Durham University

# Electrical Engineering 2

## ENGI2191

### Power Factor Correction or Reactive Power Compensation

## Lecture Objectives:

### Aim of this lecture:

The aim of this lecture is to understand the concepts of power factor correction or reactive power compensation in electrical networks and power systems.

### Intended Learning Outcomes:

**At the completion of the lecture and associated problems you should be able to:**

- Understand the concept of reactive power in electric networks.
- Identify the importance of reactive power in electric networks.
- Calculate capacitive reactive power for power factor correction.

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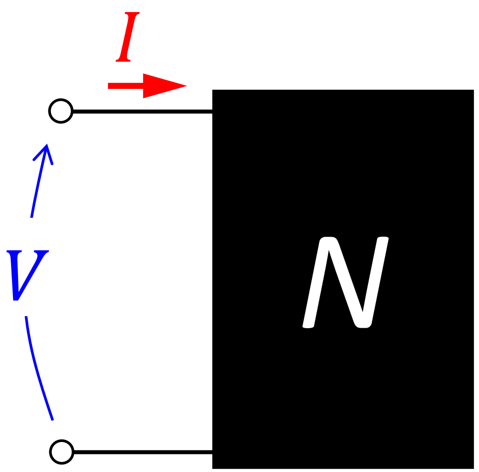
# Power Factor Correction or Reactive Power Compensation

## Complex Power and Components:




$$\boldsymbol{V} = V_{rms} < \theta_v$$

$$\boldsymbol{I} = I_{rms} < \theta_i$$

$$\boldsymbol{S} = \underbrace{V_{rms} I_{rms} \cos(\varphi)}_{\text{Active power, P}} + j \underbrace{V_{rms} I_{rms} \sin(\varphi)}_{\text{Reactive power, Q}}$$

$$P = \mathrm{Re}\,[\mathbf{S}] = V_{rms} I_{rms} \cos(\varphi)$$ **W, kW, MW**

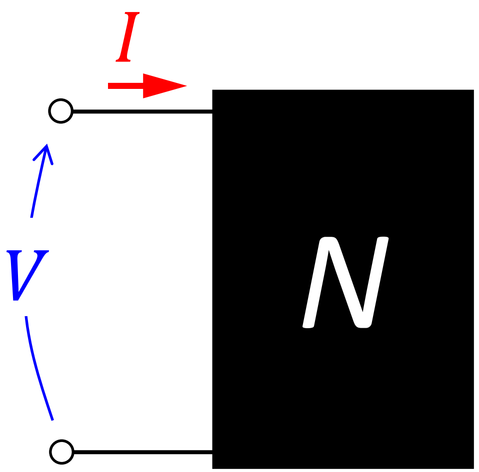
$$Q = \mathrm{Im}\,[\mathbf{S}] = V_{rms} I_{rms} \sin(\varphi)$$ **VAR, kVAR, MVAR**

$$\boldsymbol{S} = P + jQ$$

**The magnitude of the complex power *S* is defined as apparent power:**

$$S = |\boldsymbol{S}| = \sqrt{P^2 + Q^2} = V_{rms}\, I_{rms}$$ **VA, kVA, MVA**

## Complex Power and Components:



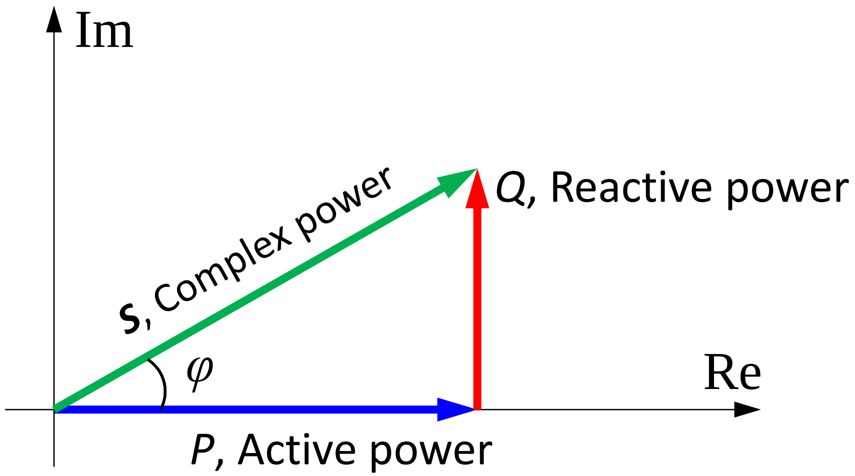

$$\boldsymbol{S} = V_{rms} I_{rms}\ \cos(\varphi) + j\, V_{rms} I_{rms}\ sin\ (\varphi)$$

$$\boldsymbol{S} = P + jQ$$

$$\boldsymbol{V} = V_{rms} < \theta_v$$

$$\boldsymbol{I} = I_{rms} < \theta_i$$

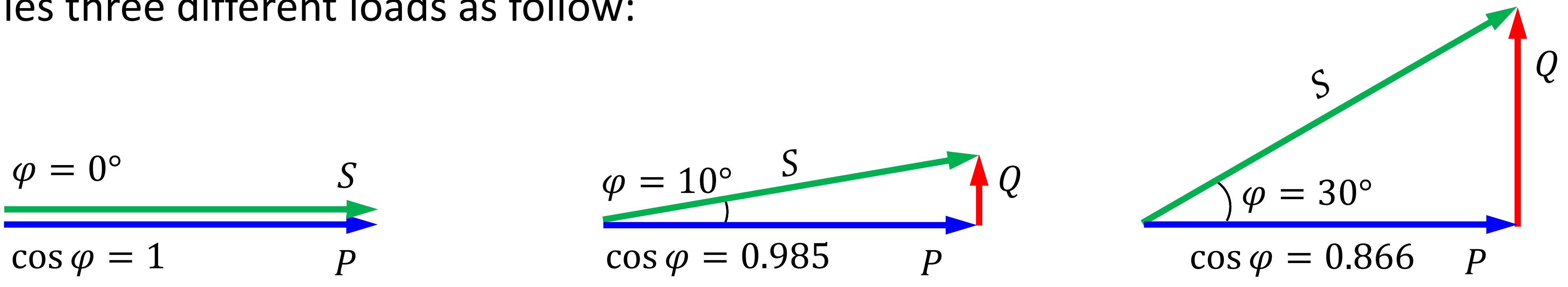
The relationship between complex, active and reactive power is shown by a phasor diagram, known as "power triangle":




$$\begin{cases} P = S\ \cos(\varphi) \\ Q = S\ \sin(\varphi) \end{cases}$$

## Power factor correction:

An electric generator with apparent power of $S = 100\ kVA$ is assumed. This generator supplies three different loads as follow:

