Chapter 3

Power Plant Economics and Variable Load Problem

3.1 TERMS AND FACTORS

The main terms and factors are as follows:

1. Load Factor

It is defined as the ratio of the average load to the peak load during a certain prescribed period of time. The load factor of a power plant should be high so that the total capacity of the plant is utilized for the maximum period that will result in lower cost of the electricity being generated. It is always less than unity.

High load factor is a desirable quality. Higher load factor means greater average load, resulting in greater number of power units generated for a given maximum demand. Thus, the fixed cost, which is proportional to the maximum demand, can be distributed over a greater number of units (kWh) supplied. This will lower the overall cost of the supply of electric energy.

2. Utility Factor

It is the ratio of the units of electricity generated per year to the capacity of the plant installed in the station. It can also be defined as the ratio of maximum demand of a plant to the rated capacity of the plant. Supposing the rated capacity of a plant is 200 mW. The maximum load on the plant is 100 mW at load factor of 80 per cent, then the utility will be

$$= (100 \times 0.8)/(200) = 40\%$$

3. Plant Operating Factor

It is the ratio of the duration during which the plant is in actual service, to the total duration of the period of time considered.

4. Plant Capacity Factor

It is the ratio of the average loads on a machine or equipment to the rating of the machine or equipment, for a certain period of time considered.

Since the load and diversity factors are not involved with 'reserve capacity' of the power plant, a factor is needed which will measure the reserve, likewise the degree of utilization of the installed equipment. For this, the factor "Plant factor, Capacity factor or Plant Capacity factor" is defined as,

Plant Capacity Factor = (Actual kWh Produced)/(Maximum Possible Energy that might have produced during the same period)

Thus the annual plant capacity factor will be,

= (Annual kWh produced)/[Plant capacity (kW) × hours of the year]

The difference between load and capacity factors is an indication of reserve capacity.

5. Demand Factor

The actual maximum demand of a consumer is always less than his connected load since all the appliances in his residence will not be in operation at the same time or to their fullest extent. This ratio of' the maximum demand of a system to its connected load is termed as demand factor. It is always less than unity.

6. Diversity Factor

Supposing there is a group of consumers. It is known from experience that the maximum demands of the individual consumers will not occur at one time. The ratio of the sum of the individual maximum demands to the maximum demand of the total group is known as diversity factor. It is always greater than unity.

High diversity factor (which is always greater than unity) is also a desirable quality. With a given number of consumers, higher the value of diversity factor, lower will be the maximum demand on the plant, since,

Diversity factor = Sum of the individual maximum Demands/Maximum demand of the total group

So, the capacity of the plant will be smaller, resulting in fixed charges.

7. Load Curve

It is a curve showing the variation of power with time. It shows the value of a specific load for each unit of the period covered. The unit of time considered may be hour, days, weeks, months or years.

8. Load Duration Curve

It is the curve for a plant showing the total time within a specified period, during which the load equaled or exceeded the values shown.

9. Dump Power

This term is used in hydro plants and it shows the power in excess of the load requirements and it is made available by surplus water.

10. Firm Power

It is the power, which should always be available even under emergency conditions.

11. Prime Power

It is power, may be mechanical, hydraulic or thermal that is always available for conversion into electric power.

12. Cold Reserve

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

13. Hot Reserve

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

14. Spinning Reserve

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

15. Plant Use Factor

This is a modification of Plant Capacity factor in that only the actual number of hours that the plant was in operation is used. Thus Annual Plant Use factor is,

= (Annual kWh produced) / [Plant capacity (kW) × number of hours of plant operation]

3.2 FACTOR EFFECTING POWER PLANT DESIGN

Following are the factor effecting while designing a power plant.

(1) Location of power plant

(2) Availability of water in power plant

(3) Availability of labour nearer to power plant

(4) Land cost of power plant

(5) Low operating cost

(6) Low maintenance cost

(7) Low cost of energy generation

(8) Low capital cost

3.3 EFFECT OF POWER PLANT TYPE ON COSTS

The cost of a power plant depends upon, when a new power plant is to set up or an existing plant is to be replaced or plant to be extended. The cost analysis includes

1. Fixed Cost

It includes Initial cost of the plant, Rate of interest, Depreciation cost, Taxes, and Insurance.

2. Operational Cost

It includes Fuel cost, Operating labour cost, Maintenance cost, Supplies, Supervision, Operating taxes.

3.3.1 INITIAL COST

The initial cost of a power station includes the following:

1. Land cost

2. Building cost

3. Equipment cost

4. Installation cost

5. Overhead charges, which will include the transportation cost, stores and storekeeping charges, interest during construction etc.

To reduce the cost of building, it is desirable to eliminate the superstructure over the boiler house and as far as possible on turbine house also.

Adopting unit system where one boiler is used for one turbogenerator can reduce the cost on equipment. Also by simplifying the piping system and elimination of duplicate system such as steam headers and boiler feed headers. Eliminating duplicate or stand-by auxiliaries can further reduce the cost.

When the power plant is not situated in the proximity to the load served, the cost of a primary distribution system will be a part of the initial investment.

3.3.2 RATE OF INTEREST

All enterprises need investment of money and this money may be obtained as loan, through bonds and shares or from owners of personal funds. Interest is the difference between money borrowed and money returned. It may be charged at a simple rate expressed as % per annum or may be compounded, in which case the interest is reinvested and adds to the principal, thereby earning more interest in subsequent years. Even if the owner invests his own capital the charge of interest is necessary to cover the income that he would have derived from it through an alternative investment or fixed deposit with a bank. Amortization in the periodic repayment of the principal as a uniform annual expense.

3.3.3 DEPRECIATION

Depreciation accounts for the deterioration of the equipment and decrease in its value due to corrosion, weathering and wear and tear with use. It also covers the decrease in value of equipment due to obsolescence. With rapid improvements in design and construction of plants, obsolescence factor is of enormous importance. Availability of better models with lesser overall cost of generation makes it imperative to replace the old equipment earlier than its useful life is spent. The actual life span of the plant has, therefore, to be taken as shorter than what would be normally expected out of it.

