Chapter 3 Power Factor Improvement

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3.1 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.

The component *I* cos φ is known as active or wattful component, whereas component *I* sin φ is called the reactive or wattless component. 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*.

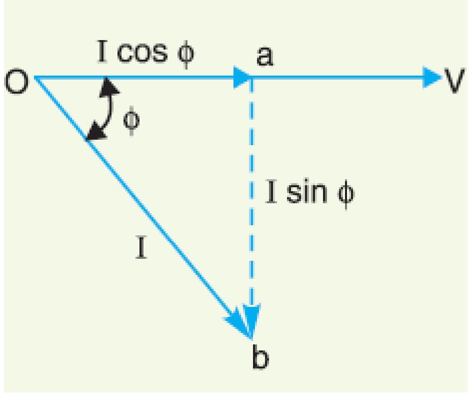

Fig. 6-1

3.2 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. 6.1 is multiplied by voltage *V*, then we get the power triangle *OAB* shown in Fig. 3.2 where

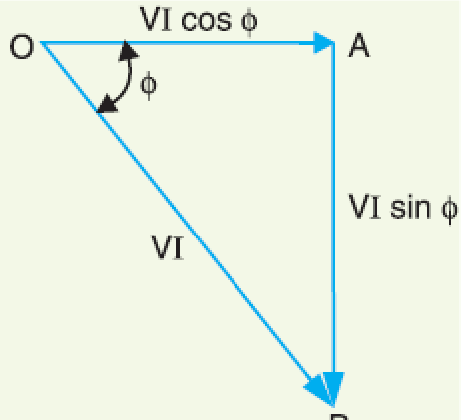

Fig. 6.2

$OA = VI \cos\varphi$ and represents the *active power* in watts or kW

$AB = VI \sin\varphi$ and represents the *reactive power* in VAR or kVAR

$OB = VI$ and represents the *apparent power* in VA or kVA

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 (apparent power)^2 = (active power)^2 + (reactive power)^2

or (kVA)2 = (kW)2 + (kVAR)2

(*ii*) Power factor, $\cos \varphi = OA/OB$

=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.

(*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.

$$\text{kVAR} = \text{kVA} \sin \phi = \frac{\text{kW}}{\cos \phi} \sin \phi$$

$$\therefore \quad \text{kVAR} = \text{kW} \tan \phi$$

(*iv*) If a capacitor is connected in parallel with the load, then the lagging reactive power o the load will be partly neutralised, thus improving the power factor of the load.

6.3 Disadvantages of Low Power Factor

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

$$P = V_L I_L \cos\phi \qquad \text{(For single phase supply)}$$

$$\therefore \quad I_L = \frac{P}{V_L \cos\phi} \qquad ...(i)$$

$$P = \sqrt{3}\, V_L I_L \cos\phi \qquad \text{(For 3 phase supply)}$$

$$\therefore \quad I_L = \frac{P}{\sqrt{3}\, V_L \cos\phi} \qquad ...(ii)$$

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 of Low Power Factor

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

Now, $kVA = kW / \cos \varphi$

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.

Disadvantages of Low 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

6.4 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.

6.5 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.

