Module -5 - Economics

A power station is required to deliver power to a large number of consumers to meet their requirements.

* However while designing and building a power station, efforts should be made such that the overall economy, per unit cost of production is as low as possible.
* There are several factors which influence the production cost such as cost of land & equipment, depreciation of equipment, interest and capital investment etc.
* Economics of power generation

The art of determining the per unit [ie one kwh] cost of production of electrical energy is known as economics of power generation.

The economics of power generation is considered as most important factor in power plant engineering.

* A consumer will use electric power only if it is supplied at reasonable cost. Therefore power stn engineer has to select the convient method to produce electric power as cheap as possible so that consumers are satisfied to use electrical methods.

The following factors are more commonly used in the economics of power generation :-

i) Interest :- The cost of use of money is known as interest. The rate of interest depends upon market position & other factors, usually it vary from 4 to 8% per annum.

ii) depreciation :- The decrease in the value of the power plant equipment & building due to constant use is known as depreciation.

* **Effect of variable load on power system.**

The load on a power station varies from time to time due to uncertain demands of the consumers is known as varible load on power station.

A power station is designed to meet the load requirements of consumer, a consumer require their small or bulk power ~~required~~ in accordance with the demands of their activities.

* The varible load on a power station introduces many complexities in its operation, they are as fallows

i) **Need of additional equipment**

ii) increase in production cost

* **Need of additional equipment:-** The variable load on a power station needs to have addational equipment. for example let us consider a steam power station, in which coal, air & water are the raw materials, in order to produce variable power, the supply of these materials will be varied correspondingly.

* For a instance if the power demand on the plant increases it must be followed by the supply of coal, air & water to the boiler to meet increased demand, so that additional equipment is installed.

* In moder power plant, much equipment is placed to adjust the rate of the supply of raw material according the variation in power demand.

* **Increase in production cost** :- The variable load on power plant increases the cost of production of electrical energy. An alternator operates at maximum efficiency near its rated capacity. If a single generator is used, it would have poor efficiency during light load on the power plant.

* ∴ in practice a no of alternators of different capacity are installed so that, the alternator can be operated at full load capacity, use of alternators increase initial cost per kW of the plant capacity.

* **Cost analysis**

The overall annual cost of electrical energy generated by a power station is expressed in two forms namely

① three part form ② two part form

* **Three part form** :- in this method the overall annual cost of electrical energy generated is divided into three parts i.e fixed cost, semifixed cost, running cost.

Total annual cost of energy = Fixed cost + semifixed cost + running cost

= constant + propotional to max demand + propotional to kWh generated

$$= Rs\left[a + b\,kW + c\,kWh\right]$$

where a = annual fixed cost, it is independent of maximum demand & energy output

b = constant which is multiplied by maximum kW demand on the station, gives the annual semifixed cost.

c = a constant which is multiplied by kWh output per annum gives annual running cost b] **Two port tariff** :- It is convient to give annual cost of energy in two part form, Here annual cost is divided into fixed sum per kW of maximum demand + running charges per unit of energy.

$\therefore$ Total annual cost of

$$\text{energy} = RS(A\,kW + B\,kWh)$$

Where A = a constant which is multiplied by max kW demand

B = a constant which is multiplied by kWh generated annualy gives annual running cost.

* **Methods of determining depreciation.**

i) Straight line method

ii) diminishing value method.

iii) Sinking fund method.

* **Straight line method** :- In this method, a constant depreciation charge is made every year on the basis of total depreciation & useful life of the property.

* usually annual depreciation charge will be equal to the total depreciation divided by the useful life of the property,

They if the initial cost of equipment is RS 1,00,000 & its scrap value is RS 10,000 after useful life of 20 years then,

$$\text{Annal depreciation charge} = \frac{\text{Total depreciation}}{\text{useful life}}$$

$$= \frac{1,00,000 - 10,000}{20} = 4,500.$$

In general, the annual depreciation charge on the straight line can be expressed as $= \frac{P-S}{n}$.

where P = Initial cost of equipment
n = useful life of equipment in years.
S = Scrap or salvage value after the useful life of the plant.

The straight line method is extremely simple and it is easy to apply as the annual depreciation charge can be calculated from total depreciation & useful life of equipment.

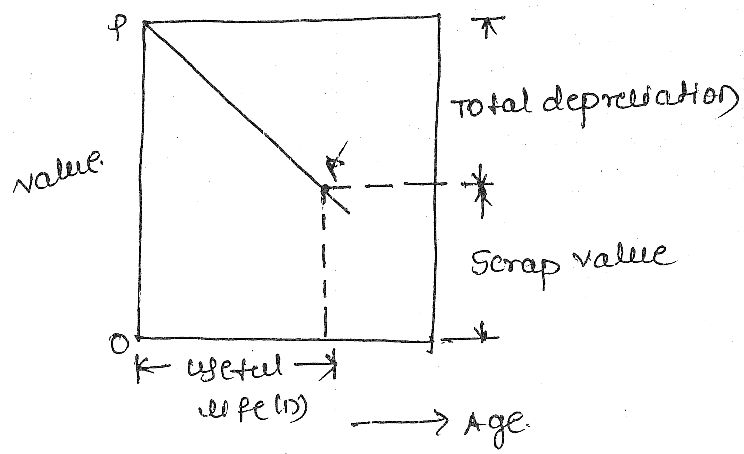


fig-a).

