Module 5
Economics

INTRODUCTION

- In all engineering works, the question of cost is of first importance.
- In most cases the cost decides whether a certain project will be carried out or not, although political and other considerations may intervene sometimes.
- The electrical power supplier is required to supply power to a large number of consumers to meet their requirements.
- While designing electrical power generating stations & other systems efforts are made to achieve overall economy so that the per unit cost of generation is lowest as possible.

- This will enable the supplier to supply electrical energy to its consumers at reasonable rates.

- The problem of determining the cost of any scheme is often difficult, because the cost varies considerably with time and tariff conditions.

- Economic problem occurs in the fields of generation, transmission, distribution and utilization of electrical power.

- The electrical engineer has to adopt the cheapest & most convenient scheme after having study of the relative costs of possible schemes.

EFFECT OF VARIABLE LOAD ON POWER SYSTEM

- Generation of power becomes costly
  - For optimum operation, alternators are designed in such a way that maximum efficiency occurs at (or very close to) their rated capacity.
  - Hence, when the load varies and becomes low, the alternator will not be loaded up to its rated capacity and its working efficiency is reduced.
  - This consequently increases the cost of production.

- Increased Losses
  - Due to variation in loading conditions, various machines like transformers, electronic devices and other machines show increased losses due to magnetization characteristics, saturation and variation in parameters.
  - This decreases the overall efficiency of the system.

EFFECT OF VARIABLE LOAD ON POWER SYSTEM (contd.)

- Difficulty in controlling the system
  - When the load changes, the frequency of the system also varies.
  - For proper operation, the frequency must be within the permissible limits.
  - In order to keep the frequency within limits, additional control equipment's are required.
  - Such equipment's increase the cost and complexity of the system.
  - Requirement of additional equipment
  - Variable loading necessitates the use of speed governors, voltage and frequency sensors, microcontrollers and other closed loop control equipment's to exert control over the system and maintain all parameters within permissible ranges.

CLASSIFICATION OF COSTS

- Fixed Cost

  - This cost is independent of maximum demand and energy output.
  - It is due to the annual cost of organization, interest on the capital of land and salaries of high officials.
  - The annual expenditure on central organization and salaries of high officials is fixed since it has to meet whether the plant has high or low maximum demand or it generates less or more energy
  - Further, the capital investment on the land is fixed and hence the amount of interest is also fixed.

CLASSIFICATION OF COSTS

Semi Fixed Cost

- The cost depends upon the maximum demand but is independent of energy output.

- The semi fixed cost is due to annual interest and depreciation on the capital cost of the generating plant, transmission and distribution network, buildings & other civil works, all types of taxes, insurance charges & salaries of management & clerical staff.

- Also yearly compensation given to workers is included under this head.

CLASSIFICATION OF COSTS

Semi Fixed Cost

- The semi fixed cost is approximately proportional to maximum demand.
- The size and cost of the installation is governed by the maximum demand on the power plant.
- The greater the maximum demand on power plant, the greater is its size and cost of installation.
- Further taxes, insurance charges & strength of clerical staff depend upon the size of the plant and hence upon the maximum demand.

CLASSIFICATION OF COSTS

❑ Running Cost (or) Operating Cost

- This cost depends upon the number of hours the plant is in operation or upon the number of units of electrical energy is generated.

- The running or operating cost is due to annual cost of fuel, lubricating oil, water, maintenance and repair cost of equipment and wages and salaries of operational and maintenance staff and salaries of supervisory staff engaged in the running of the plant.

- The operating cost is approximately proportional to units generated.

CLASSIFICATION OF COSTS

❑ Running Cost (or) Operating Cost

- Total annual cost incurred in the power generation is represented by

$$E = a + b\ KW + c\ KWh$$

Where a, b and c are constants

- Fixed and semi fixed cost being independent of the amount of energy generated is also called standing cost.

- In deciding any scheme for any given service the choice must be such that the total operating cost be minimum

COST ANALYSIS OF POWER PLANTS

Introduction

- The generating cost per unit (KWh) of energy depends upon the cost covering the purchase, installation and erection of equipment, cost of fuel, labour, repair etc.
- The generation cost can, broadly be divided into fixed cost and the operating or running cost.

Fixed Cost

- The annual fixed cost consists of the interest on the total investment, all types of taxes and insurance charges, salaries of high officials, management and clerical staff.

- The annual contribution to the fund to pay off the capital expended after useful life of the plant and yearly compensation paid to the workers is also included in the annual fixed cost.

- This cost varies approximately in direct proportion with the installed capacity of the plant and does not depend upon the fact weather the plant supplies any energy or not.

Fixed Cost

- The total investment or capital cost of a plant includes the preliminary cost, cost of land and other real estate, cost of design and planning, cost of building and equipment, cost of transportation, erection and installation of equipment and over heads etc.
- In case of hydroelectric power plants, the capital costs of plants include the costs of dams, earthwork, railhead, highways and other civil works.
- In addition to it, cost of land & building will depend upon the location of the plant.
- If plant is situated near city than land will be costlier.

Fixed Cost

- The cost of steam plant located near a river where adequate supply of cooling water is available, would be lesser than that of one in which cooling towers or ponds would have to be made available.

- A plant having a smaller number of large sized generating units costs less than a plant of the same total generating capacity but having a large number of small sized units.

- The capital costs of the plants vary widely, even in case of plants of similar types, and depend to a large extent on market conditions.

- The operating cost of a plant means the expenses which vary with the extent of operation or the amount of energy generated.

Running Cost (or) Operating Cost

- The cost is due to annual cost of fuel, lubricating oil, water, maintenance and repair cost of equipment and wages and salaries of operational and maintenance staff and salaries of supervisory staff engaged on the running of the plant.

- The operating cost is approximately proportional to units generated.

- In steam, diesel and gas plants, the operating costs form a major portions of total annual cost whereas in hydro, nuclear & solar plants, the fixed costs overshadow the small operating cost.

Investor Profit

- If the power plant is the public property, as is the case in India, then the customers will be taxpayers to share the burden of the Government.
- For this purpose, there is an item in the rates to cover taxes in place of the investors profit.
- Theses taxes will be paid by the consumers in the form of electric consumption bill.

INTEREST AND DEPRECIATION

- Usually money is borrowed from banks or insurance companies or other financial institutions for big projects such as generating plant and at the end of a year, the undertaking is required to pay the interest on the capital cost.

- Even if equipment is purchased out of reserve cash, the normal rate of interest must still be allowed for, since the money might otherwise be earning this interest.

- If a capital outlay required for a certain installation is P and the rate of interest per unit is r per annum then an amount of rP per annum must be provided as interest, and this added to annual operating cost.

INTEREST AND DEPRECIATION

- Rate of interest to be paid depends upon the money market position and the credit of the borrower and varies between 8 to 10 per cent per annum.

- If the installation were to last for ever, the interest is the only charge that would have to be made.

- In practice after a certain time the plant and machinery have to be replaced, due to its getting old, obsolete & inadequate and it is, therefore, necessary to set aside certain amount annually to produce a sufficient sum at the end of ones.

