Power Distribution Systems

Lecture 8

Reactive Power Compensation

Introduction

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

Power factor is the measure of how effectively your electrical equipment converts electric power (supplied by your power utility) into useful power output.

In technical terms, it is the **ratio of Active Power** (kW)) to **the Apparent Power** (kVA) of an electrical installation.

$$\text{Power factor, } \cos\phi = \frac{\text{Active Power}}{\text{Reactive Power}} = \frac{\text{kW}}{\text{kVA}}$$

Introduction

kW is Working Power (also called Actual Power or Active Power or Real Power). It is the power that actually powers the equipment and performs useful work.

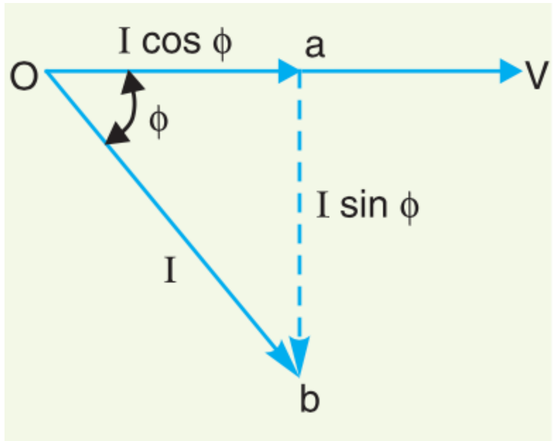
kVAR is Reactive Power. It is the power that magnetic equipment (transformer, motor and relay) needs to produce the magnetizing flux.

kVA is Apparent Power. It is the “vectorial summation” of kVAR and kW.

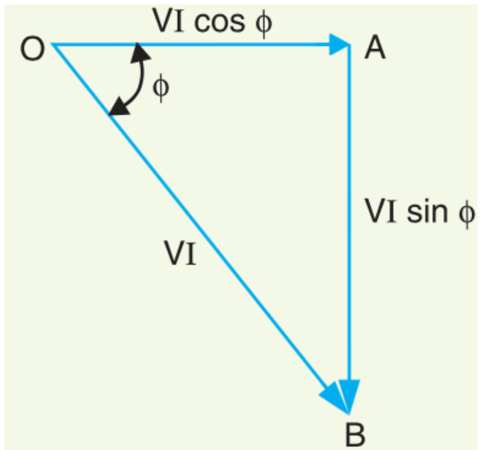
Power Factor

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 figure on the side.



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 first figure is multiplied by voltage *V*, then we get the power triangle *OAB* shown in second figure.



It may be noted that value of power factor can never be more than unity.

Power Factor

Let us illustrate the power relations in an a.c. circuit with an example. Suppose a circuit draws a current of 10 A at a voltage of 200 V and its p.f. is 0·8 lagging. Then,

Apparent power	$= VI$	$=200\times10$	$=2000$VA
Active power	$= VI\cos\phi$	$=200\times10\times0{\cdot}8$	$=1600$W
Reactive power	$= VI\sin\phi$	$=200\times10\times0{\cdot}6$	$=1200$VAR

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.,* $I \sin \phi$).

Power Factor

Simple analogy in order to better understand these terms....

•Electrical power comes in two distinct parts – just like a frothy latte

•The coffee body is ‘active power’ that you can use to do work.

•The froth on top is ‘reactive power’. Some is useful, but too much is simply a waste – the same as the foam you leave behind in your glass.

$$\text{Power Factor} = \frac{\text{Real Power kW } \textit{coffee}}{\sqrt{\text{Apparent Power } (\text{kW}^2 + \text{kVAr}^2)\ \textit{coffee + froth}}}$$

What Causes Low Power Factor

Most loads (80%) in electrical distribution system are inductive in nature. The cause of low power factor is only due to inductive loads. Inductive loads responsible for low p.f. are as follows;

Transformers draws a magnetizing current from the supply. At normal load this current does not affect the p.f., but they draws larger amount of magnetizing current at light load, causes low primary current p.f.

Most of ac motors are induction type motors (1Φ and 3 Φ). At light load these motors work at extremely low p.f. of the order of 0.2 to 0.3 and rises to 0.8 or 0.9 at full load.

Arc lamps, electric discharge lamps, welding equipment and industrial heating furnaces operated at low lagging power factor.