The following methods are used to calculate the depreciation cost:

(1) Straight line method

(2) Percentage method

(3) Sinking fund method

(4) Unit method.

Straight Line Method. It is the simplest and commonly used method. The life of the equipment or the enterprise is first assessed as also the residual or salvage value of the same after the estimated life span. This salvage value is deducted from the initial capital cost and the balance is divided by the life as assessed in years. Thus, the annual value of decrease in cost of equipment is found and is set aside as depreciation annually from the income. Thus, the rate of depreciation is uniform throughout the life of the equipment. By the time the equipment has lived out its useful life, an amount equivalent to its net cost is accumulated which can be utilized for replacement of the plant.

Percentage Method. In this method the deterioration in value of equipment from year to year is taken into account and the amount of depreciation calculated upon actual residual value for each year. It thus, reduces for successive years.

Sinking Fund Method. This method is based on the conception that the annual uniform deduction from income for depreciation will accumulate to the capital value of the plant at the end of life of the plant or equipment. In this method, the amount set aside per year consists of annual installments and the interest earned on all the installments.

Let,

A = Amount set aside at the end of each year for n years.

n = Life of plant in years.

S = Salvage value at the end of plant life.

i = Annual rate of compound interest on the invested capital.

P = Initial investment to install the plant.

Then, amount set aside at the end of first year = A

Amount at the end of second year

$= A + \text{interest on } A = A + Ai = A(1 + i)$

Amount at the end of third year

$= A(1 + i) + \text{interest on } A(1 + i)$

$= A(1 + i) + A(1 + i)i$

$= A(1 + i)^2$

Amount at the end of nth year = $A(1 + i)^n - 1$

Total amount accumulated in n years (say x)

= sum of the amounts accumulated in n years

i.e., $x = A + A(1 + i) + A(1 + i)^2 + ... + A(1 + i)^{n-1}$

$= A[1 + (1 + i) + (1 + i)^2 + ... + (1 + i)^{n-1}]$ ...(1)

Multiplying the above equation by $(1 + i)$, we get

$x(1 + i) = A[(1 + i) + (1 + i)^2 + (1 + i)^3 + ... + (1 + i)^n]$ ...(2)

Subtracting equation (1) from (2), we get

$x.i = [(1 + i)^n - 1] A$

$x = [\{(1 + i)^n - 1\}/i]A$, where $x = (P - S)$

$P - S = [\{(1 + i)^n - 1\}/i]A$

$A = (P - S)[i/\{(1 + i)^n - 1\}]A$

Unit Method. In this method some factor is taken as a standard one and, depreciation is measured by that standard. In place of years equipment will last, the number of hours that equipment will last is calculated. This total number of hours is then divided by the capital value of the equipment. This constant is then multiplied by the number of actual working hours each year to get the value of depreciation for that year. In place of number of hours, the number of units of production is taken as the measuring standard.

3.3.4 OPERATIONAL COSTS

The elements that make up the operating expenditure of a power plant include the following

(1) Cost of fuels.

(2) Labour cost.

(3) Cost of maintenance and repairs.

(4) Cost of stores (other than fuel).

(5) Supervision.

(6) Taxes.

3.3.5 COST OF FUELS

In a thermal station fuel is the heaviest item of operating cost. The selection of the fuel and the maximum economy in its use are, therefore, very important considerations in thermal plant design. It is desirable to achieve the highest thermal efficiency for the plant so that fuel charges are reduced. The cost of fuel includes not only its price at the site of purchase but its transportation and handling costs also. In the hydro plants the absence of fuel factor in cost is responsible for lowering the operating cost. Plant heat rate can be improved by the use of better quality of fuel or by employing better thermodynamic conditions in the plant design.

The cost of fuel varies with the following:

(1) Unit price of the fuel.

(2) Amount of energy produced.

(3) Efficiency of the plant.

3.3.6 LABOUR COST

For plant operation labour cost is another item of operating cost. Maximum labour is needed in a thermal power plant using. Coal as a fuel. A hydraulic power plant or a diesel power plant of equal capacity requires a lesser number of persons. In case of automatic power station the cost of labour is reduced to a great extent. However labour cost cannot be completely eliminated even with fully automatic station, as they will still require some manpower for periodic inspection etc.

3.3.7 COST OF MAINTENANCE AND REPAIRS

In order to avoid plant breakdowns maintenance is necessary. Maintenance includes periodic cleaning, greasing, adjustments and overhauling of equipment. The material used for maintenance is also charged under this head. Sometimes an arbitrary percentage is assumed as maintenance cost. A good plan of maintenance would keep the sets in dependable condition and avoid the necessity of too many stand-by plants.

Repairs are necessitated when the plant breaks down or stops due to faults developing in the mechanism. The repairs may be minor, major or periodic overhauls and are charged to the depreciation fund of the equipment. This item of cost is higher for thermal plants than for hydro-plants due to complex nature of principal equipment and auxiliaries in the former.

3.3.8 COST OF STORES

The items of consumable stores other than fuel include such articles as lubricating oil and greases, cotton waste, small tools, chemicals, paints and such other things. The incidence of this cost is also higher in thermal stations than in hydro-electric power stations.

3.3.9 SUPERVISION

In this head the salary of supervising staff is included. A good supervision is reflected in lesser breakdowns and extended plant life. The supervising staff includes the station superintendent, chief engineer, chemist, engineers, supervisors, stores incharges, purchase officer and other establishment. Again, thermal stations, particularly coal fed, have a greater incidence of this cost than the hydro-electric power stations.

3.3.10 TAXES

The taxes under operating head includes the following:

(*i*) Income tax

(*ii*) Sales tax

(*iii*) Social security and employee's security etc.

3.4 EFFECT OF PLANT TYPE ON RATES (TARIFFS OR ENERGY ELEMENT)

Rates are the different methods of charging the consumers for the consumption of electricity. It is desirable to charge the consumer according to his 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.

