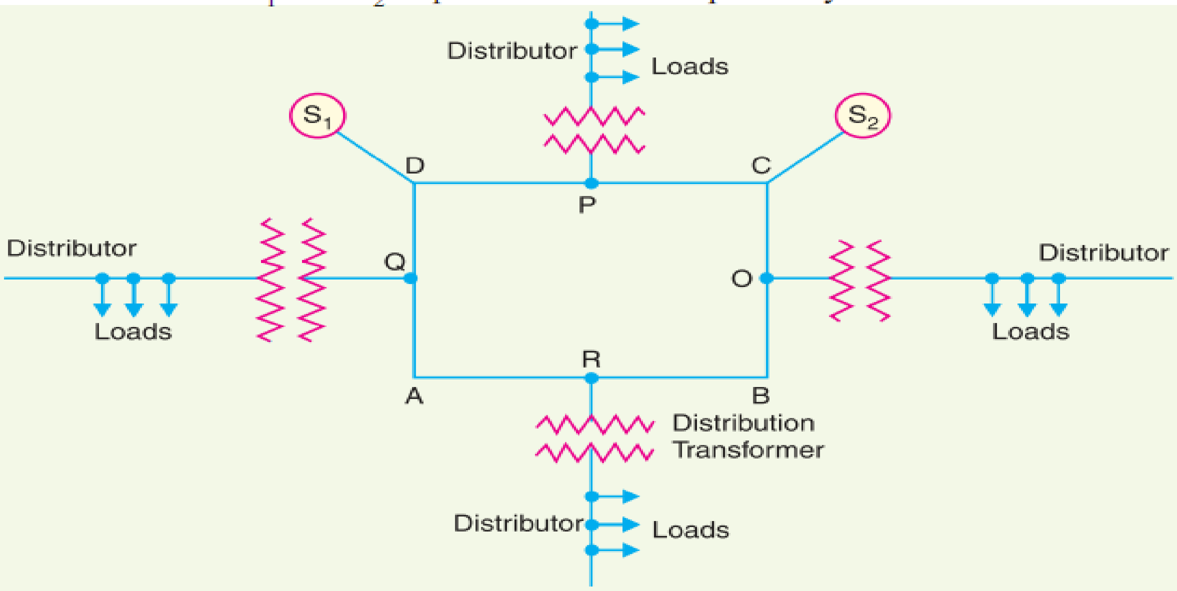


Fig. 12.10

* Thus the distributor from point *M* is supplied by the feeders SLM and SRQPONM.

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.

13.1 Types of D.C. Distributors

The most general method of classifying d.c. distributors is the way they are fed by the feeders. On this basis, d.c. distributors are classified as:

(i) Distributor fed at one end

(ii) Distributor fed at both ends

(iii) Distributor fed at the centre

(iv) Ring distributor.

(i) **Distributor fed at one end.** In this type of feeding, the distributor is connected to the supply at one end and loads are taken at different points along the length of the distributor. Fig. 13.1 shows the single line diagram of a d.c. distributor AB fed at the end A (also known as *singly fed distributor*) and loads I_1, I_2 and I_3 tapped off at points C, D and E respectively.

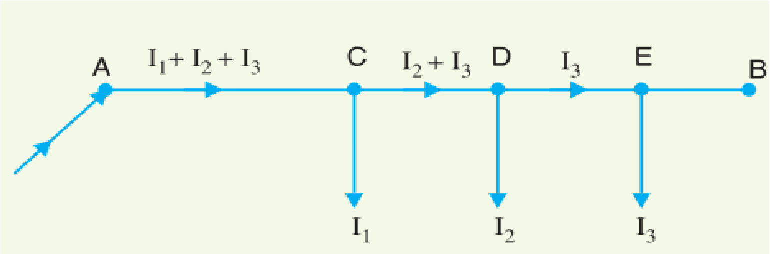


Fig. 13.1

The following points are worth noting in a singly fed distributor :

(a) The current in the various sections of the distributor away from feeding point goes on decreasing. Thus current in section AC is more than the current in section CD and current in section CD is more than the current in section DE.

(b) The voltage across the loads away from the feeding point goes on decreasing. Thus in Fig. 13.1, the minimum voltage occurs at the load point E.

(c) In case a fault occurs on any section of the distributor, the whole distributor will have to be disconnected from the supply mains. Therefore, continuity of supply is interrupted.

(ii) **Distributor fed at both ends.** In this type of feeding, the distributor is connected to the supply mains at both ends and loads are tapped off at different points along the length of the distributor. The voltage at the feeding points may or may not be equal. Fig. 13.2 shows a distributor AB fed at the ends A and B and loads of I_1, I_2 and I_3 tapped off at points C, D and E respectively. Here, the load voltage goes on decreasing as we move away from one feeding point *say A*, reaches minimum value and then again starts rising and reaches maximum value when we reach the other feeding point B. The minimum voltage occurs at some load point and is never fixed. It is shifted with the variation of load on different sections of the distributor.

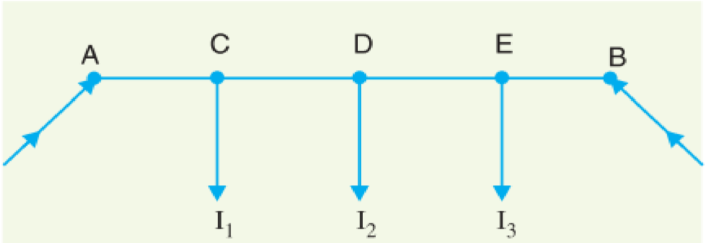


Fig. 13.2

Advantages

(a) If a fault occurs on any feeding point of the distributor, the continuity of supply is maintained from the other feeding point.

(b) In case of fault on any section of the distributor, the continuity of supply is maintained from the other feeding point.

(c) The area of X-section required for a doubly fed distributor is much less than that of a singly fed distributor.

(*iii*) **Distributor fed at the centre.** In this type of feeding, the centre of the distributor is connected to the supply mains as shown in Fig. 13.3. It is equivalent to two singly fed distributors, each distributor having a common feeding point and length equal to half of the total length.

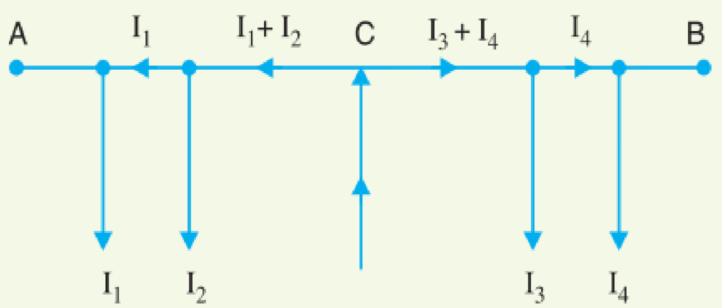


Fig. 13.3

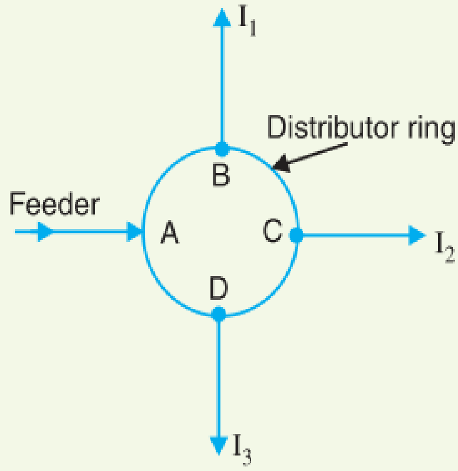


Fig. 13.4

(*iv*) **Ring mains.** In this type, the distributor is in the form of a closed ring as shown in Fig.13.4. It is equivalent to a straight distributor fed at both ends with equal voltages, the two ends being brought together to form a closed ring. The distributor ring may be fed at one or more than one point.

In d.c. distribution calculations, one important point of interest is the determination of point of minimum potential on the distributor. The point where it occurs depends upon the loading conditions and the method of feeding the distributor. The distributor is so designed that the minimum potential on it is not less than 6% of rated voltage at the consumer's terminals. In the next sections, we shall discuss some important cases of d.c. distributors separately.

13.3 D.C. Distributor Fed at one End—Concentrated Loading

Fig. 13.5 shows the single line diagram of a 2-wire d.c. distributor AB fed at one end A and having concentrated loads I_1, I_2, I_3 and I_4 tapped off at points C, D, E and F respectively.

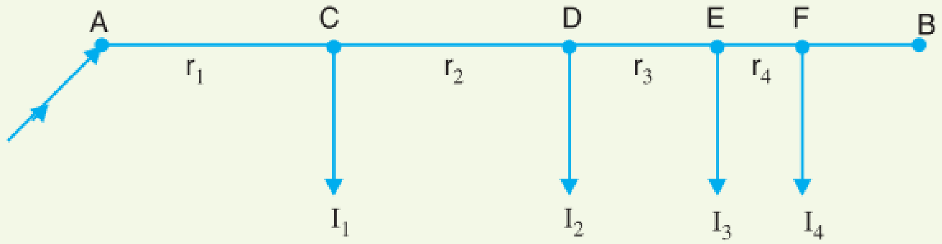


Fig. 13.5

Let r_1, r_2, r_3 and r_4 be the resistances of both wires (go and return) of the sections AC, CD, DE and EF of the distributor respectively.

Current fed from point A $= I_1 + I_2 + I_3 + I_4$

Current in section AC $= I_1 + I_2 + I_3 + I_4$

Current in section CD $= I_2 + I_3 + I_4$

Current in section DE $= I_3 + I_4$

Current in section EF $= I_4$

Voltage drop in section AC $= r_1 (I_1 + I_2 + I_3 + I_4)$

Voltage drop in section CD $= r_2 (I_2 + I_3 + I_4)$

Voltage drop in section DE $= r_3 (I_3 + I_4)$

Voltage drop in section EF $= r_4 I_4$

∴ Total voltage drop in the distributor

$$= r_1 (I_1 + I_2 + I_3 + I_4) + r_2 (I_2 + I_3 + I_4) + r_3 (I_3 + I_4) + r_4 I_4$$

It is easy to see that the minimum potential will occur at point F which is farthest from the feeding point A.

Example 13.1. *A 2-wire d.c. distributor cable AB is 2 km long and supplies loads of 100A, 150A,200A and 50A situated 500 m, 1000 m, 1600 m and 2000 m from the feeding point A. Each conductor has a resistance of 0·01 Ω per 1000 m. Calculate the p.d. at each load point if a p.d. of 300 V is maintained at point A.*

Solution. Fig. 13.6 shows the single line diagram of the distributor with its tapped currents.

Resistance per 1000 m of distributor $= 2 \times 0{\cdot}01 = 0{\cdot}02\,\Omega$

Resistance of section AC, R_{AC} $= 0{\cdot}02 \times 500/1000 = 0{\cdot}01\,\Omega$

Resistance of section CD, R_{CD} $= 0{\cdot}02 \times 500/1000 = 0{\cdot}01\,\Omega$

Resistance of section DE, R_{DE} $= 0{\cdot}02 \times 600/1000 = 0{\cdot}012\,\Omega$

Resistance of section EB, R_{EB} $= 0{\cdot}02 \times 400/1000 = 0{\cdot}008\,\Omega$

Referring to Fig. 13.6, the currents in the various sections of the distributor are :

$I_{EB} = 50$ A ; $I_{DE} = 50 + 200 = 250$ A

$I_{CD} = 250 + 150 = 400$ A ; $I_{AC} = 400 + 100 = 500$ A

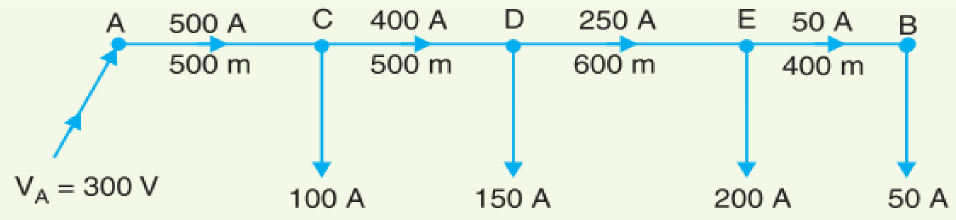


Fig. 13.6

P.D. at load point C, V_C = Voltage at A − Voltage drop in AC

$$= V_A - I_{AC} R_{AC}$$

$$= 300 - 500 \times 0{\cdot}01 = \mathbf{295\ V}$$

P.D. at load point D, $V_D = V_C - I_{CD} R_{CD}$

$$= 295 - 400 \times 0{\cdot}01 = \mathbf{291\ V}$$

P.D. at load point E, $V_E = V_D - I_{DE} R_{DE}$

$$= 291 - 250 \times 0{\cdot}012 = \mathbf{288\ V}$$

P.D. at load point B, $V_B = V_E - I_{EB} R_{EB}$

$$= 288 - 50 \times 0{\cdot}008 = \mathbf{287{\cdot}6\ V}$$

Example 13.2. *A 2-wire d.c. distributor AB is 300 metres long. It is fed at point A. The various loads and their positions are given below :*

At point	*distance from A in metres*	*concentrated load in amperes*
C	*40*	*30*
D	*100*	*40*
E	*150*	*100*
F	*250*	*50*

If the maximum permissible voltage drop is not to exceed 10 V, find the cross-sectional area of the distributor. Take $\rho = 1{\cdot}78 \times 10^{-8}\ \Omega m$.

Solution. The single line diagram of the distributor along with its tapped currents is shown in Fig. 13.7. Suppose that resistance of 100 m length of the distributor is r ohms. Then resistance of various sections of the distributor is :

$$R_{AC} = 0{\cdot}4\,r\,\Omega \quad ; \quad R_{CD} = 0{\cdot}6\,r\,\Omega \quad ; \quad R_{DE} = 0{\cdot}5\,r\,\Omega \quad ; \quad R_{EF} = r\,\Omega$$

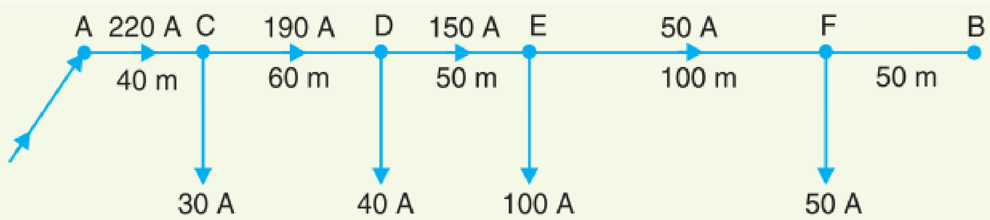


Fig. 13.7

Referring to Fig. 13.7, the currents in the various sections of the distributor are :

$I_{AC} = 220$ A ; $I_{CD} = 190$ A ; $I_{DE} = 150$ A ; $I_{EF} = 50$ A

Total voltage drop over the distributor

$$= I_{AC} R_{AC} + I_{CD} R_{CD} + I_{DE} R_{DE} + I_{EF} R_{EF}$$

$$= 220 \times 0{\cdot}4r + 190 \times 0{\cdot}6r + 150 \times 0{\cdot}5r + 50 \times r$$

$$= 327\ r$$

As the maximum permissible drop in the distributor is 10 V,

$$\therefore \quad 10 = 327\ r$$

or $$r = 10/327 = 0{\cdot}03058\ \Omega$$

$$\text{X-sectional area of conductor} = \frac{{}^*\rho\, l}{r/2} = \frac{1{\cdot}78 \times 10^{-8} \times 100}{\dfrac{0{\cdot}03058}{2}} = 116{\cdot}4 \times 10^{-6}\ \text{m}^2 = \mathbf{1{\cdot}164\ cm^2}$$

Example 13.3. *Two tram cars (A & B) 2 km and 6 km away from a sub-station return 40 A and 20 A respectively to the rails. The sub-station voltage is 600 V d.c. The resistance of trolley wire is 0·25 Ω/km and that of track is 0·03 Ω/km. Calculate the voltage across each tram car.*

Solution. The tram car operates on d.c. supply. The positive wire is placed overhead while the rail track acts as the negative wire. Fig. 13.8 shows the single line diagram of the arrangement.

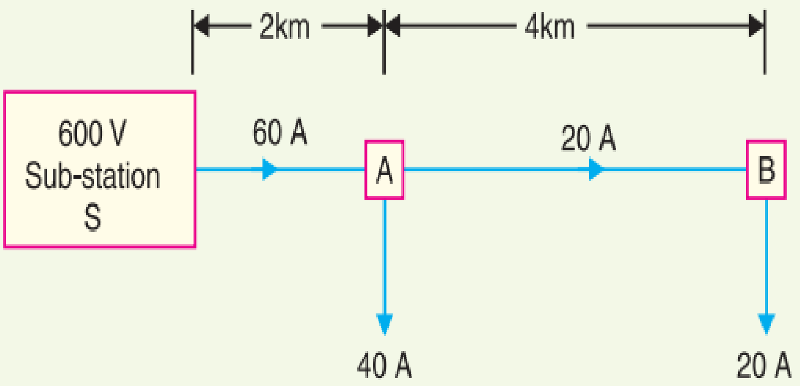


Fig. 13.8

Resistance of trolley wire and track/km

$$= 0{\cdot}25 + 0{\cdot}03 = 0{\cdot}28\Omega$$

Current in section $SA = 40 + 20 = 60$ A

Current in section $AB = 20$ A

Voltage drop in section $SA = 60 \times 0{\cdot}28 \times 2 = 33{\cdot}6$ V

Voltage drop in section $AB = 20 \times 0{\cdot}28 \times 4 = 22{\cdot}4$ V

$\therefore$ Voltage across tram $A = 600 - 33{\cdot}6 =$ **566·4 V**

Voltage across tram $B = 566{\cdot}4 - 22{\cdot}4 =$ **544 V**

Example 13.4. *The load distribution on a two-wire d.c. distributor is shown in Fig. 13.9. The cross-sectional area of each conductor is 0·27 cm^2. The end A is supplied at 250 V. Resistivity of the wire is ρ = 1·78 μ Ω cm. Calculate (i) the current in each section of the conductor (ii) the two-core resistance of each section (iii) the voltage at each tapping point.*

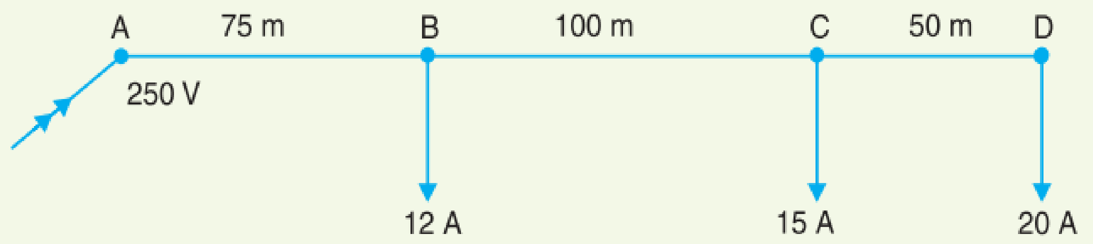


Fig. 13.9

Solution.

(*i*) Currents in the various sections are :

$$\text{Section } CD, I_{CD} = \mathbf{20\ A}\ ;\ \text{section } BC, I_{BC} = 20 + 15 = \mathbf{35\ A}$$

$$\text{Section } AB, I_{AB} = 20 + 15 + 12 = \mathbf{47\ A}$$

(*ii*) Single-core resistance of the section of 100 m length

$$= \rho \frac{l}{a} = 1{\cdot}78 \times 10^{-6} \times \frac{100 \times 100}{0{\cdot}27} = 0{\cdot}066\,\Omega$$

* Note that resistance of each conductor of l = 100 m is $r/2$.

The resistances of the various sections are :

$$R_{AB} = 0{\cdot}066 \times 0{\cdot}75 \times 2 = \mathbf{0{\cdot}099\,\Omega}\ ;\ R_{BC} = 0{\cdot}066 \times 2 = \mathbf{0{\cdot}132\,\Omega}$$

$$R_{CD} = 0{\cdot}066 \times 0{\cdot}5 \times 2 = \mathbf{0{\cdot}066\,\Omega}$$

(*iii*) Voltage at tapping point *B* is

$$V_B = V_A - I_{AB}\,R_{AB} = 250 - 47 \times 0{\cdot}099 = \mathbf{245{\cdot}35\ V}$$

Voltage at tapping point *C* is

$$V_C = V_B - I_{BC}\,R_{BC} = 245{\cdot}35 - 35 \times 0{\cdot}132 = \mathbf{240{\cdot}73\ V}$$

Voltage at tapping point *D* is

$$V_D = V_C - I_{CD}\,R_{CD} = 240{\cdot}73 - 20 \times 0{\cdot}066 = \mathbf{239{\cdot}41\ V}$$

13.4 Uniformly Loaded Distributor Fed at One End

Fig 13.11 shows the single line diagram of a 2-wire d.c. distributor *A B* fed at one end *A* and loaded uniformly with *i* amperes per metre length. It means that at every 1 m length of the distributor, the load tapped is *i* amperes. Let *l* metres be the length of the distributor and *r* ohm be the resistance per metre run.

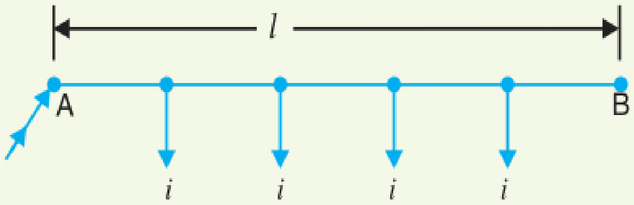


Fig. 13.11

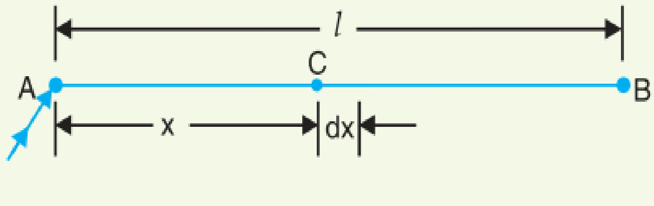


Fig. 13.12

Consider a point *C* on the distributor at a distance *x* metres from the feeding point *A* as shown in Fig. 13.12. Then current at point *C* is

$$= i\,l - i\,x \text{ amperes} = i\,(l - x) \text{ amperes}$$

Now, consider a small length *dx* near point *C*. Its resistance is *r dx* and the voltage drop over length *dx* is

$$dv = i\,(l - x)\,r\,dx = i\,r\,(l - x)\,dx$$

Total voltage drop in the distributor upto point *C* is

$$v = \int_0^x i\,r\,(l - x)\,dx = i\,r\left(l\,x - \frac{x^2}{2}\right)$$

The voltage drop upto point *B* (*i.e.* over the whole distributor) can be obtained by putting $x = l$ in the above expression.

∴ Voltage drop over the distributor *AB*

$$= i\,r\left(l \times l - \frac{l^2}{2}\right)$$

$$= \tfrac{1}{2}\,i\,r\,l^2 = \tfrac{1}{2}\,(i\,l)\,(r\,l)$$

$$= \tfrac{1}{2}\,I\,R$$

where $i\,l = I$, the total current entering at point *A*

$r\,l = R$, the total resistance of the distributor

Thus, in a uniformly loaded distributor fed at one end, the total voltage drop is equal to that produced by the whole of the load assumed to be concentrated at the middle point.

Example 13.5. *A 2-wire d.c. distributor 200 metres long is uniformly loaded with 2A/metre. Resistance of single wire is 0·3 Ω/km. If the distributor is fed at one end, calculate :*

(*i*) *the voltage drop upto a distance of 150 m from the feeding point*

(*ii*) *the maximum voltage drop*

Solution.

Current loading, $i = 2$ A/m

Resistance of distributor per metre run,

$$r = 2 \times 0{\cdot}3/1000 = 0{\cdot}0006\,\Omega$$

Length of distributor, $l = 200$ m

(*i*) Voltage drop upto a distance x metres from feeding point

$$= i\,r\left(l\,x - \frac{x^2}{2}\right)$$ [See Art. 13·4]

Here, $x = 150$ m

∴ Desired voltage drop $= 2 \times 0{\cdot}0006\left(200 \times 150 - \dfrac{150 \times 150}{2}\right) =$ **22·5 V**

(*ii*) Total current entering the distributor,

$$I = i \times l = 2 \times 200 = 400 \text{ A}$$

Total resistance of the distributor,

$$R = r \times l = 0{\cdot}0006 \times 200 = 0{\cdot}12\,\Omega$$

∴ Total drop over the distributor

$$= \frac{1}{2}\,I\,R = \frac{1}{2} \times 400 \times 0{\cdot}12 = \mathbf{24\ V}$$

Example 13.6. *A uniform 2-wire d.c. distributor 500 metres long is loaded with 0.4 ampere/metre and is fed at one end. If the maximum permissible voltage drop is not to exceed 10 V, find the cross-sectional area of the distributor conductor. Take* $\rho = 1{\cdot}7 \times 10^{-6}$ *Ω cm.*

Solution.

Current entering the distributor, $I = i \times l = 0{\cdot}4 \times 500 = 200$ A

Max. permissible voltage drop $= 10$ V

Let r ohm be the resistance per metre length of the distributor (both wires).

Max. voltage drop $= \frac{1}{2}\,I\,R$

or $10 = \frac{1}{2}\,I\,r\,l$ [∵ $R = r\,l$]

or $$r = \frac{2 \times 10}{I \times l} = \frac{2 \times 10}{200 \times 500} = 0{\cdot}2 \times 10^{-3}\,\Omega$$

∴ Area of cross-section of the distributor conductor is

$$a = \frac{\rho\,l}{r/2} = \frac{1{\cdot}7 \times 10^{-6} \times 100^{*} \times 2}{0{\cdot}2 \times 10^{-3}} = \mathbf{1{\cdot}7\ cm^2}$$

Example 13.7. *A 250 m, 2-wire d.c. distributor fed from one end is loaded uniformly at the rate of 1·6 A/metre. The resistance of each conductor is 0·0002 Ω per metre. Find the voltage necessary at feed point to maintain 250 V (i) at the far end (ii) at the mid-point of the distributor.*

Solution.

Current loading, $i = 1 \cdot 6 \text{ A/m}$

Current entering the distributor, $I = i \times l = 1 \cdot 6 \times 250 = 400 \text{ A}$

Resistance of the distributor per metre run

$$r = 2 \times 0 \cdot 0002 = 0 \cdot 0004 \, \Omega$$

Total resistance of distributor, $R = r \times l = 0 \cdot 0004 \times 250 = 0 \cdot 1 \, \Omega$

(*i*) Voltage drop over the entire distributor

$$= \frac{1}{2} I R = \frac{1}{2} \times 400 \times 0 \cdot 1 = 20 \text{ V}$$

∴ Voltage at feeding point = 250 + 20 = **270 V**

(*ii*) Voltage drop upto a distance of *x* metres from feeding point

$$= i\, r \left(l\, x - \frac{x^2}{2} \right)$$

Here $x = l/2 = 250/2 = 125$ m

∴ Voltage drop $= 1 \cdot 6 \times 0 \cdot 0004 \left(250 \times 125 - \frac{(125)^2}{2} \right) = 15 \text{ V}$

∴ Voltage at feeding point = 250 + 15 = **265 V**

Example 13.8. *Derive an expression for the power loss in a uniformly loaded distributor fed at one end.*

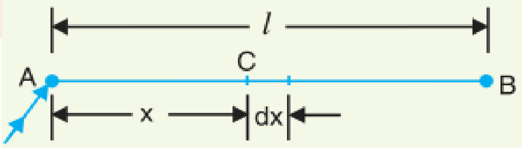


Fig. 13.13

Solution. Fig. 13.13 shows the single line diagram of a 2-wire d.c. distributor *AB* fed at end *A* and loaded uniformly with *i* amperes per metre length.

Let l = length of the distributor in metres

r = resistance of distributor (both conductors) per metre run

Consider a small length *dx* of the distributor at point *C* at a distance *x* from the feeding end *A*. The small length *dx* will carry current which is tapped in the length *CB*.

∴ Current in $dx = i\, l - i\, x = i\,(l - x)$

* Because we have assumed that *r* ohm is the resistance of 1m (= 100 cm) length of the distributor.

Power loss in length dx = (current in length $dx)^2$ × Resistance of length dx

$$= [i\,(l - x)]^2 \times r\, dx$$

Total power loss *P* in the whole distributor is

$$P = \int_0^l [i\,(l - x)]^2 \, r\, dx = \int_0^l i^2 \left(l^2 + x^2 - 2\, lx \right) r\, dx$$

$$= i^2 r \int_0^l \left(l^2 + x^2 - 2\, lx \right) dx = i^2 r \left[l^2 x + \frac{x^3}{3} - \frac{2lx^2}{2} \right]_0^l$$

$$= i^2 r \left[l^3 + \frac{l^3}{3} - l^3 \right] = i^2 \times \frac{r\, l^3}{3}$$

$$\therefore \quad P = \frac{i^2\, r\, l^3}{3}$$

Example 13.9. *Calculate the voltage at a distance of 200 m of a 300 m long distributor uniformly loaded at the rate of 0.75 A per metre. The distributor is fed at one end at 250 V. The resistance of the distributor (go and return) per metre is 0·00018 Ω. Also find the power loss in the distributor.*

Solution.

Voltage drop at a distance x from supply end

$$= i\,r\left(l\,x - \frac{x^2}{2}\right)$$

Here $i = 0{\cdot}75$ A/m; $l = 300$ m ; $x = 200$ m ; $r = 0{\cdot}00018\ \Omega$/m

$$\therefore \quad \text{Voltage drop} = 0{\cdot}75 \times 0{\cdot}00018\left[300 \times 200 - \frac{(200)^2}{2}\right] = 5.4 \text{ V}$$

Voltage at a distance of 200 m from supply end

$$= 250 - 5{\cdot}4 = \mathbf{244{\cdot}6\ V}$$

Power loss in the distributor is

$$P = \frac{i^2\,r\,l^3}{3} = \frac{(0{\cdot}75)^2 \times 0{\cdot}00018 \times (300)^3}{3} = \mathbf{911{\cdot}25\ W}$$

13.5 Distributor Fed at Both Ends — Concentrated Loading

Whenever possible, it is desirable that a long distributor should be fed at both ends instead of at one end only, since total voltage drop can be considerably reduced without increasing the cross-section of the conductor. The two ends of the distributor may be supplied with (*i*) equal voltages (*ii*) unequal voltages.

(*i*) Two ends fed with equal voltages. Consider a distributor *A B* fed at both ends with equal voltages *V* volts and having concentrated loads I_1, I_2, I_3, I_4 and I_5 at points *C*, *D*, *E*, *F* and *G* respectively as shown in Fig. 13.14. As we move away from one of the feeding points, *say A*, p.d. goes on decreasing till it reaches the minimum value at some load point, *say E*, and then again starts rising and becomes *V* volts as we reach the other feeding point *B*.

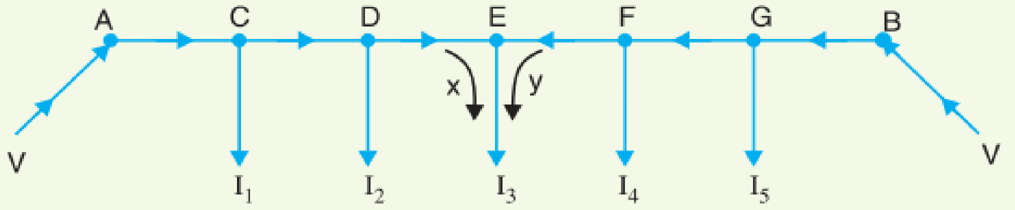


Fig. 13.14

All the currents tapped off between points *A* and *E* (minimum p.d. point) will be supplied from the feeding point *A* while those tapped off between *B* and *E* will be supplied from the feeding point *B*. The current tapped off at point *E* itself will be partly supplied from *A* and partly from *B*. If these currents are *x* and *y* respectively, then,

$$I_3 = x + y$$

Therefore, we arrive at a very important conclusion that at the point of minimum potential, current comes from both ends of the distributor.

Point of minimum potential. It is generally desired to locate the point of minimum potential. There is a simple method for it. Consider a distributor *A B* having three concentrated loads I_1, I_2 and I_3 at points *C*, *D* and *E* respectively. Suppose that current supplied by feeding end *A* is I_A. Then current distribution in the various sections of the distributor can be worked out as shown in Fig. 13.15 (*i*). Thus

$$I_{AC} = I_A \, ; \qquad I_{CD} = I_A - I_1$$

$$I_{DE} = I_A - I_1 - I_2 \, ; \qquad I_{EB} = I_A - I_1 - I_2 - I_3$$

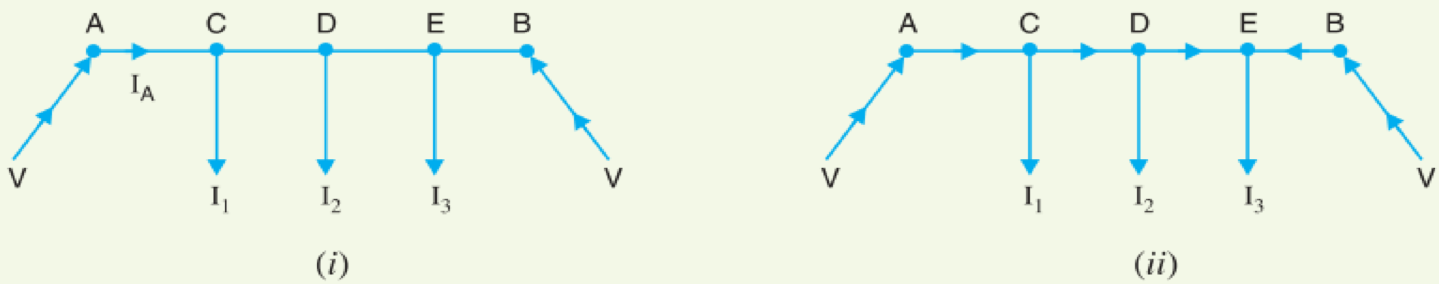


Fig. 13.15

Voltage drop between *A* and *B* = Voltage drop over *A B*

or $$V - V = I_A R_{AC} + (I_A - I_1) R_{CD} + (I_A - I_1 - I_2) R_{DE} + (I_A - I_1 - I_2 - I_3) R_{EB}$$

From this equation, the unknown I_A can be calculated as the values of other quantities are generally given. Suppose *actual* directions of currents in the various sections of the distributor are indicated as shown in Fig. 13.15 (*ii*). The load point where the currents are coming from both sides of the distributor is the point of minimum potential *i.e.* point *E* in this case (*ii*) **Two ends fed with unequal voltages.** Fig. 13.16 shows the distributor AB fed with unequal voltages ; end A being fed at V_1 volts and end B at V_2 volts. The point of minimum potential can be found by following the same procedure as discussed above. Thus in this case,

Voltage drop between A and B = Voltage drop over AB

or $V_1 - V_2$ = Voltage drop over AB

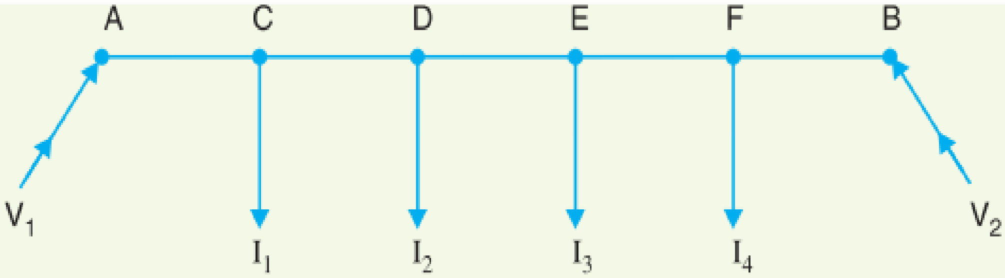


Fig. 13.16

Example 13.10. *A 2-wire d.c. street mains AB, 600 m long is fed from both ends at 220 V. Loads of 20 A, 40 A, 50 A and 30 A are tapped at distances of 100m, 250m, 400m and 500 m from the end A respectively. If the area of X-section of distributor conductor is 1cm², find the minimum consumer voltage. Take* $\rho = 1{\cdot}7 \times 10^{-6}\ \Omega$ *cm.*

Solution. Fig. 13.17 shows the distributor with its tapped currents. Let I_A amperes be the current supplied from the feeding end A. Then currents in the various sections of the distributor are as shown in Fig. 13.17.

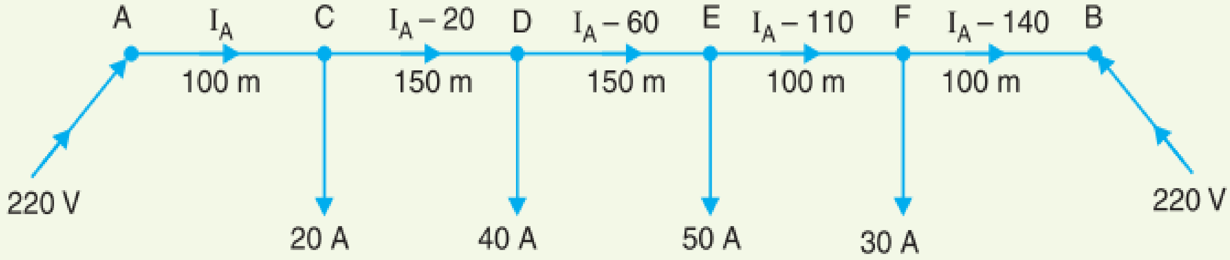


Fig. 13.17

Resistance of 1 m length of distributor

$$= 2 \times \frac{1{\cdot}7 \times 10^{-6} \times 100}{1} = 3{\cdot}4 \times 10^{-4}\ \Omega$$

Resistance of section AC, R_{AC} = $(3{\cdot}4 \times 10^{-4}) \times 100 = 0{\cdot}034\ \Omega$

Resistance of section CD, R_{CD} = $(3{\cdot}4 \times 10^{-4}) \times 150 = 0{\cdot}051\ \Omega$

Resistance of section DE, R_{DE} = $(3{\cdot}4 \times 10^{-4}) \times 150 = 0{\cdot}051\ \Omega$

Resistance of section EF, R_{EF} = $(3{\cdot}4 \times 10^{-4}) \times 100 = 0{\cdot}034\ \Omega$

Resistance of section FB, R_{FB} = $(3{\cdot}4 \times 10^{-4}) \times 100 = 0{\cdot}034\ \Omega$

$$\text{Voltage at } B = \text{Voltage at } A - \text{Drop over length } AB$$

or $$V_B = V_A - [I_A R_{AC} + (I_A - 20) R_{CD} + (I_A - 60) R_{DE} + (I_A - 110) R_{EF} + (I_A - 140) R_{FB}]$$

or $$220 = 220 - [0\cdot034 I_A + 0\cdot051 (I_A - 20) + 0\cdot051 (I_A - 60) + 0\cdot034 (I_A - 110) + 0\cdot034 (I_A - 140)]$$

$$= 220 - [0\cdot204 I_A - 12\cdot58]$$

or $$0\cdot204 I_A = 12\cdot58$$

$\therefore$ $$I_A = 12\cdot58/0\cdot204 = 61\cdot7 \text{ A}$$

The *actual distribution of currents in the various sections of the distributor is shown in Fig. 13.18. It is clear that currents are coming to load point *E* from both sides *i.e.* from point *D* and point *F*. Hence, *E* is the point of minimum potential.

$\therefore$ Minimum consumer voltage,

$$V_E = V_A - [I_{AC} R_{AC} + I_{CD} R_{CD} + I_{DE} R_{DE}]$$

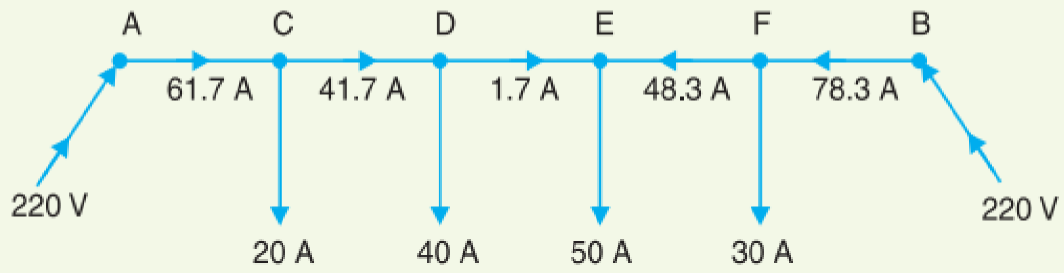


Fig. 13.18

$$= 220 - [61\cdot7 \times 0\cdot034 + 41\cdot7 \times 0\cdot051 + 1\cdot7 \times 0\cdot051]$$

$$= 220 - 4\cdot31 = \mathbf{215\cdot69 \text{ V}}$$

---

* Knowing the value of I_A, current in any section can be determined. Thus,

Current in section CD, $I_{CD} = I_A - 20 = 61\cdot7 - 20 = 41\cdot7 \text{ A}$ from *C* to *D*

Current in section EF, $I_{EF} = I_A - 110 = 61\cdot7 - 110 = -48\cdot3 \text{ A}$ from *E* to *F*

$= 48\cdot3 \text{ A}$ from *F* to *E*

Example 13.11. *A 2-wire d.c. distributor AB is fed from both ends. At feeding point A, the voltage is maintained as at 230 V and at B 235 V. The total length of the distributor is 200 metres and loads are tapped off as under :*

25 A at 50 metres from A ; 50 A at 75 metres from A

30 A at 100 metres from A ; 40 A at 150 metres from A

The resistance per kilometre of one conductor is 0·3 Ω. Calculate :

(*i*) *currents in various sections of the distributor*

(*ii*) *minimum voltage and the point at which it occurs*

Solution. Fig. 13.19 shows the distributor with its tapped currents. Let I_A amperes be the current supplied from the feeding point *A*. Then currents in the various sections of the distributor are as shown in Fig 13.19.

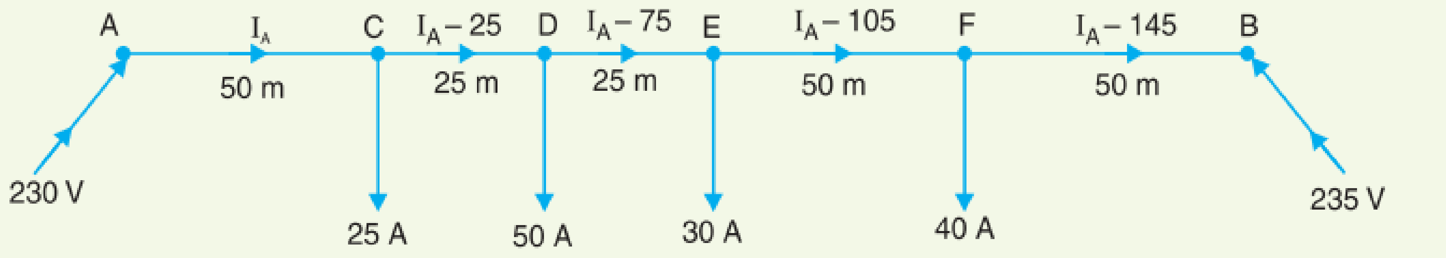


Fig. 13.19

Resistance of 1000 m length of distributor (both wires)

$$= 2 \times 0{\cdot}3 = 0{\cdot}6\,\Omega$$

Resistance of section AC, $R_{AC} = 0{\cdot}6 \times 50/1000 = 0{\cdot}03\,\Omega$

Resistance of section CD, $R_{CD} = 0{\cdot}6 \times 25/1000 = 0{\cdot}015\,\Omega$

Resistance of section DE, $R_{DE} = 0{\cdot}6 \times 25/1000 = 0{\cdot}015\,\Omega$

Resistance of section EF, $R_{EF} = 0{\cdot}6 \times 50/1000 = 0{\cdot}03\,\Omega$

Resistance of section FB, $R_{FB} = 0{\cdot}6 \times 50/1000 = 0{\cdot}03\,\Omega$

Voltage at B = Voltage at A – Drop over AB

or $$V_B = V_A - [I_A R_{AC} + (I_A - 25) R_{CD} + (I_A - 75) R_{DE} + (I_A - 105) R_{EF} + (I_A - 145) R_{FB}]$$

or $$235 = 230 - [0{\cdot}03\, I_A + 0{\cdot}015\,(I_A - 25) + 0{\cdot}015\,(I_A - 75) + 0{\cdot}03\,(I_A - 105) + 0{\cdot}03\,(I_A - 145)]$$

or $$235 = 230 - [0{\cdot}12\, I_A - 9]$$

$$\therefore \quad I_A = \frac{239 - 235}{0{\cdot}12} = 33{\cdot}34\text{ A}$$

(*i*) ∴ Current in section AC, $I_{AC} = I_A =$ **33·34 A**

Current in section CD, $I_{CD} = I_A - 25 = 33{\cdot}34 - 25 =$ **8·34 A**

Current in section DE, I_{DE} = $I_A - 75 = 33\cdot34 - 75 = -41\cdot66$ A *from D to E*

= **41·66 A** *from E to D*

Current in section EF, I_{EF} = $I_A - 105 = 33\cdot34 - 105 = -71\cdot66$ A *from E to F*

= **71·66 A** *from F to E*

Current in section FB, I_{FB} = $I_A - 145 = 33\cdot34 - 145 = -111\cdot66$ A *from F to B*

= **111·66 A** *from B to F*

(*ii*) The actual distribution of currents in the various sections of the distributor is shown in Fig. 13.20. The currents are coming to load point *D* from both sides of the distributor. Therefore, load point *D* is the point of minimum potential.

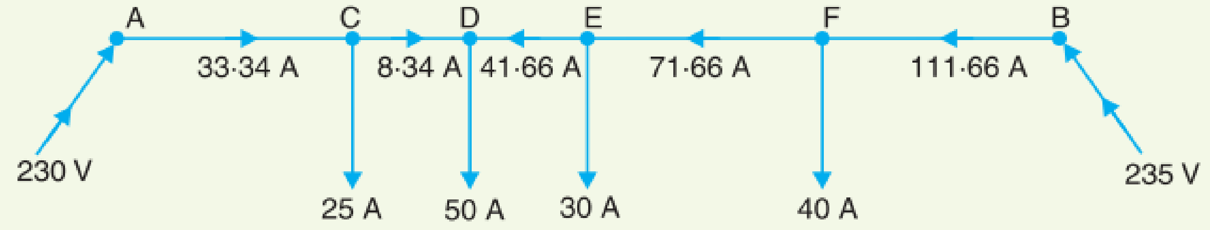


Fig. 13.20

Voltage at D, V_D = $V_A - [I_{AC} R_{AC} + I_{CD} R_{CD}]$

= $230 - [33\cdot34 \times 0\cdot03 + 8\cdot34 \times 0\cdot015]$

= $230 - 1\cdot125 =$ **228·875 V**

Example 13.12. *A two-wire d.c. distributor AB, 600 metres long is loaded as under :*

Distance from A (metres) :	*150*	*300*	*350*	*450*
Loads in Amperes :	*100*	*200*	*250*	*300*

The feeding point A is maintained at 440 V and that of B at 430 V. If each conductor has a resistance of 0·01 Ω per 100 metres, calculate :

(*i*) *the currents supplied from A to B,* (*ii*) *the power dissipated in the distributor.*

Solution. Fig. 13.21 shows the distributor with its tapped currents. Let I_A amperes be the current supplied from the feeding point *A*. Then currents in the various sections of the distributor are as shown in Fig.13.21.