The above fig. shows the graphical representation of the ~~abo~~ straight line method, it is clear that the initial cost of the equipment i.e P decreases with increase in. Straight line represents constant value of depreciation.

* Diminishing value method:-

In this method, depreciation value is made every year at a fixed rate based on diminished value of the equipment. For example suppose the initial cost the equipment is RS 10,000 & its Scrap value after its useful life is zero. If annual rate of depreciation 10%, then depreciation for 1st year = 0.1×10,000 RS = 1000. ∴ the value of the equipment is decreased by 1000 and becomes 9000. and for the next year the value of the equipment becomes 8100.

*For the 3rd year the value of the equipment becomes.

8100 − 810 = 7290.

* Mathematical treatment

Let p = capital cost of equipment

n = useful life of the equipment in years

s = Scrap value after the useful life

Suppose the annual unit of depreciation is x, then it is desired to calculate the value of x in terms of p, n & s.

∴ value of the equipment after one year.

$$= p - px = p(1-x)$$

Value of the equipment for next year.

= diminished value − annual depreciation

$$= [p - px] - [(p-px)x]$$

$$= p - px - px + px^2$$

$$= p(x^2 + 2x + 1]$$

$$= p(1-x)^2$$

∴ Value of the equipment after n years

$$= p(1-x)^n$$ //.

But the value of the equipment after n years is equal to the scrap value S.

$$\therefore S = P(1-x)^n$$

$$(1-x)^n = S/P$$

$$1-x = (S/P)^{1/n}$$

$$x = 1 - (S/P)^{1/n} \quad \text{——} (1)$$

from the above equation annual depreciation can be easily found.

$\therefore$ depreciation for 1st year $= xP$

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

This method is more rational than the straight line method. the below fig shows graphical representation of the method. as shown The initial value P of the equipment reduces through depreciation to the scrap value S over the path PA

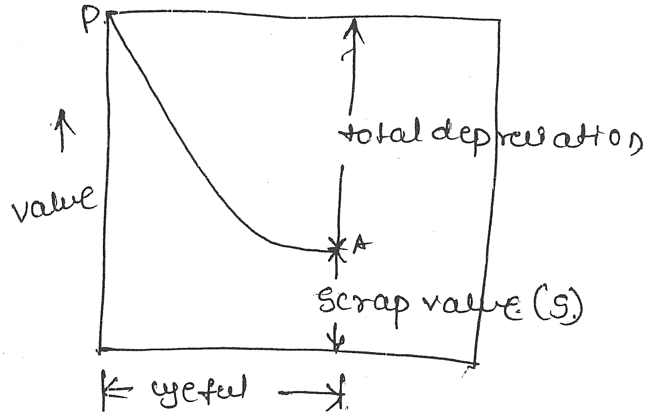


fig -

* **Sinking fund method** :- In this method, a fixed depreciation charge is made every year and interest compounded on it annualy.

* The constant depreciation charge is such that the total amount of annual instalments + the total amount of interest accumulations equal to the cost of replacement of equipment after its useful life.

Let p = Initial value of equipment

n = useful life of equipment in years

S = Scrap value after useful life

r = annual rate of interest expressed as decimal

cost of replacement $= p - S$

* Suppose an amount of q is set as depreciation charge every year & interest compounded on it is $p-S$ is available after n years

An amount of q at annual interest rate of r, will become $q(1+r)^n$ at the end of n years

* Now the amount q deposited at the end of 1st year will earn compound interest for $n-1$ years become $q(1+r)^{n-1}$ i.e.

* amount of q deposited at the end of 2nd year

$= q[1+r]^{n-2}$

at the 3rd year $= q(1+r)^{n-3}$

* Similarly at the end of $n-1$ years $= q(1+r)^{n-(n-1)}$

$= q(1+r)$

$\therefore$ total fund after n years $= q(1+r)^{n-1} + q(1+r)^{n-2} + \ldots + q(1+r)$

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

the sum is given by total fund $= q\frac{(1+r)^n - 1}{r}$

the total fund must be equal to the total cost of replacement of the equipment

$$P - S = q\left[\frac{(1+r)^n - 1}{r}\right]$$

or sinking fund $q = (P-S)\left[\frac{r}{(1+r)^n - 1}\right]$, it gives uniform annual depreciation charge.

* **Different terms considered for power plants & their significance**

1) **connected load** :- The sum of the continuous ratings of all the electrical equipments connected to the supply system is known as connected load.

for example if a consumer has connections of five 100-watt lamps and a power point of 500 watts, then connected load of the consumer is 5x100+500 = 1000 watts. The sum of the connected load of all the consumers is the connected load to the power station.

* **Maximum demand** :- It is the greatest demand of load on the power station during given period.

The load on the power station varies from time to time. Maximum demand on the power station is generally less than the connected load because all the consumers do not switch their connected load at a time.

* **Average load or Average demand**:- The average load or demand on the power station is the averge of loads occuring on the power station at various events (day or month or year).

depending upon the duration of time period such as a day, month or yeal, we get daily or monthly or annual averge load.