3.4.1 REQUIREMENTS OF A TARIFF

Tariff should satisfy the following requirements:

(1) It should be easier to understand.

(2) It should provide low rates for high consumption.

(3) It should encourage the consumers having high load factors.

(4) It should take into account maximum demand charges and energy charges.

(5) It should provide less charges for power connections than for lighting.

(6) It should avoid the complication of separate wiring and metering connections.

3.4.2 TYPES OF TARIFFS

The various types of tariffs are as follows,

(1) Flat demand rate

(2) Straight line meter rate

(3) Step meter rate

(4) Block rate tariff

(5) Two part tariff

(6) Three part tariff.

The various types of tariffs can be derived from the following general equation:

$$Y = DX + EZ + C$$

where

Y = Total amount of bill for the period considered.

D = Rate per kW of maximum demand.

X = Maximum demand in kW.

E = Energy rate per kW.

Z = Energy consumed in kWh during the given period.

C = Constant amount to be charged from the consumer during each billing period.

Various type of tariffs are as follows:

(1) Flat Demand Rate. It is based on the number of lamps installed and a fixed number of hours of use per month or per year. The rate is expressed as a certain price per lamp or per unit of demand (kW) of the consumer. This energy rate eliminates the use of metering equipment. It is expressed by the expression.

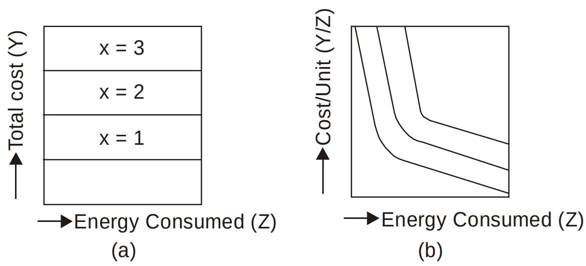


Fig. 3.1

(2) Straight Line Meter Rate. According to this energy rate the amount to be charged from the consumer depends upon the energy consumed in kWh which is recorded by a means of a kilowatt hour meter. It is expressed in the form

$$Y = EZ$$

This rate suffers from a drawback that a consumer using no energy will not pay any amount although he has incurred some expense to the power station due to its readiness to serve him. Secondly since the rate per kWh is fixed, this tariff does not encourage the consumer to use more power.

(3) Step Meter Rate. According to this tariff the charge for energy consumption goes down as the energy consumption becomes more. This tariff is expressed as follows.

$$Y = EZ \qquad \text{If } 0 \le Z \le A$$

$$Y = E_1Z_1 \qquad \text{If } A \le Z_1 \le B$$

$$Y = E_2Z_2 \qquad \text{If } B \le Z_2 \le C$$

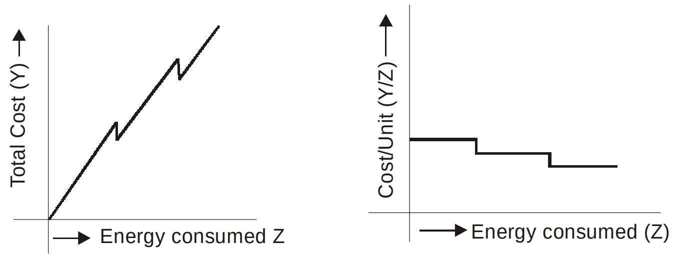
And so on. Where E, E_1, E_2 are the energy rate per kWh and A, B and C, are the limits of energy consumption.

(4) Block Rate Tariff. According to this tariff a certain price per units (kWh) is charged for all or any part of block of each unit and for succeeding blocks of energy the corresponding unit charges decrease.

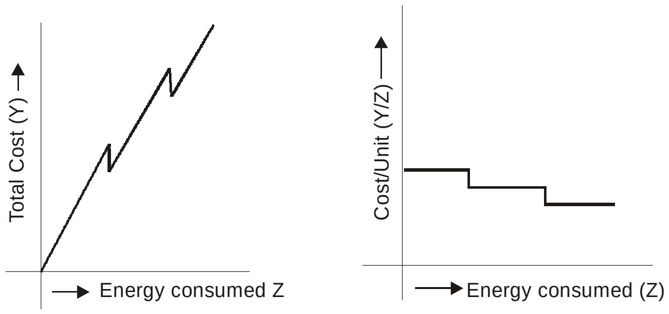
It is expressed by the expression

$$Y = E_1Z_1 + E_2Z_2 + E_3Z_3 + E_4Z_4 + ...$$

where E_1, E_2, E_3.... are unit energy charges for energy blocks of magnitude Z_1, Z_z, Z_g,.... respectively.



Step meter rate



Step meter rate

Fig. 3.2

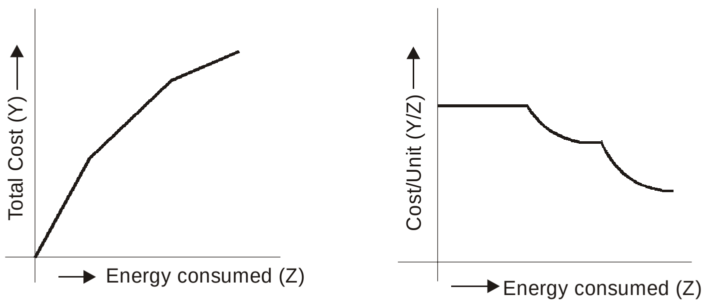


Fig. 3.3

(5) Two Part Tariff (Hopkinson Demand Rate). In this tariff the total charges are based on the maximum demand and energy consumed. It is expressed as

$$Y = D . X + EZ$$

A separate meter is required to record the maximum demand. This tariff is used for industrial loads.

(6) Three-Part Tariff (Doherty Rate). According to this tariff the customer pays some fixed amount in addition to the charges for maximum demand and energy consumed. The fixed amount to be charged depends upon the occasional increase in fuel price, rise in wages of labour etc. It is expressed by the expression

$$Y = DX + EZ + C.$$

3.5 EFFECT OF PLANT TYPE ON FIXED ELEMENTS

Various types of fixed element are :

(1) Land

(2) Building

(3) Equipment

(4) Installation of Machine

(5) Design and planning

The fixed element means which are not movable, and for any types of power plant, the fixed elements play a major role. Since each cost is added to the final cost of our product (electricity in case of Power plant). So when a power plant is established, the first selection is fixed element.

