

Power factor correction

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Square D

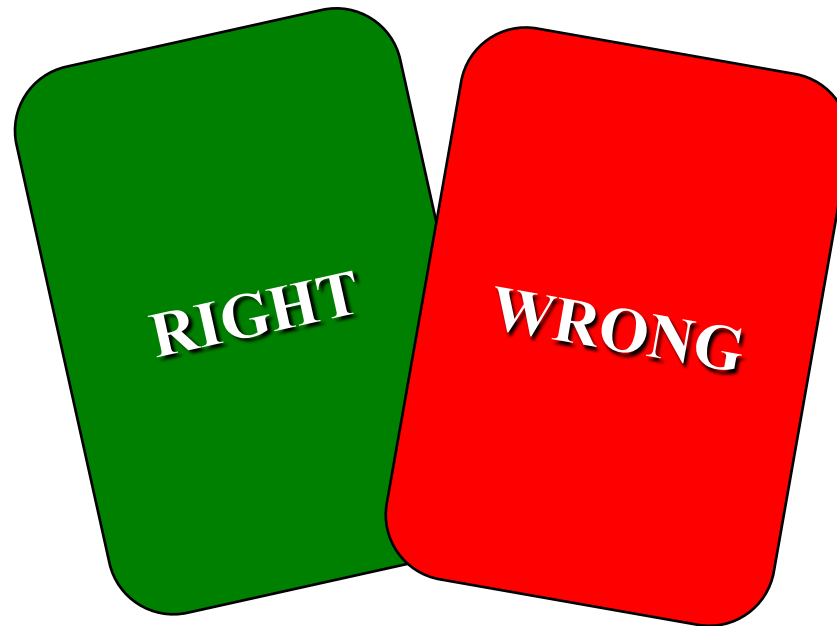
Telemecanique

Training module I01



Introduction

- Power factor correction allows to increase the available power on the secondary of the transformer.



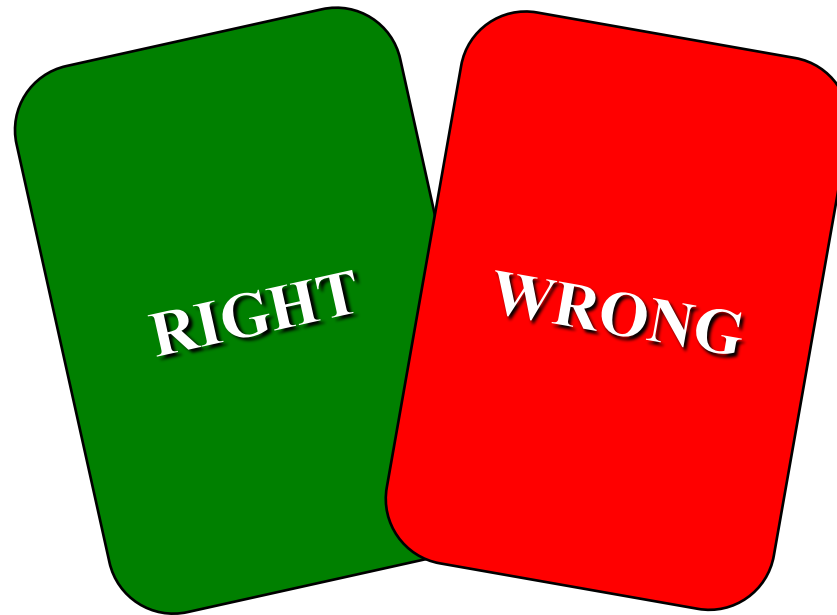
Introduction



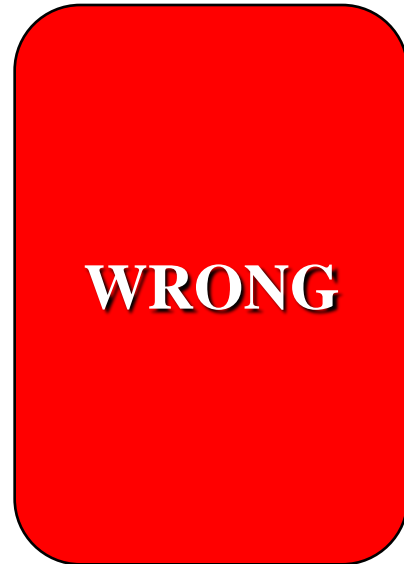
The capacitors supply reactive energy.
So the transformer does not have to supply it.

Introduction

- Reactive power is useless in the network.



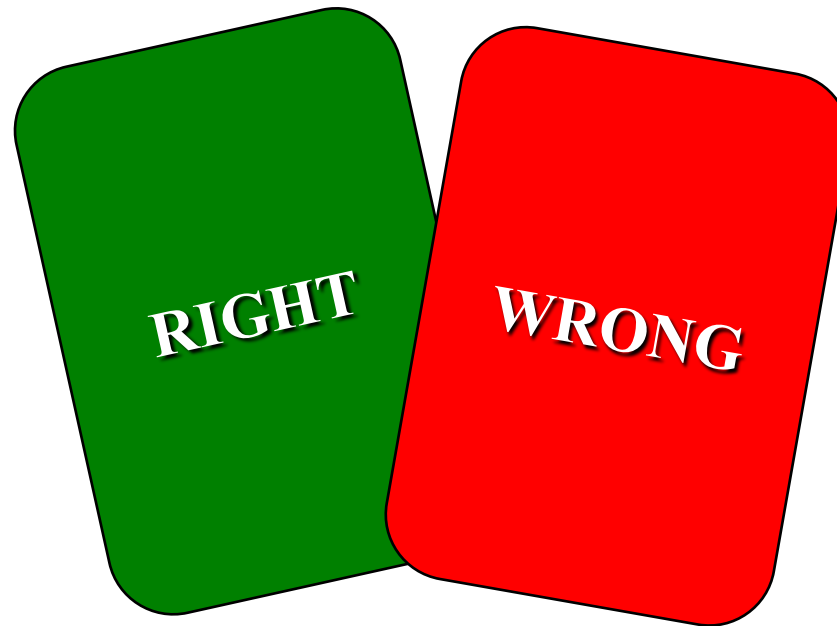
Introduction



This energy allows to magnetize the magnetic circuits of the motors and transformers although it products no work.

Introduction

- Compensate reactive power consists in increasing the $\cos \phi$ of the installation.



Introduction



The $\cos \phi$ represents the efficiency of the network.
More it is close to 1, and better is the efficiency of the network

Electric energy

■ Essential notions

- $\cos \varphi$, $\tan \varphi$, power factor,
- Active power, reactive power, apparent power,
- Fundamental magnitudes, RMS magnitudes,
- Difference between $\cos \varphi$ and power factor.

Electric energy

Agreement

- By agreement, an inductive load consumes reactive energy. We speak about inductive $\cos \varphi$.
- A capacitive load produces reactive energy. We speak about capacitive $\cos \varphi$.
- Most of loads are inductive loads (motors, transformers, ...). They consume reactive energy.
- Because of the inductive nature of the loads connected on the network, displacement factor is inductive in most cases.

Electric energy

Recalls

- Any electric system (cable, line, transformer, engine, lighting,...) using the AC current needs two forms of energy:

- ***Consumed active energy (kWh)***

It results from the use of the active power P (kW) of the loads.

It is converted into mechanical power (work) or heat (losses,...).

It is the “useful” energy

- ***Consumed reactive power (kvarh)***

It is used for magnetizing of the motors and the transformers.

It corresponds to the reactive power Q (kvar) of the loads.

It depends on the displacement between the tension and the current.

It is a “necessary energy” but it produces no work”

Electric energy

Definitions

- Reactive power used by the loads is supplied by the electric network. This power has to be supplied added to active power.

- Reactive power in the electric network causes:
 - Transformers overload,
 - Cables and lines heating,
 - ...so **losses**.

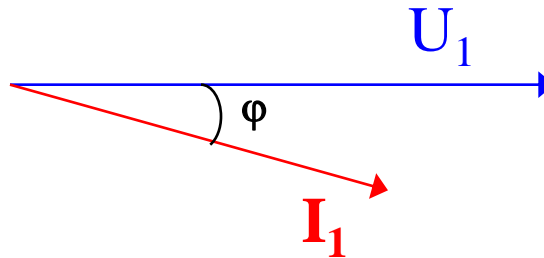
- For these reasons, reactive energy must be produced as close as possible to the loads, to prevent the unnecessary circulation of current in the network.

This is what is known as “**power factor correction**”

Electric energy

Definitions

- **Cos φ** : It depends on the displacement between current and voltage fundamental magnitudes.



FRESNEL diagram

$$\cos \varphi_1 = \frac{P_1}{S_1}$$

P_1 : active power of the fundamental component.

S_1 : apparent power of the fundamental component.

Electric energy

Definitions

- **Power factor**

$$PF = \frac{\text{active power (kW)}}{\text{apparent power (kVA)}} = \frac{P}{S}$$

- If currents and voltages are perfectly sinusoidal, power factor is equal to $\cos \varphi$.

Electric energy

Definitions

- $\tan \varphi$ is often used instead of $\cos \varphi$.
- $\tan \varphi$

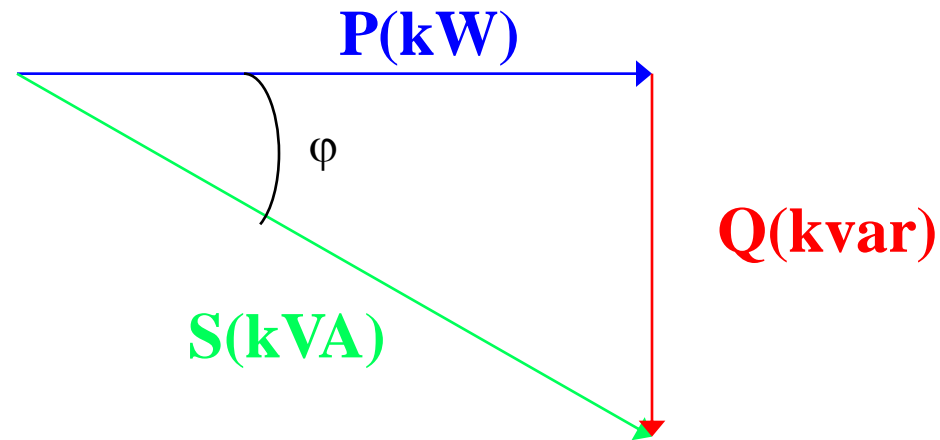
$$\tan \varphi = \frac{\text{reactive power (kvar)}}{\text{active power (kW)}} = \frac{Q}{P}$$

Without harmonics only

Why compensate reactive power?

Graphical illustration

- Before power factor correction



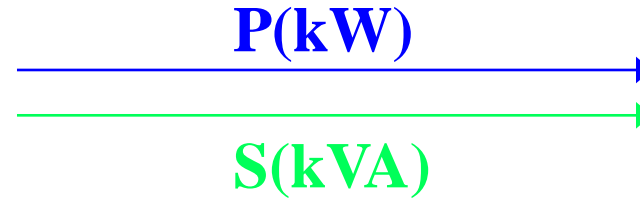
$$S > P$$

$$\text{Cos } \varphi < 1$$

Why compensate reactive power?

Graphical illustration

- After power factor correction



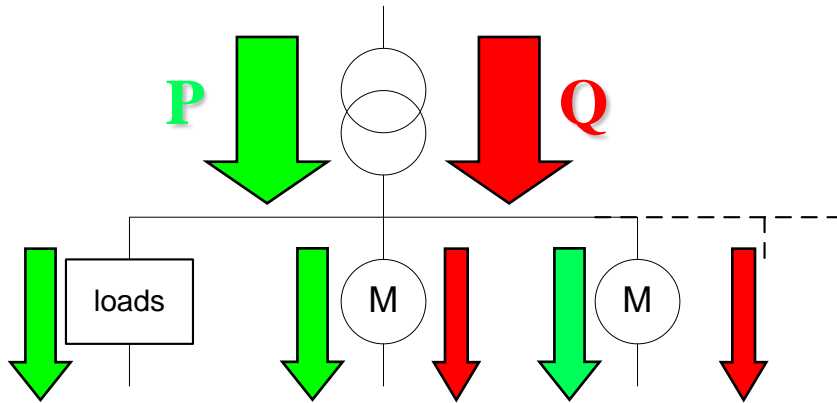
$$S = P$$

$$\text{Cos } \varphi = 1$$

Why compensate reactive power?