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

$$\text{Monthly avg load} = \frac{\text{No of units (kWh) generated in a month}}{\text{No of hours in month } (24\times30)}$$

$$\text{yearly avg load} = \frac{\text{No of units (kWh) generated in yeal}}{8760\text{ hours } (24\times365)}$$

* **Load factor**:- The ratio of average load to the maximum demand during a given period is known as load factor.

$$\text{Load factor} = \frac{\text{average load}}{\text{Maximum demand}}$$

If plant operation is for T hours

$$\text{Load factor} = \frac{\text{averge load} \times T}{\text{Maximum demand} \times T}$$

$$= \frac{\text{units generated in T hours}}{\text{Max demand} \times \text{T hours}}$$

usually the load factor may be daily, monthly or annual load factor if the time period is considered as a day or month or year.

Load factor is less than 1 because average load is always less than the maximum demand

* **Diversity factor** :- it is defined as ~~the sum of~~ it is the ratio of the sum of individual maximum demands of individual category to the maximum demand of the power station.

$$\text{diversity factor} = \frac{\text{Sum of individual Max. demands}}{\text{Maximum demand of the station}}$$

The value of diversity factor is always more than 1.

* **demand factor** (peak load factor) :- The ratio of actual maximum demand on the system to the total rated load connected to the system is known as demand factor it is always less than unity.

$$\text{demand factor} = \frac{\text{Maximum demand}}{\text{connected load}}$$

* **plant capacity factor** :- The plant capacity factor is similar to the load factor. The load factor refers to the total load on the station and total capacity of the station, whereas plant factor relates only to one particular plant, it the ratio of average load to the rated capacity of the power plant.

$$\text{plant factor} = \frac{\text{Average load or avg demand}}{\text{Rated capacity of power plant}}$$

Where as plant capacity factor is defined as the actual energy generated divided by the max-possible energy that could have been produced during a given period.

$$\text{plant capacity factor} = \frac{\text{Actual energy produced}}{\text{Max. energy that could have been produced}}$$

$$= \frac{\text{Average demand} \times T}{\text{plant capacity} \times T}$$

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

* **plant utilization factor** :- it is defined as the ratio of maximum demand on power station to the rated capacity of the power plant. it is always less than 1

$$\text{utilization factor} = \frac{\text{Max demand on power station}}{\text{Rated capacity of the power plant}}$$

* **Interconnected grid system**

The connection of several generating stations in parallel is known as Interconnected grid system.

The various problems facing by the power engineers are considerably reduced by interconnecting different power stations in parallel. Even though the interconnection of station include extra cost, but it is gaining much favour these days.

* Some of the advantages of interconnected s/m are as follows.

1) exchange of peak loads :- An important advantage of interconnected system is that, the peak load of the power station can be exchanged.

* If the load curve of a power station shows a peak demand which is more than the rated capacity of the plant, then excess load can be shared by other stations interconnected with it.

2) Use of older plants :- The interconnected s/m makes it is possible to use the older & less efficient plants to carry peak loads for short durations & interconnected s/m gives a direct key to the use of obsolete plants.

3) Ensures economical operation :- The interconnected s/m makes the operation of power station quite economical, because the sharing of load among the power station is arranged in such a way that, more efficient stations work continuously throughout the year at a high load factor. & less efficient plants work for p only for peak load condition.

4) increases the diversity factor :- The load curves of different interconnected stations, are generally different due to which the result is that the maximum demand on the s/m is reduced as compared to the sum of individual maximum demands on power stations.
In otherwords the diversity factor of the s/m is improved, thereby increasing the effective capacity of the system.

* Reduces plant reserve capacity :- Every power station is required to have a standby unit for emergencies. When several power stations are connected in parallel, the reserve capacity of the s/m is much reduced, which increases the efficiency of the s/m.

* Increased reliability of supply :- The interconnected s/m increases the reliability of the supply. If a major breakdown occurs on one station then continuity of supply can be maintained by other healthy station.

* Choice of size and number of generating plants.

The load on a power system is never constant it varies at the different times of the day. The peak load occurs only a short duration, a single generating unit is not economical to meet the varying load, because a single generating unit will have very poor efficiency during the light load on the power station.

* Therefore in actual practice, a no of generating units of different sizes are installed in a power station.

* The selection of the number and sizes of the units are decided based on the annual load curve of the station.

* The number and size of the units are selected in such a way that they correctly fit the station load curve.

* The selection criteria for number & size of generating units have following points →

① The no and size of the generating units should be selected such that they approximately fit the annual load curve of the station.

2) The units should be preferably of different capacity to meet the load requirements

3) The capacity of the plant should be made 15% to 20% more than the maximum demand to meet the future load requirements

4) There should be a spare generating units so that the repair & overhauling can be carried out.

5) The tendancy to select a large no of units of smaller capacity is, to fit the load curve very accurately.

* Tariffs

The rate at which electrical energy is supplied to a consumer is known as tariff. Tariff include the total cost of producing and supplying electrical energy + profit. tariff can't be same for all types of consumers.

* objectives of tariff

1) To recover the cost of ~~[illegible]~~ capital investment in ~~gene~~ in generating, transmitting and distributing equipment.

2) To recover the cost of operation, supply & maintenance of the equipment.

3) To recover the cost of metering equipment, billing, collection costs.

4) To have a suitable profit on the capital investment.

5) To recover the cost of production of electrical energy at the power station.

* 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
   i) kVA maximum demand tariff.
   ii) Sliding scale tariff.
   iii) kWh and KVAR tariff.

