2/11/2020

Unit - IV

Introduction:

* The quantity of power transmitted & distributed is based on the power factor (p.f) of load & the parameters of the T/m lines
* Almost all the power s/m loads are of the inductive type & have undesirably low lagging p.f.
* Low pf & increase in currents results in additional losses in all the components of power s/m from the generating station to the consumer.
* A pf close to unity is preferred for the economical & better distribution of electrical energy

Power Factor - Definition:

* Power factor is defined as the ratio of real power P to apparent power S & is denoted by cosϕ.

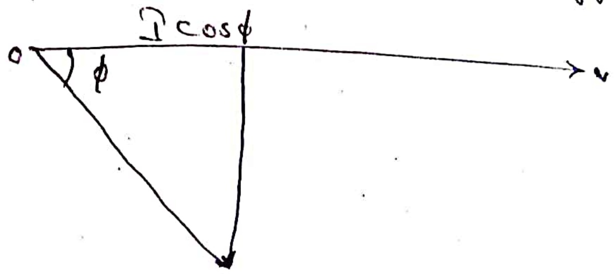
(or)

* power factor is defined as the ~~ratio of~~ Cosine of angle b/w voltage & current in an AC ckt and is denoted by cos ϕ.

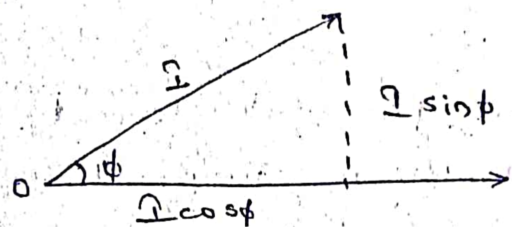
$$\therefore \text{power factor} = \cos\phi = \frac{P}{S}$$

$$= \frac{P}{VI} = \frac{\text{Active power}}{\text{Apparent power}}$$

* For all types of inductive loads, the angle b/w voltage V & current I is negative & the cosine of this angle is called the lagging p.f.



* For all types of capacitive loads, the angle b/w voltage V & current I is positive & the cosine of this angle is called the leading power factor.



Causes of Low power factor:

* The induction motors works at a low lagging pf at light loads and improved pf with increased loads.
* The T/F's have a lagging pf beco'z they draw magnetizing current.
* Miscellaneous equipment like arc lamps, electric discharge lamps, welding equipment etc., operates at a low p.f.
* The industrial heating furnaces operate at a low lagging p.f.
* The variation of load on the power s/m also causes low power factor.

Effects of low power Factor:

* For a given load P, with voltage V_L & pf cosϕ the load current is given by

$$I_L = \frac{P}{\sqrt{3} V_L \cos\phi}$$

* From the above expression for a given load it is clear that, if the pf is low, the load current will be higher.
* This leads to the following effects.

Effect on T/m lines:

* For the fixed active power to be transmitted over the line, the lower the p/f the higher will be the load current to be carried by the line.
* Since the max. permissible current density of the line conductor is fixed, the cross sectional area of the conductor is to be increased in order to carry larger current.
* This results in an increased volume of the conductor material which in turn, increases the capital cost of T/m lines.
* Further, increase in current causes increase in line losses with a reduction in the efficiency of the line.
* Also, the line voltage regulation is poor.

→ **Effect on Transformers**

* A reduction in the p/f causes a reduction in the kW capacity of a T/F

→ **Effect of switch gear & Busbar:**

* The lower the p/f at which a given power is to be supplied, the larger is the cross sectional area of the bus bar & the larger is the contact surface of the switch gear.

→ **Effecte on Generators:**

* With a low p/f, the kW capacity of a generator is reduced
* The power supplied by the exciter is increased
* The cu losses in the generator are increased, which results in low efficiency of the generator

→ Effect on prime movers

* When the power factor is decreased, the alternator develops more reactive kVA, ie; the reactive power generated is more
* This requires a certain amount of power to be supplied by the prime mover
* Therefore, a part of the prime mover capacity is idle & it represents dead investment.
* The efficiency of prime mover is reduced.

⟹ Effect on existing power Systems

* For the same active power, the operation of an existing power system at a lower power factor necessitates the overloading of the equipment when a full rated load is drawn.

Advantages of power factor Improvement

* The kW capacity of the prime movers is better utilized due to decreased reactive power.
* This increases the kilowatt capacity of the alternators, T/F's & the lines.
* The efficiency of the s/m is increased.
* The cost per unit decreases.
* The voltage regulation of the lines is improved.
* Power losses in the s/m are reduced due to reduction in load current.
* Investment on generators, T/F's, T/m lines & distributors per kW of the load supplied is reduced.
* kVA demand changes for large consumers undergoes reduction.

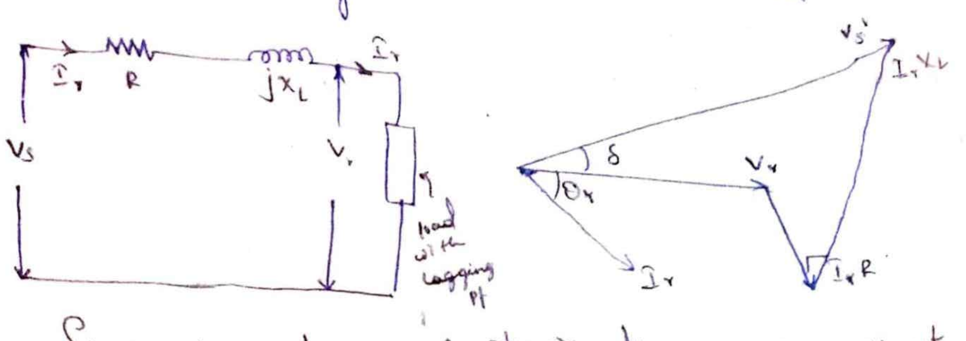
Methods of Improving power Factor:

* In case of inductive loads the pf is lagging.
* This lagging pf can be compensated by using devices that are called Compensators.
* These are i) Static Capacitors
  ii) Synchronous Condensers
  iii) phase Advancers