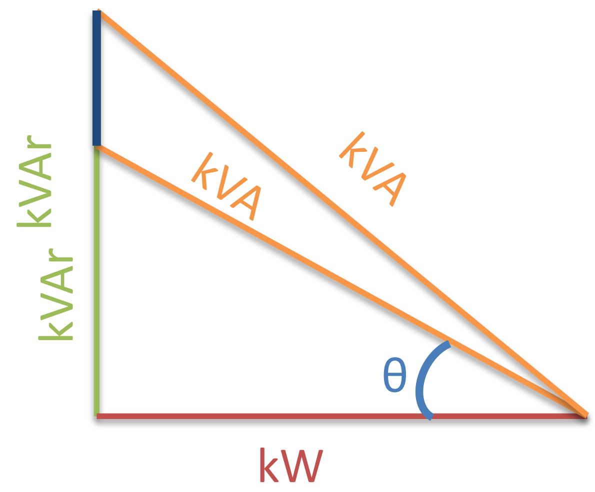
What Causes Low Power Factor

Different types of electrical load have different Power Factors according to its nature.

Name of Equipment	Power Factor Percent
Lightly loaded induction motor	0.20 Lagging
Full Loaded induction motor	0.80 Lagging
Neon-lighting equipment	0.30 - 0.70 Lagging
Incandescent lamps	1.0 Unity
All types of resistance heating devices (e.g. toaster, heater)	1.0 Unity

What Causes Low Power Factor

Reactive power (KVAR) required by inductive loads increases the amount of apparent power (KVA) in distribution system.
This increase in reactive and apparent power results in a larger angle measured between KW and KVA.
As θ increases, cosine θ (or power factor) decreases.



Why should the Power Factor be Improved?

Lower the Utility bill

Inductive loads require reactive power, caused your low power factor. This increase in required reactive power (KVAR) causes an increase in required apparent power (KVA), which is what the utility is supplying.

So, a facility's low power factor causes the utility to have to increase its generation and transmission capacity in order to handle this extra demand.

To penalize customers for low power factors (generally lower than 0.9), utilities apply reactive power charge.

By raising your power factor, you use less kVAr.

In Turkiye, reactive penalty limits are as noted below

$Q_L/P=0.33$ $Q_C/P=0.20$ for contracted power is between 9 kW and 29.9 kW

$Q_L/P=0.20$ $Q_C/P=0.15$ for contracted power is higher than 29.9 kW

Why should the Power Factor be Improved?

Smaller kVA Rating

Electric machines (alternators, transformers, switchgears) are always rated in kVA. kVA rating of any equipment varies inversely with the p.f., therefore low p.f. increases the kVA rating, as a result kVA rating making the equipment larger and expensive.

By raising the power factor, kVA rating can be reduced

For example, a 1,000 kVA transformer with an 80% power factor provides 800 kW (600 kVAr) of power to the main bus.

$$1000\ \text{kVA} = \sqrt{(800\ \text{kW})^2 + (\ ?\ \text{kVAr})^2}$$

$$\text{kVAr} = 600$$

By increasing the power factor to 90%, more kW can be supplied for the same amount of kVA.

$$1000\ \text{KVA} = \sqrt{(900\ \text{kW})^2 + (\ ?\ \text{kVAr})^2}$$

$$\text{kVAr} = 436$$

The kW capacity of the system increases to 900 kW and the utility supplies only 436 kVAr.

Why should the Power Factor be Improved?

Smaller Conductor Size

To transmit a fixed amount of power at constant voltage, the conductor will have to carry more current at low factor. 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.

Reduced diameter of conductors

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

Why should the Power Factor be Improved?

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Less Copper Losses

The larger amount of current at low power factor causes more IR^2 losses in all the elements of the system.

The higher power factor, the less copper losses

Improved Voltage Regulation

Larger amount of current produces large voltage drops (IR drops) in alternators, transformers, transmission lines and distributors. This results in poor voltage regulation.

By raising the cos θ, voltage drops can be reduced meaning better voltage regulation