7). Three part tariff.

* **Simple tariff:-** it is the simplest type of tariff, in which cost of energy consumption is considered based on the no of units consumed. it is also known as uniform rate tariff.

In this type of tariff, price charged per unit is constant ie it will not vary with increase or decrease in number of units consumed. The total consumption of electrical energy at the consumer side is recorded by means of energymeter.

* ~~The advantage of such type of tariff is, it is more fair to different types of consumers & it is quite simple in calculations~~

* **disadvantages:-**

① There is no discrimination b/n different types of consumers., every consumer has to pay equal fixed charges.

ii) the cost of per unit delivered is high.

iii) It does not encourage the use of electricity.

* Flat rate tariff :- When different type of consumers are charged at different per unit rates, it is called as flat rate tariff.

In this type of tariff, the consumers are grouped into different classes and each class of consumer is charged at a different uniform rate.

The advantage of such type of tariff is that it is more fair to the different types of consumer & it is quite simple in calculation.

* disadvantages :-

① Separate meters are required for light load, power load etc.

② as the tariff varies according to the way of supply is used & it is very expensive & complicated.

* Block rate tariff :- In this type of tariff a given block of energy is charged at a specified rate and the succeeding Blocks of energy are charged at progressively reduced rates known as block rate tariff.

In block rate tariff, energy consumption is divided into blocks & the price per unit is fixed in each block. The price per unit in 1st block is highest and it is reduced for succeeding blocks of energy.

For an example initially 25 units may be charged at the rate of RS. 4.00paise/unit, The next 40 units may be charged at the rate of RS 3.50 per unit. The consumption exceeding 65 units may be charged at the rate of 3.00/unit.

* The advantage of such type of tariff is that the consumer will get an incentive for consuming more electrical energy, which increase the load factor and reduces the generation cost.

* The drawback is, it lacks a measure of the consumer demand.

* Two part tariff :- When the rate of electrical energy is charged based on the maximum demand of the consumer and the no of units consumed, it is known two part tariff.

In two part tariff, the total charge made by the consumer is split in two components ie fixed charge and running charge. The fixed charge is dependent on the maximum demand of the consumer where as running charges are depend upon the no of units consumed by the consumer.

This type of tariff is generally applicable to industrial consumers.

* advantages

1) it is easily understood by consumers.
2) It recovers fixed charges which depend upon the max. demand of the consumer but independent of the no of units consumed.

* disadvantages

i) The consumer has to pay the fixed charges irrespective of the fact that, whether he has consumed or not consumed the electrical energy.

2) There is always error in assessing the max demand of the consumer.

5) **Maximum demand tariff** :- It is similar to that of the two part tariff except that in this case max demand is actually measured by max. demand indicator instead of assessing it on the basis of reliable value.

In this method the drawback of two part tariff method is removed. It is applicable ~~to~~ to all bulk supplies and large industrial consumer. at the same this type of tariff is not suitable for small consumer as separate max demand meter is required.

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

The efficiency of plant and equipment depends upon the powerfactor, ∴ in order ~~to increase~~ to increase the utility of the plant & the equipment to the maximum, the power plant must be operated at the most economical power factor.

Therefore sometime the consumer has to pay penalty for poor power factor. by applying the following types of power factor tariffs.

a) KVA Maximum demand tariff
b) kWh and kVAR tariff
c) Average power factor tariff

* **KVA Maximum demand tariff** :- In this type tariff, the fixed charge is based on Maximum kVA demand instead of Maximum kW. kVA maximum demand tariff encourages the consumer to operate their machines and other equipment at the improved power factor and hence the consumer has to pay more.

on the other hand the consumer tries to improve the pf of his load by installing the pf improvement device which will be more economical.

* **kWh and kVARh tariff** :- In this type of tariff, the consumer not only pay for the real energy consumed ie kWh but also for the reactive energy kVARh. If the pf is low, the consumer has to pay more for kVARh, Hence he tries to improve the power factor by installing pf improvement device due to which reactive energy KVARh decreases.

* **pf penalty or bonus tariff** :- In this type of tariff, a certain pf say 0.9 lagging is taken as reference pf. If the load pf is less than this, the consumer has to pay penalty.

on the other hand if the pf is more than 0.9 he will be rewarded with a bonus.

* **Three part tariff** :- When the total charge to be made from the consumer is split into three part ie, fixed, semifixed and running charge, then it is known as three part tariff

Total charge = RS $(a + b \times kW + c \times kWh)$

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

b = charge/kW of maximum demand.

c = charge/kWh of energy consumed.

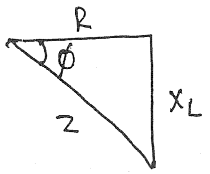
This type of tariff is generally applied to big consumers.