Effect of plant on land is as cost of land.

3.6 EFFECT OF PLANT TYPE ON CUSTOMER ELEMENTS

The costs included in these charges depend upon the number of customers. The various costs to be considered are as follows:

(1) Capital cost of secondary distribution system and depreciation cost, taxes and interest on this capital cost.

(2) Cost of inspection and maintenance of distribution lines and the transformers.

(3) Cost of labour required for meter reading and office work.

(4) Cost of publicity.

3.7 INVESTOR'S PROFIT

If the power plant is the public property, as is the case in India, then the customers will be the 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 investor's profit. The consumers in the form of electric consumption bills will pay these taxes. This amount is collected in twelve installments per year or six installments per year.

The investor expects a satisfactory return on the capital investment. The rate of profit varies according to the business conditions prevailing in different localities.

Adopting the following economical measures can reduce cost of power generation:

(1) By reducing initial investment in the power plant.

(2) By selecting generating units of adequate capacity.

(3) By running the power plant at maximum possible load factor.

(4) By increasing efficiency of fuel burning devices so that cost of fuel used is reduced.

(5) By simplifying the operation of the power plant so that fewer power-operating men are required.

(6) By installing the power plant as near the load centre as possible.

(7) By reducing transmission and distribution losses.

3.8 ECONOMICS IN PLANT SELECTION

A power plant should be reliable. The capacity of a power plant depends upon the power demand. The capacity of a power plant should be more than predicted maximum demand. It is desirable that the number of generating units should be two or more than two. The number of generating units should be so chosen that the plant capacity is used efficiently. Generating cost for large size units running at high load factor is substantially low. However, the unit has to be operated near its point of maximum economy for most of the time through a proper load sharing programme. Too many stand bys increase the capital investment and raise the overall cost of generation.

The thermal efficiency and operating cost of a steam power plant depend upon the steam conditions such as throttle pressure and temperature.

The efficiency of a boiler is maximum at rated capacity. Boiler fitted with heat recovering devices like air preheater, economiser etc. gives efficiency of the order of 90%. But the cost of additional equipment (air preheater economiser) has to be balanced against gain in operating cost.

Power can be produced at low cost from a hydropower plant provided water is available in large quantities. The capital cost per unit installed is higher if the quantity of water available is small. While installing a hydropower plant cost of land, cost of water rights, and civil engineering works cost should be properly considered as they involve large capital expenditure.

The other factor, which influences the choice of hydropower plant, is the cost of power transmission lines and the loss of energy in transmission. The planning, design and construction of a hydro plant is difficult and takes sufficient time.

The nuclear power plant should be installed in an area having limited conventional power resources. Further a nuclear power plant should be located in a remote or unpopulated are to avoid damage due to radioactive leakage during an accident and also the disposal of radioactive waste should be easy and a large quantity of water should be available at the site selected. Nuclear power becomes competitive with conventional coal fired steam power plant above the unit size of 500 mW.

The capital cost of a nuclear power plant is more than a steam power plant of comparable size. Nuclear power plants require less space as compared to any other plant of equivalent size. The cost of maintenance of the plant is high.

The diesel power plant can be easily located at the load centre. The choice of the diesel power plant depends upon thermodynamic considerations. The engine efficiency improves with compression ratio but higher pressure necessitates heavier construction of equipment with increased cost. Diesel power plants are quite suitable for smaller outputs. The gas turbine power plant is also suitable for smaller outputs. The cost of a gas turbine plant is relatively low. The cost of gas turbine increases as the sample plant is modified by the inclusion of equipment like regenerator, reheater, and intercooler although there is an improvement in efficiency of the plant by the above equipment. This plant is quite useful for regions where gaseous fuel is available in large quantities.

In order to meet the variable load the prime movers and generators have to act fairly quickly to take up or shed load without variation of the voltage or frequency of the system. This requires that supply of fuel to the prime mover should be carried out by the action of a governor. Diesel and hydropower plants are quick to respond to load variation as the control supply is only for the prime mover. In a steam power plant control is required for the boilers as well as turbine. Boiler control may be manual or automatic for feeding air, feed water fuel etc. Boiler control takes time to act and therefore, steam powers plants cannot take up the variable load quickly. Further to cope with variable load operation it is necessary for the power station to keep reserve plant ready to maintain reliability and continuity of power supply at all times. To supply variable load combined working of power stations is also economical.

For example to supply a load the base load may be supplied by a steam power plant and peak load may be supplied by a hydropower plant or diesel power plant.

The size and number of generating units should be so chosen that each will operate on about full load or the load at which it gives maximum efficiency. The reserve required would only be one unit of the largest size. In a power station neither there should be only one generating unit nor should there be a large number of small sets of different sizes. In steam power plant generating sets of 80 to 500 mW are quite commonly used whereas the maximum size of diesel power plant generating sets is about 4000 kW. Hydro-electric generating sets up to a capacity of 200 mW are in use in U.S.A.

3.9 ECONOMIC OF POWER GENERATION

Economy is the main principle of design of a power plant. Power plant economics is important in controlling the total power costs to the consumer. Power should be supplied to the consumer at the lowest possible cost per kWh. The total cost of power generation is made up of fixed cost and operating cost. Fixed cost consists of interest on capital, taxes, insurance and management cost. Operating cost consists of cost of fuel labour, repairs, stores and supervision. The cost of power generation can be reduced by,

(*i*) Selecting equipment of longer life and proper capacities.

(*ii*) Running the power station at high load factor.

(*iii*) Increasing the efficiency of the power plant.

(*iv*) Carrying out proper maintenance of power plant equipment to avoid plant breakdowns.

(*v*) Keeping proper supervision as a good supervision is reflected in lesser breakdowns and extended plant life.

(*vi*) Using a plant of simple design that does not need highly skilled personnel.