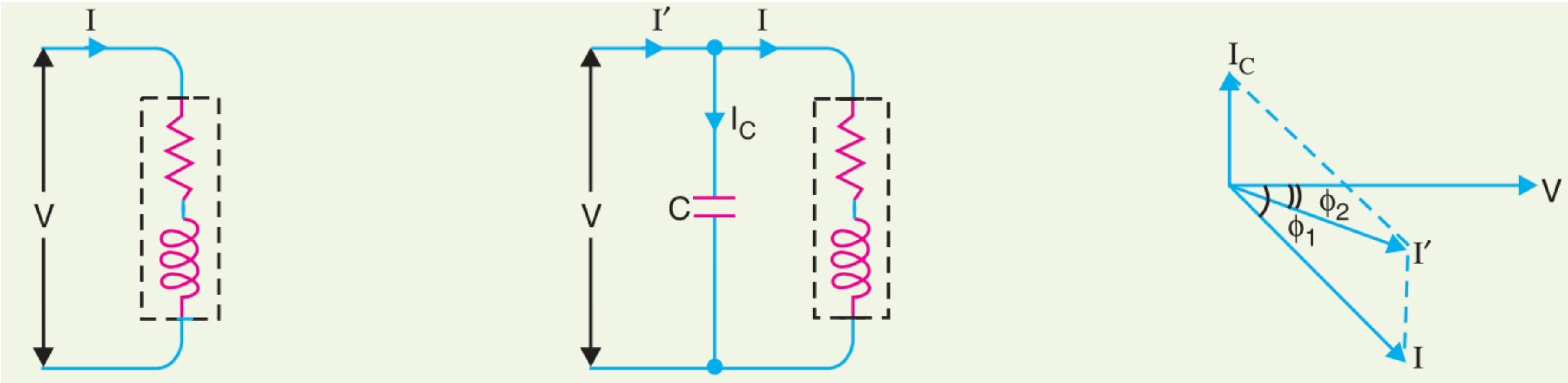
Power Factor Improvement

Poor power factor can be improved by compensation.

The process of supplying reactive power (lagging or leading) to bring the P.F closer to unity is known as power factor correction or improvement.

Power Factor Improvement

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.



The circuit current I' after p.f. correction is less than the original circuit current I.

$$I\cos\phi_1 = I'\cos\phi_2$$
$$I'\sin\phi_2 = I\sin\phi_1 - I_C$$
$$VI'\sin\phi_2 = VI\sin\phi_1 - VI_C$$

Net kVAr *after* p.f. correction = Lagging kVAr *before* p.f. correction − leading kVAr of equipment

Power Factor Improvement

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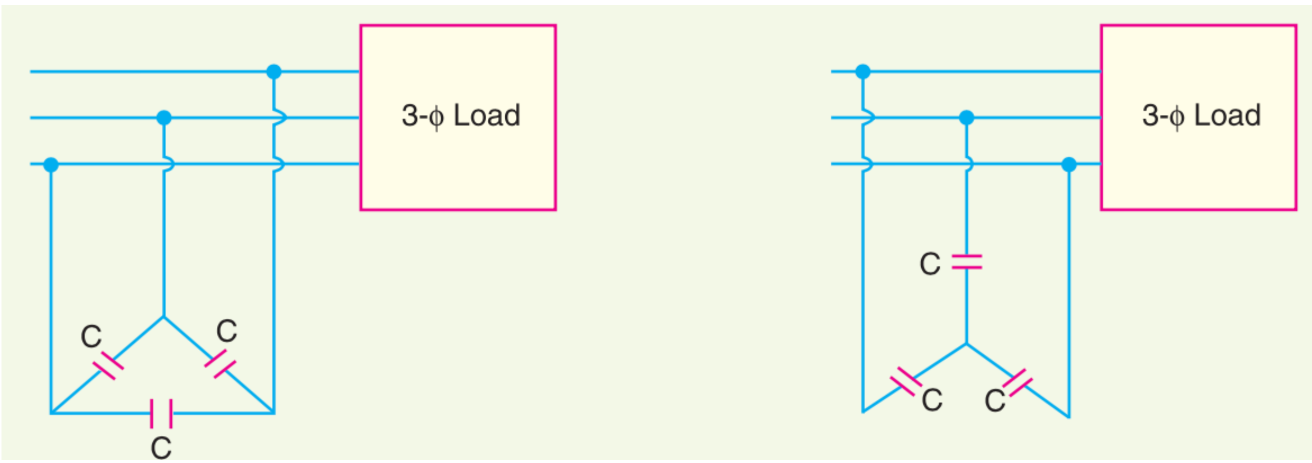
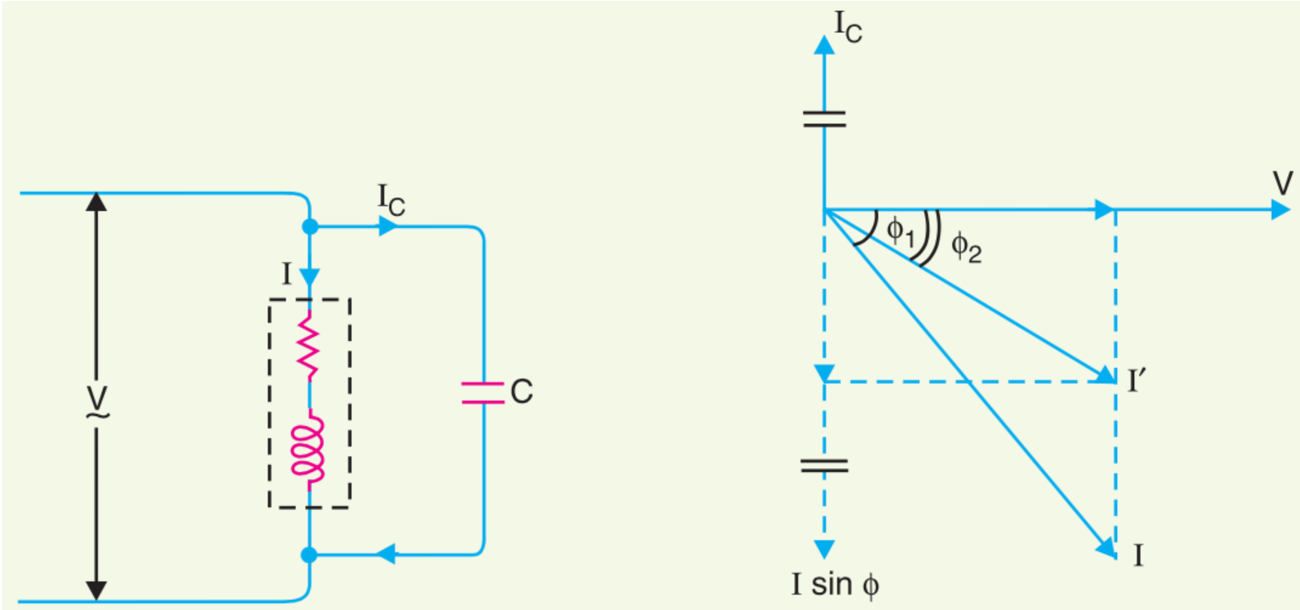
The power factor can be improved by connecting capacitors or synchronous condenser (over-excited synchronous motor running on no load) in parallel with the equipment operating at lagging power factor. (The lagging p.f. is assumed)