* **power factor**

The power factor of an ac circuit can be defined into three different ways.

i) power factor $= \cos\phi$

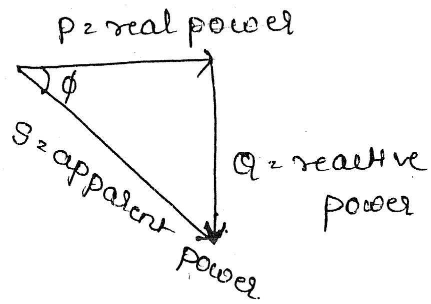
The powerfactor of an ac circuit is defined as the cosine of the angle b/n voltage and current.

ii) 

The impedance diagram for an inductive load is as shown above from which $\cos\phi = R/Z$

Therefore the powerfactor of an ac circuit is defined as the ratio of resistance to impedance of the circuit.

iii) The relation b/w real power, and apparent power in an ac circuit is as shown below.



from the fig, $\cos\phi = \frac{\text{Real power}}{\text{Apparent power}} = kW/kVA$

∴ the pf of an ac circuit is defined as the ratio of real power to apparent power.

* **disadvantages of Low power factor**

The power factor plays an important role in ac circuits since power consumed depends on this factor.

$P = V_L I_L \cos\phi$ for single phase supply.

$\Rightarrow I_L = P/V_L\cos\phi$ —— ①

$P = \sqrt{3} V_L I_L \cos\phi$ for 3-φ supply.

$I_L = P/\sqrt{3} V_L \cos\phi$ —— ②

from the above eqn it is clear that, the load current is inversely propotional to the power factor. low pf causes high load ch which introduces the following disadvantages

1) The kVA rating of alternators & transformers are propotional to the load current, If pf is low, the ch drawn will be more. ∴ large generators and transformers are required to deliver the same load at Low power factor.

* Module-5 * disadvantages of LPF.

ii) ~~at increased~~ ~~c/n~~ due to the increase in current because of low pf, the voltage drop in line also increases & voltage across load decreases. The reduced voltage adversely affects the performance of the loads.

If it is an incandescent lamp, its illumination is drastically reduced.

* If it is a fluorescent tube, it won't light up. If it is an motor, its starting torque is adversely affected.

3) The current carrying capacity of the bus bar, conductors, and switchgear equipments depends on the cross-sectional area. due to low p.f. the current is increased and cross-sectional areas of the bus bar, conductors and contact surface of the switch gear has to be increased, which causes additional expenditure.

4). as c/n is increased due to low pf. the copper losses (I^2R) are increased & hence, efficiency is decreased.

* Causes of low power factor

The low p.fs are caused mainly because of the type of load connected to the supply. Most of the industrial and domestic loads are inductive nature hence the c/n drawn by these loads lag applied voltage by certain angle which causes the reduction in pf.

The various types of loads which are the causes of low powerfactor are →.

1) Most of the ac motors are of induction type (1ϕ & 3ϕ) which are more widely used in industries & agriculture

at light load, they operate at very low power factor of 0.3 to 0.4, at full load they operate at 0.8pf, single phase induction motors also operate at low pf of 0.6.

* Transformers draw magnetizing current from the supply to produce flux in core, at normal load, which will not affect pf more, But at light load, the magnetizing c/n makes the total c/n to lag more w.r.t to applied voltage hence pf decreases.

* due to their typical characteristics, the arc lamps used in cinema projector work at low pf.

* The arc furnaces & induction furnaces work at low pf.

* The current limiting reactors used to minimize fault currents, fluorescent lamps work at low pfs

* short transmission lines also work at low pfs.

IMP

* **Advantages of power factor improvement**

The improvement of the power factor using pf improvement devices have the following advantages.

1) The kVA rating of the generator can be reduced for a given kW of power supplied to the load, this reduces the cost per kW of power generated.

2) The sizes of conductors, cables and switchgear are reduced, as the c/n drawn is reduced

3) The copper losses are reduced and hence the efficiency of transmission of power is increased.

4) The regulation of the power s/m is improved, as the voltage drop in line is decreased.

5) The fixed charges and running charges are reduced.

* **Cost of Electrical energy.**

The total cost of electrical energy generated can be divided into three parts

i) Fixed cost

ii) Semifixed cost

iii) Running or operating cost.

* **Fixed cost** :- It is the cost which is independent of maximum demand and no of units generated.

The fixed cost is due to the annual cost of central organization, interest on capital cost of land & salaries of high officials.

* The annual expenditure on the central organization and salaries of high officals are fixed, it has to met whether the plant has high or low demand or it generates less or more units.

* The capital investment on the land is fixed hence the amount of interest is also fixed.

* **Semi-fixed cost** :- It is cost which depends upon maximum demand but independent of no of units generated.

* The semi-fixed cost is directly propotional to the maximum demand on power station & is on account of annual interest and depreciation on capital investment of building & equipment, taxes, salaries of management and clerical staff.

* The maximum demand on the power station determines its size and cost of installation.
* The taxes and clerical staff depend upon the size of the plant & on maximum demand.

iii) Running (operational) cost :- Running cost depends upon the no of units generated.

* The running cost is on account of annual cost of fuel, lubricating oil, maintenance repair and salaries of operating staff. The running cost is directly propotional to the number of units generated by the station.
* It is clear that if the power station generates more units, it will have high running cost & vice versa.

* Interest and depreciation Related to power plant.

1) Interest :- The cost of use of money is known as interest.
Generally the big projects of power plants need large amount of capital. The required amount is generally borrowed from banks and other financial organizations, for this the company has to pay the annual interest on that amount.

* Even if the company has spent, out of its reserve funds the interest must be allowed for, since this amount could have earned interest if deposited in a bank.
* Therefore while calculating the cost of production of electrical energy, the interest payble on the capital investment must be included.
* However the rate of interest depends upon market position & other factors & it may vary from 4% to 8% per annum.

ii) **Depreciation** :- The decrease in the value of power plant equipment & building due to constant use is known as depreciation.