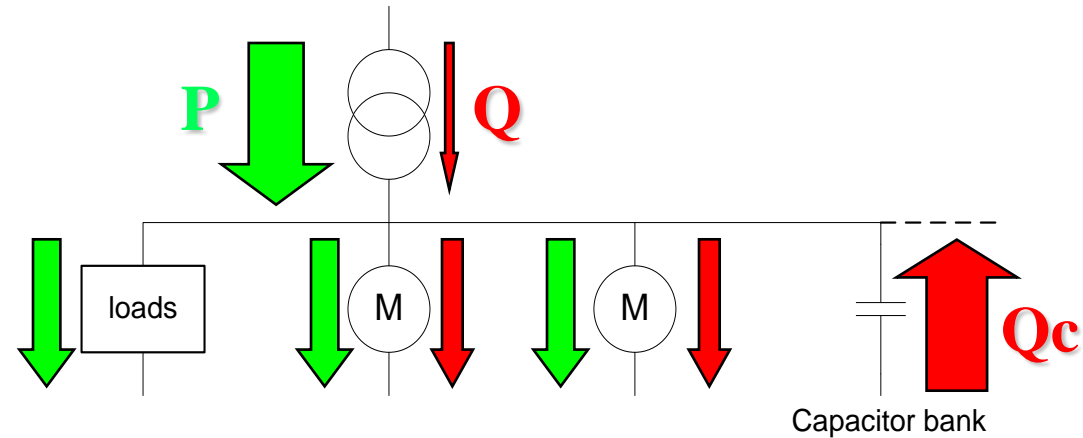
Users advantages

Without power factor correction



- ❑ Important Joule losses in cables.
- ❑ Important voltage drops in cables.
- ❑ Penalties by the utilities (in France for example).

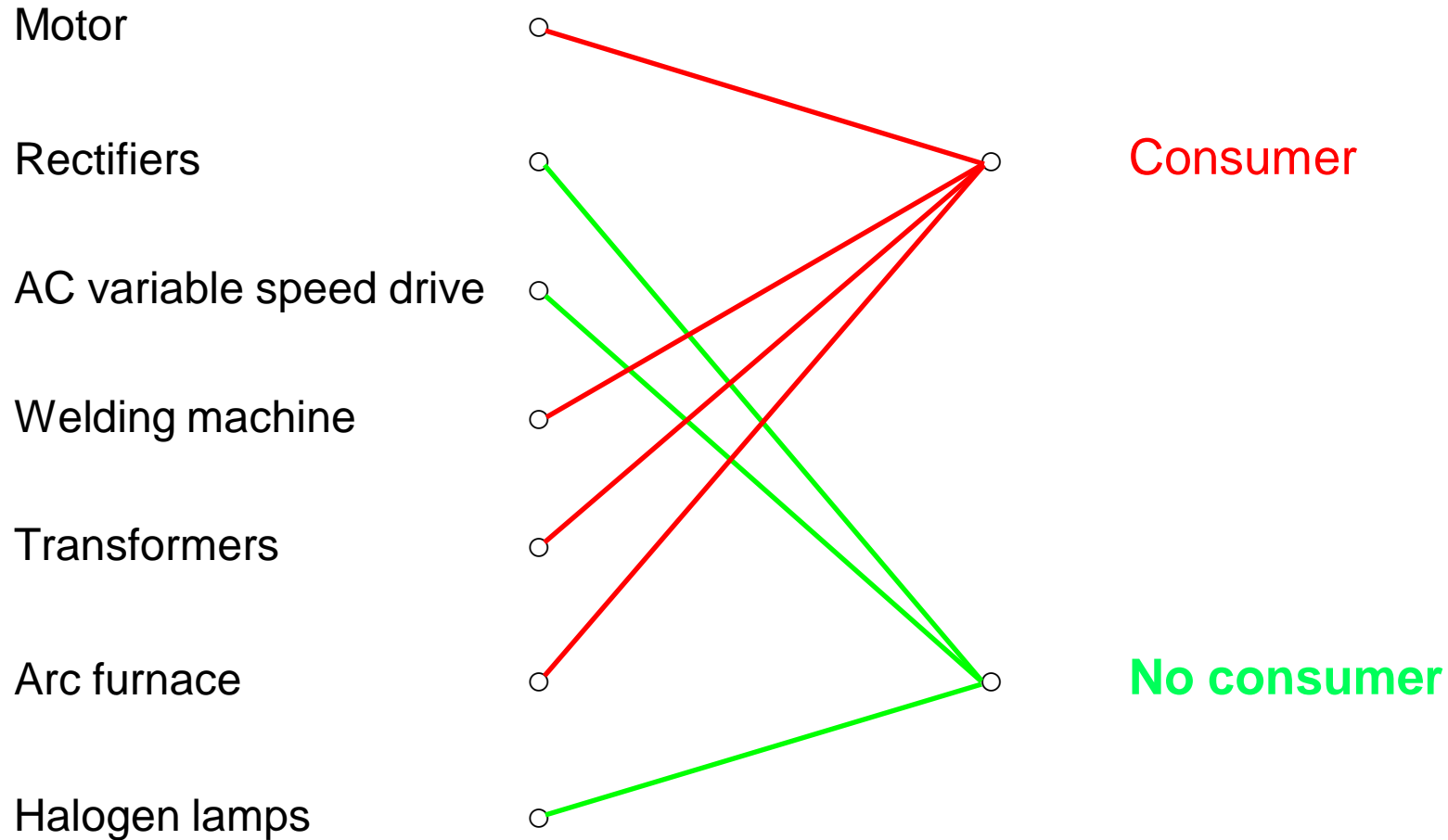
With power factor correction



- ❑ Decrease of consumed reactive energy.
- ❑ No distributor penalties.
- ❑ Increase of available power on the secondary of the transformers.

Why compensate reactive power?

Consumer or no consumer?



How to correct power factor?

Generalities

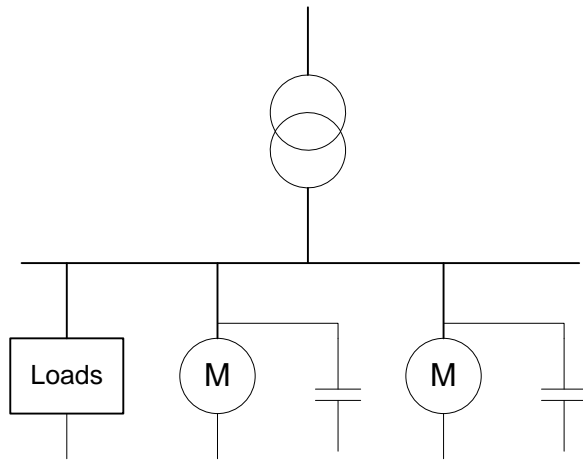
- By producing reactive power as close as possible to the loads.
- By installing capacitors on the network. Capacitors generate reactive power on the network.
It is the easiest and the most common way.
- Capacitors are put in parallel on the network loads by optimizing their position according to economic criteria.
- On all voltage levels.

How to correct power factor?

Modes of correction

■ Individual correction

The capacitor bank is connected closest to the loads



ADVANTAGES

The reactive power is done where it is consumed.

It is the best way to reduce the apparent power, losses and voltage drops into the conductors.

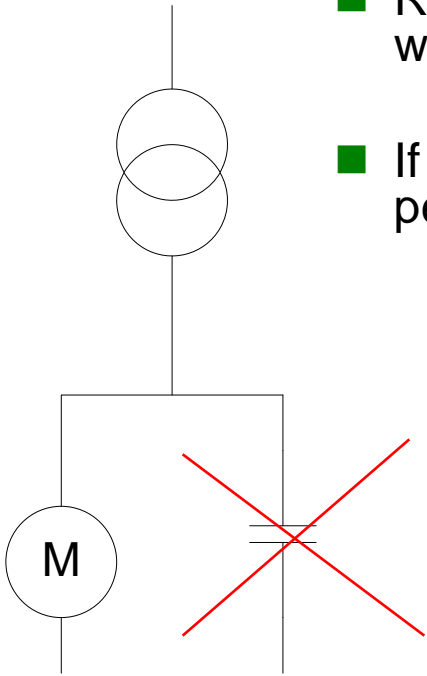
DRAWBACKS

The cost because small capacitors are more expensive than big ones.

How to correct power factor?

Motor and individual correction

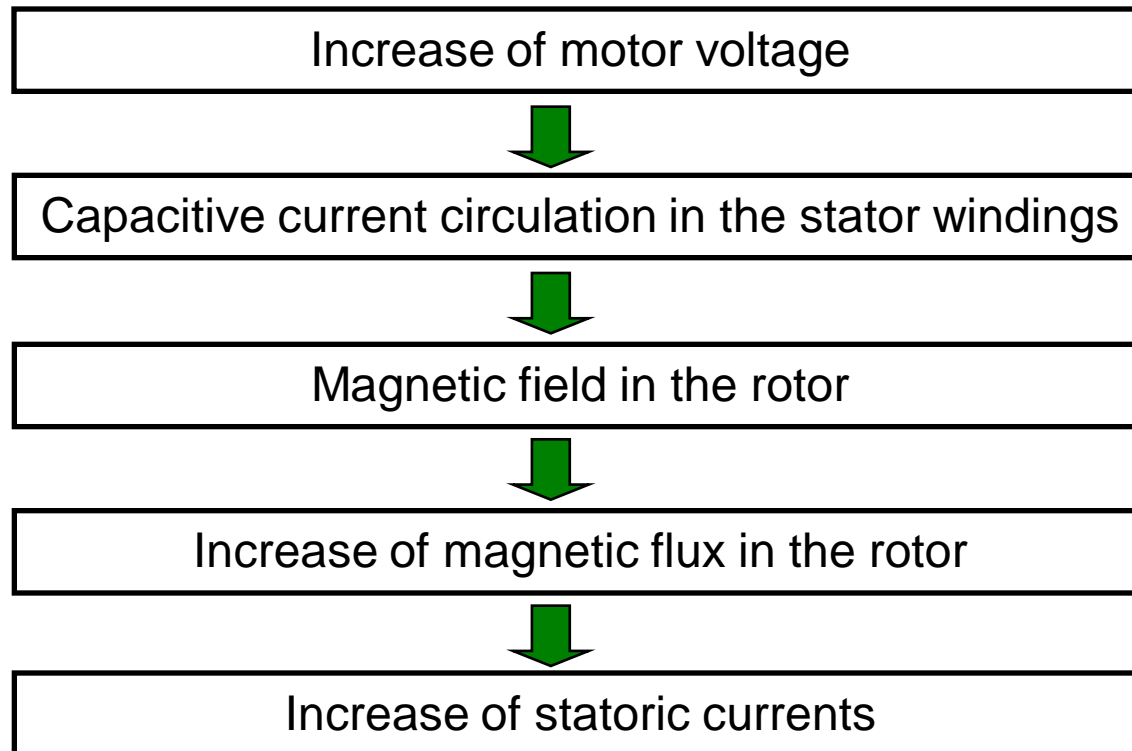
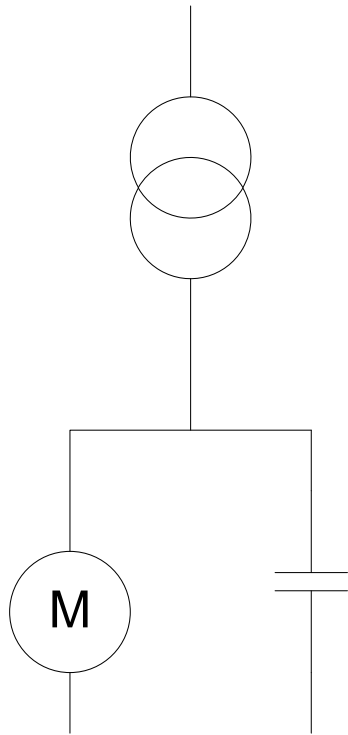
- A motor still turns when power supply is stopped.
- Rotor magnetic inertia induces an electromotive force in stator windings since a short time.
- If there is no capacitor bank => electromotive force disappear in few periods.



How to correct power factor?

Motor and individual correction

- If the motor is compensated:



»self-excitation » phenomena

How to correct power factor?

Motor and individual correction: solutions

- Solution 1: Limit the capacitor bank power

$$Q_c \leq 0,9 \times I_0 \times U_n \times \sqrt{3}$$

- Q_c : capacitor bank power
- I_0 : no load current of the motor
- U_n : rated motor voltage

How to correct power factor?