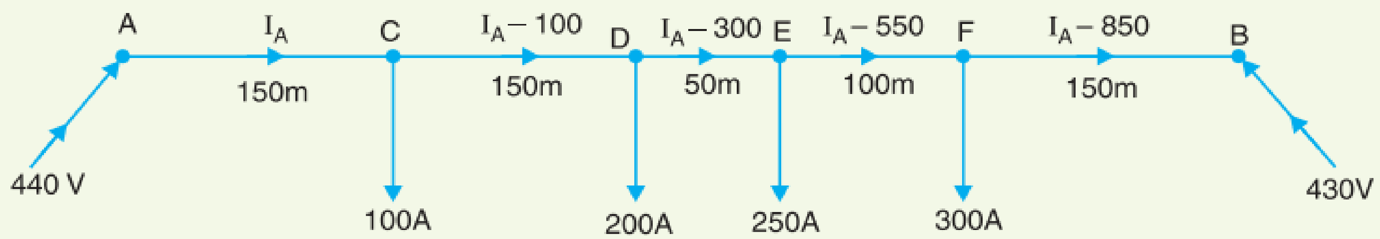


Fig. 13.21

Resistance of 100 m length of distributor (both wires)

= $2 \times 0\cdot01 = 0\cdot02\,\Omega$

Resistance of section AC, R_{AC} = $0\cdot02 \times 150/100 = 0\cdot03\,\Omega$

Resistance of section CD, R_{CD} = $0\cdot02 \times 150/100 = 0\cdot03\,\Omega$

Resistance of section DE, R_{DE} = $0\cdot02 \times 50/100 = 0\cdot01\,\Omega$

Resistance of section EF, R_{EF} = $0\cdot02 \times 100/100 = 0\cdot02\,\Omega$

Resistance of section FB, R_{FB} = $0\cdot02 \times 150/100 = 0\cdot03\,\Omega$

$$\text{Voltage at } B = \text{Voltage at } A - \text{Drop over } AB$$

or
$$V_B = V_A - [I_A R_{AC} + (I_A - 100) R_{CD} + (I_A - 300) R_{DE} + (I_A - 550) R_{EF} + (I_A - 850) R_{FB}]$$

or
$$430 = 440 - [0{\cdot}03 I_A + 0{\cdot}03 (I_A - 100) + 0{\cdot}01 (I_A - 300) + 0{\cdot}02 (I_A - 550) + 0{\cdot}03 (I_A - 850)]$$

or
$$430 = 440 - [0{\cdot}12 I_A - 42{\cdot}5]$$

$\therefore$
$$I_A = \frac{482 \cdot 5 - 430}{0 \cdot 12} = 437{\cdot}5 \text{ A}$$

The actual distribution of currents in the various sections of the distributor is shown in Fig.13.22. Incidentally, E is the point of minimum potential.

(*i*) Referring to Fig. 13.22, it is clear that

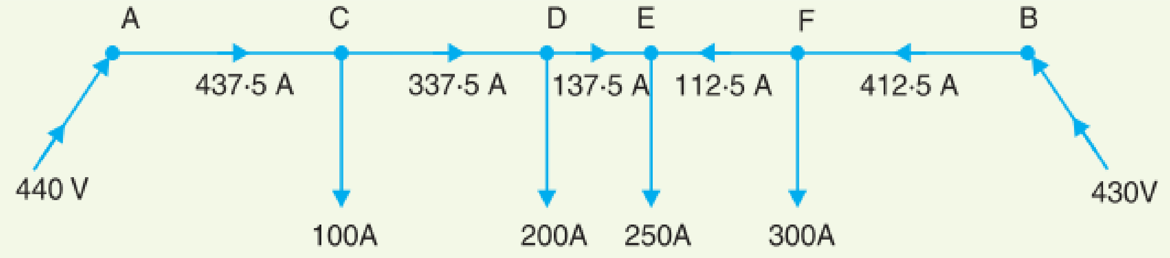


Fig. 13.22

Current supplied from end A, I_A = **437·5 A**

Current supplied from end B, I_B = **412·5 A**

(*ii*) Power loss in the distributor

$$= I_{AC}^2 R_{AC} + I_{CD}^2 R_{CD} + I_{DE}^2 R_{DE} + I_{EF}^2 R_{EF} + I_{FB}^2 R_{FB}$$

$$= (437{\cdot}5)^2 \times 0{\cdot}03 + (337{\cdot}5)^2 \times 0{\cdot}03 + (137{\cdot}5)^2 \times 0{\cdot}01 + (112{\cdot}5)^2 \times 0{\cdot}02 + (412{\cdot}5)^2 \times 0{\cdot}03$$

= 5742 + 3417 + 189 + 253 + 5104 = 14,705 watts = **14·705 kW**

Example 13.13. *An electric train runs between two sub-stations 6 km apart maintained at voltages 600 V and 590 V respectively and draws a constant current of 300 A while in motion. The track resistance of go and return path is 0·04 Ω/km. Calculate :*

(*i*) *the point along the track where minimum potential occurs*

(*ii*) *the current supplied by the two sub-stations when the train is at the point of minimum potential*

Solution. The single line diagram is shown in Fig. 13.23 where substation A is at 600 V and sub-station B at 590 V. Suppose that minimum potential occurs at point M at a distance x km from the substation A. Let I_A amperes be the current supplied by the sub-station A. Then current supplied by sub-station B is $300 - I_A$ as shown in Fig 13.23.

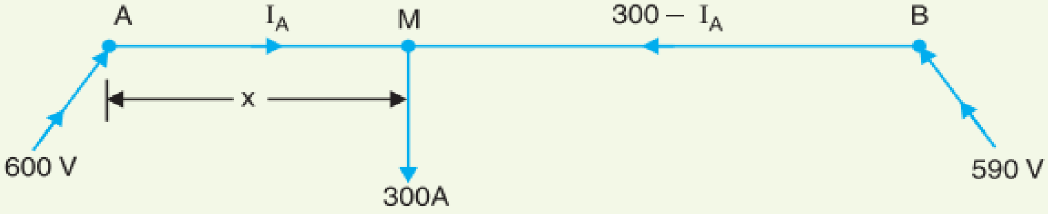


Fig. 13.23

Resistance of track (go and return path) per km

$$= 0\cdot04\ \Omega$$

Track resistance for section AM, $R_{AM} = 0\cdot04\,x\ \Omega$

Track resistance for section MB, $R_{MB} = 0\cdot04\,(6-x)\Omega$

$$\text{Potential at } M,\ V_M = V_A - I_A R_{AM} \quad \text{... }(i)$$

Also,

$$\text{Potential at } M,\ V_M = V_B - (300 - I_A) R_{MB} \quad \text{... }(ii)$$

From equations (*i*) and (*ii*), we get,

$$V_A - I_A R_{AM} = V_B - (300 - I_A) R_{MB}$$

or $600 - 0\cdot04\,x\,I_A = 590 - (300 - I_A) \times 0\cdot04\,(6-x)$

or $600 - 0\cdot04\,x\,I_A = 590 - 0\cdot04\,(1800 - 300\,x - 6\,I_A + I_A \times x)$

or $600 - 0\cdot04\,x\,I_A = 590 - 72 + 12\,x + 0\cdot24\,I_A - 0\cdot04\,xI_A$

or $0\cdot24\,I_A = 82 - 12\,x$

or $I_A = 341\cdot7 - 50\,x$

Substituting the value of I_A in eq. (*i*), we get,

$$V_M = V_A - (341\cdot7 - 50\,x) \times 0\cdot04\,x$$

$\therefore$ $V_M = 600 - 13\cdot7\,x + 2x^2$ ...(*iii*)

(*i*) For V_M to be minimum, its differential coefficient *w.r.t.* x must be zero *i.e.*

$$\frac{d}{dx}(600 - 13\cdot7\,x + 2x^2) = 0$$

or $0 - 13\cdot7 + 4x = 0$

$\therefore$ $x = 13\cdot7/4 =$ **3·425 km**

i.e. minimum potential occurs at a distance of 3·425 km from the sub-station A.

(*ii*) $\therefore$ Current supplied by sub-station A

$= 341\cdot7 - 50 \times 3\cdot425 = 341\cdot7 - 171\cdot25 =$ **170·45 A**

Current supplied by sub-station B $= 300 - I_A = 300 - 170\cdot45 =$ **129·55 A**

13.6 Uniformly Loaded Distributor Fed at Both Ends

We shall now determine the voltage drop in a uniformly loaded distributor fed at both ends. There can be two cases *viz.* the distributor fed at both ends with (*i*) equal voltages (*ii*) unequal voltages. The two cases shall be discussed separately.

(*i*) **Distributor fed at both ends with equal voltages.** Consider a distributor AB of length l metres, having resistance r ohms per metre run and with uniform loading of i amperes per metre run as shown in Fig. 13.24. Let the distributor be fed at the feeding points A and B at equal voltages, say V volts. The total current supplied to the distributor is $i\,l$. As the two end voltages are equal, therefore, current supplied from each feeding point is $i\,l/2$ *i.e.*

Current supplied from each feeding point

$$= \frac{i\,l}{2}$$

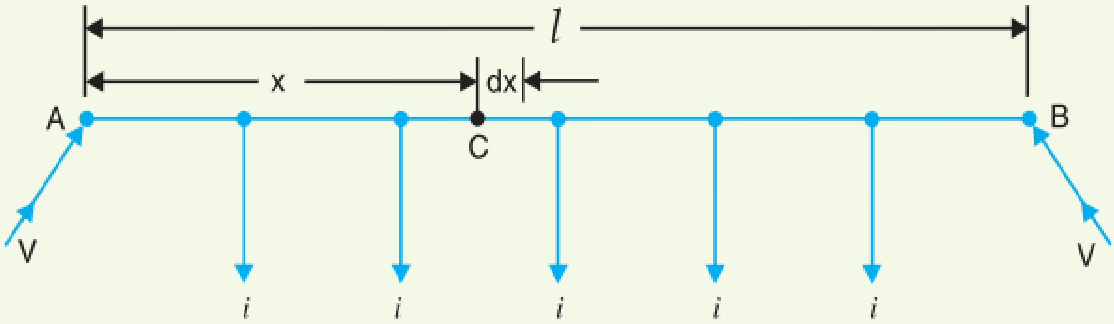


Fig. 13.24

Consider a point C at a distance x metres from the feeding point A. Then current at point C is

$$= \frac{i\,l}{2} - i\,x = i\left(\frac{l}{2} - x\right)$$

Now, consider a small length dx near point C. Its resistance is $r\,dx$ and the voltage drop over length dx is

$$dv = i\left(\frac{l}{2} - x\right) r\,dx = i\,r\left(\frac{l}{2} - x\right) dx$$

$$\therefore \quad \text{Voltage drop upto point } C = \int_0^x i\,r\left(\frac{l}{2} - x\right) dx = i\,r\left(\frac{l\,x}{2} - \frac{x^2}{2}\right)$$

$$= \frac{i\,r}{2}\left(l\,x - x^2\right)$$

Obviously, the point of minimum potential will be the mid-point. Therefore, maximum voltage drop will occur at mid-point *i.e.* where $x = l/2$.

$$\therefore \quad \text{Max. voltage drop} = \frac{i\,r}{2}\left(l\,x - x^2\right)$$

$$= \frac{i\,r}{2}\left(l \times \frac{l}{2} - \frac{l^2}{4}\right) \qquad \text{[Putting } x = l/2\text{]}$$

$$= \frac{1}{8}\,i\,r\,l^2 = \frac{1}{8}(i\,l)(r\,l) = \frac{1}{8}\,I\,R$$

where $i\,l = I$, the total current fed to the distributor from both ends

$r\,l = R$, the total resistance of the distributor

$$\text{Minimum voltage} = V - \frac{I\,R}{8} \text{ volts}$$

(*ii*) **Distributor fed at both ends with unequal voltages.** Consider a distributor *AB* of length *l* metres having resistance *r* ohms per metre run and with a uniform loading of *i* amperes per metre run as shown in Fig. 13.25. Let the distributor be fed from feeding points *A* and *B* at voltages V_A and V_B respectively.

Suppose that the point of minimum potential *C* is situated at a distance *x* metres from the feeding point *A*. Then current supplied by the feeding point *A* will be *$i\,x$.

* As *C* is at minimum potential, therefore, there is no current at this point. Consequently, current in section *AC* (*i.e.* $i\,x$) will be the current supplied by feeding point *A*.

∴ Voltage drop in section $AC = \dfrac{i\,r\,x^2}{2}$ volts

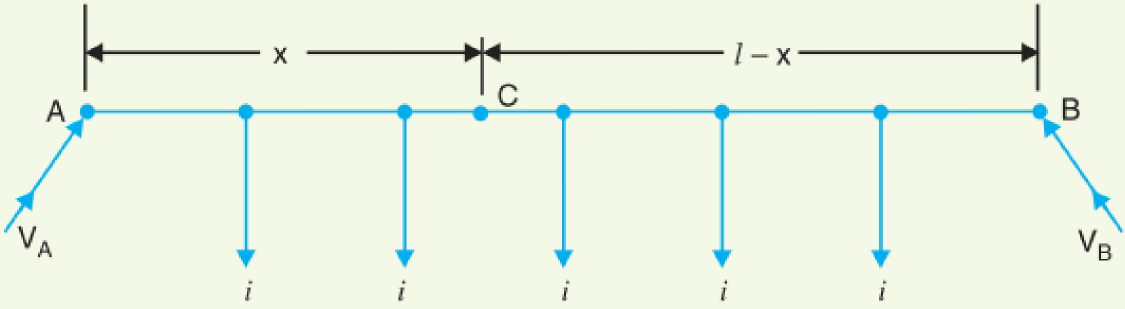


Fig. 13.25

As the distance of C from feeding point B is $(l - x)$, therefore, current fed from B is $i\,(l - x)$.

$$\therefore \quad \text{Voltage drop in section } BC = \frac{i\,r\,(l-x)^2}{2} \text{ volts}$$

$$\text{Voltage at point } C,\ V_C = V_A - \text{Drop over } AC$$

$$= V_A - \frac{i\,r\,x^2}{2} \qquad \ldots(i)$$

$$\text{Also, voltage at point } C,\ V_C = V_B - \text{Drop over } BC$$

$$= V_B - \frac{i\,r\,(l-x)^2}{2} \qquad \ldots(ii)$$

From equations (i) and (ii), we get,

$$V_A - \frac{i\,r\,x^2}{2} = V_B - \frac{i\,r\,(l-x)^2}{2}$$

Solving the equation for x, we get,

$$x = \frac{V_A - V_B}{i\,r\,l} + \frac{l}{2}$$

As all the quantities on the right hand side of the equation are known, therefore, the point on the distributor where minimum potential occurs can be calculated.

Example 13.14. *A two-wire d.c. distributor cable 1000 metres long is loaded with 0·5 A/metre. Resistance of each conductor is 0·05 Ω/km. Calculate the maximum voltage drop if the distributor is fed from both ends with equal voltages of 220 V. What is the minimum voltage and where it occurs ?*

Solution.

Current loading, $i = 0{\cdot}5$ A/m

Resistance of distributor/m, $r = 2 \times 0{\cdot}05/1000 = 0{\cdot}1 \times 10^{-3}\ \Omega$

Length of distributor, $l = 1000$ m

Total current supplied by distributor, $I = i\,l = 0{\cdot}5 \times 1000 = 500$ A

Total resistance of the distributor, $R = r\,l = 0{\cdot}1 \times 10^{-3} \times 1000 = 0{\cdot}1\ \Omega$

$$\therefore \quad \text{Max. voltage drop} = \frac{I\,R}{8} = \frac{500 \times 0{\cdot}1}{8} = \mathbf{6{\cdot}25\ V}$$

Minimum voltage will occur at the mid-point of the distributor and its value is

$$= 220 - 6{\cdot}25 = \mathbf{213{\cdot}75\ V}$$

Example 13.15. *A 2-wire d.c. distributor AB 500 metres long is fed from both ends and is loaded uniformly at the rate of 1·0 A/metre. At feeding point A, the voltage is maintained at 255 V and at B at 250 V. If the resistance of each conductor is 0·1 Ω per kilometre, determine :*

(*i*) *the minimum voltage and the point where it occurs*

(*ii*) *the currents supplied from feeding points A and B*

Solution. Fig. 13.26 shows the single line diagram of the distributor.

Voltage at feeding point *A*, $V_A = 255$ V

Voltage at feeding point *B*, $V_B = 250$ V

Length of distributor, $l = 500$ m

Current loading, $i = 1$ *A*/m

Resistance of distributor/m, $r = 2 \times 0 \cdot 1/1000 = 0 \cdot 0002\,\Omega$

(*i*) Let the minimum potential occur at a point *C* distant *x* metres from the feeding point *A*. As proved in Art. 13.6,

$$x = \frac{V_A - V_B}{i\,r\,l} + \frac{l}{2} = \frac{255 - 250}{1 \times 0 \cdot 0002 \times 500} + 500/2$$

$$= 50 + 250 = \textbf{300 m}$$

i.e. minimum potential occurs at 300 m from point *A*.

Minimum voltage, $$V_C = V_A - \frac{ir\,x^2}{2} = 255 - \frac{1 \times 0 \cdot 0002 \times (300)^2}{2}$$

$$= 255 - 9 = \textbf{246 V}$$

(*ii*) Current supplied from *A* $= i\,x = 1 \times 300 =$ **300 A**

Current supplied from *B* $= i\,(l - x) = 1\,(500 - 300) =$ **200 A**

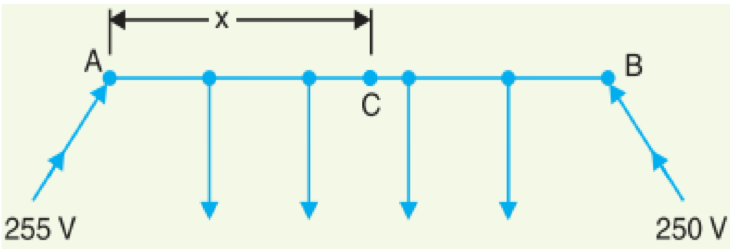


Fig. 13.26

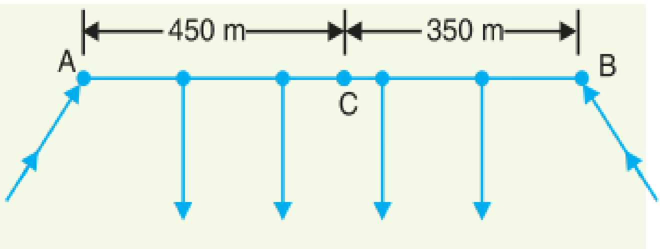


Fig. 13.27

Example 13.16. *A 800 metres 2-wire d.c. distributor AB fed from both ends is uniformly loaded at the rate of 1·25 A/metre run. Calculate the voltage at the feeding points A and B if the minimum potential of 220 V occurs at point C at a distance of 450 metres from the end A. Resistance of each conductor is 0·05 Ω/km.*

Solution. Fig. 13.27 shows the single line diagram of the distributor.

Current loading, $i = 1 \cdot 25$ A/m

Resistance of distributor/m, $r = 2 \times 0 \cdot 05/1000 = 0 \cdot 0001\ \Omega$

Voltage at C, $V_C = 220$ V

Length of distributor, $l = 800$ m

Distance of point C from A, $x = 450$ m

$$\text{Voltage drop in section } AC = \frac{i\,r\,x^2}{2} = \frac{1 \cdot 25 \times 0 \cdot 0001 \times (450)^2}{2} = 12 \cdot 65 \text{ V}$$

∴ Voltage at feeding point A, $V_A = 220 + 12 \cdot 65 =$ **232·65 V**

$$\text{Voltage drop in section } BC = \frac{i\,r\,(l-x)^2}{2} = \frac{1 \cdot 25 \times 0 \cdot 0001 \times (800-450)^2}{2}$$

$$= 7 \cdot 65 \text{ V}$$

∴ Voltage at feeding point B, $V_B = 220 + 7 \cdot 65 =$ **227·65 V**

Example 13.17.

(*i*) *A uniformly loaded distributor is fed at the centre. Show that maximum voltage drop = I R/8 where I is the total current fed to the distributor and R is the total resistance of the distributor.*

(*ii*) *A 2-wire d.c. distributor 1000 metres long is fed at the centre and is loaded uniformly at the rate of 1·25 A/metre. If the resistance of each conductor is 0·05 Ω/km, find the maximum voltage drop in the distributor.*

Solution. (*i*) Fig. 13.28 shows distributor AB fed at centre C and uniformly loaded with i amperes/metre. Let l metres be the length of the distributor and r ohms be the resistance per metre run. Obviously, maximum voltage drop will occur at either end.

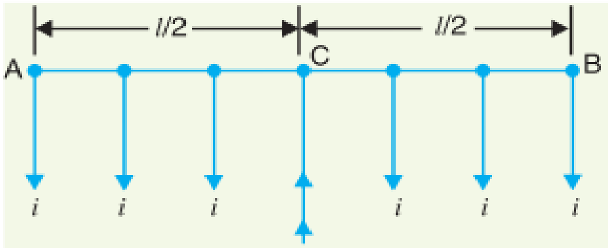


Fig. 13.28

∴ Max. voltage drop = Voltage drop in half distributor

$$= \frac{1}{2}\left(\frac{i\,l}{2}\right)\left(\frac{r\,l}{2}\right) = \frac{1}{8}(i\,l)(r\,l)$$

$$= \frac{1}{8} I R$$

where $i\,l = I$, the total current fed to the distributor

$r\,l = R$, the total resistance of the distributor

(*ii*) Total current fed to the distributor is

$$I = i\,l = 1 \cdot 25 \times 1000 = 1250 \text{ A}$$

Total resistance of the distributor is

$$R = r\,l = 2 \times 0 \cdot 05 \times 1 = 0 \cdot 1\ \Omega$$

Max. voltage drop $= \frac{1}{8} I R = \frac{1}{8} \times 1250 \times 0 \cdot 1 =$ **15.62 V**

Example 13.18. *Derive an expression for the power loss in a uniformly loaded distributor fed at both ends with equal voltages.*

Solution. Consider a distributor *AB* of length *l* metres, having resistance *r* ohms per metre run with uniform loading of *i* amperes per metre run as shown in Fig.13.29. Let the distributor be fed at the feeding points *A* and *B* at equal voltages, say V volts. The total current supplied by the distributor is *i l*. As the two end voltages are equal, therefore, current supplied from each feeding point is *i l*/2.

Current supplied from each feeding point = $\frac{i\,l}{2}$

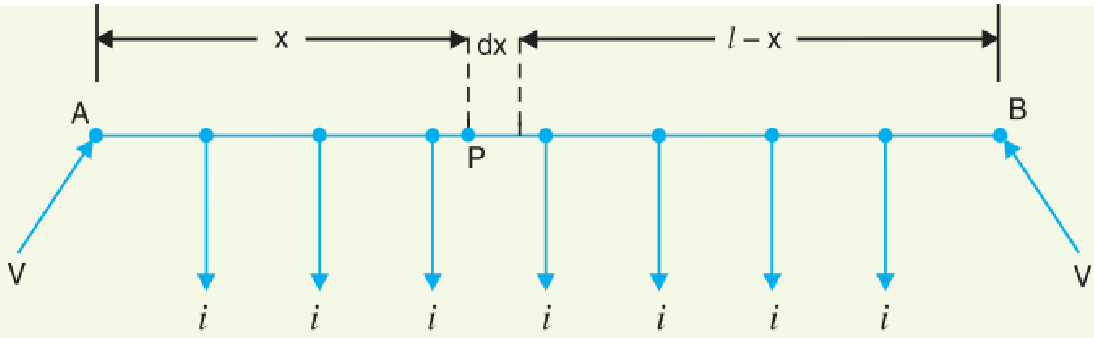


Fig. 13.29

Consider a small length *dx* of the distributor at point *P* which is at a distance *x* from the feeding end *A*.

$$\text{Resistance of length } dx = r\,dx$$

$$\text{Current in length } dx = \frac{i\,l}{2} - i\,x = i\left(\frac{l}{2} - x\right)$$

$$\text{Power loss in length } dx = (\text{current in } dx)^2 \times \text{Resistance of } dx$$

$$= \left[i\left(\frac{l}{2} - x\right)\right]^2 \times r\,dx$$

Total power loss in the distributor is

$$P = \int_0^l \left[i\left(\frac{l}{2} - x\right)\right]^2 r\,dx = i^2 r \int_0^l \left(\frac{l^2}{4} - l\,x + x^2\right) dx$$

$$= i^2 r\left[\frac{l^2 x}{4} - \frac{l\,x^2}{2} + \frac{x^3}{3}\right]_0^l = i^2 r\left[\frac{l^3}{4} - \frac{l^3}{2} + \frac{l^3}{3}\right]$$

$$\therefore \quad P = \frac{i^2\,r\,l^3}{12}$$

13.7 Distributor with Both Concentrated and Uniform Loading

There are several problems where a distributor has both concentrated and uniform loadings. In such situations, the total drop over any section of the distributor is equal to the sum of drops due to concentrated and uniform loading in that section. We shall solve a few problems by way of illustration.

Example 13.19. *A 2-wire d.c. distributor AB, 900 metres long is fed at A at 400 V and loads of 50 A, 100 A and 150 A are tapped off from C, D and E which are at a distance of 200 m, 500 m and 800 m from point A respectively. The distributor is also loaded uniformly at the rate of 0.5 A/m. If the resistance of distributor per metre (go and return) is 0.0001 Ω, calculate voltage (i) at point B and (ii) at point D.*

Solution. This problem can be solved in two stages. First, the drop at any point due to concentrated loading is found. To this is added the voltage drop due to uniform loading.

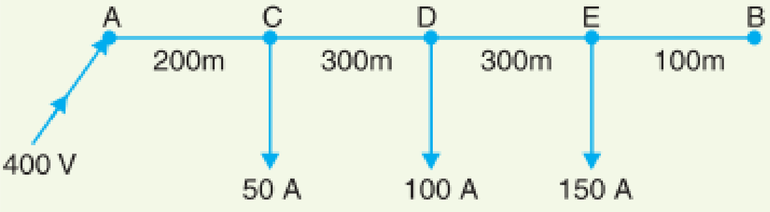


Fig. 13.30

Drops due to concentrated loads. Fig. 13.30 shows only the concentrated loads tapped off from the various points. The currents in the various sections are :

$$I_{AC} = 300 \text{ A} \,;\, I_{CD} = 250 \text{ A} \,;\, I_{DE} = 150 \text{ A}$$

$$\text{Drop in section } AC = I_{AC} R_{AC} = 300 \times (200 \times 0{\cdot}0001) = 6 \text{ V}$$

$$\text{Drop in section } CD = 250 \times (300 \times 0{\cdot}0001) = 7{\cdot}5 \text{ V}$$

$$\text{Drop in section } DE = 150 \times (300 \times 0{\cdot}0001) = 4{\cdot}5 \text{ V}$$

$$\text{Total drop over } AB = 6 + 7{\cdot}5 + 4{\cdot}5 = 18 \text{ V}$$

Drops due to uniform loading

$$\text{Drop over } AB = \frac{i\,r\,l^2}{2} = \frac{0\cdot5 \times 0\cdot0001 \times (900)^2}{2} = 20\cdot25 \text{ V}$$

$$\text{Drop over } AD = i\,r\left(l\,x - \frac{x^2}{2}\right)$$

Here, $l = 900 \text{ m} \,;\, x = 500 \text{ m}$

$$\therefore \quad \text{Drop over } AD = 0{\cdot}5 \times 0{\cdot}0001 \left(900 \times 500 - \frac{500^2}{2}\right) = 16{\cdot}25 \text{ V}$$

(*i*) Voltage at point B = V_A – Drop over AB due to conc. and uniform loadings

$= 400 - (18 + 20{\cdot}25) =$ **361·75 V**

(*ii*) Voltage at point D = V_A – Drop over AD due to conc. and uniform loadings

$= 400 - (6 + 7{\cdot}5 + 16{\cdot}25) =$ **370·25 V**

Example 13.20. *Two conductors of a d.c. distributor cable AB 1000 m long have a total resistance of 0·1 Ω. The ends A and B are fed at 240 V. The cable is uniformly loaded at 0·5 A per metre length and has concentrated loads of 120 A, 60 A, 100 A and 40 A at points distant 200 m, 400 m, 700 m and 900 m respectively from the end A. Calculate (i) the point of minimum potential (ii) currents supplied from ends A and B (iii) the value of minimum potential.*

Solution.

Distributor resistance per metre length, $r = 0{\cdot}1/1000 = 10^{-4}\ \Omega$

Uniform current loading, $i = 0{\cdot}5$ A/m

(i) **Point of minimum potential.** The point of minimum potential is not affected by the uniform loading of the distributor. Therefore, let us consider the concentrated loads first as shown in Fig. 13.31. Suppose the current supplied by end *A* is *I*. Then currents in the various sections will be as shown in Fig. 13.31.

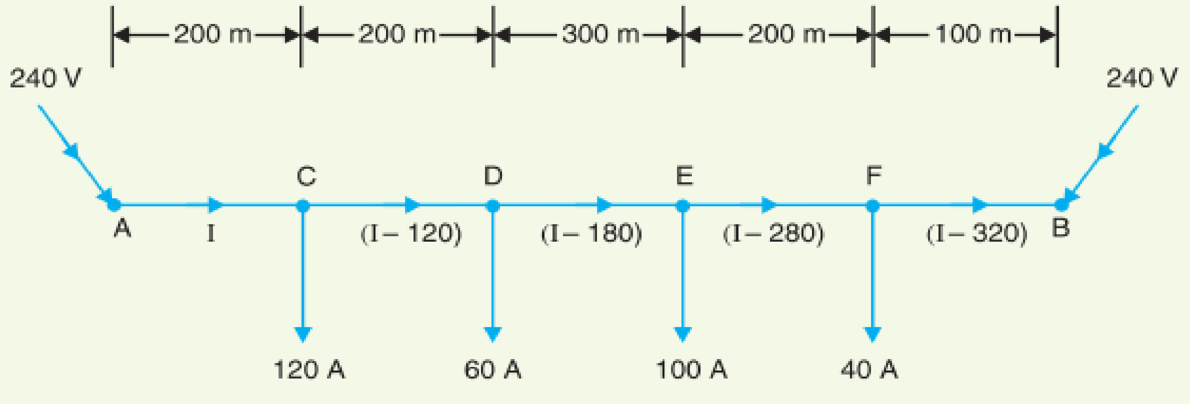


Fig. 13.31

$$V_A - V_B = \text{Drop over the distributor } AB$$

$$240 - 240 = I_{AC}\,R_{AC} + I_{CD}\,R_{CD} + I_{DE}\,R_{DE} + I_{EF}\,R_{EF} + I_{FB}\,R_{FB}$$

or $$0 = 10^{-4}\,[I \times 200 + (I - 120)\ 200 + (I - 180)\ 300 + (I - 280)\ 200 + (I - 320) \times 100]$$

or $$0 = 1000\,I - 166000 \quad \therefore \quad I = 166000/1000 = 166 \text{ A}$$

The actual distribution of currents in the various sections of the distributor due to concentrated loading is shown in Fig. 13.32. It is clear from this figure that *D is the point of minimum potential.*

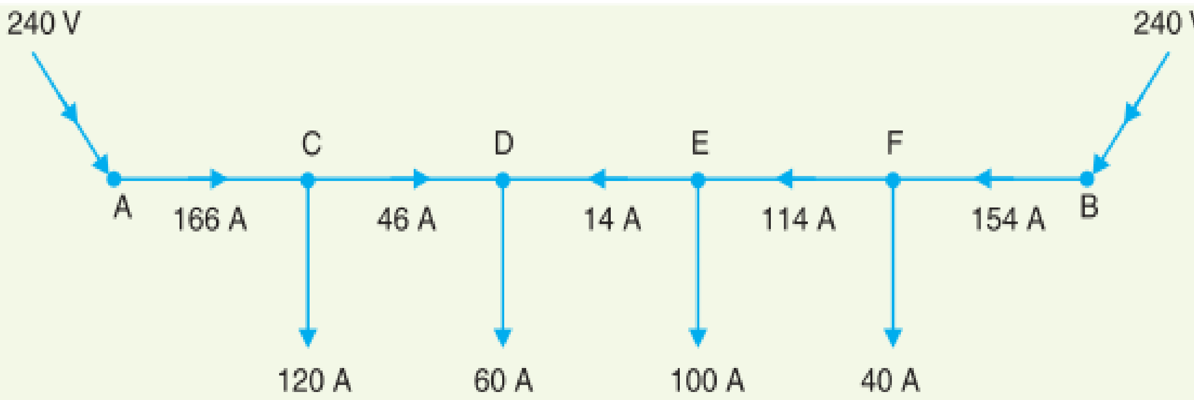


Fig. 13.32

(ii) The feeding point A will supply 166 A due to concentrated loading *plus* $0{\cdot}5 \times 400 = 200$ A due to uniform loading.

$\therefore$ Current supplied by A, I_A = 166 + 200 = **366 A**

The feeding point B will supply a current of 154 A due to concentrated loading *plus* $0 \cdot 5 \times 600 = 300$ A due to uniform loading.

$\therefore$ Current supplied by B, I_B = 154 + 300 = **454 A**

(*iii*) As stated above, D is the point of minimum potential.

$\therefore$ Minimum potential, V_D = V_A – Drop in AD due to conc. loading – Drop in AD due to uniform loading

Now, Drop in AD due to conc. loading $= I_{AC}\, R_{AC} + I_{CD}\, R_{CD}$

$$= 166 \times 10^{-4} \times 200 + 46 \times 10^{-4} \times 200$$

$$= 3 \cdot 32 + 0 \cdot 92 = 4 \cdot 24 \text{ V}$$

Drop in AD due to uniform loading $= \dfrac{i\, r^*\, l^2}{2} = \dfrac{0 \cdot 5 \times 10^{-4} \times (400)^2}{2} = 4\, V$

$\therefore$ $V_D = 240 - 4 \cdot 24 - 4$ = **231·76 V**

Example 13.21. *A d.c. 2-wire distributor AB is 500m long and is fed at both ends at 240 V. The distributor is loaded as shown in Fig 13.33. The resistance of the distributor (go and return) is 0·001Ω per metre. Calculate (i) the point of minimum voltage and (ii) the value of this voltage.*

Solution. Let D be the point of **minimum potential and let x be the current flowing in section CD as shown in Fig 13.33. Then current supplied by end B will be $(60 - x)$.

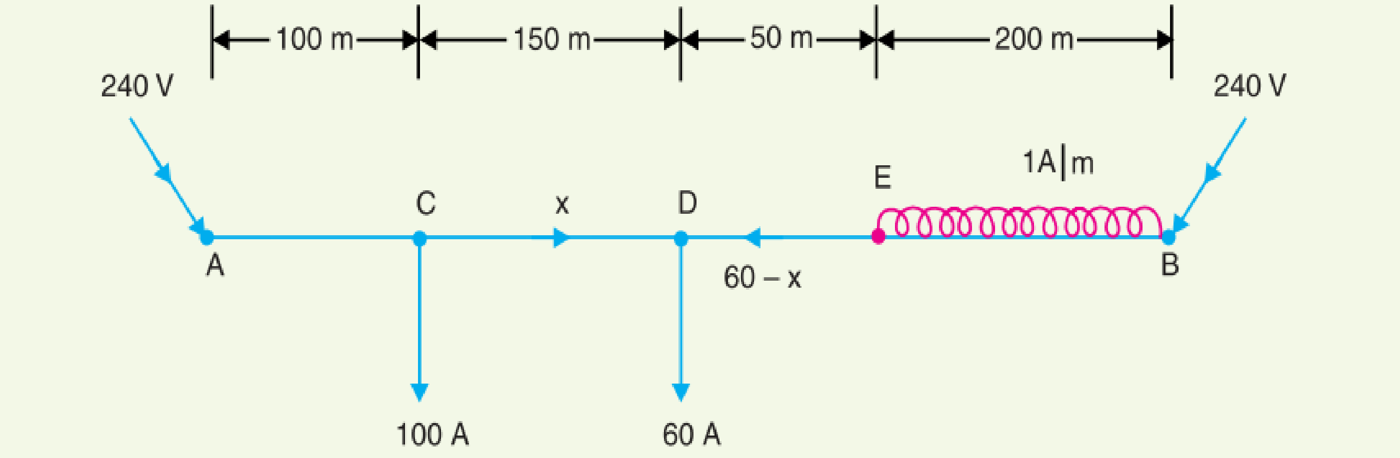


Fig. 13.33

(*i*) If r is the resistance of the distributor (go and return) per metre length, then,

Voltage drop in length AD $= I_{AC}\, R_{AC} + I_{CD}\, R_{CD}$

$$= (100 + x) \times 100\, r + x \times 150\, r$$

Voltage drop in length BD $= \dfrac{i\, r\, l^2}{2} + (60 - x) \times 250\, r$

$$= \frac{1 \times r \times (200)^2}{2} + (60 - x) \times 250\,r$$

Since the feeding points *A* and *B* are at the same potential,

$$\therefore \quad (100 + x) \times 100\,r + x \times 150\,r = \frac{1 \times r \times (200)^2}{2} + (60 - x)\,250\,r$$

or $$100x + 10000 + 150x = 20000 + 15000 - 250x$$

or $$500x = 25000 \quad \therefore\; x = 50 \text{ A}$$

---

* Drop due to uniform loading can be determined by imagining that the distributor is cut into two at point *D* so that *AD* can be thought as a distributor fed at one end and loaded uniformly.

** You may carry out the calculation by assuming *C* to be point of minimum potential. The answer will be unaffected.

The actual directions of currents in the various sections of the distributor are shown in Fig. 13.34. Note that currents supplied by *A* and *B* meet at *D*. *Hence point D is the point of minimum potential.*

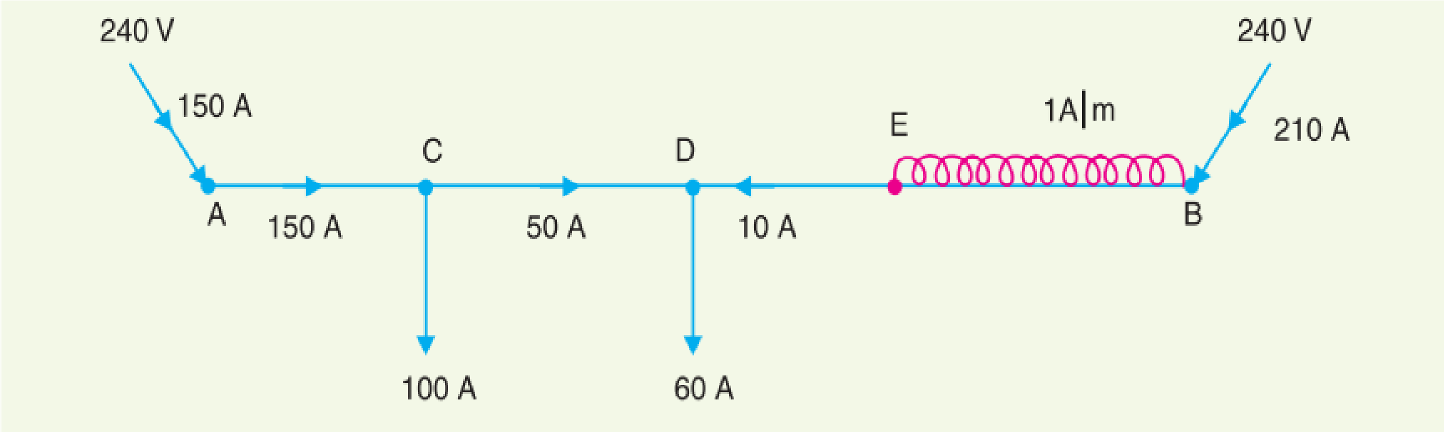


Fig. 13.34

(ii)

$$\text{Total current} = 160 + 1 \times 200 = 360 \text{ A}$$

$$\text{Current supplied by } A, I_A = 100 + x = 100 + 50 = 150 \text{ A}$$

$$\text{Current supplied by } B, I_B = 360 - 150 = 210 \text{ A}$$

$$\text{Minimum potential, } V_D = V_A - I_{AC}\,R_{AC} - I_{CD}\,R_{CD}$$

$$= 240 - 150 \times (100 \times 0{\cdot}001) - 50 \times (150 \times 0{\cdot}001)$$

$$= 240 - 15 - 7{\cdot}5 = \mathbf{217{\cdot}5\ V}$$

13.8 Ring Distributor

A distributor arranged to form a closed loop and fed at one or more points is called a *ring distributor*. Such a distributor starts from one point, makes a loop through the area to be served, and returns to the original point. For the purpose of calculating voltage distribution, the distributor can be considered as consisting of a series of open distributors fed at both ends. The principal advantage of ring distributor is that by proper choice in the number of feeding points, great economy in copper can be affected.

The most simple case of a ring distributor is the one having only one feeding point as shown in Fig. 13.36(*ii*). Here A is the feeding point and tappings are taken from points B and C. For the purpose of calculations, it is equivalent to a straight distributor fed at both ends with equal voltages.

13.9 Ring Main Distributor with Interconnector

Sometimes a ring distributor has to serve a large area. In such a case, voltage drops in the various sections of the distributor may become excessive. In order to reduce voltage drops in various sections, distant points of the distributor are joined through a conductor called *interconnector*. Fig. 13.38 shows the ring distributor *ABCDEA*. The points *B* and *D* of the ring distributor are joined through an interconnector *BD*. There are several methods for solving such a network. However, the solution of such a network can be readily obtained by applying Thevenin's theorem. The steps of procedure are :

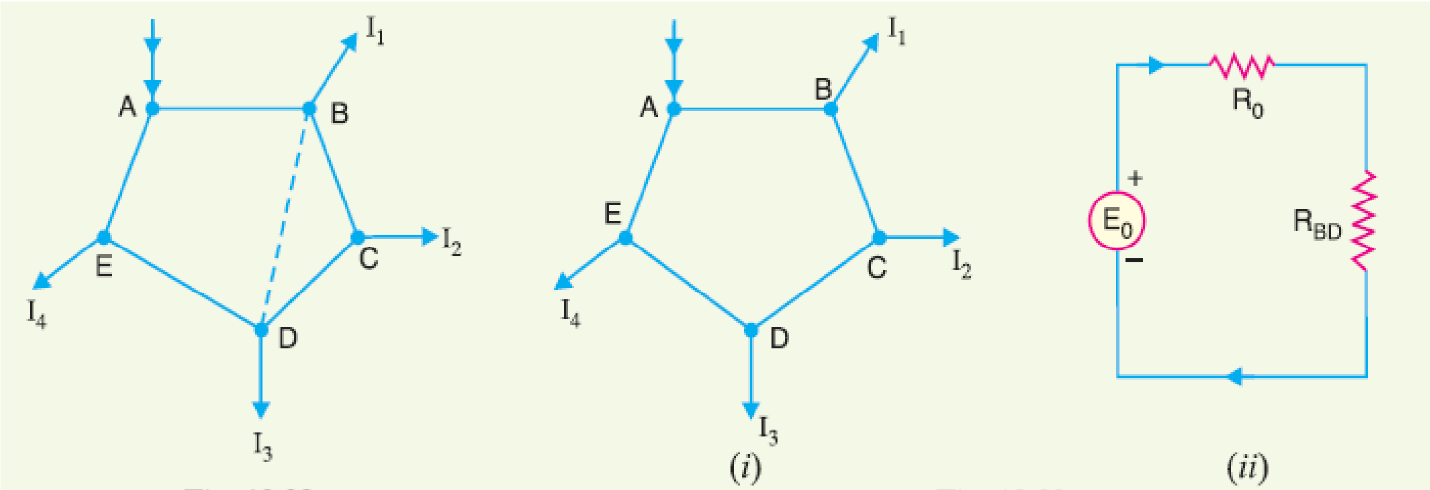


Fig. 13.38 **Fig. 13.39**

(*i*) Consider the interconnector *BD* to be disconnected [See Fig. 13.39 (*i*)] and find the potential difference between *B* and *D*. This gives Thevenin's equivalent circuit voltage E_0.

(*ii*) Next, calculate the resistance viewed from points *B* and *D* of the network composed of distribution lines only. This gives Thevenin's equivalent circuit series resistance R_0.

(*iii*) If R_{BD} is the resistance of the interconnector *BD*, then Thevenin's equivalent circuit will be as shown in Fig. 13.39 (*ii*).

$$\therefore \qquad \text{Current in interconnector } BD = \frac{E_0}{R_0 + R_{BD}}$$

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

Example 13.22. *A 2-wire d.c. ring distributor is 300 m long and is fed at 240 V at point A. At point B, 150 m from A, a load of 120 A is taken and at C, 100 m in the opposite direction, a load of 80 A is taken. If the resistance per 100 m of single conductor is 0·03 Ω, find :*

(*i*) *current in each section of distributor*

(*ii*) *voltage at points B and C*

Solution.

Resistance per 100 m of distributor

$$= 2 \times 0{\cdot}03 = 0{\cdot}06\ \Omega$$

Resistance of section AB, $R_{AB} = 0{\cdot}06 \times 150/100 = 0{\cdot}09\ \Omega$

Resistance of section BC, $R_{BC} = 0{\cdot}06 \times 50/100 = 0{\cdot}03\ \Omega$

Resistance of section CA, $R_{CA} = 0{\cdot}06 \times 100/100 = 0{\cdot}06\ \Omega$

(*i*) Let us suppose that a current I_A flows in section AB of the distributor. Then currents in sections BC and CA will be $(I_A - 120)$ and $(I_A - 200)$ respectively as shown in Fig. 13.36 (*i*).

According to Kirchhoff's voltage law, the voltage drop in the closed loop $ABCA$ is zero *i.e.*

$$I_{AB} R_{AB} + I_{BC} R_{BC} + I_{CA} R_{CA} = 0$$

or $$0{\cdot}09\, I_A + 0{\cdot}03\,(I_A - 120) + 0{\cdot}06\,(I_A - 200) = 0$$

or $$0{\cdot}18\, I_A = 15{\cdot}6$$

$\therefore$ $$I_A = 15{\cdot}6/0{\cdot}18 = 86{\cdot}67 \text{ A}$$

The actual distribution of currents is as shown in Fig. 13.36 (*ii*) from where it is seen that B is the point of minimum potential.

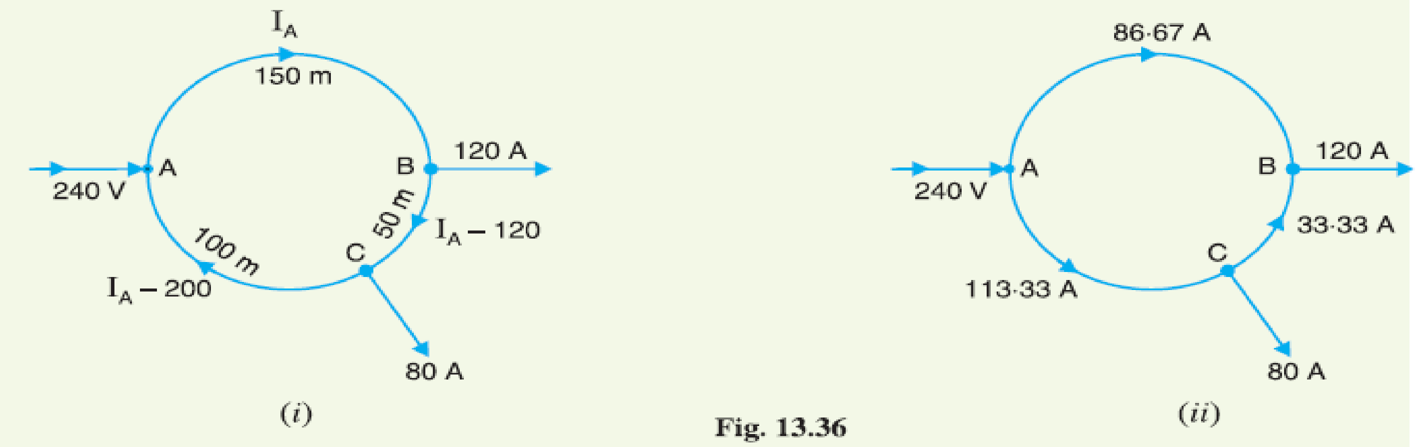


Fig. 13.36

Current in section AB, $I_{AB} = I_A =$ **86·67 A** *from A to B*

Current in section BC, $I_{BC} = I_A - 120 = 86{\cdot}67 - 120 = -33{\cdot}33$ A

$=$ **33.33 A** *from C to B*

Current in section CA, $I_{CA} = I_A - 200 = 86{\cdot}67 - 200 = -113{\cdot}33$ A

$=$ **113 ·33 A** *from A to C*

(*ii*) Voltage at point B, $V_B = V_A - I_{AB} R_{AB} = 240 - 86{\cdot}67 \times 0{\cdot}09 =$ **232·2 V**

Voltage at point C, $V_C = V_B + I_{BC} R_{BC}$

$= 232{\cdot}2 + 33{\cdot}33 \times 0{\cdot}03 =$ **233·2 V**

Example 13.23. *A 2-wire d.c. distributor ABCDEA in the form of a ring main is fed at point A at 220 V and is loaded as under :*

10A at B ; 20A at C ; 30A at D and 10 A at E.

The resistances of various sections (go and return) are : AB = 0·1 Ω ; BC = 0·05 Ω ; CD = 0·01 Ω ; DE = 0·025 Ω and EA = 0·075 Ω. Determine :

(i) the point of minimum potential

(ii) current in each section of distributor

Solution. Fig. 13.37 (*i*) shows the ring main distributor. Let us suppose that current *I* flows in section *AB* of the distributor. Then currents in the various sections of the distributor are as shown in Fig. 13.37 (*i*).