- The amount is known as depreciation and depends upon the type and make of machines.

METHODS OF DETERMINATION OF DEPRECIATION

Introduction

- Depreciation is the most important item in the fixed costs and it represents the reduction in the value of equipment and other property of the plant every year due to continuous wear and tear.

- This can be reduced by proper maintenance of the equipment and the buildings.

- To account for the depreciation, a certain fixed amount is set aside every year so that by the time the life span of the plant is over, the total amount accumulated equals replacement cost

Methods commonly used for determination of annual depreciation charges are

- Straight Line Method
- Diminishing Value Method (or) Declining Balance Method
- Sinking Fund Method

Straight Line Method

- This method assumes that certain depreciation occurs according to the straight line law.
- In this method, a constant depreciation charge is made every year on the basis of total depreciation and useful life of the equipment.

$$i.e \quad \text{Annual Depreciation Charge} = \frac{\text{Initial Cost} - \text{Salvage Value}}{\text{Number of years of useful life}} = \frac{P - S}{n}$$

- This method is very popular because of its simplicity but it does not take into account the amount of interest earned by the amount set aside yearly.
- **Salvage value:** Estimated resale value of an asset at the end of its useful life.

Diminishing Value Method (or) Declining Balance Method

- In this method provision is made for setting each year a fixed rate, first applied to the original cost and then to diminishing value, such rate depending upon the useful life of the plant.

- This method results in distribution of the total expenses on the plant over its total useful life because in this method depreciation charges are heavy in early years when maintenance charges are low and depreciation charges are low in late years when maintenance charges are heavy.

- The serious drawback of this method is that an heavy burden towards depreciation charges is imposed in early years when plant is to develop and build up its income.

- Let the capital cost of the plant be P, salvage value after useful life of equipment of n years be S.

Diminishing Value Method (or) Declining Balance Method

- The value of plant after one year = P (1- x)
- The value of plant after two years = P (1- x) (1- x) = P (1- x)^2
- The value of plant after n years, S = P (1- x)^n

$$OR \quad (1-x) = \left(\frac{S}{P}\right)^{1/n} \qquad OR \qquad x = 1 - \left(\frac{S}{P}\right)^{1/n}$$

- Deposit to be made by first year of completion of the plant $\quad x^P = P\left[1 - \left(\frac{S}{P}\right)^{1/n}\right]$
- Deposit to be made by first year of completion of the plant

$$x\,(1-x)P = \left(\frac{S}{P}\right)^{1/n} \quad P\left[1 - \left(\frac{S}{P}\right)^{1/n}\right]$$

Sinking Fund Method

- A sinking fund method is a technique for depreciating an asset in book keeping records while generating money to purchase a replacement for the asset when it reaches the end of its useful life.

- As compared to straight line method, it requires smaller annual amounts.

- If the annual deposit be q, it will earn the interest rq in one year.

  Where r= rate of interest per annum expressed as fraction

Sinking Fund Method (

- So that it will worth $q + rq = q\ (1 + r)$ at the end of one year
- Thus its value will be multiplied by the ratio $(1 + r)$ every year
- At the end of two years $= q\ (1 + r)^2$
- At the end of two years $= q\ (1 + r)^3$
- At the end of two years $= q\ (1 + r)^n$
- Thus amount of q deposited at the end of first year in n-1 years will be $= q\ (1 + r)^{n-1}$
- An amount of q deposited at the end of second year in n-1 years will be $= q\ (1 + r)^{n-2}$

Sinking Fund Method

- The amount of q deposited at the end of (n-1)th year in one year will be $= q(1+r)$
- Thus after n years total sinking fund will be

$$= q\left[(1+r)^{n-1} + (1+r)^{n-2} + (1+r)^{n-3} + \cdots (1+r)\right]$$

- The above termsare in geometrical progression

$$Total\ Sum, Q = q\left[\frac{(1+r)^{n-1}}{r}\right]$$

Where Q = Cost of replacement which is equal to (P-S)

$$Annual\ Deposit,, Q = q\left[\frac{Qr}{(1+r)^{n-1}}\right]$$

Economics of Power Generation

- The generation of electrical energy economically requires long experience to decide about the type, location and the rating of generating stations.
- The generating stations may be steam, hydro, nuclear, diesel or any other types.
- This factor mainly depends upon the natural sources available in the areas.
- Steam power stations are best suited near coal fields and also adopted where coal supply is available in the areas
- Steam power stations are best suited near coal fields and also adopted where coal supply is available in plenty at reasonable rates

- Hydropower stations are best suited in case water is available at certain height.
- Nuclear power stations are best suited in area far away from collieries and where fuel costs are high & alternative cheap hydropower is not available.
- Diesel power stations are installed where supply of coal and water is not available.
- The power station should be as possible to the load so that the transmission cost and losses are minimum
- The other considerations for the design of the power station are reliability, minimum capital and operating costs.

- For this necessary layout should be such that the maintenance and repairs can be carried out easily.

- Equipment must be standard one so that capital cost is reduced and replacement of worn out parts becomes easy and equipment used should be simple so that it can be operated by semi-skilled workers.

- The design of station should be such that it should be divided into number of sections to avoid complete shutdown of the station when fault occurs.

- The equipment should be automatic whenever in order to save the labour cost provided the reliability of system should not be affected

- Before a power project is taken into hand, the project engineer should have the following information with him.
  - ✓ Estimate of probable load
  - ✓ Future load conditions
- Location of the loads, especially in case of hydroelectric generating stations because the cost of transmission is also required to be considered.
- For deciding the type and rating of generating plant it is necessary that engineer may be familiar with the following important terms

Energy:

- Energy is defined as the power consumption in the particular period of time.
- It is expressed in Kilo-Watt hour (KWh).
- Mechanical work done over a period of time is also a form of energy like heat.

Work done:

- Work done is defined as the distance travelled by the applied force.
- Its unit is Newton metre (or) Joules.
- Electrical work is the product of voltage difference and the current flows in the conductor.
- Electrical work = Power = Volt x Amp = Watt = Joule/sec

Installed capacity:

- Installed capacity is the designed power generation capacity of a plant.
- It is expressed in terms of energy generated per unit time (MWh).

Power:

- It is the rate of work or work done per unit time.
- It is generally expressed as Joules/second or MW.
- The basic unit is watt (Joules per second).

Heat Rate:

- Heat rate is the amount of energy (kJ) that the fuel must supply to produce unit amount of electrical energy (kWh).
- It is expressed as kJ/kWh or kilo Calories/KWh.
- This represents the overall efficiency of a power plant.

Turbine Heat Rate:

- Turbine heat rate is the amount of heat steam must deliver to produce unit of heat.
- It is expressed in Kilo-Watt Hour (KWh).

Thermal Efficiency:

Thermal efficiency is the amount of heat carried by the steam per unit amount of heat delivered through the fuel.

Combustion Efficiency:

Combustion efficiency is defined as the ratio of the amount of energy or heat released by the fuel to the energy contained in the burnt fuel.

Outage:

Outage is another term for shut down of the plant either for planned maintenance (Planned outage) or due to unforeseen break down (forced outage).