Motor and individual correction: solutions

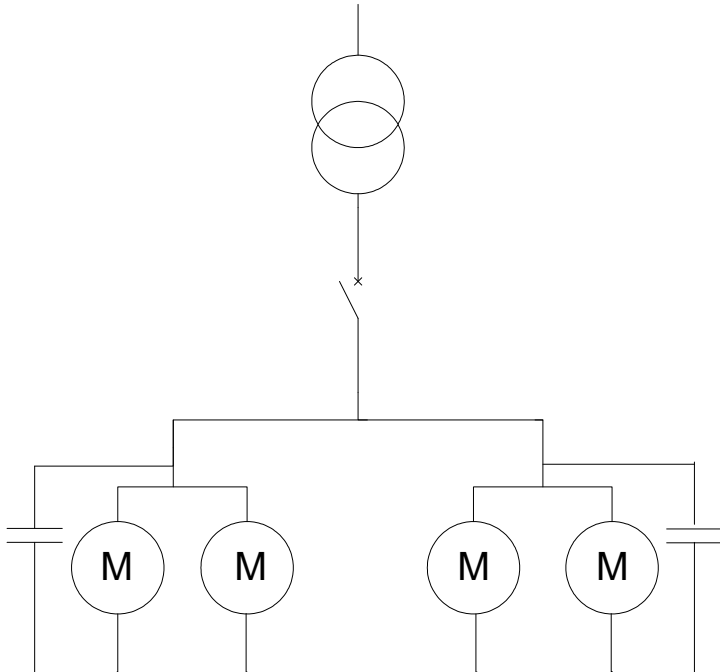
- Solution 2: Disconnect the capacitor bank when the motor stops.
- A contactor is installed on the capacitor bank which allows an automatic disconnection when the motor stops.

How to correct power factor?

Modes of correction

■ Sector correction

The capacitor bank is connected at the supply end of the installation sector and supplies reactive energy by sector.



ADVANTAGES

Investments are less expensive than individual correction.

The sector correction is advised for installations where many loads are used in same time.

DRAWBACKS

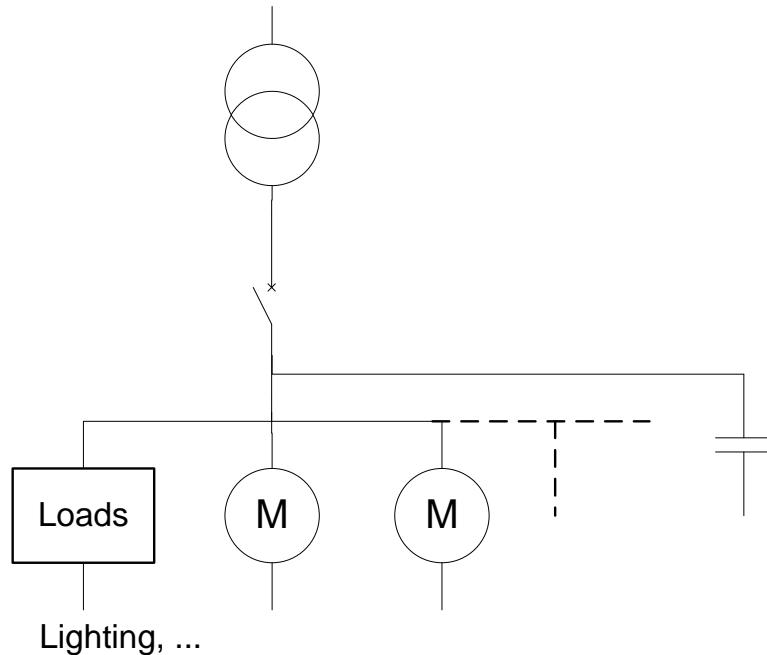
The connection cables of the loads are not compensated.

How to correct power factor?

Modes of correction

■ Global correction

Capacitor bank is connected to busbars of the main LV distribution board.



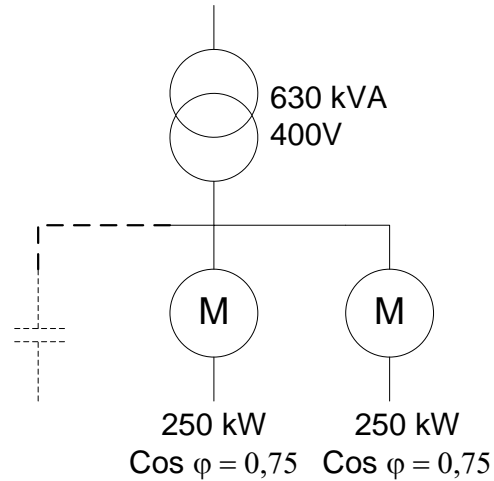
ADVANTAGES

It is an interesting economical solution if the loads are stable and continuous.

DRAWBACKS

Reactive power circulates everywhere in the installation

Exercise: Advantages of power factor correction



Data

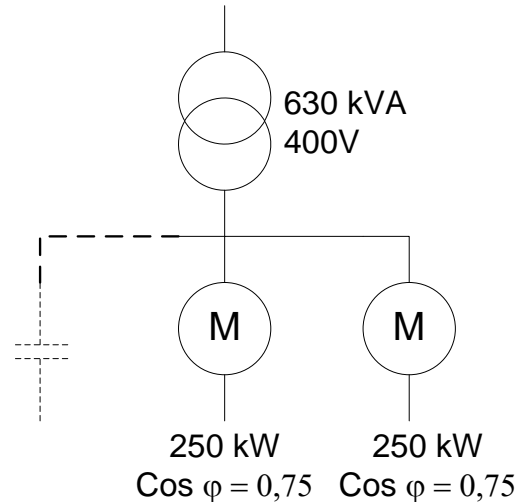
- 2 motors $P=250\text{kW}$ $\text{cos } \varphi = 0,75$
- Target $\text{cos } \varphi=0,93$

Pb: Which capacitor bank do you install?

- Reactive power?
- Type? Fixe or automatic?



Exercise: Advantages of power factor correction



Installation without capacitor bank

- ❑ Apparent power demand 667 kVA
- ❑ $\text{Cos } \varphi = 0,75$
- ❑ Electricity bill
- ❑ Overloaded transformer

Installation with capacitor bank

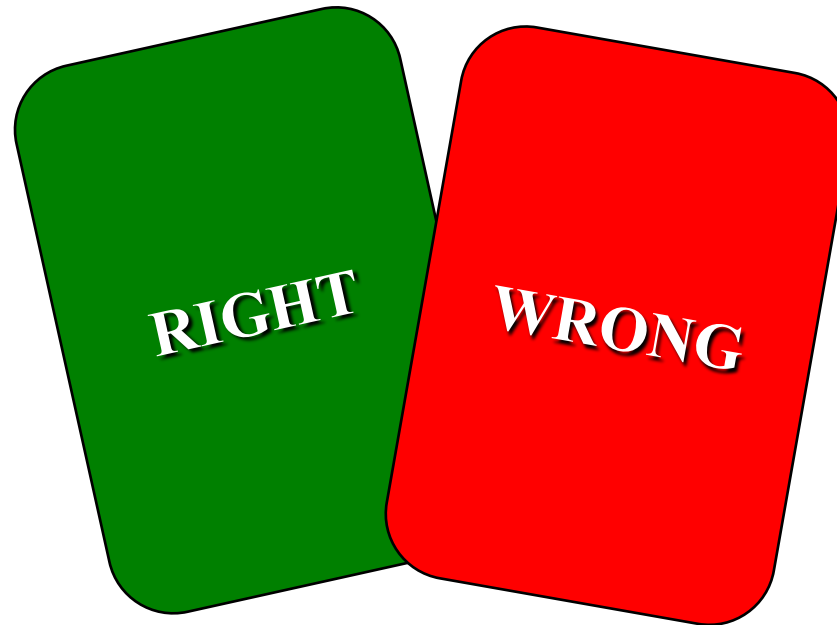
- ❑ Apparent power demand 537 kVA
- ❑ $\text{Cos } \varphi = 0,93$
- ❑ No electricity bill
- ❑ No overloaded transformer
- ❑ 93 kVA available

Harmonics

Harmonics

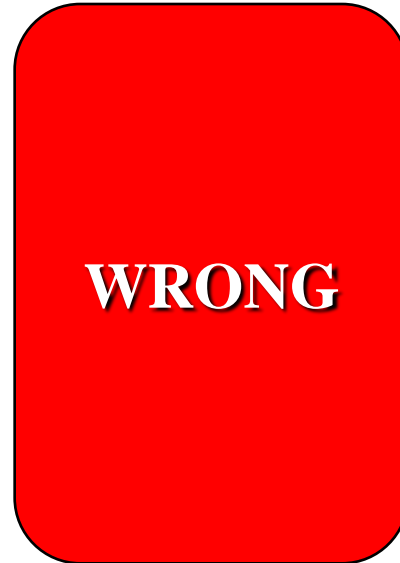
Introduction

- Motors generate harmonic currents



Harmonics

Introduction

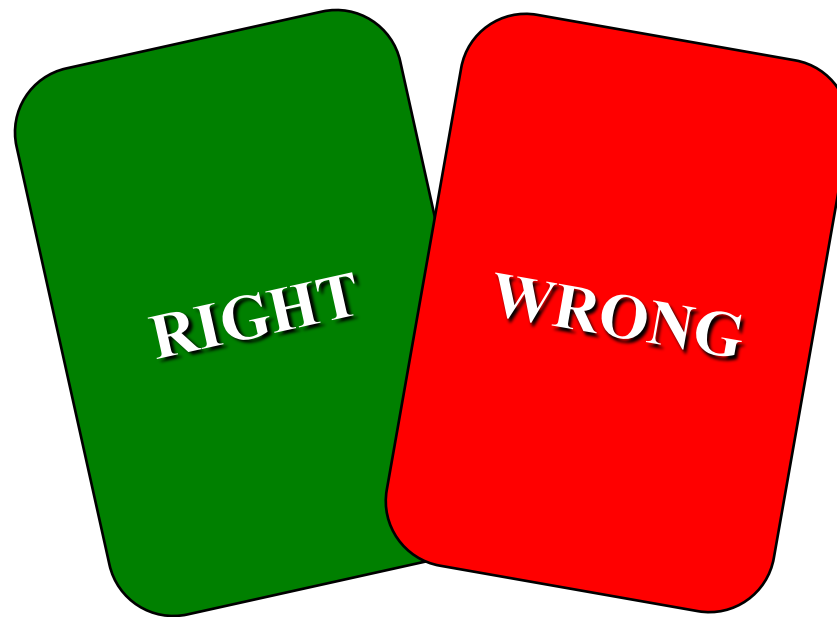


Installing loads using electronic power like variable speed drive for motors increase harmonic pollution on electric networks.

Harmonics

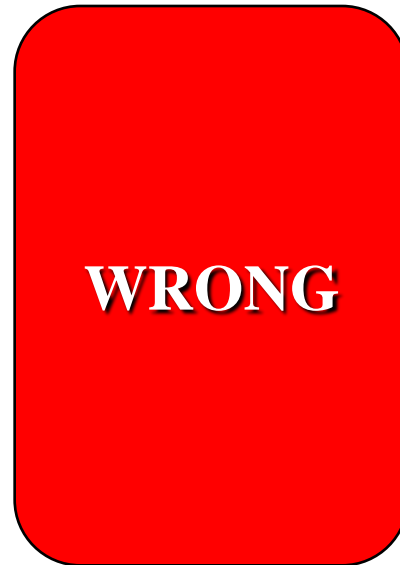
Introduction

- Harmonic currents have no effects on the network and on capacitor bank



Harmonics

Introduction

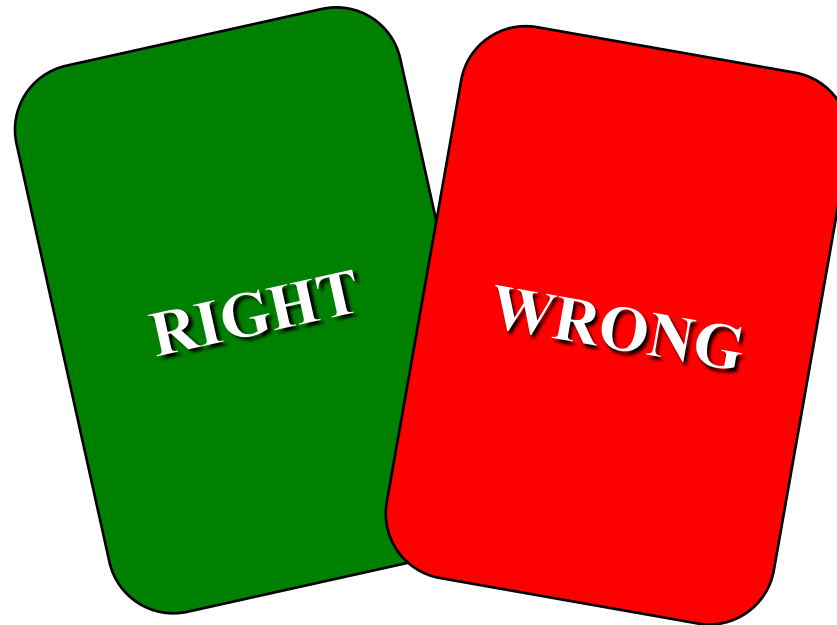


The effects are very important on the network (overheating of the transformer, ...) and on capacitor banks (overload and risk of destruction)

Harmonics

Introduction

- Capacitor banks do not generate harmonic currents.