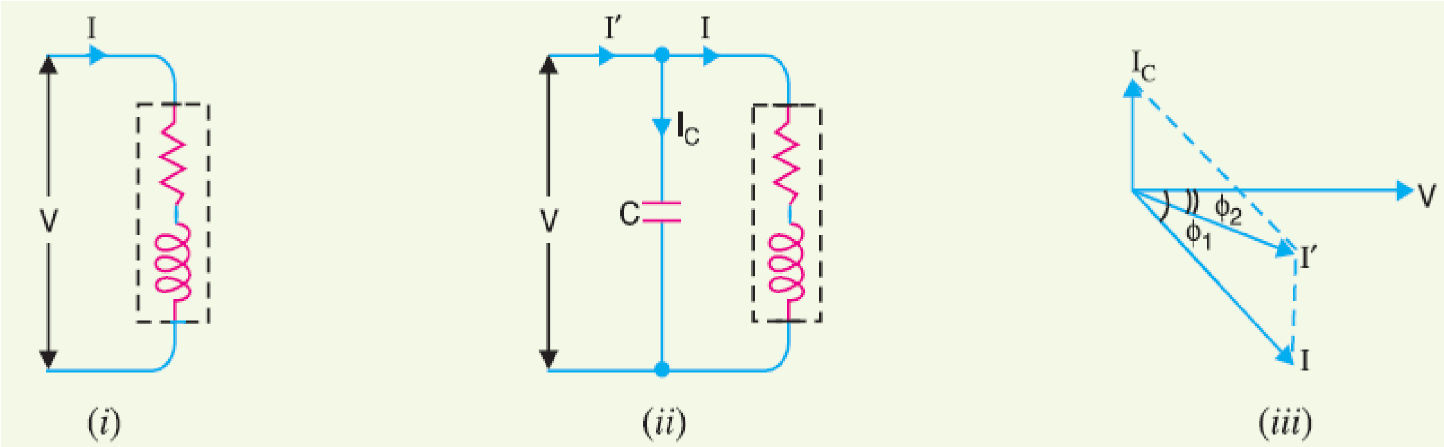

Fig. 6.3

6.6 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.

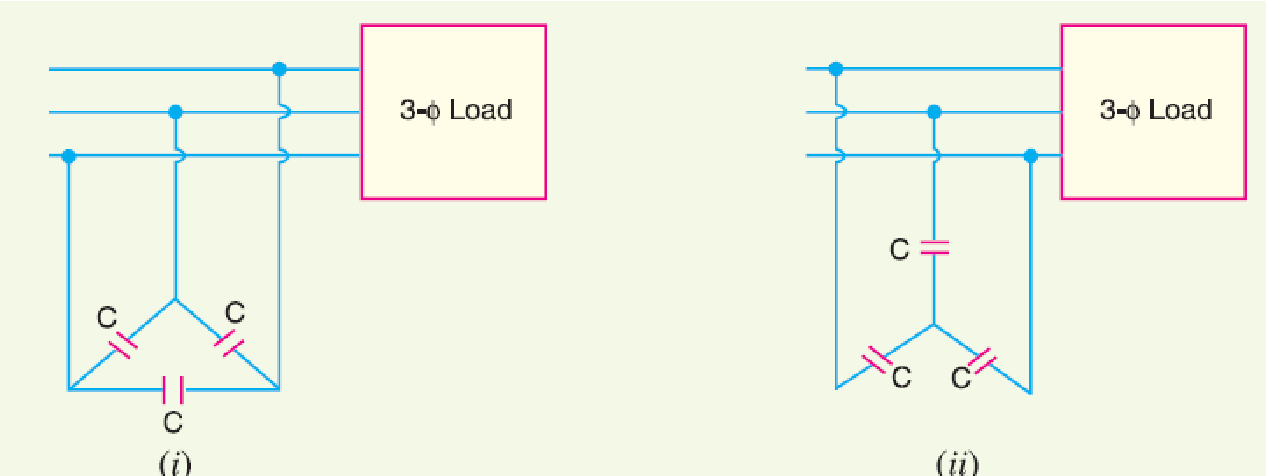

Fig. 6.4

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

6.6 Power Factor Improvement Equipment

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.

6.7 Calculations of Power Factor Correction

Consider an inductive load taking a lagging current I at a power factor cos φ1. 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. 6.6 (*i*) shows a capacitor connected across the load. The capacitor takes a current IC which leads the supply voltage V by 90^o. The current IC partly cancels the lagging reactive component of the load current as shown in the phasor diagram in Fig. 6.6 (*ii*). The resultant circuit current becomes I' and its angle of lag is φ2. It is clear that φ2 is less than φ1so that new p.f. cos φ2 is more than the previous p.f. cos φ1.

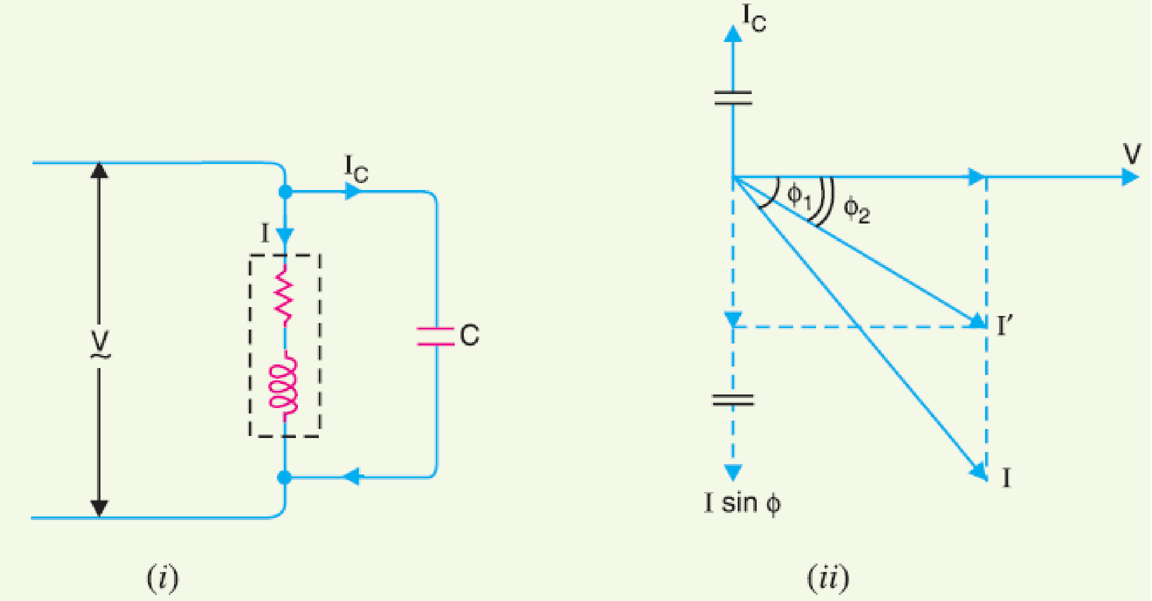

Fig. 6.6

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, $\quad I' \sin \phi_2 = I \sin \phi_1 - I_C$

or $\quad I_C = I \sin \phi_1 - I' \sin \phi_2$

$\therefore$ Capacitance of capacitor to improve p.f. from $\cos \phi_1$ to $\cos \phi_2$

$$= \frac{I_C}{\omega V} \qquad \left(\because X_C = \frac{V}{I_C} = \frac{1}{\omega C} \right)$$

Power triangle

Power triangle. The power factor correction can also be illustrated from power triangle. Thus referring to Fig. 6.7, the power triangle *OAB* is for the power factor cos φ1, whereas power triangle *OAC* is for the improved power factor cos φ2. 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 φ2.

Leading kVAR supplied by p.f. correction equipment

$= BC = AB - AC$

$$= \text{kVAR}_1 - \text{kVAR}_2$$

$$= OA\,(\tan\phi_1 - \tan\phi_2)$$

$$= \text{kW}\,(\tan\phi_1 - \tan\phi_2)$$

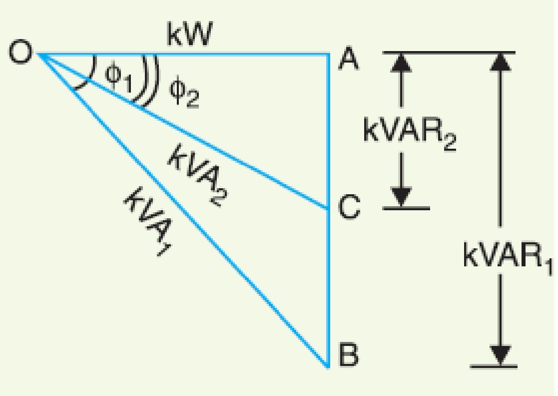

Fig. 6.7

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

Example

Example 6.1 *An alternator is supplying a load of 300 kW at a p.f. of 0·6 lagging. If the power factor is raised to unity, how many more kilowatts can alternator supply for the same kVA loading ?*

Solution :

$$\text{kVA} = \frac{\text{kW}}{\cos\phi} = \frac{300}{0 \cdot 6} = 500 \text{ kVA}$$

$$\text{kW at } 0{\cdot}6 \text{ p.f.} = 300 \text{ kW}$$

$$\text{kW at 1 p.f.} = 500 \times 1 = 500 \text{ kW}$$

$\therefore$ Increased power supplied by the alternator

$$= 500 - 300 = \mathbf{200\ kW}$$

3.8 Importance of Power Factor Improvement

(*i*) ***For consumers.*** A consumer* has to pay electricity charges for his maximum demand in kVA plus the units consumed. If the consumer improves the power factor, then there is a reduction in his maximum kVA demand and consequently there will be annual saving due to maximum demand charges. Although power factor improvement involves extra annual expenditure on account of p.f. correction equipment, yet improvement of p.f. to a *proper value* results in the net annual saving for the consumer.

(*ii*) ***For generating stations.*** A generating station is as much concerned with power factor improvement as the consumer. The generators in a power station are rated in kVA but the useful output depends upon kW output. As station output is kW = kVA × cos φ, therefore, number of units supplied by it depends upon the power factor. The greater the power factor of the generating station, the higher is the kWh it delivers to the system. This leads to the conclusion that improved power factor increases the earning capacity of the power station.

6.9 Most Economical Power Factor

If a consumer improves the power factor, there is reduction in his maximum kVA demand and hence there will be annual saving over the maximum demand charges. However, when power factor is improved, it involves capital investment on the power factor correction equipment. The consumer will incur expenditure every year in the shape of annual interest and depreciation on the investment made over the p.f. correction equipment. Therefore, the *net annual saving* will be equal to the annual saving in maximum demand charges *minus* annual expenditure incurred on p.f. correction equipment.

The value to which the power factor should be improved so as to have maximum net annual saving is known as the **most economical power factor.**

Most Economical Power Factor

Consider a consumer taking a peak load of P kW at a power factor of cos φ1and charged at a rate of Rs ***x*** per kVA of maximum demand per annum. Suppose the consumer improves the power factor to cos φ2 by installing p.f. correction equipment. Let expenditure incurred on the p.f. correction equipment be Rs ***y*** per kVAR per annum. The power triangle at the original p.f. cos φ1 is OAB and for the improved p.f. cos φ2, it is OAC.

kVA max. demand at cos ϕ_1, $\text{kVA}_1 = P/\cos\phi_1 = P\sec\phi_1$

kVA max. demand at cos ϕ_2, $\text{kVA}_2 = P/\cos\phi_2 = P\sec\phi_2$

Annual saving in maximum demand charges

$$= \text{Rs } x\,(\text{kVA}_1 - \text{kVA}_2)$$

$$= \text{Rs } x\,(P\sec\phi_1 - P\sec\phi_2)$$

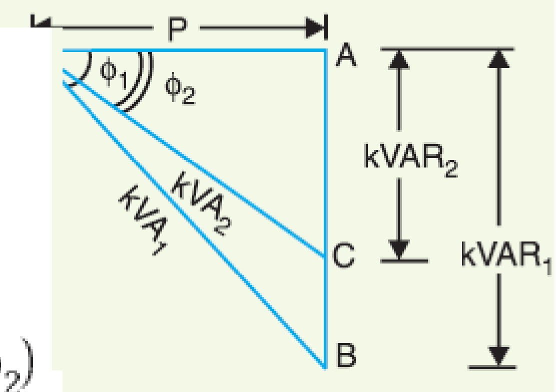

Fig. 6.13

Most Economical Power Factor

$$= \text{Rs } x\,P\,(\sec\phi_1 - \sec\phi_2) \qquad \ldots(i)$$

Reactive power at $\cos\phi_1$, $\text{kVAR}_1 = P\tan\phi_1$

Reactive power at $\cos\phi_2$, $\text{kVAR}_2 = P\tan\phi_2$

Leading kVAR taken by p.f. correction equipment

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

Annual cost of p.f. correction equipment

$$= \text{Rs } Py\,(\tan\phi_1 - \tan\phi_2) \qquad \ldots(ii)$$

$$\text{Net annual saving, } S = \text{exp. }(i) - \text{exp. }(ii)$$

$$= xP\,(\sec\phi_1 - \sec\phi_2) - yP\,(\tan\phi_1 - \tan\phi_2)$$

In this expression, only φ2 is variable while all other quantities are fixed. Therefore, the net annual saving will be maximum if differentiation of above expression *w.r.t.* φ2 is zero *i.e*

Most Economical Power Factor

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

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

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

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

or $$-x\tan\phi_2 + y\sec\phi_2 = 0$$

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

or $$\sin\phi_2 = y/x$$

∴ Most economical power factor, $$\cos\phi_2 = \sqrt{1-\sin^2\phi_2} = \sqrt{1-(y/x)^2}$$

It may be noted that the most economical power factor (*cos φ2*) depends upon the relative costs of supply and *p.f.* correction equipment but is independent of the original *p.f. cos φ1*.

Example

Example 6.13 *A factory which has a maximum demand of 175 kW at a power factor of 0·75 lagging is charged at L.E 72 per kVA per annum. If the phase advancing equipment costs L.E 120 per kVAR, find the most economical power factor at which the factory should operate. Interest and depreciation total 10% of the capital investment on the phase advancing equipment.*

Solution :

Power factor of the factory, cos φ1 = 0·75 lagging

Max. demand charges, *x* = L.E 72 per kVA per annum

Expenditure on phase advancing equipment, *y* = L.E 120 × 0·1 = Rs 12* /kVAR/annum

Most economical p.f. at which factory should operate is

$$\cos \phi_2 = \sqrt{1-(y/x)^2} = \sqrt{1-(12/72)^2} = \mathbf{0{\cdot}986\ lagging}$$

Example 6.14 *A consumer has an average demand of 400 kW at a p.f. of 0·8 lagging and annual load factor of 50%. The tariff is L.E 50 per kVA of maximum demand per annum plus 5 piaster per kWh. If the power factor is improved to 0·95 lagging by installing phase advancing equipment, calculate :*
(*i*) *the capacity of the phase advancing equipment*
(*ii*) *the annual saving effected*
The phase advancing equipment costs L.E 100 per kVAR and the annual interest and depreciation together amount to 10%.

Solution :

Max. kW demand, $P = 400/0{\cdot}5 = 800$ kW

Original p.f., $\cos \varphi 1 = 0{\cdot}8$ lag ; Final p.f., $\cos \varphi 2 = 0{\cdot}95$ lag

$\varphi 1 = \cos^{-1} (0{\cdot}8) = 36{\cdot}9^o$; $\tan \varphi 1 = \tan 36{\cdot}9^o = 0{\cdot}75$

$\varphi 2 = \cos^{-1} (0{\cdot}95) = 18{\cdot}2^o$; $\tan \varphi 2 = \tan 18{\cdot}2^o = 0{\cdot}328$

(*i*) Leading kVAR taken by phase advancing equipment

$= P(\tan \varphi 1 - \tan \varphi 2) = 800\,(0{\cdot}75 - 0{\cdot}328) = 337$ kVAR

∴ Capacity of phase advancing equipment should be **337 kVAR.**

Most Economical Power Factor

(*ii*) Max. demand charges, x = L.E 50/kVA/annum

Expenditure on phase advancing equipment

y = L.E 0·1 × 100 = L.E 10/kVAR/annum

Max. kVA demand at 0·8 p.f. = 800/0·8 = 1000 kVA

Max. kVA demand at 0·95 p.f. = 800/0·95 = 842 kVA

Annual saving in maximum demand charges

= L.E 50 (1000 − 842) = L.E 7900

Annual expenditure on phase advancing equipment

= L.E (y × capacity of equipment)

= L.E 10 × 337 = 3370

∴ Net annual saving = L.E (7900 − 3370) = **L.E 4530**