6.1. Concept of Power Factor

- **Power factor** is the factor upto which the power is **actively used** out of the total power generated. **Meaning,** the power generated is apparent power, out of which, the active usable power is apparent power times the power factor.
- The **Power Factor (P.F.)** is a ratio of the real power that is used to do work and the apparent power that is supplied to the circuit.
- $P.F. = \frac{kW}{kVA}$
- The P.F. is widely known as the **cosine angle** between fundamental voltage and current.
- The P.F. is a **dimensionless number** in the closed interval of 0 to 1.
- Power factors are usually stated as **"leading"** or **"lagging"** to show the sign of the phase angle.
- The P.F. of 1 means that the voltage and current waveforms are **in phase**.
- When the power factor is 1, all the energy supplied by the source is consumed by the load.
- The P.F. of less than or greater than 1 means that the voltage and current waveforms are **not in phase**.
- **Capacitive loads** are leading (current leads voltage), and **inductive loads** are lagging (current lags voltage).
- Due to energy stored in the load and returned to the source, or due to a non-linear load that **distorts the wave shape** of the current drawn from the source.

6.2. Types of Power Factor

From the concept, power factor can be classified as following:

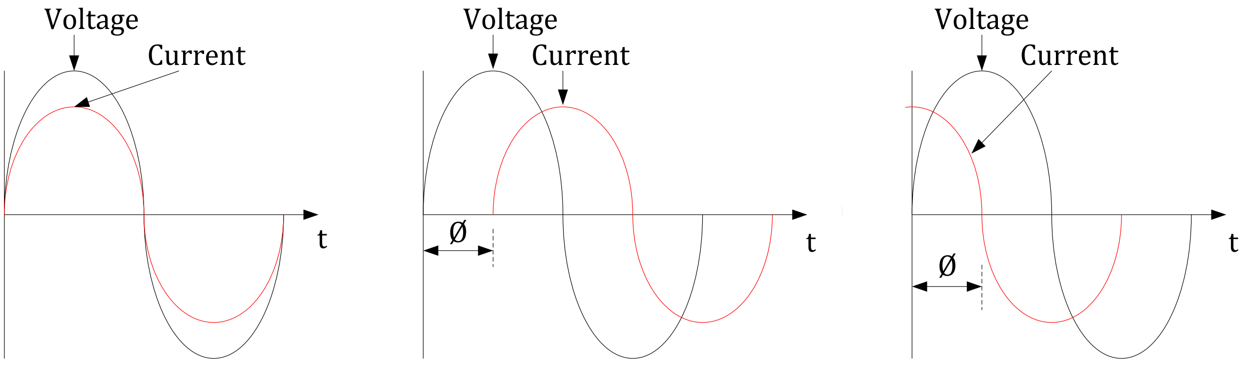
1) As per the supply consideration;
    - Displacement power factor
    - True power factor
2) As per the nature of load consideration;
    - Unity power factor
    - Lagging power factor
    - Leading power factor

Displacement power factor

- **Displacement power factor** is the cosine of the angle between fundamental voltage and current waveforms.
- **The fundamental waveforms** are by definition pure sinusoids. But if the waveform distortion is due to harmonics, the power factor angles are different than what would be for the fundamental wave alone.
- The **presence of harmonics** also affects overall power factor of the system.

True power factor or Distortion power factor

- True power factor is calculated as the ratio between the total active power used in a circuit (including harmonics) and the total apparent power (including harmonics) supplied from the source.
- $\textbf{True power factor} = \frac{\textbf{Total active power}}{\textbf{Total apparent power}}$
- Utility penalties are based on the true power factor of a facility.



Resistive circuit
Ø = 0, Unity power factor

Inductive circuit
Lagging power factor

Capacitive circuit
Leading power factor

Figure 6.1 Types of power factor as per nature of load

As shown in figure 6.1,

Unity power factor (for resistive load)

- If a purely resistive load is connected to a power supply, current and voltage will change polarity in step, the power factor will be unity (1), and the electrical energy flows in a single direction across the network in each cycle.
- When the power factor is 1, all the energy supplied by the source is consumed by the load.
- Unity power factor occurs in resistive type load.
- For pure resistive load, power factor angle becomes 0°.

Lagging power factor (for inductive load)

- If the resulting current phase angle is more negative in relation to the driving (source) voltage phase angle, then the power factor is said to be **"lagging".**
- Lagging power factor occurs in inductive type load.
- For pure inductive load, power factor angle becomes 90°.

Leading power factor (for capacitive load)

- If the resulting current phase angle is more positive in relation to the driving (source) voltage phase angle, then the power factor is said to be **"leading".**
- Leading power factor occurs in inductive type load.
- For pure capacitive load, power factor angle becomes -90°.

- The driving (source) voltage phase is often assumed to be zero (for convenience) and in that situation it is immediately obvious that a lagging power factor condition is indicated by a negative sign for the current phase angle. Similarly a positive sign for the current phase angle indicates a leading power factor.

6.3. Power Factor Correction

Two ways to improve the power factor and minimize the apparent power drawn from the power source are:

1) Reduce the lagging reactive current demand of the loads
2) Compensate for the lagging reactive current drawn by supplying leading reactive current to the power system

- Lagging reactive current represent the inductance of the power system and power system components.
- Lagging reactive current demand may not be totally eliminated but may be reduced by using power system devices or components designed to operate with low reactive current requirements.
- Practically no devices in a typical power system require leading reactive current to function; therefore, in order to produce leading currents certain devices must be inserted in a power system.
- These devices are referred to as power factor correction equipment.

Advantages of power factor improvement

- Reduces reactive component of network
- Reduces total current in system from source to end
- Reduces $I^2 R$ power losses
- Increases Voltage level at load end (i.e. voltage drop is reduced)
- Reduces kVA loading on source generators
- Reduces kVA loading on transformers
- Reduces Line and cable loading
- High P.F. can help in utilizing the full capacity of the electrical system
- Reduces heating in equipments
- Reduces energy losses and operating costs
- Increases equipment life

Cost benefits of power factor improvement

- Reduces kVA charges (Maximum Demand charges) in utility billing
- Reduces distribution losses (kWh) within plant network
- Improves voltage at motor terminals and performance of motors
- Eliminates penalty charges
- Reduces an investment on system facilities such as transformers, cables, switchgears etc.

Example:

- A chemical industry has installed a 1500 kVA transformer
- Actual Maximum Demand (M.D.) was 1160 kVA at 0.70 P.F. lagging
- %Loading of transformer was 77.30% (i.e. 1160/1500)
- Industry installs 410 kVAr capacitors to improve P.F.

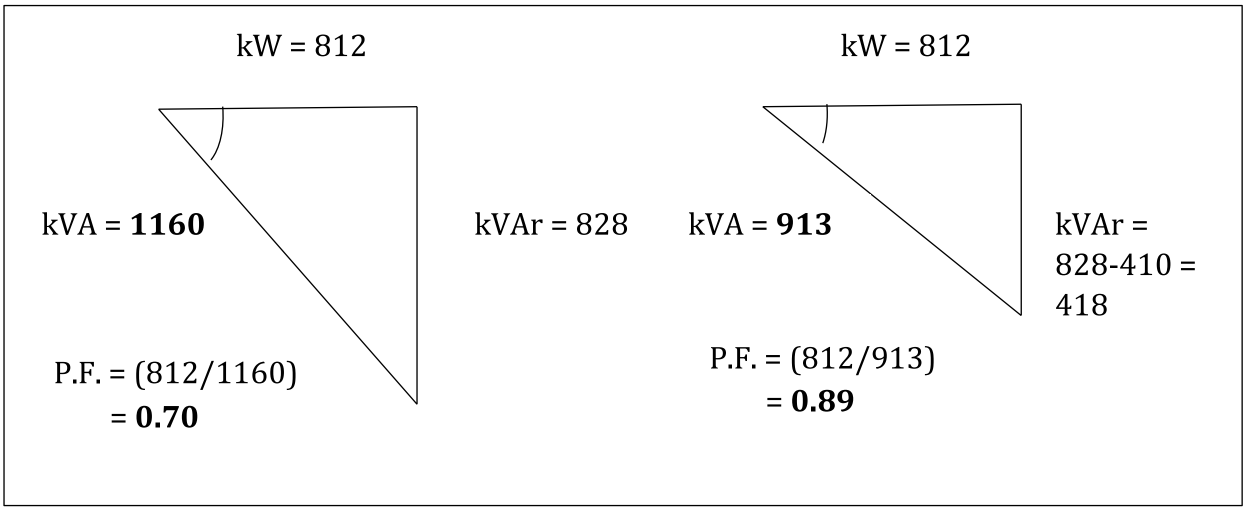


Figure 6.2 Power factor before and after improvement

6.4. Addition of capacitors at different locations of power system for power factor correction

- There are following major three locations in the distribution system where capacitors could be installed for power factor correction.

Case-1 Capacitor on supply terminal of equipment

Advantages:

1) Increases load capability of distribution system
2) Can be switched with equipment
3) No additional switching is required
4) Better voltage regulation
5) Capacitor sizing is simplified
6) Capacitors are coupled with equipment and move with equipment if rearrangements are instituted

Disadvantages:

1) Small capacitors have more per kVAr cost than larger units

Note: The rating of capacitor should not be greater than no-load magnetizing kVAr of motor. It may create over-voltage or transient torque.

Case-2 Capacitor with group of equipments

Advantages:

1) Increases load capability of the service

2) Reduces material costs relative to individual correction
3) Reduces installation costs relative to individual correction

Disadvantages:

1) Switching means may be required to control amount of capacitance used

Note: The capacitors installed at PCC or MCC level can be grouped together.

When several motors are running intermittently, the capacitors are permitted to be on line all the time, reducing kVA demand regardless of the load.

Case-3 Capacitor at main service (at PCC and MCC)

Advantages:

1) Low installation cost

Disadvantages:

1) Switching will be required to control amount of capacitance used
2) Does not improve the load capabilities of the distribution system

Note:

1) From energy point of view, capacitor location at receiving substation helps utility to reduce losses.
2) Locating capacitors at tail end (user end) will help to reduce losses within the plant and directly benefit the user by reduced consumption.
3) At user end, %Distribution losses in kWh will be proportional to

$$\left[\mathbf{1}-\left(\frac{\boldsymbol{PF1}}{\boldsymbol{PF2}}\right)^{\mathbf{2}}\right]\times\mathbf{100}$$

As per Bureau of Efficiency's guidelines (BEE),

The required kVAr

to improve power factor, $= \mathrm{kW}\times[\tan\{\cos^{-1}P.F.1\}-\tan\{\cos^{-1}P.F.2\}]$

Where, kW = Total running plant load

P.F.1 = Existing power factor (e.g. 0.85)

P.F.2 = Improved power factor (e.g. 0.99)

6.5. Performance Assessment of Power Factor Correction Capacitors

There are basically four points which should be considered for assessment of power factor capacitors.

- **Voltage Effects**
  a. Ideally capacitor voltage rating is to match the supply voltage.
  b. If voltage is lower, the reactive **kVAr produced will be the ratio** $\left(\frac{\boldsymbol{V1}}{\boldsymbol{V2}}\right)^{\mathbf{2}}$

  Where, V1 = Actual supply voltage

V2 = Rated voltage

- **Material of capacitors**
  a. Paper / Polypropylene
  b. Power loss per kVAr in capacitors as well as life vary w.r.t. choice of dielectric material
- **Connections**
  a. Shunt capacitor connections for almost all applications
  b. Series capacitors are adopted for voltage boosting in distribution
- **Operational Performance**
  a. By monitoring capacitor charging current w.r.t. rated charging current
  b. Capacity of fused elements should be as per requirements
  c. Portable analyzers can be used for measuring kVAr and currents
  d. Capacitors consume 0.2 to 6.0 watt per kVAr, which is negligible in comparison to benefits

LTBC- H 25 kvar

Heavy Duty 25 kvar Power Capacitor

Un	Qn 50 Hz	In 50 Hz
440 V	25.0 kvar	32.8 Amp
415 V	22.2 kvar	30.9 Amp
400 V	20.7 kvar	29.9 Amp

3X137.1 μF 3 Phase D SH MPP
-10/D Case Max 65° C NPCB
Ui 3/-kV
IS 13340:1993
IS: 13340
CM/L 1432640
E
06N13
Sr.No.1110319871 87
DISCHARGE CAPACITOR BEFORE HANDLING

Figure 6.3 Typical name-plate of power factor correction capacitor

Few Crosschecks:

a. Nameplates can be misleading w.r.t. ratings
b. It is good to check actual charging currents
c. Capacitor boxes may contain only insulated compound and insulated terminals with no capacitor element inside
d. Capacitors for 1-phase motor starting and those for lighting circuits for voltage boost, are not power factor capacitors and these cannot withstand power system conditions

Figure 6.3 shows the typical nameplate of power factor correction capacitor

6.6. Automatic Power Factor Controller (APFC)

- The name **APFC** (**A**utomatic **P**ower **F**actor **C**ontroller), itself explains the function and the purpose of it (Figure 6.4).

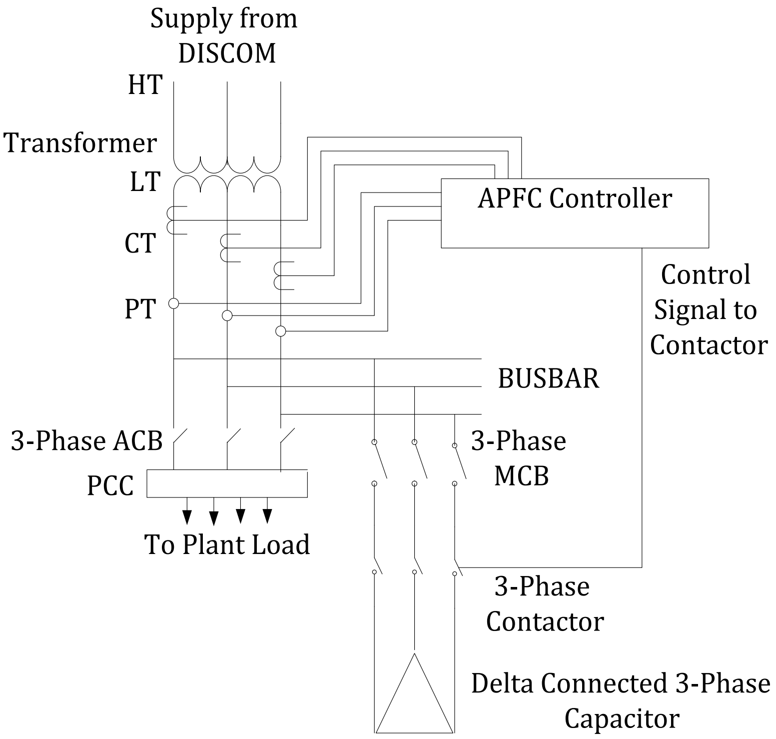


Figure 6.4 Typical diagram of automatic power factor controller

- As per the name, it is the bank of capacitors switched by an automatic controller.
- Figure 6.4 shows only one capacitor for simplicity, in actual practice bank of capacitors are used.
- It is an automatic system adjusting itself to control the P.F. above a desired value by a bank of capacitors switched by means of contactors.
- The contactors are controlled by a regulator that measures P.F. In the network.
- Depending upon the load reactance (kVAr), the controller will adjust the P.F. by switching the necessary no. of capacitors from the bank.
- The switched capacitors compensate required load kVAr.

There are basically three types of APFC technology used for power factor correction.

- ➢ Conventional contactor based switching (Figure 6.4)
- ➢ L-C based switching
- ➢ Thyristorised switching

6.7. Voltage rise due to capacitance

- The flow of capacitive current through the power system impedance can actually produce a voltage rise.
- Depending on the voltage levels and the reactive power demand of the loads, the capacitors may be switched in or out in discreet steps.

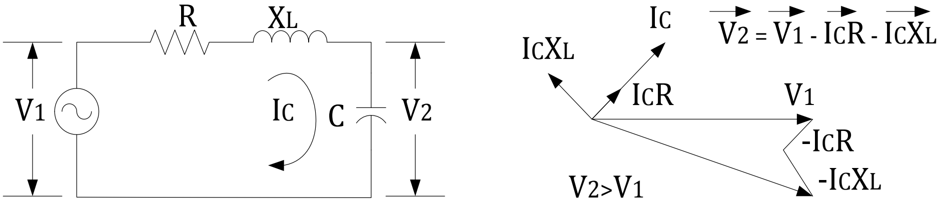


Figure 6.5 Schematic and phasor diagram showing voltage rise due to capacitive current flowing through line impedance diagram of automatic power factor controller

- The **Voltage rise** in the power system is one reason why the utilities do not permit large levels of uncompensated leading kVAr to be drawn from the power lines (Figure 6.5).
- During the process of **selecting capacitor banks for power factor correction**, the utilities should be consulted to determine the level of leading kVAr that can be drawn.
- But, **during light load periods**, the leading reactive power is not fully compensated and therefore might be objectionable to the utility.
- For applications **where large swings in reactive power** requirements are expected, a switched capacitor bank might be worth the investment.