Harmonics

Introduction



Capacitor banks do not generate but they can **amplify** them in certain cases.

Harmonics

Introduction

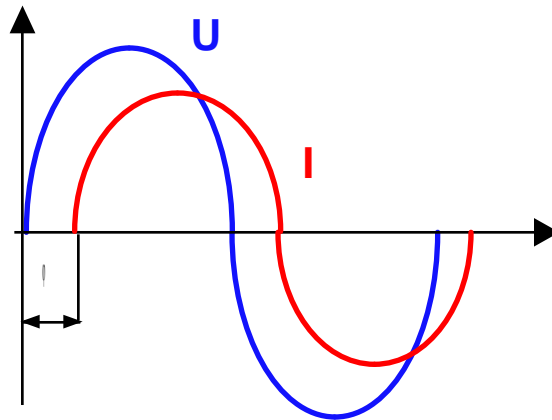
- Installing loads using electronic power like variable speed drive for motors increase harmonic pollution on electric networks.
- No linear loads distort voltage waveform due to the propagation of harmonic currents throw network impedance. The network is said « polluted ».
- Harmonic effects are bad for the network components and especially for capacitor banks.
The network behavior has to be studied.

Harmonics

Harmonic origin

- Most electric networks supply alternative sinusoidal voltage with a frequency of 50 or 60 Hz depending on countries.
- A motor, when it is connected on the network, absorbs a current which has the same waveform as the supply voltage and the same frequency.

This load is said « linear ».



Linear load

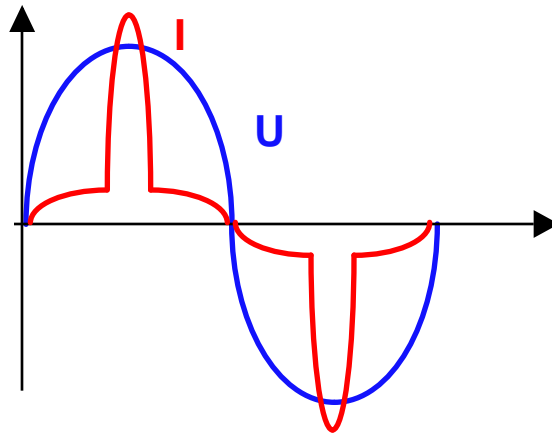
A load is said to be "linear" when the current it draws has the same waveform as the supply voltage. Such a current has no harmonic components.

Examples : resistors in electric heaters, inductive loads under steady-state conditions (motors, transformers, etc.)

Harmonics

Harmonic origin

- It exists some loads which current waveform is different as the supply voltage waveform.
These loads are said « no linear ».



No linear load

A load is said to be "non-linear" when the current it draws does not have the same waveform as the supply voltage. The current then has a high harmonic content. The harmonic spectrum depends on the type of load.

Examples: variable speed drives, rectifiers, switch-mode power supplies, motors during startup, transformers during switch-on

Harmonics

Harmonic origin

- **Waveform deformation is due to sinusoidal waveforms whose the frequency is multiple of the fundamental frequency which add to the fundamental waveform.** That are « harmonics »
- To conclude, no linear loads which absorb no sinusoidal currents which are harmonics current generators.
- Generally, all components which use “rectifier” function of the alternative waveform with diode or thyristor bridge, generate harmonics currents.
- In industry, the most common harmonic generator is the variable speed drive which allows a high flexibility for the motor control.

Harmonics

Definitions

- Any periodic signal of frequency "f", whatever its waveform, can be represented as the sum below:

$$s(t) = S_0 + \sum_{n=1}^{50} S_n \sqrt{2} \sin(n\omega t + \varphi_n)$$

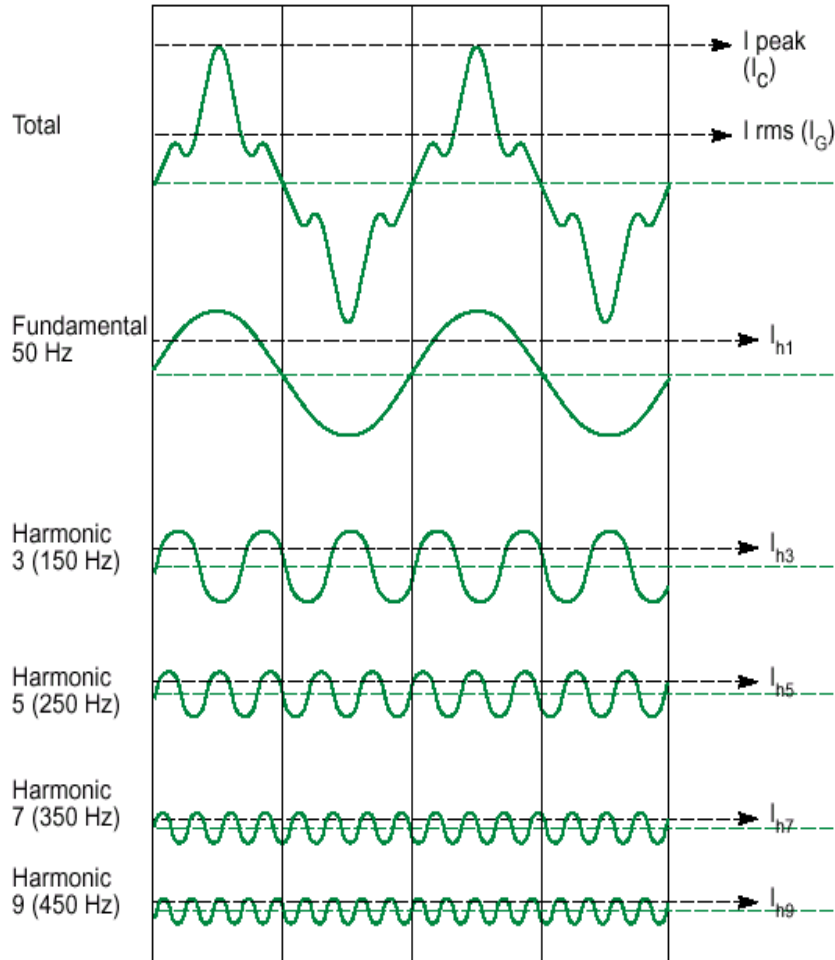
with S_0 , DC component, generally equal to zero,

S_n , the rms value of the fundamental signal with a « n » frequency equal to « n » times the fundamental one.

- The signal is a **sum of fundamental** component and **harmonics** components.

Harmonics

Definitions



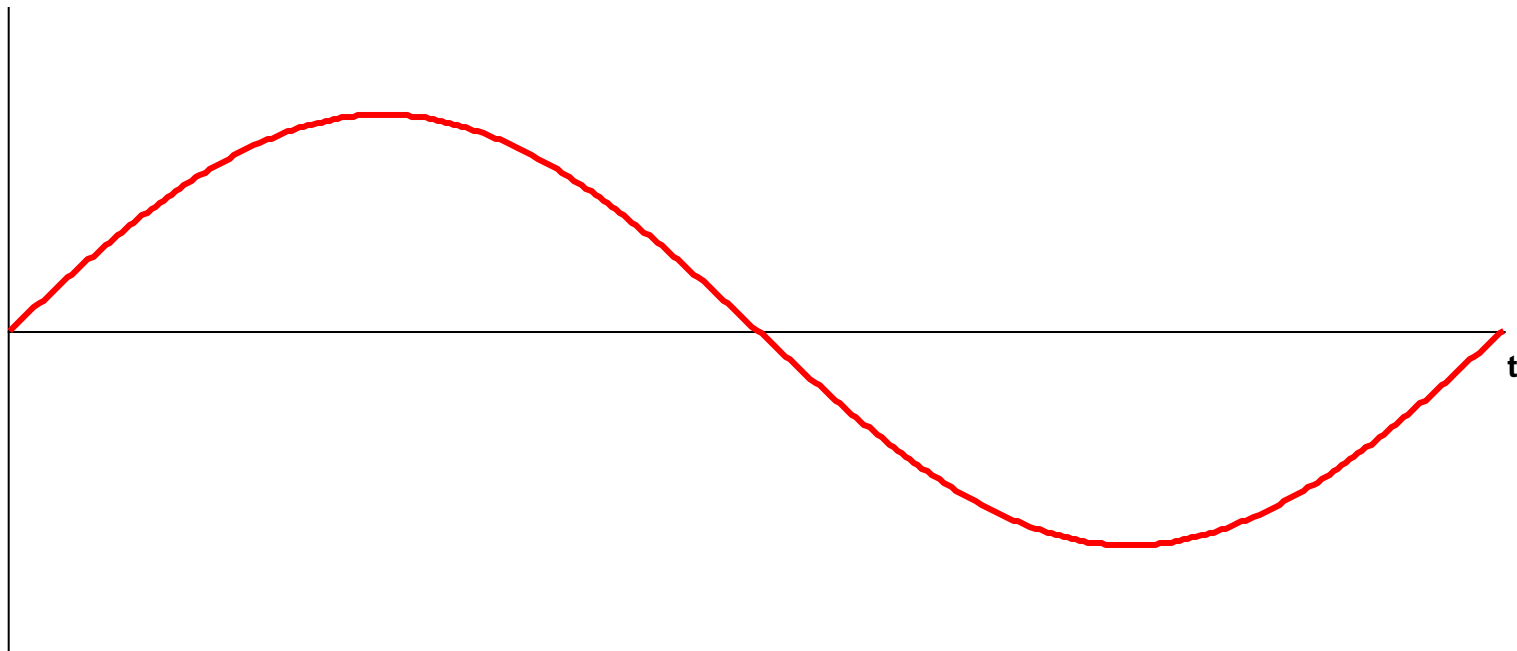
- The **fundamental component** : The fundamental is the sinusoidal component of frequency f equal to the power supply one.
- The **harmonics components** : The harmonic component of « n » rank is the sinusoid with a fn frequency equal to « n » times the f power supply network one.
- **Harmonic rank** : Integer number equal to the ratio between fn harmonic frequency and f fundamental frequency.

Harmonics

Definitions

- It is the sum of the fundamental...