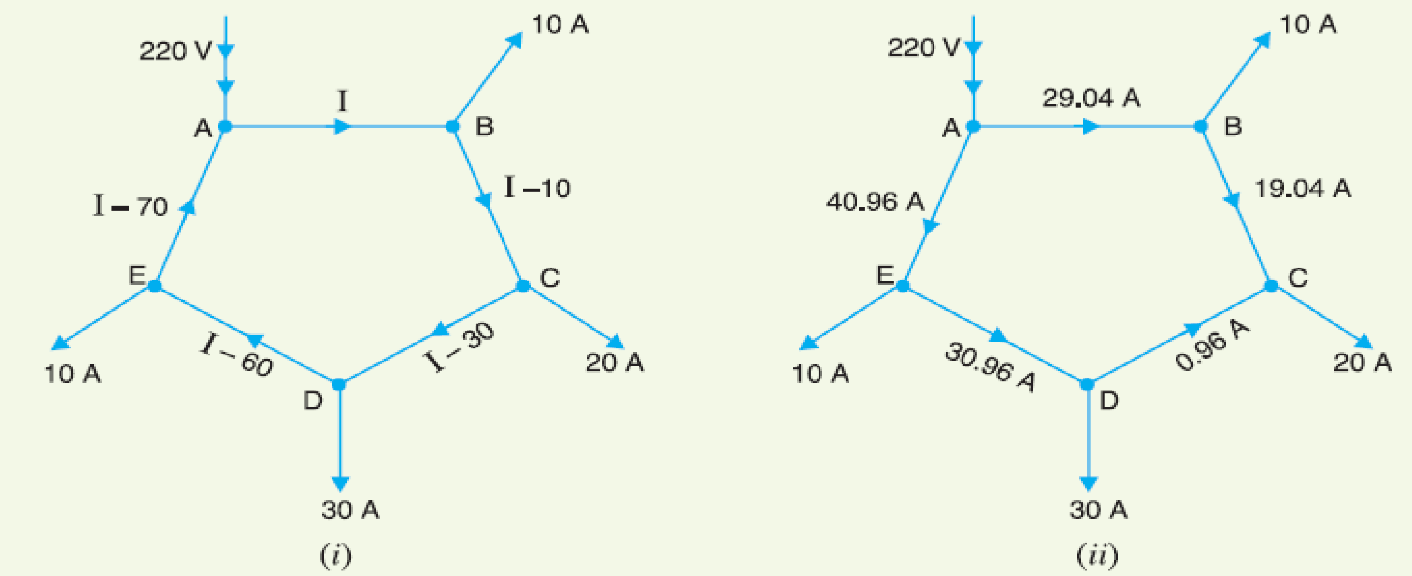


Fig. 13.37

(*i*) According to Kirchhoff's voltage law, the voltage drop in the closed loop *ABCDEA* is zero *i.e.*

$$I_{AB}\,R_{AB} + I_{BC}\,R_{BC} + I_{CD}\,R_{CD} + I_{DE}\,R_{DE} + I_{EA}\,R_{EA} = 0$$

or $$0{\cdot}1I + 0{\cdot}05\,(I - 10) + 0{\cdot}01\,(I - 30) + 0{\cdot}025\,(I - 60) + 0{\cdot}075\,(I - 70) = 0$$

or $$0{\cdot}26\,I = 7{\cdot}55$$

$$\therefore \quad I = 7{\cdot}55/0{\cdot}26 = 29{\cdot}04 \text{ A}$$

The actual distribution of currents is as shown in Fig. 13.37 (*ii*) from where it is clear that *C* is the point of minimum potential.

∴ *C* is the point of minimum potential.

(*ii*) Current in section *AB* = *I* = **29·04 A** *from A to B*

Current in section *BC* = $I - 10 = 29{\cdot}04 - 10 =$ **19·04 A** *from B to C*

Current in section *CD* = $I - 30 = 29{\cdot}04 - 30 = -\,0{\cdot}96$ A = **0·96 A** *from D to C*

Current in section *DE* = $I - 60 = 29{\cdot}04 - 60 = -\,30{\cdot}96$ A = **30·96 A** *from E to D*

Current in section *EA* = $I - 70 = 29{\cdot}04 - 70 = -\,40{\cdot}96$ A = **40·96 A** *from A to E*

Example 13.24. *A d.c. ring main ABCDA is fed from point A from a 250 V supply and the resistances (including both lead and return) of various sections are as follows : AB = 0·02 Ω ; BC = 0·018 Ω ; CD = 0·025 Ω and DA = 0·02 Ω. The main supplies loads of 150 A at B ; 300 A at C and 250 A at D. Determine the voltage at each load point.*

If the points A and C are linked through an interconnector of resistance 0·02 Ω, determine the new voltage at each load point.

Solution.

Without Interconnector. Fig. 13.40 (*i*) shows the ring distributor without interconnector. Let us suppose that a current *I* flows in section *AB* of the distributor. Then currents in various sections of the distributor will be as shown in Fig. 13.40 (*i*).

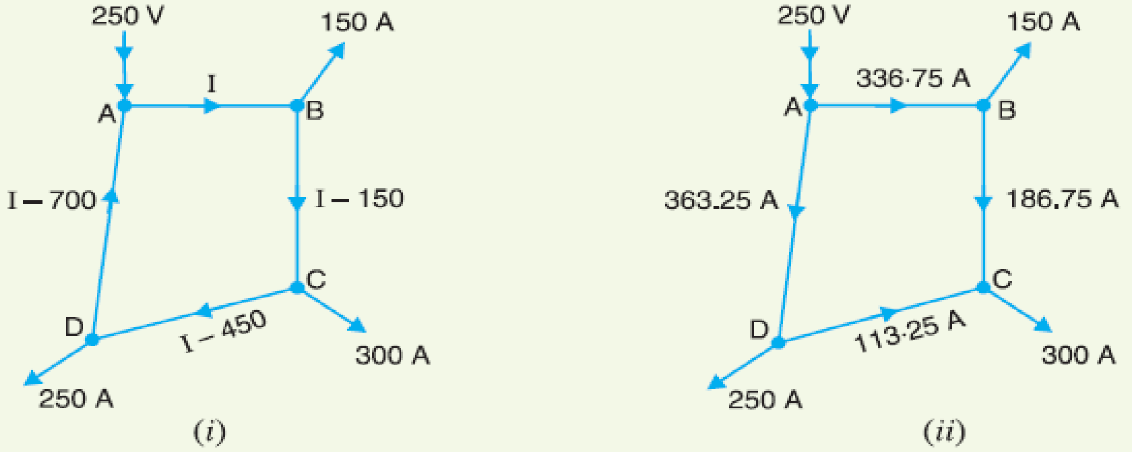


Fig. 13.40

According to Kirchhoff's voltage law, the voltage drop in the closed loop *ABCDA* is zero *i.e.*

$$I_{AB}\,R_{AB} + I_{BC}\,R_{BC} + I_{CD}\,R_{CD} + I_{DA}\,R_{DA} = 0$$

or $\quad 0{\cdot}02I + 0{\cdot}018\,(I - 150) + 0{\cdot}025\,(I - 450) + 0{\cdot}02\,(I - 700) = 0$

or $\quad 0{\cdot}083\,I = 27{\cdot}95$

∴ $\quad I = 27{\cdot}95/0{\cdot}083 = 336{\cdot}75$ A

The actual distribution of currents is as shown in Fig. 13.40 (*ii*).

Voltage drop in *AB* = 336·75 × 0·02 = 6·735 V

Voltage drop in *BC* = 186·75 × 0·018 = 3·361 V

Voltage drop in *CD* = 113·25 × 0·025 = 2·831 V

Voltage drop in *DA* = 363·25 × 0·02 = 7·265 V

∴ Voltage at point *B* = 250 – 6·735 = **243·265 V**

Voltage at point *C* = 243·265 – 3·361 = **239·904 V**

Voltage at point *D* = 239·904 + 2·831 = **242·735 V**

With Interconnector. Fig. 13.41 (*i*) shows the ring distributor with interconnector *AC*. The current in the interconnector can be found by applying Thevenin's theorem.

E_0 = Voltage between points *A* and *C*

= 250 – 239·904 = 10·096 V

R_0 = Resistance viewed from points *A* and *C*

$$= \frac{(0\cdot 02 + 0\cdot 018)\,(0\cdot 02 + 0\cdot 025)}{(0\cdot 02 + 0\cdot 018) + (0\cdot 02 + 0\cdot 025)} = 0\cdot 02\ \Omega$$

R_{AC} = Resistance of interconnector = 0·02 Ω

Thevenin's equivalent circuit is shown in Fig. 13.41 (*ii*). Current in interconnector *AC*

$$= \frac{E_0}{R_0 + R_{AC}} = \frac{10 \cdot 096}{0 \cdot 02 + 0 \cdot 02} = 252 \cdot 4 \ A \textit{ from A to C}$$

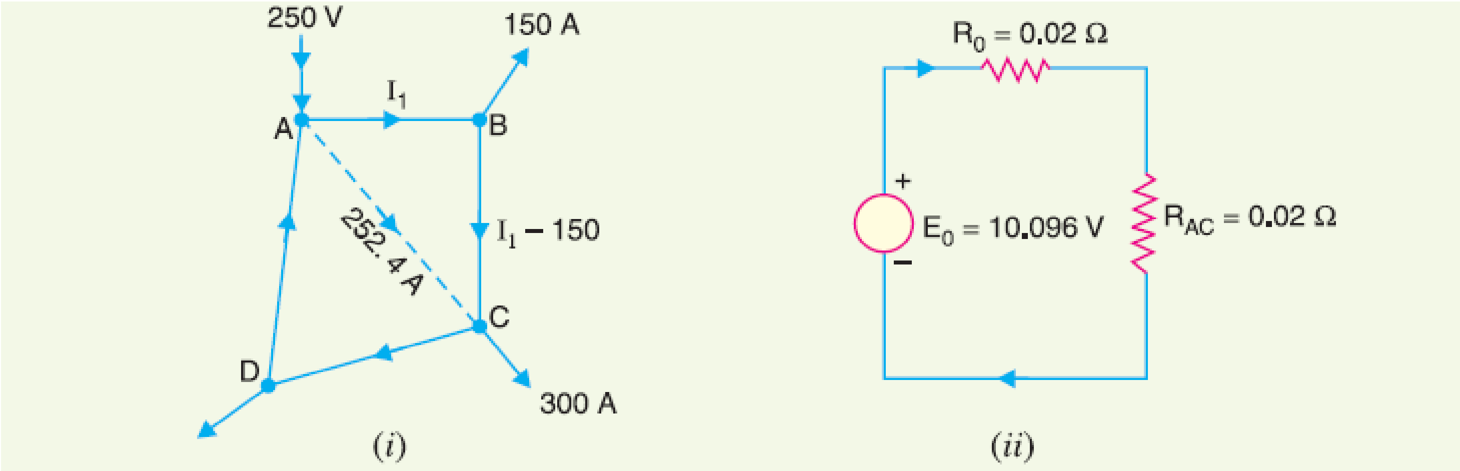


Fig. 13.41

Let us suppose that current in section *AB* is I_1. Then current in section *BC* will be $I_1 - 150$. As the voltage drop round the closed mesh *ABCA* is zero,

$\therefore \quad 0{\cdot}02\, I_1 + 0{\cdot}018\,(I_1 - 150) - 0{\cdot}02 \times 252{\cdot}4 = 0$

or $\quad 0{\cdot}038\, I_1 = 7{\cdot}748$

$\therefore \quad I_1 = 7{\cdot}748/0{\cdot}038 = 203{\cdot}15$ A

The actual distribution of currents in the ring distributor with interconnector will be as shown in Fig. 13.42.

Drop in *AB* $= 203{\cdot}15 \times 0{\cdot}02 = 4{\cdot}063$ V

Drop in *BC* $= 53{\cdot}15 \times 0{\cdot}018$

$= 0{\cdot}960$ V

Drop in *AD* $= 244{\cdot}45 \times 0{\cdot}02 = 4{\cdot}9$ V

$\therefore$ Potential of *B* $= 250 - 4{\cdot}063$

$=$ **245·93 V**

Potential of *C* $= 245{\cdot}93 - 0{\cdot}96$

$=$ **244·97 V**

Potential of *D* $= 250 - 4{\cdot}9 =$ **245·1 V**

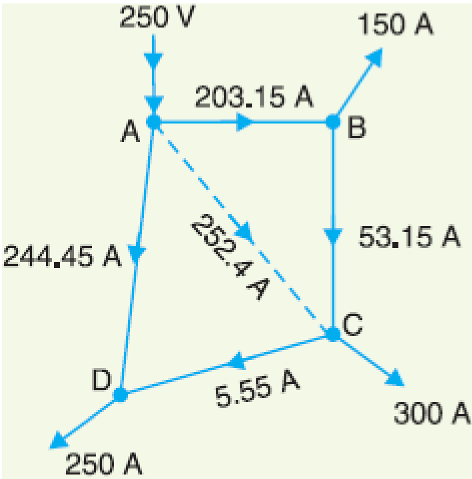


Fig. 13.42

It may be seen that with the use of interconnector, the voltage drops in the various sections of the distributor are reduced.

Example 13.25. *Fig. 13.43 shows a ring distributor with interconnector BD. The supply is given at point A. The resistances of go and return conductors of various sections are indicated in the figure. Calculate :*

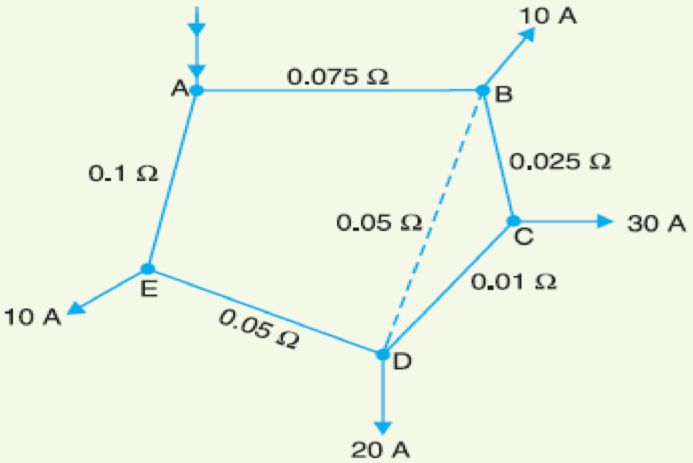


Fig. 13.43

(*i*) *current in the interconnector*

(*ii*) *voltage drop in the interconnector*

Solution. When interconnector *BD* is removed, let the current in branch *AB* be *I*. Then current distribution will be as shown in Fig. 13.44 (*i*). As the total drop round the ring *ABCDEA* is zero,

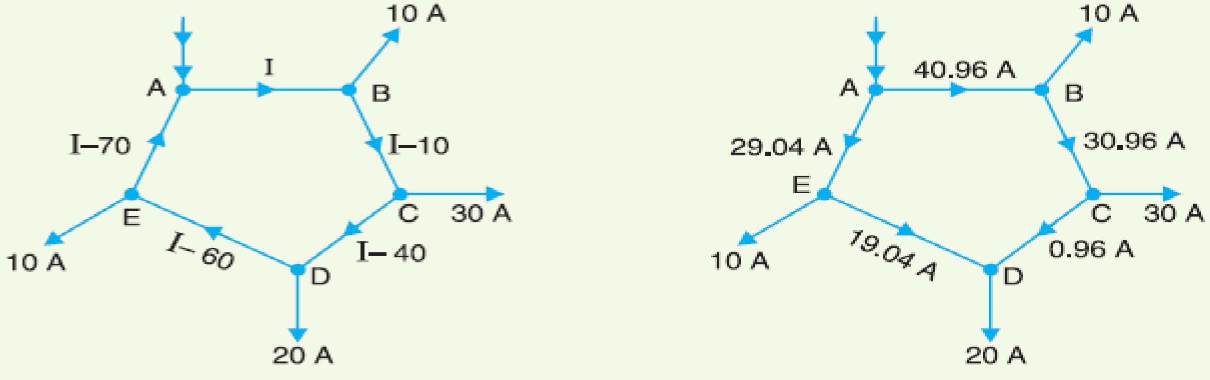


Fig. 13.44

$\therefore \quad 0{\cdot}075\, I + 0{\cdot}025\,(I - 10) + 0{\cdot}01\,(I - 40) + 0{\cdot}05\,(I - 60) + 0{\cdot}1\,(I - 70) = 0$

or $\quad 0{\cdot}26\, I = 10{\cdot}65$

$$\therefore \quad I = \frac{10\cdot 65}{0\cdot 26} = 40\cdot 96 \text{ A}$$

The actual distribution of currents will be as shown in Fig. 13.44 (*ii*).

$$\text{Voltage drop along } BCD = 30{\cdot}96 \times 0{\cdot}025 + 0{\cdot}96 \times 0{\cdot}01$$
$$= 0{\cdot}774 + 0{\cdot}0096 = 0{\cdot}7836 \text{ V}$$

This is equal to Thevenin's open circuited voltage E_0 *i.e.*

$$E_0 = 0{\cdot}7836 \text{ V}$$

$$R_0 = \text{Resistance viewed from } B \text{ and } D$$

$$= \frac{(0\cdot 075 + 0\cdot 1 + 0\cdot 05)\,(0\cdot 025 + 0\cdot 01)}{(0\cdot 075 + 0\cdot 1 + 0\cdot 05) + (0\cdot 025 + 0\cdot 01)}$$

$$= \frac{(0\cdot 225)\,(0\cdot 035)}{0\cdot 225 + 0.035} = 0\cdot 03\ \Omega$$

(*i*) Current in interconnector *BD* is

$$I_{BD} = \frac{E_0}{R_0 + R_{BD}} = \frac{0\cdot 7836}{0\cdot 03 + 0.05} = \mathbf{9.8\ A}$$

(*ii*) Voltage drop along interconnector *BD*

$$= I_{BD}\, R_{BD} = 9{\cdot}8 \times 0{\cdot}05 = \mathbf{0{\cdot}49\ V}$$

Introduction

In the beginning of electrical age, electricity was generated, transmitted and distributed as direct current. The principal disadvantage of d.c. system was that voltage level could not readily be changed, except by the use of rotating machinery, which in most cases was too expensive. With the development of transformer by George Westinghouse, a.c. system has become so predominant as to make d.c. system practically extinct in most parts of the world. The present day large power system has been possible only due to the adoption of a.c. system.

Now-a-days, electrical energy is generated, transmitted and distributed in the form of alternating current as an economical proposition. The electrical energy produced at the power station is transmitted at very high voltages by 3-phase, 3-wire system to step-down sub-stations for distribution. The distribution system consists of two parts *viz.* primary distribution and secondary distribution. The primary distribution circuit is 3-phase, 3-wire and operates at voltages (3·3 or 6·6 or 11kV) somewhat higher than general utilisation levels. It delivers power to the secondary distribution circuit through distribution transformers situated near consumers' localities. Each distribution transformer steps down the voltage to 400 V and power is distributed to ultimate consumers' by 400/230 V, 3-phase, 4-wire system. In this chapter, we shall focus our attention on the various aspects of a.c. distribution.

14.1 A.C. Distribution Calculations

A.C. distribution calculations differ from those of d.c. distribution in the following respects :

(*i*) In case of d.c. system, the voltage drop is due to resistance alone. However, in a.c. system, the voltage drops are due to the combined effects of resistance, inductance and capacitance.

(*ii*) In a d.c. system, additions and subtractions of currents or voltages are done arithmetically but in case of a.c. system, these operations are done vectorially.

(*iii*) In an a.c. system, power factor (p.f.) has to be taken into account. Loads tapped off form the distributor are generally at different power factors. There are two ways of referring power factor *viz*

(*a*) It may be referred to supply or receiving end voltage which is regarded as the reference vector.

(*b*) It may be referred to the voltage at the load point itself.

There are several ways of solving a.c. distribution problems. However, symbolic notation method has been found to be most convenient for this purpose. In this method, voltages, currents and impedances are expressed in complex notation and the calculations are made exactly as in d.c. distribution.

14.2 Methods of Solving A.C. Distribution Problems

In a.c. distribution calculations, power factors of various load currents have to be considered since currents in different sections of the distributor will be the vector sum of load currents and not the arithmetic sum. The power factors of load currents may be given (*i*) *w.r.t.* receiving or sending end voltage or (*ii*) *w.r.t.* to load voltage itself. Each case shall be discussed separately.

(*i*) Power factors referred to receiving end voltage. Consider an a.c. distributor AB with concentrated loads of I_1 and I_2 tapped off at points C and B as shown in Fig. 14.1. Taking the receiving end voltage V_B as the reference vector, let lagging power factors at C and B be $\cos\phi_1$ and $\cos\phi_2$ *w.r.t.* V_B. Let R_1, X_1 and R_2, X_2 be the resistance and reactance of sections AC and CB of the distributor.

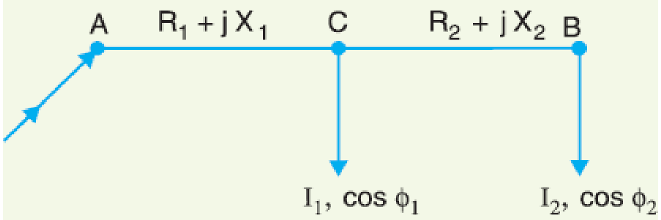


Fig. 14.1

Impedance of section AC, $\overrightarrow{Z_{AC}} = R_1 + j X_1$

Impedance of section CB, $\overrightarrow{Z_{CB}} = R_2 + j X_2$

Load current at point C, $\overrightarrow{I_1} = I_1(\cos\phi_1 - j\sin\phi_1)$

Load current at point B, $\overrightarrow{I_2} = I_2(\cos\phi_2 - j\sin\phi_2)$

Current in section CB, $\overrightarrow{I_{CB}} = \overrightarrow{I_2} = I_2(\cos\phi_2 - j\sin\phi_2)$

Current in section AC,
$$\overrightarrow{I_{AC}} = \overrightarrow{I_1} + \overrightarrow{I_2} = I_1(\cos\phi_1 - j\sin\phi_1) + I_2(\cos\phi_2 - j\sin\phi_2)$$

Voltage drop in section CB,
$$\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}}\,\overrightarrow{Z_{CB}} = I_2(\cos\phi_2 - j\sin\phi_2)(R_2 + jX_2)$$

Voltage drop in section AC,
$$\overrightarrow{V_{AC}} = \overrightarrow{I_{AC}}\,\overrightarrow{Z_{AC}} = \left(\overrightarrow{I_1} + \overrightarrow{I_2}\right) Z_{AC}$$

$$= [I_1(\cos\phi_1 - j\sin\phi_1) + I_2(\cos\phi_2 - j\sin\phi_2)]\,[R_1 + jX_1]$$

Sending end voltage, $\vec{V_A} = \vec{V_B} + \vec{V_{CB}} + \vec{V_{AC}}$

Sending end current, $\vec{I_A} = \vec{I_1} + \vec{I_2}$

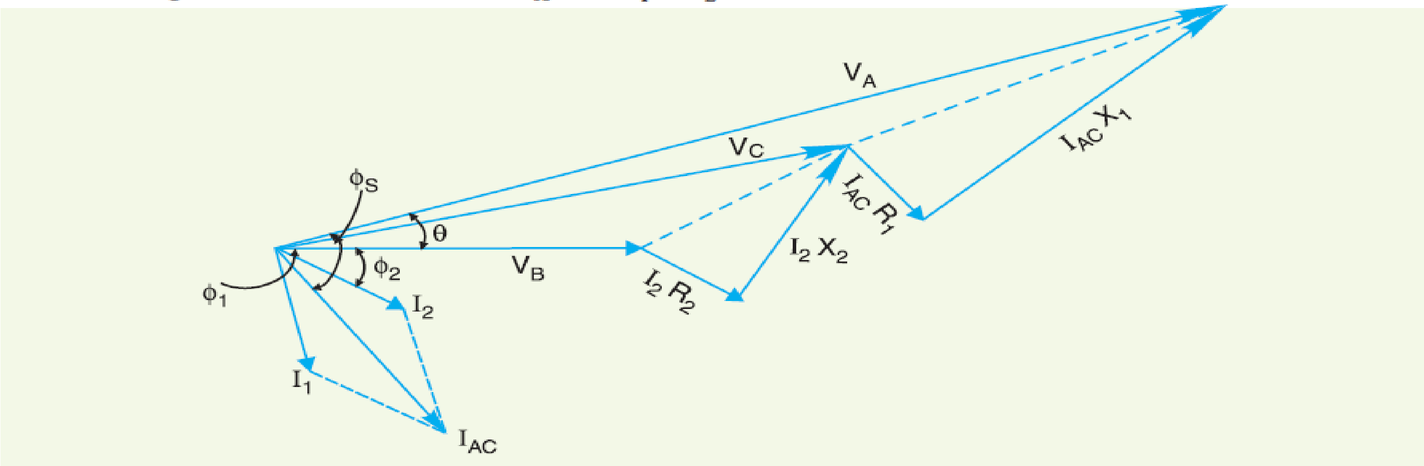


Fig. 14.2

The vector diagram of the a.c. distributor under these conditions is shown in Fig. 14.2. Here, the receiving end voltage V_B is taken as the reference vector. As power factors of loads are given *w.r.t.* V_B, therefore, I_1 and I_2 lag behind V_B by ϕ_1 and ϕ_2 respectively.

***(ii)* Power factors referred to respective load voltages.** Suppose the power factors of loads in the previous Fig. 14.1 are referred to their respective load voltages. Then ϕ_1 is the phase angle between V_C and I_1 and ϕ_2 is the phase angle between V_B and I_2. The vector diagram under these conditions is shown in Fig. 14.3.

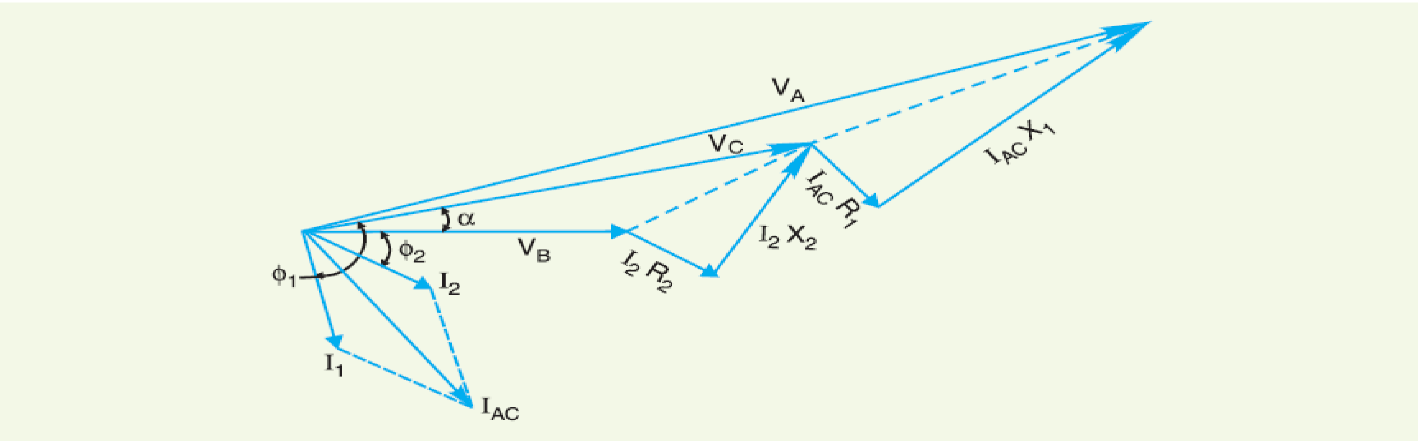


Fig. 14.3

Voltage drop in section $CB = \vec{I_2}\,\vec{Z_{CB}} = I_2(\cos\phi_2 - j\sin\phi_2)(R_2 + jX_2)$

Voltage at point $C = \vec{V_B}$ + Drop in section $CB = V_C \angle \alpha$ (say)

Now $\vec{I_1} = I_1 \angle -\phi_1$ *w.r.t.* voltage V_C

$\therefore$ $\vec{I_1} = I_1 \angle -(\phi_1 - \alpha)$ *w.r.t.* voltage V_B

i.e. $\vec{I_1} = I_1[\cos(\phi_1 - \alpha) - j\sin(\phi_1 - \alpha)]$

Now $\vec{I_{AC}} = \vec{I_1} + \vec{I_2}$

$$= I_1[\cos(\phi_1 - \alpha) - j\sin(\phi_1 - \alpha)] + I_2(\cos\phi_2 - j\sin\phi_2)$$

Voltage drop in section $AC = \vec{I_{AC}}\,\vec{Z_{AC}}$

$\therefore$ Voltage at point $A = V_B$ + Drop in CB + Drop in AC

Example 14.1. *A single phase a.c. distributor AB 300 metres long is fed from end A and is loaded as under :*

(*i*) *100 A at 0·707 p.f. lagging 200 m from point A*

(*ii*) *200 A at 0·8 p.f. lagging 300 m from point A*

The load resistance and reactance of the distributor is 0·2 Ω and 0·1 Ω per kilometre. Calculate the total voltage drop in the distributor. The load power factors refer to the voltage at the far end.

Solution. Fig. 14.4 shows the single line diagram of the distributor.

Impedance of distributor/km $= (0{\cdot}2 + j\,0{\cdot}1)\ \Omega$

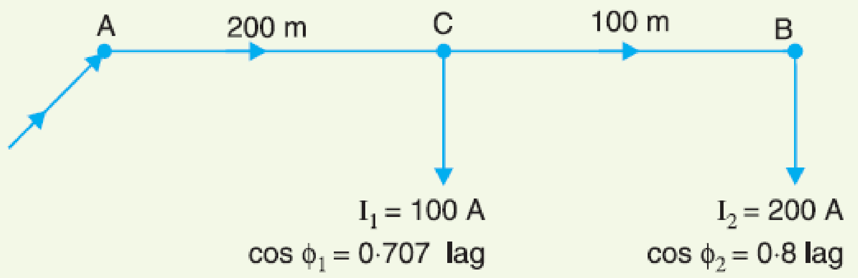


Fig. 14.4

Impedance of section *AC*, $\overrightarrow{Z_{AC}} = (0{\cdot}2 + j\,0{\cdot}1) \times 200/1000 = (0{\cdot}04 + j\,0{\cdot}02)\ \Omega$

Impedance of section *CB*, $\overrightarrow{Z_{CB}} = (0{\cdot}2 + j\,0{\cdot}1) \times 100/1000 = (0{\cdot}02 + j\,0{\cdot}01)\ \Omega$

Taking voltage at the far end *B* as the reference vector, we have,

Load current at point *B*, $\overrightarrow{I_2} = I_2\,(\cos\phi_2 - j\sin\phi_2) = 200\,(0{\cdot}8 - j\,0{\cdot}6)$

$= (160 - j\,120)$ A

Load current at point *C*, $\overrightarrow{I_1} = I_1\,(\cos\phi_1 - j\sin\phi_1) = 100\,(0{\cdot}707 - j\,0{\cdot}707)$

$= (70{\cdot}7 - j\,70{\cdot}7)$ A

Current in section *CB*, $\overrightarrow{I_{CB}} = \overrightarrow{I_2} = (160 - j\,120)$ A

Current in section *AC*, $\overrightarrow{I_{AC}} = \overrightarrow{I_1} + \overrightarrow{I_2} = (70{\cdot}7 - j\,70{\cdot}7) + (160 - j\,120)$

$= (230{\cdot}7 - j\,190{\cdot}7)$ A

Voltage drop in section *CB*, $\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}}\ \overrightarrow{Z_{CB}} = (160 - j\,120)\,(0{\cdot}02 + j\,0{\cdot}01)$

$= (4{\cdot}4 - j\,0{\cdot}8)$ volts

Voltage drop in section *AC*, $\overrightarrow{V_{AC}} = \overrightarrow{I_{AC}}\ \overrightarrow{Z_{AC}} = (230{\cdot}7 - j\,190{\cdot}7)\,(0{\cdot}04 + j\,0{\cdot}02)$

$= (13{\cdot}04 - j\,3{\cdot}01)$ volts

Voltage drop in the distributor $= \overrightarrow{V_{AC}} + \overrightarrow{V_{CB}} = (13{\cdot}04 - j\,3{\cdot}01) + (4{\cdot}4 - j\,0{\cdot}8)$

$= (17{\cdot}44 - j\,3{\cdot}81)$ volts

Magnitude of drop $= \sqrt{(17\cdot 44)^2 + (3\cdot 81)^2}$ = **17·85 V**

Example 14.2. *A single phase distributor 2 kilometres long supplies a load of 120 A at 0·8 p.f. lagging at its far end and a load of 80 A at 0·9 p.f. lagging at its mid-point. Both power factors are* *referred to the voltage at the far end. The resistance and reactance per km (go and return) are 0·05 Ω and 0·1 Ω respectively. If the voltage at the far end is maintained at 230 V, calculate :*

(i) voltage at the sending end

(ii) phase angle between voltages at the two ends.

Solution. Fig. 14.5 shows the distributor *AB* with *C* as the mid-point

Impedance of distributor/km $= (0{\cdot}05 + j\,0{\cdot}1)\ \Omega$

Impedance of section *AC*, $\vec{Z}_{AC} = (0{\cdot}05 + j\,0{\cdot}1) \times 1000/1000 = (0{\cdot}05 + j\,0{\cdot}1)\ \Omega$

Impedance of section *CB*, $\vec{Z}_{CB} = (0{\cdot}05 + j\,0{\cdot}1) \times 1000/1000 = (0{\cdot}05 + j\,0{\cdot}1)\ \Omega$

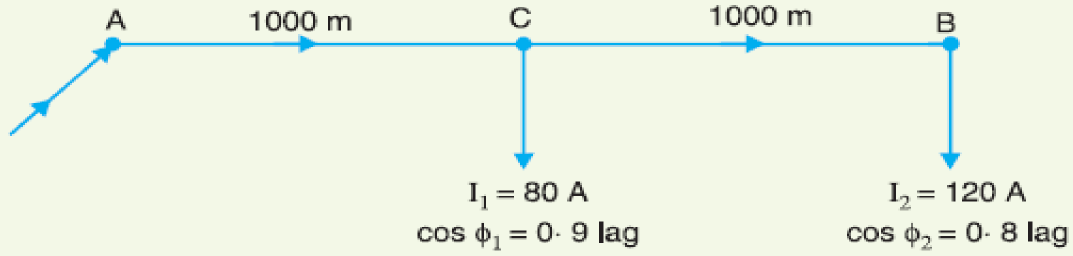


Fig. 14.5

Let the voltage V_B at point *B* be taken as the reference vector.

Then, $\vec{V}_B = 230 + j\,0$

(*i*) Load current at point *B*, $\vec{I}_2 = 120\,(0{\cdot}8 - j\,0{\cdot}6) = 96 - j\,72$

Load current at point *C*, $\vec{I}_1 = 80\,(0{\cdot}9 - j\,0{\cdot}436) = 72 - j\,34{\cdot}88$

Current in section *CB*, $\vec{I}_{CB} = \vec{I}_2 = 96 - j\,72$

Current in section *AC*, $\vec{I}_{AC} = \vec{I}_1 + \vec{I}_2 = (72 - j\,34{\cdot}88) + (96 - j\,72)$

$= 168 - j\,106{\cdot}88$

Drop in section *CB*, $\vec{V}_{CB} = \vec{I}_{CB}\,\vec{Z}_{CB} = (96 - j\,72)\,(0{\cdot}05 + j\,0{\cdot}1)$

$= 12 + j\,6$

Drop in section *AC*, $\vec{V}_{AC} = \vec{I}_{AC}\,\vec{Z}_{AC} = (168 - j\,106{\cdot}88)\,(0{\cdot}05 + j\,0{\cdot}1)$

$= 19{\cdot}08 + j\,11{\cdot}45$

∴ Sending end voltage, $\vec{V}_A = \vec{V}_B + \vec{V}_{CB} + \vec{V}_{AC}$

$= (230 + j\,0) + (12 + j\,6) + (19.08 + j\,11.45)$

$= 261.08 + j\,17.45$

Its magnitude is $= \sqrt{(261{\cdot}08)^2 + (17{\cdot}45)^2}$ = **261·67 V**

(*ii*) The phase difference θ between V_A and V_B is given by :

$$\tan\theta = \frac{17{\cdot}45}{261{\cdot}08} = 0{\cdot}0668$$

∴ $\theta = \tan^{-1} 0{\cdot}0668 =$ **3·82°**

Example 14.3. *A single phase distributor one km long has resistance and reactance per conductor of 0·1 Ω and 0·15 Ω respectively. At the far end, the voltage V_B = 200 V and the current is 100 A at a p.f. of 0·8 lagging. At the mid-point M of the distributor, a current of 100 A is tapped at a p.f. of 0·6 lagging with reference to the voltage V_M at the mid-point. Calculate :*

(*i*) *voltage at mid-point*

(*ii*) *sending end voltage V_A*

(*iii*) *phase angle between V_A and V_B*

Solution. Fig. 14.6 shows the single line diagram of the distributor *AB* with *M* as the mid-point.

Total impedance of distributor $= 2(0\cdot1 + j\,0\cdot15) = (0\cdot2 + j\,0\cdot3)\ \Omega$

Impedance of section *AM*, $\overrightarrow{Z_{AM}} = (0\cdot1 + j\,0\cdot15)\ \Omega$

Impedance of section *MB*, $\overrightarrow{Z_{MB}} = (0\cdot1 + j\,0\cdot15)\ \Omega$

Let the voltage V_B at point *B* be taken as the reference vector.

Then, $\overrightarrow{V_B} = 200 + j\,0$

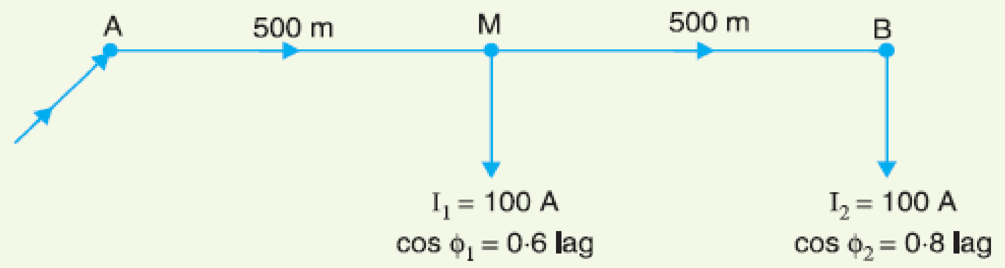


Fig. 14.6

(*i*) Load current at point *B*, $\overrightarrow{I_2} = 100\,(0\cdot8 - j\,0\cdot6) = 80 - j\,60$

Current in section *MB*, $\overrightarrow{I_{MB}} = \overrightarrow{I_2} = 80 - j\,60$

Drop in section *MB*, $\overrightarrow{V_{MB}} = \overrightarrow{I_{MB}}\ \overrightarrow{Z_{MB}}$

$= (80 - j\,60)\,(0\cdot1 + j\,0\cdot15) = 17 + j\,6$

∴ Voltage at point *M*, $\overrightarrow{V_M} = \overrightarrow{V_B} + \overrightarrow{V_{MB}} = (200 + j\,0) + (17 + j\,6)$

$= 217 + j\,6$

Its magnitude is $= \sqrt{(217)^2 + (6)^2}$ = **217·1 V**

Phase angle between V_M and V_B, $\alpha = \tan^{-1} 6/217 = \tan^{-1} 0{\cdot}0276 = 1{\cdot}58^\circ$

(*ii*) The load current I_1 has a lagging p.f. of 0·6 *w.r.t.* V_M. It lags behind V_M by an angle $\phi_1 = \cos^{-1} 0{\cdot}6 = 53{\cdot}13^\circ$

∴ Phase angle between I_1 and V_B, $\phi'_1 = \phi_1 - \alpha = 53{\cdot}13^\circ - 1{\cdot}58 = 51{\cdot}55^\circ$

Load current at M, $\vec{I_1} = I_1 (\cos \phi_1' - j \sin \phi_1') = 100 (\cos 51{\cdot}55^\circ - j \sin 51{\cdot}55^\circ)$

$= 62{\cdot}2 - j\,78{\cdot}3$

Current in section AM, $\overrightarrow{I_{AM}} = \vec{I_1} + \vec{I_2} = (62{\cdot}2 - j\,78{\cdot}3) + (80 - j\,60)$

$= 142{\cdot}2 - j\,138{\cdot}3$

Drop in section AM, $\overrightarrow{V_{AM}} = \overrightarrow{I_{AM}}\,\overrightarrow{Z_{AM}} = (142{\cdot}2 - j\,138{\cdot}3)(0{\cdot}1 + j\,0{\cdot}15)$

$= 34{\cdot}96 + j\,7{\cdot}5$

Sending end voltage, $\vec{V_A} = \vec{V_M} + \overrightarrow{V_{AM}} = (217 + j\,6) + (34{\cdot}96 + j\,7{\cdot}5)$

$= 251{\cdot}96 + j\,13{\cdot}5$

Its magnitude is $= \sqrt{(251{\cdot}96)^2 + (13{\cdot}5)^2}$ = **252·32 V**

(*iii*) The phase difference θ between V_A and V_B is given by :

$$\tan\theta = 13{\cdot}5/251{\cdot}96 = 0{\cdot}05358$$

∴ $\theta = \tan^{-1} 0{\cdot}05358 =$ **3·07°**

Hence supply voltage is 252·32 V and leads V_B by 3·07°.

Example 14.4. *A single phase ring distributor ABC is fed at A. The loads at B and C are 20 A at 0.8 p.f. lagging and 15 A at 0.6 p.f. lagging respectively ; both expressed with reference to the voltage at A. The total impedance of the three sections AB, BC and CA are (1 + j 1), (1+ j2) and (1 + j3) ohms respectively. Find the total current fed at A and the current in each section. Use Thevenin's theorem to obtain the results.*

Solution. Fig. 14.7 (*i*) shows the ring distributor *ABC*. Thevenin's theorem will be used to solve this problem. First, let us find the current in *BC*. For this purpose, imagine that section *BC* is removed as shown in Fig. 14.7 (*ii*).

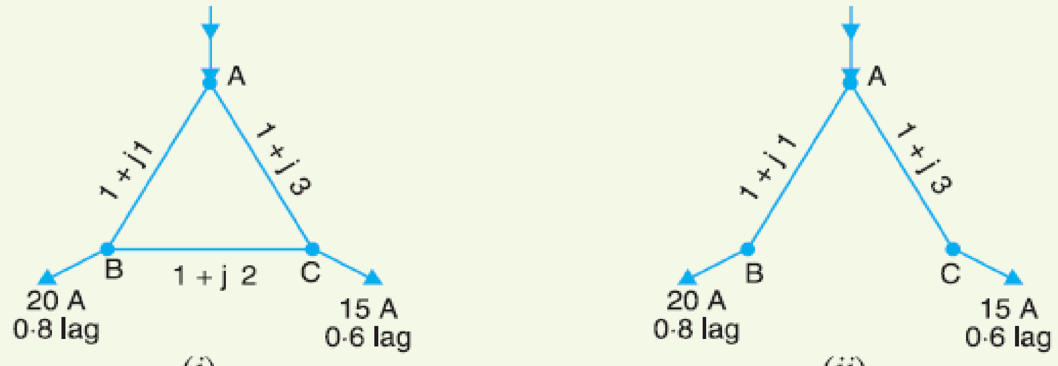


Fig. 14.7

Referring to Fig.14.7 (*ii*), we have,

Current in section *AB* $= 20\,(0{\cdot}8 - j\,0.6) = 16 - j\,12$

Current in section *AC* $= 15\,(0{\cdot}6 - j\,0{\cdot}8) = 9 - j\,12$

Voltage drop in section *AB* $= (16 - j\,12)\,(1 + j1) = 28 + j\,4$

Voltage drop in section *AC* $= (9 - j\,12)\,(1 + j\,3) = 45 + j\,15$

Obviously, point *B* is at higher potential than point *C*. The p.d. between *B* and *C* is Thevenin's equivalent circuit e.m.f. E_0 *i.e.*

Thevenin's equivalent circuit e.m.f., E_0 = p.d. between *B* and *C*

$= (45 + j\,15) - (28 + j\,4) = 17 + j\,11$

Thevenin's equivalent impedance Z_o can be found by looking into the network from points *B* and *C*.

Obviously, $Z_0 = (1 + j1) + (1 + j\,3) = 2 + j4$

$$\therefore \quad \text{Current in } BC = \frac{E_0}{Z_0 + \text{Impedance of } BC}$$

$$= \frac{17 + j11}{(2 + j4) + (1 + j2)} = \frac{17 + j11}{3 + j6}$$

$$= 2{\cdot}6 - j\,1{\cdot}53 = \mathbf{3\angle{-30{\cdot}48°}\ A}$$

$$\text{Current in } AB = (16 - j\,12) + (2{\cdot}6 - j\,1{\cdot}53)$$

$$= 18{\cdot}6 - j\,13{\cdot}53 = \mathbf{23\angle{-36{\cdot}03°}\ A}$$

$$\text{Current in } AC = (9 - j\,12) - (2{\cdot}6 - j\,1{\cdot}53)$$

$$= 6{\cdot}4 - j\,10{\cdot}47 = \mathbf{12{\cdot}27\angle{-58{\cdot}56°}\ A}$$

$$\text{Current fed at } A = (16 - j\,12) + (9 - j\,12)$$

$$= 25 - j\,24 = \mathbf{34{\cdot}65\angle{-43{\cdot}83°}\ A}$$

Example 14.5. *A 3-phase, 400V distributor AB is loaded as shown in Fig.14.8. The 3-phase load at point C takes 5A per phase at a p.f. of 0·8 lagging. At point B, a 3-phase, 400 V induction motor is connected which has an output of 10 H.P. with an efficiency of 90% and p.f. 0·85 lagging.*

If voltage at point B is to be maintained at 400 V, what should be the voltage at point A ? The resistance and reactance of the line are 1Ω and 0·5Ω per phase per kilometre respectively.

Solution. It is convenient to consider one phase only. Fig.14.8 shows the single line diagram of the distributor. Impedance of the distributor per phase per kilometre = $(1 + j\,0{\cdot}5)\ \Omega$.

Impedance of section AC, $\overrightarrow{Z_{AC}} = (1 + j\,0{\cdot}5) \times 600/1000 = (0{\cdot}6 + j\,0{\cdot}3)\ \Omega$

Impedance of section CB, $\overrightarrow{Z_{CB}} = (1 + j\,0{\cdot}5) \times 400/1000 = (0{\cdot}4 + j\,0{\cdot}2)\ \Omega$

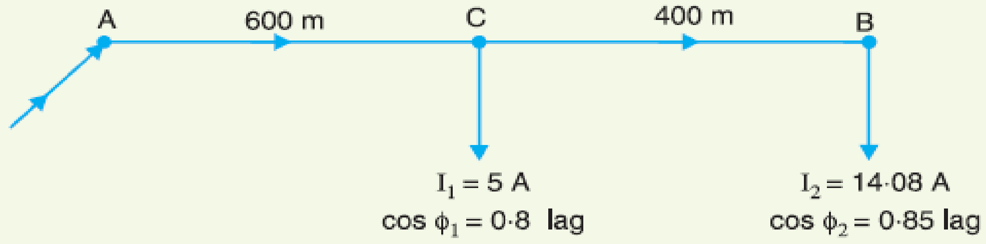


Fig. 14.8

Phase voltage at point B, $V_B = 400/\sqrt{3} = 231$ V

Let the voltage V_B at point B be taken as the reference vector.