Availability:

- Availability is the fraction of the time a plant is available for generation.
- A plant may be partially available due to lack of operation of some components of the plant. It is called partial availability.

Interconnected Grid System:

The connection of several generating stations are connected in parallel is known as an interconnected grid system.

Load Factor:

Load factor is defined as the ratio of an Average load to the Maximum load.

$$Load\ Factor = \frac{Average\ load}{Maximum\ load.}$$

Diversity Factor:

Diversity factor is defined as the ratio of sum of individual maximum demands to the maximum demand on the power plant.

$$\text{Diversity Factor} = \frac{\text{sum of individual maximum demands}}{\text{Maximum demand on the power plant}}$$

Utilization Factor:

Utilization factor is defined as the ratio of Maximum load to the Rated capacity of the plant.

$$\text{Utilization Factor} = \frac{\text{Maximum load}}{\text{Rated capacity of plant}}$$

Plant Use Factor:

Plant use factor is defined as the ratio of KWh generated output to the product of rated capacity of plant and the number of hours for which the plant was in operation.

$$\text{Plant use Factor} = \frac{\text{KWh generated output}}{\text{Rated capacity of plant}}$$

Capacity Factor:

Capacity factor is defined as the ratio of Average load to the Rated capacity of the plant. It is also called as Plant Capacity Factor.

$$\text{Capacity Factor} = \frac{\text{Average load}}{\text{Rated capacity of plant}} = \frac{\text{Total energy output in a period}}{\text{Rated capacity of plant}}$$

Plant Use Factor:

Plant use factor is defined as the ratio of KWh generated output to the product of rated capacity of plant and the number of hours for which the plant was in operation.

$$\text{Plant use Factor} = \frac{\text{KWh generated output}}{\text{Rated capacity of plant}}$$

Capacity Factor:

Capacity factor is defined as the ratio of Average load to the Rated capacity of the plant. It is also called as Plant Capacity Factor.

$$\text{Capacity Factor} = \frac{\text{Average load}}{\text{Rated capacity of plant}} = \frac{\text{Total energy output in a period}}{\text{Rated capacity of plant}}$$

Demand factor:

Demand factor is defined as the ratio of Maximum demand on the station to the total load connected to the plant.

$$Demand\ Factor = \frac{Maximum\ demand}{total\ connected\ load}$$

Reserve Factor:

Reserve factor is defined as the ratio of Load factor to the capacity factor.

$$Reserve\ Factor = \frac{Load\ factor}{Capacity\ factor}$$

Plant Reserve Capacity:

Plant reserve capacity is defined as the difference between the Rated Capacity of the plant ant the Maximum demand on the plant.

$$Reserve\ Capacity = Rated\ capacity\ of\ the\ plant - Maximum\ demand\ on\ the\ plant$$

Coincidence Factor:

Coincidence factor is defined as the ratio of Capacity factor to the Load factor.

$$Coincidence\ Factor = \frac{1}{Reserve\ Factor} = \frac{Capacity\ factor}{Load\ factor}$$

Load Curve

- The curve showing the variation of the load on the power station with respect to time is known as Load curve.

- The load on a power station is never constant because it varies time to time.

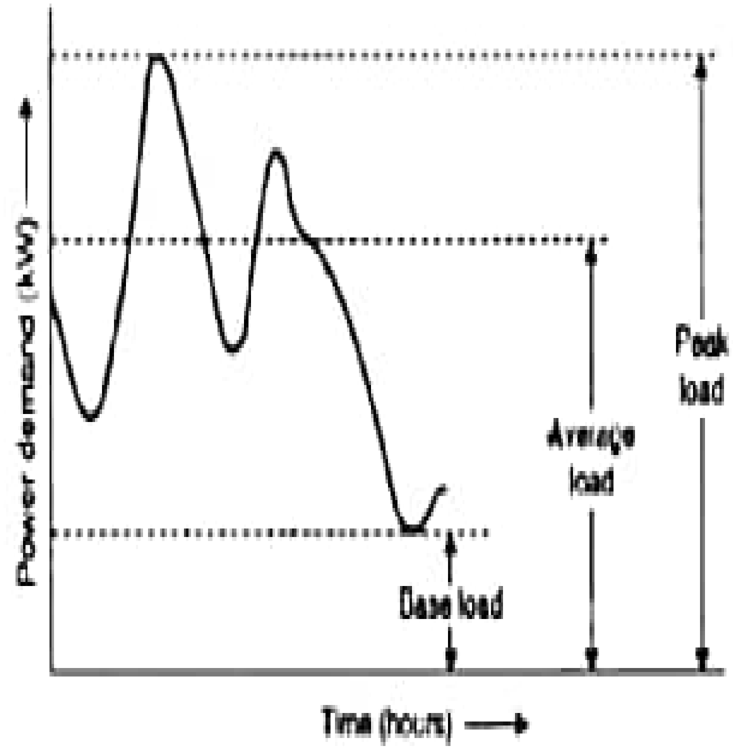


Fig.1 Graphical representation of Load (Load curve)

IMPORTANT DEFINITIONS FOR LOAD CURVE

Base Load

The unvarying load which occurs almost the whole day on the station is called as Base load.

Peak Load

- The various peak demands of load over and above the base load of the station is known as Peak Load.
- It is also known as Peak Demand.

Connected Load

The sum of the continuous ratings of all the equipments connected to the power system is called connected load.

Maximum Load

- Maximum load is the greatest demand on the given period during a given period.
- It is also known as Maximum Demand.

Types of Load Curve

- The load variation during the whole day is plotted against the time is called as Daily Load Curve.

- The load variation during the whole month is plotted against the time is called as Monthly Load Curve. This can be obtained from the daily load curve of that month.

- The load variation during the whole year is plotted against the time is called as Yearly Load Curve. This can be obtained from the monthly load curve of that particular Year.

Significance of Load Curve

- The area under the load curve represents the energy generated in the period considered.
- The area under the curve divided by the total number of hours gives the average load on the power station.
- The peak load indicated by the load curve is the graph represents the maximum demand of the power station.
- Load curve helps in selecting the size and number of generating units of the power station. Load curves give full information about the incoming load.
- Load curve helps in deciding the operation schedule of the station. Load curves also help to estimate the generating cost.