* If the power plant equipment were to last forever, then interest on the capital investment would have been ~~made~~ the only charge to be made.

* Hence in practice, every power station has a useful life ranging from 50 to 60 years, once the station is gets installed, gradually the equipments are subjected to wear & tear, hence the value of plant is gets reduced. " This reduction in the value of power plant every year is known annual depreciation. due to depreciation the plant has to be replaced by the new after its useful life.

* Therefore suitable amount is set as depreciation equal to the cost of replacement, of power plant equipment.

Basically there are 3 different methods are used to calculate depreciation

a) straight line method
b) diminishing value method.
c) sinking fund method.

* **Methods of improving the power factor.**

The various methods used for improvement of pf are as follows

1) By using static capacitors
2) By using synchronous condensors
3) By using phase advancers
4) By using phase compensated motors.

* **By using static capacitors :-**

a) **Single phase circuits :-** Consider an inductive load consisting of R and L connected to an ac supply of voltage E. as shown in below fig.

Let I_1 be the load c/n which lags the applied voltage E by an angle ϕ_1, Let $\cos\phi_1$ be pf of the load circuit. Now the capacitor C is connected across the load to improve the pf of the circuit. The c/n I_c drawn by the capacitor leads the applied voltage by an angle 90°. Let I_2 be the total c/n drawn from the supply, which is the vector sum of I_1 & I_c.

Now the c/n I_2 lags applied voltage E by an angle of ϕ_2, ϕ_2 is less than ϕ_1 i.e pf is improved from $\cos\phi_1$ to $\cos\phi_2$, the circuit connections & vector diagram are as shown below.

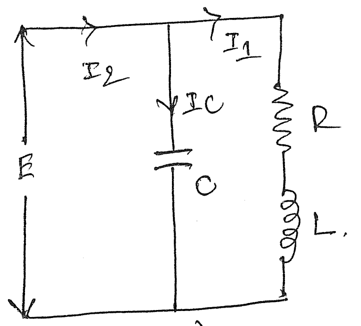


fig-a)

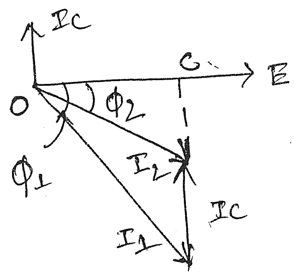


fig-b.

from the vector diagram, we find that

$$OC = I_1\cos\phi_1 = I_2\cos\phi_2$$

$$\text{or } I_2 = \frac{I_1\cos\phi_1}{\cos\phi_2} \quad \text{——— (1)}$$

also $$EI_1\cos\phi_1 = EI_2\cos\phi_2$$

$$P_1 = P_2 = P. \quad \text{——— (2)}$$

from the equation ② it is clear that the power taken from supply is not changed, when the pf is improved from $\cos\phi_1$ to $\cos\phi_2$ & the c/n drawn by the load also remains constant

The power diagram is as shown below.

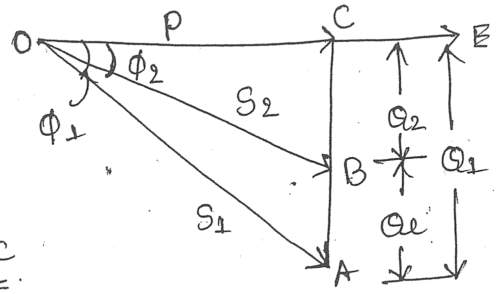


fig - C

Let P = active power taken from supply.

Q_1 = reactive power taken by the load.

Q_2 = reactive power taken by the supply after connecting the capacitor.

Q_c = reactive power taken by the capacitor.

$$Q_c = Q_1 - Q_2 = P\tan\phi_1 - P\tan\phi_2$$
$$= P(\tan\phi_1 - \tan\phi_2)$$

ie $EI_C = EI_1\cos\phi_1(\tan\phi_1 - \tan\phi_2)$

$$I_C = I_1\cos\phi_1(\tan\phi_1 - \tan\phi_2) \quad \text{——— ③}$$
$$= I_2\cos\phi_2(\tan\phi_1 - \tan\phi_2) \quad [\because P = EI_2\cos\phi_2]$$

$$I_C = \frac{E}{X_C}$$
$$= E/(1/\omega C) = E\omega C \quad \text{or} \quad C = I_C/\omega E \quad \text{——— ④}$$

the equation ④ gives the value of capacitance required to improve the pf from $\cos\phi_1$ to $\cos\phi_2$.

* Three phase circuits

The power factor improvement problems in 3-phase circuits are solved on 1-phase basis, for the improvement of pf in three phase circuits the capacitors required in each phase are either connected in star or in delta fashion as shown below.