Then, $\overrightarrow{V_B} = 231 + j\,0$

Line current at B
$$= \frac{\text{H.P.} \times 746}{\sqrt{3} \times \text{line voltage} \times \text{p.f.} \times \text{efficiency}}$$
$$= \frac{10 \times 746}{\sqrt{3} \times 400 \times 0{\cdot}85 \times 0{\cdot}9} = 14{\cdot}08 \text{ A}$$

∴ *Current/phase at B, $I_2 = 14{\cdot}08$ A

Load current at B, $\overrightarrow{I_2} = 14{\cdot}08\,(0{\cdot}85 - j\,0{\cdot}527) = 12 - j\,7{\cdot}4$

Load current at C, $\overrightarrow{I_1} = 5\,(0{\cdot}8 - j\,0{\cdot}6) = 4 - j\,3$

Current in section AC, $\overrightarrow{I_{AC}} = \overrightarrow{I_1} + \overrightarrow{I_2} = (4 - j\,3) + (12 - j\,7{\cdot}4)$
$= 16 - j\,10{\cdot}4$

Current in section CB, $\overrightarrow{I_{CB}} = \overrightarrow{I_2} = 12 - j\,7{\cdot}4$

Voltage drop in CB, $\overrightarrow{V}_{CB} = \overrightarrow{I}_{CB}\overrightarrow{Z}_{CB} = (12 - j\,7{\cdot}4)\,(0{\cdot}4 + j\,0{\cdot}2)$
$= 6{\cdot}28 - j\,0{\cdot}56$

Voltage drop in AC, $\overrightarrow{V}_{AC} = \overrightarrow{I}_{AC}\overrightarrow{Z}_{AC} = (16 - j\,10{\cdot}4)\,(0{\cdot}6 + j\,0{\cdot}3)$
$= 12{\cdot}72 - j\,1{\cdot}44$

* In a 3-phase system, if the type of connection is not mentioned, then star connection is understood.

Voltage at A per phase, $\overrightarrow{V}_A = \overrightarrow{V}_B + \overrightarrow{V}_{CB} + \overrightarrow{V}_{AC}$
$= (231 + j\,0) + (6{\cdot}28 - j\,0{\cdot}56) + (12{\cdot}72 - j\,1{\cdot}44)$
$= 250 - j\,2$

Magnitude of V_A/phase $= \sqrt{(250)^2 + (2)^2} = 250$ V

∴ Line voltage at A $= \sqrt{3} \times 250 =$ **433 V**

Example 14.6. *A 3-phase ring main ABCD fed at A at 11 kV supplies balanced loads of 50 A at 0.8 p.f. lagging at B, 120 A at unity p.f. at C and 70 A at 0·866 lagging at D, the load currents being referred to the supply voltage at A. The impedances of the various sections are :*

Section AB = $(1 + j\,0{\cdot}6)\ \Omega$; *Section BC* = $(1{\cdot}2 + j\,0{\cdot}9)\ \Omega$

Section CD = $(0{\cdot}8 + j\,0{\cdot}5)\ \Omega$; *Section DA* = $(3 + j\,2)\ \Omega$

Calculate the currents in various sections and station bus-bar voltages at B, C and D.

Solution. Fig.14.9 shows one phase of the ring main. The problem will be solved by Kirchhoff's laws. Let current in section *AB* be $(x + j\,y)$.

∴ Current in section *BC*, $\overrightarrow{I_{BC}} = (x + j\,y) - 50\,(0{\cdot}8 - j\,0{\cdot}6) = (x - 40) + j\,(y + 30)$

Current in section *CD*, $\overrightarrow{I_{CD}} = [(x - 40) + j\,(y + 30)] - [120 + j\,0]$

$= (x - 160) + j\,(y + 30)$

Current in section *DA*, $\overrightarrow{I_{DA}} = [(x - 160) + j\,(y + 30)] - [70\,(0{\cdot}866 - j\,0{\cdot}5)]$

$= (x - 220{\cdot}6) + j\,(y + 65)$

Drop in section *AB* $= \overrightarrow{I_{AB}}\ \overrightarrow{Z_{AB}} = (x + jy)\,(1 + j0{\cdot}6)$

$= (x - 0{\cdot}6y) + j\,(0{\cdot}6x + y)$

Drop in section *BC* $= \overrightarrow{I_{BC}}\ \overrightarrow{Z_{BC}}$

$= [(x - 40) + j\,(y + 30)]\,[(1{\cdot}2 + j\,0{\cdot}9)]$

$= (1{\cdot}2x - 0{\cdot}9\,y - 75) + j\,(0{\cdot}9x + 1{\cdot}2\,y)$

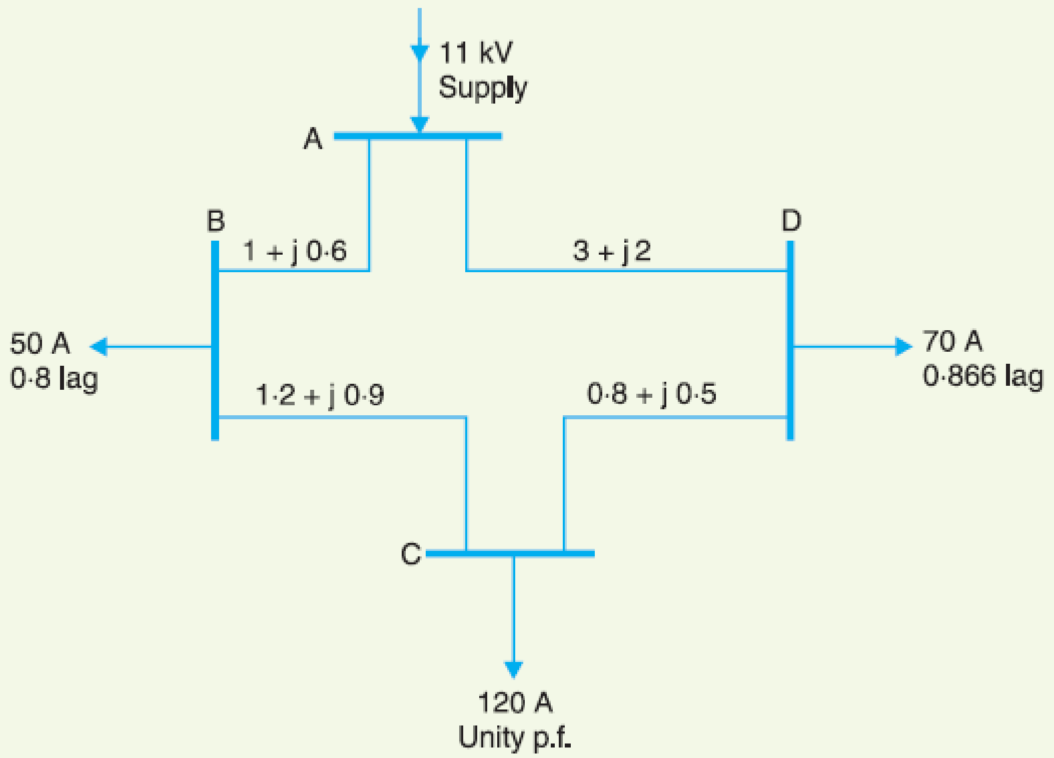


Fig. 14.9

$$\text{Drop in section } CD = \overrightarrow{I_{CD}}\ \overrightarrow{Z_{CD}}$$
$$= [(x - 160) + j\ (y + 30)]\ [(0{\cdot}8 + j\ 0{\cdot}5)]$$
$$= (0{\cdot}8x - 0{\cdot}5y - 143) + j\ (0{\cdot}5x + 0{\cdot}8y - 56)$$
$$\text{Drop in section } DA = \overrightarrow{I_{DA}}\ \overrightarrow{Z_{DA}}$$
$$= [(x - 220{\cdot}6) + j\ (y + 65)]\ [(3 + j\ 2)]$$
$$= (3x - 2y - 791{\cdot}8) + j\ (2x + 3y - 246{\cdot}2)$$

Applying Kirchhoff's voltage law to mesh $ABCDA$, we have,

Drop in AB + Drop in BC + Drop in CD + Drop in DA = 0

or
$$[(x - 0{\cdot}6y) + j\ (0{\cdot}6x + y)] + [(1{\cdot}2x - 0{\cdot}9y - 75) + j\ (0{\cdot}9x + 1{\cdot}2y)] + [(0{\cdot}8x - 0{\cdot}5y - 143) + j\ (0{\cdot}5x + 0{\cdot}8y - 56)] + [(3x - 2y - 791{\cdot}8) + j\ (2x + 3y - 246{\cdot}2)] = 0$$

or
$$(6x - 4y - 1009{\cdot}8) + j\ (4x + 6y - 302{\cdot}2) = 0$$

As the real (or active) and imaginary (or reactive) parts have to be separately zero,

$\therefore \quad 6x - 4y - 1009{\cdot}8 = 0$

and $\quad 4x + 6y - 302{\cdot}2 = 0$

Solving for x and y, we have,

$$x = 139{\cdot}7 \text{ A} \quad ; \quad y = -42{\cdot}8 \text{ A}$$

Current in section AB = **$(139{\cdot}7 - j\ 42{\cdot}8)$ A**

Current in section BC $= (x - 40) + j\ (y + 30)$

$= (139{\cdot}7 - 40) + j\ (-42{\cdot}8 + 30) =$ **$(99{\cdot}7 - j\ 12{\cdot}8)$ A**

Current in section CD $= (x - 160) + j\ (y + 30)$

$= (139{\cdot}7 - 160) + j\ (-42{\cdot}8 + 30)$

$=$ **$(-20{\cdot}3 - j\ 12{\cdot}8)$ A**

Current in section DA $= (x - 220{\cdot}6) + j\ (y + 65)$

$= (139{\cdot}7 - 220{\cdot}6) + j\ (-42{\cdot}8 + 65)$

$=$ **$(-80{\cdot}9 + j\ 22{\cdot}2)$ A**

Voltage at supply end A, $\quad V_A = 11000/\sqrt{3} = 6351$ V/phase

$\therefore$ Voltage at station B, $\quad \overrightarrow{V_B} = \overrightarrow{V_A} - \overrightarrow{I_{AB}}\ \overrightarrow{Z_{AB}}$

$= (6351 + j\ 0) - (139{\cdot}7 - j\ 42{\cdot}8)\ (1 + j\ 0{\cdot}6)$

$=$ **$(6185{\cdot}62 - j\ 41{\cdot}02)$ volts/phase**

Voltage at station C, $\quad \overrightarrow{V_C} = \overrightarrow{V_B} - \overrightarrow{I_{BC}}\ \overrightarrow{Z_{BC}}$

$= (6185{\cdot}62 - j\ 41{\cdot}02) - (99{\cdot}7 - j\ 12{\cdot}8)\ (1{\cdot}2 + j\ 0{\cdot}9)$

$=$ **$(6054{\cdot}46 - j\ 115{\cdot}39)$ volts/phase**

Voltage at station D, $\quad \overrightarrow{V_D} = \vec{V}_C - \overrightarrow{I_{CD}}\ \overrightarrow{Z_{CD}}$

$= (6054{\cdot}46 - j\ 115{\cdot}39) - (-20{\cdot}3 - j\ 12{\cdot}8) \times (0{\cdot}8 + j\ 0{\cdot}5)$

$=$ **$(6064{\cdot}3 - j\ 95)$ volts/phase**

14.3 3-Phase Unbalanced Loads

The 3-phase loads that have the same impedance and power factor in each phase are called balanced loads. The problems on balanced loads can be solved by considering one phase only ; the conditions in the other two phases being similar. However, we may come across a situation when loads are unbalanced *i.e.* each load phase has different impedance and/or power factor. In that case, current and power in each phase will be different. In practice, we may come across the following unbalanced loads :

(*i*) Four-wire star-connected unbalanced load

(*ii*) Unbalanced Δ-connected load

(*iii*) Unbalanced 3-wire, *Y*-connected load

The 3-phase, 4-wire system is widely used for distribution of electric power in commercial and industrial buildings. The single phase load is connected between any line and neutral wire while a 3-phase load is connected across the three lines. The 3-phase, 4-wire system invariably carries *unbalanced loads. In this chapter, we shall only discuss this type of unbalanced load.

14.4 Four-Wire Star-Connected Unbalanced Loads

We can obtain this type of load in two ways. First, we may connect a 3-phase, 4-wire unbalanced load to a 3-phase, 4-wire supply as shown in Fig. 14.10. Note that star point *N* of the supply is connected to the load star point *N*′. Secondly, we may connect single phase loads between any line and the neutral wire as shown in Fig.14.11. This will also result in a 3-phase, 4-wire **unbalanced load because it is rarely possible that single phase loads on all the three phases have the same magnitude and power factor. Since the load is unbalanced, the line currents will be different in magnitude and displaced from one another by unequal angles. The current in the neutral wire will be the phasor sum of the three line currents *i.e.*

Current in neutral wire, $I_N = I_R + I_Y + I_B$ ...*phasor sum*

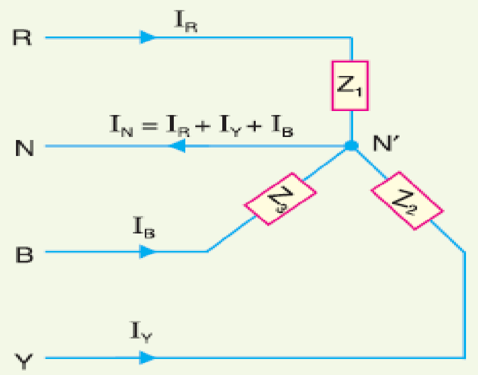


Fig. 14.10

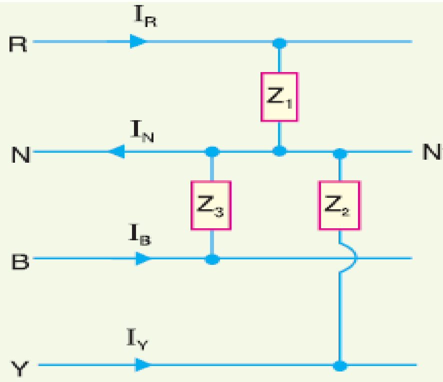


Fig. 14.11

The following points may be noted carefully :

(*i*) Since the neutral wire has negligible resistance, supply neutral *N* and load neutral *N*′ will be at the same potential. It means that voltage across each impedance is equal to the phase voltage of the supply. However, current in each phase (or line) will be different due to unequal impedances.

(*ii*) The amount of current flowing in the neutral wire will depend upon the magnitudes of line currents and their phasor relations. In most circuits encountered in practice, the neutral current is equal to or smaller than one of the line currents. The exceptions are those circuits having severe unbalance.

* No doubt 3-phase loads (*e.g.* 3-phase motors) connected to this supply are balanced but when we add single phase loads (*e.g.* lights, fans etc.), the balance is lost. It is because it is rarely possible that single phase loads on all the three phases have the same magnitude and power factor.

** In actual practice, we never have an unbalanced 3-phase, 4-wire load. Most of the 3-phase loads (*e.g.* 3-phase motors) are 3-phase, 3-wire and are balanced loads. In fact, these are the single phase loads on the 3-phase, 4-wire supply which constitute unbalanced, 4-wire *Y*-connected load.

Example 14.7. *Non-reactive loads of 10 kW, 8 kW and 5 kW are connected between the neutral and the red, yellow and blue phases respectively of a 3-phase, 4-wire system. The line voltage is 400V. Calculate (i) the current in each line and (ii) the current in the neutral wire.*

Solution. This is a case of unbalanced load so that the line currents (and hence the phase currents) in the three lines will be different. The current in the *neutral wire will be equal to the phasor sum of three line currents as shown in Fig. 14.12.

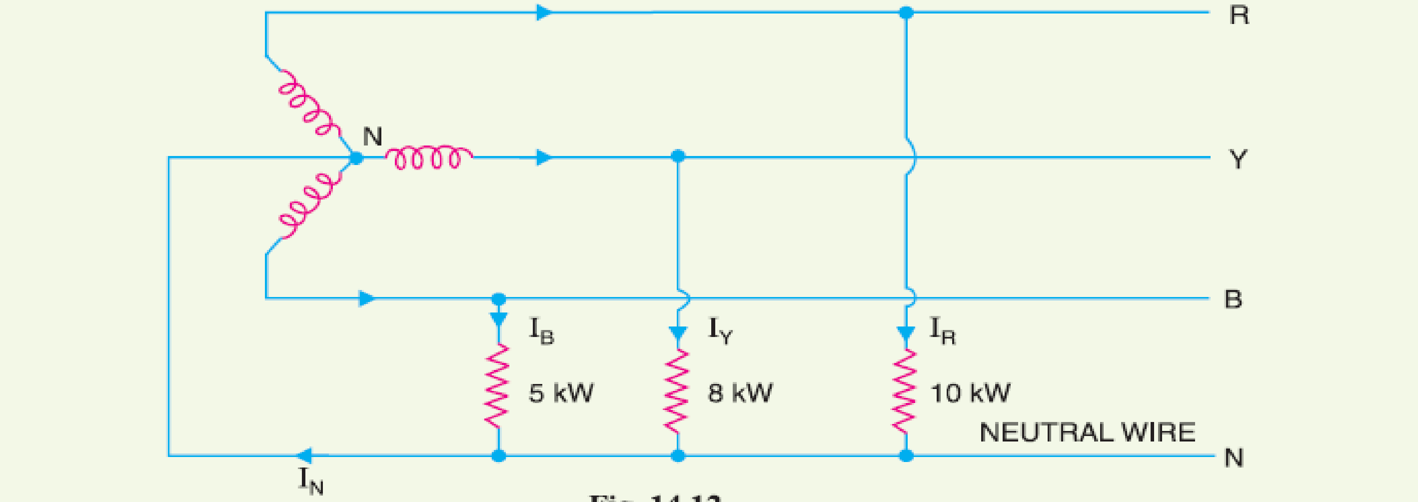


Fig. 14.12

(i)

$$\text{Phase voltage} = 400/\sqrt{3} = 231 \text{ V}$$

$$I_R = 10 \times 10^3/231 = \mathbf{43{\cdot}3\ A}$$

$$I_Y = 8 \times 10^3/231 = \mathbf{34{\cdot}6\ A}$$

$$I_B = 5 \times 10^3/231 = \mathbf{21{\cdot}65\ A}$$

(ii) The three lines currents are represented by the respective phasors in Fig. 14.13. Note that the three line currents are of different magnitude but displaced 120° from one another. The current in the neutral wire will be the phasor sum of the three line currents.

Resolving the three currents along *x*-axis and *y*-axis, we have,

$$\text{Resultant horizontal component} = I_Y \cos 30^\circ - I_B \cos 30^\circ$$

$$= 34{\cdot}6 \times 0{\cdot}866 - 21{\cdot}65 \times 0{\cdot}866 = 11{\cdot}22 \text{ A}$$

$$\text{Resultant vertical component} = I_R - I_Y \cos 60^\circ - I_B \cos 60^\circ$$

$$= 43{\cdot}3 - 34{\cdot}6 \times 0{\cdot}5 - 21{\cdot}65 \times 0{\cdot}5 = 15{\cdot}2 \text{ A}$$

As shown in Fig. 14.14, current in neutral wire is

$$I_N = \sqrt{(11\cdot22)^2 + (15\cdot2)^2} = \mathbf{18{\cdot}9\ A}$$

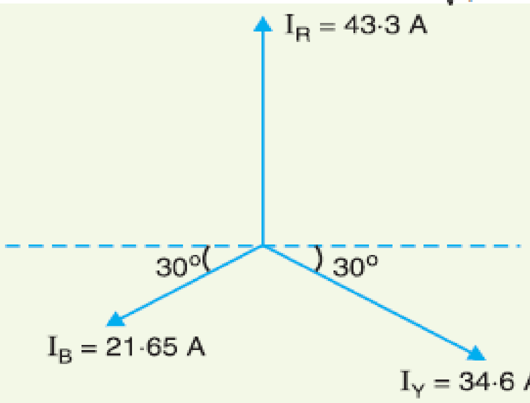


Fig. 14.13

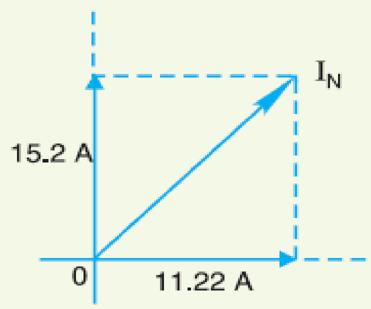


Fig. 14.14

* Had the load been balanced (*i.e.* each phase having identical load), the current in the neutral wire would have been zero.

Example 14.8. *A 3-phase, 4-wire system supplies power at 400 V and lighting at 230 V. If the lamps is use require 70, 84 and 33 amperes in each of the three lines, what should be the current in the neutral wire ? If a 3-phase motor is now started, taking 200 A from the lines at a p.f. of 0·2 lagging, what should be the total current in each line and the neutral wire ? Find also the total power supplied to the lamps and the motor.*

Solution. Fig. 14.15 shows the lamp load and motor load on 400 V/230 V, 3-phase, 4-wire sypply.

Lamp load alone. If there is lamp load alone, the line currents in phases *R*, *Y* and *B* are 70 *A*, 84 *A* and 33 *A* respectively. These currents will be 120° apart (assuming phase sequence *RYB*) as shown in Fig.14.16.

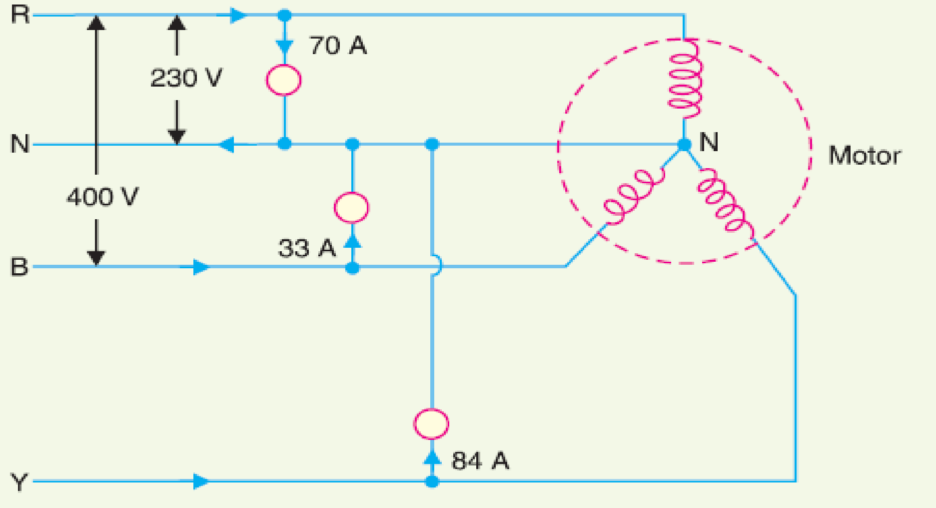


Fig. 14.15

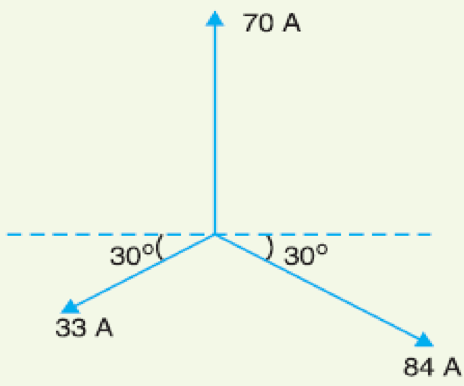


Fig. 14.16

Resultant *H*-component $= 84 \cos 30° - 33 \cos 30° = 44{\cdot}17$ A

Resultant V-component $= 70 - 33 \cos 60° - 84 \cos 60° = 11{\cdot}5$ A

∴ Neutral current, $I_N = \sqrt{(44{\cdot}17)^2 + (11{\cdot}5)^2} =$ **45·64 A**

Both lamp load and motor load

When motor load is also connected along with lighting load, there will be no change in current in the neutral wire. It is because the motor load is balanced and hence no current will flow in the neutral wire due to this load.

∴ Neutral current, $I_N =$ **45·64 A** ...*same as before*

The current in each line is the phasor sum of the line currents due to lamp load and motor load.

Active component of motor current $= 200 \times \cos \phi_m = 200 \times 0{\cdot}2 = 40$ A

Reactive component of motor current $= 200 \times \sin \phi_m = 200 \times 0{\cdot}98 = 196$ A

$$\therefore \quad I_R = \sqrt{(\text{sum of active comp.})^2 + (\text{reactive comp.})^2}$$

$$= \sqrt{(40+70)^2 + (196)^2} = \textbf{224·8 A}$$

$$I_Y = \sqrt{(40+84)^2 + (196)^2} = \textbf{232 A}$$

$$I_B = \sqrt{(40+33)^2 + (196)^2} = \textbf{209·15 A}$$

Power supplied

Power supplied to lamps $= 230\,(70 + 84 + 33) \times 1 =$ **43010 W** $(\because \cos \phi_L = 1)$

Power supplied to motor $= \sqrt{3}\ V_L I_L \cos \phi_m$

$$= \sqrt{3} \times 400 \times 200 \times 0{\cdot}2 = \textbf{27712 W}$$

Example 14.9. *The three line leads of a 400/230 V, 3-phase, 4-wire supply are designated as R, Y and B respectively. The fourth wire or neutral wire is designated as N. The phase sequence is RYB. Compute the currents in the four wires when the following loads are connected to this supply :*

From R to N : 20 kW, unity power factor

From Y to N : 28·75 kVA, 0·866 lag

From B to N : 28·75 kVA, 0·866 lead

If the load from B to N is removed, what will be the value of currents in the four wires ?

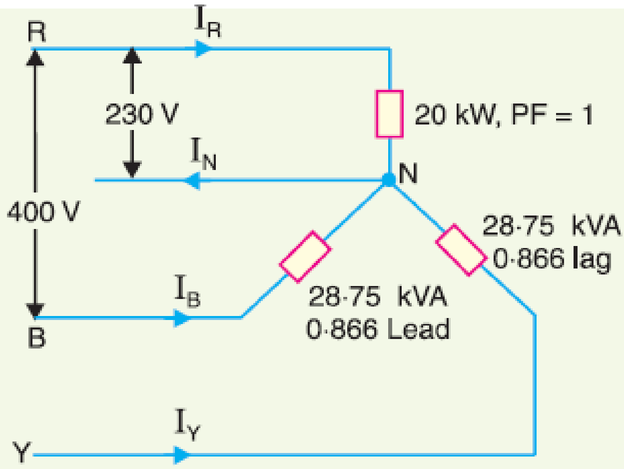


Fig. 14.17

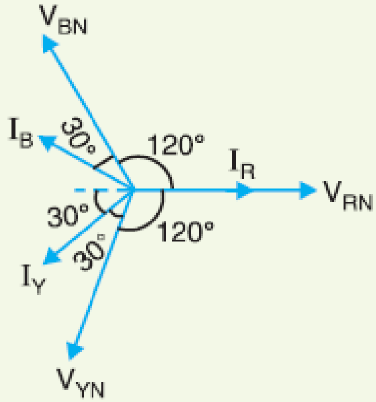


Fig. 14.18

Solution. Fig. 14.17 shows the circuit diagram whereas Fig.14.18 shows its phasor diagram. The current I_R is in phase with V_{RN}, current I_Y lags behind its phase voltage V_{YN} by $\cos^{-1} 0{\cdot}866 = 30°$ and the current I_B leads its phase voltage V_{BN} by $\cos^{-1} 0{\cdot}866 = 30°$.

$$I_R = 20 \times 10^3/230 = \mathbf{89{\cdot}96\ A}$$
$$I_Y = 28{\cdot}75 \times 10^3/230 = \mathbf{125\ A}$$
$$I_B = 28{\cdot}75 \times 10^3/230 = \mathbf{125\ A}$$

The current in the neutral wire will be equal to the phasor sum of the three line currents I_R, I_Y and I_B. Referring to the phasor diagram in Fig.14.18 and resolving these currents along x-axis and y-axis, we have,

Resultant X-component $= 86{\cdot}96 - 125 \cos 30° - 125 \cos 30°$
$= 86{\cdot}96 - 108{\cdot}25 - 108{\cdot}25 = -129{\cdot}54$ A

Resultant Y-component $= 0 + 125 \sin 30° - 125 \sin 30° = 0$

$\therefore$ Neutral current, $I_N = \sqrt{(-129\cdot54)^2 + (0)^2} = \mathbf{129{\cdot}54A}$

When load from B to N removed. When the load from B to N is removed, the various line currents are :

I_R = **86·96A** in phase with V_{RN} ; I_Y = **125A** lagging V_{YN} by 30° ; I_B = **0 A**

The current in the neutral wire is equal to the phasor sum of these three line currents. Resolving the currents along x-axis and y-axis, we have,

Resultant X-component $= 86{\cdot}96 - 125 \cos 30° = 86{\cdot}96 - 108{\cdot}25 = -21{\cdot}29$ A

Resultant Y-component $= 0 - 125 \sin 30° = 0 - 125 \times 0{\cdot}5 = -62{\cdot}5$ A

$\therefore$ Neutral current, $I_N = \sqrt{(-21\cdot29)^2 + (-62\cdot5)^2} = \mathbf{66{\cdot}03\ A}$

Example 14.10. *A 3-phase, 4-wire distributor supplies a balanced voltage of 400/230 V to a load consisting of 30 A at p.f. 0·866 lagging for R-phase, 30 A at p.f. 0·866 leading for Y phase and 30 A at unity p.f. for B phase. The resistance of each line conductor is 0·2 Ω. The area of X-section of neutral is half of any line conductor. Calculate the supply end voltage for R phase. The phase sequence is RYB.*

Solution. The circuit diagram is shown in Fig. 14.19. Since neutral is half the cross-section, its resistance is 0·4 Ω. Considering the load end and taking V_R as the reference vector, the phase voltages can be written as :

$$\vec{V_R} = 230 \angle 0^\circ \text{ volts} \;;\; \vec{V_Y} = 230 \angle -120^\circ \text{ volts} \;;\; \vec{V_B} = 230 \angle 120^\circ \text{ volts}$$

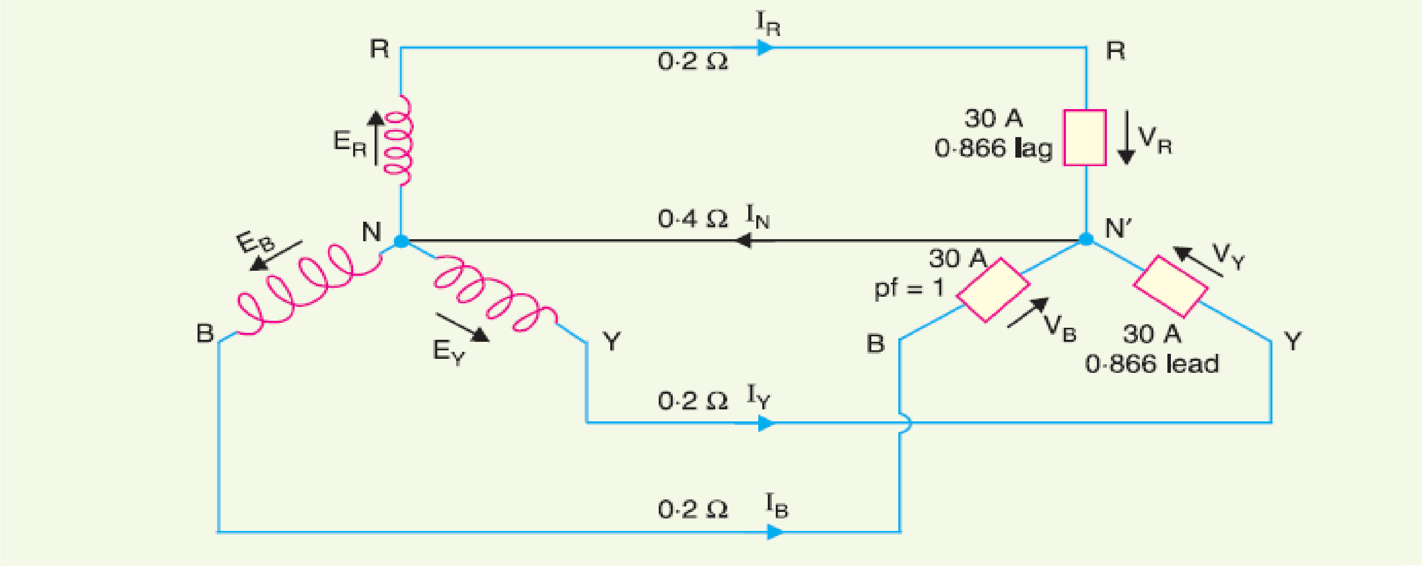


Fig. 14.19

The vector diagram of the circuit is shown in Fig. 14.20. The line current I_R lags behind V_R by an angle $\cos^{-1} 0{\cdot}866 = 30^\circ$. The current I_Y leads V_Y by 30° and the current I_B is in phase with V_B. Referring to the vector diagram of Fig.14.20, the line currents can be expressed as :

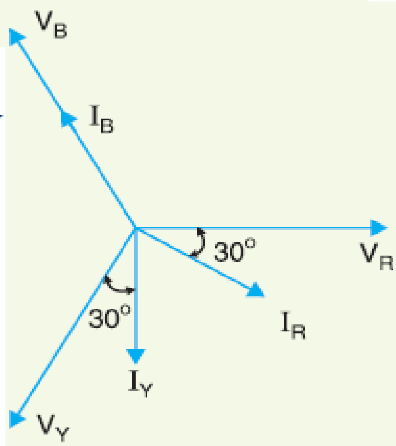


Fig. 14.20

$$\vec{I_R} = 30 \angle -30^\circ \text{ amperes}$$

$$\vec{I_Y} = 30 \angle -90^\circ \text{ amperes}$$

$$\vec{I_B} = 30 \angle 120^\circ \text{ amperes}$$

Current in neutral wire, $\vec{I_N} = \vec{I_R} + \vec{I_Y} + \vec{I_B}$

$$= 30 \angle -30^\circ + 30 \angle -90^\circ + 30 \angle 120^\circ$$

$$= 30\,(0{\cdot}866 - j\,0{\cdot}5) - 30\,(j) + 30\,(-0{\cdot}5 + j\,0{\cdot}866)$$

$$= 10{\cdot}98 - j\,19{\cdot}02$$

Let the supply voltage of phase R to neutral be $\vec{E_R}$. Then,

$$\vec{E_R} = \vec{V_R} + \text{Drop in } R \text{ phase} + \text{Drop in neutral}$$

$$= (230 + j\,0) + 0{\cdot}2 \times 30 \angle -30^\circ + (10{\cdot}98 - j\,19{\cdot}02) \times 0{\cdot}4$$

$$= 230 + 6\,(0{\cdot}866 - j\,0{\cdot}5) + 0{\cdot}4\,(10{\cdot}98 - j\,19{\cdot}02)$$

$$= 239{\cdot}588 - j\,10{\cdot}608$$

$$= \mathbf{239{\cdot}8 \angle -2{\cdot}54^\circ \text{ volts}}$$

Example 14.11. *In a 3-phase, 4-wire, 400/230 V system, a lamp of 100 watts is connected to one phase and neutral and a lamp of 150 watts is connected to the second phase and neutral. If the neutral wire is disconnected accidentally, what will be the voltage across each lamp ?*

Solution. Fig. 14.21 (*i*) shows the lamp connections. The lamp L_1 of 100 watts is connected between phase R and neutral whereas lamp L_2 of 150 watts is connected between phase Y and the neutral.

$$\text{Resistance of lamp } L_1, \quad R_1 = \frac{(230)^2}{100} = 529\ \Omega$$

$$\text{Resistance of lamp } L_2, \quad R_2 = \frac{(230)^2}{150} = 352{\cdot}67\ \Omega$$

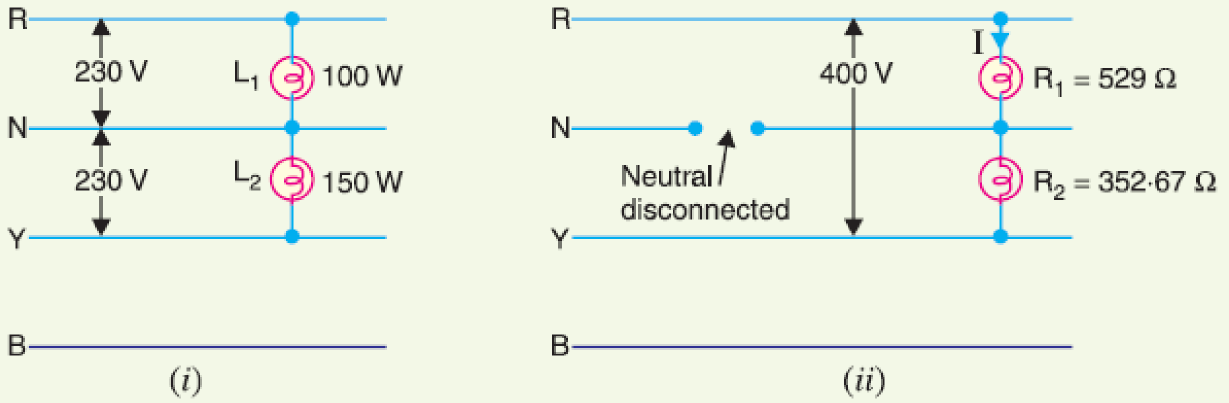


Fig. 14.21

When the neutral wire is disconnected as shown in Fig. 14.21 (*ii*), the two lamps are connected in series and the p.d. across the combination becomes equal to the line voltage E_L (= 400 V).

$$\text{Current through lamps, } I = \frac{E_L}{R_1 + R_2} = \frac{400}{529 + 352{\cdot}67} = 0{\cdot}454 \text{ A}$$

$$\text{Voltage across lamp } L_1 = I R_1 = 0{\cdot}454 \times 529 = \mathbf{240\ V}$$

$$\text{Voltage across lamp } L_2 = I R_2 = 0{\cdot}454 \times 352{\cdot}67 = \mathbf{160\ V}$$

Comments. The voltage across 100-watt lamp is increased to 240 V whereas that across 150-watt is decreased to 160 V. Therefore, 100-watt lamp becomes brighter and 150-watt lamp becomes dim. It may be noted here that if 100-watt lamp happens to be rated at 230 V, it may burn out due to 240 V coming across it.

14.5. Ground Detectors

Ground detectors are the devices that are used to detect the ground fault for ungrounded a.c. systems. When a ground fault occurs on such a system, immediate steps should be taken to clear it. If this is not done and a second ground fault happens, a short circuit occurs.

Fig.14.22 shows how lamps are connected to an un-grounded 3-phase system for the detection of ground fault. If ground fault occurs on any wire, the lamp connected to that wire will be dim and the lamps connected to healthy (un-grounded) wire will become brighter.

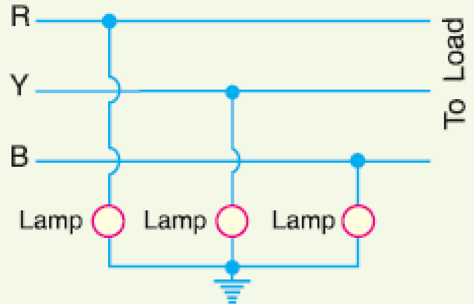


Fig. 14.22

UNIT-IV SUB-STATIONS

25.1 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.

25.2 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.

1. 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.

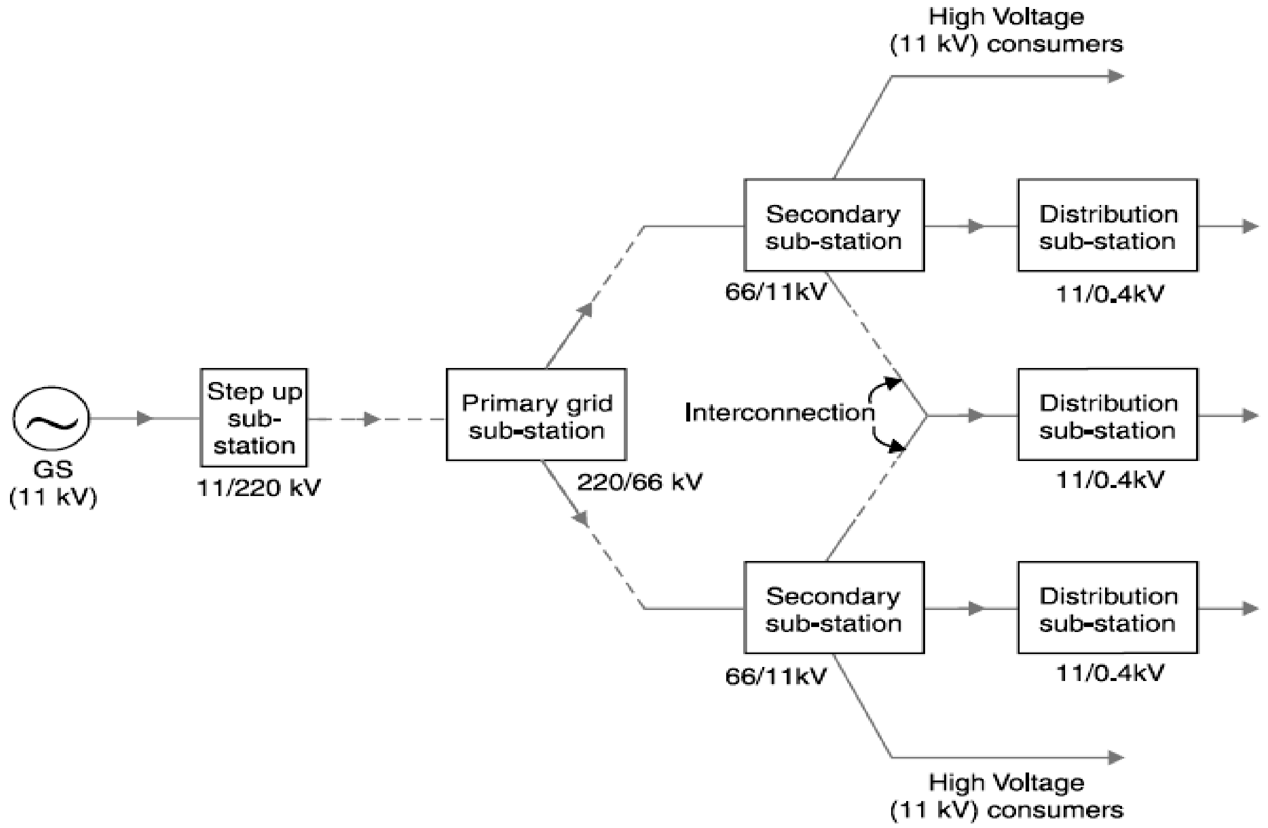
(*iv*) **Frequency changer sub-stations.** Those sub-stations which change the supply frequency are known as frequency changer sub-stations. Such a frequency change may be required for industrial utilisation.

(*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.

Transformer Sub-Stations

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



(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 66 kV 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
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.

25.5 Pole-Mounted Sub-Station

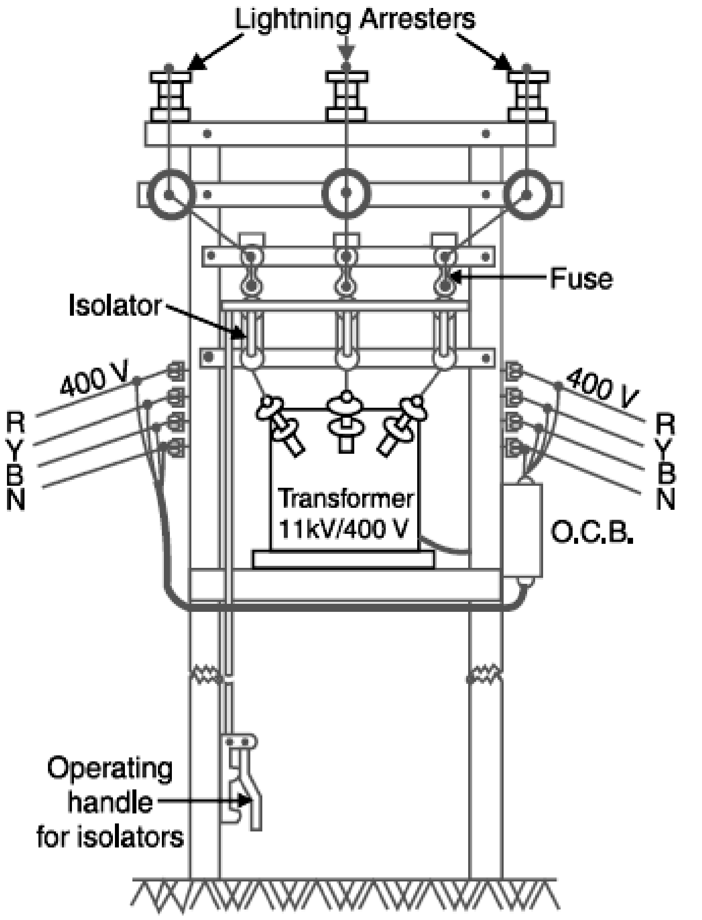
It is a distribution sub-station placed overhead on a pole. It is the cheapest form of sub-station as it does not involve any building work. Fig 25.2 (*i*) shows the layout of pole-mounted sub-station whereas Fig. 25.2 (*ii*) shows the schematic connections. The transformer and other equipment are mounted on H-type pole (or 4-pole structure).

Sub-Station

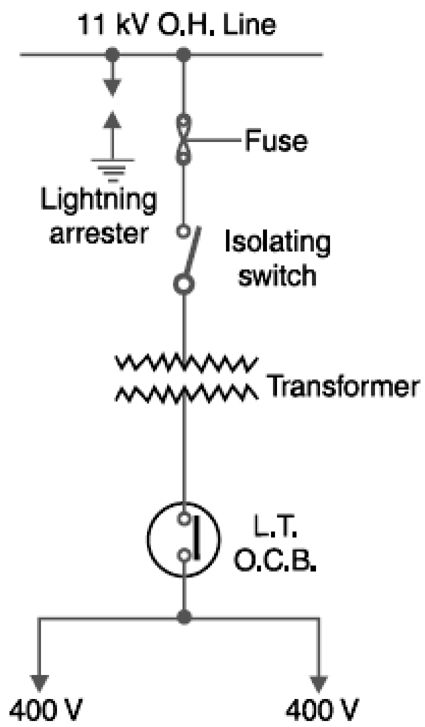
The 11 kV line is connected to the transformer (11kV / 400 V) through gang isolator and fuses. The lightning arresters are installed on the H.T. side to protect the sub-station from lightning strokes. The transformer steps down the voltage to 400V, 3-phase, 4-wire supply. The voltage between any two 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. The pole-mounted sub-stations are generally used for transformer capacity upto *200 kVA. The following points may be noted about pole-mounted sub-stations :

(*i*) There should be periodical check-up of the dielectric strength of oil in the transformer and O.C.B.

(*ii*) In case of repair of transformer or O.C.B., both gang isolator and O.C.B. should be shut off.

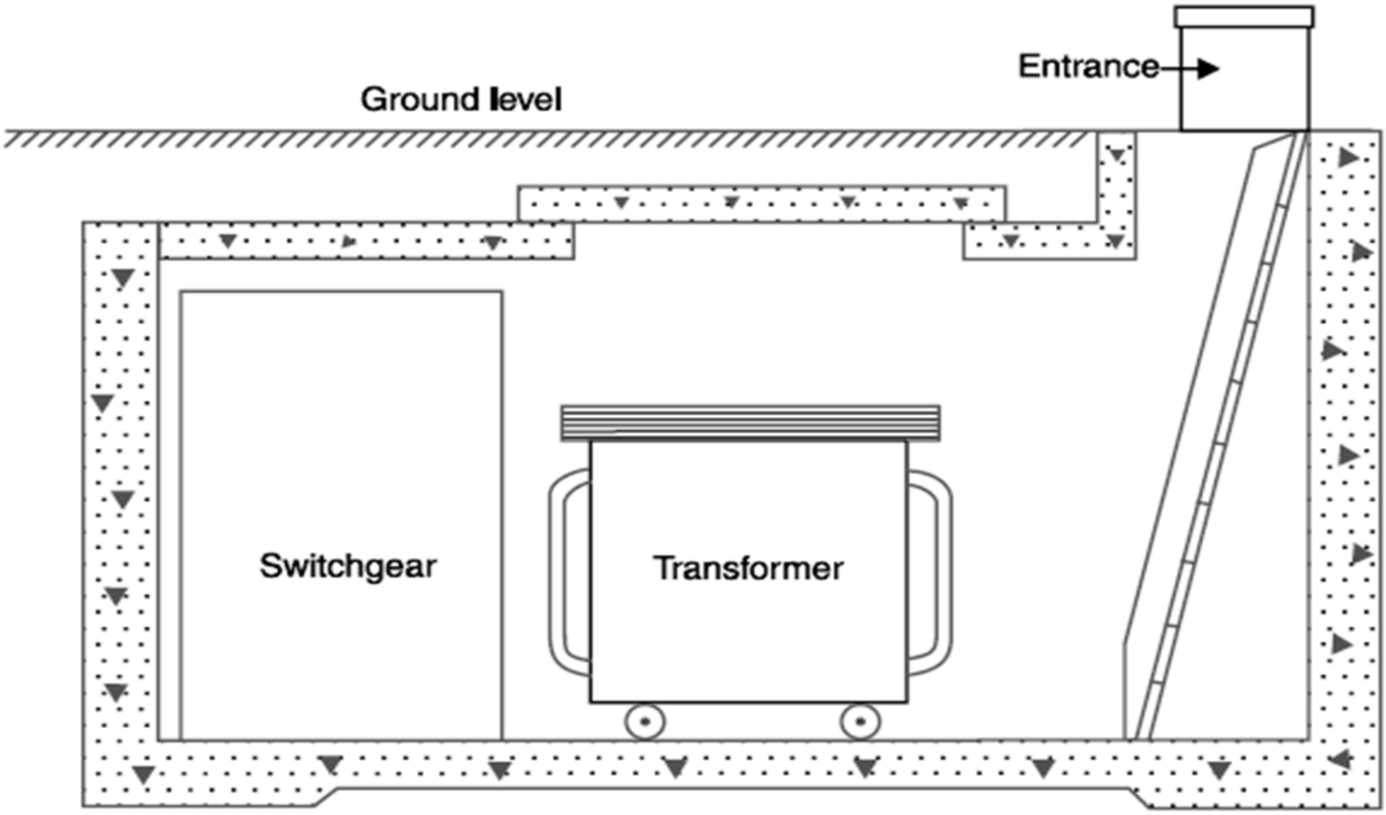


(i)



(ii)

layout of pole-mounted sub-station



Underground Sub-Station

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.