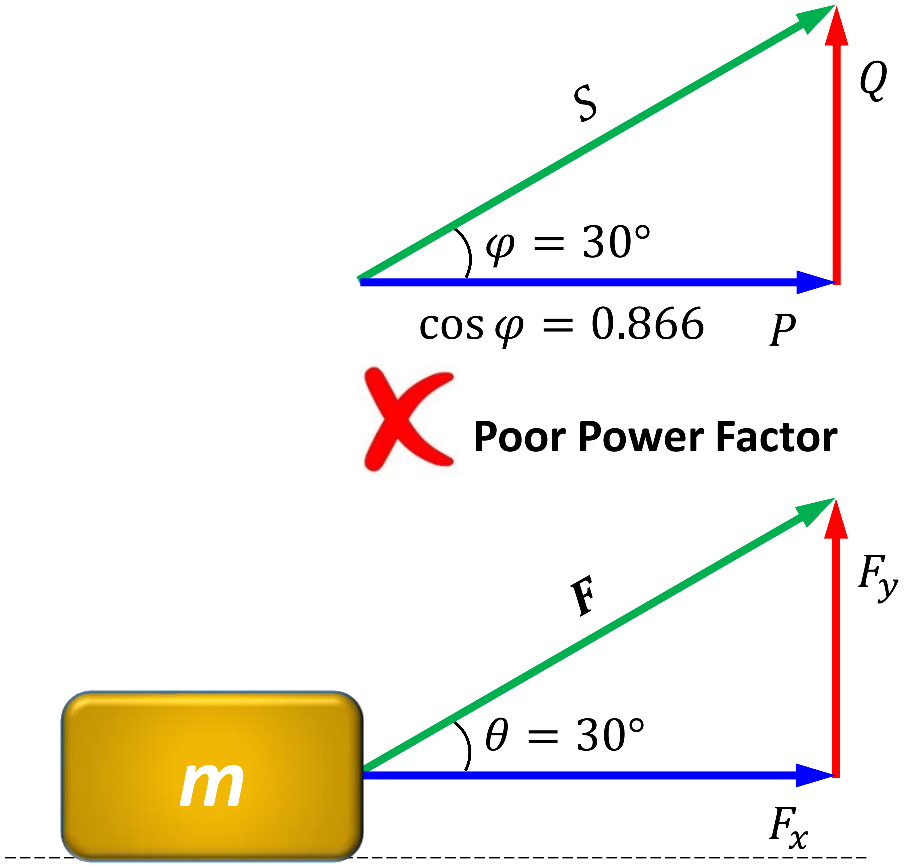


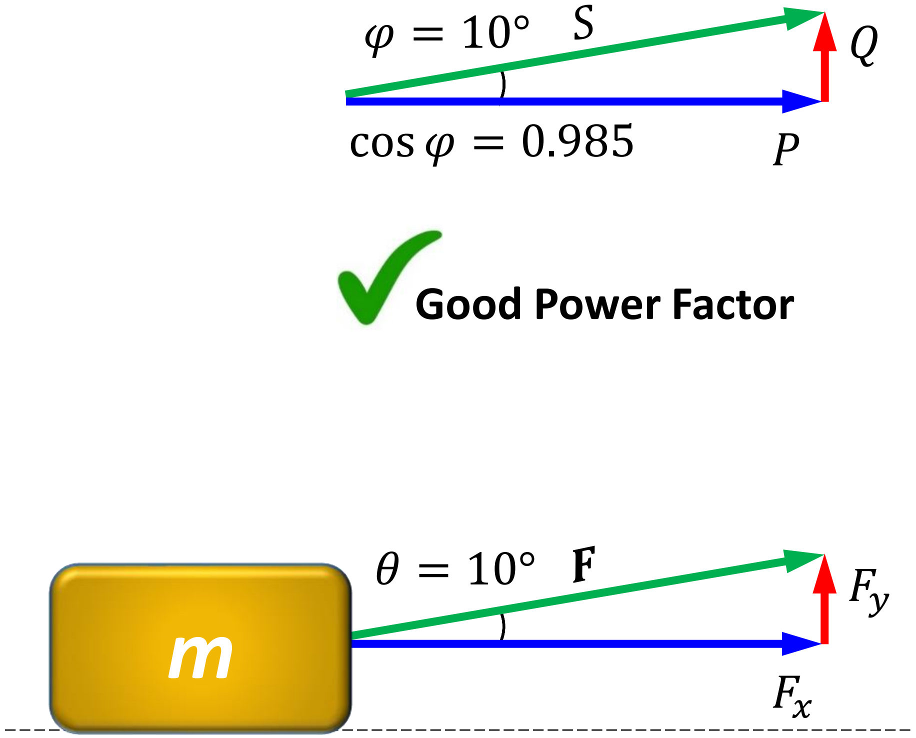

$$\begin{cases} P = 100\ kW \\ Q = 0 \end{cases} \qquad \begin{cases} P = 98.5\ kW \\ Q = 17.4\ kVAR \end{cases} \qquad \begin{cases} P = 86.6\ kW \\ Q = 50\ kVAR \end{cases}$$

The generator can generate $100\ kW$ active power under unity power factor (resistive load). However, with inductive loads the effective power is reduced by a factor of $\cos\varphi$.

**This results in lower operational efficiency.**

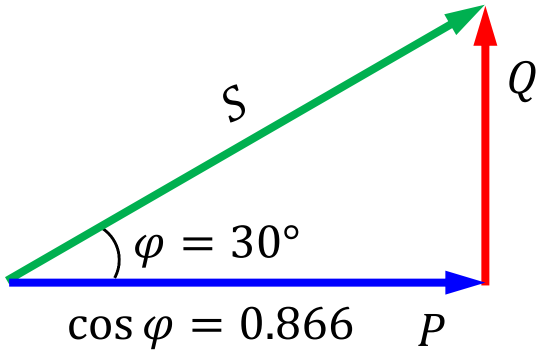
## Power factor correction:



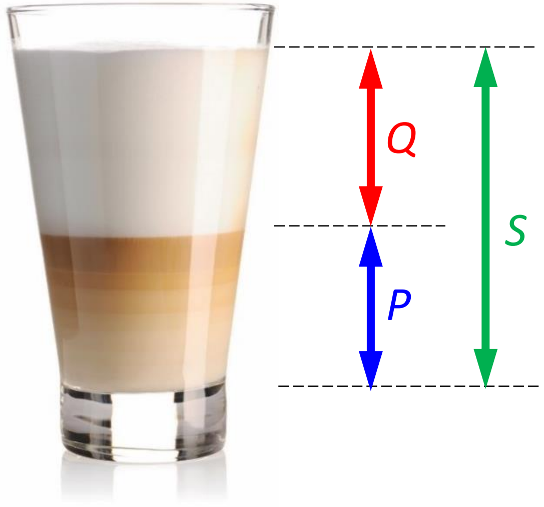



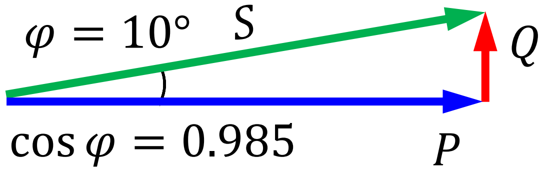

In the design and operation of electric networks and power systems, high power factor (low reactive power) is always a key objective.