Power plant selection depends upon the fixed cost and operating cost. The fuel costs are relatively low and fixed cost and operation and maintenance charges are quite high in a case of a nuclear power plant. The fuel cost in quite high in a diesel power plant and for hydro power plant the fixed charges are high of the order of 70 to 80% of the cost of generation. Fuel is the heaviest items of operating cost in a steam power station. A typical proportion of generating cost for a steam power station is as follows :

Fuel cost	= 30 to 40%
Fixed charges for the plant	= 50 to 60%
Operation and maintenance cost	= 5 to 10%

The power generating units should be run at about full load or the load at which they can give maximum efficiency. The way of deciding the size and number of generating units in the power station is to choose the number of sets to fit the load curve as closely at possible. It is necessary for a power station to maintain reliability and continuity of power supply at all times. In an electric power plant the capital cost of the generating equipment's increases with an increase in efficiency. The benefit of such increase in the capital investment will be realised in lower fuel costs as the consumption of fuel decreases with an increase in cycle efficiency.

Fig. 3.4 shows the variation of fixed cost and operation cost with investment.

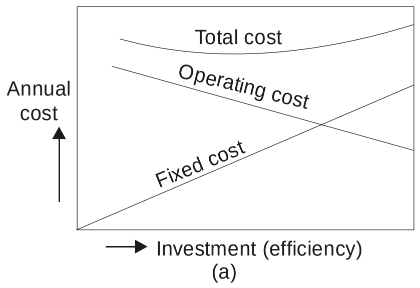


Fig. 3.4

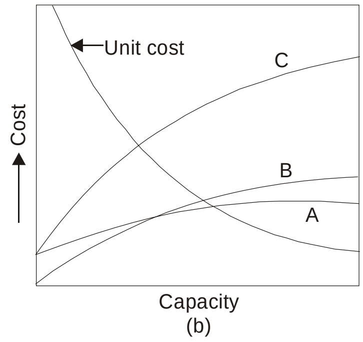


Fig. 3.5

Fig. 3.5 shows the variation of various costs of power plant versus its capacity.

3.10 INDUSTRIAL PRODUCTION AND POWER GENERATION COMPARED

Industrial production is directly related to the power generation. Since in India, the major problem is of electricity. It is not possible to give 24 hr electricity to the industries. And each industrial production is based on power generation, each machine is runs by electricity, so if there is a problem of electricity in any industry, then it is directly suffer the total production.

So for run a plant for 24 hr, there is necessary to a power generation unit. And the power generation unit is of any type (*i.e.*, diesel, steam, gas turbine, etc.), which we learn in next chapters.

3.11 LOAD CURVES

The load demand on a power system is governed by the consumers and for a system supplying industrial and domestic consumers, it varies within wide limits. This variation of load can be considered as daily, weekly, monthly or yearly. Typical load curves for a large power system are shown in Fig. 3.6. These curves are for a day and for a year and these show the load demanded by the consumers at any particular time. Such load curves are termed as "Chronological load Curves". If the ordinates of the chronological load curves are arranged in the descending order of magnitude with the highest ordinates on left, a new type of load curve known as "load duration curve" is obtained. Fig. 3.6 shows such a curve. If any point is taken on this curve then the abscissa of this point will show the number of hours per year during which the load exceeds the value denoted by its ordinate. Another type of curve is known as "energy load curve" or the "integrated duration curve". This curve is plotted between the load in kW or MW and the total energy generated in kWh. If any point is taken on this curve, abscissa of this point show the total energy in kWh generated at or below the load given by the ordinate of this point. Such a curve is shown in Fig. 3.6. In Fig. 3.6(*b*), the lower part of the curve consisting of the loads which are to be supplied for almost the whole number of hours in a year, represents the "Base Load", while the upper part, comprising loads which are required for relatively few hours per year, represents the "Peak Load".

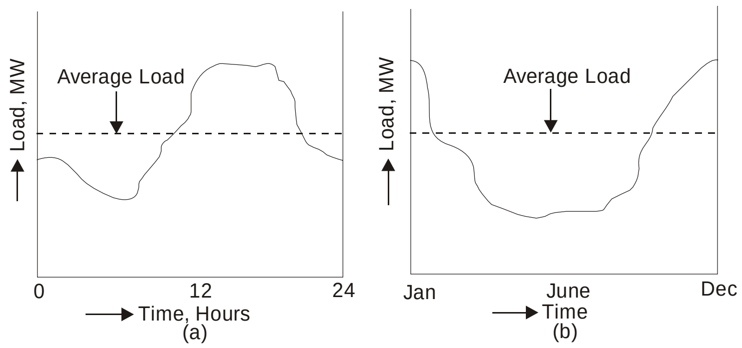


Fig. 3.6. Chronological Load Curves (*a*) Daily Load Curve (*b*) Yearly Load Curve.

3.12 IDEAL AND REALIZED LOAD CURVES

From the standpoint of equipment needed and operating routine, the ideal load on a power plant would be one of constant magnitude and steady duration. However, the shape of the actual load curve (more frequently realized) departs far from this ideal, Fig. 3.7. The cost to produce one unit of electric power in the former case would be from 1/2 to 3/4 of that for the latter case, when the load does not remain constant or steady but varies with time. This is because of the lower first cost of the equipment due to simplified control and the elimination of various auxiliaries and regulating devices.

Also, the ideal load curve will result in the -improved operating conditions with the various plant machines (for example turbine and generators etc.) operating at their best efficiency. The reason behind the shape of the actual realized load curve is that the various users of electric power (industrial, domestic etc.) impose highly variable demands upon the capacity of the plant.

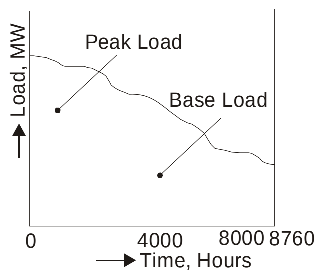


Fig. 3.7. Load Duration Curve.