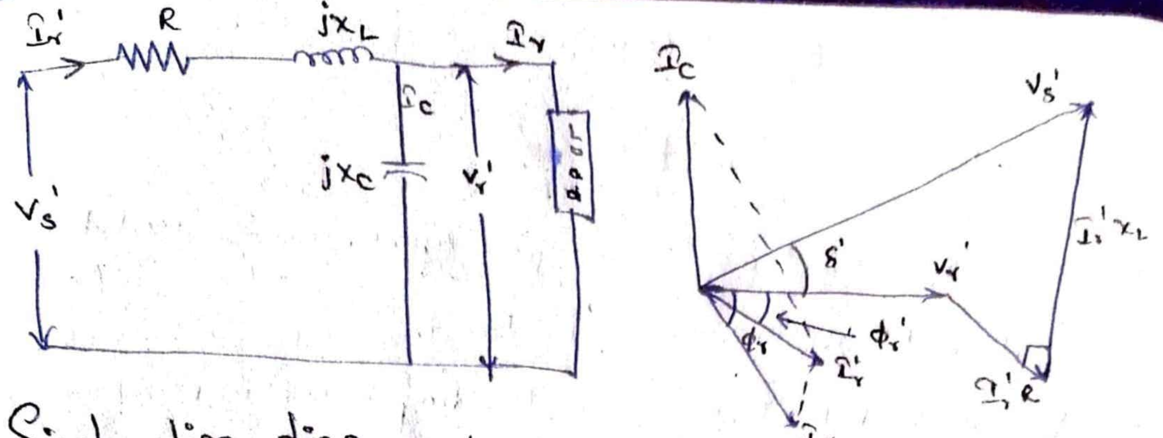
Static Capacitors:

Leading ↓ anticlockwise

* Static capacitors are connected across the mains at the load end.
* This supplies a reactive component of the current to reduce the out-of-phase component of current required by an inductive load. i.e; it modifies the characteristics of an inductive load by drawing a leading current which counteracts or opposes the lagging component of the inductive load current at the point of installation.
* So the reactive power transmitted over the line is reduced, thereby the voltage across the load is maintained within the specified limits.
* By the application of the shunt capacitor to a line the magnitude of source current can be reduced, the power factor can be improved & consequently the voltage drop b/w the sending & receiving ends is also reduced.



Single line diagram & phasor diagram of without static shunt capacitive Compensation



Single line diagram & phasor diagram of with static shunt capacitive Compensation

* Voltage drop of the line without shunt capacitor is given by

$$V_d = I_r R \cos\phi + I_r X_L \sin\phi$$

* voltage drop of the line with shunt capacitor is given by

$$V_d' = I_r R \cos\phi + (I_r - I_c) X_L \sin\phi.$$

where, I_c is the reactive component of current Leading the supply voltage by 90°.

* The voltage rise due to the location of the capacitor is the difference b/w the voltage drops & is given as

$$\text{Voltage rise} = I_c X_L$$

Advantages of static Shunt Capacitors

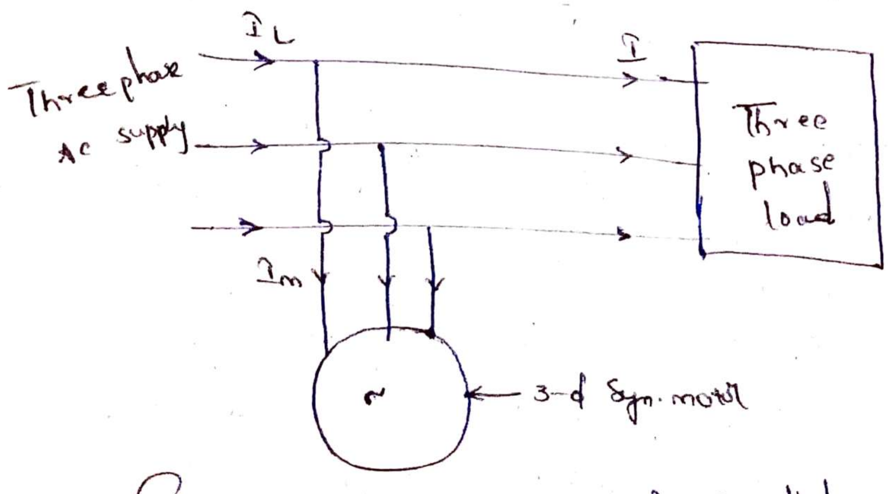
* Losses are low.
* It requires less maintenance, because there are no rotating parts.
* Easy installation.

Disadvantages of Static Shunt Capacitors

* Less service life.
* Easily damaged due to excess of voltage.
* Its repair is uneconomical.
* Difficult to control switching position of capacitors becoz of removing or adding the capacitors in the ckt for different p.f's.

Synchronous Condenser:

* The syn. condenser is a synchronous motor running without a mechanical load.
* A syn. motor takes a leading current when over-excited and therefore behaves as a capacitor. It is connected in parallel to the supply of load.
* It generates leading current to neutralize the lagging component of the load current resulting in improved p.f.
* Various (finite) values of power factor can be achieved by the addition (or deletion) of units (capacitors) to (or from) the bank.
* However by using a syn. condenser a step less (smooth) variation of the p.f with the added advantage of ease of control can be realised.
* For lower kVAR requirement static capacitor may be used.
* However, for a kVAr requirement in excess of 10,000, syn. condenser are preferable & economical.



Syn. m/c is connected in parallel with the supply

* Let P_1 be the active power of load.
* $\cos\phi_1$ is the power factor of load without syn. condenser.
* $\cos\phi_2$ is the p.f of load after using syn. Condenser.
* P_s is the active power taken by the syn. condenser from the supply.
* The rating & p.f at which the syn. condenser is operating can be calculated as follows
* Reactive power of load, $Q_1 = P_1 \tan\phi_1$.
* When syn. Condenser is connected in the ckt.
* Total load (active power) $P = P_1 + P_s$
* Total reactive power, $Q_2 = P \tan\phi_2$
* Reactive power supplied by the syn. condenser,