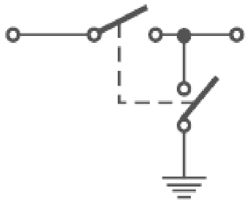
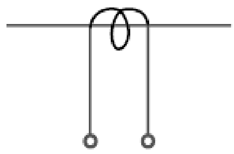
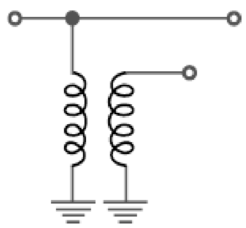
(*iii*) There should be provision for emergency lighting and protection against fire.

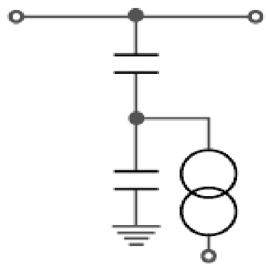
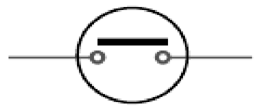
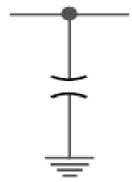
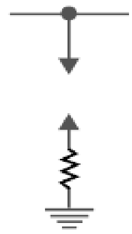
(*iv*) There should be good ventilation.

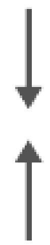
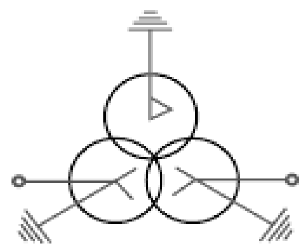
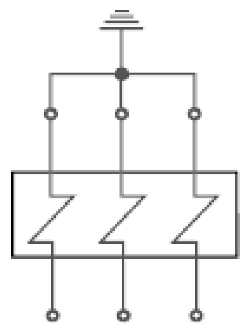
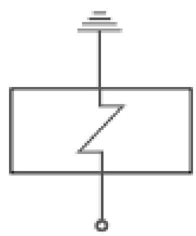
(*v*) There should be provision for remote indication of excessive rise in temperature so that H.V. supply can be disconnected.

(*vi*) The transformers, switches and fuses should be air cooled to avoid bringing oil into the premises.

Symbols for Equipment in Sub-Stations

S.No.	Circuit element	Symbol
1	Bus-bar	
2	Single-break isolating switch	
3	Double-break isolating switch	
4	On load isolating switch	
5	Isolating switch with earth Blade	
6	Current transformer	
7	Potential transformer	

8	Capacitive voltage transformer	
9	Oil circuit breaker	
10	Air circuit breaker with overcurrent tripping device	
11	Air blast circuit breaker	
12	Lightning arrester (active gap)	
13	Lightning arrester (valve type)	

S.No.	Circuit element	Symbol
14	Arcing horn	
15	3-ϕ Power transformer	
16	Overcurrent relay	
17	Earth fault relay	

25.8 Equipment in a Transformer Sub-Station

The equipment required for a transformer sub-station depends upon the type of sub-station, service requirement and the degree of protection desired. However, in general, a transformer sub-station has the following main equipment :

1. Bus-bars. When a number of lines operating at the same voltage have to be directly connected electrically, bus-bars are used as the common electrical component. 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

A detailed discussion on these bus-bar arrangements has already been made in Art. 16.3. However, their practical applications in sub-stations are discussed in Art. 25.9.

2. 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.

3. 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.

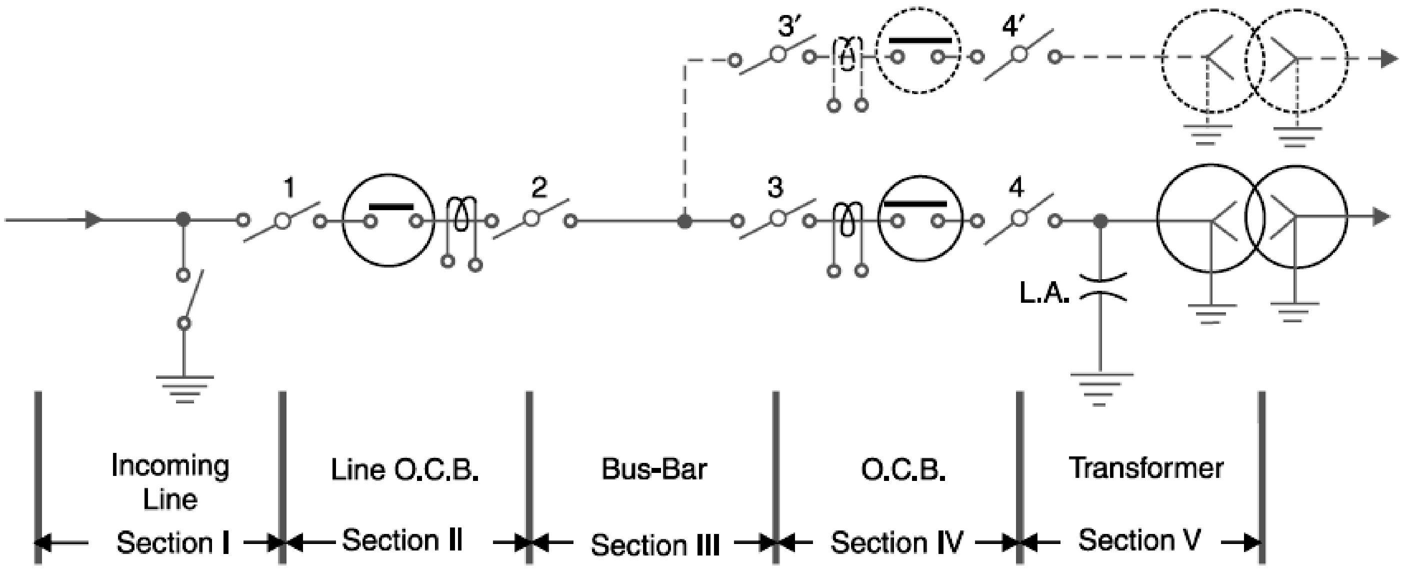


Fig. 25.4

Fig. 25.4 shows the use of isolators in a typical sub-station. 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.

4. 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. For detailed discussion of these breakers, the reader may refer to chapter 19.

5. Power Transformers. A power transformer is used in a 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

* For example, consider that the isolators are connected on both sides of a circuit breaker. If the isolators are to be opened, the C.B. must be opened first.

** An isolator cannot be used to open a circuit under normal conditions. It is because it has no provision to quench the arc that is produced during opening operation. Hence the use of circuit breaker is essential.

*** where a step-up transformer is used to step-up generation voltage to a high value (say 132 kV or 220 kV or more) for transmission of electric power.

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.

6. 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 in essentially a step-up 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 5A. Similarly, if current in the line is 50A, 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.

7. 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.

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

(*i*) fuses
(*ii*) carrier-current equipment
(*iii*) sub-station auxiliary supplies

25.9 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.

Fig. 25.5 shows single bus-bar arrangement in a sub-station. 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.

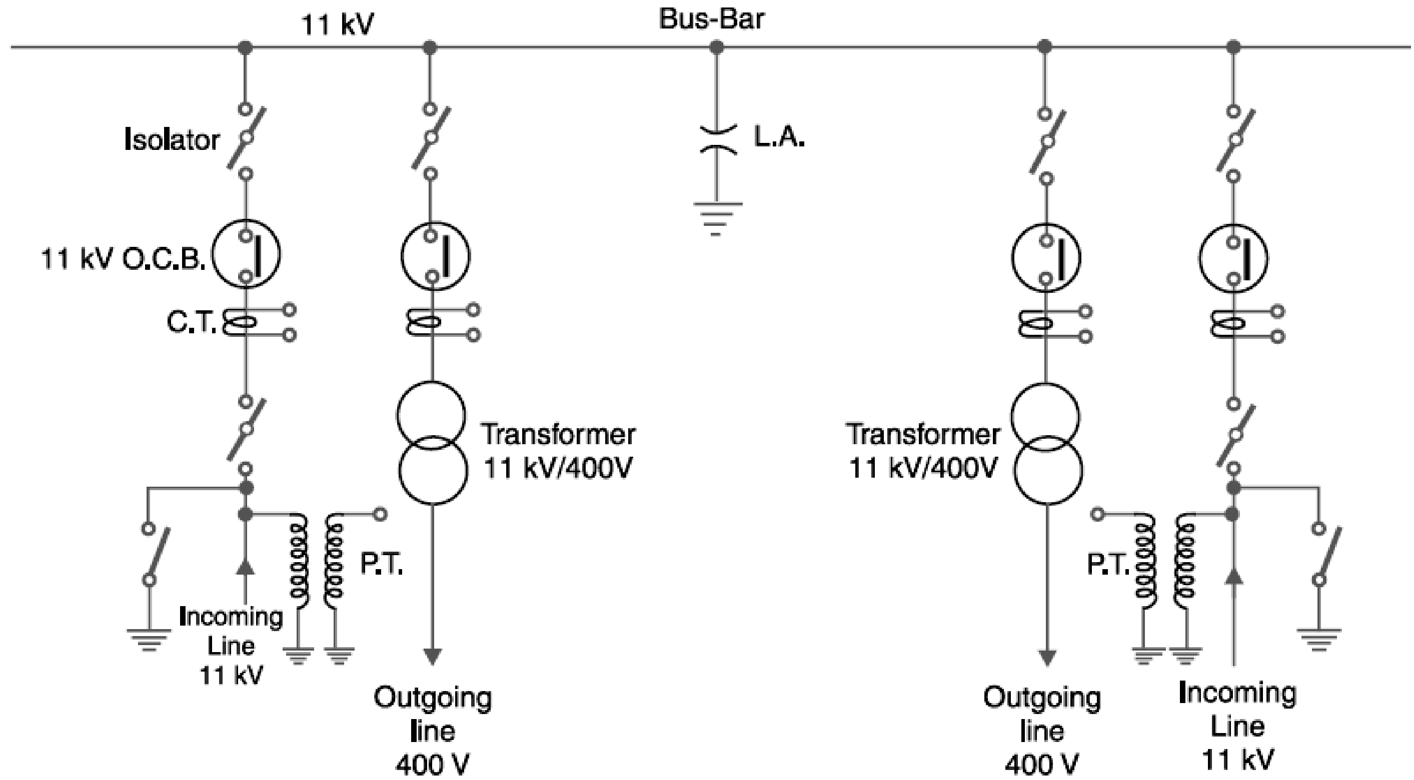


Fig. 25.5

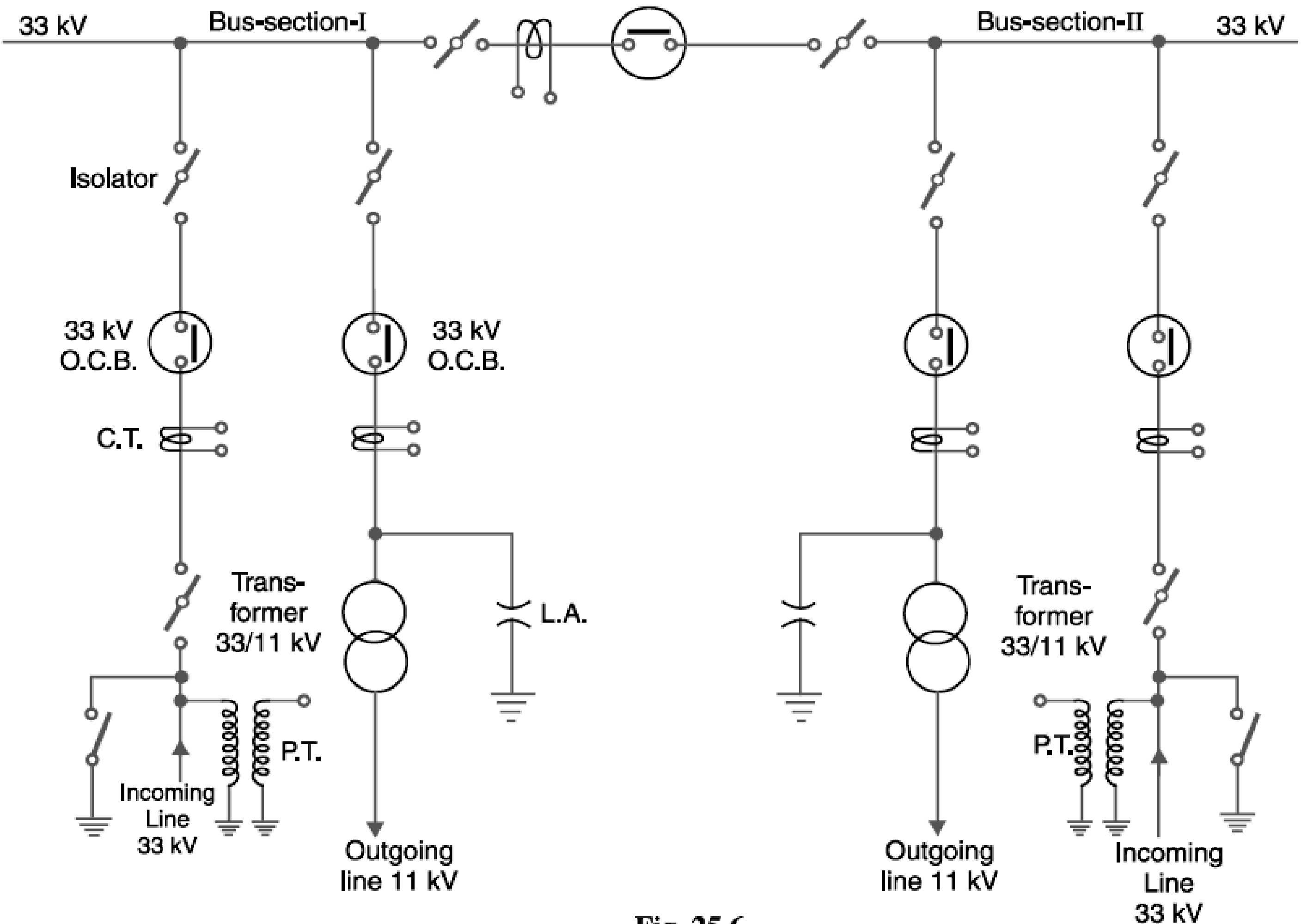


Fig. 25.6

***(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 occuring 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.

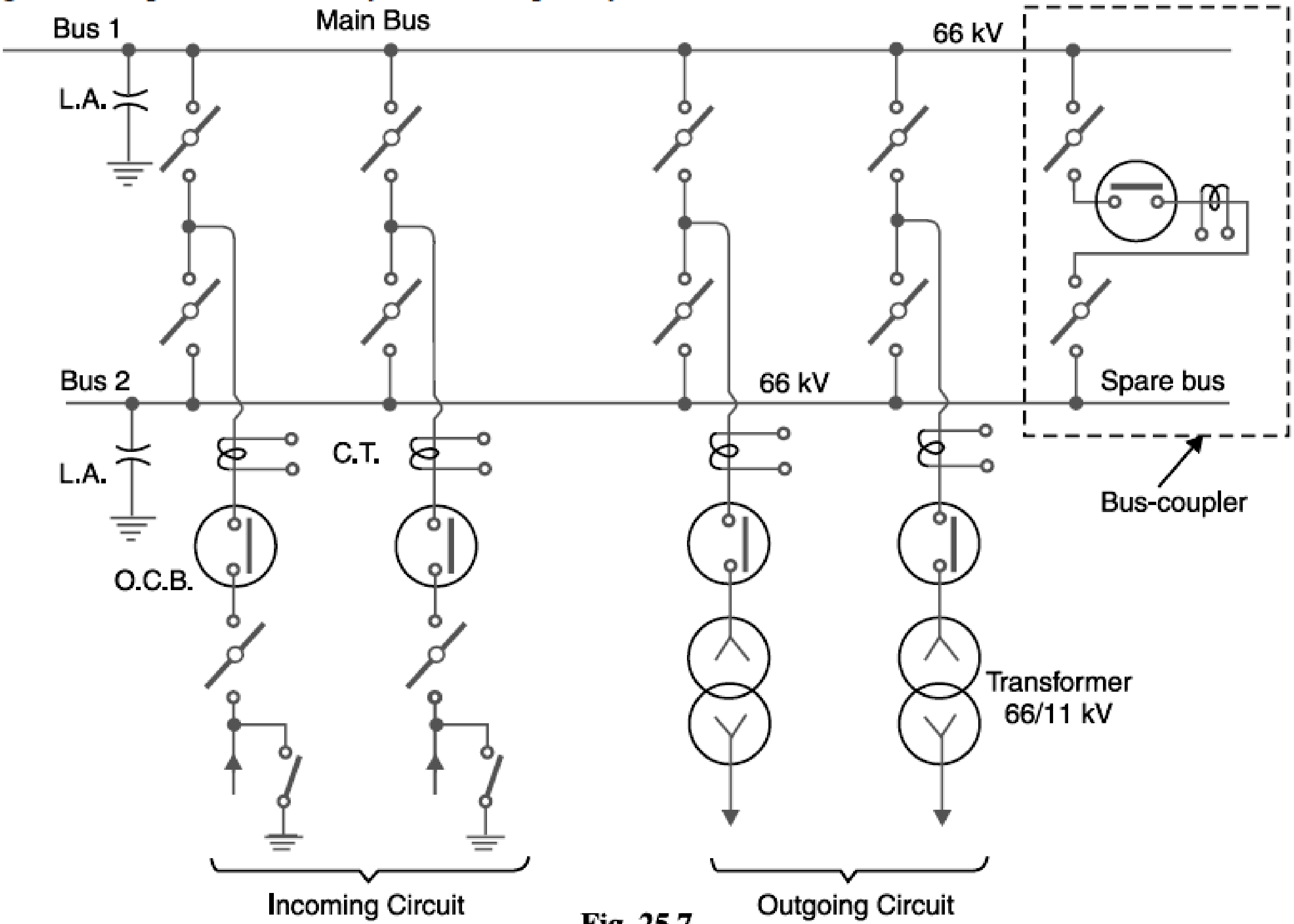


Fig. 25.7

Fig. 25.7 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.

25.10 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 sub-station 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.

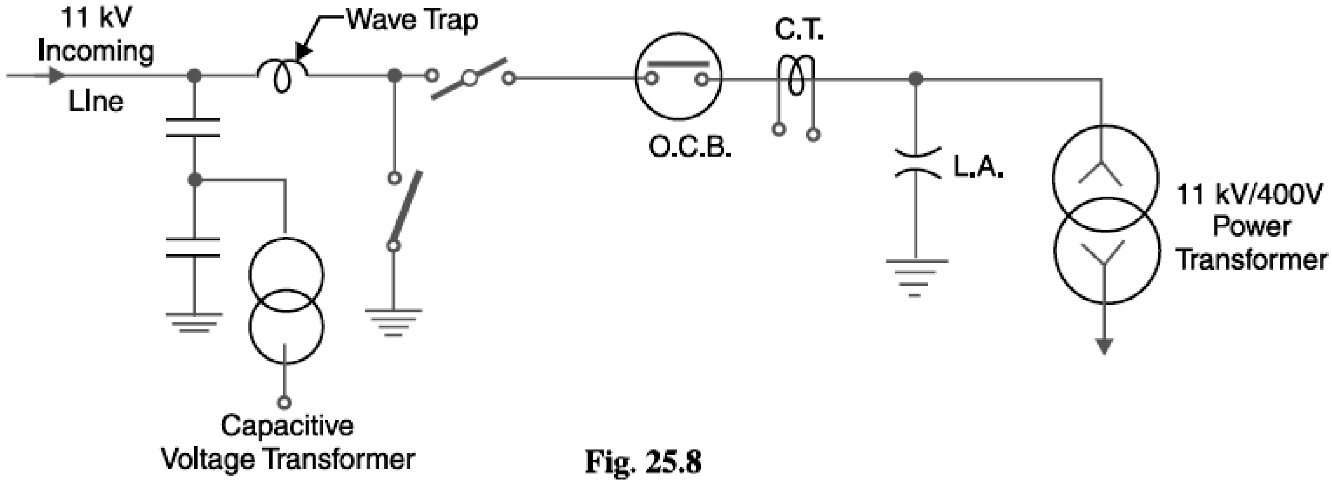


Fig. 25.8

(*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 66kV 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.

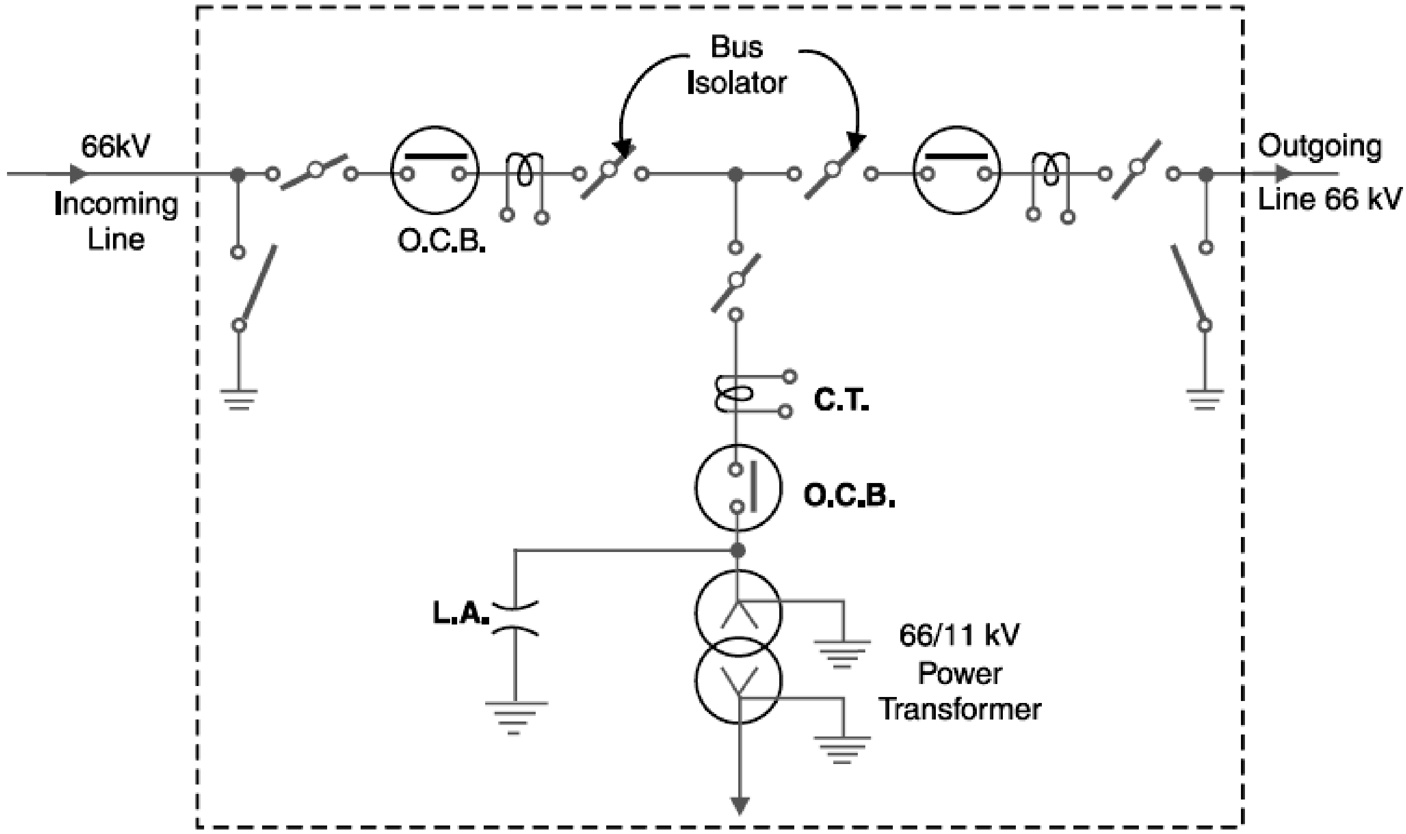

Bus
Isolator
66kV
Incoming
Line
O.C.B.
Outgoing
Line 66 kV
C.T.
O.C.B.
L.A.
66/11 kV
Power
Transformer

Fig. 25.9

25.11 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 :

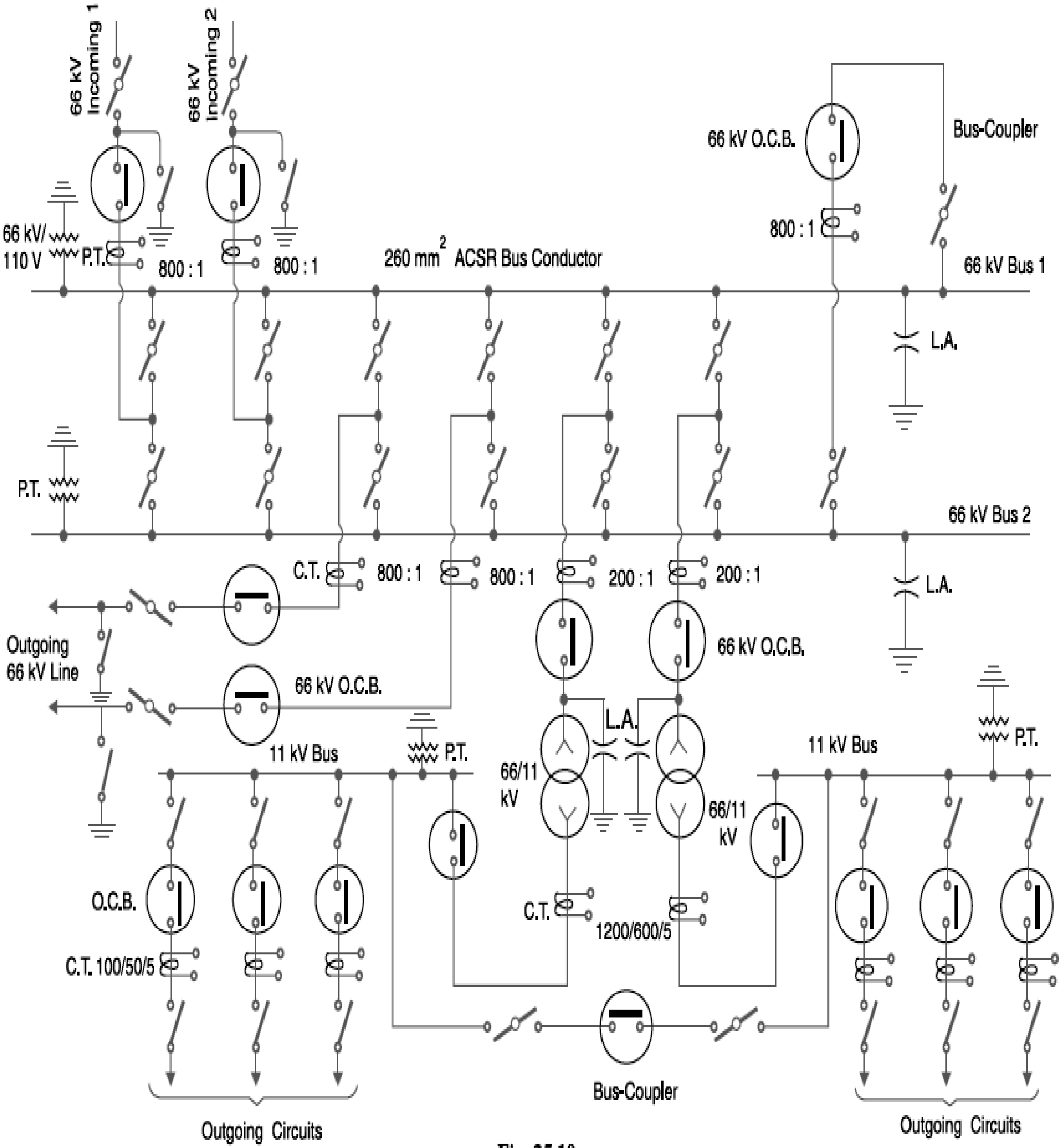


Fig. 25.10

(*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.) and 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.

25.12 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.

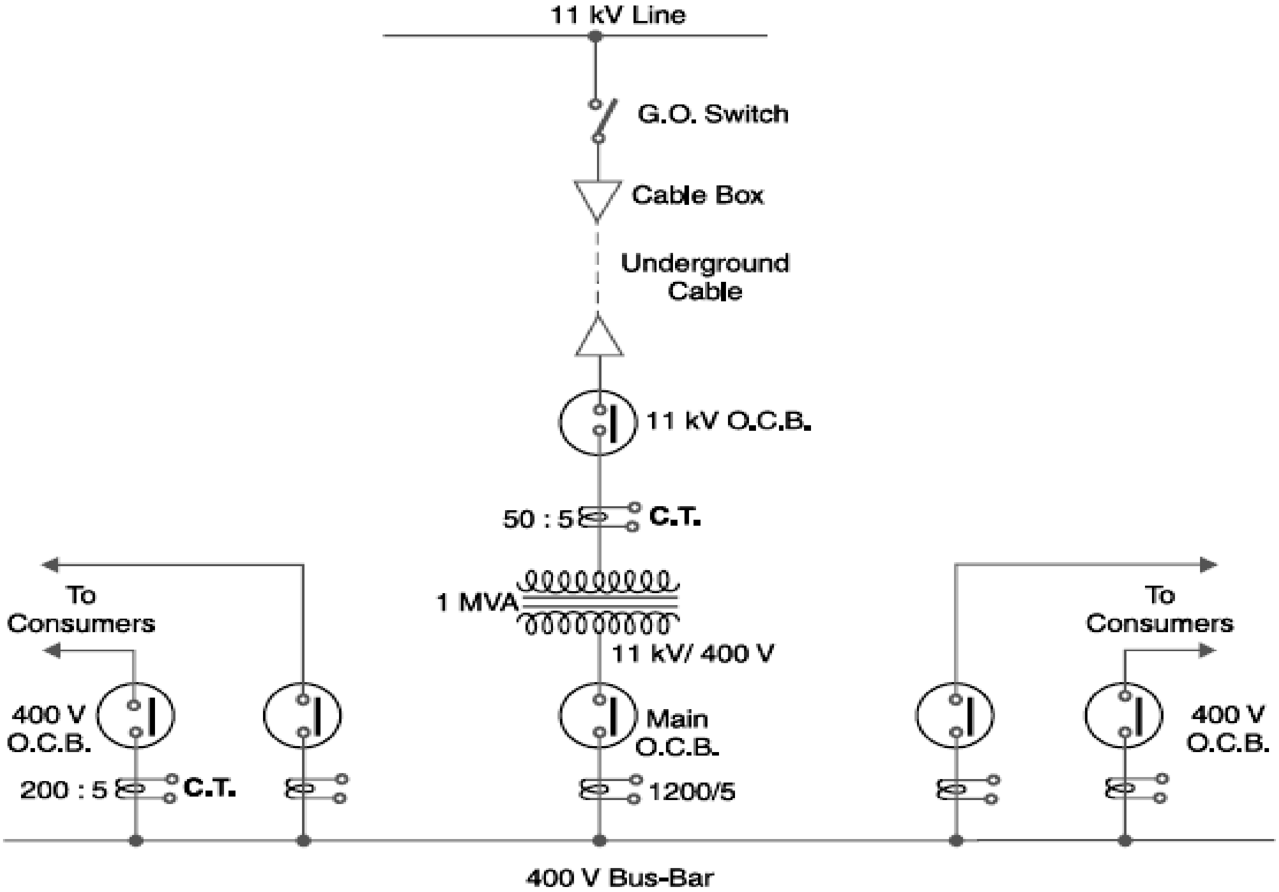


Fig. 25.11

(*iv*) The CTs are located at suitable places in the sub-station circuit and supply for the metering and indicating instruments and relay circuits.

SELF - TEST

1. **Fill in the blanks by appropriate words/figures :**
   (*i*) A sub-station .... some characteristic of electric supply.
   (*ii*) Most of the sub-stations in the power system change.................. of electric supply.
   (*iii*) An ideal location for the sub-station would be at the .... of load.
   (*iv*) Pole-mounted sub-stations are used for .... distribution.
   (*v*) The voltage rating of the transformer in a pole-mounted sub-station is............. .
   (*vi*) Single bus-bar arrangement in sub-stations is used for voltages less then ....
   (*vii*) For voltages greater than 33kV, ... bus-bar arrangement is employed.
   (*viii*) The kVA rating of transformer in a pole-mounted sub-station does not exceed..................
   (*ix*) An indoor sub-station is .... expensive than outdoor sub-station.
   (*x*) Fault location is .... in an outdoor sub-station than in indoor sub-station.
2. **Pick up the correct words/figures from brackets and fill in the blanks :**
   (*i*) Outdoor sub-station requires .... space. (*more, less*)
   (*ii*) The possibility of fault escalation is .... in outdoor sub-station than that of indoor sub-station. (*more, less*)
   (*iii*) Majority of distribution sub-stations are of .... type. (*pole-mounted, indoor, outdoor*)
   (*iv*) Power factor correction sub-stations are generally located at the .... end of a transmission line. (*sending, receiving*)
   (*v*) Underground sub-stations are generally located in................. (*thickly populated areas, villages*)

ANSWERS TO SELF-TEST

1. (*i*) changes (*ii*) voltage level (*iii*) centre of gravity (*iv*) secondary (*v*) 11 kV/400 V (*vi*) 33 kV (*vii*) duplicate (*viii*) 200 (*ix*) more (*x*) easier
2. (*i*) more (*ii*) less (*iii*) pole-mounted (*iv*) receiving (*v*) thickly populated areas

For generation, transmission and distribution of electrical power, a.c. supply system is used. As the generating stations can not be erected in the midst of populated areas, the transmission network is inevitable. Thus power is delivered to the consumers through a network of transmission and distribution. It may be required at many points in the power system to change its characteristics such as voltage, ac to dc in case of high voltage dc transmission (HVDC), frequency, p.f. of the supply system. The substation accomplishes this task.

Now consider that voltage is generated at the generating station(typical value 6.6 or 11 kV). For gaining suitable advantages such as smaller conductor size, less loss and more efficiency of transmission, this voltage is stepped upto either 132 kV, 220 kV or 400 kV for transmission purposes. Now step up transformer along with other required equipments performing this task is called substation. At some points ac is required to convert into dc in cases of traction and electroplating. Again substation performs this task. The type of equipments as required by substation depends on service requirement. Based on this there are several types of substations.

Thus a substation may be defined as an assembly of apparatus which is used to change the characteristics of supply system such as voltage, frequency, a.c. to d.c. or p.f.

During distribution of electrical power also, substations are needed to step down the transmission voltage to suitable value. Thus substation is a link between generating stations and consumers of electricity. The main function of substation is to receive power transmitted at high voltage, reduce it to suitable value for distribution and provide facilities for switching.

Some substations act as switching stations where various connections between different transmission lines are made. These substations have additional functions of providing points where protective devices may be installed which can operate or disconnect the faulty circuit under abnormal conditions. They provide regulation of voltage on outgoing distribution feeders. The power factor improving devices may also be installed in a substation. Also overall monitoring of proper operation of a power system is possible with the help of substation. Hence its study is essential.

UNIT-VI POWER FACTOR AND VOLTAGE CONTROL

POWER FACTOR:

Introduction

The electrical energy is almost exclusively generated, transmitted and distributed in the form of alternating current. Therefore, the question of power factor immediately comes into picture. Most of the loads (*e.g.* induction motors, arc lamps) are inductive in nature and hence have low lagging power factor. The low power factor is highly undesirable as it causes an increase in current, resulting in additional losses of active power in all the elements of power system from power station generator down to the utilisation devices. In order to ensure most favourable conditions for a supply system from engineering and economical standpoint, it is important to have power factor as close to unity as possible. In this chapter, we shall discuss the various methods of power factor improvement.

6.1 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 ϕ 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 ϕ. The phasor diagram of the circuit is shown in Fig. 6.1. The circuit current I can be resolved into two perpendicular components, namely ;

(*a*) $I\cos\phi$ in phase with V

(*b*) $I\sin\phi$ 90° out of phase with V

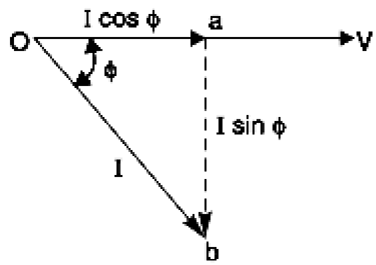


Fig. 6.1

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 ϕ 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.

6.2 Power Triangle

The analysis of power factor can also be made in terms of power drawn by the a.c. circuit. If each side of the current triangle *oab* of Fig. 6.1 is multiplied by voltage *V*, then we get the power triangle *OAB* shown in Fig. 6.2 where

$OA = VI\cos\phi$ 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

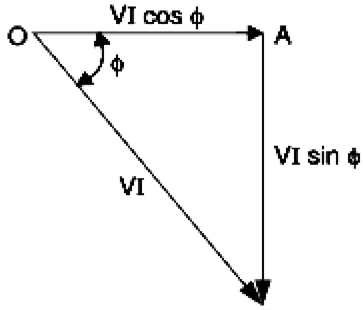


Fig. 6.2

The following points may be noted form 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, $\cos\phi = \dfrac{OA}{OB} = \dfrac{\text{active power}}{\text{apparent power}} = \dfrac{\text{kW}}{\text{kVA}}$

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.

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

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

* If the current lags behind the voltage, the reactive power drawn is known as lagging reactive power. However, if the circuit current leads the voltage, the reactive power is known as leading reactive power.

(*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 $= \dfrac{R}{Z} = \dfrac{\text{Resistance}}{\text{Impedance}}$

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

(*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,

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

$$\text{Active power} = VI\cos\phi = 200 \times 10 \times 0{\cdot}8 = 1600 \text{ W}$$

$$\text{Reactive power} = VI\sin\phi = 200 \times 10 \times 0{\cdot}6 = 1200 \text{ VAR}$$

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.*, $I\sin\phi$).

6.3 Disadvantages of Low Power Factor

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

$$P = V_L I_L \cos \phi \qquad \text{(For single phase supply)}$$

$$\therefore \quad I_L = \frac{P}{V_L \cos \phi} \qquad ...(i)$$

$$P = \sqrt{3}\, V_L I_L \cos \phi \qquad \text{(For 3 phase supply)}$$

$$\therefore \quad I_L = \frac{P}{\sqrt{3}\, V_L \cos \phi} \qquad ...(ii)$$

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.

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

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.

* The electrical machinery is rated in kVA because the power factor of the load is not known when the machinery is manufactured in the factory.

(*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

6.4 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 in lower than 0·8. The following are the causes of low power factor:

(*i*) Most of the a.c. motors are of induction type (1ϕ and 3ϕ 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.

6.5 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.

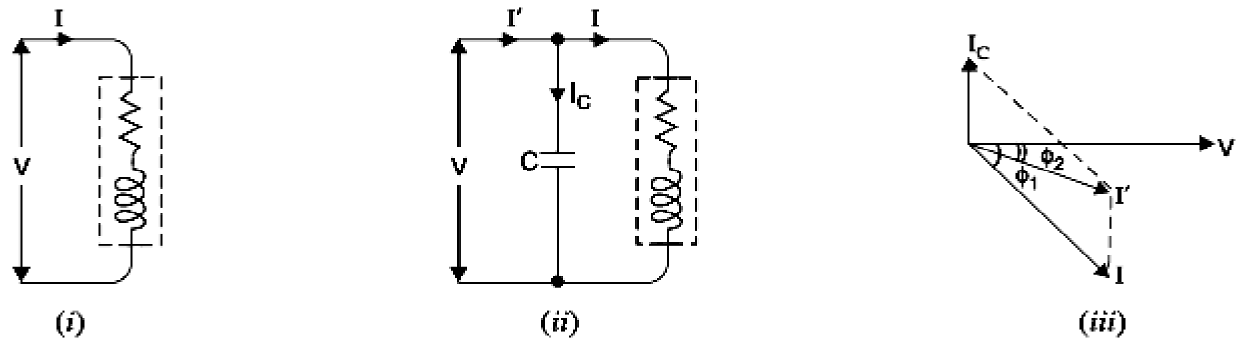


Fig. 6.3

Illustration. To illustrate the power factor improvement by a capacitor, consider a single *phase load taking lagging current I at a power factor $\cos \phi_1$ as shown in Fig. 6.3.

The capacitor C is connected in parallel with the load. The capacitor draws current I_C which leads the supply voltage by 90°. The resulting line current I' is the phasor sum of I and I_C and its angle of lag is ϕ_2 as shown in the phasor diagram of Fig. 6.3. (*iii*). It is clear that ϕ_2 is less than ϕ_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.

(*ii*) 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.

$$\therefore \quad I \cos \phi_1 = I' \cos \phi_2$$

(*iii*) 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 $\quad I \cos \phi_1 = I' \cos \phi_2$

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

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

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

$$\therefore \quad VI' \sin \phi_2 = VI \sin \phi_1 - VI_C \qquad \text{[Multiplying by } V\text{]}$$

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

6.6 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.

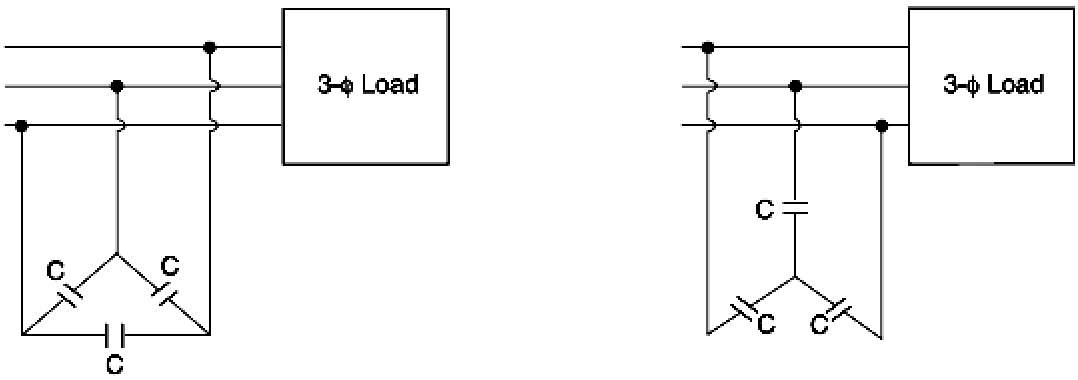


Fig. 6.4

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**

* The treatment can be used for 3-phase balanced loads *e.g.*, 3-ϕ induction motor. In a balanced 3-ϕ load, analysis of one phase leads to the desired results.

** To distinguish from the so called *synchronous condenser* which is a synchrnous motor running at no load and taking leading current.

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

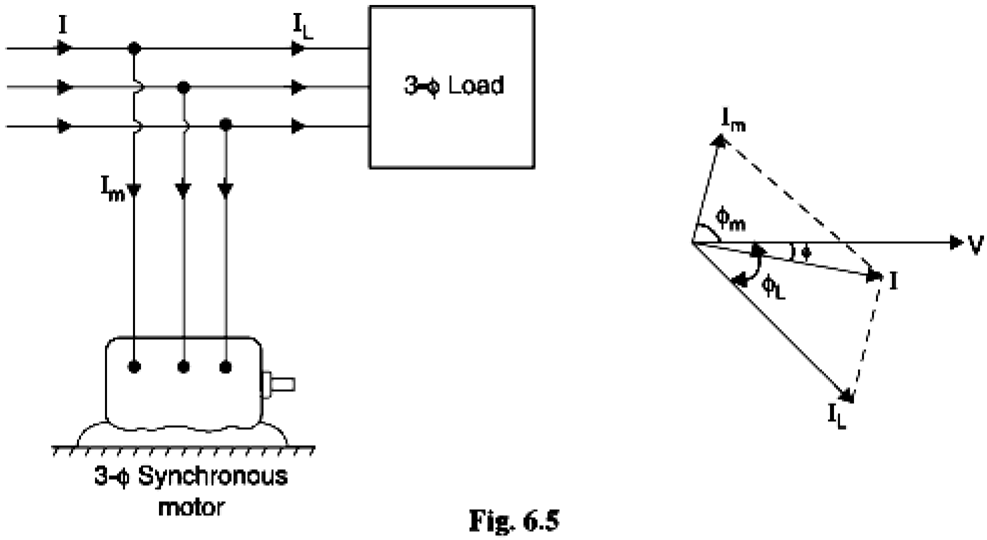


Fig. 6.5

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 † control of power factor.

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* If the motor is ideal *i.e.*, there are no losses, then $\phi_m = 90^\circ$. However, in actual practice, losses do occur in the motor even at no load. Therefore, the currents I_m leads the voltage by an angle less than 90°.

† The *p.f.* improvement with capacitors can only be done in steps by switching on the capacitors in various groupings. However, with synchronous motor, any amount of capacitive reactance can be provided by changing the field excitation.

(*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.

Note. The reactive power taken by a synchronous motor depends upon two factors, the d.c. field excitation and the mechanical load delivered by the motor. Maximum leading power is taken by a synchronous motor with maximum excitation and zero load.

Synchronous Condenser

Static Capacitor

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°. 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.

6.7 Calculations of Power Factor Correction

Consider an inductive load taking a lagging current I at a power factor cos ϕ_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°. 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 ϕ_2. It is clear that ϕ_2 is less than ϕ_1 so that new p.f. cos ϕ_2 is more than the previous p.f. cos ϕ_1.

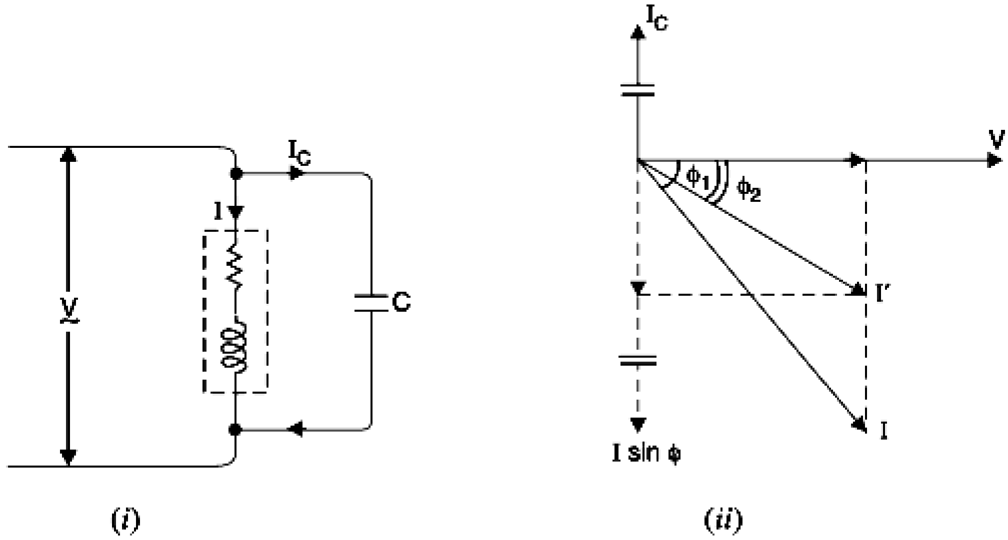

Fig. 6.6

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

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

or $I_C = I \sin\phi_1 - I' \sin\phi_2$

∴ Capacitance of capacitor to improve p.f. from cos ϕ_1 to cos ϕ_2

$$= \frac{I_C}{\omega V} \qquad \left(\because X_C = \frac{V}{I_C} = \frac{1}{\omega C}\right)$$

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 ϕ_1, whereas power triangle OAC is for the improved power factor cos ϕ_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 ϕ_2.