Fundamental

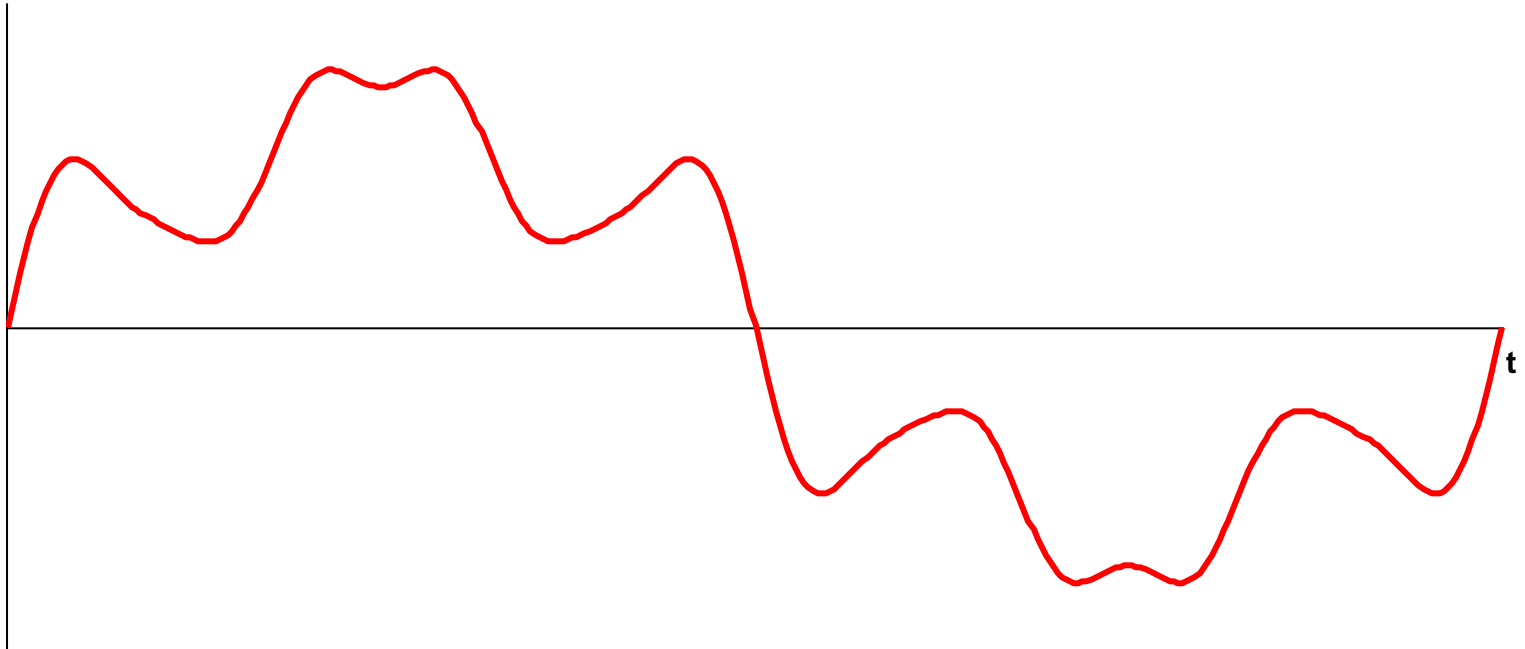


Only the fundamental ($f=50\text{Hz}$ or 60Hz) provides energy

Harmonics

Definitions

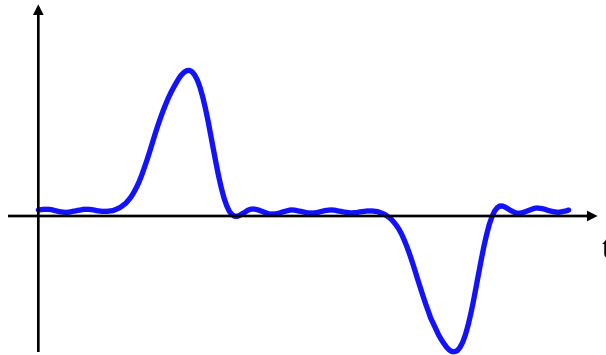
So the result is...



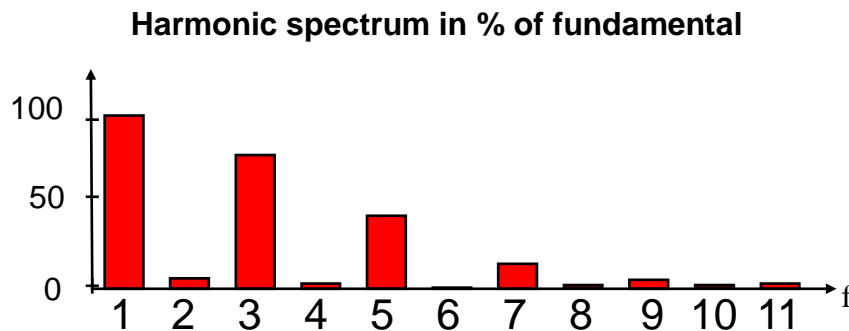
Harmonics

Representations

■ TEMPORAL representation



■ FREQUENTIAL representation



Spectrum

The spectrum of a signal is the graph representing the amplitudes of the various harmonics as a function of their respective frequencies.

(ex : rank 5 = 250Hz (if $f=50\text{Hz}$))

Harmonics

The rms value

- The **RMS VALUE** of a current or a voltage, is the **DC current or voltage value which causes the same heating** in a resistor (for periodic signals).
- Mathematically, the rms value of an harmonics deformed signal is defined by:

$$\text{rms value} = \sqrt{H_1^2 + H_2^2 + H_3^2 + \dots + H_{50}^2}$$

H1 is the fundamental value

H2, H3... correspond to the rms of each harmonic component.

Example : Rms current calculation by a single phase computer load

I1=56.2A, I3=27.2A, I5=2.7A, I7=9.2A and I9=7.8A

$$I_{rms} = \sqrt{56.2^2 + 27.2^2 + 2.7^2 + 9.2^2 + 7.8^2} = 63.6A$$

Harmonics

Harmonic distortion

- The **TOTAL HARMONIC DISTORTION** (THD) represents the deformation of the fundamental sinusoidal signal by harmonics.
- Mathematically, current or voltage total harmonic distortion is calculated by:

$$THD = 100 \frac{\sqrt{\sum_{n=2}^{n=50} Hn^2}}{H1}$$

- This is the ratio of the rms value of the harmonics to the rms value of the fundamental. It is a percent value (%).
- Standards define total harmonic distortion differently. The denominator is Hrms instead of H1.

Harmonic generators

Generalities

■ ELECTRONIC POWER EQUIPMENTS

- Variable speed drives
- Thyristor controlled equipments
- Static converters (UPS)

■ Loads using electric arc

- Arc furnaces
- welding machines
- Lighting

■ Equipment with magnetic circuits

- Alternators
- Transformers

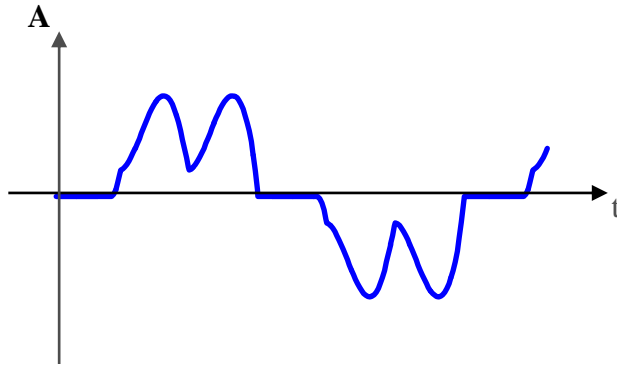
Harmonics generators

Variable speed drive

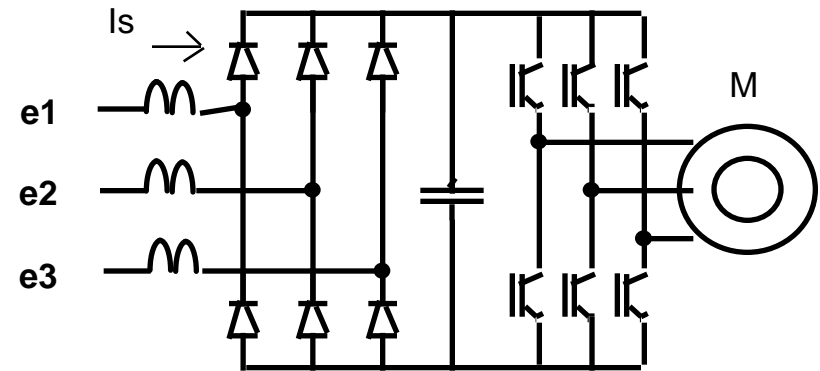
- 3-phase loads
- Draws high harmonic currents of orders 5, 7, 11, 13

■ CURRENT DRAWN I_s

THDI=44%

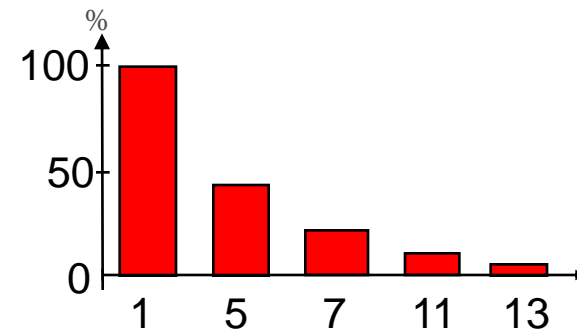


· DIAGRAM



■ HARMONIC SPECTRUM

35% H5, 15% H7, 8% H11, ...



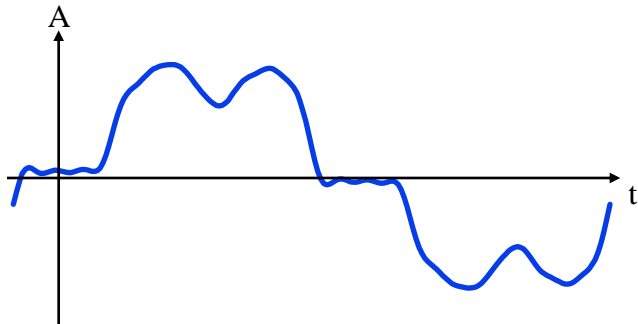
Harmonics generators

Rectifiers / chargers

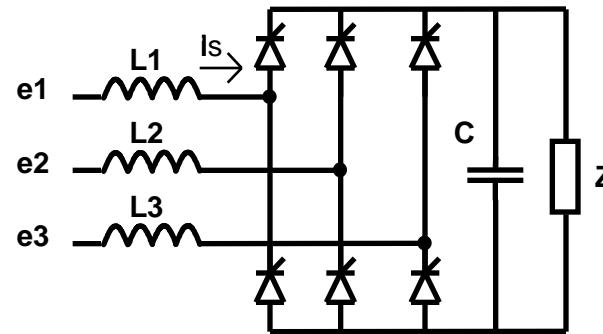
- 3-phase loads
- Controlled Graëtz bridge
- Draws high harmonic currents of orders 5, 7, 11, 13

■ CURRENT DRAWN I_s

S=122KVA THDI=30%

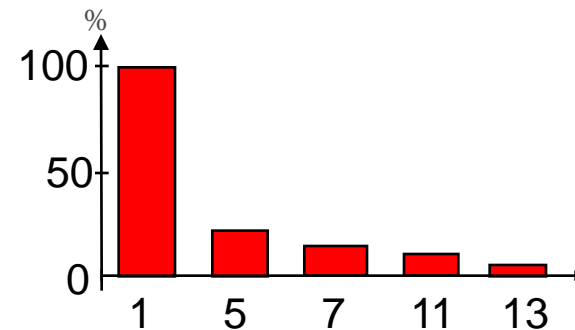


■ DIAGRAM



■ HARMONIC SPECTRUM

19% H5, 11% H7, 6% H11, ...

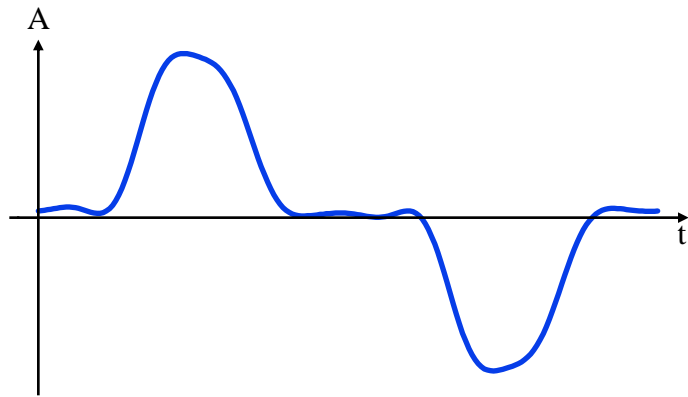


Harmonic generators

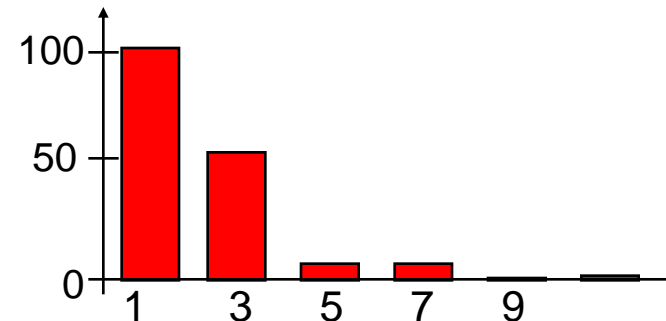
Welding machines

- Single-phase loads
- Current with a high harmonic content
- Lasts between 20 and 50 cycles

- **CURRENT DRAWN I_s**
 $I_s=341A$ THDI=58%



- **HARMONIC SPECTRUM**
56% H3, 9% H5, 9% H7

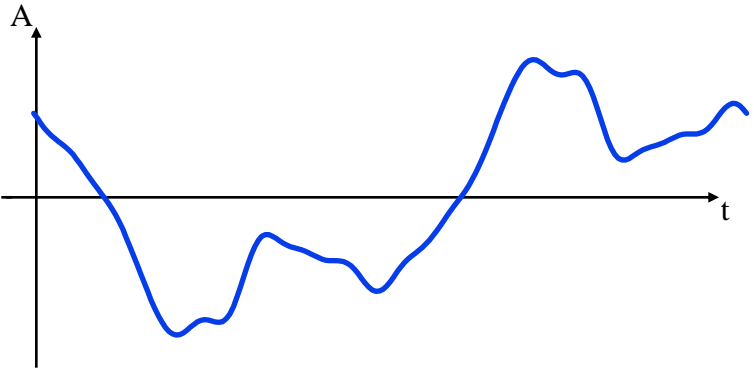


Harmonic generators

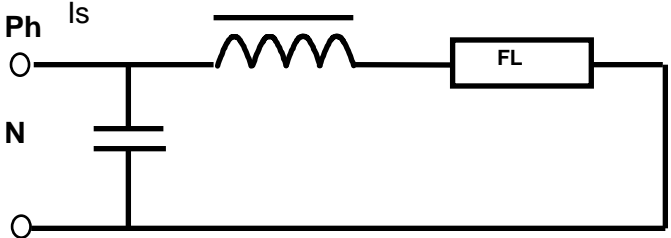
Lighting

- Single-phase loads
- H3 harmonic current

■ CURRENT DRAWN I_s
 $S=22\text{KVA}$ THDI=53%

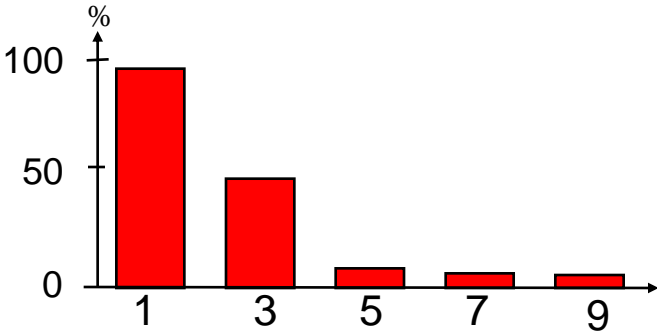


■ DIAGRAM



■ HARMONIC SPECTRUM

51% H3, 11% H5, 8% H9...



Harmonics effects on electric equipments

Generalities

- The most known harmonics effects are destruction of capacitor banks or circuit-breakers due to the high harmonic level amplified by resonances.
- They are seen on internal factory networks.
- Another effect is transformers and neutral conductors heating due to 3rd harmonic current.
- Three main effects:
 - **Immediate effects** are instantaneous on the equipments as for example measure instruments of precision and TV screens,
 - **Short-term effects** (from few seconds to few hours) are for example circuit-breaker disconnection and dysfunction of sensible applications,
 - **Long-term effects** (more than few hours) are over heating of conductors, transformers, alternators and capacitor banks.

Harmonics effects on electric equipments

In other words, immediate effects are...

- **The disturbance of electronic systems**
 - Bad commutation of the thyristors because of the deformation of the voltage waveform,
 - Disturbance of the remote control systems of the energy distributors.

- **Noises and vibrations**
 - Pulsatory torques due to the harmonic rotating field in machines inducing vibrations.
 - Electrodynamical strains inducing vibrations and noises in electromagnetic instruments (transformer).

- **Difference between potential and mass.** The flow of harmonic currents in conductors induces a voltage drop. In the case of the TNC neutral mode, the equipment masses are not with the same potential, which can disturb the systems of exchanges of information.

Harmonics effects on electric equipments

In other words, immediate effects are...

- **Iron losses** and **eddy current losses** in transformers and machines.

- Losses in conductors

- **Harmonic resonance due to the use of capacitor banks on the electrical network.**
 - Increase of total harmonic distortion on the network
 - Accelerated ageing of capacitors

Capacitors on polluted networks

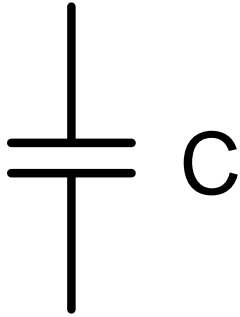
What are the problems?

- On the networks, the existence of capacitive elements can cause series and parallel resonances with the lines reactors, the transformers and the loads.
- The presence of resonances within an electrical supply network involves a certain number of risks due to the harmonic disturbances.

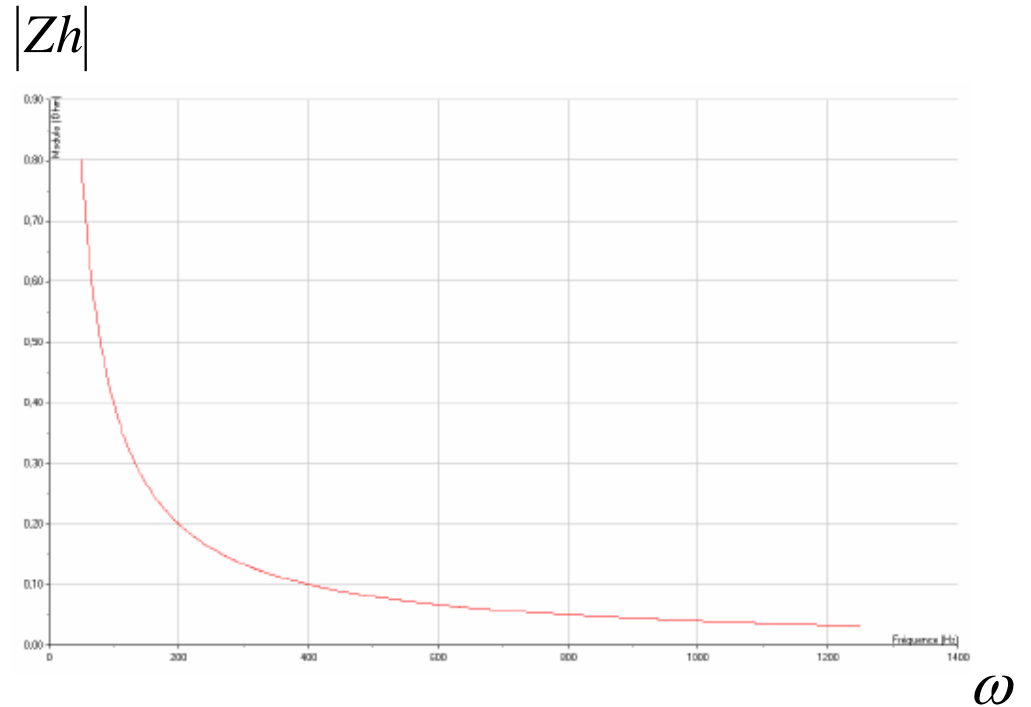
Capacitors on polluted networks

Basis concept: characteristic impedance

- Capacitor



$$|Z_h| = \frac{1}{C\omega h}$$



Capacitors on polluted networks

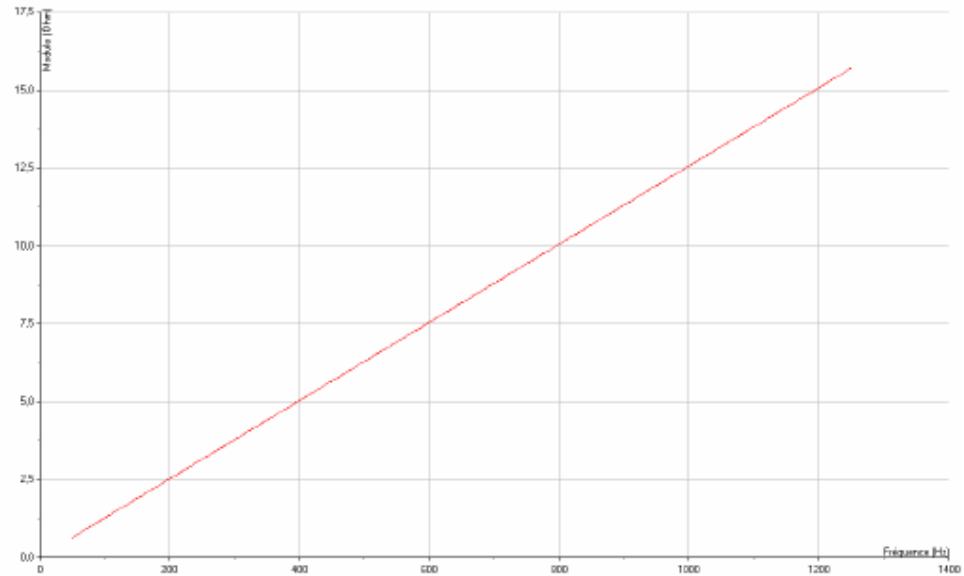
Basis concept: characteristic impedance

■ Reactor



$$|Z_h| = L\omega$$

$|Z_h|$



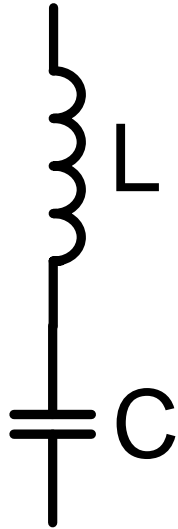
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Examples: transformers, motors, upstream network...

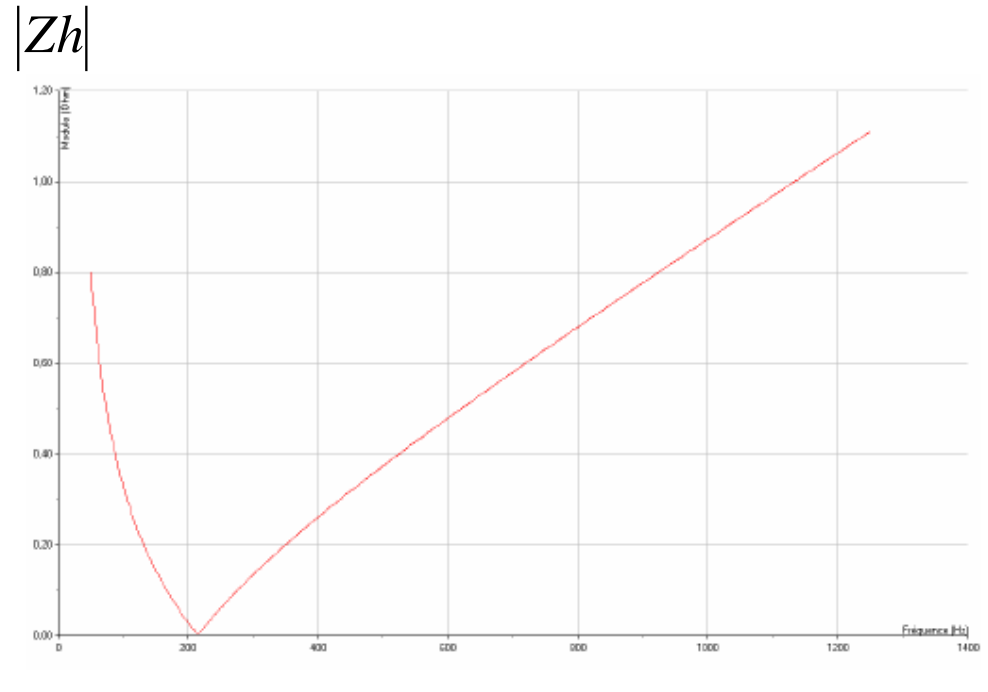
Capacitors on polluted networks

Basis concept: characteristic impedance

- Reactor + capacitor in series



$$|Zh| = \frac{LC\omega^2 h^2 - 1}{C\omega h}$$

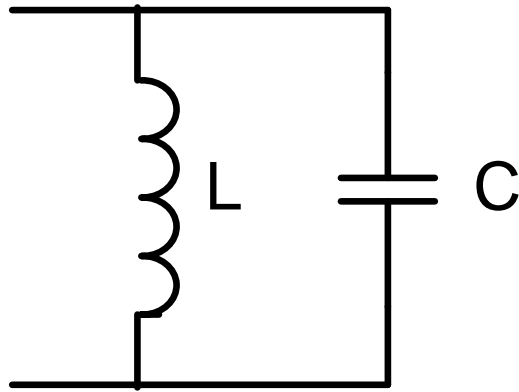


Examples: capacitor banks with detuned reactor or passive filter

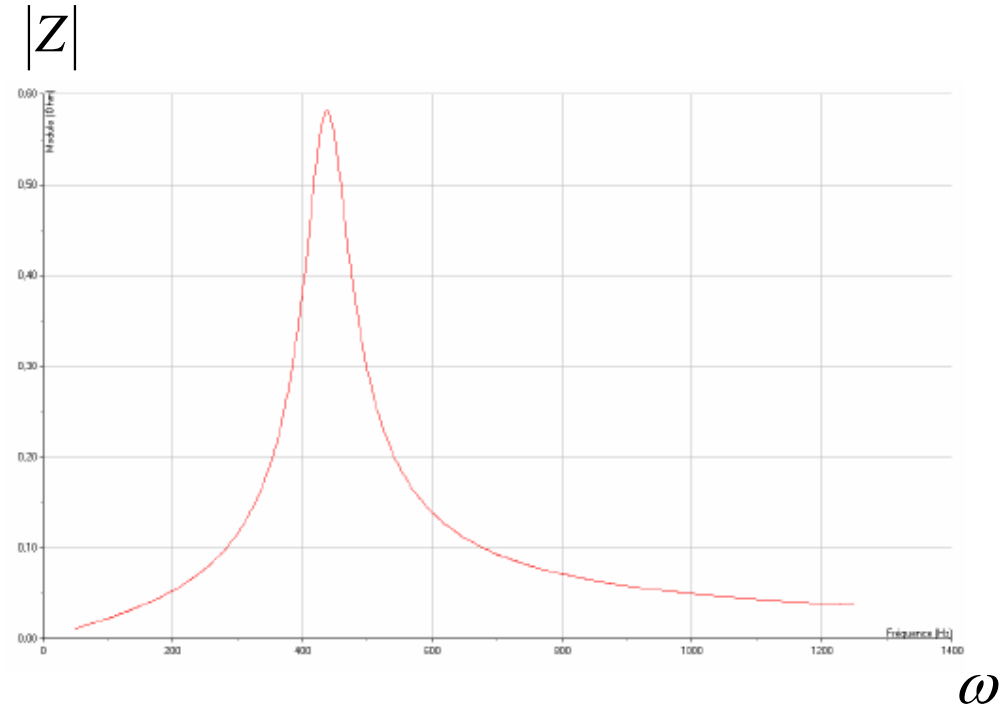
Capacitors on polluted networks

Basis concept: characteristic impedance

- Reactor + capacitor in parallel



$$|Z| = \frac{L\omega}{1 - LC\omega^2}$$

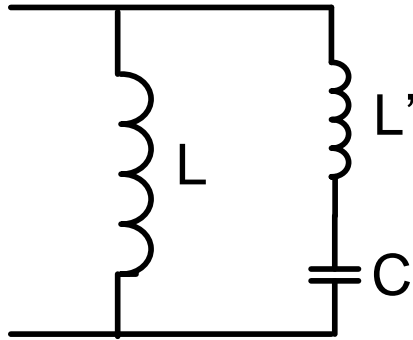


Examples: capacitor banks connected on network

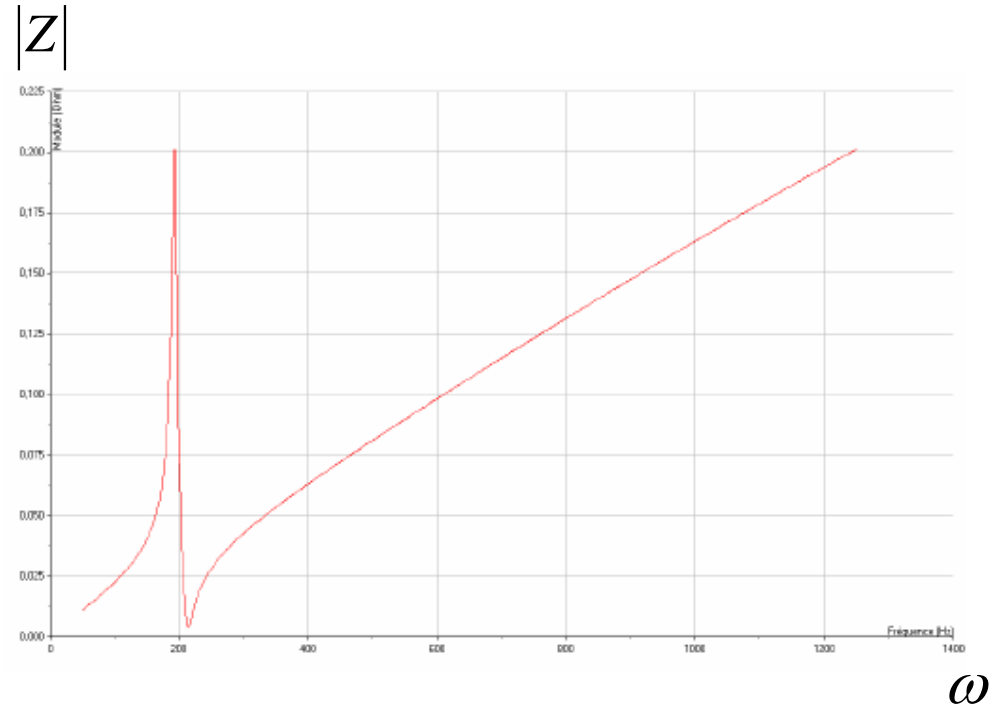
Capacitors on polluted networks

Basis concept: characteristic impedance

- Reactor in parallel with capacitor and reactor in series



$$|Z_h| = \frac{L\omega h(1 - L'C\omega^2 h^2)}{1 - (L - L')C\omega^2 h^2}$$

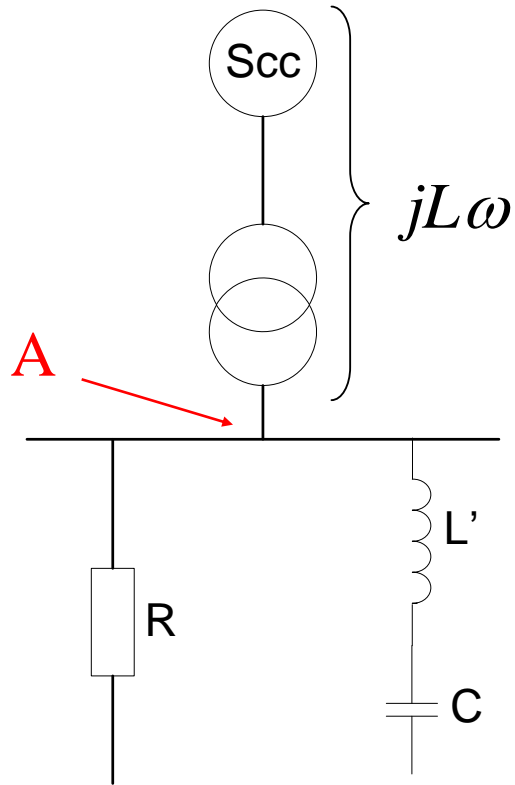


Examples: capacitor banks with detuned reactor connected on network

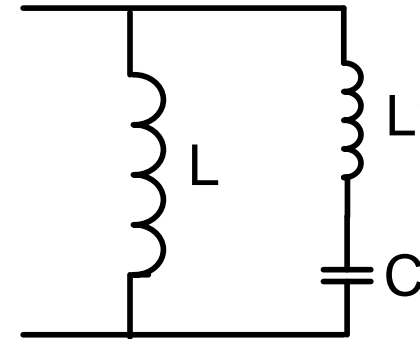
Capacitors on polluted networks

Basis concept: characteristic impedance

■ Example



Equivalent diagram (at point A)

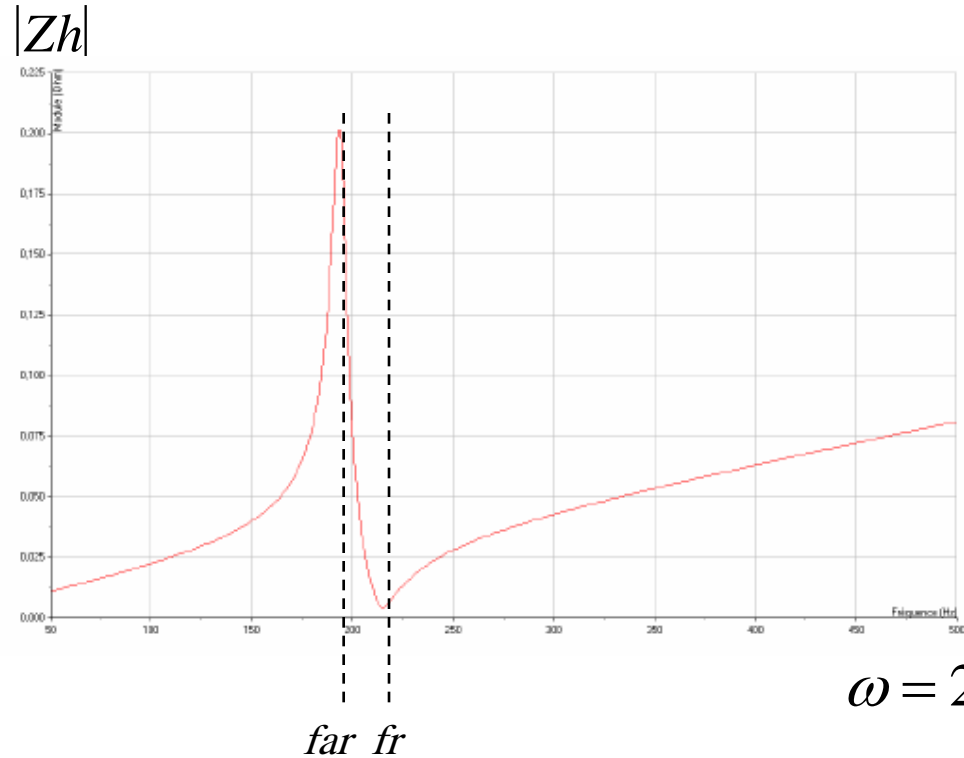
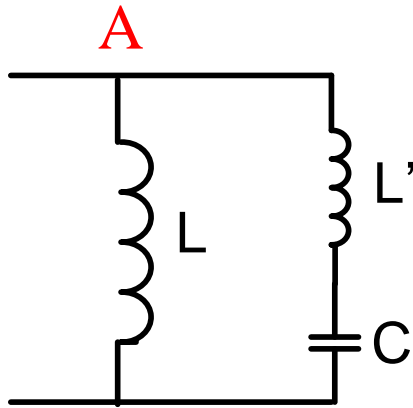


(By neglecting R)

Capacitors on polluted networks

Basis concept: characteristic impedance

■ Example



$$|Z_h| = \frac{L\omega h(1 - L'C\omega^2 h^2)}{1 - (L - L')C\omega^2 h^2}$$

$$f_{ar} = \frac{1}{2 \times \pi \times \sqrt{(L' + L)C}}$$

$$f_r = \frac{1}{2 \times \pi \times \sqrt{L'C}}$$

Capacitors on polluted networks

Basis concept: Resonance

- For each harmonic rank h , there is an equivalent diagram.
- For each harmonic rank you can write the following Ohm rule:

$$V_h = Z_h \times I_h$$

V_h is the h rank harmonic voltage

I_h is the h rank harmonic current

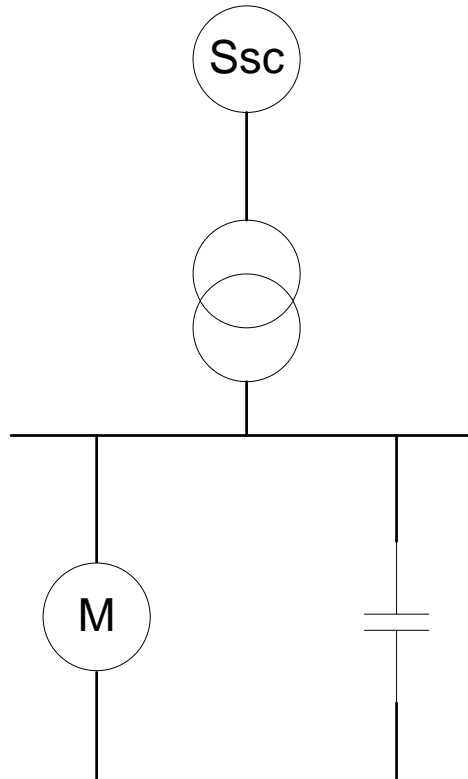
Z_h is the h rank harmonic impedance

- If Z_h is high but $I_h=0 \Rightarrow V_h=0$ no problem of resonance
- If Z_h is high and $I_h \neq 0 \Rightarrow V_h$ is high risk of resonance