Load Duration Curve

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

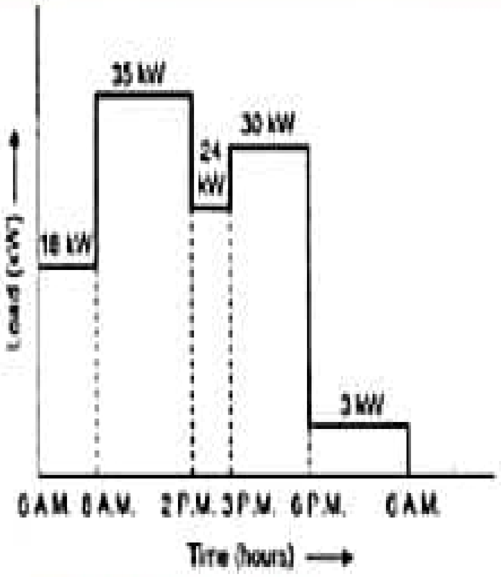


Fig.2 Daily Load Curve

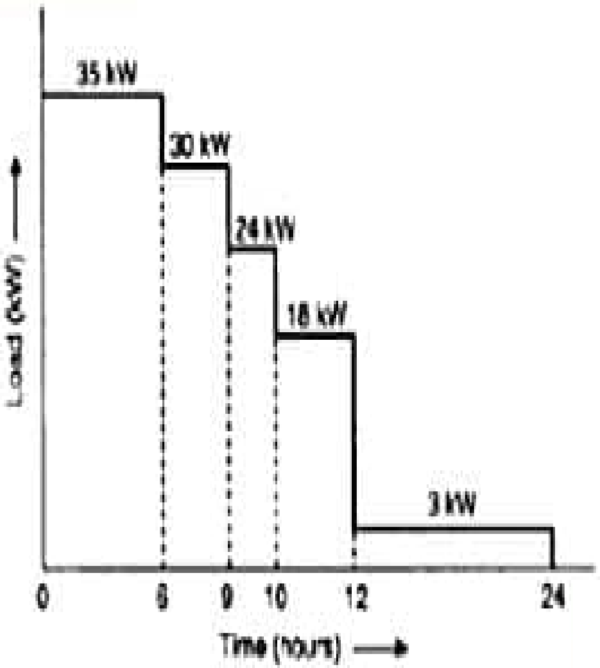


Fig.3 Load Duration Curve

Significance of Load Duration Curve

- The area under the load duration curve and the corresponding chronological load curve is equal.
- Load duration curve represents total energy delivered by the generating station with optimized operating units.
- Load duration curve gives a clear analysis of generating power economically.
- Proper selection of base load power plants and peak load power plants becomes easier.

Integrated Load Duration Curve

- This curve gives the total number of units generated for the given demand
- The ordinate represents the demand in KW or MW and the abscissa represents the units (Kwh) generated at or below a given demand.
- Such a curve can be obtained from the load duration curve keeping the abscissa corresponding to each ordinate equal to the area of the duration curve up to the value of ordinate.

Mass Curve

- The mass curve gives the total energy consumed by the load up to particular time in a day.
- This curve can be easily plotted from the chronological load curve by summing up the energy consumed up to different times starting at the zero time.
- This curve is used in the study of variations between the rate of water flow and the electrical load and for the determination of the necessary storage.

Average Load

The average of all the loads occurring at the various instants on the generating station is called average load.

The total electrical energy delivered in a given period divided by the time period is called as average load.

$$Average\ Load = \frac{KWh\ Energy\ supplied\ in\ a\ period}{Time\ period}$$

$$Daily\ Average\ Load = \frac{KWh\ Energy\ supplied\ in\ a\ day}{24}$$

$$Monthly\ Average\ Load = \frac{KWh\ Energy\ supplied\ in\ a\ day}{24 \times 30}$$

Variable Load

The load on a power plant varies from time to time due to uncertain demands of the consumers are known as Variable load.

Effects of Variable Load

Need of an additional equipment

Increase in production cost

Interconnected Load

The connection of two or more loads in parallel condition is known as an interconnected load.

Advantages

- ✓ Exchange of peak loads
- ✓ Use of older plants
- ✓ Ensures an economical operation
- ✓ Increases diversity factor
- ✓ Reduces plant reserve capacity
- ✓ Increases reliability of supply.

Base Load Plant

- Base load plant is a type of plant which supplies to a constant load demand in more efficient manner.
- Such plants run 100% of the time.
- Examples: Nuclear and Coal fired plants.

Peak Load Plant

- Peal load plant is a type of plant whicl supplies to both constant load demanc as well as maximum demand.
- This plant helps over short term (15% demand peak.
- Gas turbine, hydro plant can be used.

Cold Reserve

Cold reserve is that reserve generating capacity which is not in operation but can be made available for service.

Spinning Reserve

Spinning reserve is that reserve generating capacity which is connected to the bus and is ready to take the load.

Hot Reserve

Hot reserve is that reserve generating capacity which is in operation but not in service.

TYPES OF LOADS

Residential Load

This type of load includes domestic lights, power needed for domestic appliances such as radios, television, water heaters, refrigerators, electric cookers and small motors for pumping water.

Commercial Load

It includes lighting for shops, advertisements and electrical appliances used in shops and restaurants etc. This load occurs for some hours during the day time.

Industrial Load

It consists of load demand of various industries. The magnitude of this type of load depends on the type of industry.

TYPES OF LOADS (contd.)

Municipal Load

It consists of street lighting, power required for water supply and drainage purposes. This pumping process occurs at the night time only.

Traction Load

It includes trams, cars, trolley, buses and railways. This type of load has wide variation depends on time.

Irrigation Load

This type of load includes electrical power needed for pumps driven by electric motors to supply water to fields. This type of load is supplied for night 12 Hours.

LOAD SHARING

- Base load plants run throughout the year and have high load factors
- The economic characteristics of base load plants should be such that they supply power at high capital costs but low cost of operation.
- Hydro and nuclear power plants are usually classified as base load plants.
- Peak load plants run for a few hours in the year and work at low load factors.
- The economic characteristics of peak load plants should be such that they supply power at low capital costs, although at high cost of operation.

LOAD SHARING

- Peak load power plants should be capable of starting quickly.

- Let the operating costs of base load and peak load be Rs (a_1 KW + B_1 KWh) and Rs (a_2 KW + b_2 KWh). Where $a_1 > a_2$ and $b_1 > b_2$

- Let P be the maximum demand on the power plant and x be the total number of units generated

- If P_1 is the maximum demand on base load point and x_1 is the number of units generated by the base load point

- Peak load on Peak load point $x_2 = x - x_1$

LOAD SHARING (contd.)

Total annual cost of operation of the system

$$C = a_1 P_1 + a_2 (P - P_1) + b_1 x_1 + b_2 (x - x_1)$$

$$= P_1 (a_1 - a_2) + a_2 P + x_1 (b_1 - b_2) + b_2 x$$

Or $\frac{dc}{dP_1} = (a_1 - a_2) + \frac{dx_1}{dP_1}(b_1 - b_2)$

LOAD SHARING

For maximum cost, $\frac{dc}{dP_1} = 0$

Therefore $(a_1 - a_2) + \frac{dx_1}{dP_1}(b_1 - b_2) = 0$

$$\frac{dx_1}{dP_1} = \frac{a_1}{b_2} - \frac{a_2}{b_1} \; Hours$$

ie., for economic load sharing peak load power plant will operate for

$$\frac{a_1}{b_2} - \frac{a_2}{b_1} \; Hours \; per \; year$$

CHOICE OF SIZE AND NUMBER OF GENERATING PLANTS

- The number of units and the size of each unit is decided from the load curve.
- The following factor should be considered while deciding the number of units and preparing operating schedule.
- The total capacity of the generating units must be capable of meeting the peak demand of the power station.
- Machines operate with maximum efficiency at the three fourth of the rated capacity, hence the number and size of units must be so selected that they operate at maximum efficiency.

