Lecture 2. Energy Efficient Electrical Services Part 1

Energy Efficient Electrical Services

Much energy is needlessly wasted in buildings through poor design and maintenance of electrical services. The energy that is wasted is of the worst kind, namely expensive electrical energy, which can be up to five times as expensive as the unit cost of heat.

Unfortunately, excessive electrical energy consumption is all too often overlooked by misguided building designers, who focus on thermal energy consumption, which is relatively inexpensive. Much of energy is wasted through poorly designing lighting systems, running pumps and fans and heating systems.

There are a number of relatively simple technologies that can be applied to motor drives and luminaire installations to dramatically reduce energy costs.

2.1. Power Factor

Electric induction motors and fluorescent lamp fittings are classic examples of reactive (i.e. inductive) electrical loads. Reactive (A.C circuits) electrical loads are important because, unlike resistive loads such as incandescent light, they cause the current to become out of phase with the voltage. This, in simple terms, means that items of equipment which are inductive in nature draw a larger current than would be anticipated by their useful power rating. Ultimately, it is the consumer who has to pay for this additional current.

Power factor can be defined as the "The cosine of angle between voltage and current in an a.c circuit".

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. 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 figure 2.1:

- 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.

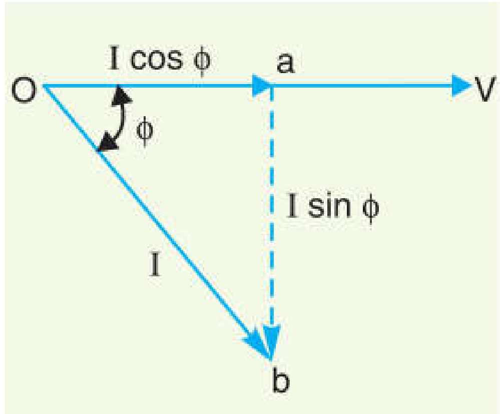

Figure 2.1

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.

- 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.
- Sometimes power factor is expressed as a percentage. Thus 0·8 lagging power factor may be expressed as 80% lagging.

2.2. Power Triangle

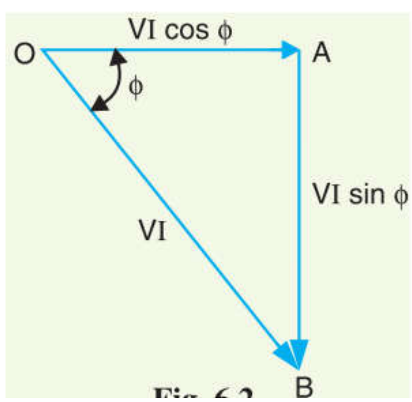

Figure 2.2

- *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

$$Power\ Factor, cos\ \theta = \frac{OA}{OB} = \frac{Active\ power}{apparent\ power} = \frac{kW}{kVA}$$

- Thus the power factor of a circuit may also be defined as the ratio of active power to the apparent power.
- 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
  *(*If the current lags behind the voltage, the reactive power drawn is known as lagging reactive power. However, if the circuit current leads the voltage, the reactive power is known as leading reactive power.)*
- 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 neutralized, thus improving the power factor of the load.
- The power factor of a circuit can be defined in one of the following three ways:

$$Power\ factor = cos\theta = cosine\ of\ angle\ between\ V\ and\ I$$

$$Power\ factor = \frac{R}{Z} = \frac{Resistance}{Impedance}$$

$$Power\ factor = \frac{VIcos\theta}{VI} = \frac{Active\ power}{Apparent\ Power}$$

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

Suppose a circuit draws a current of 10 A at a voltage of 200 V and its p.f. is 0·8 lagging:

$$Apparent\ power = VI = 200 \times 10 = 2000VA$$

$$Active\ power = VIcos\theta = 200 \times 10 \times 0.8 = 1600W$$

$$Reactive\ power = VIsin\theta = 200 \times 10 \times 0.6 = 1200VAR$$

The circuit receives an apparent power of 2000 VA and is able to convert only 1600 watts into active power. The reactive power is 1200 VAR and does no useful work. It merely flows into and out of the circuit periodically. In fact, reactive power is a liability on the source because the source has to supply the additional current (*i.e., I* sin φ).