The capacitor (generally known as static 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. For three-phase loads, the capacitors can be connected in delta or star.



Calculations of Power Factor Correction

Consider an inductive load taking a lagging current *I* at a power factor $\cos\phi_1$.



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

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

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

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

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

Calculations of Power Factor Correction

The power factor correction can also be illustrated from power triangle.

Leading kVAr supplied by p.f. correction equipment = $BC = AB - AC$

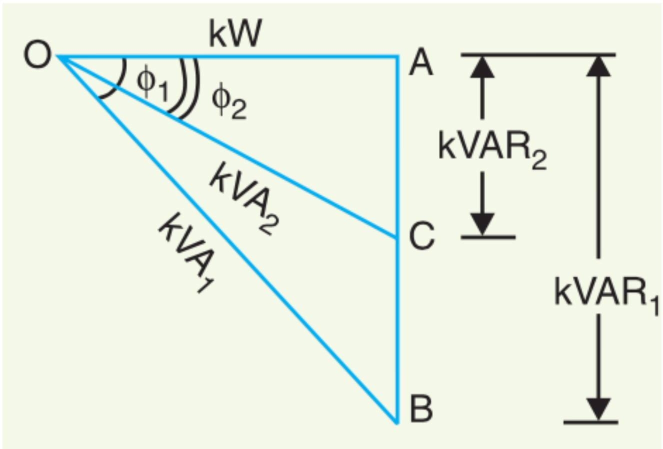
$= kVAr - kVAr_{12}$

$= OA(\tan\phi - \tan\phi)_{12}$

$= kW(\tan\phi - \tan\phi\ )_{12}$

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

Correct amount of capacitance must be used, otherwise p.f. goes from lagging to leading which is also undesired condition.



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Example 8.1

A single phase motor connected to 400 V, 50 Hz supply takes 31.7 A 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.

Example 8.2

A single phase a.c. generator supplies the following loads :

(*i*) *Lighting load of 20 kW at unity power factor.*

(*ii*) *Induction motor load of 100 kW at p.f. 0.707 lagging.*

(*iii*) *Synchronous motor load of 50 kW at p.f. 0.9 leading.*

Calculate the total kW and kVA delivered by the generator and the power factor at which it works.

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Example 8.3

A 3-phase, 5 kW induction motor has a p.f. of 0.75 lagging. A bank of capacitors is connected in delta across the supply terminals and p.f. raised to 0.9 lagging. Determine the kVAr rating of the capacitors connected in each phase.

Example 8.4

A 3-phase, 50 Hz, 400 V motor develops 100 H.P. (74.6 kW), the power factor being 0.75 lagging and efficiency 93%. A bank of capacitors is connected in delta across the supply terminals and power factor raised to 0.95 lagging. Each of the capacitance units is built of 4 similar 100 V capacitors. Determine the capacitance of each capacitor.

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Example 8.5

A factory operates at 0.8 p.f. lagging and has a monthly demand of 750 kVA. The monthly power rate is \$ 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 \$ 20,000 and fixed charges are estimated at 10% per year. Calculate the annual saving effected by the use of capacitors.