CHOICE OF SIZE AND NUMBER OF GENERATING PLANTS

- Reliability of service is a very important factor.

- There should be a spare set of capacity of that largest unit in the power station so that maintenance and repairs of working units may be carried out without any disturbance in power supply.

- The growth of the demand in near future should be kept in view.

- The capacity of the power station should be 15 or 20 % more than expected maximum demand.

CHOICE OF SIZE AND NUMBER OF GENERATING PLANTS

- Minimum number of generating units chosen could be one having a capacity equal the maximum demand on the power station.
- Large size units have lower capital cost per KW, needless floor area & have better efficiency. Thus large size units are economical because of initial investment & operating cost.
- The size and number of generating units may be so chosen as to fit the load curve as closely as possible.
- Then each unit can be made to operate in such a way that it operates almost at full load or at a load to give maximum efficiency.

TARIFF

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

- Cost of Producing Electricity depends upon the magnitude of Electricity consumed by load.
- Tariff fixation has to be given to different types of consumers (*e.g.*, industrial, domestic and commercial).
- Tariff fixing for different consumers is more complicated.

Objectives of tariff.

Electrical energy is sold at such a rate so that it not only returns the cost but also earns reasonable profit. Tariff should include the following objectives:

- Recovery of cost of producing electrical energy at the power station.
- Recovery of cost on the capital investment in transmission and distribution systems.
- Recovery of cost of operation and maintenance of supply of electrical energy
- A suitable profit on the capital investment.

Characteristics of a Tariff:

(i) Proper return:

- The total receipts from the consumers must be equal to the cost of producing and supplying electrical energy plus reasonable profit.
- This will enable the electric supply company to ensure continuous and reliable service to the consumers.

(ii) Fairness:

- The tariff must be fair so that different types of consumers are satisfied with the rate of charge of electrical energy.
- A big consumer should be charged at a lower rate than a small consumer with fixed charges and thus reducing overall production cost of electrical energy.
- A consumer whose load conditions do not deviate much from the non-variable load should be charged at a lower rate than big consumers with variable load.

(iii) Simplicity:

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

(iv) Reasonable profit:

- The profit element in the tariff should be reasonable.
- An electric supply company is a public utility company and generally enjoys the benefits of monopoly.
- The investment is relatively safe due to non-competition in the market and the profit is to be restricted to 8% or so per annum.

(v) Attractive:

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

Factors Affecting the Tariffs

The following factors are taken into accounts to decide the electricity tariff:

- Types of Load
- Maximum demand
- The time at which load is required
- The power factor of load
- The amount of energy used

TYPES OF TARIFF

1. Simple Tariff
2. Flat rate Tariff
3. Block rate Tariff
4. Two part Tariff
5. Maximum demand tariff
6. Power Factor Tariff
7. Three part Tariff

(1) Simple Tariff

Definition

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

Advantages

- In simple tariff, the cost does not vary with increase or decrease in number of units consumed.
- The consumption of electrical energy at the consumer terminals is recorded by means of an energy meter.
- This is the simplest of all tariffs and is easily understood by the consumers.

Disadvantages

- Every consumer has to pay equally for the fixed charges irrespective of load variation.
- The cost per unit delivered is high.
- It does not encourage the use of electricity.

(2) Flat Rate Tariff

Definition

- When different types of consumers are charged at different uniform per unit rates, it is called a flat rate tariff.
- In this type of tariff, the consumers are grouped into different classes and each class of consumers is charged at a different uniform rate.
- The different classes of consumers are made taking into account their diversity and load factors.

(2) Flat Rate Tariff

Disadvantages

- Separate meters are required for lighting load, power load etc.
- The application of such a tariff and complicated.
- A particular class of consumers is charged at the same rate irrespective of the magnitude of energy consumed.

Advantages

- This tariff is more benefit to different types of consumers
- Flat rate tariff is quite simple in calculations.

(3) Block Rate Tariff

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

(3) Block Rate Tariff

Advantages

- The consumer gets an incentive to consume more electrical energy.
- This increases the load factor of the system and hence the cost of generation is reduced.

Disadvantages

- It lacks a measure of the consumer demand.
- This type of tariff is being used for majority of residential and small commercial consumers.

(4) Two Part Tariff

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

- In two-part tariff, the total charge to be made from the consumer is split into two components viz., fixed charges and running charges.

- The fixed charges depend upon the maximum demand of the consumer while the running charges depend upon the number of units consumed by the consumer.

- Thus, the consumer is charged at a certain amount per KW of maximum demand plus a certain amount per KWh of energy consumed.

(4) Two Part Tariff

- Total charges = Rs (b × KW + c × KWh)

Where, b = charge per KW of maximum demand

c = charge per KWh of energy consumed

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

Advantages

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

Disadvantages

- The consumer has to pay the fixed charges irrespective of energy consumed
- There is always error in assessing the maximum demand of the consumer.

(5) Maximum Demand Tariff

It is similar to two-part tariff with the only difference that the maximum demand is actually measured by installing maximum demand meter in the premises of the consumer.

Advantages

- The maximum demand is assessed merely on the basis of the rateable value.
- This type of tariff is mostly applied to big consumers.

Disadvantages

- It is not suitable for a small consumer.
- Separate maximum demand meter is required.

(6) Power Factor Tariff

- The tariff in which power factor of the consumer load is taken into consideration is known as power factor tariff.
- A low power factor increases the rating of station equipment and line losses. A consumer having low power factor must be penalized.

The following are the important types of power factor tariff:

(i) KVA Maximum Demand Tariff

- It is a modified form of two-part tariff.
- In this case, the fixed charges are made on the basis of maximum demand in KVA and not in KW.
- A low power factor consumer has to contribute more towards the fixed charges.

(6) Power Factor Tariff

(ii) Sliding Scale Tariff

- This is also known as average power factor tariff.
- In this case, an average power factor, say 0·8 lagging, is taken as the reference.
- If the power factor of the consumer falls below this factor, suitable additional charges are made.
- If the power factor is above the reference, a discount is allowed to the consumer.

(iii) KW and KVAR Tariff

- In this type, both active power (KW) and reactive power (KVAR) supplied are charged separately.
- A consumer having low power factor will draw more reactive power and hence shall have to pay more charges.

(7) Three Part Tariff

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

- Total charge = Rs $(a + b \times KW + c \times KWh)$

  Where, a = fixed charge made during each billing period.
  b = charge per KW of maximum demand,
  c = charge per KWh of energy consumed.

- It may be seen that by adding fixed charge to two-part tariff, it becomes three-part tariff. The principal objection of this type of tariff is that the charges are split into three components.

TYPES OF CONSUMERS AND THEIR TARIFFS

- **Residential Consumers**:
  - These are regular households.
  - They typically pay a fixed rate for electricity, water, gas, etc.
  - Their tariffs are usually based on usage tiers: the more they consume, the higher the rate per unit.

- **Commercial Consumers**:
  - These are businesses, shops, restaurants, etc.
  - They may have different tariffs depending on their usage patterns and peak/off-peak hours.
  - Tariffs for commercial consumers often include demand charges based on the maximum power they draw at any given time.