$$Q = Q_1 - Q_2$$

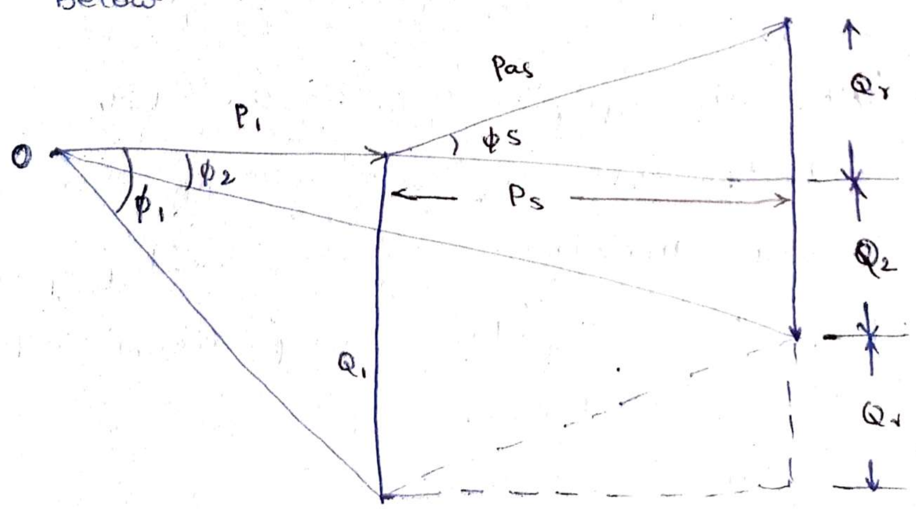
* Rated kVA of syn. Condenser is given by

$$P_{as} = \sqrt{P_s^2 + Q_r^2}$$

* Power factor of syn. Condenser is given by

$$\cos\theta_2 = \frac{P_s}{P_{as}}$$

=) phasor diagram of syn. Condenser is shown below.



Advantages of Synchronous Condenser:

* A syn. condenser has an inherently sinusoidal wave form & the harmonic voltage does not exist.
* It can supply as well as absorb kVAr.
* The pf can be varied smoothly.
* It allows the over-loading for short periods.
* The high inertia of the syn. condenser reduces the effect of sudden changes in the s/m load and improves the stability of the s/m.
* It reduces the switching surges due to sudden connection or disconnection of lines in the s/m.

Disadvantages of Syn. Condenser

* power loss increases.
* Uneconomical for small ratings.
* It is not possible to add or take away the unit & to alter the rating of the syn. condenser.
* The cost of maintenance is high.
* It produces noise.

Phase Advancers

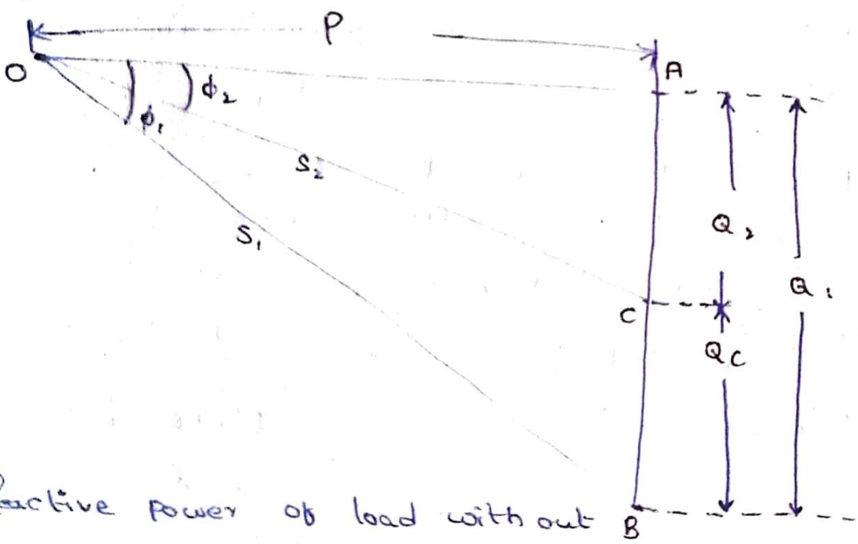
* There are special commutator m/c's, which are used to improve the p.f of the induction motor.
* When the supply is given to the stator of an induction motor, it takes a lagging current.
* Therefore, the induction motor has low lagging p.f
* For compensating this lagging current, a phase advancer (mounted on same shaft) is used.
* It supplies mmf to the rotor ckt at slip frequency.

Advantages

* The Lagging reactive power drawn by the motor is reduced by compensating the stator lagging current at slip frequency.
* Wherever the use of syn. motors is not suitable, a phase advancer can be used.

Generation of Reactive power using static capacitors

* Let P be the active power of load.
* $\cos\phi_1$ is the power factor of load without static capacitor.
* $\cos\phi_2$ is the p.f of load with static capacitor.
* Q_1 be the reactive power of load without static capacitor.
* Q_2 be the reactive power of load with static capacitor.
* Reactive power of load without static capacitor is given by $Q_1 = P\tan\phi_1$



* Reactive power of load without static capacitor is given by $Q_1 = P\tan\phi_1$.
* Reactive power of load with static capacitor is given by $Q_2 = P\tan\phi_2$.
* Hence reactive power supplied by the static capacitor is given by $Q_C = Q_1 - Q_2$

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

* knowing the leading kVAr (Q) supplied by the shunt capacitor, the capacitor current can be calculated as

$$I_C = \frac{Q_C}{\sqrt{3}\, V_{L-L}}$$

$$X_C = \frac{V_{ph}}{I_{c\,ph}}$$
$$= 2\pi f C$$
$$\therefore C = \frac{X_C}{2\pi f}$$

Problems

1. A 440V, 3-ϕ distribution feeder has a load of 100 kW at lagging pf with the load current of 200 A. If the p.f is to be improved. Determine the following.
   i) Uncorrected pf & reactive load
   ii) new corrected pf after installing a shunt capacitor of 75 kVAr.

Sol i) Uncorrected power factor $= \cos\phi = \frac{P}{\sqrt{3} V_L I_L}$

$$= \frac{100 \times 10^3}{\sqrt{3} \times 440 \times 200}$$
$$= 0.656 \text{ lag}$$

Reactive load, $Q_L = P\tan\phi$
$$= 115.055 \text{ kVAr}$$

$Q_C = 75$ kVAr (Given)

ii) Corrected power factor $= \frac{P}{\sqrt{P^2 + (Q_L - Q_C)^2}}$

$$= \frac{100}{\sqrt{100^2 + (115.055 - 75)^2}}$$
$$= 0.928 \text{ lag}$$

2) A syn. motor having a power consumption of 50 kW is connected in parallel with a load of 200 kW having a power factor of 0.8 lag. If the combined load has a power factor of 0.9, what is the value of leading

reactive power supplied by the motor & at what power factor is it working.

Sol Let, pf angle of motor = ϕ_1

power factor angle of load = $\phi_2 = \cos^{-1}(0.8)$

$= 36.87°$

Combined pf angle (both motor & load),

$\phi = \cos(0.9) = 25.84°$

$\tan\phi_2 = \tan 36°.87' = 0.75$

$\tan\phi = \tan 25°.84' = 0.4842$

Combined power, $P = 200 + 50 = 250\,kW$

Total kVAr of combined s/m is given by

$P\tan\phi = 250 \times 0.4842$

$= 121.05\,kVAr$

Load kVAr $= 200 \times \tan\phi_2 = 200 \times 0.75$

$= 150\,kVAr$

Leading kVAr supplied by synchronous motor is given as $Q_c = 150 - 121.05$

$= 28.95\,kVAr.$

power factor angle at which the motor is working is given by

$\phi_1 = \tan^{-1}\frac{28.95}{50}$

$= 30.07°.$

power factor at which the motor is working is given as $\cos\phi_1 = 0.865$ (Lead)

3) A 3-ϕ 5 kW induction motor has a power factor of 0.85 lag. A bank of capacitor is connected in delta across the Supply terminal & power factor raised to 0.95 lag. Determine the kVAr rating of the capacitor in each phase.

Sol The active power of the induction motor, $P = 5\,kW$ when the pf is Changed from 0.85 lag to 0.95 lag, by Connecting a condenser bank

The leading kVAr taken by the Condenser bank is given by

$$Q_c = p\tan\phi_1 - p\tan\phi_2$$

$$Q_c = 5(0.6197 - 0.3287)$$

$$= 1.455 \text{ kVAr}$$

Hence rating of capacitor connected in each phase is calculated as $1.455/3$

$$= 0.485 \text{ kVAr}$$

Most Economical power factor when kW demand is Constant :

* For improving the pf of load at the consumer end, the consumer must provide the equipment required for the purpose.
* Therefore, there is a capital investment necessary for the required correction equipment.
* At the same time, there is a saved amount due to the reduced demand in kVA.
* Therefore, the net annual savings is equal to the difference b/w the annual savings in max. demand charges & the annual expenditure incurred on power factor correction equipment.
* The value of a p.f at which the net annual saving is maximum is known as the most economical power factor.
* Consider a peak load of P kW, which is taken by the consumer at a powerfactor of $\cos\phi_1$ & charge on max. demand be Rs. x per kVA per annum.
* Then the reactive component of load, $Q = p\tan\phi_1$
* kVA demand of load is given by

$$\boxed{S = \frac{P}{\cos\phi_1}}$$

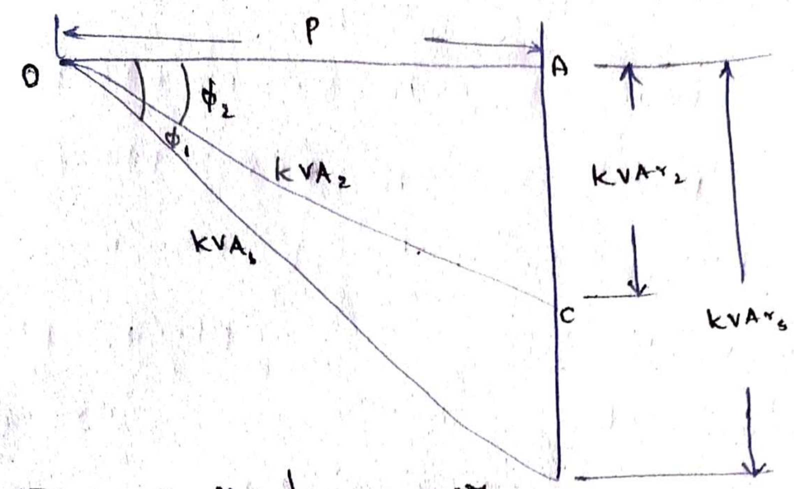


Fig: phasor diagram for Constant kW demand.

* If the consumer improves the power factor to $\cos\phi_2$ by installing power factor correction equipment.
* Let the expenditure incurred on the power factor correction equipment be Rs. y per kVAr per annum.
* The power triangle at the original power factor $\cos\phi_1$ is OAB & for the ~~improved~~ improved power factor $\cos\phi_2$, it is OAC as shown in the figure
* kVA maximum demand at $\cos\phi_1$ is given by

$$kVA_1 = \frac{P}{\cos\phi_1}$$

* kVA maximum demand at $\cos\phi_2$ is given by

$$kVA_2 = \frac{P}{\cos\phi_2}$$

* Becoz of the improvement in the pf, the kVA$_1$ max. demand is reduced from kVA to kVA$_2$ (since the real power remains unchanged)
* Annual saving in max. demand is given by

$$= Rs.\ x\ (kVA_1 - kVA_2)$$

$$= Rs.\ x \left[\frac{P}{\cos\phi_1} - \frac{P}{\cos\phi_2}\right]$$

$= Rs.\ xP\left[\frac{1}{\cos\phi_1} - \frac{1}{\cos\phi_2}\right]$

* Reactive power at $\cos\phi_1$, $kVAr_1 = P\tan\phi_1$

* Reactive power at $\cos\phi_2$, $kVAr_2 = P\tan\phi_2$

* Leading kVAr supplied by pf correction equipment is given as $Q_C = P\tan\phi_1 - P\tan\phi_2$

* So, annual charges towards phase advancing plant $= Rs.\ yP(\tan\phi_1 - \tan\phi_2)$

* Net annual saving towards phase advancing ckt

$$S = xP\left[\frac{1}{\cos\phi_1} - \frac{1}{\cos\phi_2}\right] - yP(\tan\phi_1 - \tan\phi_2)$$

* In this expression, only ϕ_2 is variable while all other quantities are fixed.

* For maximum net annual saving,

$$\frac{d}{d\phi_2}(S) = 0$$

$$\frac{d}{d\phi_2}\left[xP(\sec\phi_1 - \sec\phi_2) - yP(\tan\phi_1 - \tan\phi_2)\right] = 0$$

$$\frac{d}{d\phi_2}(xP\sec\phi_1) - \frac{d}{d\phi_2}(xP\sec\phi_2) - \frac{d}{d\phi_2}(yP\tan\phi_1) + \frac{d}{d\phi_2}(yP\tan\phi_2) = 0$$

$$0 - xP\sec\phi_2\tan\phi_2 - 0 + yP\sec^2\phi_2 = 0$$

or $-xP\tan\phi_2 + yP\sec\phi_2 = 0$

$$\tan\phi_2 = \frac{y}{x}\sec\phi_2$$

$$\sin\phi_2 = \frac{y}{x}$$

Most economical power factor

$$\cos\phi = \sqrt{1 - \sin^2\phi_2}$$

$$= \sqrt{1 - \left(\frac{y}{x}\right)^2}$$

Or $\cos\phi = \cos\left[\sin^{-1}\frac{y}{x}\right]$

Most Economical power factor when KVA demand is Constant

* The necessity of calculating the most economical power ~~fott~~ factor when the KVA max demand is constant arises when power-supply agencies try to improve the power factor so that the KVA maximum demand on the station is reduced.
* Since the cost of the plant is proportional to the KVA installed, an improvement in the power factor reduces the cost of the plant
* Further, the revenue returns are the function of the active power supplied.
* The KVA o/p is constant & equal to S.
* The power factor is improved from $\cos\phi_1$ to $\cos\phi_2$ due to the addition of Q KVAr leading.
* Consequently, the real power is increased from P_1 to P_2.

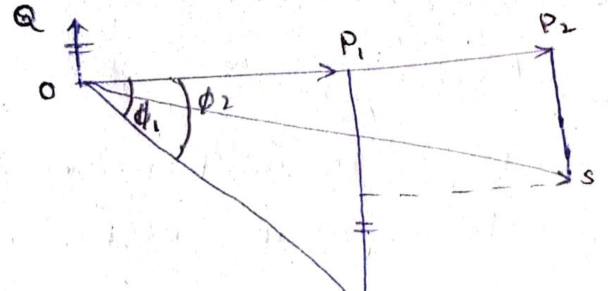


fig: Phasor diagram for Constant KVA max. demand.

* Let the annual interest & depreciation Charges for a capacitor = X Rs/KVAr.
* Let the net return per kW of installed capacity ~~for~~ per year = Rs. Y.
* From phasor diagram, leading KVAr supplied by the pf improvement equipment is given as

$Q = S(\sin\phi_1 - \sin\phi_2)$

* Annual charge on capacitor installation is expressed as Rs. $XS(\sin\phi_1 - \sin\phi_2)$.

* Annual increase in revenue return because of increase in the real power can be calculated as

Rs $Y(P_2 - P_1) = Y(S\cos\phi_2 - S\cos\phi_1) = YS(\cos\phi_2 - \cos\phi_1)$

* Net Saving $= YS(\cos\phi_2 - \cos\phi_1) - XS(\sin\phi_1 - \sin\phi_2)$

* In this expression, only ϕ_2 is variable while all other quantities are fixed.

* For maximum net annual saving.

$$\frac{d}{d\phi_2}(\text{Net Saving}) = 0$$

$$\frac{d}{d\phi_2}[YS(\cos\phi_2 - \cos\phi_1) - XS(\sin\phi_1 - \sin\phi_2)]$$

(or) $YS(-\sin\phi_2 - 0) - XS(0 - \cos\phi_2) = 0$

(or) $YS(-\sin\phi_2) = XS(-\cos\phi_2)$

(or) $\tan\phi_2 = \dfrac{X}{Y}$

* Most economical power factor, when the kVA maximum demand is a constant.

$$\cos\phi = \cos\left(\tan^{-1}\frac{X}{Y}\right)$$

* It may be noted that the most economical power factor ($\cos\phi$) depends upon the relative costs of supply & power factor correction equipment but is independent of the original p.f. $\cos\phi_1$.

⇒ A consumer is charged at a rate of Rs. 75 per annum per kVA of maximum demand plus a flat rate per kwh. The phase advancing unit can be purchased at a rate of Rs. 70 per kVA. The rate of interest & depreciation on the capital is 12.5%. Find the most economical pf to which it can be improved.

Sol Annual Charge towards interest & depreciation of the phase advancing equipment.

$$= Rs.\ 70 \times \frac{12.5}{100}$$

$$= Rs.\ 8.75$$

Annual Charge per kVA = Rs. 75.00

Let ϕ_2 be the angle corresponding to the most economical pf

$$\therefore \sin\phi_2 = \frac{8.75}{75}$$

$$= 0.1166$$

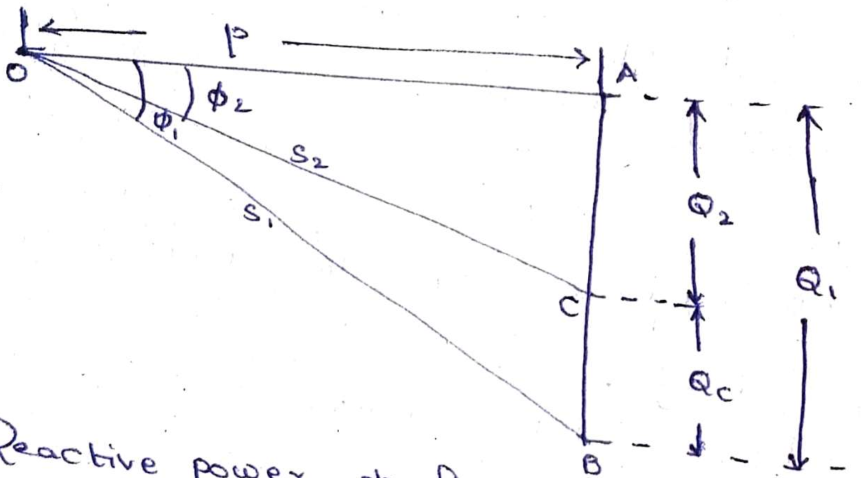
The most economical pf to which it can be improved is

$$\cos\phi_2 = \cos(\sin^{-1} 0.1166)$$

$$= 0.9932 \text{ lag}$$

Power factor Correction:

* Let P be the active power of load
* $\cos\phi_1$ is the power factor of load without pf correction equipment device.
* $\cos\phi_2$ is the power factor of load with pf correction equipment device.
* Q_1 be the reactive power of load without pf correction equipment device.
* Q_2 be the reactive power of load with pf correction equipment device.
* Reactive power of load without power factor correction equipment device is given by
  $Q_1 = P\tan\phi_1$



* Reactive power of load without power factor correction equipment device is given by
  $Q_1 = P\tan\phi_1$.
* Reactive power of load with pf correction equipment device is given by $Q_2 = P\tan\phi_2$
* Hence reactive power supplied by the pf correction equipment device is given by

$Q_c = Q_1 - Q_2$

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

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

Reddy

Economic Justification

* Loads on electric utility systems include two components : active power (measured in kw) and reactive power (measured in kilovars).
* Active power has to be generated at power plants, whereas reactive power can be provided by either power plants or capacitors.
* It is a well-known fact that shunt power capacitors are the most economical source to meet the reactive power requirements of inductive loads and T/m lines operating at a lagging power factor.
* In general, the economic benefits that can be derived from capacitor installation can be summarized as follows :

1. Released generation capacity
2. Released T/m capacity
3. Released distribution substation capacity
4. Additional advantages in distribution s/m.
   a. Reduced energy (copper) losses.
   b. Reduced voltage drop & consequently improved voltage regulation.
   c. Released capacity of feeder & associated apparatus.
   d. postponement or elimination of capital expenditure due to s/m improvements and/or expansions.
   e. Revenue increases due to voltage improvements.

Benefits due to Released Generation Capacity

* The released generation capacity due to installation of capacitors can be calculated approximately from the formula

$$\Delta S_G = \begin{cases} \left[\left(1 - \dfrac{Q_c^2 \times \cos^2\theta}{S_G^2}\right)^{1/2} + \dfrac{Q_c \times \sin\theta}{S_G} - 1\right] S_G & \text{when } Q_c > 0.10\, S_G \\ Q_c \times \sin\theta & \text{when } Q_c < 0.10\, S_G \end{cases}$$

where

* ΔS_G is the released generation capacity beyond max. generation capacity at original pf, kVA.
* S_G is the generation capacity, kVA
* Q_c is the reactive power due to corrective capacitors applied, kvar
* $\cos\theta$ is the original (or uncorrected or old) pf before application of capacitors.

∴ The annual benefits due to the released generation capacity can be expressed as

$$\Delta \$_G = \Delta S_G \times C_G \times i_G$$

where

$\Delta \$_G$ is the annual benefits due to released generation capacity, \$/year

ΔS_G is the released generation capacity beyond max. generation capacity at original power-factor kVA.

C_G is the cost of (peaking) generation, \$/kW

i_G is the annual fixed charge rate applicable to generation

Benefits due to released T/m Capacity

* The released substation capacity due to the installation of capacitors can be found approximately from

$$\Delta S_T = \begin{cases} \left[\left(1 - \frac{Q_c^2 \times \cos^2\theta}{S_T^2}\right)^{1/2} + \frac{Q_c \times \sin\theta}{S_T} - 1\right] S_T; & \text{when } Q_c > 0.10 S_T \\ Q_c \times \sin\theta & \text{when } Q_c < 0.10 S_T \end{cases}$$

where

ΔS_T is the released distribution substation capacity beyond max. substation capacity at original pf, kVA.

S_T is the ~~distribution~~ T/m substation capacity, kVA

Hence, the annual benefits due to the released substation capacity can be calculated as

$$\Delta \$_T = \Delta S_T \times C_T \times i_T$$

where

- $\Delta \$_T$ is the annual benefits due to released T/m capacity, \$/year
- ΔS_T is the released T/m capacity beyond max. T/m capacity at original pf, kVA.
- C_T is the cost of T/m line & associated apparatus, \$/kVA.
- i_T is the annual fixed charge rate applicable to transmission.

Benefits due to released Distribution Substation Capacity:

* The released distribution substation capacity due to the installation of capacitors can be found approximately from

$$\Delta S_S = \begin{cases} \left[\left(1 - \frac{Q_c^2 \times \cos^2\theta}{S_S^2}\right)^{1/2} + \frac{Q_c \times \sin\theta}{S_S} - 1\right] S_S & \text{when } Q_c > 0.10 S_S \\ Q_c \times \sin\theta & \text{when } Q_c \leq 0.10 S_S \end{cases}$$

where

ΔS_S is the released distribution substation capacity beyond max. substation capacity at original power factor kVA.

S_S is the distribution substation capacity, kVA.

Hence the annual benefits due to the released substation capacity can be calculated as

$$\Delta \$_S = \Delta S_S \times C_S \times i_S$$

where

$\Delta \$_S$ is the annual benefits due to the released substation capacity, \$/year

ΔS_S is the released substation capacity, kVA

C_S is the cost of substation & associated apparatus, \$/kVA.

i_S is the annual fixed charge rate applicable to substation.

Benefits due to Reduced Energy Loss:

The annual energy losses are reduced as a result of decreasing copper losses due to installation of capacitors. The conserved energy can be expressed as

$$\Delta ACE = \frac{Q_{C,3\phi} R(2S_{L,3\phi} \sin\theta - Q_{C,3\phi}) 8760}{1000 \times V_{L-L}^2}$$

where

* ΔACE is the annual observed energy, kwh/year
* $Q_{C,3\phi}$ is the 3-ϕ reactive power due to corrective capacitors applied, kvar.
* R is the total line resistance to load center, Ω
* $Q_{L,3\phi}$ is the original, that is, uncorrected, 3-ϕ load, kVA.
* $\sin\theta$ is the sine of original (uncorrected) power factor angle
* V_{L-L} is the line to line voltage, kV.

Therefore, the annual benefits due to the conserved energy can be calculated as

$$\Delta \$_{ACE} = \Delta ACE \times EC$$

where

* ΔACE is the annual benefits due to conserved energy, \$/year
* EC is the cost energy, \$/kwh.

Benefits due to Released feeder Capacity

Without including the released regulator or substation capacity, this additional feeder capacity can be calculated as

$$\Delta S_F = \frac{(Q_{c,3\phi})\, x}{x \sin\theta + r \cos\theta} \text{ kVA}$$

Therefore, the annual benefits due to the released feeder capacity can be calculated as

$$\Delta \$_F = \Delta S_F \times C_F \times i_F$$

where

$\Delta \$_F$ is the annual benefits due to released feeder capacity, \$/year

ΔS_F is the released feeder capacity, kVA

C_F is the cost of installed feeder, \$/kVA

i_F is the annual fixed charge rate applicable to the feeder.

Benefits due to reduced voltage drops :

The following advantages can be obtained by the installation of capacitors into a ckt :

1. The effective line current is reduced, and consequently, both IR and IX_L voltage drops are decreased, which results in improved voltage regulation.
2. The pf improvement further decreases the effect of reactive line voltage drop.

The percent voltage drop that occurs in a given ckt can be expressed as

$$\% VD = \frac{S_{L,3\phi}\,(r\cos\theta + x\sin\theta)\,l}{10 \times V^2_{L-L}}$$

where

$\% VD$ is the percent voltage drop

$S_{L,3\phi}$ is the three phase load, kVA

r is the line resistance, ohm/mi

x is the line reactance, ohm/mi

l is the length of conductor, mi

V_{L-L} is the line to line voltage, kV

Benefits due to reduced voltage drops

The voltage drop that can be calculated from equation is the basis for the application of the capacitors. After the application of the capacitor, the s/m yields a voltage rise due to the improved power factor & the reduced effective line current. Therefore, the voltage drops due to IR and IX_L are minimized.

The approximate value of the percent voltage rise along the line can be calculated as

$$\% VR = \frac{Q_{c,3\phi} \times x \times l}{10 \times V^2_{L-L}}$$

Furthermore, an additional voltage rise phenomenon through every T/F from the generating source to the capacitor occurs due to the application of capacitor. It is independent of load & pf of the line & can be expressed as

$$\% VR_T = \left(\frac{Q_{c,3\phi}}{S_{T,3\phi}}\right) x_T$$

where

$\% VR_T$ is the percent voltage rise through the transformer

$S_{T3\phi}$ is the total phase transformer rating, kVA

X_T is the percent transformer reactance (approx. equal to the transformer's nameplate impedance).

Procedure to determine best capacitor location

* In general, the best location for capacitors can be found by optimizing power loss and voltage regulation.
* A feeder voltage profile study is performed to warrant the most effective location for capacitors and the determination of a voltage that is within recommended limits.
* The general iteration process involved is summarized in the following steps.

Step 1: Collect the following ckt & load information:

a. Any two of the following for each load: kVA, kVAr's, kw and load power factor.

b. Desired corrected power of ckt.

c Feeder ckt voltage

d A feeder ckt map that shows locations of loads and presently existing capacitor banks.

Step 2: Determine the kilowatt load of the feeder and the PF.

Step 3: Calculate the correction factor of the load necessary to correct the feeder ckt PF, from the original to the desired PF. To determine the kVA of capacitors required, multiply this correction factor by the total kw of the feeder ckt.

Step 4: Determine the individual kVA's and pf for each load or group of loads.

Step 5: To determine the kVAr's on the line, multiply individual load or groups of loads by their respective reactive factors.

Step 6: Develop a nomograph to determine the line loss per km due to the inductive loads tabulated in step 4 & 5. Multiply these line losses by their respective line lengths in thousands of feet. Repeat this process for all loads & line section & add them to find the total inductive ~~line~~ line loss.

Step 7: In the case of having presently existing capacitors on the feeder, perform the same calculations as in step 6, but this time subtract the capacitive line loss from the total inductive line loss. Use the capacitor kVAr's determined in step 3 and the nomograph developed for step 6 and find the line ~~lo~~ loss in each line section due to capacitors.

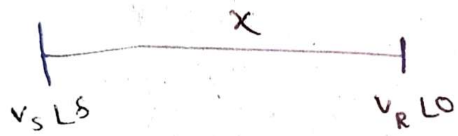
Step 8: To find the distance to capacitors location, divide the total inductive line loss by capacitive line loss per thousand feet. If this quotient is greater than the line section length

a. Divide the remaining inductive line loss by the capacitive line loss per in the next line section to find the location.

b. If this quotient is still greater than the line section length, repeat step 8a.

Step 9: Print the results and check for the voltage limits.

Dependency of voltage on Reactive power flow:



From the above diagram

$$V_S \angle \delta = V_R \angle 0 + jIX$$

$$\Rightarrow jIX = V_S - V_R$$

$$I = \frac{V_S - V_R}{jX}$$

Apparent power $S = VI^*$

$$S^* = V^* I$$

$$S^* = V_R^* I$$

$$S^* = V_R \left[\frac{V_S - V_R}{jX} \right]$$

$$S^* = V_R \left[\frac{V_S \angle \delta - V_R \angle 0}{X \angle 90^\circ} \right]$$

$$S^* = \frac{V_S V_R}{X} \angle \delta - 90^\circ - \frac{V_R^2}{X} \angle -90^\circ$$

$$P - jQ = \frac{V_S V_R}{X} (\cos(\delta - 90^\circ) + j\sin(\delta - 90^\circ)) - \frac{V_R^2}{X} [\cos(-90^\circ) + j\sin(-90^\circ)]$$

Hence

$$-jQ = \frac{V_S V_R}{X} j(-(\sin(90 - \delta))) - \frac{V_R^2}{X} j(-\sin 90)$$

$$-jQ = -j \frac{V_S V_R}{X} \cos\delta + j \frac{V_R^2}{X} (1)$$

$$-jQ = -j \left[\frac{V_S V_R}{X} \cos\delta - \frac{V_R^2}{X} \right]$$

$$Q = \frac{V_S V_R}{X} \cos\delta - \frac{V_R^2}{X}$$

$$Q = \frac{V_R}{X} \left[V_S \cos\delta - V_R \right]$$ i.e; $Q \alpha V_R$ (or) V_S

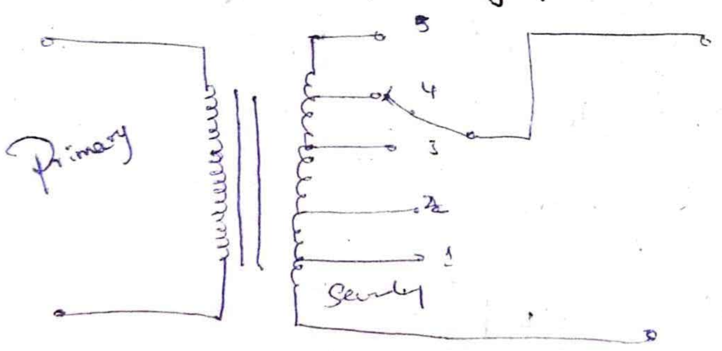
Tap Changing T/F

* A tap Changing T/F is a static device having a no. of tap settings on its secondary side for obtaining different secondary voltages.
* The basic function of this device is to change the transformation ratio, whereby the voltage in the secondary ckt is varied making possible voltage control at all voltage levels at any load.
* The supply may not be interrupted when tap changing is done with & without load.

The types of tap changing T/F's are :

1. off load tap changing T/F
2. On " " " "

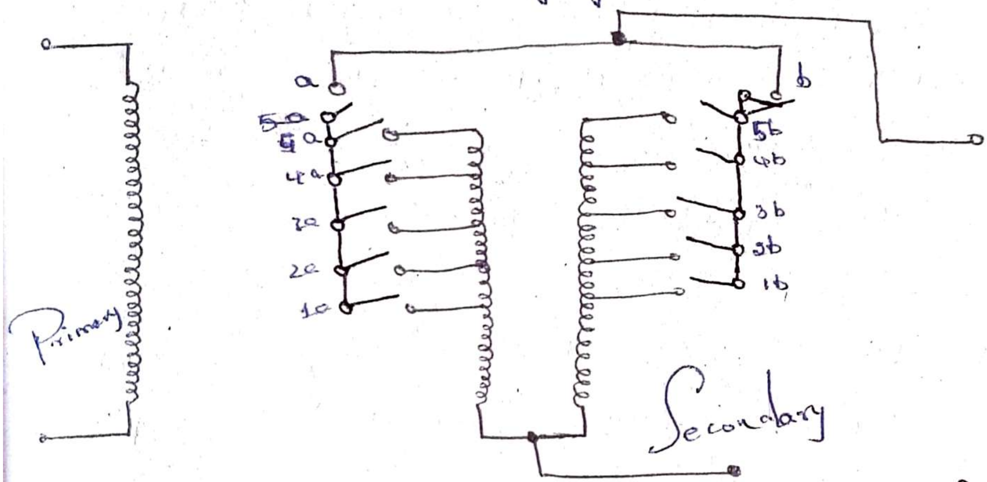
Off Load Tap Changing T/F



* The off load tap changing T/F is a T/F which requires the disconnection of the T/F from load when the tap setting is to be changed.
* The output of the secondary side of the T/F changes with the change in tap position of the secondary wdg.
* The secondary voltage is minimum, when the movable arm makes contact with stud 1; whereas it is max. when it is in position N.

* when load on the T/F increases, the voltage across secondary terminal decreases.
* This can be increased to the desired value by adding the no. of turns on the secondary terminal of the T/F by changing taps.
* Thus, in the case of tap changing T/F's, the main drawback is that the taps are changed only after the removal of the load.
* This can be overcome by using an on-load tap changing T/F with reactors.

On Load Tap Changing Transformer:



* To supply uninterrupted power to the load (consumer), tap changing has to be performed when the system is on loaded.
* The secondary wdg in a tap-changing T/F consists of two identical parallel wdgs with similar tappings. For example 1, 2 --- N & 1', 2' -- N' are the tappings on both the parallel wdgs of such a T/F.
* These two parallel wdgs are controlled by switches Sa and Sb.
* In the normal operating conditions, switches S, S' and tappings 1 & 1' are closed i.e., both the secondary wdgs of a T/F are connected in

parallel and each wdg carries half of the total load current by equal sharing.

* The secondary side of a T/F is at a rated voltage under no load, when the switches S, S' are closed and movable arms make contact with stud 1 and 1' whereas it is max. (above the rated value) under no load, when the movable arms are in position N and N'.

* The voltage at secondary terminal decreases with an increase in the load.

* To compensate for the decreased voltages, it is required to change switches from positions 1 and 1', to positions 2 and 2' (no. of turns on secondary is increased).

* For this, open any one of the switches S and S, and assume S is opened.

* At this instant, the secondary wdg controlled by switch S carries full load current through one wdg.

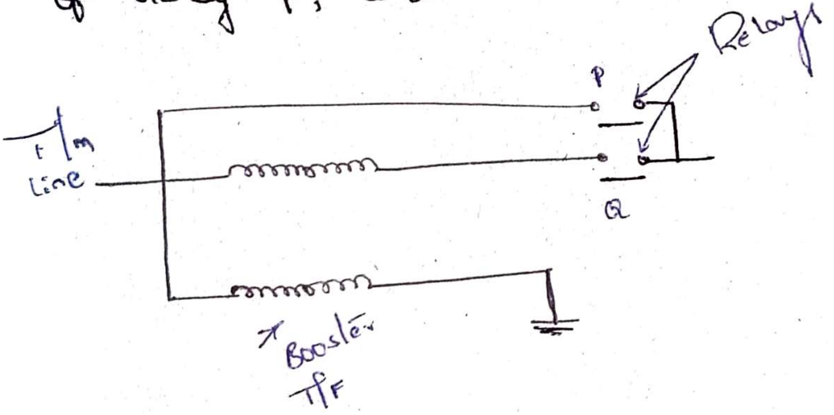
* Then, tapping is changed to position 2 on the wdg of the disconnected T/F and switch S is closed.

* After this, switch S is opened for disconnecting its winding, the tapping position is changed from 1' to 2' and then switch S is closed.

* Similarly, tapping positions can be changed without interrupting the power supply to the consumers.

Booster Transformer

* The booster transformer performs the function of boosting the voltage.
* It can be installed at a substation or at any intermediate point of line.
* The secondary of the booster T/F is connected in series with the line whose voltage is to be controlled & the primary of the booster transformer is supplied from a regulating T/F with on-load tap changing gear.
* The booster can be brought in to the ckt by the closure of relay Q and the opening of relay P, and vice versa.



* The secondary of booster T/F injects a voltage in phase with the line voltages.
* By changing the tapping on the regulating T/F, the magnitude of V can be changed and thus the feeder voltage V can be regulated.

Advantages:

* It can be installed at any intermediate point in the system.
* Rating of booster T/F is about 10% of that of the main transformer.

Disadvantages:

* More expensive than a transformer with on-Load tap changes.
* Less efficient due to losses in booster
* Requires more space.