2.3 Disadvantages of Low Power Factor

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

For single phase supply.

$$P = V_L I_L cos\theta$$

$$I_L = \frac{P}{V_L cos\theta}$$

For 3 phase supply.

$$P = \sqrt{3} V_L I_L cos\ \theta$$

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

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.

Say, $kVA = \frac{kW}{cos\ \theta}$

* The electrical machinery is rated in kVA because the power factor of the load is not known when the machinery is manufactured in the factory.

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 utilization 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 utilization of installed capacity.

2.4 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 magnetization current. This results in the decreased power factor.

2.5 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 neutralizes the lagging reactive component of load current. This raises the power factor of the load.

2.5 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:

(i) Static capacitors.
(ii) Synchronous condenser.
(iii)Phase advancers.

Assignment One:

Give (and explain) at least three advantages and three disadvantages of the following p.f correction equipment.

(i) Static capacitors.
(ii) Synchronous condenser.
(iii)Phase advancers.

2.6 Calculations of Power Factor Correction

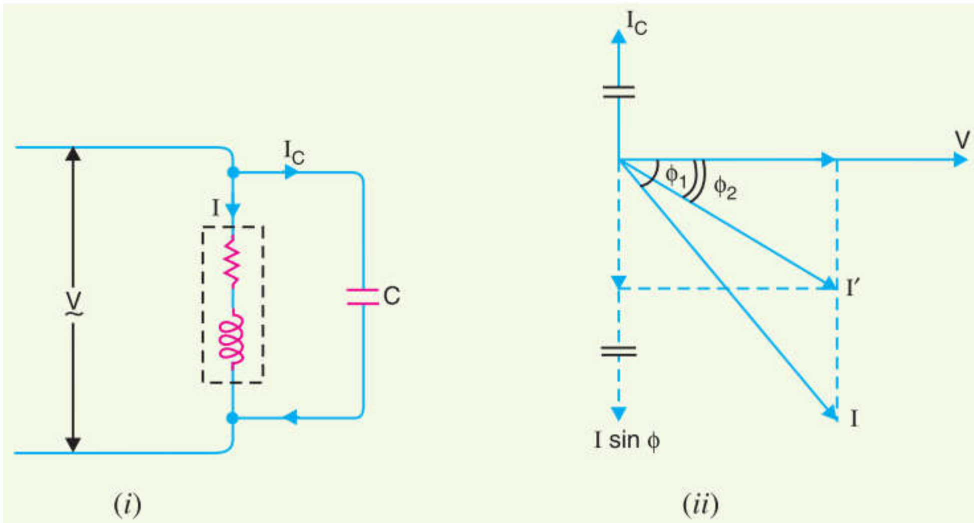

Figure 2.3

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. 2.3 (*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. 2.3(*ii*). The resultant circuit current becomes *I*′ and its angle of lag is φ_2. It is clear that φ_2 is less than φ1so that new p.f. cos φ_2 is more than the previous p.f. cos φ_1.

From the phasor diagram, it is clear that after p.f. correction, the lagging reactive component of the load is reduced to *I*′sin φ_2.

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

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

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

$$= \frac{I_C}{wV}\left(Because, X_C = \frac{V}{I_C} = \frac{1}{wC}\right)$$

#Show that $X_C = \frac{V}{I_C} = \frac{1}{wC}$

Power triangle.

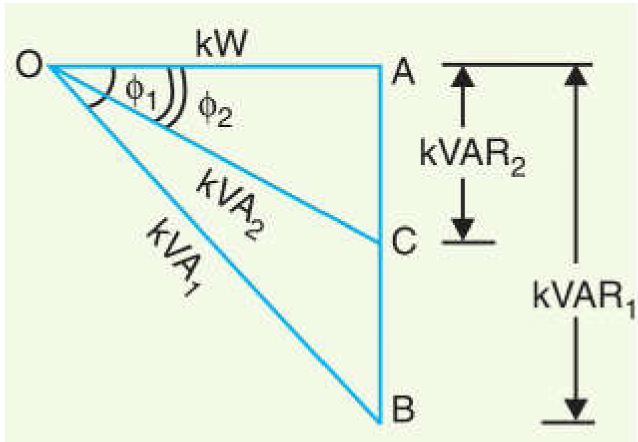

Figure 2.4

The power factor correction can also be illustrated from power triangle. Thus referring to Fig. 2.4, the power triangle *OAB* is for the power factor cos φ_1, 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 φ_2

