DEE S4
Subject - Transmission & Distribution of power
Chapter - Power Factor Improvement
Date - 8.4.2020
Smt. Srabani Chakraborty,Lect-EE/JCGP

POWER FACTOR IMPROVEMENT

Power Factor

The cosine of angle between voltage and current in an a.c. circuit is known as **power factor.**

In an a.c. circuit, there is generally a phase difference φ between voltage and current. The term cos φ is called the power factor of the circuit. If the circuit is inductive, the current lags behind the voltage and the power factor is referred to as lagging. However, in a capacitive circuit, current leads the voltage and power factor is said to be leading.

Consider an inductive circuit taking a lagging current I from supply voltage V; the angle of lag being φ. The phasor diagram of the circuit is shown in Fig. 1. The circuit current I can be resolved into two perpendicular components, namely ;
(a) I cos φ in phase with V
(b) I sin φ 90° out of phase with V

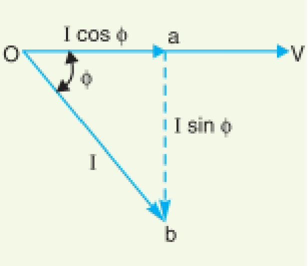


Fig. 1

The component I cos φ is known as active or wattful component, whereas component I sin φ is called the reactive or wattless component. The reactive component is a measure of the power factor. If the reactive component is small, the phase angle φ is small and hence power factor cos φ will be high. Therefore, a circuit having small reactive current (i.e., I sin φ) will have high power factor and vice-versa. It may be noted that value of power factor can never be more than unity.
(i) It is a usual practice to attach the word 'lagging' or 'leading' with the numerical value of power factor to signify whether the current lags or leads the voltage. Thus if the circuit has a p.f. of 0·5 and the current lags the voltage, we generally write p.f. as 0·5 lagging.
(ii) Sometimes power factor is expressed as a percentage. Thus 0·8 lagging power factor may be expressed as 80% lagging.

Power Triangle

The analysis of power factor can also be made in terms of power drawn by the a.c. circuit. If each side of the current triangle oab of Fig.1 is multiplied by voltage V, then we get the power triangle OAB shown in Fig. 2 where
OA = VI cos φ and represents the active power in watts or kW
AB = VI sin φ and represents the reactive power in VAR or kVAR
OB = VI and represents the apparent power in VA or kVA

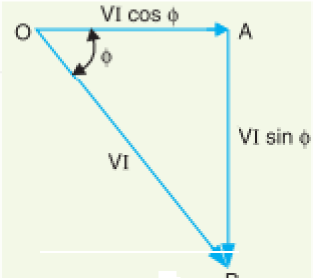


Fig. 2

The following points may be noted form the power triangle :

(i) The apparent power in an a.c. circuit has two components viz., active and reactive power at right angles to each other.

$$OB^2 = OA^2 + AB^2$$

or $$(\text{apparent power})^2 = (\text{active power})^2 + (\text{reactive power})^2$$

or $$(\text{kVA})^2 = (\text{kW})^2 + (\text{kVAR})^2$$

(ii) Power factor, cos φ = OA / OB
= active power / apparent power
= kW / kVA

Thus the power factor of a circuit may also be defined as the ratio of active power to the apparent power. This is a perfectly general definition and can be applied to all cases, whatever be the waveform.

(iii) The lagging reactive power is responsible for the low power factor. It is clear from the power triangle that smaller the reactive power component, the higher is the power factor of the circuit.

kVAR = kVA sin φ = kWsin φ / cos φ

∴ kVAR = kW tan φ

(iv) For leading currents, the power triangle becomes reversed. This fact provides a key to the power factor improvement. If a device taking leading reactive power (e.g. capacitor) is connected in parallel with the load, then the lagging reactive power of the load will be partly neutralised, thus improving the power factor of the load.

(v) The power factor of a circuit can be defined in one of the following three ways :
(a) Power factor = cos φ = cosine of angle between V and I
(b) Power factor = R / Z = Resistance / Impedance
(c) Power factor = VI cos φ / VI = Active power / Apparent Power

(vi) The reactive power is neither consumed in the circuit nor it does any useful work. It merely flows back and forth in both directions in the circuit. A wattmeter does not measure reactive power.

Disadvantages of Low Power Factor

The power factor plays an importance role in a.c. circuits since power consumed depends upon this factor.

$P = V_L I_L \cos\varphi$ (For single phase supply)

$\therefore \quad I_L = P / V_L \cos\varphi \qquad ...(i)$

$P = \sqrt{3} V_L I_L \cos\varphi$ (For 3 phase supply)

$\therefore \quad IL = P / \sqrt{3} V_L \cos\varphi \qquad ...(ii)$

It is clear from above that for fixed power and voltage, the load current is inversely proportional to the power factor. Lower the power factor, higher is the load current and vice-versa. A power factor less than unity results in the following disadvantages :

(i) Large kVA rating of equipment : The electrical machinery (e.g., alternators, transformers, switchgear) is always rated in kVA.

Now, kVA = kW / cos φ

It is clear that kVA rating of the equipment is inversely proportional to power factor. The smaller the power factor, the larger is the kVA rating. Therefore, at low power factor, the kVA rating of the equipment has to be made more, making the equipment larger and expensive.

(ii) Greater conductor size : To transmit or distribute a fixed amount of power at constant voltage, the conductor will have to carry more current at low power factor. This necessitates large conductor size. For example, take the case of a single phase a.c. motor having an input of 10 kW on full load, the terminal voltage being 250 V. At unity p.f., the input full load current would be 10,000/250 = 40 A. At 0·8 p.f; the kVA input would be 10/0·8 = 12·5 and the current input 12,500/250 = 50 A. If the motor is worked at a low power factor of 0·8, the cross-sectional area of the supply cables and motor conductors would have to be based upon a current of 50 A instead of 40 A which would be required at unity power factor.

(iii) Large copper losses : The large current at low power factor causes more I^2R losses in all the elements of the supply system. This results in poor efficiency.

(iv) Poor voltage regulation : The large current at low lagging power factor causes greater voltage drops in alternators, transformers, transmission lines and distributors. This results in the decreased voltage available at the supply end, thus impairing the performance of utilisation devices. In order to keep the receiving end voltage within permissible limits, extra equipment (i.e., voltage regulators) is required.

(v) Reduced handling capacity of system : The lagging power factor reduces the handling capacity of all the elements of the system. It is because the reactive component of current prevents the full utilisation of installed capacity.

The above discussion leads to the conclusion that low power factor is an objectionable feature in the supply system

Causes of Low Power Factor Causes of Low Power Factor

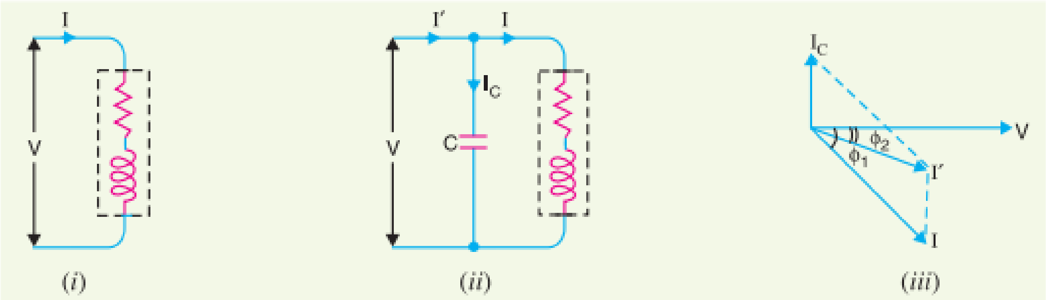
Low power factor is undesirable from economic point of view. Normally, the power factor of the whole load on the supply system in lower than 0·8. The following are the causes of low power factor:

(i) Most of the a.c. motors are of induction type (1φ and 3φ induction motors) which have low lagging power factor. These motors work at a power factor which is extremely small on light load (0·2 to 0·3) and rises to 0·8 or 0·9 at full load.
(ii) Arc lamps, electric discharge lamps and industrial heating furnaces operate at low lagging power factor.
(iii) The load on the power system is varying ; being high during morning and evening and low at other times. During low load period, supply voltage is increased which increases the magnetisation current. This results in the decreased power factor.

Power Factor Improvement

The low power factor is mainly due to the fact that most of the power loads are inductive and, therefore, take lagging currents. In order to improve the power factor, some device taking leading power should be connected in parallel with the load. One of such devices can be a capacitor. The capacitor draws a leading current and partly or completely neutralises the lagging reactive component of load current. This raises the power factor of the load.

Illustration : To illustrate the power factor improvement by a capacitor, consider a single phase load taking lagging current I at a power factor cos φ_1 as shown in Fig. 3.



(i) (ii) (iii)

Fig. 3

The capacitor C is connected in parallel with the load. The capacitor draws current I_C which leads the supply voltage by 90°. The resulting line current I′ is the phasor sum of I and I_C and its angle of lag is φ_2 as shown in the phasor diagram of Fig.3.(iii). It is clear that φ_2 is less than φ_1, so that cos φ_2 is greater than cos φ_1. Hence, the power factor of the load is improved. The following points are worth noting :

(i) The circuit current I′ after p.f. correction is less than the original circuit current I.

(ii) The active or wattful component remains the same before and after p.f. correction because only the lagging reactive component is reduced by the capacitor.
∴ $I \cos \varphi_1 = I' \cos \varphi_2$

(iii) The lagging reactive component is reduced after p.f. improvement and is equal to the difference between lagging reactive component of load (I sin φ_1) and capacitor current (I_C) i.e.,
$I' \sin \varphi_2 = I \sin \varphi 1 - I_C$

(iv) As $I \cos \varphi_1 = I' \cos \varphi_2$
∴ $VI \cos \varphi_1 = VI' \cos \varphi_2$ [Multiplying by V]
Therefore, active power (kW) remains unchanged due to power factor improvement.

(v) $I' \sin \varphi_2 = I \sin \varphi_1 - I_C$
∴ $VI' \sin \varphi_2 = VI \sin \varphi_1 - VI_C$ [Multiplying by V]
i.e., Net kVAR after p.f. correction = Lagging kVAR before p.f. correction − leading kVAR of equipment

Power Factor Improvement Equipment :

Normally, the power factor of the whole load on a large generating station is in the region of 0·8 to 0·9. However, sometimes it is lower and in such cases it is generally desirable to take special steps to improve the power factor. This can be achieved by the following equipment :

1. Static capacitors. 2. Synchronous condenser. 3. Phase advancers.

1. Static capacitor. The power factor can be improved by connecting capacitors in parallel with the equipment operating at lagging power factor. The capacitor (generally known as static capacitor) draws a leading current and

partly or completely neutralises the lagging reactive component of load current. This raises the power factor of the load. For three-phase loads, the capacitors can be connected in delta or star as shown in Fig.4. Static capacitors are invariably used for power factor improvement in factories.

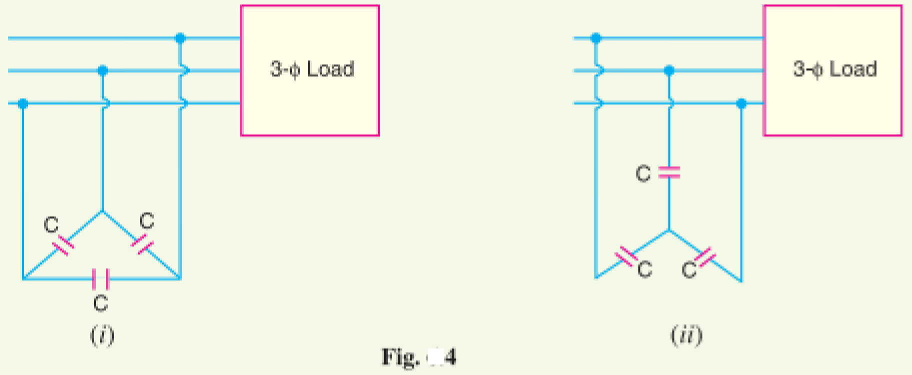


Fig. 4

Advantages
(i) They have low losses.
(ii) They require little maintenance as there are no rotating parts.
(iii) They can be easily installed as they are light and require no foundation.
(iv) They can work under ordinary atmospheric conditions.

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

2. Synchronous condenser. A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor. An over-excited synchronous motor running on no load is known as synchronous condenser. When such a machine is connected in parallel with the supply, it takes a leading current which partly neutralises the lagging reactive component of the load. Thus the power factor is improved.
Fig 5 shows the power factor improvement by synchronous condenser method. The 3φ load takes current I_L at low lagging power factor cos φ_L. The synchronous condenser takes a current I_m which leads the voltage by an angle φ_m. The resultant current I is the phasor sum of I_m and I_L and lags behind the voltage by an angle φ. It is clear that φ is less than φ_L so that cos φ is greater than cos φ_L. Thus the power factor is increased from cos φ_L to cos φ. Synchronous condensers are generally used at major bulk supply substations for power factor improvement.

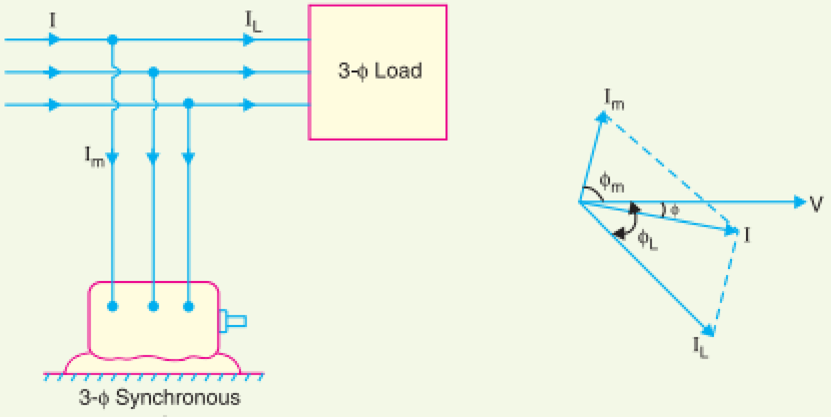


Fig. 5

Advantages
(i) By varying the field excitation, the magnitude of current drawn by the motor can be changed by any amount. This helps in achieving stepless control of power factor.
(ii) The motor windings have high thermal stability to short circuit currents.
(iii) The faults can be removed easily.

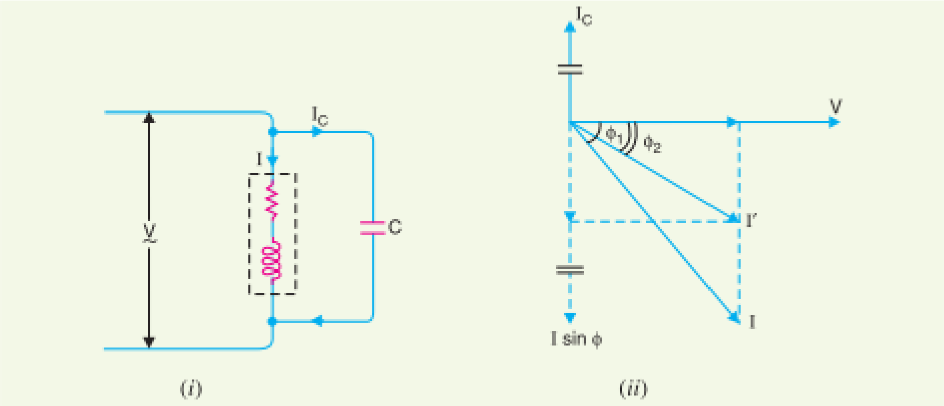
Disadvantages
(i) There are considerable losses in the motor.

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

Note : The reactive power taken by a synchronous motor depends upon two factors, the d.c. field excitation and the mechanical load delivered by the motor. Maximum leading power is taken by a synchronous motor with maximum excitation and zero load.

Calculations of Power Factor Correction

Consider an inductive load taking a lagging current I at a power factor cos φ_1. In order to improve the power factor of this circuit, the remedy is to connect such an equipment in parallel with the load which takes a leading reactive component and partly cancels the lagging reactive component of the load. Fig.6 (i) shows a capacitor connected across the load. The capacitor takes a current I_C which leads the supply voltage V by 90^o. The current I_C partly cancels the lagging reactive component of the load current as shown in the phasor diagram in Fig. 6 (ii). The resultant circuit current becomes I′ and its angle of lag is φ_2. It is clear that φ_2 is less than φ_1 so that new p.f. cos φ_2 is more than the previous p.f. cos φ_1.



(i) (ii)

Fig. 6

From the phasor diagram, it is clear that after p.f. correction, the lagging reactive component of the load is reduced to $I' \sin \varphi_2$.

Obviously, $I' \sin \varphi_2 = I \sin \varphi_1 - I_C$

or $I_C = I \sin \varphi_1 - I' \sin \varphi_2$

∴ Capacitance of capacitor to improve p.f. from cos φ_1 to cos φ_2

$= I_C / \omega V$ $\quad [\because X_C = V/I_C = 1/\omega C]$

Power triangle : The power factor correction can also be illustrated from power triangle. Thus referring to Fig.7, the power triangle OAB is for the power factor cos φ_1, whereas power triangle OAC is for the improved power factor cos φ_2. It may be seen that active power (OA) does not change with power factor improvement. However, the lagging kVAR of the load is reduced by the p.f. correction equipment, thus improving the p.f. to cos φ_2.

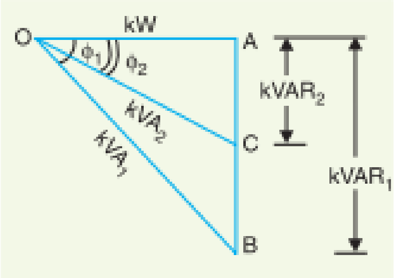


Fig. .7

Leading kVAR supplied by p.f. correction equipment

= BC
= AB – AC
$= kVAR_1 - kVAR_2$
$= OA (\tan \varphi_1 - \tan \varphi_2)$
$= kW (\tan \varphi_1 - \tan \varphi_2)$

Knowing the leading kVAR supplied by the p.f. correction equipment, the desired results can be obtained.