Leading kVAR supplied by p.f. correction equipment

$$= BC = AB - AC$$

$$= \text{kVAR}_1 - \text{kVAR}_2$$

$$= OA\,(\tan\phi_1 - \tan\phi_2)$$

$$= \text{kW}\,(\tan\phi_1 - \tan\phi_2)$$

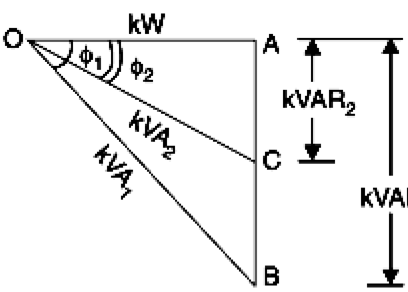

Fig. 6.7

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

Example 6.1 *An alternator is supplying a load of 300 kW at a p.f. of 0·6 lagging. If the power factor is raised to unity, how many more kilowatts can alternator supply for the same kVA loading ?*

Solution :

$$\text{kVA} = \frac{\text{kW}}{\cos\phi} = \frac{300}{0\cdot 6} = 500 \text{ kVA}$$

$$\text{kW at } 0\cdot 6 \text{ p.f.} = 300 \text{ kW}$$

$$\text{kW at } 1 \text{ p.f.} = 500 \times 1 = 500 \text{ kW}$$

∴ Increased power supplied by the alternator

$$= 500 - 300 = 200 \text{ kW}$$

Note the importance of power factor improvement. When the p.f. of the alternator is unity, the 500 kVA are also 500 kW and the engine driving the alternator has to be capable of developing this power together with the losses in the alternator. But when the power factor of the load is 0·6, the power is only 300 kW. Therefore, the engine is developing only 300 kW, though the alternator is supplying its rated output of 500 kVA.

Example 6.2 *A single phase motor connected to 400 V, 50 Hz supply takes 31·7A at a power factor of 0·7 lagging. Calculate the capacitance required in parallel with the motor to raise the power factor to 0·9 lagging.*

Solution : The circuit and phasor diagrams are shown in Figs. 6.8 and 6.9 respectively. Here motor M is taking a current I_M of 31·7A. The current I_C taken by the capacitor must be such that when combined with I_M, the resultant current I lags the voltage by an angle ϕ where $\cos\phi = 0\cdot 9$.

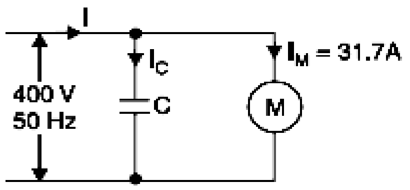

Fig. 6.8

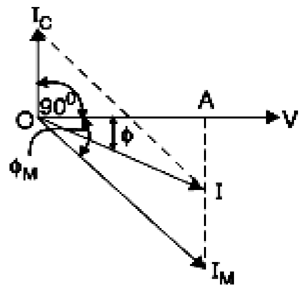

Fig. 6.9

Referring to the phasor diagram in Fig. 6.9,

$$\text{Active component of } I_M = I_M \cos\phi_M = 31\cdot 7 \times 0\cdot 7 = 22\cdot 19\text{A}$$

$$\text{Active component of } I = I\cos\phi = I \times 0\cdot 9$$

These components are represented by OA in Fig. 6.9.

$$\therefore \quad I = \frac{22\cdot 19}{0\cdot 9} = 24\cdot 65\text{A}$$

$$\text{Reactive component of } I_M = I_M \sin\phi_M = 31\cdot 7 \times 0\cdot 714^* = 22\cdot 6\text{A}$$

$$\text{Reactive component of } I = I\sin\phi = 24\cdot 65\sqrt{1-(0\cdot 9)^2}$$

$$= 24\cdot 65 \times 0\cdot 436 = 10\cdot 75 \text{ A}$$

It is clear from Fig. 6.9 that :

$$I_C = \text{Reactive component of } I_M - \text{Reactive component of } I$$

$$= 22\cdot 6 - 10\cdot 75 = 11\cdot 85\text{A}$$

But

$$I_C = \frac{V}{X_C} = V \times 2\pi f C$$

or

$$11\cdot 85 = 400 \times 2\pi \times 50 \times C$$

$$\therefore \quad C = 94\cdot 3 \times 10^{-6} \text{ F} = 94\cdot 3 \ \mu\text{F}$$

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* $\sin\phi_M = \sqrt{1-\cos^2\phi_M} = \sqrt{1-(0\cdot 7)^2} = 0\cdot 714$

Note the effect of connecting a 94·3 μF capacitor in parallel with the motor. The current taken from the supply is reduced from 31·7 A to 24·65 A without altering the current or power taken by the motor. This enables an economy to be affected in the size of generating plant and in the cross-sectional area of the conductors.

Example 6.3 *A single phase a.c. generator supplies the following loads :*

(*i*) *Lighting load of 20 kW at unity power factor.*

(*ii*) *Induction motor load of 100 kW at p.f. 0·707 lagging.*

(*iii*) *Synchronous motor load of 50 kW at p.f. 0·9 leading.*

Calculate the total kW and kVA delivered by the generator and the power factor at which it works.

Solution : Using the suffixes 1, 2 and 3 to indicate the different loads, we have,

$$kVA_1 = \frac{kW_1}{\cos\phi_1} = \frac{20}{1} = 20 \text{ kVA}$$

$$kVA_2 = \frac{kW_2}{\cos\phi_2} = \frac{100}{0\cdot707} = 141\cdot4 \text{ kVA}$$

$$kVA_3 = \frac{kW_3}{\cos\phi_3} = \frac{50}{0\cdot9} = 55\cdot6 \text{ kVA}$$

These loads are represented in Fig. 6.10. The three kVAs' are not in phase. In order to find the total kVA, we resolve each kVA into rectangular components – kW and kVAR as shown in Fig. 6.10. The total kW and kVAR may then be combined to obtain total kVA.

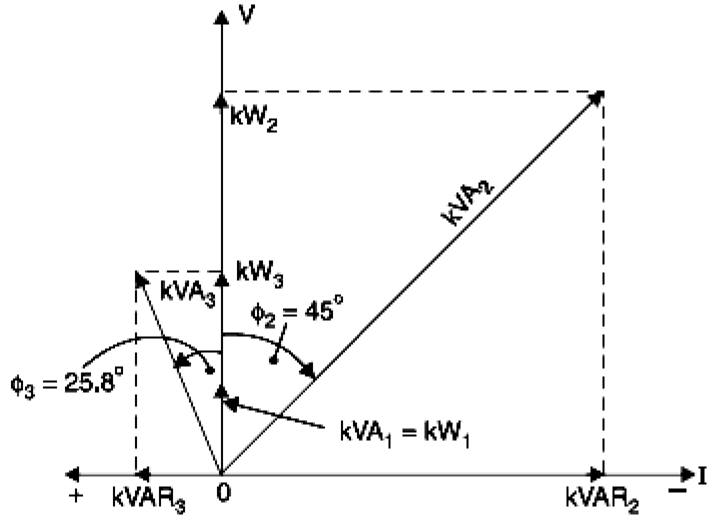

Fig. 6.10

$$kVAR_1 = kVA_1 \sin\phi_1 = 20 \times 0 = 0$$

$$kVAR_2 = kVA_2 \sin\phi_2 = -141\cdot4 \times 0\cdot707 = -100 \text{ kVAR}$$

$$kVAR_3 = kVA_3 \sin\phi_3 = +55\cdot6 \times 0\cdot436 = +24\cdot3 \text{ kVAR}$$

Note that $kVAR_2$ and $kVAR_3$ are in opposite directions ; $kVAR_2$ being a lagging while $kVAR_3$ being a leading kVAR.

$$\text{Total kW} = 20 + 100 + 50 = 170 \text{ kW}$$

$$\text{Total kVAR} = 0 - 100 + 24\cdot3 = -75\cdot7 \text{ kVAR}$$

$$\text{Total kVA} = \sqrt{(kW)^2 + (kVAR)^2} = \sqrt{(170)^2 + (75\cdot7)^2} = \mathbf{186 \text{ kVA}}$$

$$\text{Power factor} = \frac{\text{Total kW}}{\text{Total kVA}} = \frac{170}{186} = \mathbf{0\cdot914 \text{ lagging}}$$

The power factor must be lagging since the resultant kVAR is lagging.

Example 6.4 *A 3-phase, 5 kW induction motor has a p.f. of 0·75 lagging. A bank of capacitors is connected in delta across the supply terminals and p.f. raised to 0·9 lagging. Determine the kVAR rating of the capacitors connected in each phase.*

Solution :

$$\text{Original p.f., } \cos\phi_1 = 0{\cdot}75 \text{ lag} \quad ; \quad \text{Motor input, } P = 5 \text{ kW}$$
$$\text{Final p.f., } \cos\phi_2 = 0{\cdot}9 \text{ lag} \quad ; \quad \text{Efficiency, } \eta = 100\,\% \text{ (assumed)}$$
$$\phi_1 = \cos^{-1}(0{\cdot}75) = 41{\cdot}41° \quad ; \quad \tan\phi_1 = \tan 41{\cdot}41° = 0{\cdot}8819$$
$$\phi_2 = \cos^{-1}(0{\cdot}9) = 25{\cdot}84° \quad ; \quad \tan\phi_2 = \tan 25{\cdot}84° = 0{\cdot}4843$$

Leading kVAR taken by the condenser bank

$$= P(\tan\phi_1 - \tan\phi_2)$$
$$= 5\,(0{\cdot}8819 - 0{\cdot}4843) = 1{\cdot}99 \text{ kVAR}$$

∴ Rating of capacitors connected in each phase

$$= 1{\cdot}99/3 = 0{\cdot}663 \text{ kVAR}$$

Example 6.5 *A 3-phase, 50 Hz, 400 V motor develops 100 H.P. (74·6 kW), the power factor being 0·75 lagging and efficiency 93%. A bank of capacitors is connected in delta across the supply terminals and power factor raised to 0·95 lagging. Each of the capacitance units is built of 4 similar 100 V capacitors. Determine the capacitance of each capacitor.*

Solution :

$$\text{Original p.f., } \cos\phi_1 = 0{\cdot}75 \text{ lag ; Final p.f., } \cos\phi_2 = 0{\cdot}95 \text{ lag}$$
$$\text{Motor input, } P = \text{output}/\eta = 74{\cdot}6/0{\cdot}93 = 80 \text{ kW}$$
$$\phi_1 = \cos^{-1}(0{\cdot}75) = 41{\cdot}41°$$
$$\tan\phi_1 = \tan 41{\cdot}41° = 0{\cdot}8819$$
$$\phi_2 = \cos^{-1}(0{\cdot}95) = 18{\cdot}19°$$
$$\tan\phi_2 = \tan 18{\cdot}19° = 0{\cdot}3288$$

Leading kVAR taken by the condenser bank

$$= P(\tan\phi_1 - \tan\phi_2)$$
$$= 80\,(0{\cdot}8819 - 0{\cdot}3288) = 44{\cdot}25 \text{ kVAR}$$

Leading kVAR taken by each of three sets

$$= 44{\cdot}25/3 = 14{\cdot}75 \text{ kVAR} \qquad \ldots (i)$$

Fig. 6.11 shows the delta* connected condenser bank. Let C farad be the capacitance of 4 capacitors in each phase.

Phase current of capacitor is

$$I_{CP} = V_{ph}/X_C = 2\pi f C V_{ph}$$
$$= 2\pi \times 50 \times C \times 400$$
$$= 1{,}25{,}600\, C \text{ amperes}$$
$$\text{kVAR/phase} = \frac{V_{ph}\, I_{CP}}{1000}$$
$$= \frac{400 \times 1{,}25{,}600\, C}{1000}$$
$$= 50240\, C \qquad \ldots (ii)$$

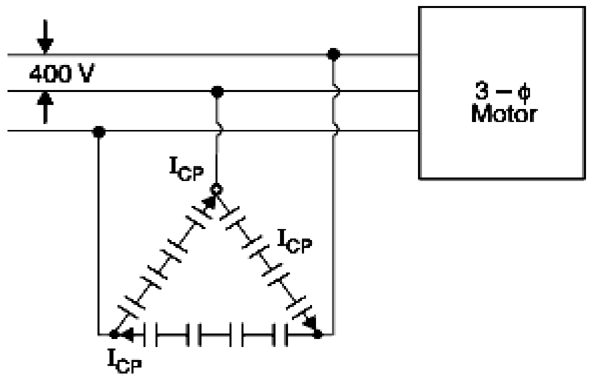

Fig. 6.11

Equating exps. (*i*) and (*ii*), we get,

$$50240\, C = 14{\cdot}75$$
$$\therefore \quad C = 14{\cdot}75/50{,}240 = 293{\cdot}4 \times 10^{-6} \text{ F} = 293{\cdot}4\ \mu\text{F}$$

Since it is the combined capacitance of four equal capacitors joined in series,

∴ Capacitance of each capacitor = 4 × 293·4 = **1173·6 μF**

* In practice, capacitors are always connected in delta since the capacitance of the capacitor required is one-third of that required for star connection.

Example 6.6. *The load on an installation is 800 kW, 0·8 lagging p.f. which works for 3000 hours per annum. The tariff is Rs 100 per kVA plus 20 paise per kWh. If the power factor is improved to 0·9 lagging by means of loss-free capacitors costing Rs 60 per kVAR, calculate the annual saving effected. Allow 10% per annum for interest and depreciation on capacitors.*

Solution.

$$\text{Load,}\quad P = 800 \text{ kW}$$

$$\cos\phi_1 = 0{\cdot}8 \;;\quad \tan\phi_1 = \tan(\cos^{-1} 0{\cdot}8) = 0{\cdot}75$$

$$\cos\phi_2 = 0{\cdot}9 \;;\quad \tan\phi_2 = \tan(\cos^{-1} 0{\cdot}9) = 0{\cdot}4843$$

Leading kVAR taken by the capacitors

$$= P(\tan\phi_1 - \tan\phi_2) = 800\,(0{\cdot}75 - 0{\cdot}4843) = 212{\cdot}56$$

Annual cost before p.f. correction

Max. kVA demand = 800/0·8 = 1000

kVA demand charges = Rs 100 × 1000 = Rs 1,00,000

Units consumed/year = 800 × 3000 = 24,00,000 kWh

Energy charges/year = Rs 0·2 × 24,00,000 = Rs 4,80,000

Total annual cost = Rs (1,00,000 + 4,80,000) = Rs 5,80,000

Annual cost after p.f. correction

Max. kVA demand = 800/0·9 = 888·89

kVA demand charges = Rs 100 × 888·89 = Rs 88,889

Energy charges = Same as before *i.e.*, Rs 4,80,000

Capital cost of capacitors = Rs 60 × 212·56 = Rs 12,750

Annual interest and depreciation = Rs 0·1 × 12750 = Rs 1275

Total annual cost = Rs (88,889 + 4,80,000 + 1275) = Rs 5,70,164

∴ Annual saving = Rs (5,80,000 − 5,70,164) = Rs 9836

Example 6.7. *A factory takes a load of 200 kW at 0·85 p.f. lagging for 2500 hours per annum. The traiff is Rs 150 per kVA plus 5 paise per kWh consumed. If the p.f. is improved to 0·9 lagging by means of capacitors costing Rs 420 per kVAR and having a power loss of 100 W per kVA, calculate the annual saving effected by their use. Allow 10% per annum for interest and depreciation.*

Solution :

$$\text{Factory load, } P_1 = 200 \text{ kW}$$

$$\cos\phi_1 = 0{\cdot}85 \;;\quad \tan\phi_1 = 0{\cdot}62$$

$$\cos\phi_2 = 0{\cdot}9 \;;\quad \tan\phi_2 = 0{\cdot}4843$$

Suppose the leading kVAR taken by the capacitors is x.

$$\therefore \quad \text{Capacitor loss} = \frac{100 \times x}{1000} = 0{\cdot}1\,x \text{ kW}$$

$$\text{Total power, } P_2 = (200 + 0{\cdot}1x) \text{ kW}$$

Leading kVAR taken by the capacitors is

$$x = P_1 \tan\phi_1 - P_2 \tan\phi_2$$

$$= 200 \times 0{\cdot}62 - (200 + 0{\cdot}1x) \times 0{\cdot}4843$$

or $\qquad x = 124 - 96{\cdot}86 - 0{\cdot}04843\,x$

$\therefore \qquad x = 27{\cdot}14/1{\cdot}04843 = 25{\cdot}89$ kVAR

Annual cost before p.f. improvement

Max. kVA demand = 200/0.85 = 235.3

kVA demand charges = Rs 150 × 235·3 = Rs 35,295

Units consumed/year = 200 × 2500 = 5,00,000 kWh

Energy charges = Rs 0·05 × 5,00,000 = Rs 25,000

Total annual cost = Rs (35,295 + 25,000) = Rs 60,295

Annual cost after p.f. improvement

Max. kVA demand = 200/0·9 = 222·2

kVA demand charges = Rs 150 × 222·2 = Rs 33,330

Energy charges = same as before *i.e.*, Rs 25,000

Annual interest and depreciation = Rs 420 × 25·89 × 0·1 = Rs 1087

Annual energy loss in capacitors = 0·1 x × 2500 = 0·1 × 25·89 × 2500 = 6472 kWh

Annual cost of losses occurring in capacitors

= Rs 0·05 × 6472 = Rs 323

∴ Total annual cost = Rs (33,330 + 25,000 + 1087 + 323) = Rs 59,740

Annual saving = Rs (60,295 − 59,740) = Rs 555

Example 6.8. *A factory operates at 0·8 p.f. lagging and has a monthly demand of 750 kVA. The monthly power rate is Rs 8·50 per kVA. To improve the power factor, 250 kVA capacitors are installed in which there is negligible power loss. The installed cost of equipment is Rs 20,000 and fixed charges are estimated at 10% per year. Calculate the annual saving effected by the use of capacitors.*

Solution.

Monthly demand is 750 kVA.

$\cos\phi = 0{\cdot}8\ ;\ \sin\phi = \sin(\cos^{-1} 0{\cdot}8) = 0{\cdot}6$

kW component of demand = kVA × cos ϕ = 750 × 0·8 = 600

kVAR component of demand = kVA × sin ϕ = 750 × 0·6 = 450

Leading kVAR taken by the capacitors is 250 kVAR. Therefore, net kVAR after p.f. improvement is 450 − 250 = 200.

∴ kVA after p.f. improvement = $\sqrt{(600)^2 + (200)^2} = 632{\cdot}45$

Reduction in kVA = 750 − 632·45 = 117·5

Monthly saving on kVA charges = Rs 8·5 × 117·5 = Rs 998·75

Yearly saving on kVA charges = Rs 998·75 × 12 = Rs 11,985

Fixed charges/year = Rs 0·1 × 20,000 = Rs 2000

Net annual saving = Rs (11,985 − 2000) = Rs 9,985

Example 6.9. *A synchronous motor improves the power factor of a load of 200 kW from 0.8 lagging to 0.9 lagging. Simultaneously the motor carries a load of 80 kW. Find (i) the leading kVAR taken by the motor (ii) kVA rating of the motor and (iii) power factor at which the motor operates.*

Solution.

Load, $P_1 = 200$ kW ; Motor load, $P_2 = 80$ kW

p.f. of load, $\cos\phi_1 = 0{\cdot}8$ lag

p.f. of combined load, $\cos\phi_2 = 0{\cdot}9$ lag

Combined load, $P = P_1 + P_2 = 200 + 80 = 280$ kW

In Fig. 6.12, Δ *OAB* is the power triangle for load, Δ *ODC* for combined load and Δ *BEC* for the motor.

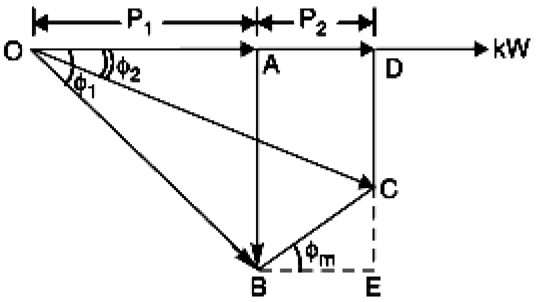

Fig. 6.12

(*i*) Leading kVAR taken by the motor

$= CE = DE - DC = AB - DC$ $\quad [\because AB = DE]$

$= P_1 \tan\phi_1 - P^* \tan\phi_2$

$= 200 \tan(\cos^{-1} 0{\cdot}8) - 280 \tan(\cos^{-1} 0{\cdot}9)$

$= 200 \times 0{\cdot}75 - 280 \times 0{\cdot}4843$

$=$ **14·4 kVAR**

(*ii*) kVA rating of the motor $= BC = \sqrt{(BE)^2 + (EC)^2} = \sqrt{(80)^2 + (14{\cdot}4)^2} =$ **81·28 kVA**

(*iii*) p.f. of motor, $\cos\phi_m = \dfrac{\text{Motor kW}}{\text{Motor kVA}} = \dfrac{80}{81{\cdot}28} =$ **0·984 leading**

* In right angled triangle *OAB*, $AB = P_1 \tan\phi_1$

In right angled triangle *ODC*, $DC = OD \tan\phi_2 = (P_1 + P_2)\tan\phi_2 = P \tan\phi_2$

Example 6.10. *A factory load consists of the following :*

(*i*) *an induction motor of 50 H.P. (37·3 kW) with 0·8 p.f. and efficiency 0·85.*

(*ii*) *a synchronous motor of 25 H.P. (18·65 kW) with 0·9 p.f. leading and efficiency 0·9.*

(*iii*) *lighting load of 10 kW at unity p.f.*

Find the annual electrical charges if the tariff is Rs 60 per kVA of maximum demand per annum plus 5 paise per kWh ; assuming the load to be steady for 2000 hours in a year.

Solution.

Input power to induction motor $= 37{\cdot}3/0{\cdot}85 = 43{\cdot}88$ kW

Lagging kVAR taken by induction motor $= 43{\cdot}88 \tan(\cos^{-1} 0{\cdot}8) = 32{\cdot}91$

Input power to synchronous motor

$= 18{\cdot}65/0{\cdot}9 = 20{\cdot}72$ kW

Leading kVAR taken by synchronous motor

$= 20{\cdot}72 \tan(\cos^{-1} 0{\cdot}9) = 10$

Since lighting load works at unity p.f., its lagging kVAR = 0.

Net lagging kVAR $= 32{\cdot}91 - 10 = 22{\cdot}91$

Total active power $= 43{\cdot}88 + 20{\cdot}72 + 10 = 74{\cdot}6$ kW

Total kVA $= \sqrt{(74{\cdot}6)^2 + (22{\cdot}91)^2} = 78$

Annual kVA demand charges $=$ Rs $60 \times 78 =$ Rs 4,680

Energy consumed/year $= 74{\cdot}6 \times 2000 = 1{,}49{,}200$ kWh

Annual Energy charges $=$ Rs $0{\cdot}05 \times 1{,}49{,}200 =$ Rs 7,460

Total annual bill $=$ kVA demand charges + Energy charges

$=$ Rs $(4680 + 7460) =$ **Rs 12,140**

Example 6.11. *A supply system feeds the following loads (i) a lighting load of 500 kW (ii) a load of 400 kW at a p.f. of 0·707 lagging (iii) a load of 800 kW at a p.f. of 0·8 leading (iv) a load of 500 kW at a p.f. 0·6 lagging (v) a synchronous motor driving a 540 kW d.c. generator and having an overall efficiency of 90%. Calculate the power factor of synchronous motor so that the station power factor may become unity.*

Solution. The lighting load works at unity p.f. and, therefore, its lagging kVAR is zero. The lagging kVAR are taken by the loads (*ii*) and (*iv*), whereas loads (*iii*) and (*v*) take the leading kVAR. For station power factor to be unity, the total lagging kVAR must be neutralised by the total leading kVAR. We know that kVAR = kW tan ϕ.

∴ Total lagging kVAR taken by loads (*ii*) and (*iv*)

$$= 400 \tan(\cos^{-1} 0{\cdot}707) + 500 \tan(\cos^{-1} 0{\cdot}6)$$

$$= 400 \times 1 + 500 \times 1{\cdot}33 = 1065$$

Leading kVAR taken by the load (*iii*)

$$= 800 \tan(\cos^{-1} 0{\cdot}8) = 800 \times 0{\cdot}75 = 600$$

∴ Leading kVAR to be taken by synchronous motor

$$= 1065 - 600 = 465 \text{ kVAR}$$

$$\text{Motor input} = \text{output/efficiency} = 540/0{\cdot}9 = 600 \text{ kW}$$

If ϕ is the phase angle of synchronous motor, then,

$$\tan\phi = \text{kVAR/kW} = 465/600 = 0{\cdot}775$$

$$\therefore \quad \phi = \tan^{-1} 0{\cdot}775 = 37{\cdot}77^\circ$$

$$\therefore \quad \text{p.f. of synchronous motor} = \cos\phi = \cos 37{\cdot}77^\circ = \mathbf{0{\cdot}79\ leading}$$

Therefore, in order that the station power factor may become unity, the synchronous motor should be operated at a p.f. of 0·79 leading.

Example 6.12. *An industrial load consists of (i) a synchronous motor of 100 metric h.p. (ii) induction motors aggregating 200 metric h.p., 0·707 power factor lagging and 82% efficiency and (iii) lighting load aggregating 30 kW.*

The tariff is Rs 100 per annum per kVA maximum demand plus 6 paise per kWh. Find the annual saving in cost if the synchronous motor operates at 0·8 p.f. leading, 93% efficiency instead of 0·8 p.f. lagging at 93% efficiency.

Solution. The annual power bill will be calculated under two conditions *viz.*, (*a*) when synchronous motor runs with lagging p.f. and (*b*) when synchronous motor runs with a leading p.f.

(*a*) **When synchronous motor runs at p.f. 0·8 lagging.** We shall find the combined kW and then calculate total kVA maximum demand using the relation :

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

$$\text{Input to synchronous motor} = \frac{100 \times 735 \cdot 5}{0 \cdot 93 \times 1000} = 79 \text{ kW}$$

*Lagging kVAR taken by the synchronous motor

$$= 79 \tan(\cos^{-1} 0{\cdot}8) = 79 \times 0{\cdot}75 = 59{\cdot}25 \text{ kVAR}$$

$$\text{Input to induction motors} = \frac{200 \times 735 \cdot 5}{0 \cdot 82 \times 1000} = 179.4 \text{ kW}$$

Lagging kVAR taken by induction motors

$$= 179{\cdot}4 \tan(\cos^{-1} 0{\cdot}707) = 179{\cdot}4 \times 1 = 179{\cdot}4 \text{ kVAR}$$

Since lighting load works at unity p.f., its lagging kVAR is zero.

$$\therefore \quad \text{Total lagging kVAR} = 59{\cdot}25 + 179{\cdot}4 = 238{\cdot}65 \text{ kVAR}$$

$$\text{Total active power} = 79 + 179{\cdot}4 + 30 = 288{\cdot}4 \text{ kW}$$

$$\text{Total kVA} = \sqrt{(238.65)^2 + (288 \cdot 4)^2} = 374{\cdot}4 \text{ kVA}$$

$$\text{Annual kVA demand charges} = \text{Rs } 100 \times 374{\cdot}4 = \text{Rs } 37{,}440$$

* Since the synchronous motor in this case runs at lagging p.f., it takes lagging kVAR.

$$\text{Energy consumed/year} = 288{\cdot}4 \times 8760 = 25{,}26384 \text{ kWh}$$

$$\text{Annual energy charges} = \text{Rs } 0{\cdot}06 \times 25{,}26{,}384 = \text{Rs } 1{,}51{,}583$$

$$\text{Total annual bill} = \text{Rs } (37{,}440 + 1{,}51{,}583) = \text{Rs } 1{,}89{,}023$$

(*b*) **When synchronous motor runs at p.f. 0·8 leading.** As the synchronous motor runs at leading p.f. of 0·8 (instead of 0·8 p.f. lagging), therefore, it takes now 59·25 leading kVAR. The lagging kVAR taken by induction motors are the same as before *i.e.*, 179·4.

$$\therefore \quad \text{Net lagging kVAR} = 179{\cdot}4 - 59{\cdot}25 = 120{\cdot}15$$

$$\text{Total active power} = \text{Same as before } i.e., 288{\cdot}4 \text{ kW}$$

$$\therefore \quad \text{Total kVA} = \sqrt{(120.15)^2 + (288 \cdot 4)^2} = 312{\cdot}4$$

$$\text{Annual kVA demand charges} = \text{Rs } 100 \times 312{\cdot}4 = \text{Rs } 31{,}240$$

$$\text{Annual energy charges} = \text{Same as before } i.e., \text{Rs } 1{,}51{,}583$$

$$\text{Total annual bill} = \text{Rs } (31{,}240 + 1{,}51{,}583) = \text{Rs } 1{,}82{,}823$$

$$\therefore \quad \text{Annual saving} = \text{Rs } (1{,}89{,}023 - 1{,}82{,}823) = \text{Rs } 6200$$

TUTORIAL PROBLEMS

1. What should be the kVA rating of a capacitor which would raise the power factor of load of 100 kW from 0·5 lagging to 0·9 lagging ? **[125 kVA]**
2. A 3-phase, 50 Hz, 3300 V star connected induction motor develops 250 H.P. (186·5 kW), the power factor being 0·707 lagging and the efficiency 0·86. Three capacitors in delta are connected across the supply terminals and power factor raised to 0·9 lagging. Calculate :
   (*i*) the kVAR rating of the capacitor bank.
   (*ii*) the capacitance of each unit. **[(*i*) 111·8 kVAR (*ii*) 10·9 μF]**
3. A 3-phase, 50 Hz, 3000 V motor develops 600 H.P. (447·6 kW), the power factor being 0·75 lagging and the efficiency 0·93. A bank of capacitors is connected in delta across the supply terminals and power factor raised to 0·95 lagging. Each of the capacitance units is built of five similar 600-V capacitors. Determine the capacitance of each capacitor. **[156 μF]**
4. A factory takes a load of 800 kW at 0·8 p.f. (lagging) for 3000 hours per annum and buys energy on tariff of Rs 100 per kVA plus 10 paise per kWh. If the power factor is improved to 0·9 lagging by means of capacitors costing Rs 60 per kVAR and having a power loss of 100 W per kVA, calculate the annual saving effected by their use. Allow 10% per annum for interest and depreciation on the capacitors. **[Rs 3972]**
5. A station supplies 250 kVA at a lagging power factor of 0·8. A synchronous motor is connected in parallel with the load. If the combined load is 250 kW with a lagging p.f. of 0.9, determine :
   (*i*) the leading kVAR taken by the motor.
   (*ii*) kVA rating of the motor.
   (*iii*) p.f. at which the motor operates. **[(*i*) 28·9 kVAR (*ii*) 57·75 kVA (*iii*) 0·866 lead]**
6. A generating station supplies power to the following :
   (*i*) a lighting load of 100 kW;
   (*ii*) an induction motor 800 h.p. (596·8 kW) p.f. 0·8 lagging, efficiency 92%;
   (*iii*) a rotary converter giving 150 A at 400 V at an efficiency of 0·95.
   What must be the power factor of the rotary convertor in order that power factor of the supply station may become unity ? **[0·128 leading]**
7. A 3-phase, 400 V synchronous motor having a power consumption of 50 kW is connected in parallel with an induction motor which takes 200 kW at a power factor of 0·8 lagging.
   (*i*) Calculate the current drawn from the mains when the power factor of the synchronous motor is unity.
   (*ii*) At what power factor should the synchronous motor operate so that the current drawn from the mains is minimum. ? **[(*i*) 421 A (*ii*) 0·316 leading]**
8. A factory load consists of the following :
   (*i*) an induction motor of 150 h.p. (111·9 kW) with 0·7 p.f. lagging and 80% efficiency ;
   (*ii*) a synchronous motor of 100 h.p. (74·6 kW) with 0·85 p.f. leading at 90% efficiency ;
   (*iii*) a lighting load of 50 kW.
   Find the annual electric charges if the tariff is Rs 100 per annum per kVA maximum demand plus 7 paise per kWh ; assuming the load to be steady throughout the year. **[Rs 1,96,070]**
9. A 3-phase synchronous motor having a mechanical load (including losses) of 122 kW is connected in parallel with a load of 510 kW at 0·8 p.f. lagging. The excitation of the motor is adjusted so that the kVA input to the motor becomes 140 kVA. Determine the new power factor of the whole system. **[0·8956 lagging]**
10. A 3-phase synchronous motor is connected in parallel with a load of 700 kW at 0·7 power factor lagging and its excitation is adjusted till it raises the total p.f. to 0.9 lagging. Mechanical load on the motor including losses is 150 kW. Find the power factor of the synchronous motor. **[0·444 leading]**

6.8 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 imporves 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 p.f. correction equipment, yet improvement of p.f. 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 kW = kVA × cos ϕ, 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.

6.9 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 p.f. correction equipment. Therefore, the *net annual saving* will be equal to the annual saving in maximum demand charges *minus* annual expenditure incurred on p.f. 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 ϕ_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 ϕ_2 by installing p.f. correction equipment. Let expenditure incurred on the p.f. correction equipment be Rs y per kVAR per annum. The power triangle at the original p.f. cos ϕ_1 is OAB and for the improved p.f. cos ϕ_2, it is OAC [See Fig. 6.13].

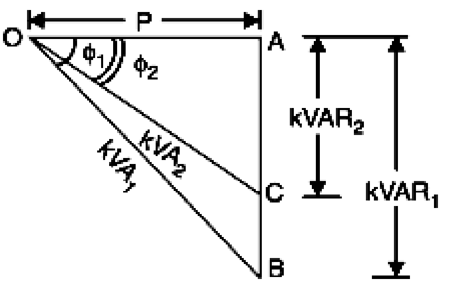

Fig. 6.13

kVA max. demand at cos ϕ_1, $kVA_1 = P/\cos\phi_1 = P\sec\phi_1$

kVA max. demand at cos ϕ_2, $kVA_2 = P/\cos\phi_2 = P\sec\phi_2$

Annual saving in maximum demand charges

$$= \text{Rs } x\,(kVA_1 - kVA_2)$$
$$= \text{Rs } x\,(P\sec\phi_1 - P\sec\phi_2)$$
$$= \text{Rs } xP\,(\sec\phi_1 - \sec\phi_2) \quad ...(i)$$

Reactive power at cos ϕ_1, $kVAR_1 = P\tan\phi_1$

Reactive power at cos ϕ_2, $kVAR_2 = P\tan\phi_2$

Leading kVAR taken by p.f. correction equipment

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

Annual cost of p.f. correction equipment

$$= \text{Rs } Py\,(\tan\phi_1 - \tan\phi_2) \quad ...(ii)$$

$$\text{Net annual saving, } S = \text{exp. } (i) - \text{exp. } (ii)$$
$$= xP\,(\sec\phi_1 - \sec\phi_2) - yP\,(\tan\phi_1 - \tan\phi_2)$$

In this expression, only ϕ_2 is variable while all other quantities are fixed. Therefore, the net annual saving will be maximum if differentiation of above expression *w.r.t.* ϕ_2 is zero *i.e.*

* The total investment for producing 1 kVAR is Rs 120. The annual interest and depreciation is 10%. It means that an expenditure of Rs 120 × 10/100 = Rs 12 is incurred on 1 kVAR per annum.

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

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

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

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

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

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

or $\sin\phi_2 = y/x$

$\therefore$ 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 p.f. correction equipment but is independent of the original p.f. $\cos\phi_1$.

Example 6.13 *A factory which has a maximum demand of 175 kW at a power factor of 0·75 lagging is charged at Rs 72 per kVA per annum. If the phase advancing equipment costs Rs 120 per kVAR, find the most economical power factor at which the factory should operate. Interest and depreciation total 10% of the capital investment on the phase advancing equipment.*

Solution :

Power factor of the factory, $\cos\phi_1$ = 0·75 lagging

Max. demand charges, x = Rs 72 per kVA per annum

Expenditure on phase advancing equipment, y = Rs 120 × 0·1 = Rs 12* /kVAR/annum

$\therefore$ Most economical p.f. at which factory should operate is

$$\cos\phi_2 = \sqrt{1-(y/x)^2} = \sqrt{1-(12/72)^2} = 0{\cdot}986 \text{ lagging}$$

Example 6.14 *A consumer has an average demand of 400 kW at a p.f. of 0·8 lagging and annual load factor of 50%. The tariff is Rs 50 per kVA of maximum demand per annum plus 5 paise per kWh. If the power factor is improved to 0·95 lagging by installing phase advancing equipment, calculate :*

(*i*) *the capacity of the phase advancing equipment*

(*ii*) *the annual saving effected*

The phase advancing equipment costs Rs 100 per kVAR and the annual interest and depreciation together amount to 10%.

Solution :

Max. kW demand, P = 400/0·5 = 800 kW

Original p.f., $\cos\phi_1$ = 0·8 lag ; Final p.f., $\cos\phi_2$ = 0·95 lag

$\phi_1 = \cos^{-1}(0{\cdot}8) = 36{\cdot}9°$; $\tan\phi_1 = \tan 36{\cdot}9° = 0{\cdot}75$

$\phi_2 = \cos^{-1}(0{\cdot}95) = 18{\cdot}2°$; $\tan\phi_2 = \tan 18{\cdot}2° = 0{\cdot}328$

(*i*) Leading kVAR taken by phase advancing equipment

= $P(\tan\phi_1 - \tan\phi_2)$ = 800 (0·75 − 0·328) = 337 kVAR

$\therefore$ Capacity of phase advancing equipment should be 337 kVAR.

(*ii*) Max. demand charges, x = Rs 50/kVA/annum

Expenditure on phase advancing equipment

y = Rs 0·1 × 100 = Rs 10/kVAR/annum

Max. kVA demand at 0·8 p.f. = 800/0·8 = 1000 kVA

Max. kVA demand at 0·95 p.f. = 800/0·95 = 842 kVA

Annual saving in maximum demand charges

= Rs 50 (1000 − 842) = Rs 7900

Annual expenditure on phase advancing equipment

= Rs (y × capacity of equipment)

= Rs 10 × 337 = 3370

$\therefore$ Net annual saving = Rs (7900 − 3370) = Rs 4530

Example 6.15 *A factory has an average demand of 50 kW and an annual load factor of 0·5. The power factor is 0·75 lagging. The tariff is Rs 100 per kVA of maximum demand per annum plus 5 paise per kWh. If loss free capacitors costing Rs 600 per kVAR are to be utilised, find the value of power factor at which maximum saving will result. The interest and depreciation together amount to 10%. Also determine the annual saving effected by improving the p.f. to this value.*

Solution :

Max. demand charge, x = Rs 100/kVA/annum

Expenditure on capacitors, y = Rs 0·1 × 600 = Rs 60/kVAR/annum

Most economical p.f., $\cos\phi_2 = \sqrt{1-(y/x)^2} = \sqrt{1-(60/100)^2} = 0{\cdot}8$ lag

Max. kW demand = 50/0·5 = 100 kW

The maximum kVA demand at 0·75 p.f. is = 100/0·75 = 133·34 kVA, whereas it is = 100/0·8 = 125 kVA at 0·8 p.f.

∴ Annual saving = Rs 100 (133·34 – 125) = **Rs 834**

Example 6.16 *A factory takes a steady load of 200 kW at a lagging power factor of 0·8. The tariff is Rs 100 per kVA of maximum demand per annum plus 5 paise per kWh. The phase advancing plant costs Rs 500 per kVAR and the annual interest and depreciation together amount to 10%. Find:*

(*i*) *the value to which the power factor be improved so that annual expenditure is minimum*

(*ii*) *the capacity of the phase advancing plant*

(*iii*) *the new bill for energy, assuming that the factory works for 5000 hours per annum.*

Solution :

Peak load of factory, P = 200 kW

Original power factor, $\cos\phi_1$ = 0·8 lagging

Max. demand charges, x = Rs 100/kVA/annum

Charges on phase advancing plant, y = Rs 500 × 0·1
= Rs 50/kVAR/annum

(*i*) Most economical power factor, $\cos\phi_2 = \sqrt{1-(y/x)^2} = \sqrt{1-(50/100)^2} = 0{\cdot}866$ **lagging**

(*ii*) Capacity of phase advancing plant = $P\,[\tan\phi_1 - \tan\phi_2]$
= 200 [tan ($\cos^{-1}$ 0·8) –tan ($\cos^{-1}$ 0·866)]
= 200 [0·75 – 0·5774] = **34·52 kVAR**

(*iii*) Units consumed/year = 200 × 5000 = 10^6 kWh

Annual energy charges = Rs 0·05 × 10^6 = Rs 50,000

Annual cost of phase advancing plant = Rs y × Capacity of plant
= Rs 50 × 34·52 = Rs 1726

Max. demand charge = Rs $x \times P/\cos\phi_2$ = Rs 100 × 200/0·866 = Rs 23,094

Annual bill for energy = Rs (50,000 + 1726 + 23,094) = **Rs 74,820**

Example 6.17 *An industrial load takes 80,000 units in a year, the average power factor being 0·707 lagging. The recorded maximum demand is 500 kVA. The tariff is Rs 120 per kVA of maximum demand plus 2·5 paise per kWh. Calculate the annual cost of supply and find out the annual saving in cost by installing phase advancing plant costing Rs 50 per kVAR which raises the p.f. from 0·707 to 0·9 lagging. Allow 10% per year on the cost of phase advancing plant to cover all additional costs.*

Solution.

Energy consumed/year = 80,000 kWh

Maximum kVA demand = 500

Annual cost of supply = M.D. Charges + Energy charges

= Rs (120 × 500 + 0·025 × 80,000)

= Rs (60,000 + 2000) = **Rs 62,000**

$\cos \phi_1 = 0{\cdot}707$ lag ; $\cos \phi_2 = 0{\cdot}9$ lag

Max. kW demand at 0·707 p.f., $P = 500 \times 0{\cdot}707 = 353{\cdot}3$ kW

Leading kVAR taken by phase advancing equipment

$= P\,[\tan \phi_1 - \tan \phi_2]$

$= 353{\cdot}3\,[\tan(\cos^{-1} 0{\cdot}707) - \tan(\cos^{-1} 0{\cdot}9)]$

$= 353{\cdot}3\,[1 - 0{\cdot}484] = 182{\cdot}3$ kVAR

Annual cost of phase advancing equipment

= Rs 182·3 × 50 × 0·1 = Rs 912

When p.f. is raised from 0·707 lag to 0·9 lag, new maximum kVA demand is = 353·3/0·9 = 392·6 kVA.

Reduction in kVA demand = 500 − 392·6 = 107·4

Annual saving in kVA charges = Rs 120 × 107·4 = Rs 12,888

As the units consumed remain the same, therefore, saving will be equal to saving in M.D. charges *minus* annual cost of phase advancing plant.

∴ Annual saving = Rs (12,882 − 912) = **Rs 11,976**

6.10 Meeting the Increased kW Demand on Power Stations

The useful output of a power station is the kW output delivered by it to the supply system. Sometimes, a power station is required to deliver more kW to meet the increase in power demand. This can be achieved by either of the following two methods :

(*i*) By increasing the kVA capacity of the power station at the same power factor (say $\cos \phi_1$). Obviously, extra cost will be incurred to increase the kVA capacity of the station.

(*ii*) By improving the power factor of the station from $\cos \phi_1$ to $\cos \phi_2$ without increasing the kVA capacity of the station. This will also involve extra cost on account of power factor correction equipment.

Economical comparison of two methods. It is clear that each method of increasing kW capacity of the station involves extra cost. It is, therefore, desirable to make economical comparison of the two methods. Suppose a power station of rating *P* kVA is supplying load at p.f. of $\cos \phi_1$. Let us suppose that the new power demand can be met either by increasing the p.f. to $\cos \phi_2$ at *P* kVA *or* by increasing the kVA rating of the station at the original p.f. $\cos \phi_1$. The power* triangles for the whole situation are shown in Fig. 6.14.

(*i*) **Cost of increasing kVA capacity of station.** Referring to Fig. 6.14, the increase in kVA capacity of the station at $\cos \phi_1$ to meet the new demand is given by :

Increase in kVA capacity

$$= BD = \frac{BF}{\cos \phi_1} = \frac{AC}{\cos \phi_1} \qquad (\because BF = AC)$$

$$= \frac{OC - OA}{\cos \phi_1}$$

$$= \frac{OE \cos \phi_2 - OB \cos \phi_1}{\cos \phi_1}$$

$$= \frac{P(\cos \phi_2 - \cos \phi_1)}{\cos \phi_1} \qquad [\because OE = OB = P]$$

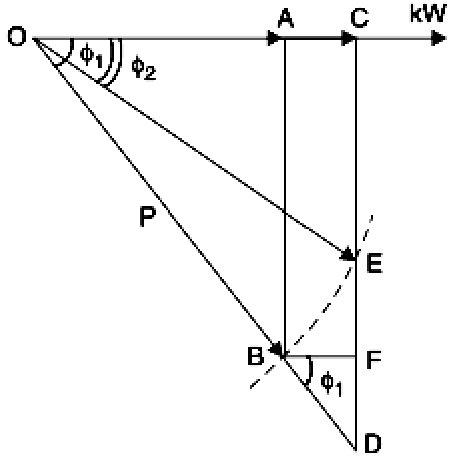

Fig. 6.14

If Rs *x* is the annual cost per kVA of the station, then,

Annual cost due to increase in kVA capacity

$$= \text{Rs } \frac{xP(\cos \phi_2 - \cos \phi_1)}{\cos \phi_1} \qquad ...(i)$$

(*ii*) **Cost of p.f. correction equipment.** Referring to Fig. 6.14, the new demand in kW can be met by increasing the p.f. from $\cos\phi_1$ to $\cos\phi_2$ at the original kVA of the station. The leading kVAR to be taken by the p.f. correction equipment is given by *ED i.e.*

Leading kVAR taken by p.f. correction equipment

$$= ED = CD - CE$$

$$= OD\sin\phi_1 - OE\sin\phi_2$$

$$= \frac{OC}{\cos\phi_1}\sin\phi_1 - OE\sin\phi_2$$

$$= \frac{OE\cos\phi_2}{\cos\phi_1}\sin\phi_1 - OE\sin\phi_2$$

$$= OE(\tan\phi_1\cos\phi_2 - \sin\phi_2)$$

$$= P(\tan\phi_1\cos\phi_2 - \sin\phi_2)$$

If Rs. y is the annual cost per kVAR of the p.f. correction equipment, then,

Annual cost on p.f. correction equipment

$$= \text{Rs } yP(\tan\phi_1\cos\phi_2 - \sin\phi_2) \quad \text{...(ii)}$$

Different cases

(*a*) The p.f. correction equipment will be cheaper if

$$\text{exp. }(ii) < \text{exp. }(i)$$

or $$yP(\tan\phi_1\cos\phi_2 - \sin\phi_2) < \frac{xP(\cos\phi_2 - \cos\phi_1)}{\cos\phi_1}$$

---

* Note the construction. Here $\Delta\, OAB$ is the power triangle for the station supplying P kVA at $\cos\phi_1$. The demand on the station is OA kW. The new demand is OC *kW*. This can be met :

(*i*) either by increasing the kVA demand of the station to OD at the same p.f. $\cos\phi_1$. Obviously, Δ OCD is the power triangle when the station is supplying OC kW at $\cos\phi_1$.

(*ii*) or by increasing the p.f. from $\cos\phi_1$ to $\cos\phi_2$ at same kVA *i.e.*, P kVA. Obviously, $OB = OE$. Therefore, $\Delta\, OCE$ is the power triangle when the station is supplying OC kW at improved p.f. $\cos\phi_2$.

or $$y(\tan\phi_1\cos\phi_2 - \sin\phi_2) < x\frac{(\cos\phi_2 - \cos\phi_1)}{\cos\phi_1}$$

(*b*) The maximum annual cost per kVAR (*i.e.*, y) of p.f. correction equipment that would justify its installation is when

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

or $$yP(\tan\phi_1\cos\phi_2 - \sin\phi_2) = \frac{xP(\cos\phi_2 - \cos\phi_1)}{\cos\phi_1}$$

or $$y\left(\frac{\sin\phi_1}{\cos\phi_1}\cos\phi_2 - \sin\phi_2\right) = \frac{x(\cos\phi_2 - \cos\phi_1)}{\cos\phi_1}$$

or $$y\left(\frac{\sin\phi_1\cos\phi_2 - \sin\phi_2\cos\phi_1}{\cos\phi_1}\right) = \frac{x(\cos\phi_2 - \cos\phi_1)}{\cos\phi_1}$$

or $$y\sin(\phi_1 - \phi_2) = x(\cos\phi_2 - \cos\phi_1)$$

$$\therefore \quad y = \frac{x(\cos\phi_2 - \cos\phi_1)}{\sin(\phi_1 - \phi_2)}$$

Example 6.18 *A power plant is working at its maximum kVA capacity with a lagging p.f. of 0·7. It is now required to increase its kW capacity to meet the demand of additional load. This can be done :*

(*i*) *by increasing the p.f. to 0·85 lagging by p.f. correction equipment*

or

(*ii*) *by installing additional generation plant costing Rs 800 per kVA.*

What is the maximum cost per kVA of p.f. correction equipment to make its use more economical than the additional plant ?