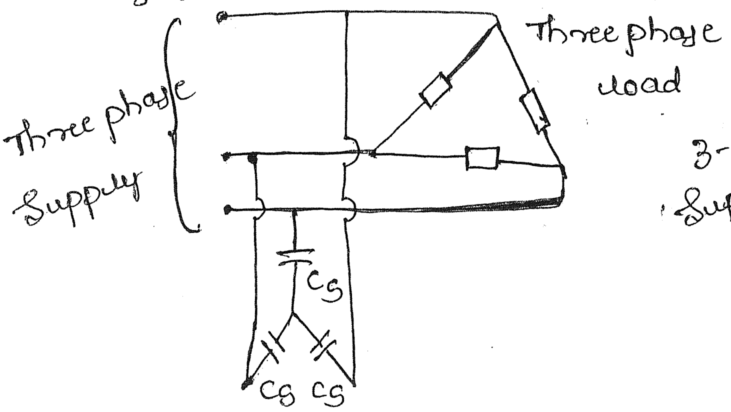


fig-a

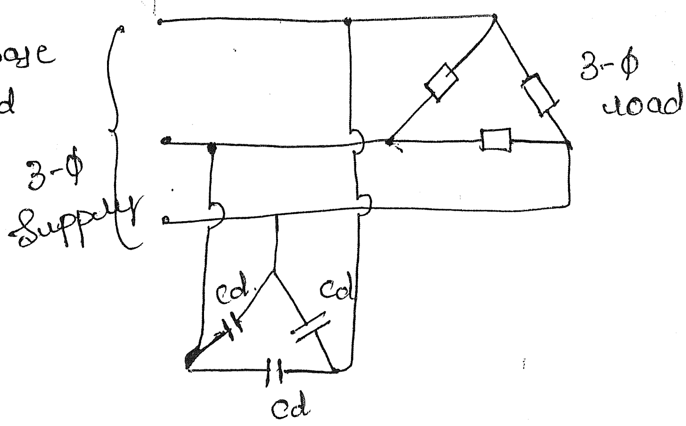


fig-b

Let E_L = line voltage

E_p = phase voltage

C_S = capacitance per phase connected in star fashion

C_d = " " " " delta "

Q_C = VAR rating of each capacitor.

When circuit is star connected

$C_S = I_C/\omega E_{ph}$ or $E_{ph} C_S = \frac{I_C}{\omega}$

$C_S = Q_C/\omega E_{ph}^2 = \frac{Q_C}{\omega (E_L/\sqrt{3})^2} = \frac{3 Q_C}{\omega E_L^2}$ —— (1)

When circuit is delta connected

$C_d = \frac{Q_C}{\omega E_{ph}^2} = \frac{Q_C}{\omega E_L^2}$ —— (2) put the value of Q_C from eqn (1)

$C_d = \frac{C_S \omega E_L^2}{3 \omega E_L^2}$ $\boxed{\therefore C_S = 3 C_d}$ — the eqn shows that the capacitance required per phase in star connection is equal to three times the capacitance per phase, when capacitors are connected in star. delta.

* Use of phase advancers.

The pf of an induction motor falls mainly due to the exciting c/n drawn from the ac mains because the exciting c/n lags the voltage by an angle of 90°. The pf can be improved with the help of set with an an exciter or phase advancer which supplies the exciting c/n to the rotor at slip frequency. Such exciter may be mounted on the same shaft as the main rotor or may be suitably driven by a primemover.

The use of phase advancer for improving pf is not economical for motors below 150kW output. There are two types of phase advancers 1) Shunt type 2) Series type, depending upon whether, the exciting winding of the phase advancer is connected in series or in ||el with the rotor winding.

* Use of phase compensated motors.

The power factor of the induction motors whose output is less than 150kW is improved by using phase compensated motors such as torda, osnos & schrage motors. They motors are costlier & require more maintenance. ∴ Such motors are used for the pf improvement, when the IM's are running at rated load for most of the time and also, if the cost of the energy saved due to higher pf is more than the extra expenditure incurred to them.

* Economics of power factor improvement.

When the pf of a slm is improved, there is a reduction in Maximum kVA demand & there will be a saving in the maximum kVA demand charges. When the pf is improved, it involves capital investment on the pf improvement device.

* Therefore certain amount of money is annually used in the form of interest on the investment made on the pf improvement device & its depreciation has to be taken into account.

* The most economical pf is that value of pf at which the annual kVA maximum demand saving charges are more

There are two methods of finding the most economical pf.

1) When kW demand is constant
2) When kVA demand is constant

* Most economical pf when kW is constant.

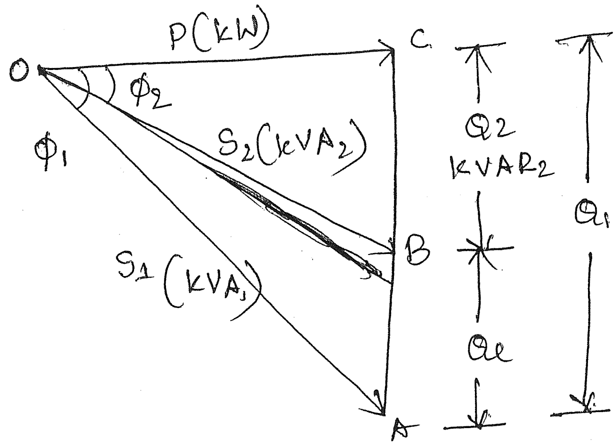


fig-a

Let P = maximum kW demand which is kept constant at a pf of $\cos\phi_1$

S_1 = total kVA at pf $\cos\phi_1$ = $kVA_1 = P\sec\phi_1$

Q_1 = total kVAR at pf $\cos\phi_1$ = $P\tan\phi_1$

The pf is improved from $\cos\phi_1$ to $\cos\phi_2$ using pf improvement device, keeping p constant, as shown in the above vector diagram.