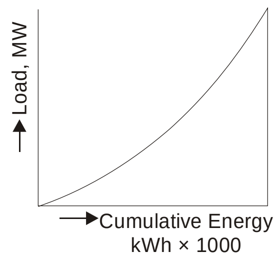


Fig. 3.8. Energy Load Curve.

3.14 EFFECT OF VARIABLE LOAD ON POWER PLANT DESIGN

The characteristics and method of use of power plant equipment is largely influenced by the extent of variable load on the plant. Supposing the load on the plant increases. This will reduce the rotational speed of the turbo-generator. The governor will come into action operating a steam valve and admitting more steam and increasing the turbine speed to its normal value. This increased amount of steam will have to be supplied by the seam generation. The governor response from load to turbine is quite prompt, but after this point, the governing response will be quite slower. The reason is explained as given below:

In most automatic combustion control systems, steam pressure variation is the primary signal used. The steam generator must operate with unbalance between heat transfer and steam demand long enough to suffer a slight but definite decrease in steam pressure. The automatic combustion controller must then increase fuel, air and water flow in the proper amount. This will affect the operation of practically every component of auxiliary equipment in the plant. Thus, there is a certain time lag element present in combustion control. Due to this, the combustion control components should be of most efficient design so that they are quick to cope with the variable load demand.

Variable load results in fluctuating steam demand. Due to this it become, very difficult to secure good combustion since efficient combustion requires the co-ordination of so many various services. Efficient combustion is readily attained under steady steaming conditions. In diesel and hydro power plants, the total governing response is prompt since control is needed only for the prime mover.

The variable load requirements also modify the operating characteristics built into equipment. Due to non-steady load on the plant, the equipment cannot operate at the designed load points. Hence for the equipment, a flat-topped load efficiency curve is more desirable than a peaked one.

Regarding the plant units, if their number and sizes have been selected to fit a known or a correctly predicted load curve, then, it may be possible to operate them at or near the point of maximum efficiency. However, to follow the variable load curve very closely, the total plant capacity has usually to be sub-divided into several power units of different sizes. Sometimes, the total plant capacity would more nearly coincide with the variable load curve, if more units of smaller unit size are employed than a few units of bigger unit size. Also, it will be possible to load the smaller units somewhere near their most efficient operating points. However, it must be kept in mind that as the unit size decreases, the initial cost per kW of capacity increases.

Again, duplicate units may not fit the load curve as closely as units of unequal capacities. However, if identical units are installed, there is a saving in the first cost because of the duplication of sizes, dimensions of pipes, foundations, wires insulations etc. and also because spare parts required are less.

3.14 EFFECT OF VARIABLE LOAD ON POWER PLANT OPERATION

In addition to the effect of variable load on power plant design, the variable load conditions impose operation problems also, when the power plant is commissioned. Even though the availability for service of the modern central power plants is very high, usually more than 95%, the public utility plants commonly remain on the “readiness-to-service” bases. Due to this, they must keep certain of their reserve capacity in “readiness-to-service”. This capacity is called “spinning reserve” and represents the equipment standby at normal operating conditions of pressure, speed etc. Normally, the spinning reserve should be at least equal to the least unit actively carrying load. This will increase the cost of electric generation per unit (kWh).

In a steam power plant, the variable load on electric generation ultimately gets reflected on the variable steam demand on the steam generator and on various other equipments. The operation characteristics of such equipments are not linear with load, so, their operation becomes quite complicated. As the load on electrical supply systems grow, a number of power plants are interconnected to meet the load. The load is divided among various power plants to achieve the utmost economy in the whole system. When the system consists of one base load plant and one or more peak load plants, the load in excess of base load plant capacity is dispatched to the best peak system, all of which are nearly equally efficient, the best load distribution needs thorough study and full knowledge of the system.

SOLVED EXAMPLES

Example 1. *Determine the thermal efficiency of a steam power plant and its coal bill per annum using the following data.*

Maximum demand = 24000 kW

Load factor = 40%

Boiler efficiency = 90%

Turbine efficiency = 92%

Coal consumption = 0.87 kg/Unit

Price of coal = Rs. 280 per tonne

Solution.

η = Thermal efficiency

= Boiler efficiency × Turbing efficiency

= 0.9 × 0.92 = 0.83

Load factor = Average Load/Maximum Demand

Average Load = 0.4 × 24000 = 9600 kW

E = Energy generated in a year = 9600 × 8760 = 841 × 10^5 kWh

Cost of coal per year = (E × 0.87 × 280)/1000

= (841 × 10^5 × 0.87 × 280)/1000

= Rs. 205 × 10^5. Ans.

Example 2. *The maximum (peak) load on a thermal power plant of 60 mW capacity is 50 mW at an annual load factor of 50%. The loads having maximum demands of 25 mW, 20 mW, 8 mW and, 5 mW are connected to the power station.*

Determine: (a) Average load on power station (b) Energy generated per year (c) Demand factor (d) Diversity factor.

Solution.

(*a*) Load factor = Average load/Maximum demand

Average load = 0.5 × 50 = 25 mW

(*b*) E = Energy generated per year

= Average load × 8760

= 219 × 10^6 kWh.

(*c*) Demand factor = Maximum demand/Connected load

= 50/(25 + 20 + 8 + 5) = 0.86

(*d*) Diversity factor = $\frac{M_1}{M_2}$

where M_1 = Sum of individual maximum demands = 25 + 20 + 8 + 5 = 58 mW

M_2 = Simultaneous maximum demand = 50 mW

Diversity factor = $\frac{58}{50}$ = **1.16. Ans.**

Example 3. *In a steam power plant the capital cost of power generation equipment is Rs. 25 × 10^5. The useful life of the plant is 30 years and salvage value of the plant to Rs. 1 × 10^5. Determine by sinking fund method the amount to be saved annually for replacement if the rate of annual compound interest is 6%.*

Solution. P = Capital cost = Rs. 20 × 10^5

S = Salvage value = Rs. 1 × 10^5

n = Useful life = 30 years

r = Compound interest

A = Amount to be saved per year for replacement

$$A = \frac{[(P - S)r]}{\{(1 + r)^n - 1} = \frac{[(20 \times 10^5 - 1 \times 10^5)0.06]}{\{(1 + 0.06)^{30} - 1\}}$$

= **Rs. 24,000. Ans.**

Example 4. *A hydro power plant is to be used as peak load plant at an annual load factor of 30%. The electrical energy obtained during the year is 750 × 10^5 kWh. Determine the maximum demand. If the plant capacity factor is 24% find reserve capacity of the plant.*

Solution.