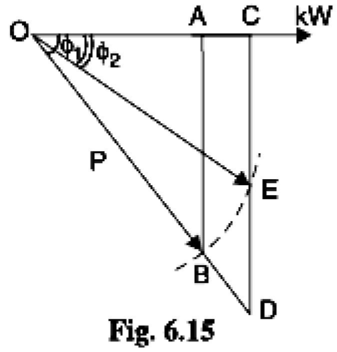

Fig. 6.15

Soloution. Let the initial capacity of the plant be *OB* kVA at a p.f. cos ϕ_1. Referring to Fig. 6.15, the new kW demand (*OC*) can be met by increasing the p.f. from 0·7 (cos ϕ_1) to 0·85 lagging (cos ϕ_2) at *OB* kVA *or* by increasing the capacity of the station to *OD* kVA at cos ϕ_1.

Cost of increasing plant capacity. Referring to Fig. 6.15, the increase in kVA capacity is *BD*.

Now $\quad OE \cos\phi_2 = OD \cos\phi_1$

or $\quad OB \cos\phi_2 = OD \cos\phi_1 \quad (\because OE = OB)$

$\therefore \quad OD = OB \times \cos\phi_2/\cos\phi_1 = OB \times 0{\cdot}85/0{\cdot}7 = 1{\cdot}2143\ OB$

Increase in the kVA capacity of the plant is

$$BD = OD - OB = 1{\cdot}2143 \times OB - OB = 0{\cdot}2143\ OB$$

$\therefore$ Total cost of increasing the plant capacity

$$= \text{Rs } 800 \times 0{\cdot}2143 \times OB$$
$$= \text{Rs } 171{\cdot}44 \times OB \qquad ...(i)$$

Cost of p.f. correction equipment.

$\cos\phi_1 = 0{\cdot}7 \qquad \therefore \quad \sin\phi_1 = 0{\cdot}714$

$\cos\phi_2 = 0{\cdot}85 \qquad \therefore \quad \sin\phi_2 = 0{\cdot}527$

Leading kVAR taken by p.f. correction equipment is

$$ED = CD - CE = OD \sin\phi_1 - OE \sin\phi_2$$
$$= 1{\cdot}2143 \times OB \sin\phi_1 - OB \sin\phi_2$$
$$= OB\,(1{\cdot}2143 \times 0{\cdot}714 - 0{\cdot}527) = 0{\cdot}34 \times OB$$

Let the cost per kVAR of the equipment be Rs *y*.

$\therefore$ Total cost of p.f. correction equipment

$$= \text{Rs } 0{\cdot}34 \times \text{OB} \times y \qquad ...(ii)$$

The cost per kVAR of the equipment that would justify its installation is when exp. (*i*) = exp. (*ii*) *i.e.,*

$$171{\cdot}44 \times OB = 0{\cdot}34 \times \text{OB} \times y$$

$\therefore \quad y = \text{Rs } 171{\cdot}44/0{\cdot}34 = \text{Rs } 504{\cdot}2$ per kVAR

If the losses in p.f. correction equipment are neglected, then its kVAR = kVA. Therefore, the maximum cost per kVA of p.f. correction equipment that can be paid is Rs 504·2.

Example 6.19. *A system is working at its maximum kVA capacity with a lagging power factor 0·7. An anticipated increase of load can be met by one of the following two methods :*

(*i*) *By raising the p.f. of the system to 0·866 by installing phase advancing equipment.*

(*ii*) *By installing extra generating plant.*

If the total cost of generating plant is Rs 100 per kVA, estimate the limiting cost per kVA of phase advancing equipment to make its use more economical than the additional generating plant. Interest and depreciation charges may be assumed 10% in each case.

Solution. The original demand is *OA* and the increased demand is *OC*. Fig. 6.16 shows the two methods of meeting the increased kW demand (*OC*).

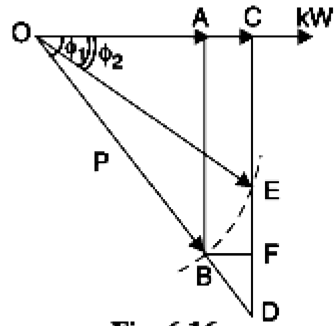

Fig. 6.16

Cost of increasing plant capacity

$$BD = OD - OB$$

$$= OB \times \frac{0 \cdot 866}{0 \cdot 70} - OB$$

$$= OB\,(1{\cdot}237 - 1)$$

$$= 0{\cdot}237 \times OB$$

∴ Annual cost of increasing the plant capacity

$$= \text{Rs } 10 \times 0{\cdot}237 \times OB$$

$$= \text{Rs. } 2{\cdot}37 \times OB \quad \text{...}(i)$$

Cost of phase advancing equipment. Leading kVAR taken by phase advancing equipment,

$$ED = CD - CE$$

$$= OD^* \sin \phi_1 - OE \sin \phi_2$$

$$= 1{\cdot}237 \times OB \times \sin \phi_1 - OB \sin \phi_2$$

$$= OB\,(1{\cdot}237 \times 0{\cdot}174 - 0{\cdot}5) = 0{\cdot}383 \times OB$$

Let the cost per kVAR of the equipment be Rs *y*.

Annual cost of phase advancing equipment

$$= \text{Rs } 0{\cdot}1 \times y \times 0{\cdot}383 \times OB \quad \text{...}(ii)$$

For economy, the two costs should be equal *i.e.*, exp. (*i*) = exp. (*ii*).

$$\therefore \quad 0{\cdot}1 \times y \times 0{\cdot}383 \times OB = 2{\cdot}37 \times OB$$

Cost of phase advancing equipment. Leading kVAR taken by phase advancing equipment,

$$ED = CD - CE$$

$$= OD^* \sin \phi_1 - OE \sin \phi_2$$

$$= 1{\cdot}237 \times OB \times \sin \phi_1 - OB \sin \phi_2$$

$$= OB\,(1{\cdot}237 \times 0{\cdot}174 - 0{\cdot}5) = 0{\cdot}383 \times OB$$

Let the cost per kVAR of the equipment be Rs *y*.

Annual cost of phase advancing equipment

$$= \text{Rs } 0{\cdot}1 \times y \times 0{\cdot}383 \times OB \quad \text{...}(ii)$$

For economy, the two costs should be equal *i.e.*, exp. (*i*) = exp. (*ii*).

$$\therefore \quad 0{\cdot}1 \times y \times 0{\cdot}383 \times OB = 2{\cdot}37 \times OB$$

or

$$y = \text{Rs } \frac{2 \cdot 37}{0 \cdot 1 \times 0 \cdot 383} = \text{Rs } 61{\cdot}88$$

If the losses in the phase advancing equipment are neglected, then its kVAR = kVA. Hence, the maximum cost per kVA of phase advancing equipment that can be paid is **Rs 61·88.**

---

* $OD = OB + BD = OB + 0{\cdot}237 \times OB = 1{\cdot}237 \times OB$

1. Fill in the blanks by inserting appropriate words/figures.

(*i*) The power factor of an a.c. circuit is given by .... power divided by .... power.

(*ii*) The lagging power factor is due to .... power drawn by the circuit.

(*iii*) Power factor can be improved by installing such a device in parallel with load which takes ....

(*iv*) The major reason for low lagging power factor of supply system is due to the use of .... motors.

(*v*) An over-excited synchronous motor on no load is known as ....

2. Pick up the correct words/figures from the brackets and fill in the blanks.

(*i*) The smaller the lagging reactive power drawn by a circuit. the .... is its power factor. (*smaller, greater*)

(*ii*) The maximum value of power factor can be .... (*1, 0·5, 0·9*)

(*iii*) KVAR = ... tan ϕ (*kW, KVA*)

(*iv*) By improving the power factor of the system, the kilowatts delivered by the generating station are .... (*decreased, increased, not changed*)

(*v*) The most economical power factor for a consumer is generally .... (*0·95 lagging, unity, 0·6 lagging*)

ANSWER TO SELF-TEST

1. (*i*) active, apparent, (*ii*) lagging reactive (*iii*) leading reactive power, (*iv*) induction (*v*) synchronous condenser.
2. (*i*) greater, (*ii*) 1, (*iii*) kW, (*iv*) increased, (*v*) 0·95 lagging.

VOLTAGE CONTROL:

Introduction

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*) alternator synchronous impedance (*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.

15.1 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 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.

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15.2 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

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 transmission as well as primary distribution systems. However, methods (*vi*) is reserved for the voltage control of a transmission line. We shall discuss each method separately in the next sections.

* 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.

15.7 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 e.m.f. of the transformer through the adjustment of its number of turns.

(*i*) **Off load tap-changing transformer.** Fig. 15.4 shows the arrangement where a number of tappings 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. 15.4, 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.

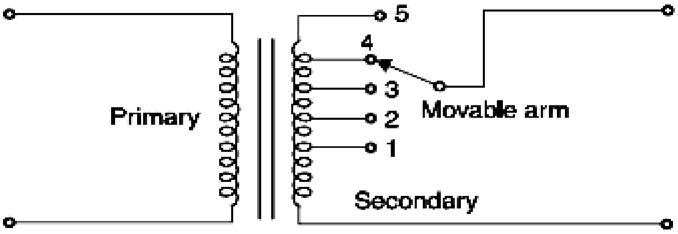


Fig. 15.4

* In a long line, difference in the receiving-end voltage between no load and full-load conditions is quite large.

The principal disadvantage of the circuit arrangement shown in Fig. 15.4 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 tappings 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. 15.5 shows diagrammatically one type of on-load tap-changing transformer. The secondary consists of two equal parallel windings which have similar tappings 1*a* ...... 5*a* and 1*b* .... 5*b*. In the normal working conditions, switches *a*, *b* and tappings with the same number remain closed and each secondary winding carries one-half of the total current. Referring to Fig. 15.5, the secondary voltage will be maximum when switches *a*, *b* and 5*a*, 5*b* are closed. However, the secondary voltage will be minimum when switches *a*, *b* and 1*a*, 1*b* are closed.

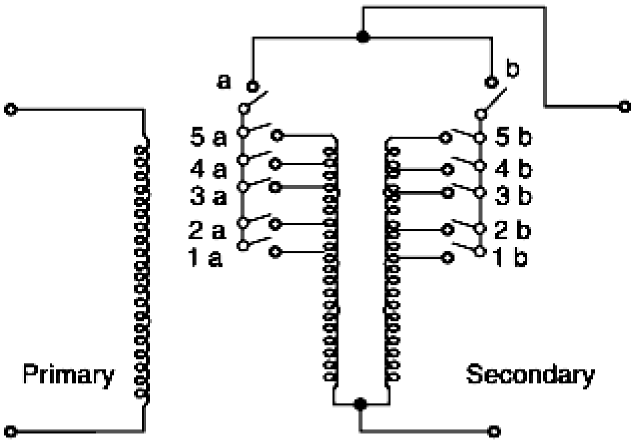


Fig. 15.5

Suppose that the transformer is working with tapping position at 4*a*, 4*b* and it is desired to alter its position to 5*a*, 5*b*. 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 5*a* and switch *a* is closed. After this, switch *b* is opened to disconnect its winding, tapping position on this winding is changed to 5*b* 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 tappings as the voltage steps.

15.8 Auto-Transformer Tap-changing

Fig. 15.6 shows diagrammatically auto-transformer tap changing. Here, a mid-tapped auto-transformer 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 tappings and the other end *b* is connected to switches across even tappings. 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. Referring to Fig. 15.6, it is clear that with switch 5 closed, minimum

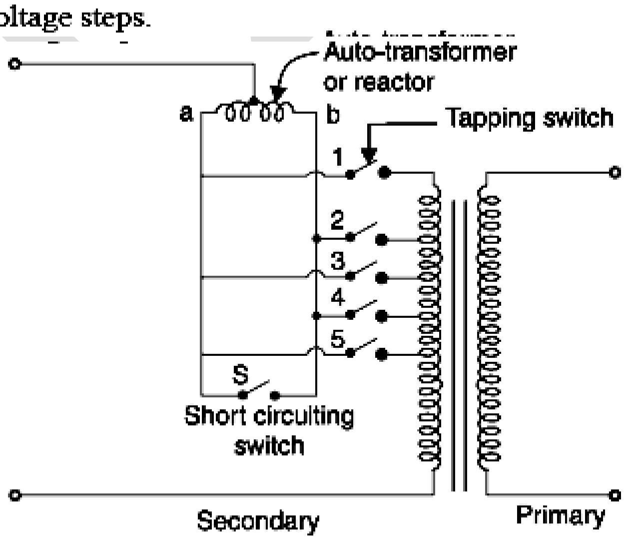


Fig. 15.6

* In the normal operation, switch *S* remains closed so that half the total current flows through each half of the reactor. Since the currents in each half of the reactor are in opposition, no resultant flux is set up and consequently there is no inductive voltage drop across it.

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.

15.9 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. 15.7. 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.

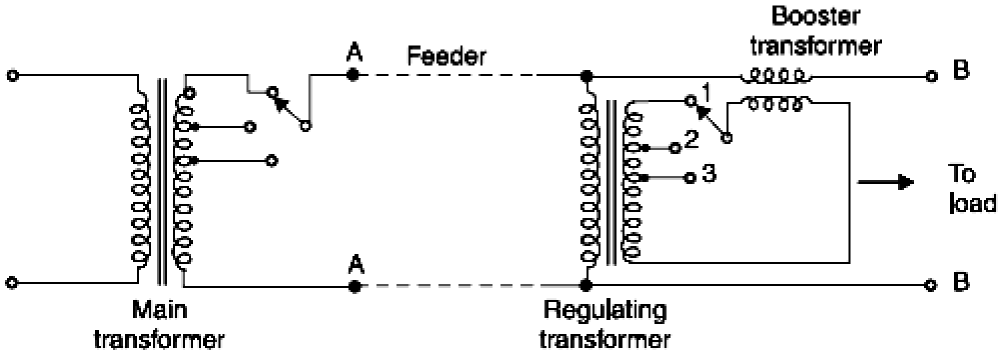


Fig. 15.7

Booster Transformer

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. 15.8 shows a three-phase booster transformer.

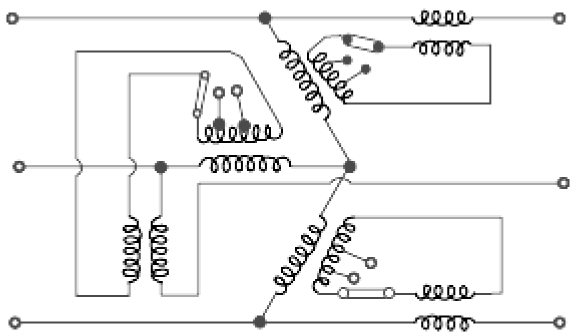


Fig. 15.8

* The on-load tap-changing gear is omitted from the diagram for the sake of simplicity.

15.11 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 ϕ_2.

(*i*) **Without synchronous condenser.** Fig. 15.12 (*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. 15.12 (*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.

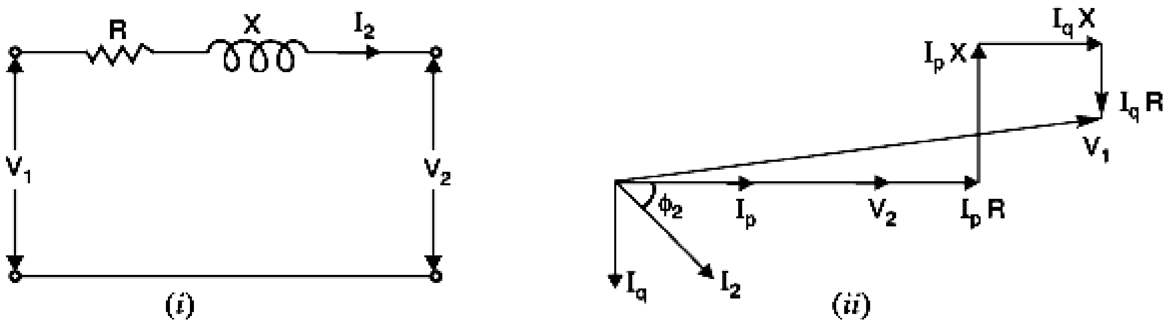


Fig. 15.12

(*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. 15.13. 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 :

* By changing the excitation of a synchronous motor, it can be made to take a leading power factor. A synchronous motor at no load and taking a leading power factor is known as a *synchronous condenser*. It is so called because the characteristics of the motor then resemble with that of a condenser.

** Neglecting the losses of the synchronous condenser, I_m will lead V_2 by 90°.

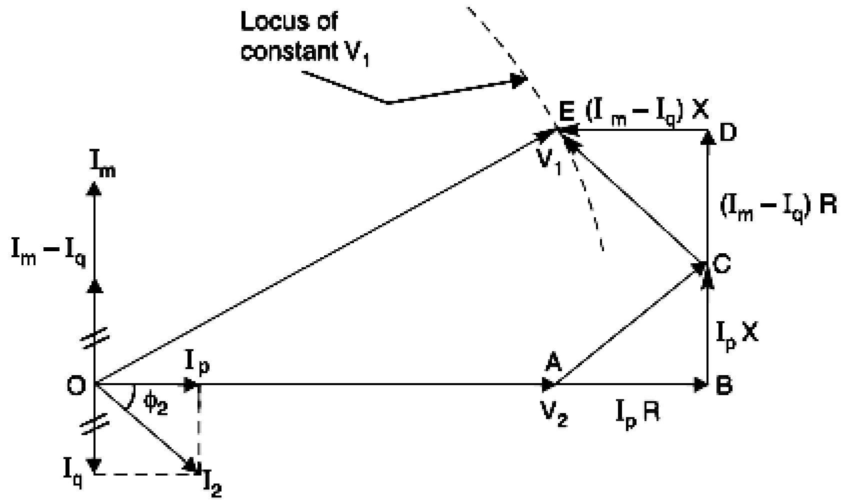


Fig. 15.13

$(I_m - I_q) R$ in phase with I_m

and $(I_m - I_q) X$ in quadrature leading with I_m

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

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

or

$$V_1^2 = [V_2 + I_p R - (I_m - I_q) X]^2 + [I_p X + (I_m - I_q) R]^2$$

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.

kVAR capacity of condenser $= \dfrac{3\, V_2\, I_m}{1000}$

Example 15.1. *A load of 10,000 kW at a power factor of 0·8 lagging is supplied by a 3-phase line whose voltage has to be maintained at 33kV at each end. If the line resistance and reactance per phase are 5 Ω and 10 Ω respectively, calculate the capacity of the synchronous condenser to be installed for the purpose. Comment on the result.*

Solution.

$$\text{Load current, } I_2 = \frac{10{,}000 \times 10^3}{\sqrt{3} \times 33 \times 10^3 \times 0\cdot8} = 218 \text{ A}$$

$$\therefore \quad I_p = I_2 \cos\phi_2 = 218 \times 0\cdot8 = 174\cdot4 \text{ A}$$

$$I_q = I_2 \sin\phi_2 = 218 \times 0\cdot6 = 130\cdot8 \text{ A}$$

$$R = 5\,\Omega\,;\, X = 10\,\Omega$$

$$\text{Sending-end voltage/phase, } V_1 = \text{Receiving end voltage/phase } (V_2)$$

$$= \frac{33 \times 10^3}{\sqrt{3}} = 19{,}053 \text{ V}$$

Let I_m be the current taken by the synchronous condenser. Referring to Fig. 15.13,

$$(19{,}053)^2 = [19{,}053 + 174\cdot4 \times 5 - 10\,(I_m - 130\cdot8)]^2 + [174\cdot4 \times 10 + (I_m - 130\cdot8)5]^2$$

Solving this equation, we get, $I_m = 231$ A

$$\text{Capacity of synchronous condenser} = \frac{3V_2\,I_m}{1000}\text{ kVAR} = \frac{3 \times 19{,}053 \times 231}{1000}\text{ kVAR}$$

$$= \textbf{13,203 kVAR}$$

Comments. This example shows that kVA capacity of the synchronous condenser is considerably greater than the kVA capacity of the load *viz* 13203 against 10000/0·8 = 12,500. Since the cost of synchronous condenser is usually very high, it would not be an economical proposition to have the same sending end and receiving end voltages. In practice, the synchronous condenser is operated in such a way so as to allow a small drop in the line.

Example 15.2. *A 3-phase overhead line has resistance and reactance per phase of 5 Ω and 20 Ω respectively. The load at the receiving end is 25 MW at 33 kV and a power factor of 0·8 lagging. Find the capacity of the synchronous condenser required for this load condition if it is connected at the receiving end and the line voltages at both ends are maintained at 33 kV.*

Solution.

$$\text{Load current, } I_2 = \frac{25 \times 10^6}{\sqrt{3} \times 33000 \times 0\cdot8} = 546\cdot8 \text{ A}$$

$$\therefore \quad I_p = I_2 \cos\phi_2 = 546\cdot8 \times 0\cdot8 = 437\cdot4 \text{ A}$$

$$I_q = I_2 \sin\phi_2 = 546\cdot8 \times 0\cdot6 = 328\cdot1 \text{ A}$$

$$R = 5\,\Omega\,;\, X = 20\,\Omega$$

$$\text{Sending end voltage/phase, } V_1 = \text{Receiving end voltage/phase, } V_2$$

$$= \frac{33 \times 10^3}{\sqrt{3}} = 19053 \text{ V}$$

Let I_m be the current taken by the synchronous condenser. Then,

$$V_1^2 = [V_2 + I_p R - (I_m - I_q) \times X]^2 + [I_p X + (I_m - I_q)\,R]^2$$

or

$$(19053)^2 = [19053 + 437\cdot4 \times 5 - (I_m - 328\cdot1) \times 20]^2 + [437\cdot4 \times 20 + (I_m - 328\cdot1) \times 5]^2$$

On solving this equation, we get, $I_m = 579\cdot5$ A

$$\text{Capacity of synchronous condenser} = \frac{3\,V_2\,I_m}{10^6}\text{ MVAR} = \frac{3 \times 19{,}053 \times 579\cdot5}{10^6} = \textbf{33·13 MVAR}$$

SELF - TEST

1. **Fill in the blanks by inserting appropriate words/figures :**
   (*i*) The statutory limit of voltage variations is .... of the declared voltage at consumer's terminals.
   (*ii*) In the automatic voltage regulators used at the generating station, the .... principle is used.
   (*iii*) The voltage variations in a Brown-Boveri regulator never exceed ....
   (*iv*) In a Tirril regulator, a .... resistance is cut in and out of the exciter field circuit of the alternator.
   (*v*) In practice, tap-changing is performed on load so that there is .... to supply.
   (*vi*) Induction regulators are used for voltage control in .... system.
   (*vii*) A synchronous condenser is generally installed at the .... end of a transmission line.
   (*viii*) The principal cause of voltage variation is the change of .... on the system.
   (*ix*) In a Tirril regulator, capacitor is provided across the relay contacts to reduce .... at the time relay contacts are opened.
2. **Pick up the correct words/figures from brackets and fill in the blanks :**
   (*i*) The voltage control equipment is used at .... in the power system. (*one point, more than one point*)
   (*ii*) The mechanical control torque in a Brown-Boveri regulator is .... whatever may be the position of drum. (*constant, variable*)
   (*iii*) The excitation control method is suitable only for .... lines. (*short, long*)
   (*iv*) It is .... to maintain the same voltage at both ends of a transmission line by synchronous condenser method. (*economical, not economical*).

ANSWERS TO SELF-TEST

1. (*i*) ± 6% (*ii*) overshooting the mark (*iii*) ± 1% (*iv*) regulating (*v*) no interruption (*vi*) primary distribution (*vii*) receiving (*viii*) load (*ix*) arcing
2. (*i*) more than one point (*ii*) constant (*iii*) short (*iv*) not economical.

UNIT-7: Economics of Power Generation

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

$$L_{av} = \frac{\text{Energy (energy consumed)}}{\text{total time (h)}} = \frac{E}{h}$$

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

$$DF = \frac{\text{Sum of individual max load within the group}}{\text{Maximum load of the system}}$$

$$= \frac{L_{\mathbf{max\,1}} + L_{\mathbf{max\,2}} + L_{\mathbf{max\,3}} + 0000}{L_{\mathbf{max}\,(\mathbf{system})}} \geq 1$$

Load factor:

Load factor is the ratio of average load during a specified period to the maximum load occurring during the period.

$$LF = \frac{L_{av}}{L_{max}}$$

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.

$$CF = \frac{\text{average load on power plant}}{\text{rated capacity of the power plant}} = \frac{L_{av}}{C} < 1$$

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.

$$DF = \frac{\text{Consumer actual max load}}{\text{Connected load}} \leq 1$$

For example, hotels DF = 0.25 – 0.95
Cold stores DF = 0.80 – 0.90

Utilization factor:

Utilization factor is the ratio of maximum demand of a system or part of the system, to the rated capacity of the system, or part of the system, under consideration.

$$UF = \frac{\text{maximum load}}{\text{rated capacity of the PP}} = \frac{L_{max}}{C} \leq 1$$

Firm power:

Firm power is the power intended always to be available even under emergency conditions.

Prime power:

Prime power is the maximum potential power constantly available for transformation into electrical power.

Cold reserve:

Cold reserve is the reserve generating capacity that is available for service but not in operation.

Hot reserve:

Hot reverse is the reserve generating capacity that is in operation but not in service.

Spinning reserve:

Spinning reserve is the reserve generating capacity that is connected to the bus and ready to take load.

Run of river station:

Run of river station is a hydro-electric station that utilizes the stream flow without water storage.

Base Load supply:

In inter connected systems with many generating stations of various types, the choice of station to supply the varying load is of considerable economic significance. Entire load of the system may be divided into two parts e.g., base load and peak load. Base load is the load which is supplied for most of the time which remains more or less constant. Peak load is the intermittent requirement at particular hours of the day and so on.

The main considerations for base load provision are:

(i) High efficiency

(ii) High availability of the system.

Even a higher capital cost is sometime favored if it can ensure resultant gain in efficiency, as the cost is spread over a large total energy value.

Nuclear power plants are invariably used as base load plants. Thermal power plants and hydroelectric power plants can also be used as base load plants.

As far as peak load plants are concerned, these plants should have:

(i) Ability to start and take full load with a short time

(ii) Low capacity cost in view of the small annual output with the efficiency only a secondary condition.

Obsolete steam plant, through less efficient can't be used to met with peak load demand. Gas turbines, diesel engine plant and pumped storage stations are also suitable for peak load operation.

Peak Load:

Load on a power plant seldom remain constant. The load varies from season to season and also in a day from hour to hour. In summer, due to fans and air conditioners the plants have generally high load as compared to winter months. During day time also lights are switched on in the evening, the load on the plant will increase. During the days of festivals like national festivals, national days etc., there is excessive demand of electrical power. A power generating plant has to meet with all such variable demand sand at the same time maintain overall economy of operation. The period during which the demand on a power station is highest is known as peak load. Peak load on a plant may exist for small duration but still the plant has to devise ways and means for meeting with such demands.

Some of the methods are given below to meet with peak load demand:

1. Peak Load Plants:

Such plants arc operated only during peak load periods. These plants must be capable of quickly starting from cold conditions. Diesel engine plants, gas turbine plants, pumped storage plants and sometimes steam power plants and hydroelectric plants are used as peak load plants. Efficiency of such plants is of secondary importance as these plants operate for limited period only.

2. Use of accumulators:

Although electrical energy cannot be stored, however steam can be stored in steam accumulators, which can be used to generate additional power during peak load period.

3. Purchasing power:

When a power plant cannot generate sufficient power to meet with the demand, it may purchase power from neighboring plants if facilities exist.

4. Load Shedding:

When there is no alternative available the supply to some consumers is cut off temporarily, which is known as load shedding. Sometimes load shedding is done by switching off feeders by rotation or by reducing system voltage or by reducing frequency.

SELECTION OF TYPE OF GENERATION

It is done on the basis of

1. Capacity of power plant

2. Probable load factor

3. Space

4. Cost of fuel and transpiration facilities

5. Availability of water

6. Interest and depreciation

7. Reliability

Cost of Electrical Energy:

Capital cost of a power plant is due to

1. Cost of land and buildings

2. Cost of generating equipment and accessories

3. Cost of transmission and distribution network

4. Cost of designing and planning the power station

In general following plants are preferred for base load operations:

1. Nuclear power plant

2. Hydro electric plant

3. Steam power plant

Following points are preferred for peak load operations:

1. Diesel engine power plant.

2. Gas turbine power plant

3. Pumped storage plant.

Cost of generation:

The cost of generating electricity in a power plant can be conveniently split into two parts: fixed costs and variable costs.

(A) Fixed Cost:

Fixed costs are to be borne by the plants irrespective of the load. These costs consist

(i) Interest on capital:

Capital cost of a plant includes the cost of land, buildings, of equipment including installation, designing, engineering etc. Since the capital cost of a plant is fixed therefore interest on the amount is considered as fixed cost.

(ii) Taxes:

A power generating and distributing company has to pay taxes to the Government. This amount is more or less fixed.

(iii) Cost of Transmission and Distribution:

Power transmission and. distribution network involves huge capital expenditure. This involves cost of transmission lines, transformers, substations and associated equipment. Interest on the capital involved is considered as a fixed cost.

(iv) Depreciation:

It is decrease in value caused by the wear due to constant use of an equipment Under the income tax laws there is provision for setting aside a fixed proportion of the capital employed, towards the depreciation fund.

(v) Insurance:

The plant and also life of some of workers working in dangerous areas, has to be insured against various risks involved. For this purpose a fixed sum is payable as premium for the insurance cover.

(vi) Salary for Managerial Staff:

Irrespective of whether the plant works or not certain managerial staff has to be retained by the organization. The salary liability of such staff is a part of the fixed cost.

(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.

9.10. FACTORS AFFECTING ECONOMICS OF GENERATION AND DISTRIBUTION OF POWER

The economics of power plant operation is greatly influenced by :

(*i*) Load factor (*ii*) Demand factor

(*iii*) Utilisation factor.

Load factor. In a *hydro-electric power station* with water available and a fixed staff for maximum output, the cost per unit generated at 100% *load factor* would be *half* the cost per unit at 50% load factor. In a *steam power station* the difference would not be so pronounced since fuel cost constitutes the major item in operating costs and does not vary in the same proportion as load factor. The cost at 100% load factor in case of this station may, therefore, be about 2/3rd of the cost at 50% load factor. For a *diesel station* the cost per unit generated at 100% load factor may be about at 3/4th of the same cost at 50% load factor. From the above discussion it follows that :

(*i*) *Hydro-electric power station should be run at its maximum load continuously on all units.*

(*ii*) *Steam power station* should be run in such a way that *all its running units are economically loaded.*

(*iii*) *Diesel power station* should be worked for *fluctuating loads* or *as a stand by.*

Demand factor and utilisation factor. *A highly efficient station, if worked at low utilisation factor, may produce power at high unit cost.*

The time of maximum demand occurring in a system is also important. In an interconnected system, *a study of the curves of all stations is necessary to plan most economical operations.*

The endeavour should be to load the most efficient and cheapest power producing stations to the greatest extent possible. Such stations, called "*base load stations*" carry full load over 24 hours *i.e.,* for three shifts of 8 hours.

- The stations in the *medium range of efficiency* are operated only during the two shifts of 8 hours during 16 hours of average load.
- The older or *less efficient stations* are used *as peak or standby stations* only, and are operated *rarely* or for *short periods of time.*

Presently there is a tendency to use units of large capacities to reduce space costs and to handle larger loads. However, the *maximum economical benefit of large sets occurs only when these are run continuously at near full load. Running of large sets for long periods at lower than maximum continuous rating increases cost of unit generated.*

9.11. HOW TO REDUCE POWER GENERATION COST ?

The cost of power generation can be *reduced by* :

1. Using a plant of simple design that *does not need highly skilled personnel.*
2. Selecting equipment of *longer life and proper capacities.*
3. Carrying out *proper maintenance* of power plant equipment to avoid plant breakdowns.
4. Running the power stations at *high load factors.*
5. Increasing the efficiency of the power plant.
6. Keeping proper supervision, which ensures *less breakdowns* and extended plant life.

9.12. POWER PLANT—USEFUL LIFE

The useful life of a power plant is that *after which repairs become so frequent and extensive that it is found economical to replace the power plant by a new one.* Useful life of some of the power plants is given below :

Plant	*Useful life*
1. Conventional thermal power plant	20–25 years
2. Nuclear power plant	15–20 years
3. Diesel power plant	About 15 years.

The useful life of some of the equipment of a *steam power plant* is given below :

Equipment	*Useful life (years)*
1. Boilers	
(*i*) Fire tube	10–20
(*ii*) Water tube	20
2. Steam turbine	5–20
3. Steam turbo-generators	10–20
4. Condensers	20
5. Pumps	15–20
6. Coal and ash machinery	10–20
7. Feed water heaters	20–30
8. Stacks	10–30
9. Stokers	10–20
10. Transformers	15–20
11. Motors	20
12. Electric meters and instruments	10–15
13. Transmission lines	10–20

UNIT-8: Tariff Methods:

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. Flat 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:

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 thereof, 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.

9.17. TARIFF FOR ELECTRICAL ENERGY

9.17.1. Introduction

The cost of generation of electrical energy consists of *fixed cost and running cost*. Since the electricity generated is to be supplied to the consumers, the total cost of generation has to be recovered from the consumers. *Tariffs or energy rates are the different methods of charging the consumers for the consumption of electricity*. It is desirable to charge the consumer according to the maximum demand (kW) and the energy consumed (kWh). *The tariff chosen should recover the fixed cost, operating cost and profit etc. incurred in generating the electrical energy*.

9.17.2. Objectives and Requirements of Tariff

Objectives of tariff :

1. Recovery of cost of capital investment in generating equipment, transmission and distribution system.
2. Recovery of the cost of operation, supplies and maintenance of the equipment.
3. Recovery of the cost of material, equipment, billing and collection cost as well as for miscellaneous services.
4. A net return on the total capital investment must be ensured.

Requirements of tariff :

1. It should be easier to understand.
2. It should provide low rates for high consumption.
3. It should be uniform over large population.
4. It should encourage the consumers having high load factors.
5. It should take into account maximum demand charges and energy charges.
6. It should provide incentive for using power during off-peak hours.
7. It should provide less charges for power connection than lighting.
8. It should have a provision of penalty for low power factors.
9. It should have a provision for higher demand charges for high loads demanded at system peaks.
10. It should apportion equitably the cost of service to the different categories of consumers.

4.7 Tariffs

For the proper management of any electricity utility, it is important to have a source of income to meet its expenses. It is also important that electricity industry should have some income for future expansion work. There are two different types of charges: *Fix* charges and *running* charges. Fixed charges include (a) capacity related: interests and depreciation, cost of plant, buildings, transmission and distribution network, part of salaries of staff and (b) consumer related: cost of meter, billing, collection, service, etc. Running charges, also called *variable cost*, include fuel cost, operation and maintenance cost and some wages.

The total cost of supply is to be shared by consumers and should pay a sum according to use. The main objectives in framing a tariff are:

(a) The consumers must readily understand the tariffs.
(b) The tariff must be equitable as amongst different consumers.
(c) The tariff should also be such as to encourage consumers to improve the power factor.
(d) The tariff should also be such as to encourage consumers to improve load factor or to transfer their demand from peak to off-peak hours.
(e) Tariffs can be modified from time to time.
(f) Use of electricity is encouraged so that the economy of utilities is improved.

There are different types of consumers who consume electricity for different purposes. They can be classified into four subgroups:

1. *Domestic* consumers use electricity for domestic purposes.
2. *Agricultural* consumers use electricity of agricultural purposes such as irrigation, thrashing, etc.
3. *Industrial* consumers use electricity for industrial production such as heavy industries, manufacturing companies, etc.
4. *Commercial* consumers use electricity for commercial purposes such as municipalities, hospitals, etc.

The general form of tariff is

$$a \text{ kWh (or hp)} + b \text{ kW} + c$$

where a, b, c are the constants. Different types of tariffs are discussed below:

Flat rate tariff. In this rate, b and c are zero. The electricity charge is directly multiplication of energy consumption and the factor a. It is simple to understand and is independent on the contracted maximum demand.

Two-part tariff. The total charge under this kind of tariff is split into two components: a fixed charge based on the maximum demand (irrespective of energy consumption) and variable charge on the basis of actual energy consumption. The main objection of this tariff scheme is that consumer has to pay even if his consumption is nil.

Block rate tariff. Under this tariff scheme, different blocks of energy consumption are charged at different rates. The problem of two-part tariff is eliminated by this tariff. For example,

First 50 units	Rs 4.00/unit
Next 50 units	Rs 3.00/unit

And for additional unit @ Rs 2.00 per unit. This is for a particular month.

Maximum demand tariff. In this scheme of tariff, the charges are calculated based on the maximum demand only. The coefficient a and c are zero.

Power factor tariff. In ac system, the size of plant not only depends on the kW but also on power factor. Power factor tariffs are devised to differentiate between good power factor users and poor power factor users. The three main classes are:

1. *kVA maximum demand tariff:* Instead of charging the maximum real power (kW) demand, maximum kVA demand is charged in addition to the charge corresponding to the energy.
2. *kWh and kVArh tariff:* Under this scheme, both kWh (real power energy) and kVArh (reactive power consumption) are charged separately.
3. *Sliding scale or average power factor tariff:* There is some extra charge if the power factor is worsening from the set value. In this scheme, if consumers improve the power factor, an incentive will be given to those consumers. Let power factor is set to 0.8 lagging. If the power factor is 0.9, some discount will be offered and if power factor is 0.7, some extra charges are taken.

Example 4.5 Load factor of a consumer is 35% and the monthly consumption is 504 kWh. If the rate of electricity is Rs 180 per kW of maximum demand plus Rs 2.00 per kWh, find

(a) the monthly bill and the average cost per kWh
(b) the overall cost per kWh if the consumption is increased by 20% with the same load factor
(c) the overall cost per kWh if the consumption remains same but load factor is increased to 40%.

Solution

$$\text{Maximum demand} = \frac{\text{Average monthly consumption}}{\text{Load factor} \times 24 \times 30} = \frac{504}{0.35 \times 720} = 2.0 \text{ kW}$$

(a) Monthly bill (Rs) = (2 × 180) + (2 × 504) = 1368

$$\text{Overall cost per kWh} = \frac{1368}{504} = \text{Rs } 2.71$$

(b) New consumption = 504 × 1.20 = 604.8 kWh

$$\text{Since the load factor is same, the maximum demand} = \frac{604.8}{0.35 \times 720} = 2.4 \text{ kW}$$

Monthly bill (Rs) = (2.4 × 180) + (2 × 604.8) = 1641.6

$$\text{Overall cost per kWh} = \frac{1641.6}{604.8} = \text{Rs } 2.71$$

(c) $$\text{Since the load factor is 40\%, the maximum demand} = \frac{504}{0.40 \times 720} = 1.75 \text{ kW}$$

Monthly bill (Rs) = (1.75 × 180) + (2 × 504) = 1323

$$\text{Overall cost per kWh} = \frac{1323}{504} = \text{Rs } 2.63$$

Example 4.6 The load variation at a power supply station is given as:

$$P = 30 - 8 * \sin(kt) + 0.325t \text{ MW}.$$

where t is time in hours of a day and $k = 0.6$ red/sec. There are three generators of 15 MW each. It is advantageous to fully load a machine before connecting the others.

Determine:

(a) Maximum demand on the system.

(b) Load factor of the system.

(c) The total installed load, if density factor is 3.

(d) The minimum no. hours of each generator is in operation.

Solution Maximum demand can be obtained by $\delta P/\delta t = 0$

Thus $-4.8 \times \cos(0.6t) + 0.325 = 0$.

$\cos(0.6t) = 0.325/4.8 = 0.0677083 = \cos(1.0503032 + 2n\pi)$ $\quad n = 0, 1, 2...$

$0.6t = 2n\pi + 1.503032$ or $2n\pi - 1.503032$, $n = 0, 1, 2...$

$t = 2.5051, 7.9669, 12.977, 18.4389, 23.449.$

During $t = 0$ to 24 hrs, the load curve has 5 maxima and minimas.

The corresponding load at these times will be

$P = 22.8325, 40.5709, 26.2359, 43.974, 29.639$ MW.

Thus

(a) Maximum demand = 43.974 MW.

(b) Average load = $(1/24) \times \int_0^{24} (30 - 8 \times \sin(0.6t) + 0.325t)\,dt$

$$= (1/24) \times [30 \times 24 + (8/0.6) \times \cos(0.6t)|_0^{24} + 0.325 \times 24^2/2] = 33.20 \text{ MW}.$$

Load factor = 33.20/43.974 = 0.755

(c) Total installed load = peak demand × Diversity factor = 43.974 × 3 = 131.922 MW.

(d) Since min. load is 22.8325 MW, two units will run for whole day, 3rd unit will run when $P > 30$MW. Hence finding the t when $P > 30$

$30 - 8 \times \sin(kt) + 0.3250 = 30$

$\sin(kt) = 0.040625t$

Using hit and trial methods (or using graph),

$t = 4.904, 11.265, 14.65, 22.94$

Unit-3 will be in operation for = (11.265 – 4.904) + (22.94 – 14.65) hrs.

= 14.651 hrs.

Example 9.29. *Two electrical units used for same purpose are compared for their economical working :*

(i) Cost of Unit-1 is Rs. 6000 and it takes 120 kW.

(ii) Cost of Unit-2 is Rs. 16800 and it takes 72 kW.

Each of them has a useful life of 40000 hours.

Which unit will prove economical if the energy is charged at Rs. 96 per kW of maximum demand per year and 6 p. per kWh ?

Assume both units run at full load.

Solution. (*i*) **Unit-1 :**

Capital cost per hour $= \frac{6000}{40000}$ = Re. 0.15

Maximum demand = 120 kW

Charge for maximum demand per hour

$$= \frac{120 \times 96}{(365 \times 24)} = \text{Rs. } 1.315$$

Energy charge per hour = Maximum demand × one hour × charge per kWh

$$= 120 \times 1 \times \frac{6}{100} = \text{Rs. } 7.2$$

∴ Total charges per hour for operation of Unit-1

$$= 0.15 + 1.135 + 7.2 = \text{Rs. } 8.485$$

(*ii*) **Unit-2 :**

Capital cost per hour $= \frac{16800}{40000}$ = Re. 0.42.

Charge for maximum demand per hour

$$= \frac{72 \times 96}{365 \times 24} = \text{Re. } 0.789$$

Energy charge per hour $= 72 \times 1 \times \frac{6}{100}$ = Rs. 4.32

Total charges per hour for the operation of Unit-2

$$= 0.42 + 0.789 + 4.32 = \text{Rs. } 5.529$$

The charges of operation for the Unit-2 per hour are less than the charges of operation for the Unit-1, therefore *Unit-2 is more economical* in this case. **(Ans.)**

Example 9.30. *The monthly electricity consumption of a residence can be approximated as under :*

Light load	*: 6 tube lights 40 watts each working for 4 hours daily*
Fan load	*: 6 fans 100 watts each working for 6 hours daily*
Refrigerator load	*: 2 kWh daily*
Miscellaneous load	*: 2 kW for 2 hours daily*

Find the monthly bill at the following tariff :

First 20 units	*Rs. 0.50/kWh*
Next 30 units	*Rs. 0.40/kWh*
Remaining units	*Rs. 0.30/kWh*
Constant charge	*Rs. 2.50 per month*

Discount for prompt payment = 5 per cent.

Solution. Total energy consumption in 30 days

$$= (6 \times 40 \times 4 \times 30 + 6 \times 100 \times 6 \times 30) \times \frac{1}{1000} + 2 \times 30 + 2 \times 2 \times 30$$

$$= (28800 + 108000) \times \frac{1}{1000} + 60 + 120 = 316.8 \text{ kWh per month}$$

The monthly bill $= \text{Rs. } [(20 \times 0.5 + 30 \times 0.4 + 266.8 \times 0.3) + 2.5]$

$= \text{Rs. } [(10 + 12 + 80.04) + 2.5] = \text{Rs. } 104.54$

$$\left[\because \text{ Remaining units per month } = 316.8 - 20 - 30 = 266.8\right]$$

Net monthly bill if the payment is made promptly

$= 104.54 \times 0.9 =$ **Rs. 94.08. (Ans.)**

Example 9.31. *An industrial undertaking has a connected load of 220 kW. The maximum demand is 180 kW. On an average each machine works for 60% time. Find the yearly expenditure on electricity if the tariff is :*

Rs. 1200 + Rs. 120 per kW of maximum demand per year + Re. 0.15 per kWh.

Solution. Energy consumption in one year

$= 180 \times 0.6 \times (365 \times 24) = 946080$ kWh

Total electricity bill $= \text{Rs. } (1200 + 120 \times 180 + 0.15 \times 946080) =$ **Rs. 164712. (Ans.)**

☞**Example 9.32.** *A Hopkinson demand rate is quoted as follows :*

Demand rates :

First 1 kW of maximum demand	*= Rs. 6/kW/month*
Next 4 kW of maximum demand	*= Rs. 5/kW/month*
Excess 5 kW of maximum demand	*= Rs. 4/kW/month*

Energy rates :

First 50 kWh	*= 7 paise/kWh*
Next 50 kWh	*= 5 paise/kWh*
Next 200 kWh	*= 4 paise/kWh*
Next 400 kWh	*= 3 paise/kWh*
Excess over 700 kWh	*= 2 paise/kWh.*

Determine : (i) The monthly bill for a total consumption of 2000 kWh and a maximum demand of 15 kW. Also find out the unit energy cost.

(ii) Lowest possible bill for a month and a corresponding unit energy cost.

Solution. (*i*) **Monthly bill and energy cost :**

Demand charges per month $= \text{Rs. } (1 \times 6 + 4 \times 5 + 10 \times 4) = \text{Rs. } 66$

Energy charge $= \text{Rs. } [50 \times 7 + 50 \times 5 + 200 \times 4 + 400 \times 3 + 1300 \times 2] \times \frac{1}{100}$

$= \text{Rs. } (350 + 250 + 800 + 1200 + 2600) \times \frac{1}{100} = \text{Rs. } 52$

∴ *Monthly bill* = 66 + 52 = **Rs. 118. (Ans.)**

Average unit energy cost $= \frac{118}{2000} \times 100 =$ **5.9 paise/kWh. (Ans.)**

(*ii*) **Lowest possible bill :**

The lowest possible bill will occur when average load

= Maximum load or at 100% load factor

∴ Maximum load = Average load $= \frac{2000}{30 \times 24} = 2.77$ kW

∴ Demand charges = Rs. (6 + 1.77 × 5) = Rs. 14.85

Energy charges will be same = Rs. 52

∴ *Minimum monthly bill* = 14.85 + 52 = **Rs. 66.85. (Ans.)**

Unity energy cost for this condition

$$= \frac{66.85}{2000} \times 100 = \textbf{3.34 paise/kWh.} \quad \textbf{(Ans.)}$$

Example 9.33. *A new factory requires a maximum demand of 700 kW and load factor of 25%. The following two suppliers are available :*

(i) Public supply tariff is Rs. 48 per kW of maximum demand plus 2.4 p. per kWh.

Capital cost = Rs. 84000

Interest and depreciation = 10 per cent

(ii) Private oil engine generating station :

Capital cost = Rs. 300000

Fuel consumption = 3 N/kWh

Cost of fuel = Rs. 8.4 per kN

Wages = 0.48 p/kWh

Maintenance cost = 0.36 p/kWh

Interest and depreciation = 15 per cent.

Find which supply will be more economical ?