6.8. Application of Synchronous Condenser for Power Factor Improvement

- One means of providing leading reactive power is by the use of synchronous motors. Synchronous motors applied for power factor control are called synchronous condensers (Figure 6.6).
- A synchronous motor normally draws lagging currents, but when its field is overexcited, the motor draws leading reactive currents.

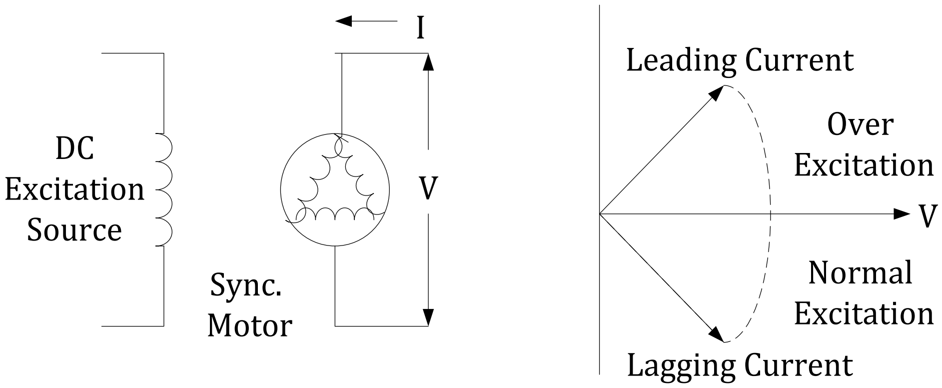


Figure 6.6 Synchronous condenser for power factor correction

- By adjusting the field currents, the **synchronous motor** can be made to operate in the lagging, unity, or leading power factor region.
- The facilities that contain large AC motors are best suited for the application. Replacing an AC induction motor with a synchronous motor operating in the leading power factor region is an effective means of power factor control.
- The **synchronous motors** are more expensive than conventional induction motors due to their construction complexities and associated control equipment.

- Some facilities and utilities use **unloaded synchronous motors** strictly for leading reactive power generation.
- The advantage of using a synchronous condenser is the lack of harmonic resonance problems sometimes found with the use of passive capacitor banks.

6.9. Application of Static VAR compensator for Power Factor Improvement

- **The Static VAR compensators** (SVCs) use static power control devices such as SCRs or IGBTs and switch a bank of capacitors and inductors to generate reactive currents of the required makeup.
- **The reactive power** is needed for several reasons. As we saw earlier, leading reactive power is needed to improve the power factor and also to raise the voltage at the end of long power lines.
- **The lagging reactive power** is sometimes necessary at the end of long transmission lines to compensate for the voltage rise experienced due to capacitive charging currents of the lines.
- **An Uncompensated**, such power lines can experience a voltage rise beyond what is acceptable. The reactors installed for such purposes are called line charge compensators.

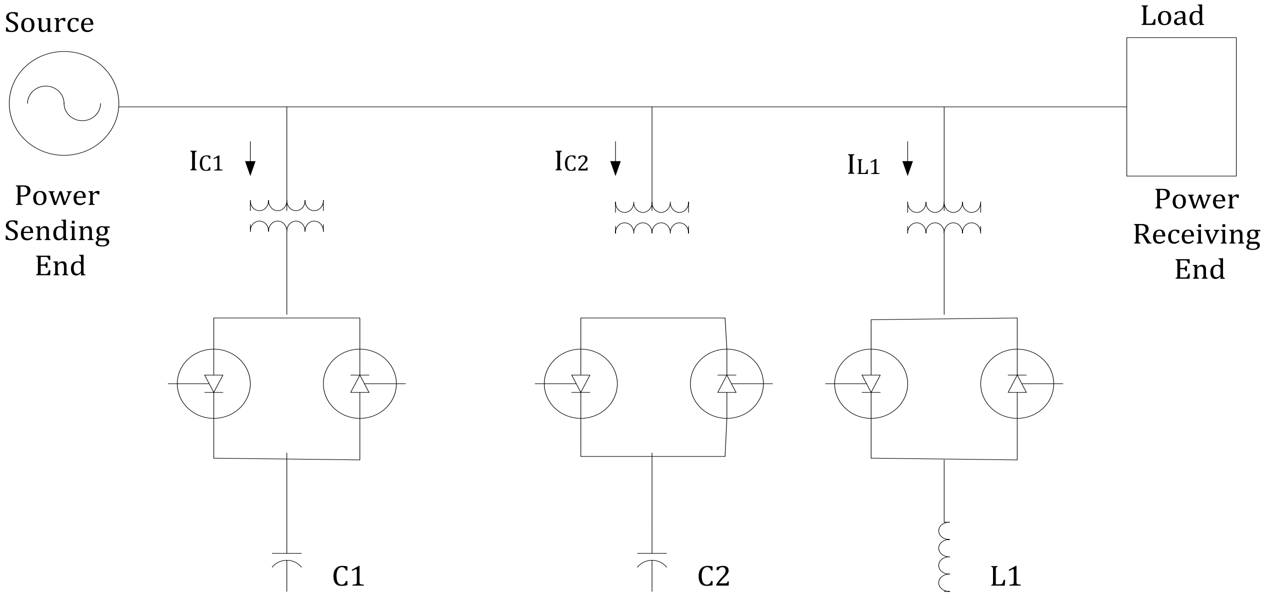


Figure 6.7 Static VAR compensator draws optimum amount of leading and lagging currents to maintain required voltage and power factor levels

- **The Static VAR compensators** perform both functions as needed. Figure contains a typical arrangement of an SVC.
- **By controlling the voltage** to the capacitors and inductors, accurate reactive current control is obtained.
- **One drawback of using SVCs** is the generation of a considerable amount of harmonic currents that may have to be filtered. The cost of SVCs is also high, so they will not be economical for small power users.
- Figure 6.7 shows typical arrangement of static VAR compensator.

6.10. Example

- **Example statement:** A 5-MVA transformer is loaded to 4.5 MVA at a power factor of 0.82 lag. Calculate the leading kVAr necessary to correct the power factor to 0.95 lag. If the transformer has a rated conductor loss equal to 1% of the transformer rating, calculate the energy saved assuming 24-hour operation at the operating load.

  Given Data:

  - Transformer capacity (rated) = 5 MVA
  - Transformer actual loading = 4.5 MVA
  - Load power factor = 0.82 lagging
  - Rated transformer loss = 1% of transformer rating
  - Operating hours = 24
  - CosØ1 = 0.82 lagging
  - CosØ2 = 0.95 lagging

  Task:

  - Required leading kVAr to correct power factor at 0.95 lagging

  Calculations:

$$Existing\ power\ factor\ angle = \emptyset_1 = \cos^{-1} 0.82 = 34.9°$$

$$Corrected\ power\ factor\ angle = \emptyset_2 = \cos^{-1} 0.95 = 18.2°$$

$$P = S_1 \cos \emptyset_1 = 4.5 \times 0.82 = 3.69\ MW$$

$$Q_1 = S_1 \sin \emptyset_1 = 4.5 \times 0.572 = 2.574\ MVAr$$

$$Q_2 = P \tan \emptyset_2 = 3.69 \times \tan 18.2 = 1.214\ MVAr$$

The leading MVAr necessary to improve the power factor from 0.82 to 0.95

= Q_1-Q_2 = **1.362 MVAr**

For a transformer load with improved power factor,

$$S_2 = \sqrt{{P_2}^2 + {Q_2}^2} = 3.885\ MVA$$

The change in transformer conductor loss = $\left[\left(\frac{4.5}{5}\right)^2 - \left(\frac{3.885}{5}\right)^2\right] = 0.206\ p.u.$

of rated losses, hence, the total energy saved = 0.206×50×24 = 247.2 kWh/day

= **90228 kWh/annum**

@7 Rs./kWh, total savings in cost = 90228×7 = **631596 Rs./annum**