## Power factor correction:

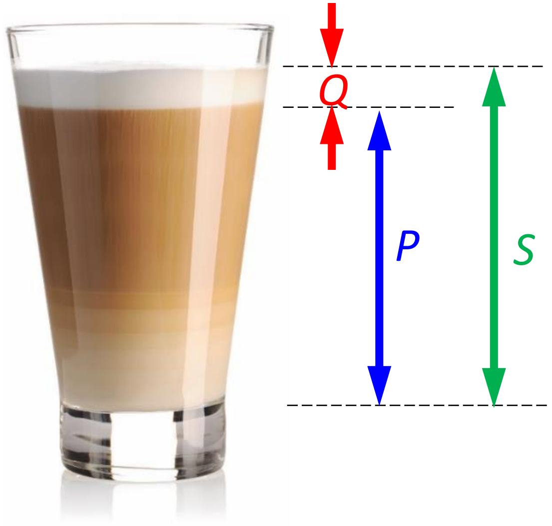



Poor Power Factor




Good Power Factor

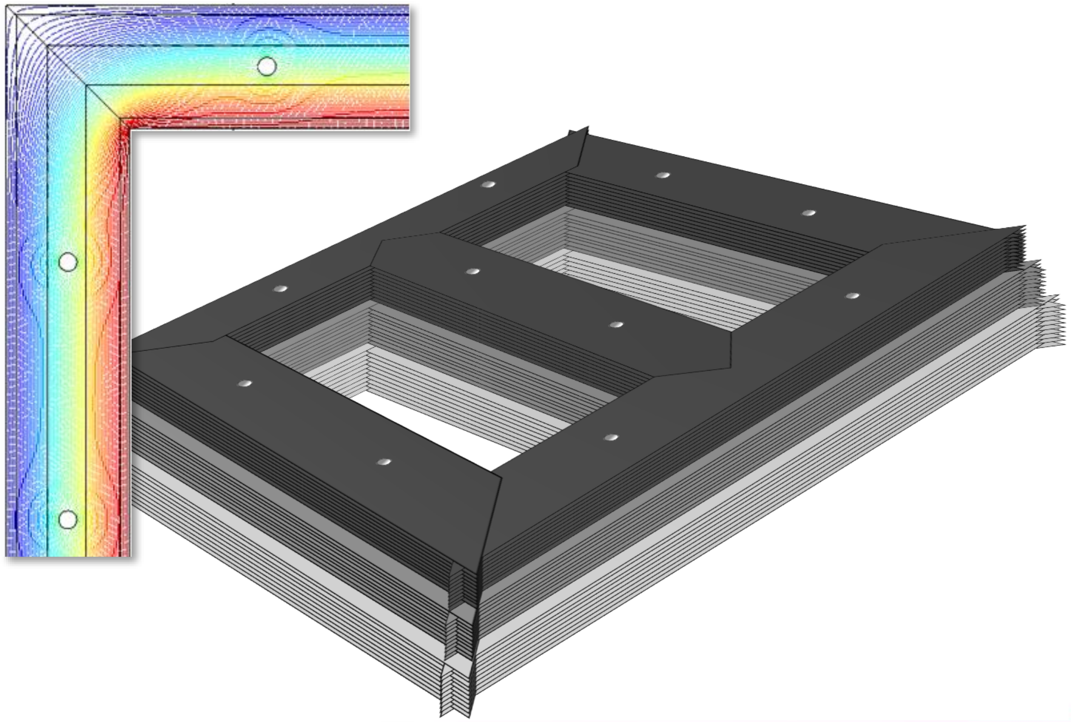


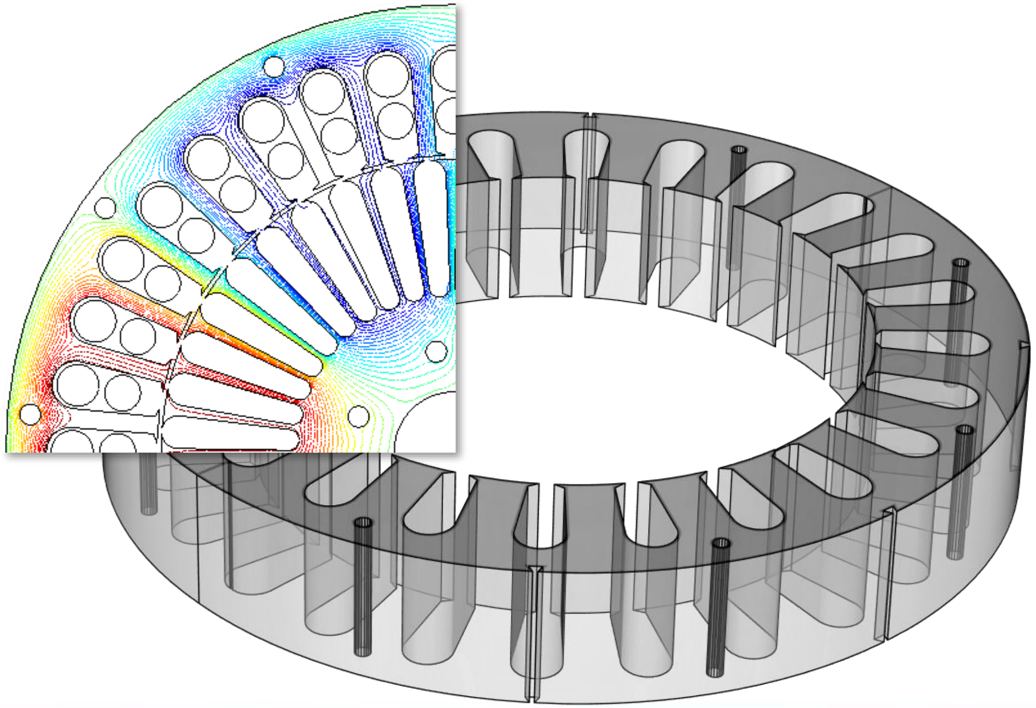

Just to have some fun!

## Power factor correction:

### What is reactive power?

- Majority of the industrial loads have inductive behaviour, it means they demand for reactive power.
- For example, we need reactive power to magnetise magnetic cores of power transformers and electrical machines.





## Power factor correction:

### What is reactive power?

So, reactive power is demanded by industrial loads (inductive loads), however it reduces operational efficiency of the grid !!!

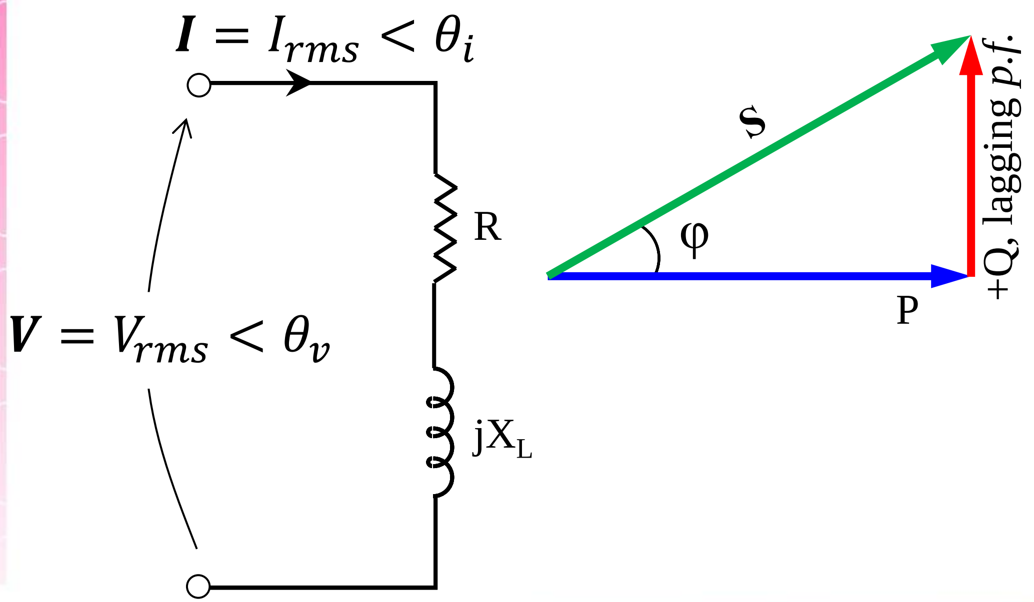
## Power factor correction:

### What is reactive power?

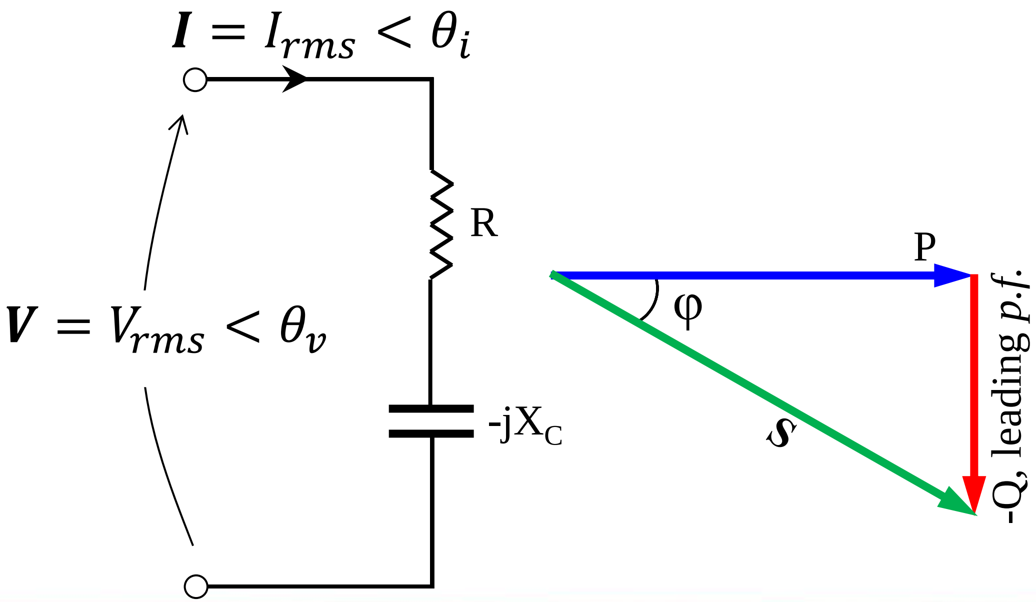
Reactive power has its origin in phase shift between current and voltage.

$$Q = V_{rms}\, I_{rms}\, \sin\varphi \qquad [VAR]$$

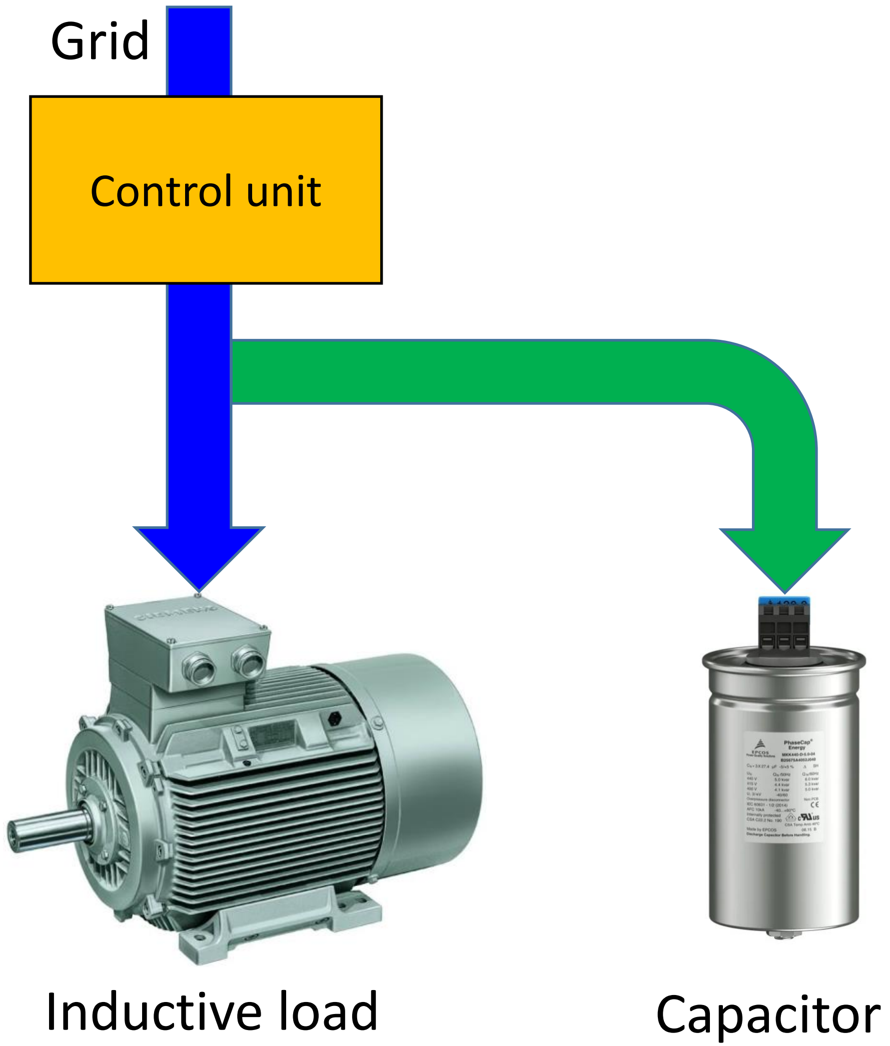
If current lags the voltage, then the device demands reactive power.

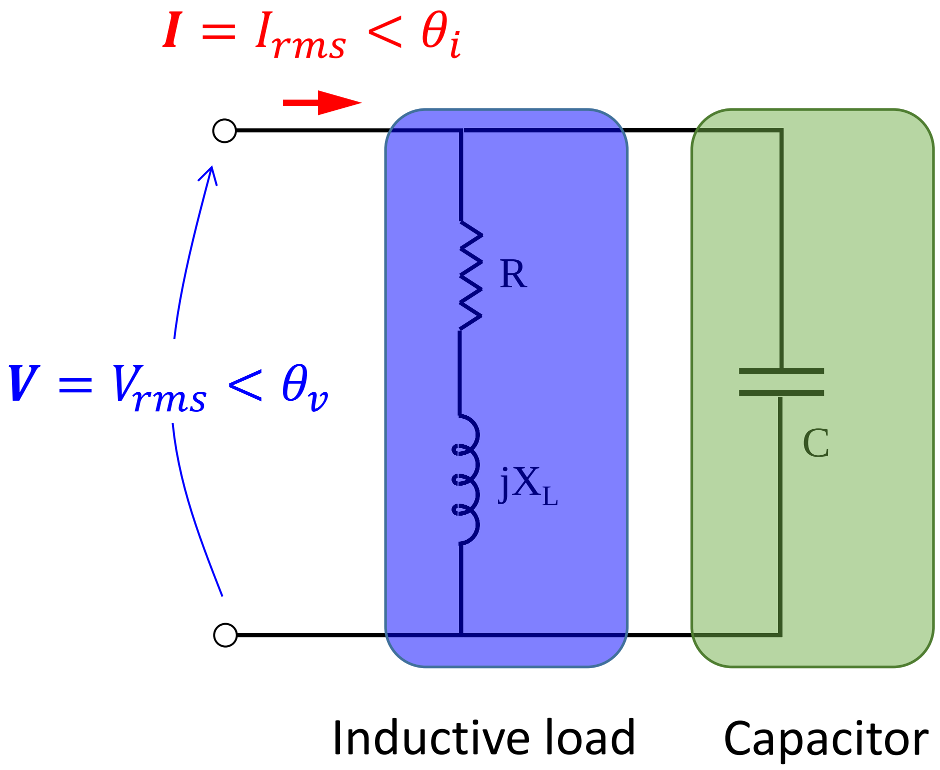



In contrast, if the voltage lags the current, then the device generates reactive power.