E = Energy generated = 750 × 105 kWh

Average load = $\frac{(750 \times 10^5)}{8760}$ = 8560 kW

where 8760 is the number of hours in year.

Load factor = 30%

M = Maximum demand

Load factor = Average load/Maximum demand

$$M = \frac{85,600}{0.3} = 28.530 \text{ kW}$$

C = Capacity of plant

$$\text{Capacity factor} = \frac{E}{(C \times 8760)}$$

$$0.24 = \frac{(750 \times 10^5)}{(C \times 8760)}$$

C = 35,667 kW

Reserve capacity = C – M = 35,667 – 28,530

= **7137 kW. Ans.**

Example 5. *A diesel power station has fuel consumption 0.2 kg per kWh. If the calorific value of the oil is 11,000 kcal per kg determine the overall efficiency of the power station.*

Solution. For 1 kWh output

Heat input = 11,000 × 0.2 = 2200 kcal.

Now 1 kWh = 862 kcal.

$$\text{Overall efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{866}{2200} = \mathbf{39.2\%}. \quad \textbf{Ans.}$$

Example 6. *A steam power station has an installed capacity of 120 MW and a maximum demand of 100 MW. The coal consumption is 0.4 kg per kWh and cost of coal is Rs. 80 per tonne. The annual expenses on salary bill of staff and other overhead charges excluding cost of coal are Rs.50 × 10^5. The power station works at a load factor of 0.5 and the capital cost of the power station is Rs. 4 × 10^5. If the rate of interest and depreciation is 10% determine the cost of generating per kWh.*

Solution. Maximum demand = 100 mW

Load factor = 0.5

Average load = 100 × 0.5 = 50 MW = 50 × 1000 = 50,000 kW.

Energy produced per year = 50,000 × 8760 = 438 × 10^6 kWh.

Coal consumption = 438 × 10^6 × (0.4/1000) = 1752 × 10^6 tonnes.

Annual Cost

(1) Cost of coal = 1752 × 10^2 × 80 = Rs. 14,016 × 10^2

(2) Salaries = Rs. 50 × 10^5

(3) Interest and depreciation = (10/100) × 4 × 10^5 = Rs. 4 × 10^4

Total cost = Rs. 14,016 × 10^3 + Rs. 50 × 10^5 + Rs. 4 × 10^4

= Rs. 19,056 × 10^3

$$\text{Cost of generation per kWh} = \left\{\frac{(19{,}056 \times 10^3)}{(438 \times 10^6)}\right\} \times 100$$

$$= \mathbf{4.35\ paise.} \quad \textbf{Ans.}$$

Example 7. *Any undertaking consumes 6 × 10^6 kWh per year and its maximum demand is 2000 kW. It is offered two tariffs.*

(*a*) *Rs. 80 per kW of maximum demand plus 3 paise per kWh.*

(*b*) *A flat rate of 6 paise per kWh.*

Calculate the annual cost of energy.

Solution.

(*a*) (According to first tariff the cost of energy)

$$= 2000 \times 80 + \left(\frac{3}{100}\right) \times 6 \times 10^6$$

$$= 160{,}000 + 180{,}000 = \textbf{Rs. 340,000.} \quad \textbf{Ans.}$$

(*b*) Cost of energy according to flat rate

$$= \left(\frac{6}{100}\right) \times 6 \times 10^6 = \textbf{Rs. 360,000.} \quad \textbf{Ans.}$$

Example 8. *Two lamps are to be compared:*

(*a*) *Cost of first lamp is Re. 1 and it takes 100 watts.*

(*b*) *Cost of second lamp is Rs. 4 and it takes 60 watts.*

Both lamps are of equal candlepower and each has a useful life of 100 hours. Which lamp will prove economical if the energy is charged at Rs. 70 per kW of maximum demand per year plus 5 paise per kWh? At what load factor both the lamps will be equally advantageous?

Solution. (*a*) **First Lamp**

$$\text{Cost of lamp per hour} = \frac{(1\times100)}{1000} = 0.1 \text{ paise}$$

$$\text{Maximum demand per hour} = \frac{100}{1000} = 0.1 \text{ kW}$$

Maximum demand charge per hour

$$= \frac{0.1\times(70\times100)}{7860} = 0.08 \text{ paise}$$

Energy consumed per hour = 0.1 × 1 = 0.1 kWh

Energy charge per hour = 0.1 × 5 = 0.5 paise

Total cost per hour = 0.1 + 0.08 + 0.5 = 0.68 paise.

(*b*) **Second Lamp**

$$\text{Cost of lamp per hour} = \frac{(4\times100)}{1000} = 0.4 \text{ paise}$$

$$\text{Maximum demand per hour} = \frac{60}{1000} = 0.06 \text{ kW}$$

$$\text{Maximum demand charge per hour} = \frac{0.06\times(70\times100)}{8760} = 0.048 \text{ paise}$$

Energy consumed per hour = 0.06 × 1 = 0.06 kWh

Energy charge per hour = 0.06 × 5 = 0.3 paise

Total cost per hour = 0.4 + 0.048 + 0.3 = 0.748 paise

Therefore the first lamp is economical

Let x be the load factor at which both lamps become equally advantageous. Only maximum demand charge changes with load factor.

$$0.1 + \frac{0.08}{x} + 0.5 = 0.4 + \frac{0.048}{x} + 0.3$$

$$x = 0.32$$

or **32%. Ans.**

Example 9. *A new factory having a minimum demand of 100 kW and a load factor of 25% is comparing two power supply agencies.*

(*a*) *Public supply tariff is Rs. 40 per kW of maximum demand plus 2 paise per kWh.*

Capital cost = Rs. 70,000

Interest and depreciation = 10%

(*b*) *Private oil engine generating station.*

Capital Cost = Rs. 250,000

Fuel consumption = 0.3 kg per kWh

Cost of fuel = Rs. 70 per tonne

Wages = 0.4 paise per kWh

Maintenance cost = 0.3 paise per kWh

Interest and depreciation = 15%.

Solution. Load factor = Average load/Maximum demand

Average load = Load factor × Maximum demand

= 0.25 × 700 = 175 kW.

Energy consumed per year = 175 × 8760 = 153.3×10^4 kWh.

(*a*) Public Supply

Maximum demand charges per year = 40 × 700 = Rs. 28,000.

$$\text{Energy charge per year} = \left(\frac{2}{100}\right) \times 153.3 \times 10^4 = 30{,}660$$

$$\text{Interest and depreciation} = \left(\frac{10}{100}\right) \times 70{,}000 = \text{Rs. } 7{,}000.$$

Total cost = Rs. [28,000 + 30,660 + 7,000] = Rs. 65,660

$$\text{Energy cost per kWh} = \left(\frac{65{,}660}{153.3 \times 10^4}\right) \times 100 = 429 \text{ paise}$$

(*b*) Private oil engine generating station

$$\text{Fuel consumption} = \frac{(0.3 \times 153.3 \times 10^4)}{1000} = 460 \text{ tonnes}$$

Cost of fuel = 460 × 70 = Rs. 32,000

Cost of wages and maintenance

= {(0.4 + 0.3)100} × 153.3×10^4 = Rs. 10,731.

Interest and depreciation

$$= \left(\frac{15}{100}\right) \times 250{,}000 = \text{Rs. } 37{,}500$$

Total cost = Rs. [33,203 + 10,731 + 37,500]

= Rs. 80,431

Energy cost per kWh

$$\left(\frac{80,431}{153.3 \times 10^4}\right) \times 100 = \textbf{5.2 paise.} \quad \textbf{Ans.}$$

THEORETICAL PROBLEMS

1. Define: load factor, utility factor, plant operating factor, capacity factor, demand factor and diversity factor.

2. What is the difference between demand factor and diversity factor?

3. What is 'diversity factor' ? List its advantages in a power system.

4. Prove that the load factor of a power system is improved by an increase in diversity of load.

5. What is meant by load curve? Explain its importance in power generation.

6. Differentiate 'dump power', 'firm power' and 'prime power'.

7. Define 'depreciation' and explain its significance.

8. Explain the sinking fund method of calculating the depreciation.

9. Discuss the factors to be considered for, 'plant selection' for a

10. How 'load duration curve' is obtained from 'load' curve ?

11. What are the principal factors involved in fixing of a tariff?

NUMERICAL PROBLEMS

12. The following data is available for a steam power station:

Maximum demand = 25,000 kW; Load factor = 0.4; Coal consumption = 0.86 kg/kWh; Boiler efficiency = 85%; Turbine efficiency = 90%; Price of coal = Rs. 55 per tonne.

Determine the following:

(*i*) Thermal efficiency of the station.

(*ii*) Coal bill of the plant for one year. [**Ans.** (*i*) 76.5% (*ii*) Rs. 41,43,480]

13. The annual peak load on a 30 mW power station is 25 mW. The power station supplies load having maximum demands of 10 mW, 8.5 mW, 5 mW and 4.5 mW. The annual load factor is 0.45. Find:

(*i*) Average load (*ii*) Energy supplied per year

(*iii*) Diversity factor (*iv*) Demand factor.

[**Ans.** (*i*) 11.25 mW (*ii*) 98.55 × 10^6 kWh (*iii*) 1.12 (*iv*) 0.9]

14. A power station has a maximum demand of 15 mW, a load factor of 0.7, a plant capacity factor of 0.525 and a plant use factor of 0.85. Find:

(*i*) The daily energy produced.

(*ii*) The reserve capacity of the plant.

(*iii*) The maximum energy that could be produced daily if the plant operating schedule is fully loaded when in operation.

[**Ans.** (*i*) 252,000 kWh (*ii*) 5,000 kW (*iii*) 296,470 kWh]

15. Determine the annual cost of a feed water softener from the following data: Cost = Rs. 80,000; Salvage value = 5%, Life = 10 years; Annual repair and maintenance cost = Rs. 2500; Annual cost of chemicals = Rs. 5000; Labour cost per month = Its. 300; Interest on sinking fund = 5%. [**Ans.** Rs. 17,140]

16. Calculate the unit cost of production of electric energy for a power station for which data are supplied as follows :

Capacity	= 50 MW
Cost per kW	= Rs. 600
Load factor	= 40%
Interest and depreciation	= 10%

Cost of fuel, taxation and salaries = Rs. 36×10^{11}. [**Ans.** 3.71 paise]

17. Estimate the generating cost per unit supplied from a power plant having the following data :

Plant capacity = 120 MW

Capital cost = Rs. 600×10^6

Annual load factor = 40%

Annual cost of fuel, taxation, oil and salaries = Rs. 600,000 Interest and depreciation = 10%

[**Ans.** 1.33 paise]

18. Estimate the generating cost per unit. supplied from a power plant having data :

Output per year = 4×10^8 kWh

Load factor = 50%

Annual fixed charges = Rs. 40 per kW

Annual running charges = 4 paise per kWh

19. A 50 MW generating station has the following data:

Capital cost = Rs. 15×10^5

Annual taxation = Rs. 0.4×10^5

Annual salaries and wages = Rs. $1.2 \times l0^6$

Cost of coal = Rs. 65 per tonne

Calorific value of coal = 5500 kcal/kg.

Rate of interest and depreciation = 12%,

Plant heat rate = 33,000 kcal/kWh

at 100% capacity and 40000 kcal/kWh at 60%.

Calculate the generating cost/kWh at 100% and 60% capacity factor.