Leading kVAR supplied by p.f. correction equipment

$$= BC = AB - AC$$

$$= kVAR_1 - kVAR_2$$

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

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

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

Example 2.1

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:

$$kVA = \frac{kW}{cos\phi} = \frac{300}{0.6} = 500kVA$$

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

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

∴ Increased power supplied by the alternator= 500 - 300 = **200 kW**

Note the importance of power factor improvement. When the p.f. of the alternator is unity, the 500 kVA are also 500 kW and the engine driving the alternator has to be capable of developing this power together with the losses in the alternator. But when the power factor of the load is 0·6, the power is only 300 kW. Therefore, the engine is developing only 300 kW, though the alternator is supplying its rated output of 500 kVA.

Example 2.2

A single phase motor connected to 400 V, 50 Hz supply takes 31·7A at a power factor of 0·7 lagging. Calculate the capacitance required in parallel with the motor to raise the power factor to 0·9 lagging.

Solution:

The circuit and phasor diagrams are shown in Figs. 2.5 and 2.6 respectively. Here motor *M* is taking a current I_M of 31·7A. The current I_C taken by the capacitor must be such that when combined with I_M, the resultant current *I* lags the voltage by an angle φ where cos φ = 0·9.

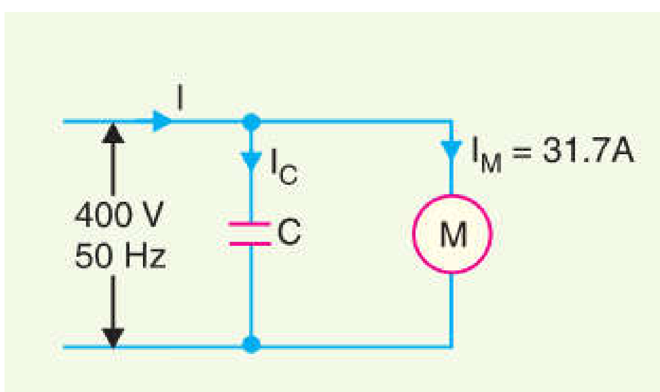

Fig.2.5

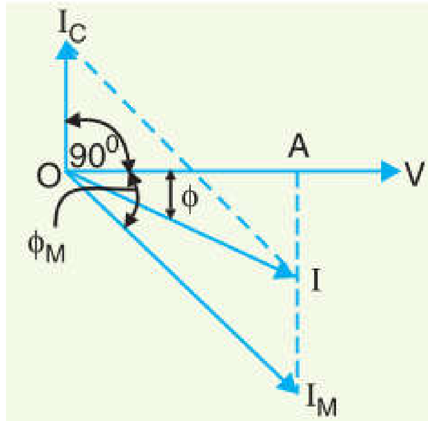

Fig.2.6

Referring to the phasor diagram in Fig. 2.6

$$Active\ component\ of\ I_M = I_M cos\phi_M = 31.7 \times 0.7 = 22.19A$$

$$Active\ component\ of\ I = Icos\phi = I \times 0.9$$

These components are represented by *OA* in Fig. 2.6

$$I = \frac{22.19}{0.9} = 24.65A$$

$$Reactive\ component\ of\ I_M = I_M sin\phi_M = I_M\sqrt{1 - cos^2\phi_M}$$

$$= 31.7 \times \sqrt{1 - (0.7)^2} = 31.7 \times 0.714 = 22.6A$$

$$Reactive\ component\ of\ I = Isin\phi = 24.65\sqrt{1 - (0.9)^2}$$

$$= 24.65 \times 0.436 = 10.75A$$

$$I_C = Reactive\ component\ of\ I_M - Reactive\ component\ of\ I$$

$$= 22.6 - 10.75 = 11.85A$$

$$But, I_C = \frac{V}{X_C} = V \times 2\pi fC$$

$$11.85 = 400 \times 2\pi \times 50 \times C$$

$$C = 94.3 \times 10^{-6}F = 94.3\mu F$$

Homework Exercise 2.1

A factory operates at 0·8 p.f. lagging and has a monthly demand of 750 kVA. The monthly power rate is Ksh. 8·50 per kVA. To improve the power factor, 250 kVA capacitors are installed in which there is negligible power loss. The installed cost of equipment is Ksh. 20,000 and fixed charges are estimated at 10% per year. Calculate the annual saving effected by the use of capacitors.

Importance of Power Factor Improvement

The improvement of power factor is very important for both consumers and generating stations as discussed below:

(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.

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.**

Consider a consumer taking a peak load of *P* kW at a power factor of cos φ1and charged at a rate of Ksh. *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 Ksh 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 [See Fig. 2.7].

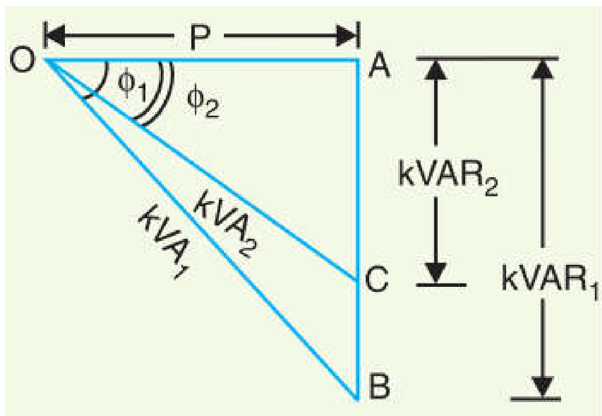

Fig.2.7

$$kVA\ max.demand\ at\ cos\phi_1, kVA_1 = P/cos\phi_1 = Psec\phi_1$$

$$kVA\ max.demand\ at\ cos\phi_2, kVA_2 = P/cos\phi_2 = Psec\phi_2$$

Annual saving in maximum demand charges

$$Ksh.x(kVA_1 - kVA_2)$$

$$Ksh.x(Psec\phi_1 - Psec\phi_2)$$

$$= Ksh.xP(sec\phi_1 - sec\phi_2) \dots\dots..(i)$$

$$Reactive\ power\ at\ cos\phi_1, kVAR_1 = Ptan\phi_1$$

$$Reactive\ power\ at\ cos\phi_2, kVAR_2 = Ptan\phi_2$$

Leading kVAR taken by p.f. correction equipment

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

Annual cost of p.f. correction equipment

$$= Ksh.Py(tan\kappa\phi_1 - tan\phi_2) \ldots\ldots\ldots.(ii)$$

Net annual saving, *S* = exp. (*i*) - exp. (*ii*)

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

In this expression, only φ_2 is variable while all other quantities are fixed. Therefore, the net annual saving will be maximum if differentiation of above expression *w.r.t.* φ_2 is zero *i.e.*

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

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

$$\frac{dy}{d\phi_2}(xPsec\phi_1) - \frac{dy}{d\phi_2}(xPsec\phi_2) - \frac{dy}{d\phi_2}(yPtan\phi_1) + yP\frac{dy}{d\phi_2}(tan\phi_2) = 0$$

$$0 - xPsec\phi_2 tantan\phi_2 - 0 + yPsec^2\phi_2 = 0$$

$$-xtan\phi_2 + ysec\phi_2 = 0$$

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

$$sin\phi_2 = {}^{y}/_{x}$$

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

It may be noted that the most economical power factor (cos φ_2) depends upon the relative costs of supply and p.f. correction equipment but is independent of the original p.f. cos φ_1.

Example 2.4

A factory which has a maximum demand of 175 kW at a power factor of 0·75lagging is charged at Ksh 72 per kVA per annum. If the phase advancing equipment costs Ksh.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.

$$Power\ factor\ of\ the\ factory, cos\phi_1 = 0.75\ lagging$$

$$Max. demand\ charges, x = Ksh. 72\ per\ kVA\ annum.$$

$$Expenditure\ on\ phase\ advancing\ equipment, y = Ksh. 120 \times 0.1$$
$$= Ksh. 12/kVAR/annum$$

The total investment for producing 1 kVAR is Ksh. 120. The annual interest and depreciation is 10%. It means that an expenditure of Ksh. 120 × 10/100 = Ksh.12 is incurred on 1 kVAR per annum.

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

$$cos\phi_2 = \sqrt{1 - (\frac{y}{x})^2} = \sqrt{1 - (12/72)^2} = 0.986$$