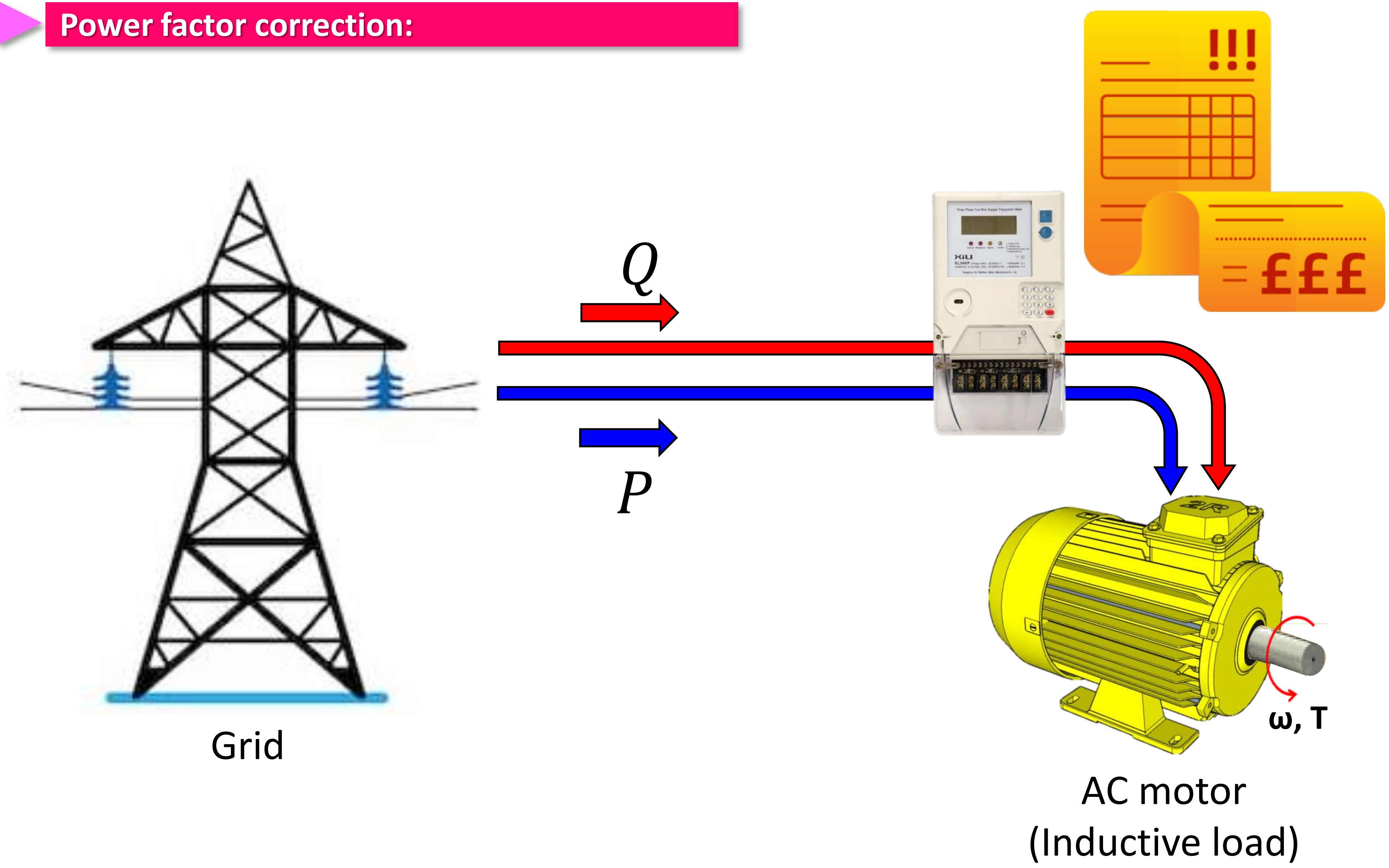


# Power factor correction:

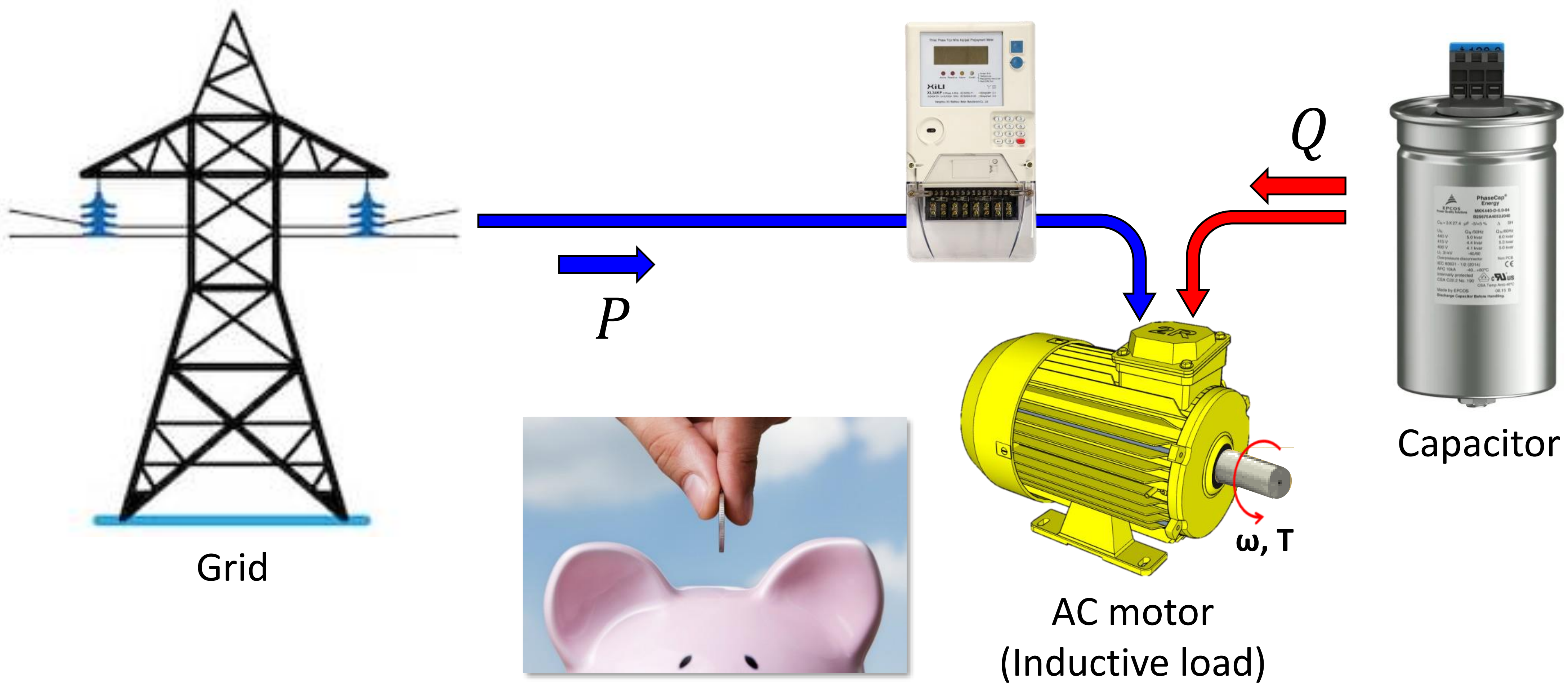


## Power factor correction:

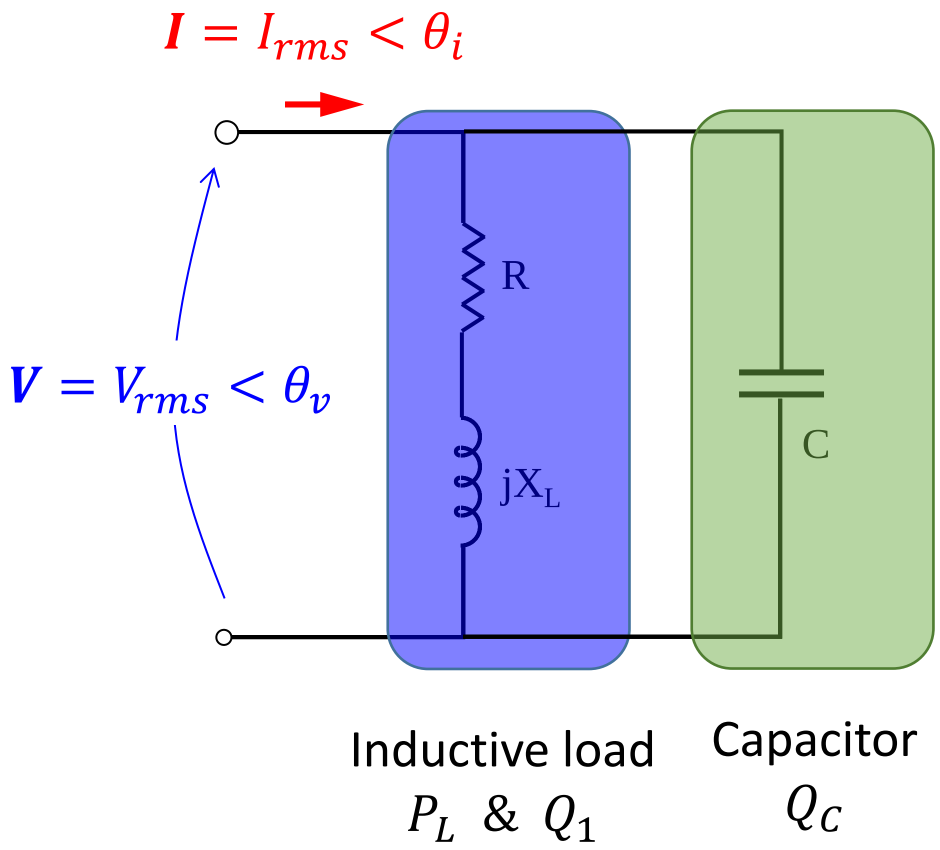


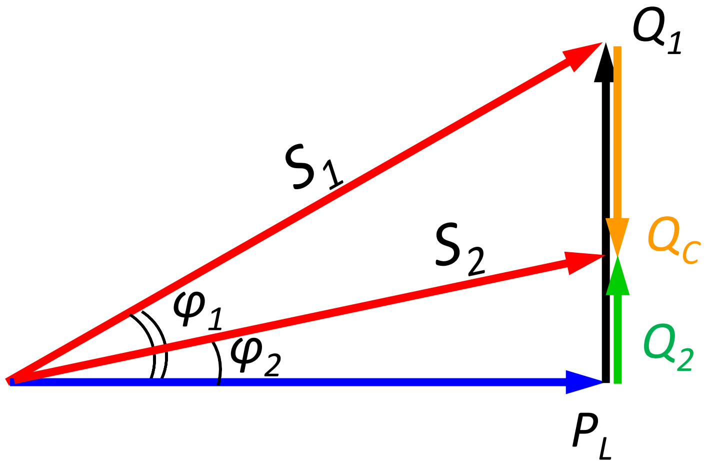
## Power factor correction:



## Power factor correction:

**How much reactive power do we need?**




Apparent power before compensation

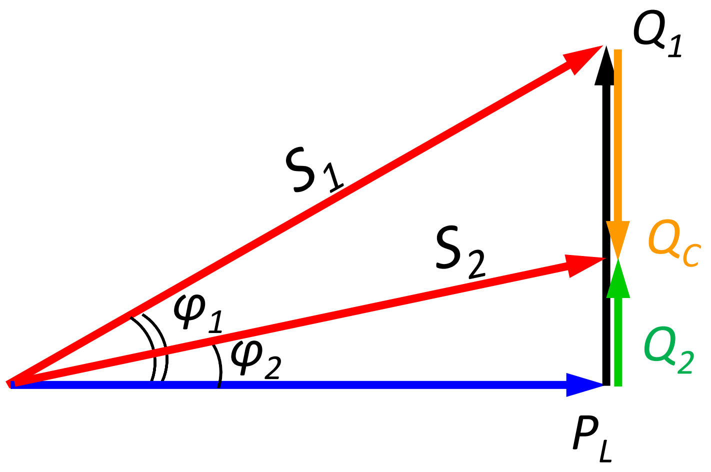
$$S_1 = \sqrt{P_L^2 + Q_1^2}$$

Apparent power after compensation

$$S_2 = \sqrt{P_L^2 + (Q_1 - Q_C)^2}$$

## Power factor correction:

**How much reactive power do we need?**




$$\begin{cases} Q_1 = P_L \tan\varphi_1 \\ Q_2 = P_L \tan\varphi_2 \end{cases}$$

$$Q_C = Q_1 - Q_2$$

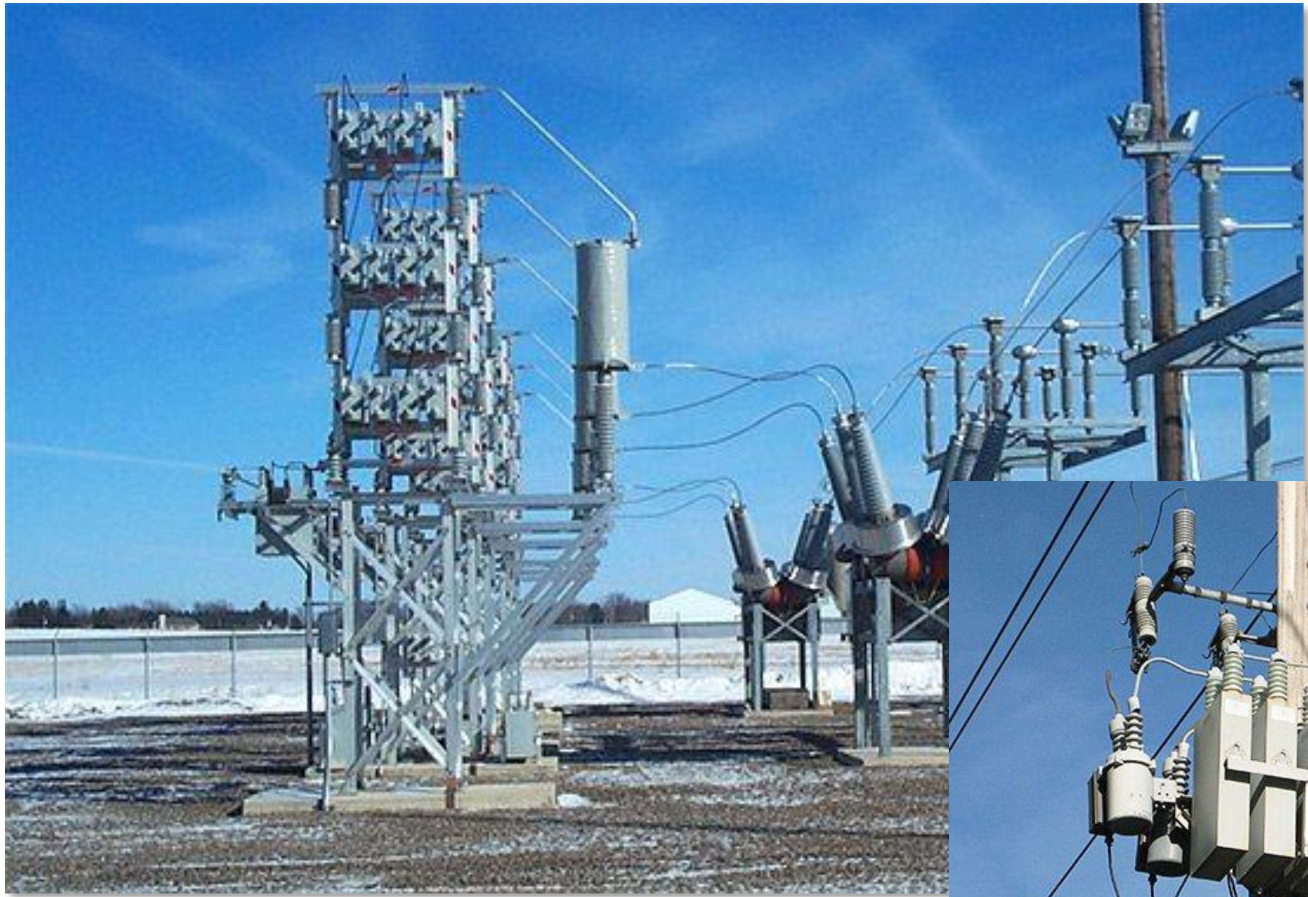
$$Q_C = P_L \tan\varphi_1 - P_L \tan\varphi_2$$

$$\boxed{Q_C = P_L\,(\tan\varphi_1 - \tan\varphi_2)}$$

**In industrial loads, typically the corrected power factor will be 0.92 to 0.95.**

## Power factor correction:

Capacitive banks:



HV substation (115 kV)

Low voltage network (400 V)

Distribution network (11 kV)

## Power factor correction:

Capacitive banks:

High Voltage Capacitor Bank

Low Voltage Capacitor Bank

## Power factor correction:

### Different types of capacitors:


1 μF, 100 V


2200 μF, 50 V

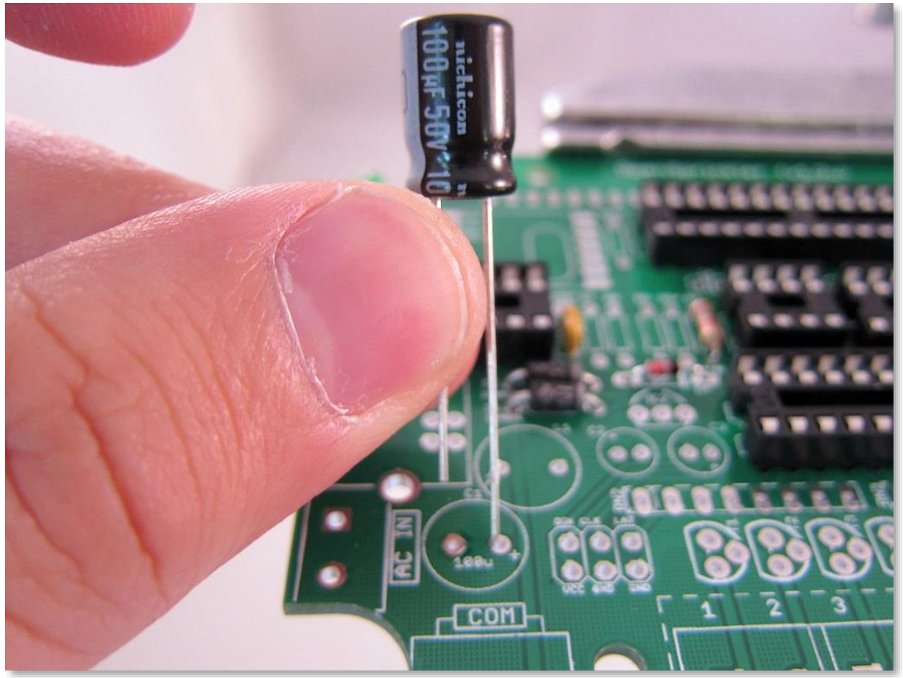
**Electronic Capacitor**


**Power Factor Correction Capacitor (PFC)**

## Power factor correction:

### Different types of capacitors:

In electronic circuits, capacitors are categorised by their capacitance in $F$. In electrical networks and power systems, capacitors are categorised by their reactive power in $kVAR$.




100 µF, 50 V capacitor in electronic circuit

75 MVAR capacitor bank at 150 kV; Zandvliet, Belgium

## Power factor correction:

### Example:

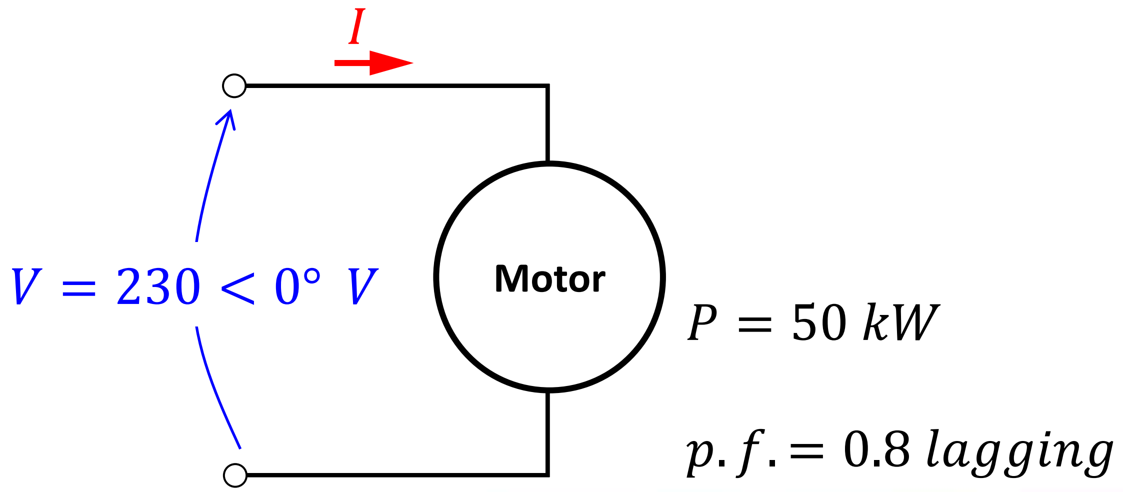
An electric motor absorbs 50 kW active power at a power factor of 0.8 lagging. The motor is supplied through a voltage source with 230 V rms and frequency of 50 Hz.

a) Find the complex power delivered to this motor.

b) Find current of the motor $i_L$.

c) Find the required capacitive reactive power to increase power factor to 0.95 lagging.

d) Calculate the current of the source after compensation.



## Power factor correction:

a) $P = V_{rms}\ I_{rms}\ \cos(\varphi) = S\cos(\varphi)$

$$S = \frac{P}{\cos(\varphi)} = \frac{50}{0.8} = 62.5 \quad \text{kVA}$$

$$Q = V_{rms}\ I_{rms}\ \sin(\varphi) = S\sin(\varphi)$$

$$\cos(\varphi) = 0.8 \quad \ggg \quad \varphi = 36.87°$$

$$Q = S\sin(\varphi) = 62.5\ \sin(36.87)$$

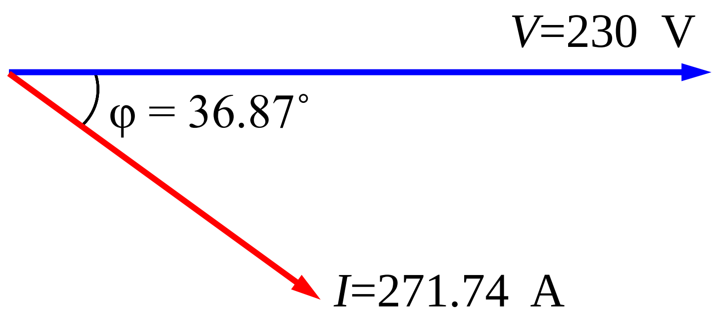
$$Q = 37.5 \quad \text{kVAR}$$

$$\boldsymbol{S} = P + jQ = 50 + j37.5 \quad \text{kVA}$$

b) $P = V_{rms}\ I_{rms}\ \cos(\varphi)$

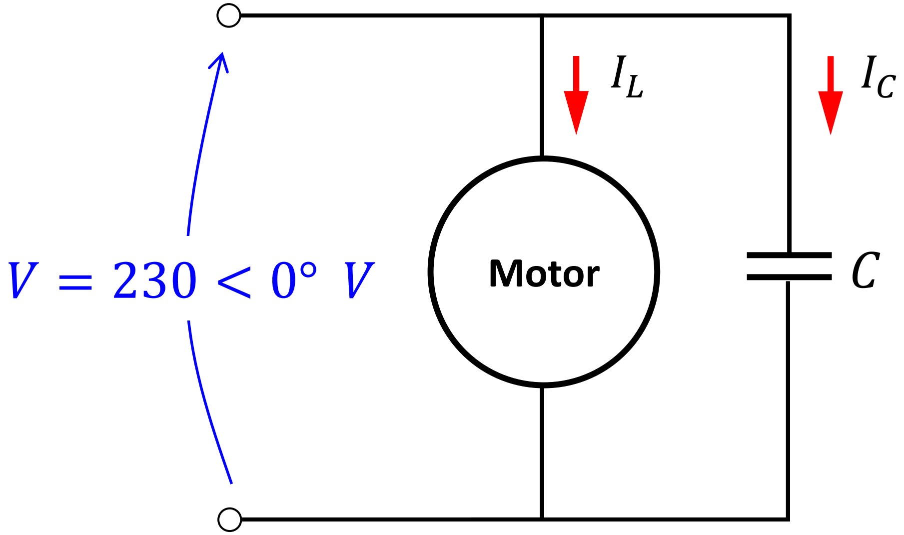
$$I_{rms} = \frac{P_L}{V_{rms}\ \cos\varphi} = \frac{50 \times 10^3}{230 \times 0.8} = 271.74\ A$$

$$\boldsymbol{I} = I_{rms}\underline{/\theta_i} = 271.74\underline{/-36.87°}$$



## Power factor correction:

c)




$$P = 50 \ kW$$

$$pf_1 = 0.8 \quad \ggg \quad \varphi_1 = 36.87°$$

$$pf_2 = 0.95 \quad \ggg \quad \varphi_2 = 18.19°$$

$$Q_C = P_L \left(\tan\varphi_1 - \tan\varphi_2\right)$$

$$Q_C = 50 \left(\tan(36.87°) - \tan(18.19°)\right)$$

$$Q_C = 21.07 \quad \text{kVAR}$$

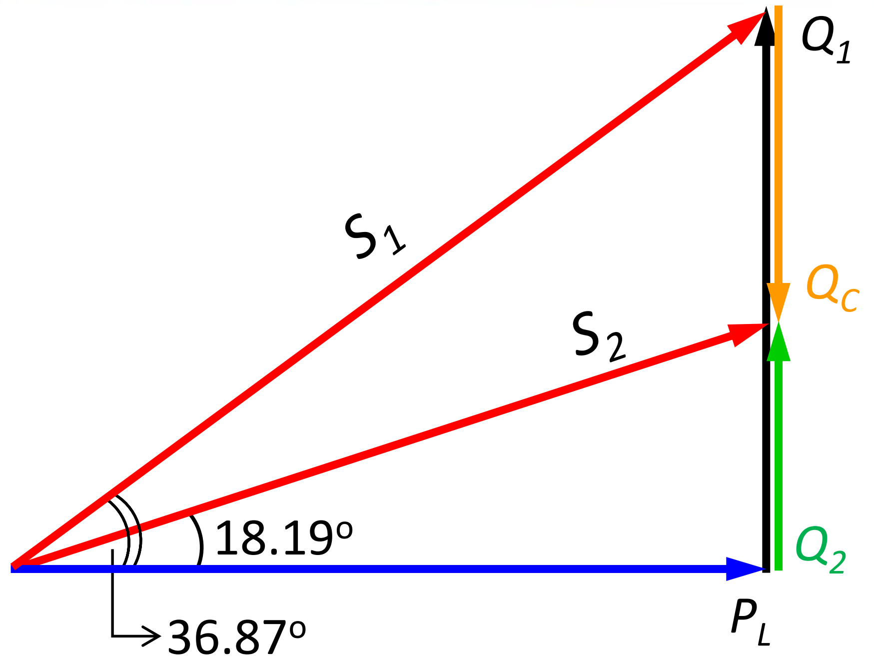
$$Q_2 = Q_1 - Q_C = 37.5 - 21.07 = 16.43 \quad \text{kVAR}$$

$$S_2 = \sqrt{P_L^2 + Q_2^2} = \sqrt{(50^2 + 16.43^2)}$$

$$S_2 = 52.63 \ \text{kVA}$$

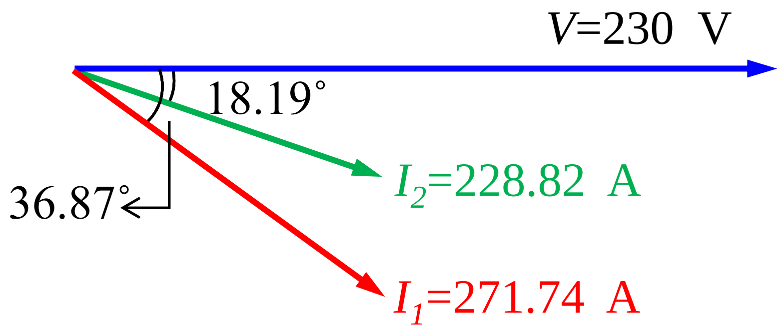
## Power factor correction:

$$\begin{cases} P_L = 50 \quad \text{kW} \\ S_1 = 62.5 \quad \text{kVA} \\ Q_1 = 37.5 \quad \text{kVAR} \end{cases} \qquad \begin{cases} S_2 = 52.63 \quad \text{kVA} \\ Q_2 = 16.43 \quad \text{kVAR} \end{cases}$$




d) $I_{rms2} = \dfrac{P_L}{V_{rms}\ \cos\varphi_2} = \dfrac{50 \times 10^3}{230\ \times \cos(18.19)} = 228.82\ A$

$$\boldsymbol{I_2} = I_{rms2}\,\underline{/\theta_i} = 228.82\,\underline{/-18.19°}\ \ \text{A}$$




Practice: Why $I_1 \cos\varphi_1 = I_2 \cos\varphi_2$ ?

## Power factor correction:

### Drill:

The following circuit operates at ω=500 rad/s and rms voltage of 100 V.

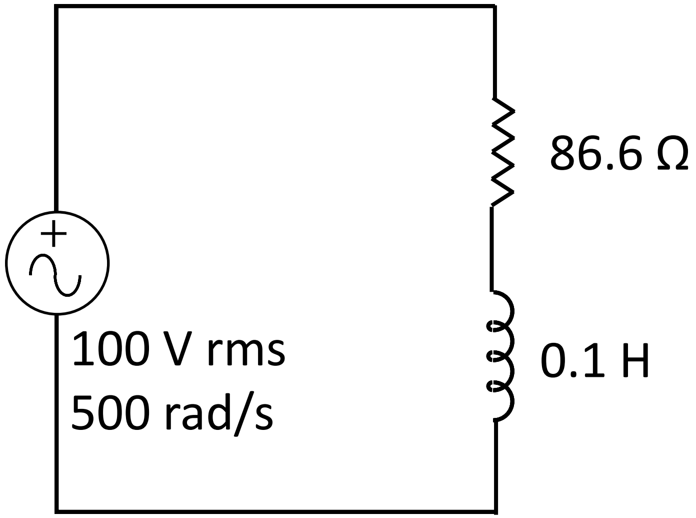
a) Find current of the load.

b) Find the complex power delivered to this load.

c) Find the required capacitive reactive power to correct power factor to 0.94 lagging

d) Draw the power triangle.

e) Calculate the power delivered by the source after compensation.




**Answer:**

a) $I = 1 < -30° \; A$

b) $S = 86.6 + j50 \quad VA$

c) $Q_c = 18.53 \, VAR$


Happy Halloween

## Module description:

### Recommended text books:

- DeCarlo Lin, "*Linear Circuit Analysis*", Oxford University Press, Second Edition, 2003
- W H Hayt, J E Kemmerly, S M Durbin, "*Engineering Circuit Analysis*", McGraw-Hill, 9th Edition, 2019