Let S_2 = Total kVA at pf $\cos\phi_2 = kVA_2 = P\sec\phi_2$.

Q_2 = Total kVAR at pf $\cos\phi_2 = kVAR_2 = P\tan\phi_2$.

The saving in kVA maximum demand $= S_1 - S_2$

$= kVA_1 - kVA_2$

$= P\sec\phi_1 - P\sec\phi_2$

$= P(\sec\phi_1 - \sec\phi_2)$

If a = rate in rupees per kVA of maximum demand per annum, then annual savings in max demand charges in rupees

$x_1 = ap(\sec\phi_1 - \sec\phi_2)$ ——— (1)

The leading kVAR supplied by the pf improvement device

$Q_c = Q_1 - Q_2$

$= P\tan\phi_1 - P\tan\phi_2$

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

Let b = is annual expenditure towards interest and depreciation on the capital investment of the pf improvement device, then annual extra expenditure because of investment on pf improvement device in rupees

$x_2 = bp(\tan\phi_1 - \tan\phi_2)$ ——— (2)

Net annual saving in rupees is given by.

$x = x_1 - x_2 = ap(\sec\phi_1 - \sec\phi_2) - bp(\tan\phi_1 - \tan\phi_2)$

The saving is maximum when $\frac{dx}{d\phi_2} = 0$

$\therefore \frac{dx}{d\phi_2} = ap(0 - \tan\phi_2\sec\phi_2) - bp(0 - \sec^2\phi_2) = 0.$

$\therefore a\tan\phi_2\sec\phi_2 = b\sec^2\phi_2$

$b/a = \frac{\tan\phi_2 \sec\phi_2}{\sec^2\phi_2} = \frac{\tan\phi_2}{\sec\phi_2} = \frac{\sin\phi_2/\cos\phi_2}{1/\cos\phi_2} = \sin\phi_2$

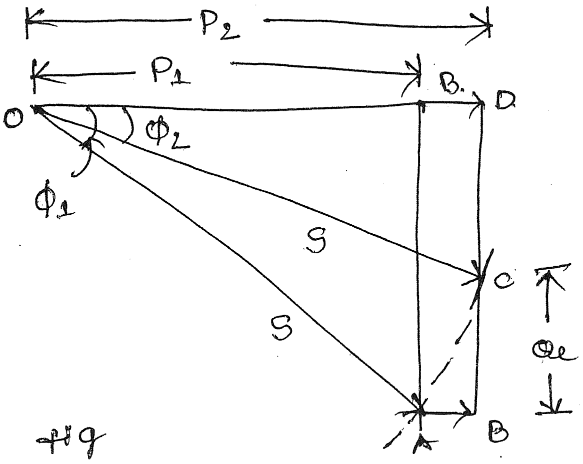
ie $\cos\phi_2 = \sqrt{1-\sin^2\phi_2} = \sqrt{1-(b/a)^2}$

∴ The most economical pf is given by

$\cos\phi_2 = \sqrt{1-(b/a)^2}$ //.

* **Most economical power factor when kVA demand is constant.**

Consider a generating plant supplying an active power P_1 at pf $\cos\phi_1$ as shown in vector diagram below.



fig

The power triangle at pf $\cos\phi_1$ is OAB, from

$OB = P_1$, $OA = S$, and $\angle AOB = \phi_1$

Now the pf is improved to $\cos\phi_2$ by supplying a leading kVAR ie Q_c keeping the kVA output constant at S. The power triangle at pf $\cos\phi_2$ is OCD from which

$OD = P_2$, $OC = S$ & $\angle COD = \phi_2$

Increase in active power output $= OD - OB = P_2 - P_1$

Let a = annual cost per kW of power generation. Then, the annual saving due to increased power output is given by

$Q_c = CE = DE - DC = BA - DC$

The reactive kVA $Q_c = S\sin\phi_1 - S\sin\phi_2 = S(\sin\phi_1 - \sin\phi_2)$

& increase in active o/p power $P_2 - P_1$, Let a = annual cost per kW

$$x_1 = a(P_2 - P_1) = a(S\cos\phi_2 - S\cos\phi_1) \quad \text{--- (1)}$$

Let b = annual cost per kVAR of the pf improvement device.

Then the annual cost of the pf improvement device is given by.

$$x_2 = bQ_c = bS(\sin\phi_1 - \sin\phi_2) \quad \text{--- (2)}$$

The saving in annual charges by the installation of pf improvement device is given by.

$$x = x_1 - x_2 = aS(\cos\phi_2 - \cos\phi_1) - bS(\sin\phi_1 - \sin\phi_2) \quad \text{--- (3)}$$

The saving will be maximum when $dx/d\phi_2 = 0$ ie

$$-aS\sin\phi_2 + bS\cos\phi_2 = 0.$$

$$a\sin\phi_2 = b\cos\phi_2 \qquad \text{ie } \tan\phi_2 = b/a = \frac{\sin\phi_2}{\cos\phi_2}.$$

$$\phi_2 = \tan^{-1} b/a \quad \text{ie}$$

Most economical pf $= \cos\phi_2 = \cos\left[\tan^{-1} b/a\right]$