Solution. Load factor $= \frac{\text{Average load}}{\text{Maximum demand}}$

∴ Average load = Load factor × maximum demand = 0.25 × 700 = 175 kW

Energy consumed per year = 175 × (365 × 24) = 1.533×10^6 kWh.

(*i*) **Public supply :**

Maximum demand charges per year

= 48 × 700 = Rs. 33600

Energy charge per year $= \frac{2.4}{100} \times 1.533 \times 10^6 =$ Rs. 36792

Interest and depreciation $= \frac{10}{100} \times 84000 =$ Rs. 8400

Total cost = Rs. (33600 + 36792 + 8400) = Rs. 78792

∴ *Energy cost per kWh* $= \frac{78792}{1.533 \times 10^6} \times 100 =$ **5.14 p.**

(*ii*) **Private oil engine generating station :**

Fuel consumption $= \frac{3 \times 1.533 \times 10^6}{1000} = 4599$ kN

Cost of fuel = 4599 × 8.4 = Rs. 38631

Cost of wages and maintenance $= \left(\frac{0.48 + 0.36}{100}\right) \times 1.533 \times 10^6 =$ Rs. 12877

Interest and depreciation $= \frac{15}{100} \times 300000 =$ Rs. 45000

Total cost = Rs. (38631 + 12877 + 45000) = Rs. 96508

Energy cost per kWh $= \frac{96508}{1.533 \times 10^6} \times 100 =$ **6.29 p.**

As the energy cost per kWh for oil engine is less than the public supply, the oil engine generation is more preferable. **(Ans.)**

☞**Example 9.34.** *A load having a maximum demand of 100 MW and a load factor of 0.4 may be supplied by one of the following schemes :*

(i) A steam station capable of supplying the whole load.

(ii) A steam station in conjunction with pump storage plant which is capable of supplying 130×10^6 kWh energy per year with a maximum output of 40 MW.

Find out the cost of energy per unit in each of the two cases mentioned above.

Use the following data :

Capital cost of steam station	*= Rs. 2000/kW of installed capacity*
Capital cost of pump storage plant	*= Rs. 1300/kW of installed capacity*
Operating cost of steam plant	*= 6 p./kWh*
Operating cost of pump storage plant	*= 0.5 p./kWh*

Interest and depreciation together on the capital invested should be taken as 12 per cent. Assume that no spare capacity is required.

Solution. (*i*) **Steam station :**

Capital cost $= 100 \times 10^3 \times 2000 = \text{Rs. } 200 \times 10^6$

Interest and depreciation $= \frac{12}{100} \times 200 \times 10^6 = \text{Rs. } 24 \times 10^6$

Average load = Load factor × maximum demand

$= 0.4 \times 100 \times 10^3 = 40000$ kW

Energy supplied per year = Average load × (365 × 24)

$= 40000 \times 365 \times 24 = 350.4 \times 10^6$ kWh

∴ Interest and depreciation charges *per unit of energy*

$$= \frac{24 \times 10^6}{350.4 \times 10^6} \times 100 = 6.85 \text{ p/kWh}$$

∴ *Total cost per unit* = 6 + 6.85 = **12.85 p/kWh. (Ans.)**

(*ii*) **Steam station in conjunction with pump-storage plant :**

The load supplied by the steam plant = 100 – 40 = 60 MW

∴ Capital cost of steam plant $= 60 \times 1000 \times 2000 = \text{Rs. } 120 \times 10^6$

Capital cost of pump storage plant $= 40 \times 1000 \times 1300 = \text{Rs. } 52 \times 10^6$

∴ Total capital cost of combined station $= 120 \times 10^6 + 52 \times 10^6 = \text{Rs. } 172 \times 10^6$

Interest and depreciation charges on capital investment

$$= \frac{12}{100} \times 172 \times 10^6 = \text{Rs. } 20.64 \times 10^6$$

∴ Operating cost of pump storage plant $= \frac{0.5}{100} \times 130 \times 10^6 = \text{Rs. } 0.65 \times 10^6$

The energy units supplied by steam station

= Total units required – energy units supplied by pump storage plant

$= 350.4 \times 10^6 - 130 \times 10^6 = 220.4 \times 10^6$ kWh

Operating cost of the steam station

$$= \frac{6}{100} \times 220.4 \times 10^6 = \text{Rs. } 13.22 \times 10^6$$

Total cost per year $= \text{Rs. } (20.64 \times 10^6 + 0.65 \times 10^6 + 13.22 \times 10^6) = \text{Rs. } 34.51 \times 10^6$

$$Total\ cost\ per\ unit = \frac{34.51 \times 10^6}{350.4 \times 10^6} \times 100 = \mathbf{9.85\ p/kWh.} \quad \textbf{(Ans.)}$$

Note : If the above example is repeated with a load factor of 0.7 it will be observed from the results that the *cost of generation becomes less with higher load factor irrespective of the type of the plant.*

Example 9.35. *The following data relate to a 2000 kW diesel power station :*

The peak load on the plant	= *1500 kW*
Load factor	= *0.4*
Capital cost per kW installed	= *Rs. 1200*
Annual costs	= *15 per cent of capital*
Annual operating costs	= *Rs. 50000*
Annual maintenance costs :	
(*i*) *Fixed*	= *Rs. 9000*
(*ii*) *Variable*	= *Rs. 18000*
Cost of fuel	= *Rs. 0.45 per kg*
Cost of lubricating oil	= *Rs. 1.3 per kg*
C.V. of fuel	= *41800 kJ/kg*
Consumption of fuel	= *0.45 kg/kWh*
Consumption of lubricating oil	= *0.002 kg/kWh*

Determine the following :

(*i*) *The annual energy generated.*

(*ii*) *The cost of generation per kWh.*

Solution. Capital cost of the plant $= 2000 \times 1200 = \text{Rs. } 2.4 \times 10^6$ per year

Interest on capital $= \frac{15}{100} \times 2.4 \times 10^6 = \text{Re. } 0.36 \times 10^6$ per year.

(*i*) **Annual energy generated** = Load factor × maximum demand × (365 × 24)

$= 0.4 \times 1500 \times 365 \times 24 = \mathbf{5.256 \times 10^6\ kWh.}$ **(Ans.)**

(*ii*) **Cost of generation :**

Fuel consumption $= 0.45 \times 5.256 \times 10^6 = 2.365 \times 10^6$ kg per year

Cost of fuel $= \text{Rs. } 0.45 \times 2.365 \times 10^6 = \text{Rs. } 1.064 \times 10^6$ per year

Lubricant consumption $= 0.002 \times 5.256 \times 10^6 = 10512$ kg per year

Cost of lubricating oil $= 1.3 \times 10512 = \text{Rs. } 13665$ per year

Total fixed cost = Interest + maintenance (fixed)

$= 0.36 \times 10^6 + 9000 = \text{Rs. } 369000$ per year

Total running or variable costs

= Fuel cost + lubricant cost + maintenance (running) + annual operating costs

$= 1.064 \times 10^6 + 13665 + 18000 + 50000 = \text{Rs. } 1145665$ per year

Total cost = Fixed cost + running cost = 369000 + 1145665 = Rs. 1514665

$$Cost\ of\ generation = \frac{1514665}{5.256 \times 10^6} \times 100 = \mathbf{28.8\ paise/kWh.} \quad \textbf{(Ans.)}$$

☞**Example 9.36.** *The annual costs of operating a 15 MW thermal plant are given below :*

Capital cost of plant	= *Rs. 1500/kW*
Interest, insurance and depreciation	= *10 per cent of plant cost*

Capital cost of primary and secondary distribution	*= Rs. 20 × 10^6*
Interest, insurance and depreciation on the capital cost of primary and secondary distribution	*= 5% the capital cost*
Plant maintenance cost	*= Rs. 100 × 10^3 per year*
Maintenance cost of primary and secondary equipment	*= Rs. 2.2 × 10^5 per year*
Salaries and wages	*= Rs. 6.5 × 10^5 per year*
Consumption of coal	*= 40 × 10^4 kN per year*
Cost of coal	*= Rs. 9 per kN*
Dividend to stockholders	*= Rs. 1.5 × 10^6 per year*
Energy loss in transmission	*= 10 per cent*
Diversity factor	*= 1.5*
Load factor	*= 0.75*
Maximum demand	*= 12 MW*

(i) Devise a two-part tariff.

(ii) Find the average cost per kWh.

Solution. (*i*) Two-part tariff :

Load factor $= \dfrac{\text{Average load}}{\text{Maximum demand}}$

$\therefore$ Average load = Load factor × maximum demand

$= 0.75 \times 12 \times 10^3 = 9000$ kW

Energy generated per year $= 9000 \times (365 \times 24) = 78.84 \times 10^6$ kWh

Cost of the plant $= 15 \times 10^3 \times 1500 = \text{Rs. } 22.5 \times 10^6$

Interest, insurance and depreciation charges of the plant

$$= \frac{10}{100} \times 22.5 \times 10^6 = \text{Rs. } 2.25 \times 10^6$$

Interest, insurance and depreciation charges of primary and secondary equipments

$$= \frac{5}{100} \times 20 \times 10^6 = \text{Rs. } 1.0 \times 10^6$$

Total fixed cost = Insurance, interest and depreciation costs + dividend to stock-holders

$= \text{Rs. } (2.25 \times 10^6 + 1.5 \times 10^6) = \text{Rs. } 3.75 \times 10^6$

Sum of individual maximum demand

= Maximum demand × diversity factor

$= 12 \times 10^3 \times 1.5 = 18000$ kW

$\therefore$ *Fixed charges per kW* $= \dfrac{3.75 \times 10^6}{18000} =$ **Rs. 208.3.**

Total variable charges = All maintenance costs + salaries and wages + fuel cost

$= (100 \times 10^3 + 2.2 \times 10^5) + 6.5 \times 10^5 + 40 \times 10^4 \times 9$

$= (1 \times 10^5 + 2.2 \times 10^5) + 6.5 \times 10^5 + 36 \times 10^5$

$= \text{Rs. } 45.7 \times 10^5$ or $\text{Rs. } 4.57 \times 10^6$

Energy transmitted = Energy generated × transmission efficiency

$$= 78.84 \times 10^6 \times \left(\frac{100 - \text{energy loss in transmission}}{100}\right)$$

$$= 78.84 \times 10^6 \times \frac{90}{100} = 70.956 \times 10^6 \text{ kWh}$$

$\therefore$ *Charges for energy consumption*

$$= \frac{4.57 \times 10^6}{70.956 \times 10^6} \times 100 = \textbf{6.44 paise/kWh.}$$

$\therefore$ *Two-part tariff* **= Rs. 208.3/kW + 6.44 paise/kWh. (Ans.)**

(*ii*) Average cost per kWh :

Total charges = Fixed charges + variable charges

$= 3.75 \times 10^6 + 4.57 \times 10^6 = \text{Rs. } 8.32 \times 10^6$

Average cost of supply $= \dfrac{8.32 \times 10^6}{70.956 \times 10^6} \times 100 =$ **11.72 paise/kWh. (Ans.)**

Example 9.37. *A 10 MW thermal power plant has the following data :*

Peak load	*= 8 MW*
Plant annual load factor	*= 0.72*
Cost of the plant	*= Rs. 800/kW installed capacity*
Interest, insurance and depreciation	*= 10 per cent of the capital cost*
Cost of transmission and distribution system	*= Rs. 350 × 10^3*
Interest, depreciation on distribution system	*= 5 per cent*
Operating cost	*= Rs. 350 × 10^3 per year*
Cost of coal	*= Rs. 6 per kN*
Plant maintenance cost	*= Rs. 30000/year (fixed)*
	= Rs. 40000/year (running)
Coal used	*= 250000 kN/year*

Assume transmission and distribution costs are to be charged to generation

(i) Devise a two-part tariff.

(ii) Average cost of generation in paise/kWh.

Solution. (*i*) **Two-part tariff :**

S. No.	*Items*	*Fixed cost per year (in Rs.)*	*Running cost per year (in Rs.)*
1.	Interest, depreciation etc. of the plant	$\frac{10}{100} \times 10000 \times 800$ = Rs. 800 × 10^3	—
2.	Interest, depreciation etc. of the transmission and distribution	$\frac{5}{100} \times 350 \times 10^3$ = 17.5 × 10^3	—
3.	Annual cost of coal	—	250000 × 6 = 1500 × 10^3
4.	Operating cost	—	= 350 × 10^3
5.	Plant maintenance cost	= 30 × 10^3	= 40 × 10^3
	Total cost	847.5 × 10^3	1890 × 10^3

∴ Grand total cost = Fixed cost + running cost

$$= 847.5 \times 10^3 + 1890 \times 10^3 = \text{Rs. } 2737.5 \times 10^3$$

Energy generated/year = Average load × (365 × 24)

= (Peak load × load factor) × (365 × 24)

$$= (8 \times 10^3 \times 0.72) \times (365 \times 24) = 50.46 \times 10^6 \text{ kWh}$$

∴ *Two-part tariff*

$$= \frac{\text{Fixed cost}}{\text{Maximum load}} + \frac{\text{Running cost}}{\text{Energy generated}}$$

$$= \frac{847.5 \times 10^3}{8 \times 10^3} + \frac{1890 \times 10^3}{50.46 \times 10^6} \times 100$$

= Rs. 105.9/kW + paise 3.74/kWh. (Ans.)

(*ii*) **Average cost generation in paise/kWh :**

Average generation cost

$$= \frac{\text{Grand total cost}}{\text{Energy generated}}$$

$$= \frac{2737.5 \times 10^3}{50.46 \times 10^6} \times 100 = \mathbf{5.42 \text{ paise/kWh.}} \quad \textbf{(Ans.)}$$

Example 9.38. *Determine the load factor at which the cost of supplying a unit of electricity is same in Diesel station as in a steam station if the respective annual fixed and running charges are given below :*

Diesel : *Rs. (40/kW + 0.06/kWh)*

Steam : *Rs. (160/kW + 0.015/kWh).*

Solution. Let, P = Maximum load in kW, and

x = Load factor (same for both the stations).

Then, Average load = $P \times x$

Cost of diesel station,

$$C_{diesel} = 40\,P + 0.06 \times P \times x \times (365 \times 24)$$

Cost of steam station,

$$C_{steam} = 160\,P + 0.015 \times P \times x \times (365 \times 24)$$

As given in the problem,

Unit energy cost (diesel station) = Unit energy cost (steam station)

$$\therefore \quad \frac{40\,P + 0.06\,Px \times (365 \times 24)}{Px \times (365 \times 24)} = \frac{160\,P + 0.015\,Px \times (365 \times 24)}{Px \times (365 \times 24)}$$

$$\therefore \quad 40\,P + 0.06\,Px \times 8760 = 160\,P + 0.015\,Px \times 8760$$

or $$40\,P + 525.6\,Px = 160\,P + 131.4\,Px$$

or $$120\,P = 394.2\,Px \quad \text{or} \quad x = \frac{120}{394.2} = 0.3$$

i.e., *Load factor* **= 0.3. (Ans.)**

Example 9.2 Find out the minimum two part tariff to be charged in the following case.

(a) Generating cost per kWh = \$ 0.004

(b) Generating cost power kW of maximum demand = \$ 1

(c) Total energy generated per year = 4500×10^4 kWh

(d) Load factor of the generating station = 60%

(e) Annual charge for distribution = \$ 2500

(f) Diversity factor = 1.3

(g) Total loss between station and consumer = 12%

Solution Load factor = $\dfrac{\text{Number of units generated}}{\text{Station maximum demand} \times 8760}$

or $$\frac{60}{100} = \frac{4500 \times 10^4}{\text{Station maximum demand} \times 8760}$$

or $$\text{Station maximum demand} = \frac{4500 \times 10^4}{0.6 \times 8760} \text{ kW}$$

$$= \frac{4500 \times 10^4}{5256} \text{ kW}$$

$$= 8561.6 \text{ kW}$$

Annual cost of generation per kW of maximum demand = \$ 1.

Total annual cost of generation 8561.6 kW = \$ 8561.6

Annual charges for distribution = \$ 2500

∴ $$\text{Annual fixed charge} = (8561.6 + 2500) = \$\ 11061.6$$

$$\text{Diversity factor} = \frac{\text{Sum of consumer's maximum demand}}{\text{Station maximum demand}}$$

$$1.3 = \frac{\text{Sum of consumer's maximum demand}}{8561.6}$$

or $$\text{Sum of consumer's maximum demand} = 8561.6 \times 1.3 = 11130.08 \text{ kW}$$

There is a 12% loss between the generating station and consumer. Therefore, the maximum demand practically

$$= 11130.08 \times (0.88) \text{ kW}$$

$$= 9794.47 \text{ kW}$$

$$\text{Fixed charges per kW of maximum demand} = \frac{11061.6}{9794.47} = 1.129$$

Therefore, the two part tariff can be described as follows:

(a) \$ 1.129 per kW of maximum demand.

(b) \$ 0.004 per kWh.

MULTIPLE CHOICE QUESTIONS

ECONOMICS OF POWER GENERATION (1-15):

1. A load curve is a plot of

(A) Load versus generation capacity

(B) Load versus current

(C) Load versus time

(D) Load versus cost of power.

Answer: C

2. For economy in generation power

(A) diversity factor should be high

(B) plant utilization factor

(C) load factor should be high

(D) load factor and diversity factor should be low.

Answer: B

3. Which of the following category of consumers can provide highest load factor ?

(A) A domestic consumer

(B) A continuous process plant

(C) A steel melting unit using arc furnace

(D) A cold storage plant.

Answer: B

4. The load of a consumer is generally measured in terms of

(A) Volts

(B) Amperes

(C) Ampere hour

(D) kW.

Answer: D

5. The normal connected load of a domestic consumer is usually

(A) up to 10 kW

(B) 10 to 20 kW

(C) 25 to 50 kW

(D) 50 to 100 kW.

Answer: A

6. Load factor during a period is

(A) Average Load / Installed Capacity

(B) Average Load / Maximum Load

(C) Maximum Load / Average Load

(D) Maximum Load / Installed Capacity.

Answer: B

7. Which of the following installation provides peaked load ?

(A) Arc furnace

(B) Air conditioner

(C) Air compressor running continuously

(D) Cold storage plant.

Answer: A

8. Demand factor is the

(A) Maximum Demand / Average Demand

(B) Maximum Demand / Connected Load

(C) Average Demand / Maximum Demand

(D) Connected Load / Maximum Demand.

Answer: B

9. During summer months the increased load is due to

(A) increased water supply

(B) vacations in institutions

(C) increased business activity

(D) increased use of fans and air conditioners.

Answer: D

10. In a system if the base load is the same as the maximum demand, the load factor will be

(A) 1

(B) Zero

(C) Infinity

(D) 1 percent.

Answer: A

11. A system having connected load of 100 kW, peak load of 80 kW. base load of 20 kW and average load of 40 kW, will have a load factor of

(A) 40%

(B) 50%

(C) 60%

(D) 80%.

Answer: B

12. Load due to one tonne air conditioner is nearly

(A)100W

(B) 200 to 500 W

(C) 1 kW to 2 kW

(D) 5 kW to 10 kW.

Answer: C

13. Load due to a ceiling fan is nearly

(A) 10W

(B) 40 to 50 W

(C) 100 to 200 W

(D) 250 W to 2000 W.

Answer: C

14. Which domestic utility item has highest power rating?

(A) Refrigerator

(B) Ceiling fan

(C) Tube light

(D) Electric iron.

Answer: D

15. A stereo with two 10 watt loudspeakers will provide electrical load of

(A) more than 12 W

(B) 12 W

(C) less than 6 W

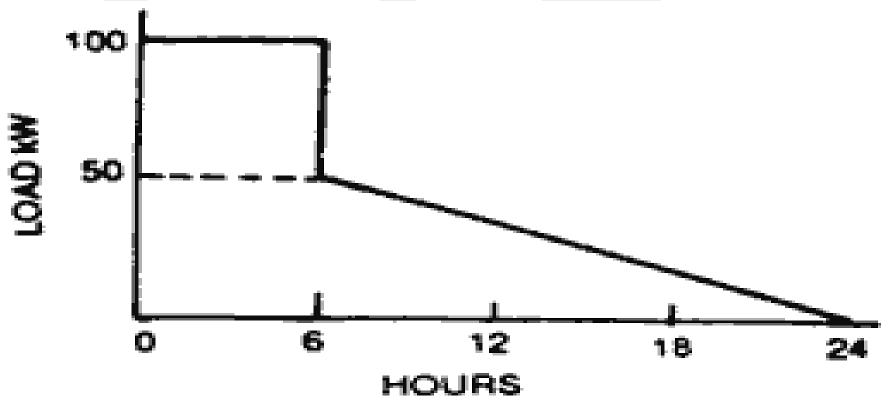
(D) 6 W.

Answer: C

1.C ----- 2.B ----- 3.B ----- 4.D ----- 5.A ----- 6.B ----- 7.A ----- 8.B ----- 9.D -----10.A ----- 11.B ----- 12.C ----- 13.C ----- 14.D ----- 15.C

ECONOMICS OF POWER GENERATION (16-30):

Questions 16 to 18 refer to the figure below.



16. The load of a system is shown in the figure above. The load factor of the system is

(A) 0.778

(B) 0.667

(C) 0.438

(D) 0.331.

Answer: C

17. Load factor for the 0-6 hour period alone is

(A) 0.438

(B) 0.876

(C) 0.999

(D) 1.0.

Answer: D

18. Load factor for the period 6-24 hours period is

(A) 0.438

(B) 0.5

(C) 0.876

(D) 1.0.

Answer: B

19. Which plant can never have 100% load factor ?

(A) Nuclear power plant

(B) Hydro electric plant

(C) Peak load plant

(D) Base load plant.

Answer: C

20. Which meter is installed at the premises of a consumer for recovery of charges of electrical energy

(A) Voltmeter

(B) Ammeter

(C) kVA meter

(D) kWh meter.

Answer: D

21. For certain industrial applications the energy requirement is 500 kWh. If the heat losses are 20 percent the total energy to be made available will be

(A) 5000 kWh

(B) 4000 kWh

(C) 6000 k Wh

(D) 6000 kWh.

Answer: D

22. A consumer finds that after running 10 kVA equipment on full load for six hours his energy consumption was 48 kW. It can be concluded that

(A) the load factor of the consumer for the day was unity

(B) the maximum demand of the consumer was 10 kW

(C) the equipment was drawing reactive power only

(D) power factor of the equipment was 0.8.

Answer: D

23. Which equipment provides fluctuating load ?

(A) Lathe machine

(B) Exhaust fan

(C) Welding transformer

(D) All of the above.

Answer: C

24. A power plant supplying energy to a city will usually experience peak demand

(A) from midnight to early morning

(B) 8 AM to 12 noon

(C) 2 PM to 6 PM

(D) 6 PM to 12 PM.

Answer: D

25. The ratio, maximum demand of the installation / sum of individual maximum demands is known as

(A) Demand factor

(B) Plant use factor

(C) Diversity factor

(D) Plant capacity factor.

Answer: C

26. In a power plant a reserve generating capacity which is in operation but not in services known as

(A) Hot reserve

(B) Cold reserve

(C) Spinning reserve

(D) Firm power.

Answer: A

27. Five consumers having peak demands of A, B, C, D, and E have individual load factors of 0.5. It can be concluded that

(A) their combined load factor will be 0.5

(B) their peak demand during the day will be (A + B + C + D + E)

(C) their combined power consumption in a day will be 12 (A + B + C + D + E)

(D) their average demands are equal.

Answer: C

28. In an interconnected system consisting of a nuclear power stations, steam station and diesel generating station, which plant can be used as base load plant?

(A) Steam station

(B) Diesel generation plant

(C) Nuclear power station

(D) Any of the above.

Answer: C

29. Fuel transportation cost is least in

(A) Diesel generating plant

(B) Steam power stations

(C) Nuclear powers plants.

Answer: C

30. Capital cost per MWh is highest in case of

(A) steam power plants

(B) diesel engine power plants

(C) nuclear power plants

(D) hydroelectric power plants.

Answer: C

All answers:

16.C ----- 17.D ----- 18.B ----- 19.C ----- 20.D ----- 21.D ----- 22.D ----- 23.C -----24.D -----25.C ----- 26.A ----- 27.C ----- 28.C ----- 29.C ----- 30.C

ECONOMICS OF POWER GENERATION (31-45):

31. A steam power station will run with maximum efficiency when it is run

(A) at low steam pressures

(B) on pulverized coal

(C) at higher speeds

(D) near full load.

Answer: D

32. Which of the following is likely to result in lower efficiency of a power station ?

(A) Varying loads

(B) Low voltage generation

(C) Low turbine speeds

(D) Non-automatic controls.

Answer:

A

Questions 33 to 36 refer to the following information.

The following factors are associated with power plant operation

I. High efficiency

II. High availability

III. Quick starting

IV. Low capital cost.

33. Which factor is least important for base load plants ?

(A) I

(B) II

(C) III

(D) IV.

Answer: C

34. Which two factors are of significant requirement for base load plant ?

(A) I and II only

(B) III and IV only

(C) II and III only

(D) I and IV only.

Answer: A

35. Which two factors are of importance for peak load plant ?

(A) I and III only

(B) II and III only

(C) I and IV only

(D) III and IV only.

Answer: D

36. Which factors are favorable to a diesel power plant as compared to a steam power plant ?

(A) I and III only

(B) I, II and III only

(C) II, III and IV only

(D) I, II. Ill and IV.

Answer: D

37. In a 440 V system, in order to obtain the minimum cost and maximum benefits, the capacitor should be installed

(A) at the load

(B) near the transformer

(C) anywhere in the circuit

(D) near the earthling point.

Answer: A

38. In case of medium sized induction motor, the power factor will be maximum at

(A) No load

(B) 50% load

(C) Full load

(D) Power factor remains constant at all loads.

Answer: C

39. A coaxial line is filled with a dielectric of relative permitivity 9. If C denotes the velocity of propagation in free space, the velocity of propagation in the line will be

(A) 3 C

(B) C

(C) C / 3

(D) C / 9.

Answer: C

40. A direct voltage is applied to a peak diode voltmeter in which scale is calibrated to read rms voltage of a sine wave. If the meter reading is 36 V rms, the value of the applied direct voltage is

(A) 25 V

(B) 36 V

(C) 51 V

(D) 72 V.

Answer: C

41. A power station has annual load factor of 50% and capacity factor of 40%. If the maximum demand is 15 MW, the reserve capacity of the plant is

(A) 1250 kw

(B) 2500 kw

(C) 3750 kw

(D) 4750 kw.

Answer: C

42. Which of the following will not contribute to low power-factor ?

(A) Partially loaded induction motors

(B) Replacement of fluorescent lamps with incandescent lamps

(C) Use of rectifiers instead of synchronous motor-generator sets for dc power supply

(D) Increased installation of electronic equipments, air- conditioning units, etc.

Answer: B

43. Which of the following may not be the effect of low plant operating power factor ?

(A) Over loaded transformers

(B) Reduced voltage level

(C) Improved illumination from lighting

(D) Over loaded cables.

Answer: C

44. Identify the incorrect relation

(A) power factor = KW / kVA

(B) kW = kVA x power factor

(C) kVA x kW = power factor

(D) kVA = kW / power factor.

Answer: C

45. The power factor of a system on a 460 V, 3 phase, 60 Hz, in which the ammeter indicates 100 amp and the watt meter reads 62 kW will be

(A) 0.95

(B) 0.78

(C) 0.65

(D) 0.55.

Answer: B

All answers:

31.D ----- 32.A ----- 33.C ----- 34.A ----- 35.D ----- 36.D ----- 37.A ----- 38.C -----39.C -----40.C -----41.C ----- 42.B -----43.C -----44.C ----- 45.B

ECONOMICS OF POWER GENERATION (46-61):

46. The simple subtraction of kilowatts from total kVA equals the kVAR when the power factor is

(A) unity

(B) 0.707

(C) lagging

(D) zero.

Answer:

A

Questions 47 to 50 refer to the data given below:

The annual peak load on a 30 MW power station is 25 MW. The power station supplies loads having maximum demands of 10 MW, 8.5 MW, 5 MW and 4.5 MW. The annual load factor is 45%.

47. The average load is

(A) 1025 kW

(B) 1125 kW

(C) 1425 kW

(D) 1625 kW.

Answer: B

48. Total energy supplied in a year is

(A) 9,875,000 kWh

(B) 8345,000 kWh

(C) 7450,000 kWh

(D) 6395,000 kWh.

Answer: A

49. Diversity factor is

(A) 3.80

(B)1.02

(C) 1.12

(D) 1.22.

Answer: C

50. Demand factor is

(A) 0.75

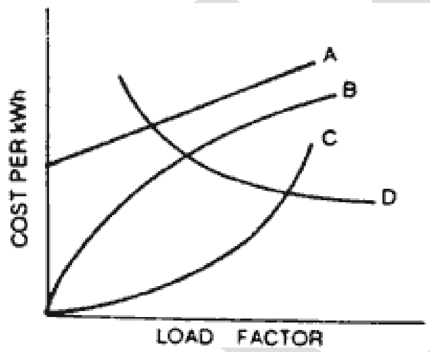
(B) 0.83

(C) 0.89

(D) 0.45.

Answer: B

51. In the figure shown below which curve represents the variation of cost of generation per kWh with the load factor, for a thermal power plant ?



(A) curve A

(B) curve B

(C) curve C

(D) curve D.

Answer: D

52. Connected load is

(A) The rating in kw of the installed electrical load of the consumer

(B) the maximum load that a consumer puts on at any time

(C) Part of the load which always remains on at the consumer ends

(D) Average load of the consumer during a specified period.

Answer: A

53. Which of the following appliance will offer the maximum load ?

(A) Toaster

(B) Refrigerator

(C) Hot plate

(D) Electric iron.

Answer: C

54. Which of the following industry will consume maximum power per tonne of product ?

(A) Zinc

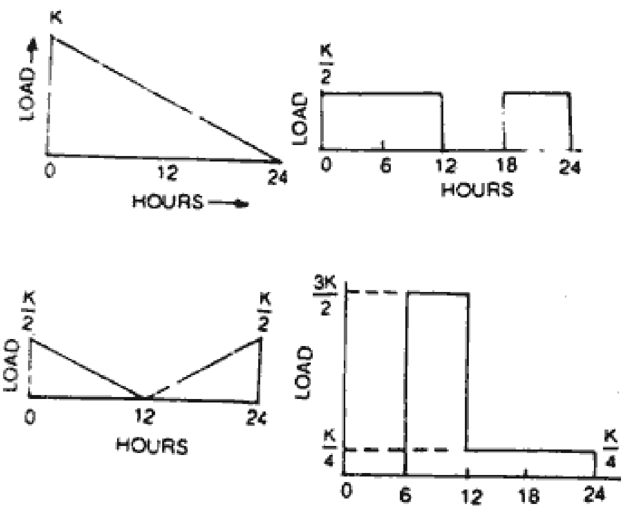
(B) Aluminium

(C) Alloy steel

(D) Cement.

Answer: B

Questions 55 to 61 refer to the figure given below:



Four different loads connected to a power Plant are shown in the figure.

55. Which load has the least value of average load?

(A) Load A

(B) Load B

(C) Load C

(D) Load D.

Answer: C

56. Which load has the highest value of average load?

(A) Load A

(B) Load B

(C) Load C

(D) Load D.

Answer: D

57. Which load has the least load factor ?

(A) Load A

(B) Load B

(C) Load C

(D) Load D.

Answer: D

58. Which load has the highest load factor ?

(A) Load A

(B) Load B

(C) Load C

(D) Load D.

Answer: B

59. If all the loads are connected to single source of power, the maximum load on the station will be

(A) 9k / 4

(B) 2k

(C) 3k

(D) 7 / 4k

Answer: C

60. The maximum load on the station will occur at

(A) 0 hr

(B) 6 hr

(C) 9 hr

(D) 12 hr.

Answer: B

61. In the above case load factor of the station will be

(A) 0.29

(B) 0.31

(C) 0.44

(D) 0.56.

Answer: D

All answer:

46.A ----- 47.B ----- 48.A ----- 49.C ----- 50.B ----- 51.D ----- 52.A ----- 53.C ----- 54.B -----55.C -----56.D ----- 57.D ----- 58.B ----- 58.C ----- 60.B ----- 61.D

Power Systems – I Unit Wise Assignment Questions

UNIT –I

1. a) What are the methods for arresting ash from flue gases? Explain any one method in detail.
   b) Discuss the natural and forced draughts and list out the difference between them.

2. a) What are the types of super heaters and explain the convection type super heater.
   b) Discuss function of condenser and where it is located.

3. Draw the schematic diagram of a coal fired thermal power plant. Label each component. Discuss briefly the functions of each component.
4. a) What is meant by fire tube boilers and what are the types as well as demerits of fire tube boiler?
   b) Explain the function of the following in thermal power plant and explain the principle of operation of each.

i) Economiser

ii) Electrostatic Precipitator

iii) Condenser

iv) Super Heater

v) Cooling Tower.

5. a) Explain the function of chimney and precipitation.
   b) Discuss the need of cooling towers and list out various types of cooling towers.

UNIT-II

1. Describe with neat sketches the construction and principle of operation of Liquid metal cooled reactor.
2. Explain clearly how the operation of nuclear reactor is controlled for generation of electrical power?
3. a) Discuss various factors associated with rapid growth of nuclear power industry.
   b) State and classify the different Nuclear reactors according to the basis of components.

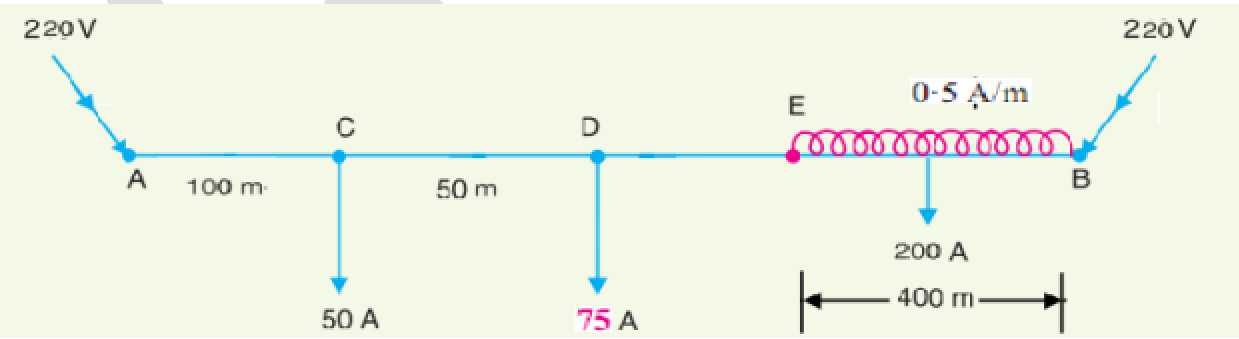
4. a) Define half life period. Derive the expression for half life period.
   b) What are the functions of moderator and control rods in a nuclear power plants.

5. a) Explain clearly the various processes that can take place, when a neutron collides with a heavy atom.
   b) What are the factors to be considered for selecting the location of site for nuclear power plant?

6. Explain in detail various types of Gas Power Stations with neat sketches for each of them.

UNIT-III

1. a) Explain different types of distribution systems with the help of neat sketches.
2. b) A DC 2 wire distributor 600m long is fed from both ends A and B at 220V shown in figure. The load consists of 50A at 100m from A, 75A at 150m from A and a uniform loading of 0.5A per meter for the last 400m. The resistance of each conductor is 0.05Ω/Km. Determine the location and magnitude of minimum voltage.



3. a) What is meant by radial and loop systems of distribution? Discuss briefly the requirements of a distribution system.
   b) A 2- wire DC ring distributor is 300 m long and is fed at 240 V at point A. At point B, 150m from A, a load of 120 A is taken and at C, 100 m in the opposite direction, a load of 80 A is taken if the resistance per 100 m of single conductor is 0.03Ω, find

   i) Current in each section of distributor   ii) Voltage at point B and C.

4. a) Give Comparison between overhead system and underground system?
   b) A uniformly loaded distributor is fed at the centre. Show that maximum voltage drop=IR/8, where I is the total current fed to the distributor and R is the total resistance of the distributor.

5. a) Give the comparison between DC and A.C systems of transmission and distribution.
   b) A 2 – wire D.C distributor 900 meters long is fed at centre and is loaded uniformly at the rate of 1.2A/m. If the resistance of each conductor is 0.04Ω/Km, find maximum voltage drop in the distributor.

UNIT-IV

1. A 3-phase distribution system power is supplied at 11 KV [line voltage] and the balanced load of 50A/phase at 0.8 lagging p.f and 70A at 0.9 lagging p.f are taken at Q and R respectively. The impedance of the feeders are PQ= [5+j9] Ω, QR= [6+j10] Ω, and RP= [4+j8]Ω. Calculate the voltage at Q and R and the current in each branch. Power factors are assumed with respect to voltage at P.

2. A 2- wire A.C feeder 1 km long supplies a load of 100 A at 0.8 p.f. lag 200 volts and its far end and a load of 60 A at 0.9 p.f. lag at its mid-point. The resistance and reactance per km [go and return] are 0.06Ω and 0.08Ω respectively. Calculate voltage drop along the distributor from sending end to mid-point and from mid-point to far end.

3. a) Explain the method of voltage drop calculations in A.C distributor.

   b) Draw the phasor diagrams of A.C distributor with concentrated loads for power factors with respect to respective load points.

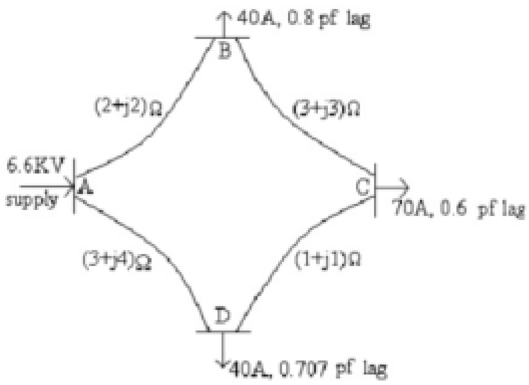
4. A single phase AC distributor 1km long has resistance and reactance per conductor of 0.1 ohm and 0.15 ohm respectively. At the far end, the voltage V_B=200V and the current is 100A at the power factor of 0.8(lagging). At the midpoint M of the distributor, a current of 100A is tapped at a power factor 0.6 lagging with reference to the voltage V_M at the midpoint. Calculate

   i) Voltage at midpoint

   ii) Sending end Voltage V_A

   iii) Phase angle between V_A and V_B

5. A 3-phase system is supplied at 6.6kV at terminal 'A' as shown in figure. The load is balanced and the p.f are lagging, calculate load current in each branch.



UNIT 5

1. a) Explain the classification of substations according to design.

   b) What are the advantages and disadvantages of outdoor substation as compared to indoor?

2. Explain the following with circuit diagrams.

i) Single bus bar arrangement with sectionalisation.

ii) Main and transfer bus bar arrangement.

3. a) What is substation? Name the factors that should be taken care of while designing and erecting a Substation?

b) What is group switching? Explain its operation in detail with the help of suitable diagram?

4. a) what are different types of bus bar arrangements?

b) Explain Double bus bar arrangement and what are its merits as well as demerits.

5. a) Compare Air Insulated and Gas insulated Substations.

b) Explain with neat sketch Single line diagram and the function of Gas Insulated Substations.

UNIT 6

1. a) Explain the disadvantages of low power factor.

b) A single phase motor connected to a 240 v, 50 Hz supply takes 20A at a pf of 0.75lag .a capacitor is shunted across the motor terminals to improve the pf to 0.90 lag, determine the capacitance of capacitor to be used?

2. a) What do you mean by power factor ?explain the necessity of improving power factor?

b) A consumer takes a steady load of 300Kw at a lagging pf of 0.7 for 3,000 hours a year .the tariff is Rs 1,300 per KVA of maximum demand per annum plus RS0.8 per kWh. The annual cost of phase advancing as Rs 130 per KVAR .determine the annual saving if the p.f of total load is improved.

3) What factors determine the economical limit of pf correction?

Show that the economical limit to which pf of a lagging load can be raised is independent of original value of pf if tariff consists of fixed charge per KVA of maximum demand plus flat rate per KWh

b) Calculate value of new pf when tariff is Rs 1350 per KVA of maximum demand plus flat rate paise 80 per KWh. assume additional cost of condensers etc. at Rs 1050 per KVA of such plant. rate of interest and depreciation together is taken as 10%.

4. a) Explain the method of voltage control in detail giving the neat connection diagram.

b) A consumer has an average demand of 400 kw at a pf of .8 lagging and annual load factor of 50% .the tariff is Rs 50 per KVA of a maximum demand per annum plus 5 paise pert KWh. if the power factor is improved to 0.95 lagging by installing phase advancing equipment calculate

The capacity of phase advancing equipment

ii) The annual saving effected .the phase advancing equipment costs Rs 100 per KVAr and annual interest and depreciation together amount to 10%

5. a) Why voltage control and pf correction are necessary in power systems? What are the disadvantages of low voltage and low pf of the system?

b) A 400 V 50 cycles three phase line delivers 207 Kw at .8 pf (lag).it is desired to bring at the line pf to unity by installing shunt capacitors .calculate the capacitors if they are

i) Star connected

ii) Delta connected

UNIT-7

1. From the following data, estimate the cost per KWH generation:-

Plant capacity--50MW

Annual load factor--40%

Capital cost—Rs.120x10^6

Annual cost of wages, taxes etc—Rs4x10^6

Annual cost of fuel lubrication etc—Rs20x10^6

Annual interest and depreciation—10%

2. State the effect of load factor and diversity factor on the cost of generation?

3. a) Define the following:

i. connected load

ii. Maximum demand

iii. Demand factor

b) A power supply is having the following loads.

If the system diversity factor is 1.5, determine

i) the maximum demand
ii) Connected load of each type

Type of load	Max. demand(KW)	Diversity of group	Demand factor
Domestic	15,000	1.25	0.7
Commercial	25,000	1.2	0.9
Industrial	50,000	1.3	0.98

4. Explain clearly how a good load factor and a good diversity factor help to keep overall cost of generation low.

5) The peak load on a 50MW power station is 39MW. It supplies power through for transformer whose connected loads are 17, 12, 9 and 10MW. The maximum demands on these transformers are 15, 10, 8 and 9MW respectively. If the annual load factor is 50% and the plant is operating for 65% of the period in the year, find out

i. average load on the station

ii. Energy supplied per year

iii) Demand factor

iv) Diversity factor and

v) Use factor for the power station

UNIT 8:

1. What type of tariff is employed for domestic consumers? Why this tariff is not employed for bulk consumers?
2. a) What is tariff? Discuss and compare various tariffs used in practice. Also, explain the reasons why power factor tariff is imposed.

   b) A generating station has the following data:

   Installed capacity=300MW, Capacity factor=50%, Annual load factor=60%, Annual cost of fuel, oil etc. = Rs. $9x10^7$, capital cost=Rs. 10^9, annual interest and depreciation 10%. Calculate

   i. The minimum reserve capacity of the station and
   ii. The cost per kWh generated.
3. An electrical supply company having a maximum load of 50 MW generates $18x10^7$ units per annum and the supply consumers have an aggregate demand of 75 MW. The annual expenses including capital charges are:

   For Fuel = Rs. 90 lakhs.

   Fixed charges concerning generation = Rs. 28 lakhs;

   Fixed charges concerning transmission and distribution = Rs. 32 lakhs;

   Assuming 90% of the fuel cost is essential to running charges and the loss in transmission and distribution as 15% of kWh generated. Deduce a two part tariff to find the actual cost of supply to the consumers.

4. a) Describe the desirable characteristics of a tariff.

   b) A steam station with an installed capacity of 120MW has the following data:

   Maximum demand =100MW; Average load factor-0.75

   Capital cost=Rs. 800/kW installed

   Interest and depreciation=12%

   Operational cost=Rs. $1x10^6$ per annum.

Maintenance cost (2/3 fixed, 3/5 variable) =Rs. $6.5x10^5$ p.a.

Cost of fuel=Rs.35 per metric ton

Calorific value of fuel=6,500 K. cal/kg

Generator efficiency =96% thermal efficiency of turbine=28% Boiler efficiency=75%

Overall thermal efficiency=20%

Determine the total fixed costs, total variable costs and the cost/ kW generated.

5. a) Discuss the flat rate and block rate tariffs.

b) A power station has an installed capacity of 20,000KW. The cost of the station is Rs. 1,200/kW. The fixed costs are 13% of the cost of investment on full load at 100% load factor, the variable costs of the station per year is 1.5 times the fixed costs. Assume that there is no reserve capacity of the plant and that are variable costs and proportional to energy production. Find the cost of generation per kWh at load factor of 100% and 20%. Comment on the results.

II B.Tech II SEM EEE SECTION STUDENT LIST

S.No	Roll No	Student Name
1	12R11A0229	MATHANGI MUKESH KUMAR
2	12R11A0240	SHANIGARAPU RAVI KIRAN
3	13R11A0201	ADEPU VINAY CHANDRA NETHA
4	13R11A0202	ADIDELA JAISON
5	13R11A0203	B PREM KUMAR
6	13R11A0204	BADDAM NIVEDITHA
7	13R11A0205	BADIKALA SAIVARMA
8	13R11A0206	BANOTH SHARATH
9	13R11A0207	BOORLA SAHASAVEERA
10	13R11A0208	CHITTLA RAMESH SAI KIRAN
11	13R11A0209	DHANWADA SREE KALYANI
12	13R11A0210	G CHAITHANYA
13	13R11A0211	G KARTHIK REDDY
14	13R11A0213	GADDAM NARESH
15	13R11A0214	GUGULOTH SUNIL KUMAR
16	13R11A0215	GUNDA PALLAE SAI CHARAN
17	13R11A0216	HARI SHANKAR SHARMA
18	13R11A0217	J SUPRIYA
19	13R11A0218	JULAKANTI BHARATH GOUD
20	13R11A0219	K HARSHAVARDHAN SAI
21	13R11A0220	KATNAPALLY SHANDILYA SHARMA
22	13R11A0221	KATTOLA HAARIKHA
23	13R11A0222	KOLA PURAM HAREESH
24	13R11A0223	KOMAL KRISHNA SAI RAM KOLLURU
25	13R11A0224	KONDETI GOPI
26	13R11A0225	KOTTE PRAVEENKUMAR
27	13R11A0226	M SAI KIRAN GOUD
28	13R11A0227	MADDIRALA SUDHARANI
29	13R11A0228	MANGA RAGHU
30	13R11A0229	MARAPALLI SAILOHITHREDDY
31	13R11A0230	MODULLA SAI SUBHASH REDDY
32	13R11A0231	MOGILI NANDA KISHORE
33	13R11A0232	MUDAM SRIKANTH
34	13R11A0233	MULAMALLA DEEPAK REDDY
35	13R11A0234	MUNJALA SHIVAKRISHNA
36	13R11A0235	P RACHITHMANIHAAR
37	13R11A0236	PESARLA SAICHARAN RAO
38	13R11A0237	PILLUTLA PAVAN KUMAR
39	13R11A0238	POLIKA BHARATH KUMAR REDDY
40	13R11A0239	RATHOD VENKATESH
41	13R11A0240	RUDANI JAY PATEL
42	13R11A0241	SAMMETA SWATHI
43	13R11A0242	SANGONDA PRAVEEN
44	13R11A0243	SHAIK MANJITH
45	13R11A0244	THATIPAMULA SAIKUMAR
46	13R11A0245	TIRUMALASETTY SAITANUJ
47	14R15A0201	MAKAM PRIYANKA
48	14R15A0202	DUSA GOUTHAM
49	14R15A0203	CH VAMSEE KRISHNA

50	14R15A0204	KOMMANABOINA MAHENDER
51	14R15A0205	VANGURU TEJASWINI
52	14R15A0206	KANNEKANTI SHIVA PRASAD
53	14R15A0207	EEGA VENU
54	14R15A0208	NARVA ANJANEYULU
55	14R15A0209	CHINTA RAHUL BABU
56	14R15A0210	ALLABOINA HARIKRISHNA
57	14R15A0211	MALOTHU ANUSHA
58	14R15A0212	THUPAKULA ASHOK REDDY
59	14R15A0213	PAIDIPALLY SHASHIPREETHAM
60	14R15A0214	VAGALDAS PRAVEEN KUMAR
61	14R15A0215	MEESALA NAGARAJ

CLOSURE REPORT:

Closure Report for the subject: POWER SYSTEMS-I

1. Total number of classes to be held as per JNTUH:
2. Total number of classes held:
3. Total number of Students who appeared for the End Semester Examinations:
4. Total number of Students passed in the End Semester Examination: