EEE270
Introduction to Electrical Energy Systems

Lecture 5 – Reactive Power Compensation

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What is reactive power ?

- Real power actually powers the equipment and performs useful work in the form of heat, light, mechanical energy, and etc…
- Reactive power <u>does not</u> do useful work in the form of heat, light, mechanical energy, and etc…
- Reactive power is required to be supplied along with real power
- Reactive power can be either inductive (lagging) or capacitive (leading)

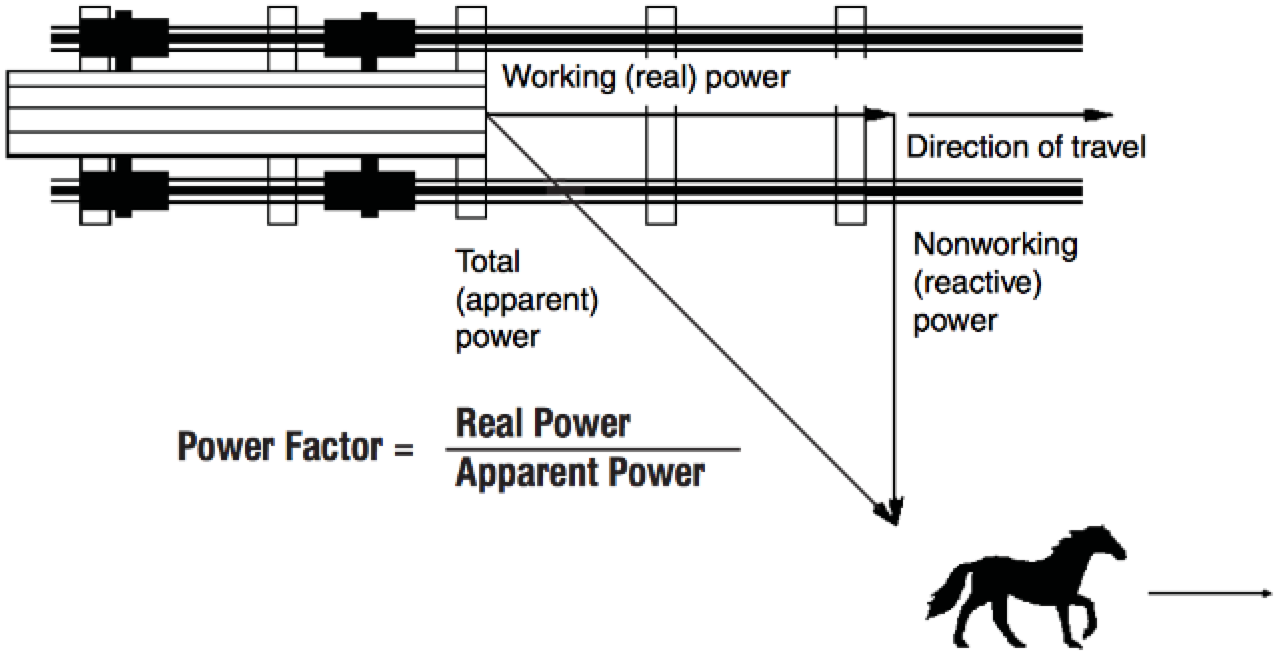


Figure source: http://www.energyinnovationproject.org/understanding-the-basics-of-reactive-power/

What is reactive power ?

- Major industrial loads such as, transformers, electric furnaces, induction motors, and etc… are inductive loads need reactive power to produce the magnetic field necessary for their operation
- Reactive power is also either generated or consumed in almost every component of the electrical systems, including generation, transmission, and distribution.
- Lagging reactive power should be supplied to inductive loads along with real power
- However it is economical to supply lagging reactive power closer to the inductive loads.

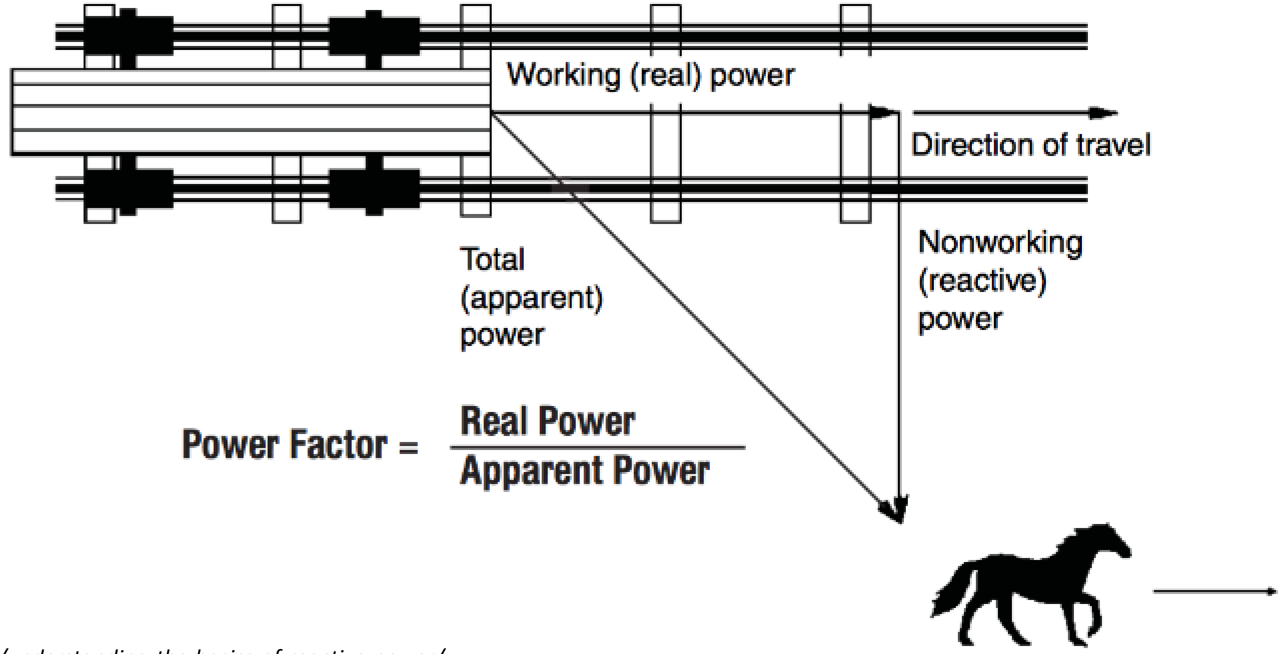


Figure source: http://www.energyinnovationproject.org/understanding-the-basics-of-reactive-power/

What is reactive power compensation ?

- Reactive power compensation is to **manage the reactive power** to enhance the operation of electrical systems

- Reactive power compensation is to produce pre-specified amount of reactive power at the consumption point (close to the loads), rather than transferring it far from the generation point

- Reactive power compensation is also known as **“VAR compensation”** or “**Power factor correction”**

- Series/shunt reactive power compensation for transmission systems is not the subject of this course and thereby omitted in this chapter

Why do we need reactive power compensation ?

- To reduce system losses
- To avoid penalty charges from utilities for excessive consumption of reactive power
- To increase system’s electrical capacity and save cost on new installations
- To improve voltage regulation and reduce voltage drop on lines and cables

Figure source: http://electrical-engineering-portal.com/

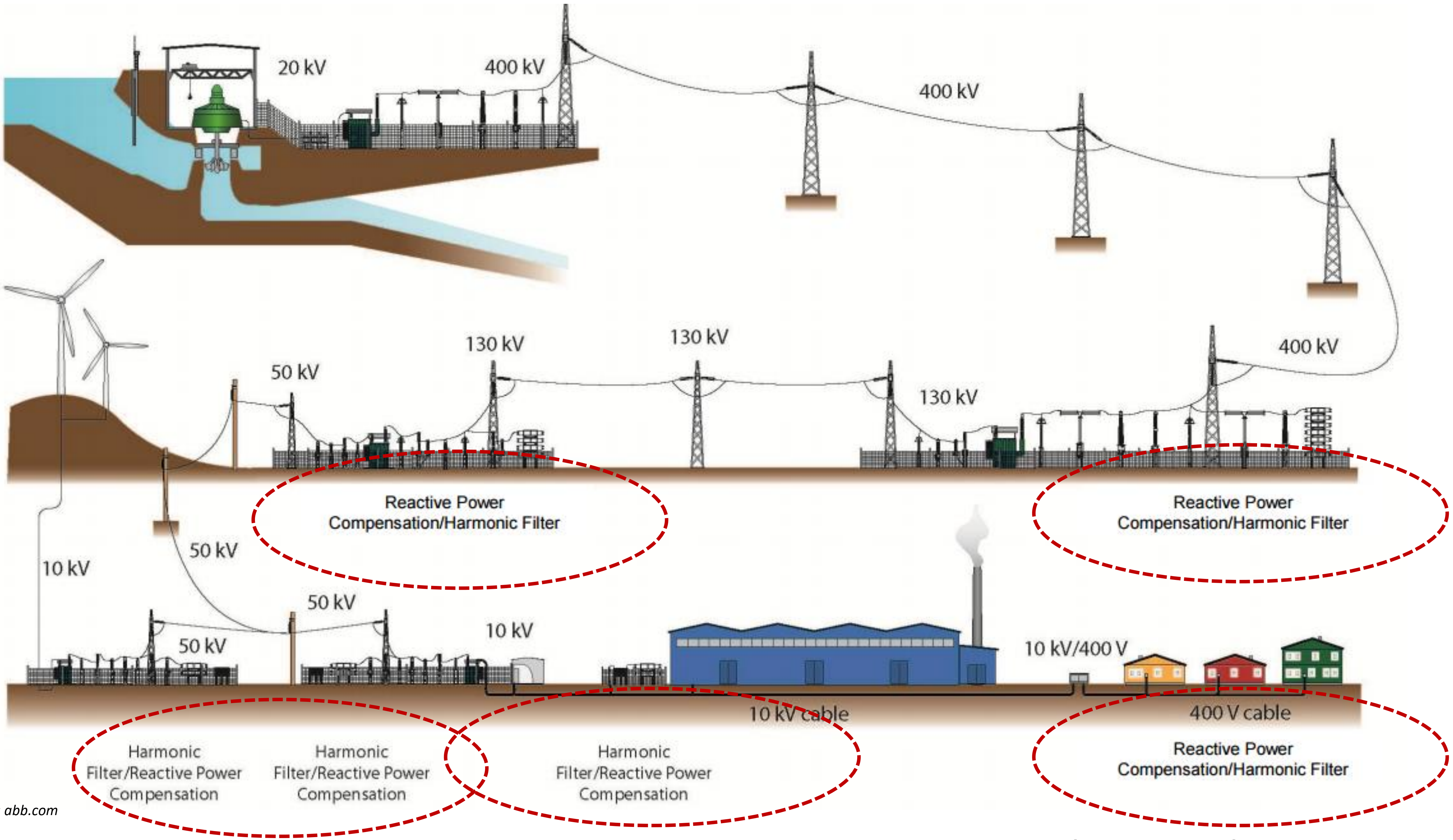


Figure source: abb.com

Reactive power compensation can be applied at <u>any voltage level</u> (LV, MV, HV)

How is reactive power compensation implemented ?

➢ Reactive power compensation is implemented with the following devices connected in **shunt** to the compensation point.

Reactive Power Compensation

Dynamic compensation
- ✓ Capacitor banks (with reactive power control relay)
- ✓ rotating synchronous condenser
- ✓ **SVC** (**S**tatic **V**ar **C**ompensator)
- ✓ **STATCOM** (**STAT**ic synchronous **COM**pensator)
- ✓ Capacitor

Response time decreases

For dynamically changing loads (active power)

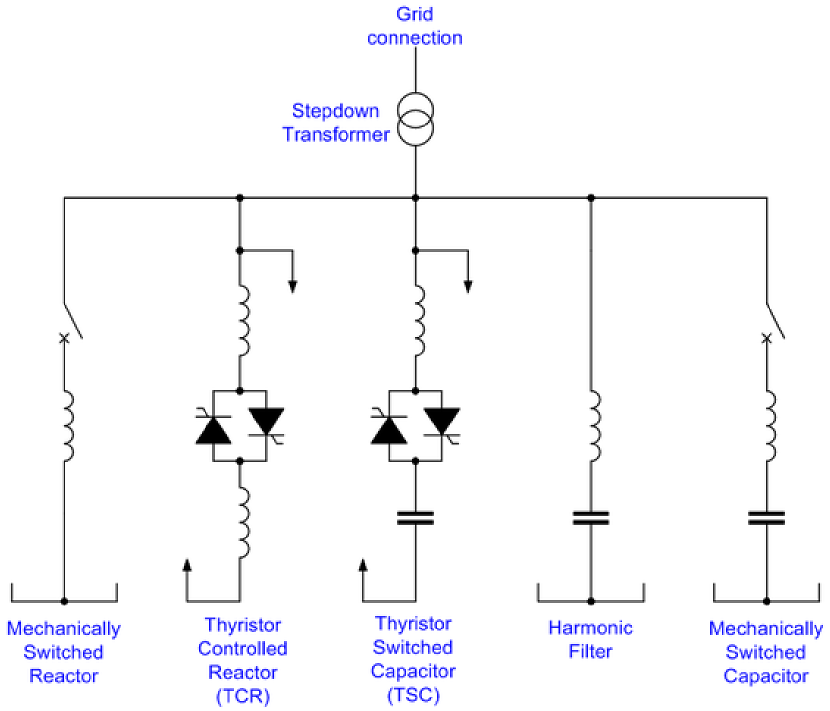
Static compensation
- ✓ Capacitor banks

For constant loads (active power)

- In 1960s, rotating **synchronous condensers** were being used
- A synchronous condenser (synchronous capacitor or synchronous compensator) is actually a synchronous motor, whose shaft is not connected to anything but spins freely.
- It is not generally preferred, because of **high losses**, **high noise**, and **expensive maintenance**

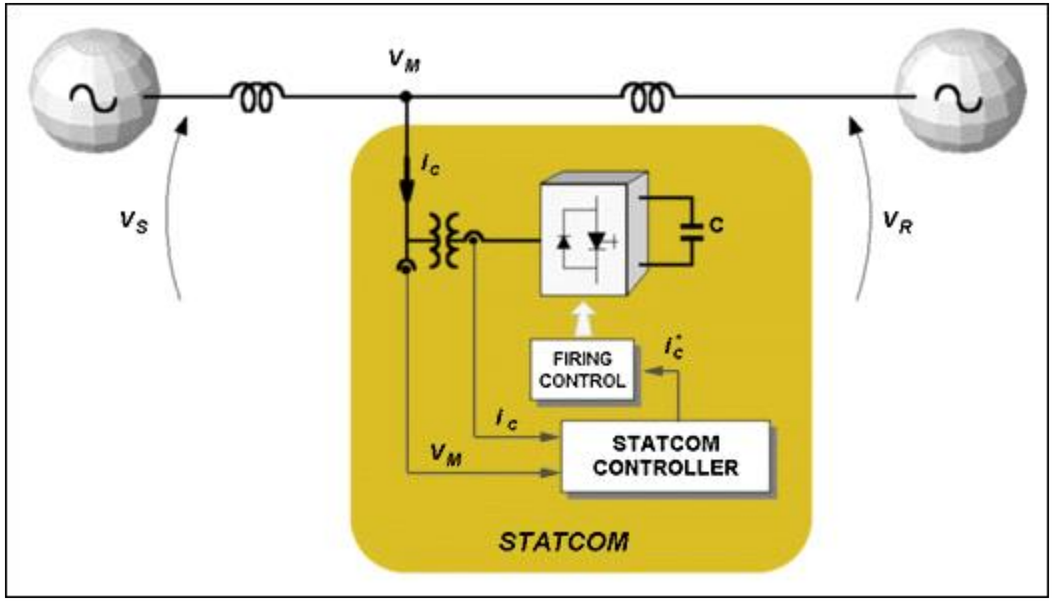
Synchronous condenser installation at Templestowe substation, Melbourne Victoria, Australia. Built by ASEA in 1966, the unit is hydrogen cooled and capable of three phase power at 125,000 kVA. Source Wikipedia.

- SVC (**S**tatic **V**ar **C**ompensator) is an electrical device for managing reactive power on distribution and transmission systems, typically to dynamically control bus voltage
- The term "**static**" refers that SVC has **non-moving parts** other than circuit breakers and disconnects, which do not move under normal operation
- SVC can either **produce** or **consume** reactive power depending on the requirements
- If the power system's reactive load is inductive (lagging), the SVC will use capacitors (usually in the form of thyristor switched capacitors (**TSC**) to generate reactive power to the system
- If the power system's reactive load is capacitive (leading), the SVC will use reactors (usually in the form of thyristor controlled reactors (**TCR**) to consume reactive power from the system
- SVC can provide **smooth and flexible control** of reactive power
- SVC act much **faster** than a **capacitor** or a **synchronous condenser**



One-line diagram of a typical SVC configuration; here employing a thyristor controlled reactor, a thyristor switched capacitor, a harmonic filter, a mechanically switched capacitor and a mechanically switched reactor. Source Wikipedia.

- STATCOM (**STAT**ic synchronous **COM**pensator) is a power electronics based static device
- STATCOM is generally based on a voltage-source converter which can produce/consume reactive power
- STATCOM can act **faster** than SVC
- Today, STATCOM is **the latest technology** for reactive power compensation



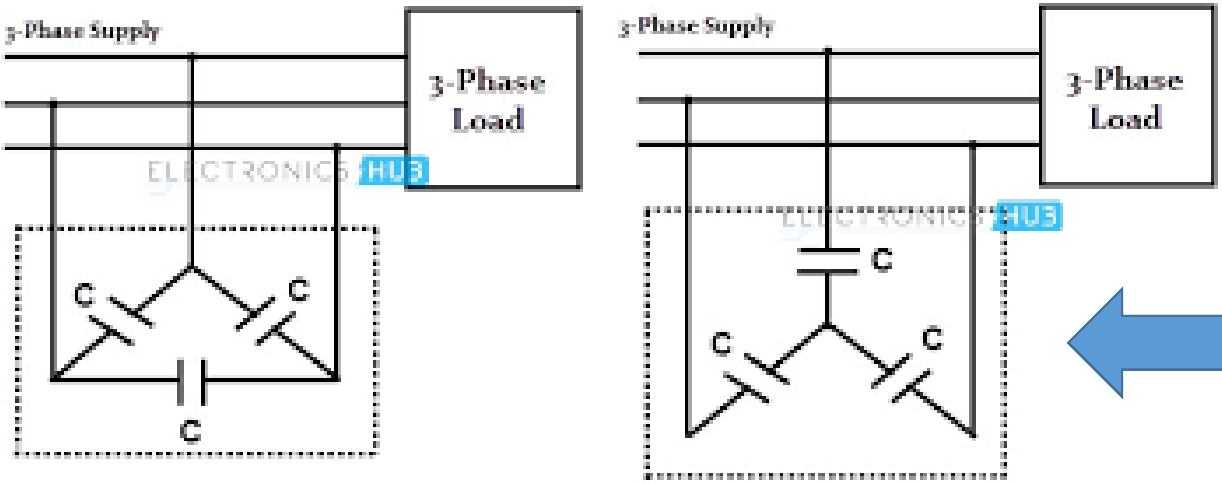
Source http://www.coe.ufrj.br/bolsa98b.htm

± 50 MVAR T-STATCOM designed in Turkey

Source http://www.guckalitesi.gen.tr/

Using **capacitor** is the **simplest and cheapest** method to generate reactive power to realize reactive power compensation in utilities

Delta connected capacitor banks



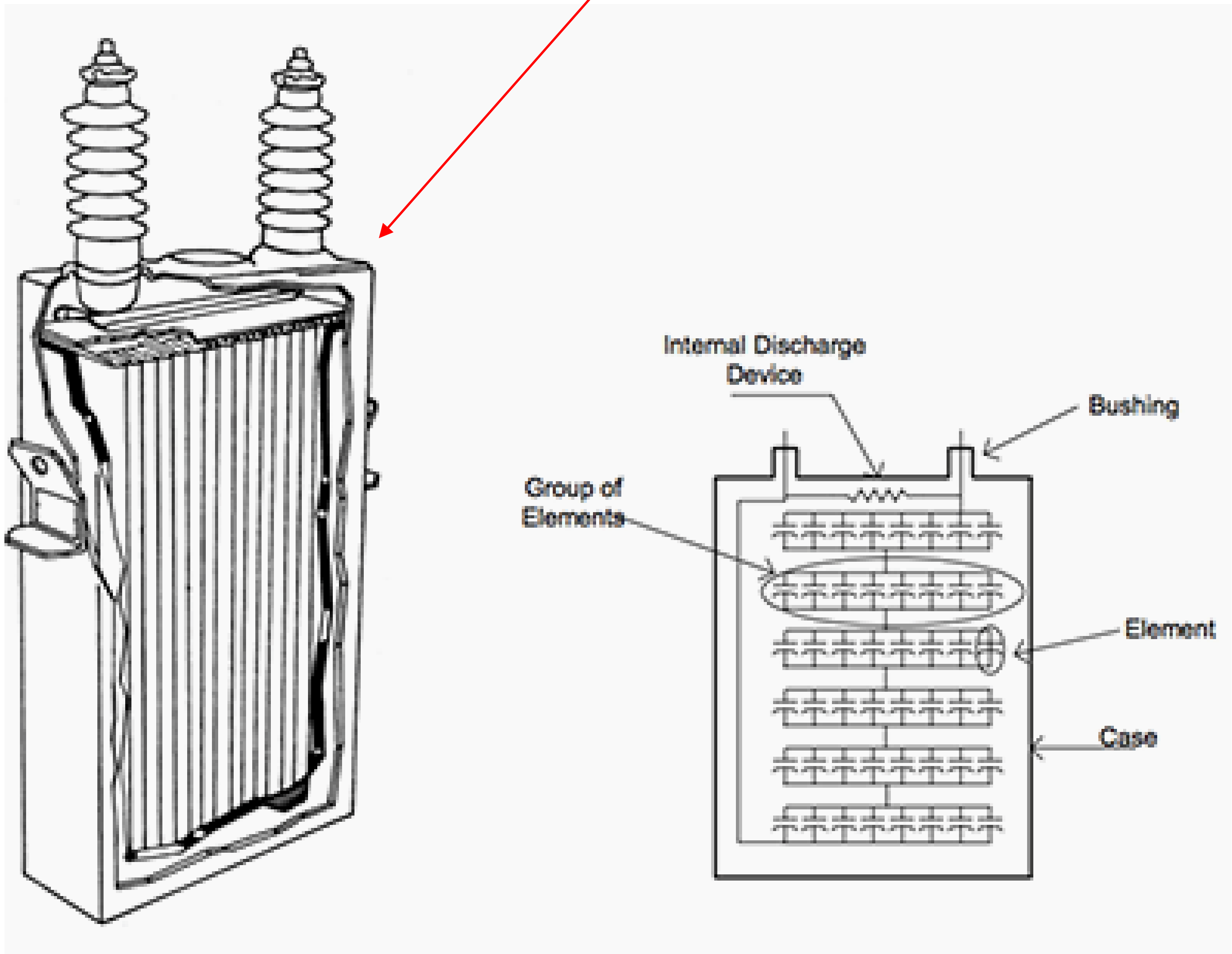
Wye connected capacitor banks

Two different connection types of capacitors to a three-phase system

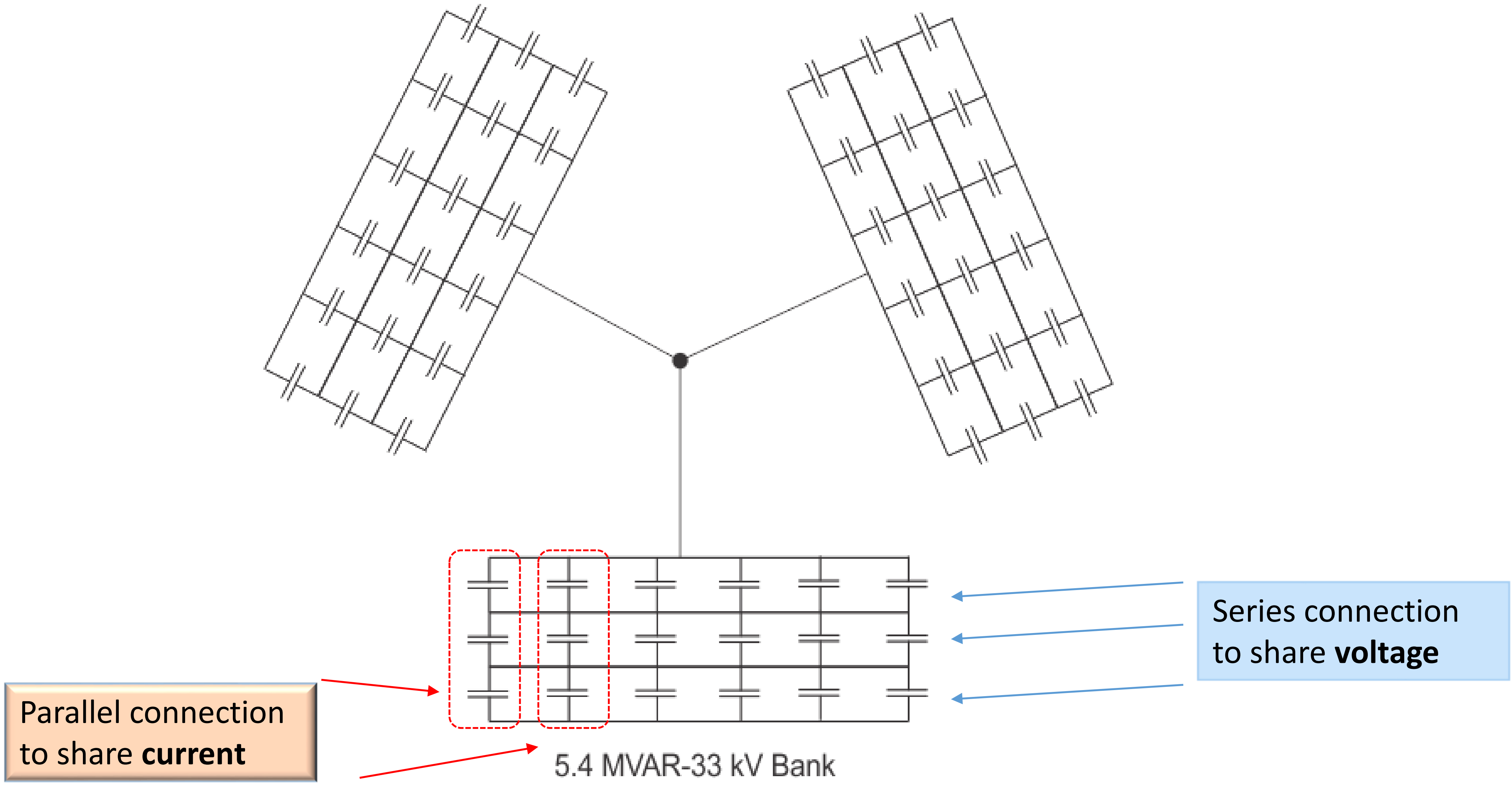
Capacitor Unit

The capacitor unit is the building block of a shunt capacitor bank. The capacitor unit is made up of individual capacitor elements, arranged in parallel/series connected groups within a steel enclosure

Each capacitor unit is provided with a discharge resistor that reduces the unit residual voltage to 50V in 5 minutes.

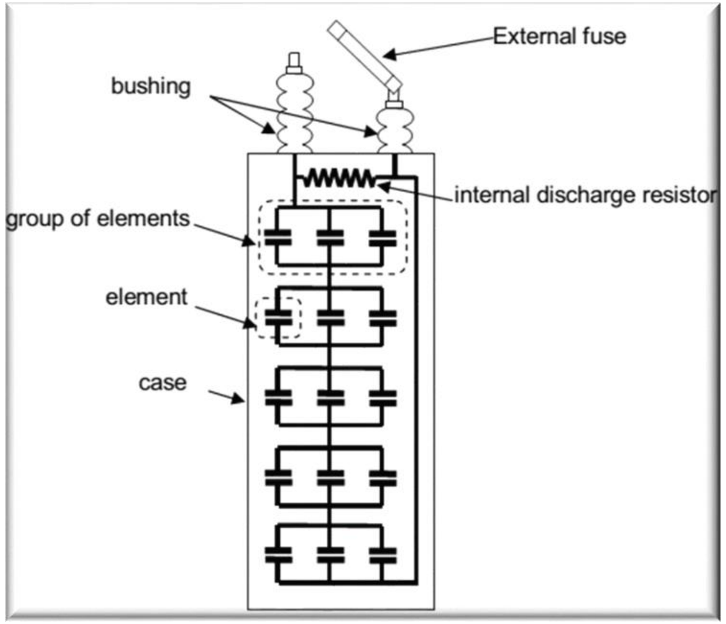


Generally capacitors are grouped together (connected in both *parallel* and *series*) to **increase MVAR rating**

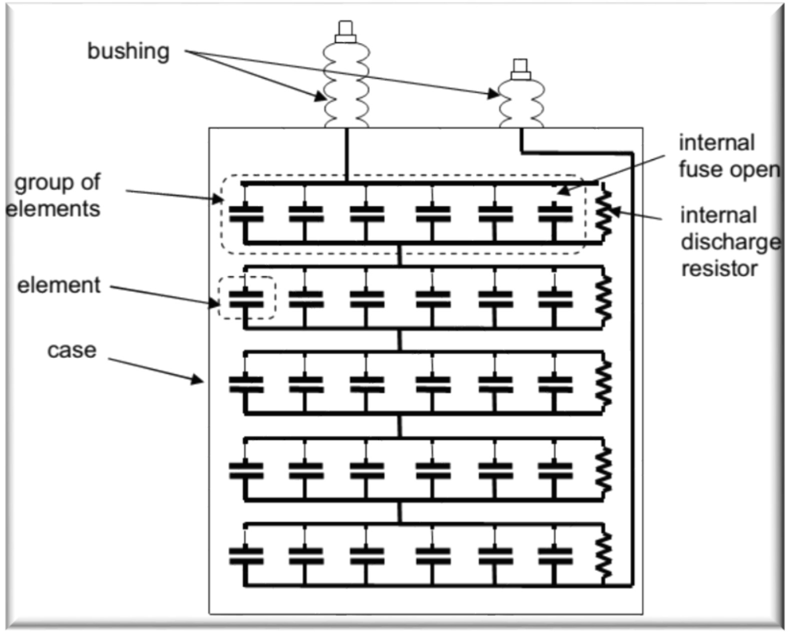


Capacitor bank configuration

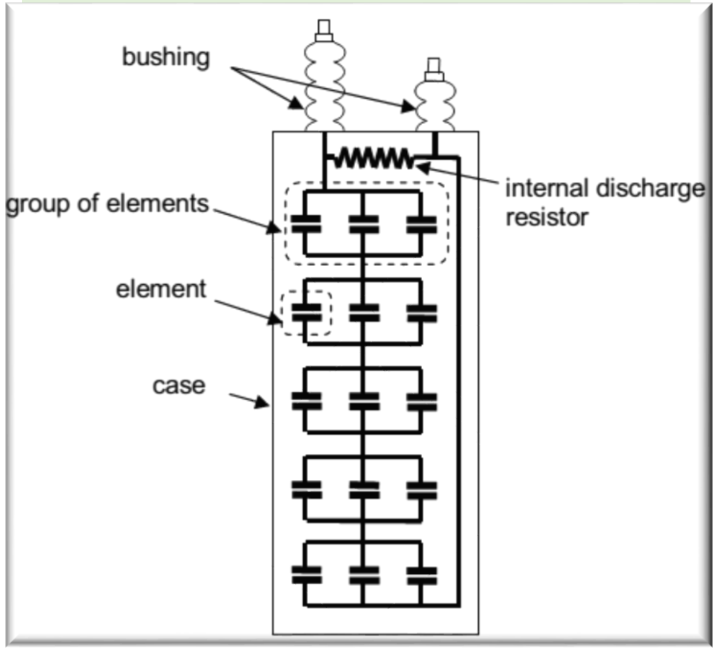
Externally Fused Capacitor Unit/Bank



Internally Fused Capacitor Unit/Bank



Fuse-less Shunt Capacitor Banks



Capacitor units are available in various voltages and sizes

Reactive power compensation panels are available in various size and capacity

Reactive power generated by a capacitor is formulated as :

$Qc = V^2 / Xc$ → Reactive power (VAR)

$Xc = 1 / wC$ → Capacitive reactance (Ω)

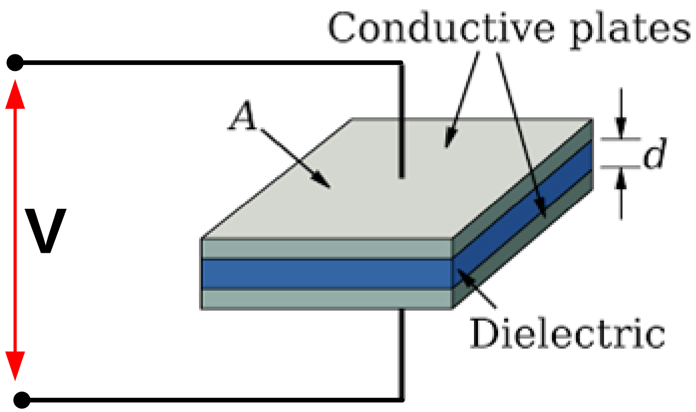
$Qc = wCV^2$ VAR → Reactive power (VAR)

↓

w=2.pi.f

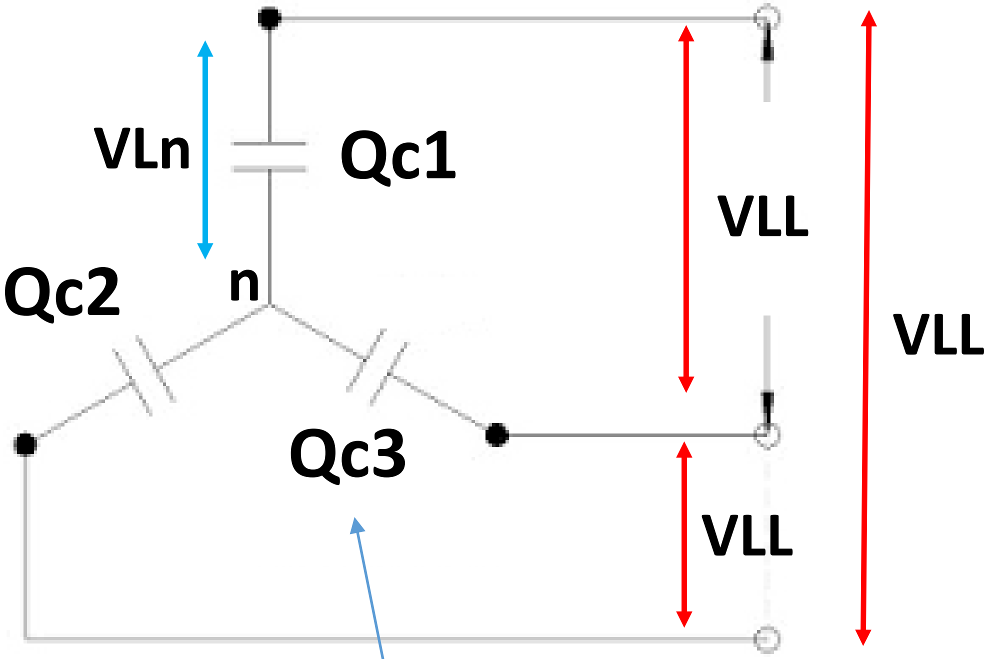
↓

Angular frequency of the capacitor voltage (rad/s)



$$C = \varepsilon_0 \varepsilon_R \frac{A}{d}$$

Total reactive power generated by wye-connected capacitors:



Reactive power generated
by each capacitor

Qtotal = Qc1 + Qc2 + Qc3

Since capacitors are identical

Qc1 = Qc2 = Qc3 = Qc

So

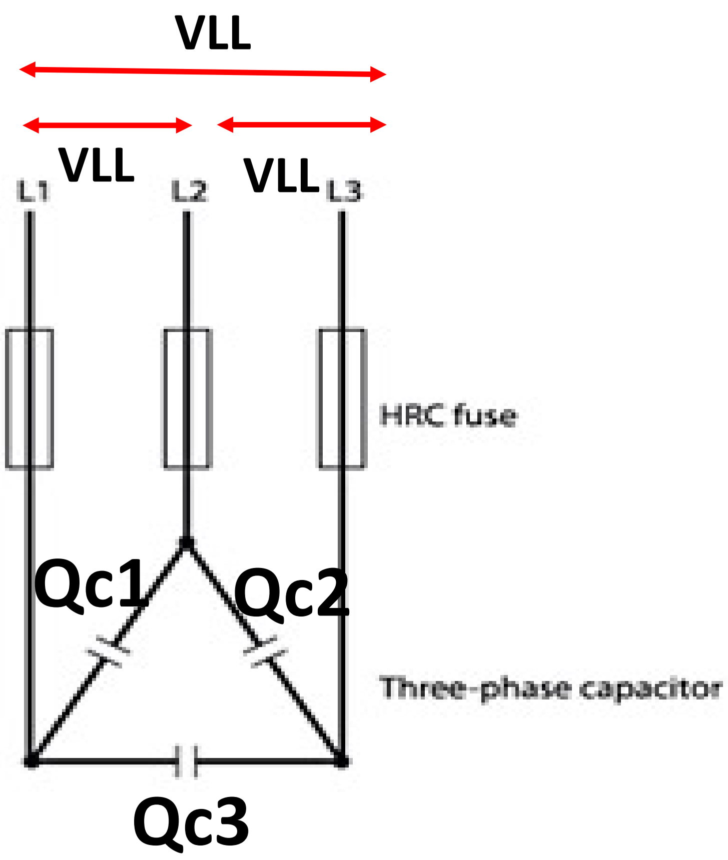
Qtotal = 3Qc = 3wC(VLn^2) VAR

Since

VLn = VLL/sqrt(3) → rms value of line-to-neutral voltage

Qtotal = wC(VLL^2) VAR → rms value of line-to-line voltage

Total reactive power generated by delta-connected capacitors:



Reactive power generated by each capacitor

Qtotal = Qc1 + Qc2 + Qc3

Since capacitors are identical

Qc1 = Qc2 = Qc3 = Qc

So

Qtotal = 3Qc = 3wC(VLL^2) VAR

rms value of line-to-line voltage

Which connection type of capacitors is more appropriate for reactive power compensation ?
Wye **or** ***delta*** **?**

In wye-connection

$$Q_{total} = wC(V_{LL}^2) \text{ VAR}$$

In delta-connection

$$Q_{total} = 3wC(V_{LL}^2) \text{ VAR}$$

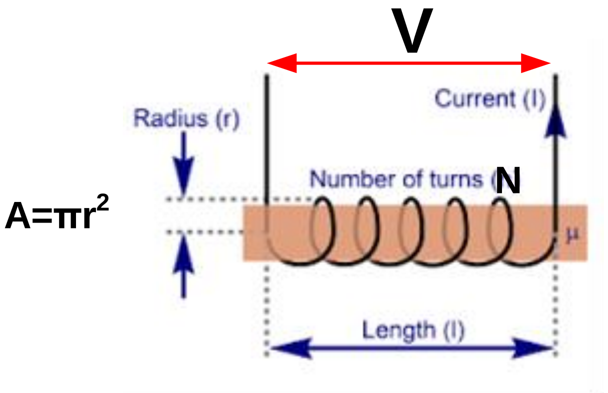
Since delta-connected capacitors produce **three-times** more than the reactive power generated by wye-connected capacitors, delta-connected capacitors are usually preferred in reactive power compensation systems.

Reactive power consumed by an inductor is formulated as :

$QL = V^2 / XL$ → Reactive power (VAR)

$XL = wL$ → Capacitive reactance (Ω)

$QL = V^2/wL$ → Reactive power (VAR)



$$L = \mu_0 \mu_R \frac{N^2 A}{l}$$

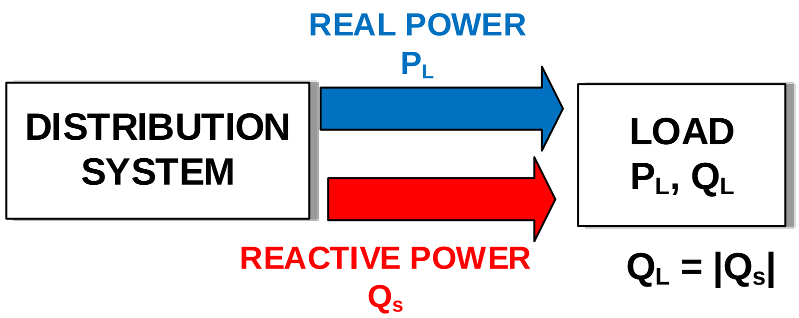
The **IEEE Std 18-1992** and **Std 1036-1992** specify the standard ratings of the capacitors designed for shunt connection to AC systems and also provide application guidelines.

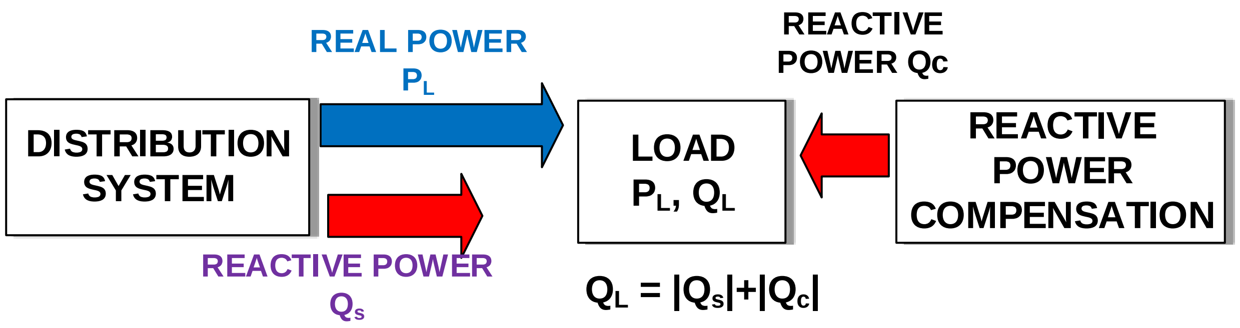
These standards stipulate that:

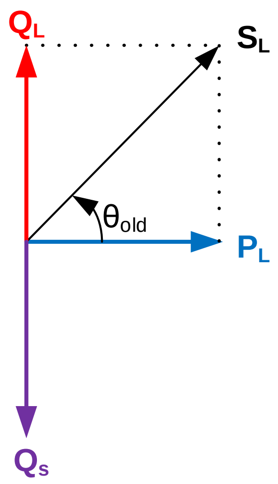
1. Capacitor units should be capable of continuous operation up to **110%** of rated terminal rms voltage and a crest (peak) voltage not exceeding **1.2 x √2** of rated rms voltage, including harmonics but excluding transients.
2. The capacitor should be able to carry **135%** of nominal current.
3. Capacitors units should not give less than **100%** nor more than **115%** of rated reactive power at rated sinusoidal voltage and frequency.
4. Capacitor units should be suitable for continuous operation at up to **135%** of rated reactive power caused by the combined effects of:

a) Voltage in excess of the nameplate rating at fundamental frequency, but not over **110%** of rated rms voltage.
b) Harmonic voltages superimposed on the fundamental frequency.
c) Reactive power manufacturing tolerance of up to **115%** of rated reactive power.

The principle of reactive power compensation



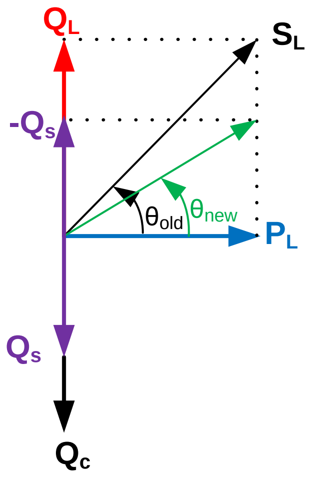




BEFORE COMPENSATION

$\theta_{old} = \tan^{-1}(Q_L/P_L)$

Reactive power compensation **does not change** real power !



AFTER COMPENSATION

$\theta_{new} = \tan^{-1}(|Q_s|/P_L)$

$\theta_{new} < \theta_{old}$

$|Q_c| = Q_L - |Q_s|$

$|Q_c| = P_L \tan\theta_{old} - P_L \tan\theta_{new}$

$|Q_c| = P_L(\tan\theta_{old} - \tan\theta_{new})$

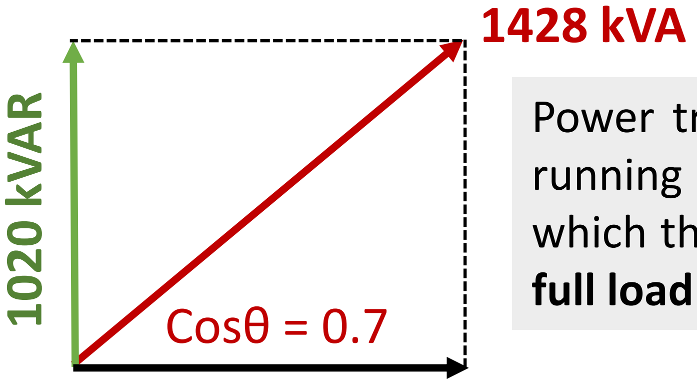
Since

$|Q_c| = V^2/|X_c|$ where $|X_c| = 1/wC$

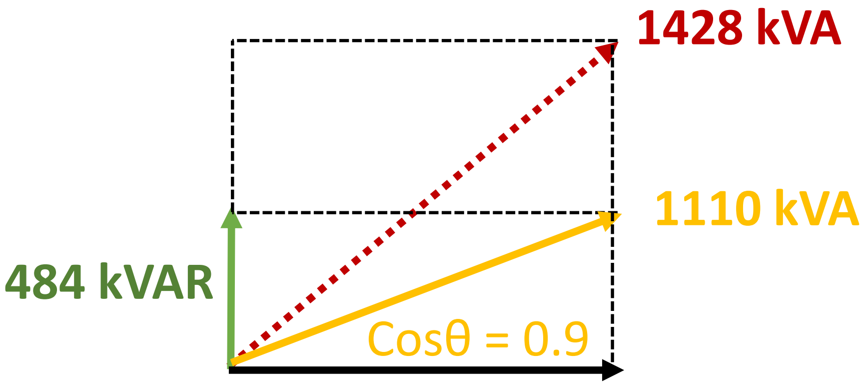
The required capacitance

$C = |Q_c| /(wV^2)$

Effect of compensation on relief in transformer loading



Power triangle of an installation running at low cosθ and for which the transformer is close to **full load**



Connected load
1000 kW

Connected load
1000 kW

1500 kVA transformer
95.2 % loading

Power triangle of the same installation where power factor correction has been applied reduces load on the transformer and releases capacity for additional loads

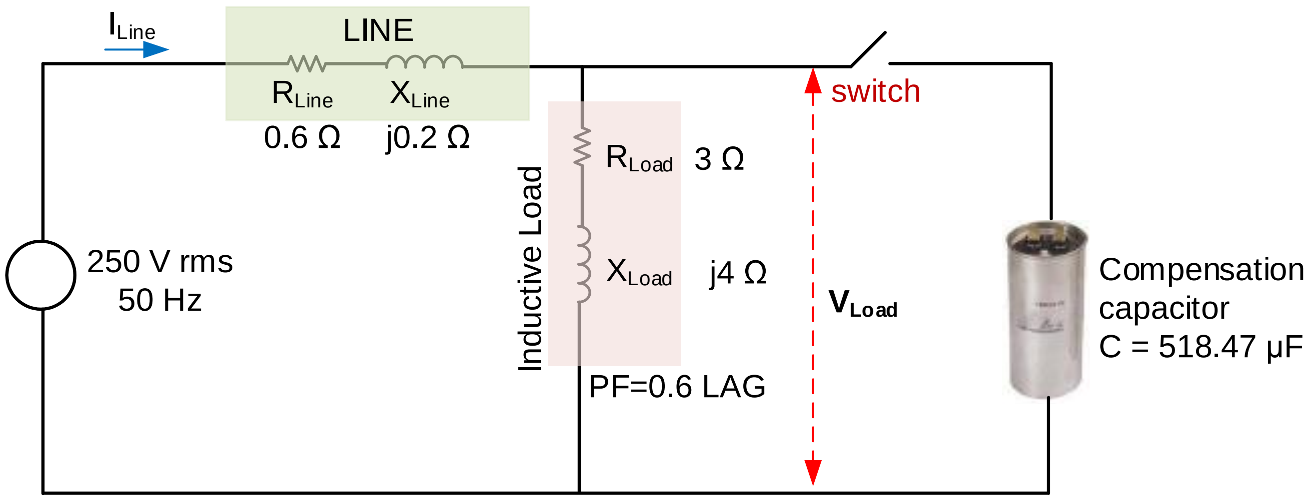
21.2 % available

1500 kVA transformer
74 % loading

Reference abb.com

Effect of compensation on voltage regulation and line loss

Consider the following single-phase system



Before compensation (switch is **OFF**)

I_{Line} = **45.19/__-49.39° A**

V_{Load} = **225.95/__3.74° V**

P_{Loss} = **1225 W**

VR = **10.64 %**

After **unity PF** compensation (switch is **ON**)

I_{Line} = **28.0/__0.0° A**

V_{Load} = **233.27/__-1.38° V**

P_{Loss} = **470 W**

VR = **7.17 %**

Benefits of compensation:

1) Line current is **decreased** by **38 %**. This yields to use smaller conductor size, so cost is reduced
2) Voltage regulation (VR) is **increased** by **3.47 %**. Power quality is improved
3) Line losses are reduced by **61.63 %**. Efficiency is improved

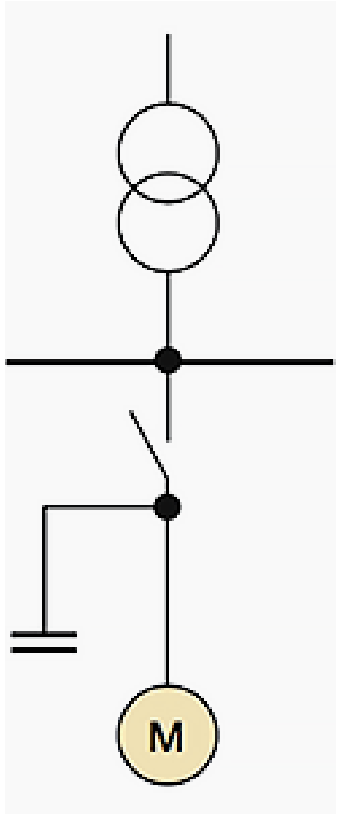
Main Types of Reactive Power Compensation

- Shunt reactive power compensation can be utilized either at load level, substation level or at transmission level.

- According to the location, compensation is divided into three types:

1) Single (direct) compensation
2) Group compensation
3) Central compensation
   a) At LV side
   b) At HV side

1) Single (direct) compensation



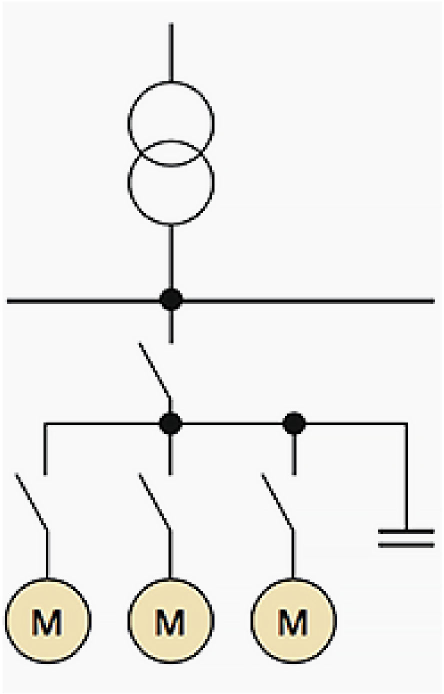
In single compensation, the capacitors are directly connected to the terminals of the individual power consumers and switched on together with them via a common switching device. Here, the capacitor power must be precisely adjusted to the respective consumers. Single compensation is frequently used for induction motors.

Advantage
It is economically favorable for

- Large individual power consumers
- Constant power demand
- Long ON times

Disadvantage
A continuous adjustment of the capacitor reactive power is not possible.

2) Group compensation



In group compensation, each compensation device is assigned to a consumer group. Such a consumer group may consist of motors or discharge lamps, for example, which are connected into supply together through a contactor or switch. In this case, special switching devices for connecting the capacitors are not required.

Advantage

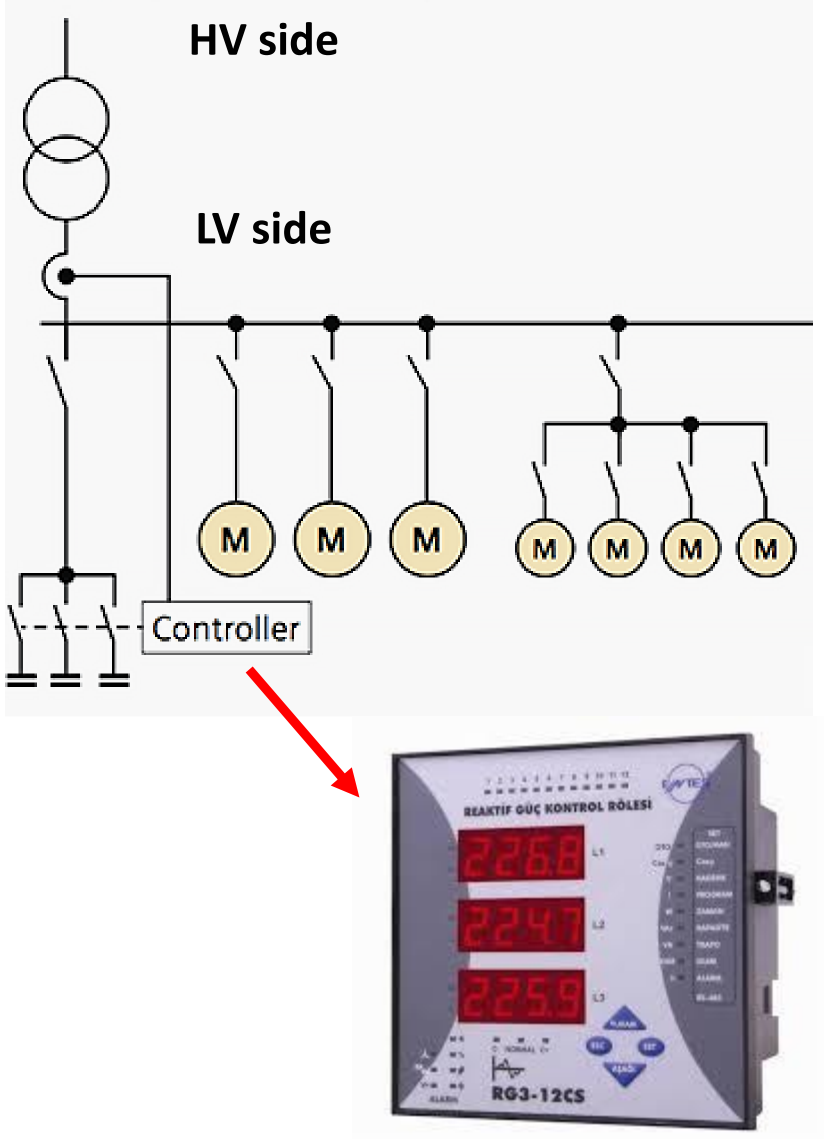
It is economically favorable for

- Large individual power consumers
- Constant power demand
- Long ON times

Disadvantage

A continuous adjustment of the capacitor reactive power is not possible.

3) Central compensation



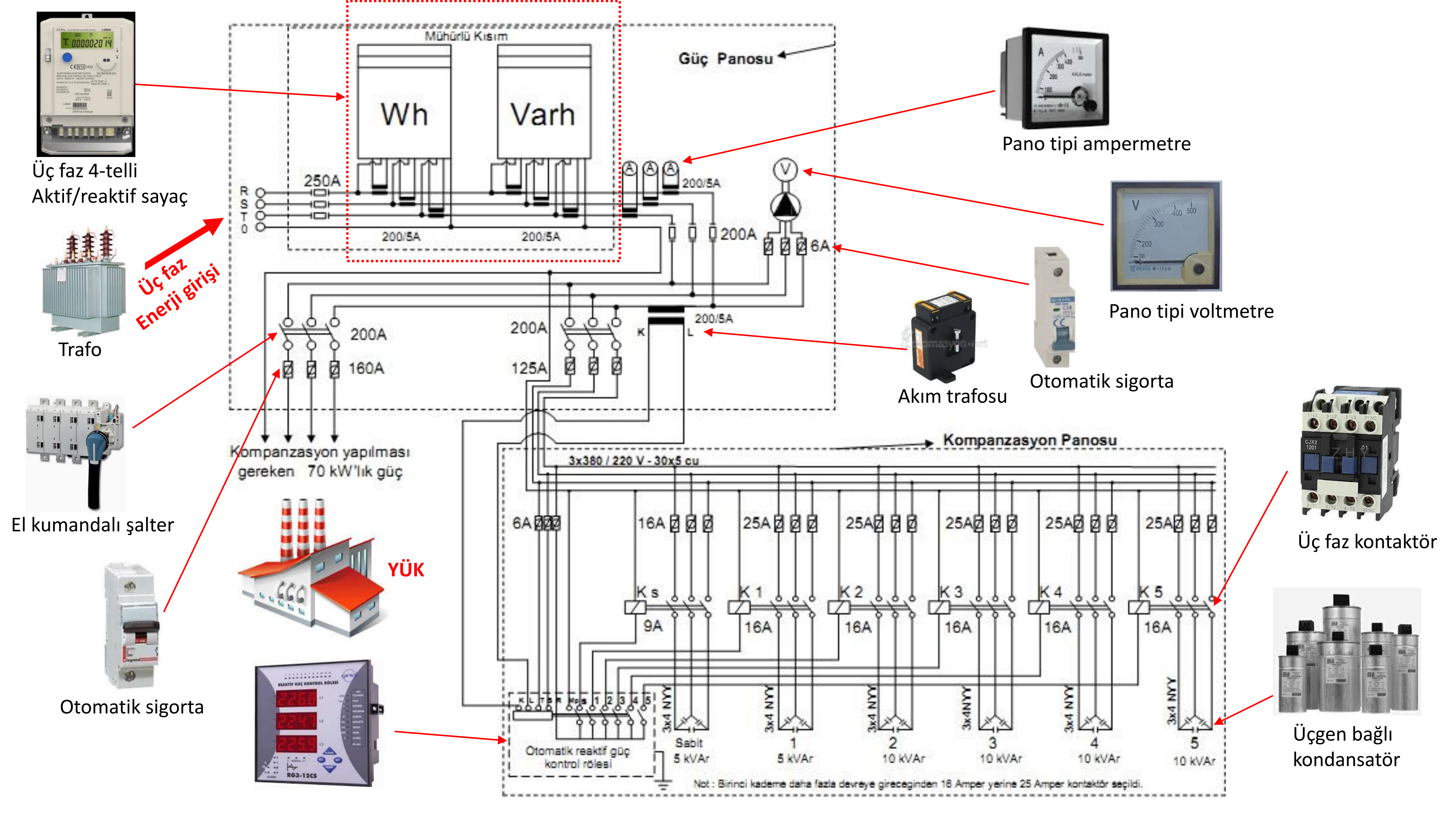
Reactive power control units are used for central compensation, which are directly assigned to a switchgear unit, distribution board, or sub-distribution board and centrally installed there. Control units contain switchable capacitor branch circuits and a controller which acquires the reactive power present at the feed-in location.

The capacitor power is chosen in such a way that the entire installation reaches the desired cos ϕ. If it deviates from the set-point, the controller switches the capacitors on or off step by step via contactors.

Advantage

It is technically favorable for

- Many small power consumers connected into supply
- Different power demands and varying ON times of the power consumers

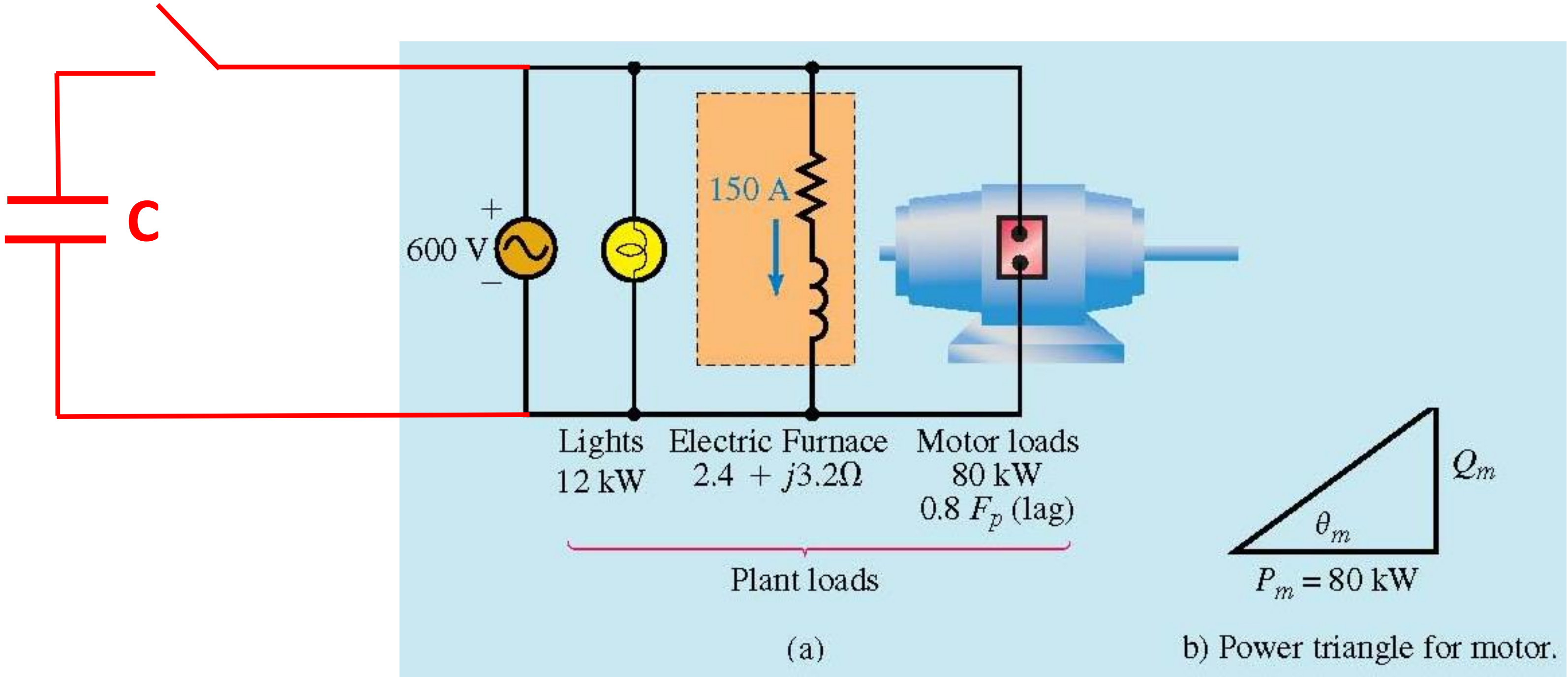


Üç faz 4-telli
Aktif/reaktif sayaç
Trafo
Üç faz
Enerji girişi
El kumandalı şalter
Otomatik sigorta
YÜK
Mühürlü Kısım
Wh
Varh
Güç Panosu
Pano tipi ampermetre
Pano tipi voltmetre
Otomatik sigorta
Akım trafosu
Üç faz kontaktör
Üçgen bağlı
kondansatör
R
S
T
0
250A
200/5A
200/5A
200/5A
200A
6A
200/5A
K
L
200A
160A
200A
125A
Kompanzasyon yapılması
gereken 70 kW'lık güç
Kompanzasyon Panosu
3x380 / 220 V - 30x5 cu
6A
16A
25A
25A
25A
25A
25A
K s
K 1
K 2
K 3
K 4
K 5
9A
16A
16A
16A
16A
16A
3x4 NYY
Sabit
5 kVAr
1
5 kVAr
2
10 kVAr
3
10 kVAr
4
10 kVAr
5
10 kVAr
Otomatik reaktif güç
kontrol rölesi
Not : Birinci kademe daha fazla devreye gireceginden 16 Amper yerine 25 Amper kontaktör seçildi.

Example: (single-phase system):

An industrial client is charged a penalty if the plant power factor drops **below 0.85**. The equivalent **single-phase** plant loads are shown in the figure. System frequency is 60 Hz. Determine

a) Total real and reactive power that the plant demands
b) Determine the value of the shunt capacitance C which is required to bring the power factor up to **0.85**
c) Determine generator current before and after compensation



<u>Example: (Three-phase system):</u>

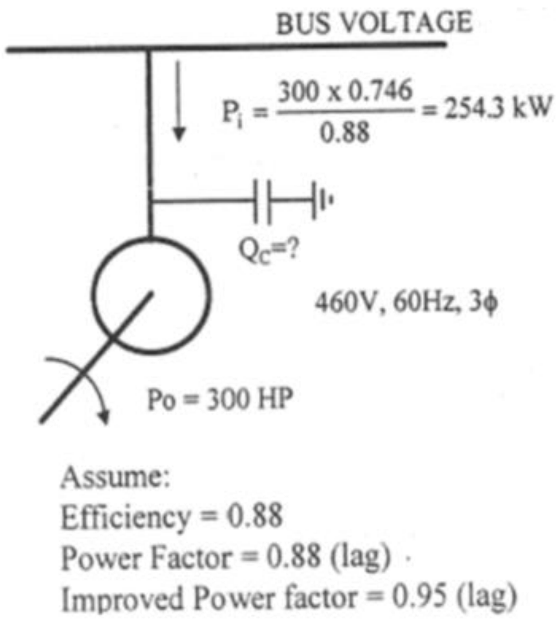
Single-line diagram of a low voltage **300 hp** three-phase motor connected to **460V (line-to-line), 60 Hz** bus is shown in the figure. Apply a compensation scheme so that the power factor of the combination (motor+capacitor banks) rises to **0.95 lagging**. (1 hp = 746W). Assume both

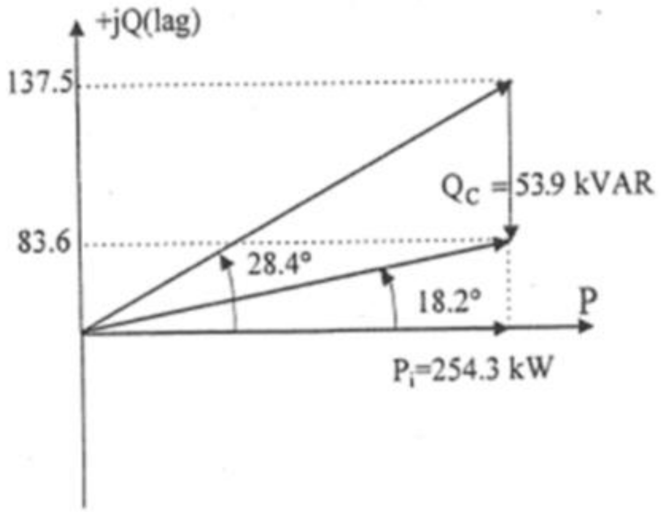
i) Wye (Y)-connected capacitors *(as shown in figure)*

ii) Delta (Δ)-connected capacitors

Compare also the **line current of the motor** *before* and *after* compensation

Low Voltage (LV) Motor:





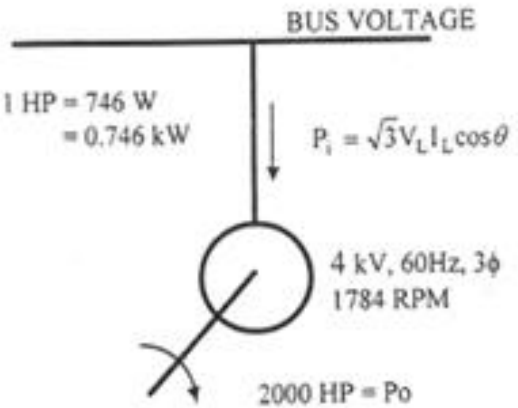
Example: (Dynamic compensation)

Single-line diagram of a medium voltage **2000 hp** three-phase motor connected to **4.0 kV (line-to-line), 60 Hz** bus is shown in the figure. (1 hp = 746W). Answer the questions

a) Apply a compensation scheme when the motor operates at **full-load**, so that the power factor of the combination (motor+capacitor banks) rises to **unity (1.0)**. Assume for both Wye and Delta-connected capacitors

b) If the motor is operated at the **70% of full-load**, apply a compensation scheme so that the power factor of the combination (motor+capacitor banks) rises to **unity (1.0)**. Assume for both Wye and Delta-connected capacitors

Medium Voltage (MV) Motor:



Efficiency $\eta = P_o/P_i$ (say 0.93)

Power Factor = 0.93 (lag)

$$I_L = \frac{P_i}{\sqrt{3}\, V_L \cos\theta} = 249 \text{ A}$$

= Rated Current

$P_o = 2{,}000 \times 0.746$

$= 1{,}492$ kW

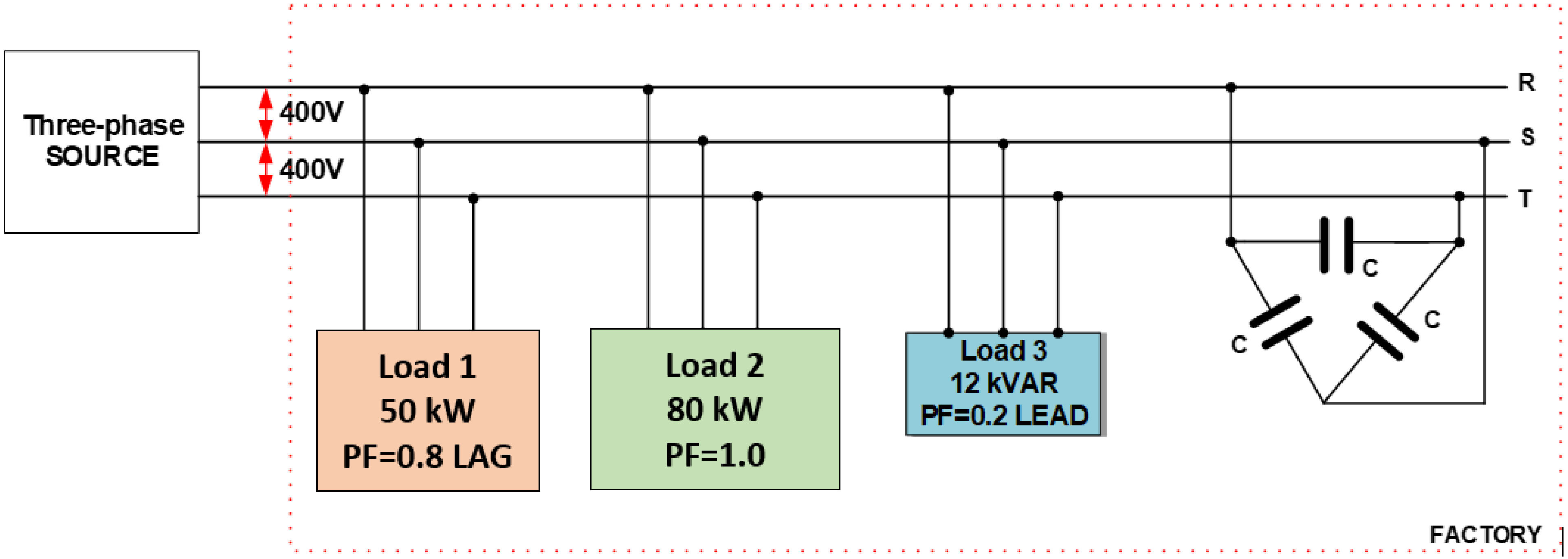
$P_i = 1{,}604.3$ kW

Example:

The following figure describes three types of loads in a factory which is fed from a three-phase 400 V (L-L) source.

a) Find the overall power factor of the factory. Is it lagging, leading, or unity ?

b) Find the value of capacitance C which are connected in delta to increase the overall power factor to unity



Problems for self-study:

P1. Find the value of the capacitance needed to correct the pf of a load of 140 kVAR at 0.85 lagging to unity. The load is supplied by a 120 Volts (rms), 60 Hz line.

P2. A 100 volts rms single-phase voltage source feeds an inductive load of (30+j40) Ω. Determine the value of capacitance to bring the power factor of the source to unity.

P3. A 0.82 pf lagging single-phase motor has an efficiency of 94% and rated at 100 hp. Calculate the kVAR needed to increase the overall power factor to 0.96 lagging. (1 hp=746 W)

P4. A 100 kVA single-phase load has a power factor of 0.95 lagging. It is required to make a reverse compensation so that the new overall power factor will be reduced to 0.8 lagging. Calculate the required kVAR (capacitive or inductive ?) to perform this action. Which element should be used (C, or L) to perform this action. If the load is fed by a 250 V rms 50 Hz source, find the value of C=? or L=?

P5. A 200 kVA single-phase load has a power factor of 0.93 lagging. It is required to make a over compensation so that the new overall power factor will be 0.4 leading. Calculate the required kVAR (capacitive or inductive ?) to perform this action. Which element should be used (C, or L) to perform this action ? If the load is fed by a 250 V rms 50 Hz source, find the value of C=? or L=?

P6. A 220 volts 50 Hz supply feeds two single-phase loads. Load 1 is a 3 hp motor at 0.7 pf lagging and Load 2 is rated at 2 kW at 0.9 pf lagging. Calculate a) the total power factor of the combined load, b) What value of capacitor must be connected to the terminals of the supply to raise the power factor to unity, c) with the capacitor connected, what is the total power factor when the motor is switched off ?

TEDAŞ Reactive Power Compensation Penalty Rates

- For residential, villa, and dwelling subscribers, a suitable meter for the contract power is installed, and no reactive or capacitive penalty is applied.
- For businesses, the implementation of a compensation system is mandatory after a **contract power of 9 kVA**. The use of a combined electric meter that measures reactive (inductive) and capacitive power is mandatory for such businesses.
- If a meter is not saving value due to user error, reactive energy fee is billed based on the amount of inductive reactive energy equal to 90% of the active energy.
- For businesses with a contract power between **9 and 50 kVA**, a penalty is applied when the *33% reactive limit* and *20% capacitive limit* are exceeded.
- For businesses with a **contract power equal or above 50 kVA**, a penalty is applied when the *20% reactive limit* and *15% capacitive limit* are exceeded.
- The percentage value is found by the ratio of the **inductive** or **capacitive reactive power** to the **active power.**
- For example, if the consumption is **Q=140 kVAR** (*inductive*) and **P=400 kW**, then **the percentage value = 140/400 = 35%**.

Example: (kVAR demand charge)

A plant with a demand of **400 kW** at **0.85 PF lagging** has a contract for power factor which is based on demand charge for kVAR. If the reactive limit is **20%** and the kVAR charge **after this limit** is **5 ₺** per month, calculate the total charge based on kVAR demand for one month and one year.

Solution:

Power factor (PF) = cosθ = 0.85 lagging ➔ θ = **31.78°** (power factor angle)

Q = P.tanθ = (400)(tan31.78°) = **248 kVAR**

20% of 400kW is **80 kVAR** (upper limit for the allowed amount of inductive kVAR value)

248-80 = 168 kVAR (subject to charge)

168 x 5 ₺ / month = **840 ₺ /month**

or

840 x 12 = **10080 ₺ /year**

Example: (kVAR demand charge)

If reactive power compensation cost is approximately **45 ₺/kVAR**, estimate the cost of a possible reactive power compensation solution to the plant in the previous example so that the plant is not charged for excess amount of kVAR. In what amount of duration does the compensation will pay for itself ?

Solution:

Since 20% of 400kW is **80 kVAR** (upper limit for demand charge for kVAR)

An amount of **248kVAR – 80kVAR = 168kVAR** of reactive power should be supplied by the reactive power compensation

So the total cost for reactive power compensation is 45 ₺ / kVAR x 168 kVAR = **7560 ₺**

As a result,

7560 ₺ / 840 ₺ = **9 months (The duration that the compensation pays for itself)**

A workplace equipped with a compensation panel can experience both inductive and capacitive penalties.

Let's explore some key factors:

1. Load Distribution in Three-Phase Electrical Installations:

In three-phase electrical systems, if single-phase loads are predominant, it is crucial to ensure that the phases are evenly distributed. The project should be implemented in a way that draws equal power from all three phases. If the loads are not evenly distributed and all the capacitors in the compensation panel are three-phase, this could lead to both inductive and capacitive penalties. In such cases, adding single-phase capacitors may be appropriate.

2. Planning the Compensation System:

Another critical factor is how your compensation system is planned. If current measurement for compensation is done from only one phase, the compensation system is not reliable. For a reliable compensation system, current information must be obtained from all three phases. To achieve this, current transformers should be connected to each of the three phases.

3. Avoiding Capacitive Penalties:

Capacitive penalties can occur if your capacitors fail to disconnect from the circuit. If the contacts of the contactors become stuck, the capacitors will remain connected, resulting in excessive capacitive energy production."

4. **Capacitive Penalties Due to System Capacitive Loads**:

Another reason for falling into capacitive penalties is the presence of **capacitive loads** in the system. Among the most significant capacitive loads in industrial settings are **Uninterruptible Power Supplies (UPS)**. While less common in small-scale businesses, another type of capacitive load is **underground cables**.

5. **Addressing Capacitive Energy in High-Load Situations:**

In establishments where capacitive loads are abundant and capacitive energy production is high, **shunt reactors** are used to compensate for capacitive energy.

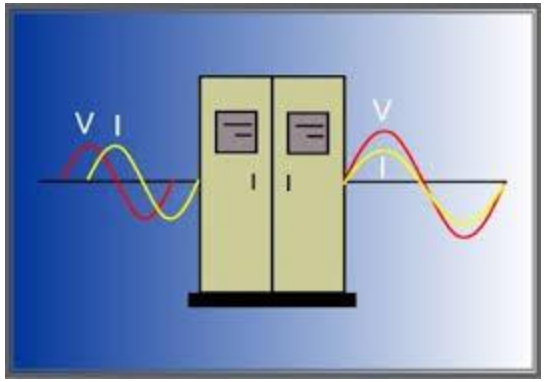
6. **Reactive Penalty Despite Compensation System:**

If you are still paying reactive penalties despite having a compensation system, consider examining the **switching speed and frequency** of your loads. If your business deals with rapidly switching loads, a contactor-based compensation system may be too slow. In such cases, **Static Var Compensation (SVC) or STATCOM (Static Synchronous Compensator) could be more suitable for handling sudden load fluctuations.

7. **Analyzing Deficiencies with an Analyzer:**

If your compensation system is in place but you continue to experience both inductive and capacitive penalties, use an **analyzer** to perform necessary measurements and identify any deficiencies in the system.

Summary
Benefits of Compensation



A) From Subscriber (Abone) point of view:

- ❑ Compensation reduces voltage dip
- ❑ Compensation reduces the current which is being drawn from distribution system
- ❑ Since current reduces, the size and the cost of the electrical apparatus such as cables, circuit breakers, fuses, and etc. reduce as well.
- ❑ Proper compensation avoids to pay reactive punishment

B) From Distribution Company (TEDAŞ) point of view:

- ❑ Compensation reduces apparent power and as a result it reduces the additional costs due to correction of voltage dip
- ❑ More efficiency can be obtained at transformer substations as a result of decreasing of apparent power
- ❑ Voltage stability is preserved in its limits. In another terms, reactive power-voltage balance is maintained

END OF THE LECTURE

Any questions ?