- **Industrial Consumers**:
  - These are large factories, manufacturing plants, etc.
  - Their tariffs can be complex, often involving negotiated rates based on usage volume and demand.
  - Industrial consumers might have incentives or penalties related to power factor correction and energy efficiency.

- **Agricultural Consumers**:
  - These are farms and agricultural operations.
  - Their tariffs may include special rates for irrigation and other farm-related activities.
  - Agricultural consumers might also have seasonal variations in their tariffs.

- **Governmental or Institutional Consumers:**
  - These include government offices, schools, hospitals, etc.
  - Their tariffs might be structured differently based on public service requirements and budget allocations.
  - Sometimes, governmental institutions enjoy special tariffs or subsidies

Power factor

- Power factor is defined as the cosine of the angle between voltage and current.
- The power factor is defined as the ratio of the active power (P) and volt-amperes
- PF = $\cos\phi$ = Active Power (W) / Apparent Power (VA)

Effects of Low Power Factor

Large Copper Losses

- Line current is inversely proportional to the power factor of the circuit.
- Copper losses will be inversely proportional to the square of power factor.
- When the power factor is low, the line current will be high, and copper losses will be higher.
- This results in low efficiency of the power system

Large kVA rating

- Electric machines such as transformers are rated in kVA.

- **kVA = kW/ CosΦ**

- Power factor of the machine is inversely proportional to its kVA rating.

- Larger kVA rating makes the equipment costly and heavier in size.

Poor Voltage Regulation

- Poor power factor results in a larger line current to be drawn by the electrical equipment.
- Large current at a low lagging power factor causes a higher voltage drop in transformers and alternators.
- This results in the decreased voltage available at the supply end of equipment and hence poor voltage regulation.

Causes of Low Power Factor

- **Harmonic Current**

The presence of harmonic current reduces the power factor in the system.

- **Improper Wiring**

Due to improper wiring or electrical accidents, an imbalance in the 3- phase power occurs which causes low power factor.

Variation in the Power System Loading

When the system is loaded lightly, the voltage increases, increasing the magnetization current demand of the machine. This causes a poor power factor in the system.

Inductive Load

- 90% of the industrial loads consist of induction motors. Such machines draw magnetizing current and set up a magnetic field for its proper working and hence work at a low power factor.

- The current drawn by inductive loads is lagging and results in poor power factor.

Methods of Power Factor Improvement

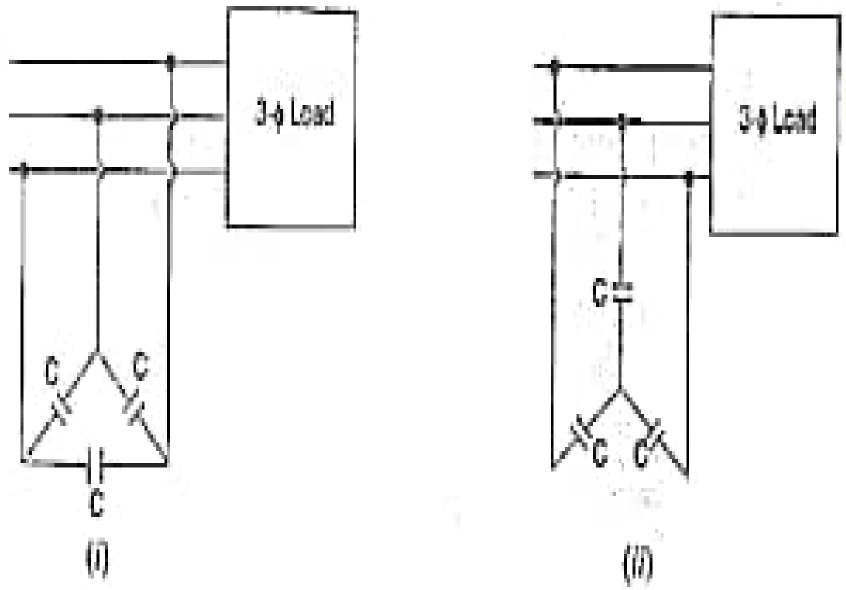
- Normally, the power factor of the whole load on a large generating station is in the region of 0.8 to 0.9.
- However, sometimes it is lower and in such cases it is generally desirable to take special steps to improve the power factor.
- This can be achieved by the following equipment:
  - ✓ Static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

(1) Static Capacitors

- The power factor can be improved by connecting capacitors in parallel with the equipment operating at lagging power factor.

- The capacitor (generally known as static capacitor) draws a leading current and partly or completely neutralizes the lagging reactive component of load current. This raises the power factor of the load.

- Static capacitors are invariably used for power factor improvement in factories.



For three-phase loads, the capacitors can be connected in delta or star as shown in Fig. (i) and (ii)

(1) Static Capacitors

Advantages

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

Disadvantages

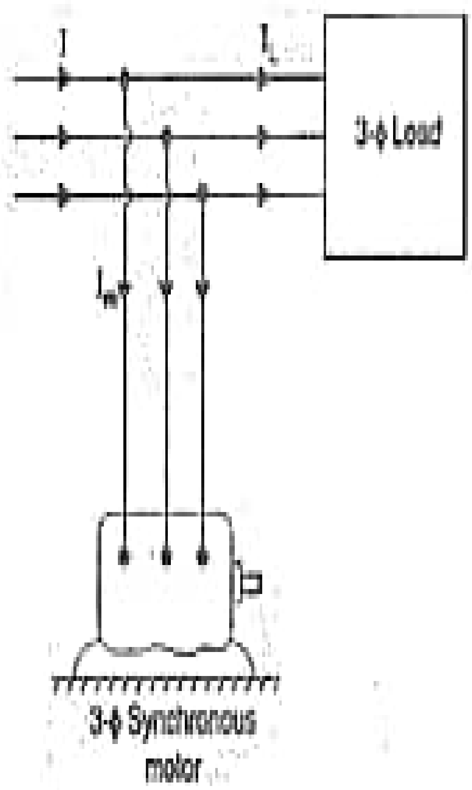
- They have short service life ranging from 8 to 10 years.
- They are easily damaged if the voltage exceeds the rated value.
- Once the capacitors are damaged, their repair is uneconomical.

(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 neutralizes the lagging reactive component of the load. Thus the power factor is improved.



(2) Synchronous Condenser

- The 3Φ load takes current I_L at low lagging power factor $Cos\Phi_L$.
- The synchronous condenser takes a current Im 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 CosΦ is greater than $Cos\Phi_L$.
- Thus the power factor is increased from $Cos\Phi_L$ to CosΦ Synchronous condensers are generally used at major bulk supply substations for power factor improvement.

Advantages

- 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.
- The motor windings have high thermal stability to short circuit currents.
- The faults can be removed easily.

Disadvantages

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

(3) Phase Advancers

- Phase advancers are used to power factor correction of induction motor.

- 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.

(3) Phase Advancers

- 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.

Advantages of Improved Power Factor

- Increase in efficiency of system and devices
- Low Voltage Drop
- Reduction in size of a conductor and cable
- An Increase in available power
- Line Losses (Copper Losses) I^2R is reduced.
- Low KWh (Kilo Watt per hour)
- Saving in the power bill.
- Appropriate Size of Electrical Machines (Transformer, Generators etc.)
- Eliminate the penalty of low power factor from the Electric Supply Company
- Better usage of power system, lines and generators etc.
- Saving in energy as well as rating and the cost of the electrical devices and equipment is reduced.

Economics of Power Factor improvement and Comparison of Methods of improving Power Factor

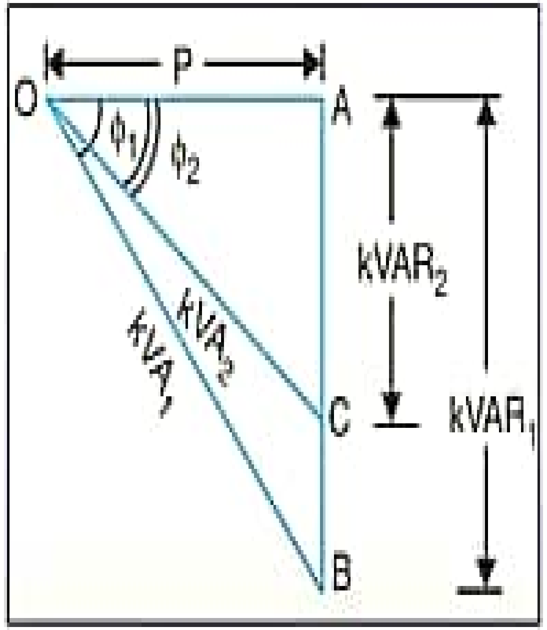
- If a consumer improves the power factor, there is reduction in his maximum kVA demand and hence there will be annual saving over the maximum demand charges. However, when power factor is improved, it involves capital investment on the power factor correction equipment.

- 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.

Most Economical Power Factor

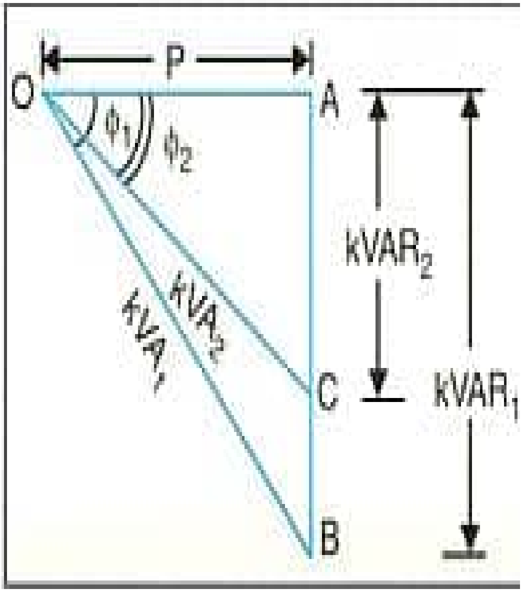
- Consider a consumer taking a peak load of P KW at a power factor of $Cos\Phi_1$ and charged at a rate of Rs *x* per KVA of maximum demand per annum.
- Suppose the consumer improves the power factor to $Cos\Phi_2$ by installing p.f. correction equipment.
- Let expenditure incurred on the p.f. correction equipment be Rs *y* per KVAR per annum.
- The power triangle at the original p.f. $Cos\Phi_1$ is OAB and for the improved p.f. $Cos\Phi_2$, it is OAC.



Most Economical Power Factor

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

$= Rs\ x\ (KVA_1 - KVA_2)$

$= Rs\ x\ (P\sec\Phi_1 - P\sec\Phi_2)$

$= Rs\ x\ P\ (\sec\Phi_1 - \sec\Phi_2)$ ....(i)

Reactive power at Cos Φ_1, $KVAR_1 = P\tan\Phi_1$

Reactive power at Cos Φ_2, $KVAR_2 = P\tan\Phi_2$

Most Economical Power Factor (contd.)

Leading KVAR taken by p.f. correction equipment

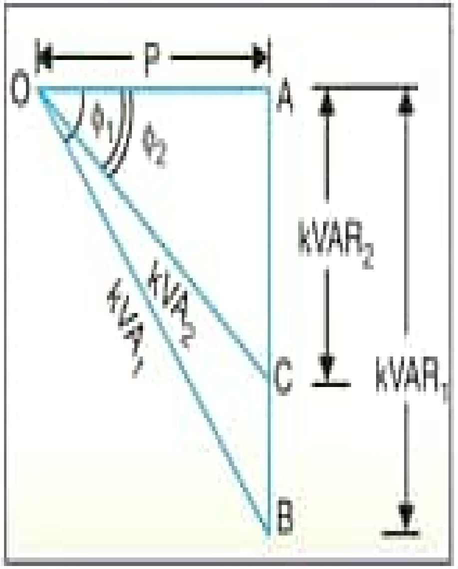
$$= P(\tan \Phi_1 - \tan \Phi_2)$$

Annual cost of p.f. correction equipment

$$= \text{Rs } P\,y\,(\tan \Phi_1 - \tan \Phi_2) \qquad \text{... (ii)}$$

Net annual saving, S = exp. (i) − exp. (ii)

$$= x\,P\,(\sec \Phi_1 - \sec \Phi_2) - y\,P\,(\tan \Phi_1 - \tan \Phi_2)$$



In this expression, only Φ_2 is variable while all other quantities are fixed.

Most Economical Power Factor

Therefore, the net annual saving will be maximum if differentiation of above expression w.r.t. Φ_2 is zero, i.e.

$$\frac{d(S)}{d\Phi_2} = 0$$

$$\frac{d}{d\Phi_2}[x\,P\,(Sec\,\Phi_1 - Sec\,\Phi_2) - y\,P\,(tan\,\Phi_1 - tan\,\Phi_2)] = 0$$

$$\frac{d}{d\Phi_2}[x\,P\,Sec\,\Phi_1] - \frac{d}{d\Phi_2}[x\,P\,Sec\,\Phi_2] - \frac{d}{d\Phi_2}[y\,P\,tan\,\Phi_1] - \frac{d}{d\Phi_2}[y\,P\,tan\,\Phi_2] = 0$$

$$0 - [x\,P\,Sec\,\Phi_2\,tan\,\Phi_2] - 0 + [y\,P\,Sec^2\Phi_2] = 0$$

$$-x\,tan\,\Phi_2 + y\,Sec\,\Phi_2 = 0$$

$$tan\,\Phi_2 = \frac{y}{x}Sec\,\Phi_2$$

$$Sin\,\Phi_2 = \frac{y}{x}$$

Most Economical Power Factor

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. $Cos\ \Phi_1$.

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.

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.

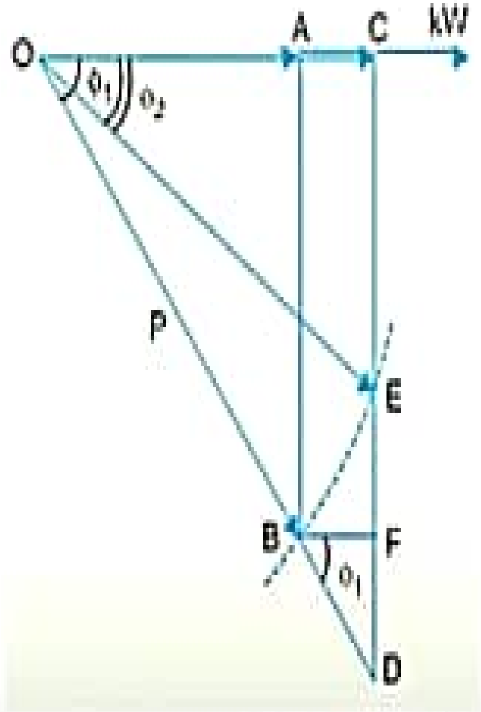
Economical Comparison of Two Methods

- 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 Φ_1.

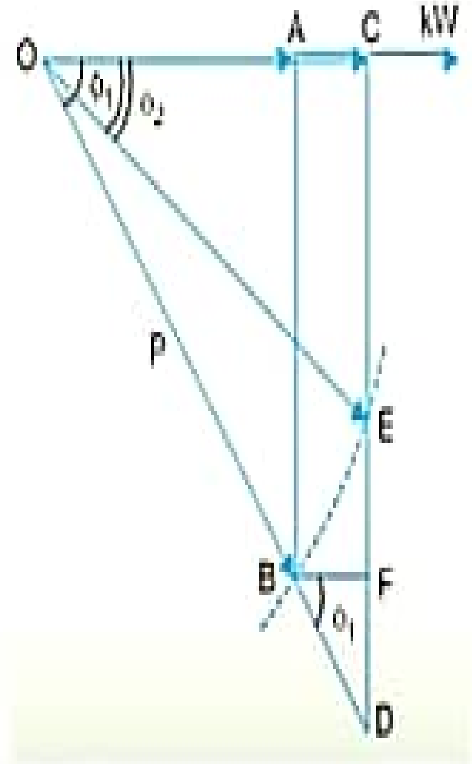
- Let us suppose that the new power demand can be met either by increasing the p.f. to CosΦ_2 at P KVA or by increasing the KVA rating of the station at the original p.f. Cos Φ_1.

- The power triangles for the whole situation are shown in Fig.



(i) Cost of increasing KVA capacity of station

Referring to Fig., the increase in KVA capacity of the station at $Cos\Phi_1$ to meet the new demand is given by:



Increase in KVA capacity

$$= BD = \frac{BF}{Cos\Phi_1} = \frac{AC}{Cos\Phi_1} \qquad (\because BF = AC)$$

$$= \frac{OC - OA}{Cos\Phi_1} = \frac{OECos\Phi_2 - OBCos\Phi_1}{Cos\Phi_1}$$

$$= \frac{P(Cos\Phi_2 - Cos\Phi_1)}{Cos\Phi_1} \qquad (\because OE = OB = P)$$

(i) Cost of increasing KVA capacity of station

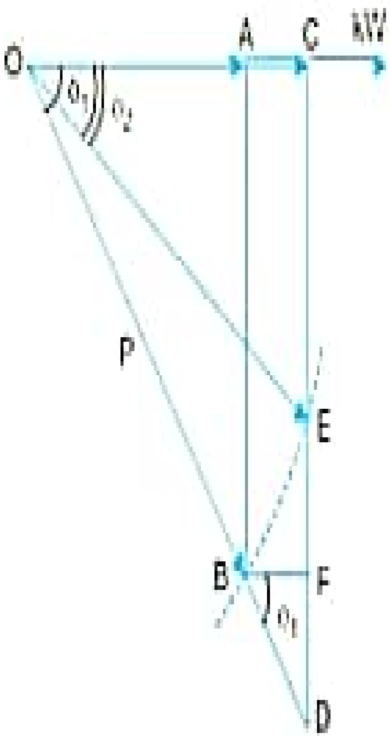
If Rs. x is the annual cost per KVA of the station, then

Annual cost due to increase in KVA capacity

$$= Rs\frac{xP(Cos\Phi_2 - Cos\Phi_1)}{Cos\Phi_1} \text{ ------- }(i)$$

(ii) Cost of p.f. correction equipment

Referring to Fig., 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 = $ED = CD - CE$

$$= ODSin\Phi_1 - OESin\Phi_2 = \frac{OC}{Cos\Phi_1}Sin\Phi_1 - OESin\Phi_2$$

$$= \frac{OECos\Phi_2}{Cos\Phi_1}Sin\Phi_1 - OESin\Phi_2$$

$$= OE(tan\Phi_1\, Cos\Phi_2 - Sin\Phi_2) = P(tan\Phi_1\, Cos\Phi_2 - Sin\Phi_2)$$

(ii) Cost of p.f. correction equipment

If Rs. *y* is the annual cost per KVAR of the p.f. correction equipment, then

Annual cost on p.f. correction equipment

$$= Rs\ y\ P(tan\Phi_1\ Cos\Phi_2 - Sin\Phi_2) ------- (ii)$$

Note the construction: Here ΔOAB 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, ΔOCD 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, ΔOCE is the power triangle when the station is supplying OC KW at improved p.f. $Cos\Phi_2$.

Different Cases

(a) The p.f. correction equipment will be cheaper if exp. (*ii*) < exp. (*i*)

or $$yP(\tan\Phi_1 \, Cos\Phi_2 - Sin\Phi_2) < \frac{xP(Cos\Phi_2 - Cos\Phi_1)}{Cos\Phi_1}$$

or $$y(\tan\Phi_1 \, Cos\Phi_2 - Sin\Phi_2) < \frac{x(Cos\Phi_2 - Cos\Phi_1)}{Cos\Phi_1}$$

Different Cases (contd.)

(b) The maximum annual cost per KVAR (i.e., y) of p.f. correction equipment that would justify its installation is when exp. (*i*) = 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 $$y\left(\frac{Sin\Phi_1 Cos\Phi_2 - Cos\Phi_1 Sin\Phi_2}{Cos\Phi_1}\right) = \frac{x(Cos\Phi_2 - Cos\Phi_1)}{Cos\Phi_1}$$

or $$y\,Sin\,(\Phi_1 - \Phi_2) = x(Cos\Phi_2 - Cos\Phi_1)$$

$$\therefore \quad y = \frac{x(Cos\Phi_2 - Cos\Phi_1)}{Sin\,(\Phi_1 - \Phi_2)}$$

Choice of Equipment

- At the time of purchasing equipment usually several alternatives are made available, each possessing one or more special features. The choice between alternative types of electrical equipment usually depends upon the relative costs of the alternative equipment.

- In selecting equipment for a particular service, the choice must fall upon that which makes the sum of the fixed charges (annual interest and depreciation on the capital cost of the equipment) and the operating charges minimum.

- It is usually found that a saving can be affected only by incurring increased fixed costs and vice-versa, for instance, an electric motor of a particular type and size of lower operating efficiency will usually cost less than a similar motor of higher efficiency, although the latter will have a lower operating cost on account of its lower loss and may, therefore, have a lower operating cost.