Capacitors on polluted networks

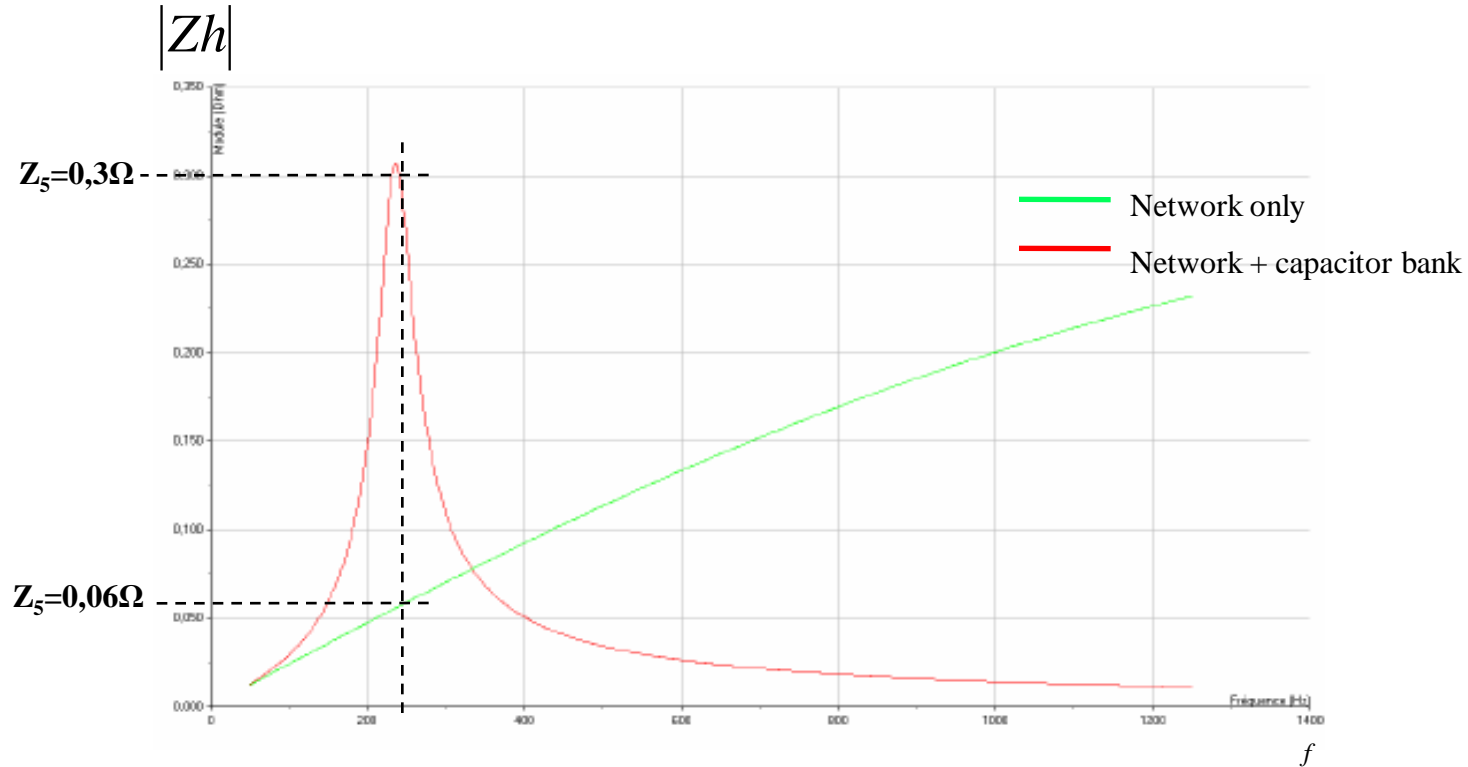
Basis concept: Resonance

- Example 1: Compensation without harmonic currents



Capacitors on polluted networks

Basic concept: Resonance



Without capacitor bank

$$V_5 = Z_5 \times I_5 = 0,06 \times 0 = 0V$$

With capacitor bank

$$V_5 = Z_5 \times I_5 = 0,3 \times 0 = 0V$$

Resonance but no risk
because no harmonic
currents

Capacitors on polluted networks

Basis concept: Resonance

- Example 2: Compensation with harmonic currents

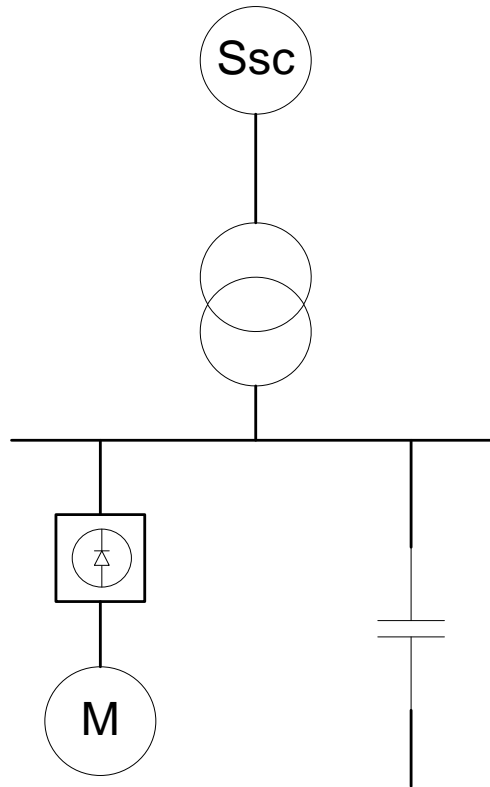
Harmonic generator (VFD)

$$I_5=30A$$

$$I_7=15A$$

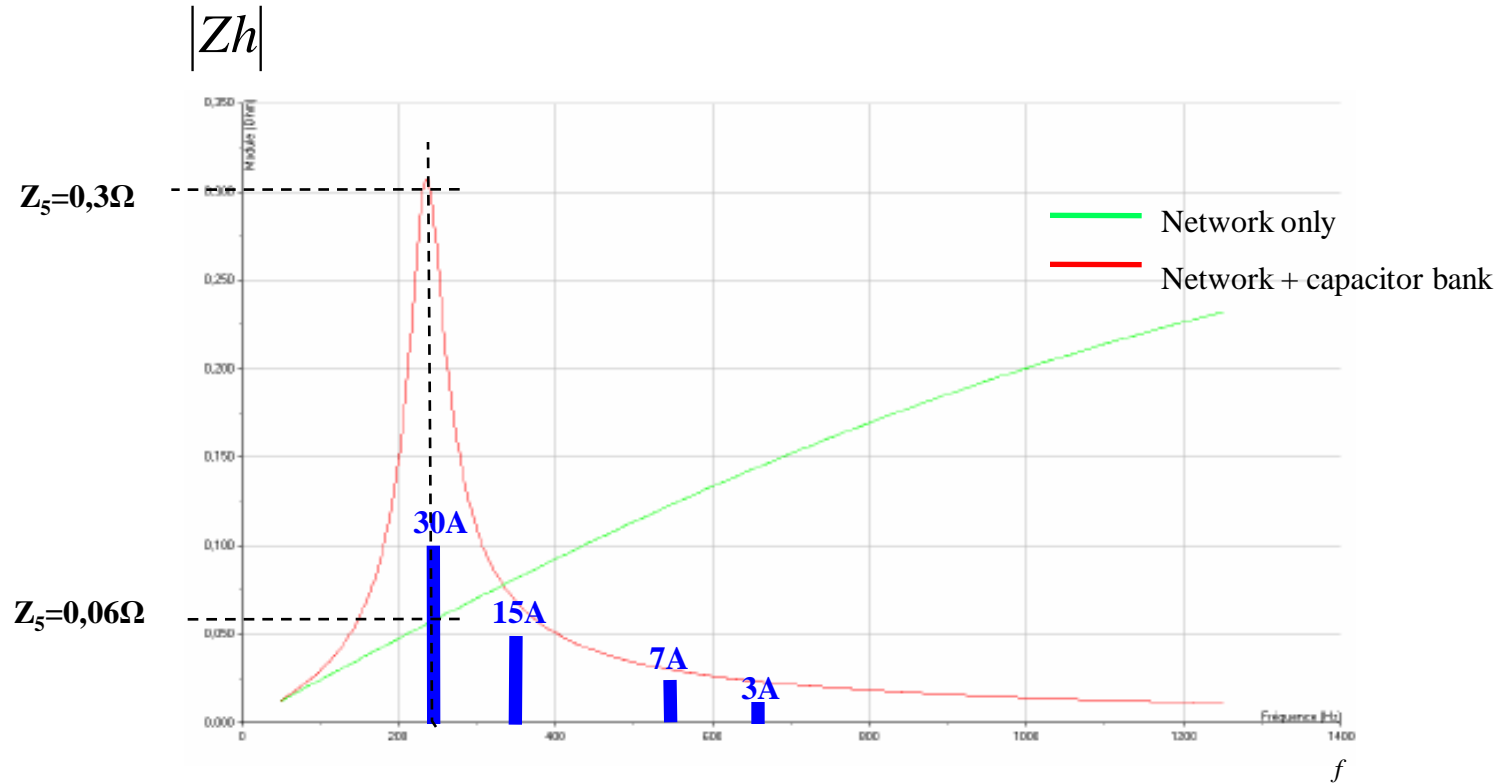
$$I_{11}=7A$$

$$I_{13}=3A$$



Capacitors on polluted networks

Basis concept: Resonance



Without capacitor bank	$V_5 = Z_5 \times I_5 = 0,06 \times 30 = 1,8V$	} Resonance on rank 5 <u>BAD SOLUTION</u>
With capacitor bank	$V_5 = Z_5 \times I_5 = 0,3 \times 30 = 9V$	

Capacitors on polluted networks

Basis concept: Resonance

Inside capacitor bank

High value of the RMS current => overload and big risk of destruction.

On the network

Increasing of the pollution on the network => big value of THD (U) and risk of disturbance of electronic device for example.

Capacitors on polluted networks

Consequences of resonance

- Several consequences
 - Increasing of harmonic voltage distortion on the busbar where the capacitor bank is connected.
 - Overload of the capacitor bank so big risk of destruction.
 - Increasing of risk of disturbance of sensible loads (electronic device,...).
 - ...

Capacitors on polluted networks

Important concept



- **Capacitors do not generate harmonics.**
- They can amplified harmonics.

Capacitors on polluted networks

Solutions

- To limit the emission of the harmonic currents injected by disturbing equipment
 - by limiting their power,,
 - by admitting the injection of harmonics of currents of higher frequencies.
 - Examples :
 - use of 12-pulse rectifier instead of 6-pulse ones,
 - use of line reactor with variable speed drives,
 - ...

Capacitors on polluted networks

Solutions

■ Detuned reactor

- A reactor is added in series with the capacitors to tune the unit before the first current injection frequency.
- Generally, the unit detuned reactor + capacitors is tuned near 215 Hz. ($f_n=50\text{Hz}$, tuning rank 4,3)
- Capacitors are thus protected against harmonic overloads.

Capacitors on polluted networks

Solutions

- Example 3: Compensation with harmonic currents

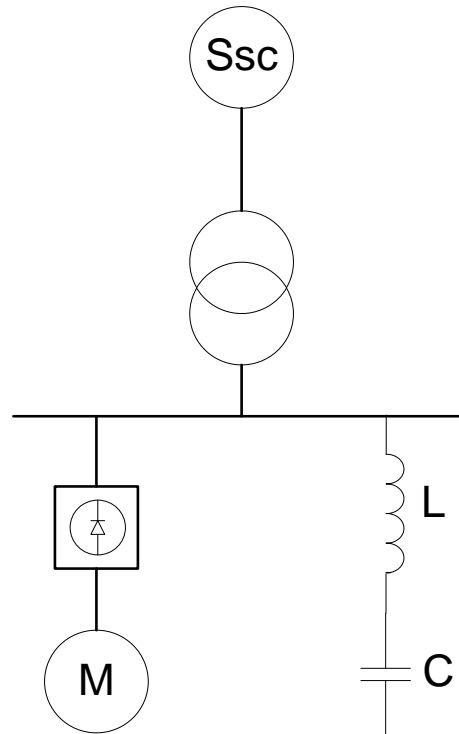
Harmonic generator (VFD)

$$I_5=30A$$

$$I_7=15A$$

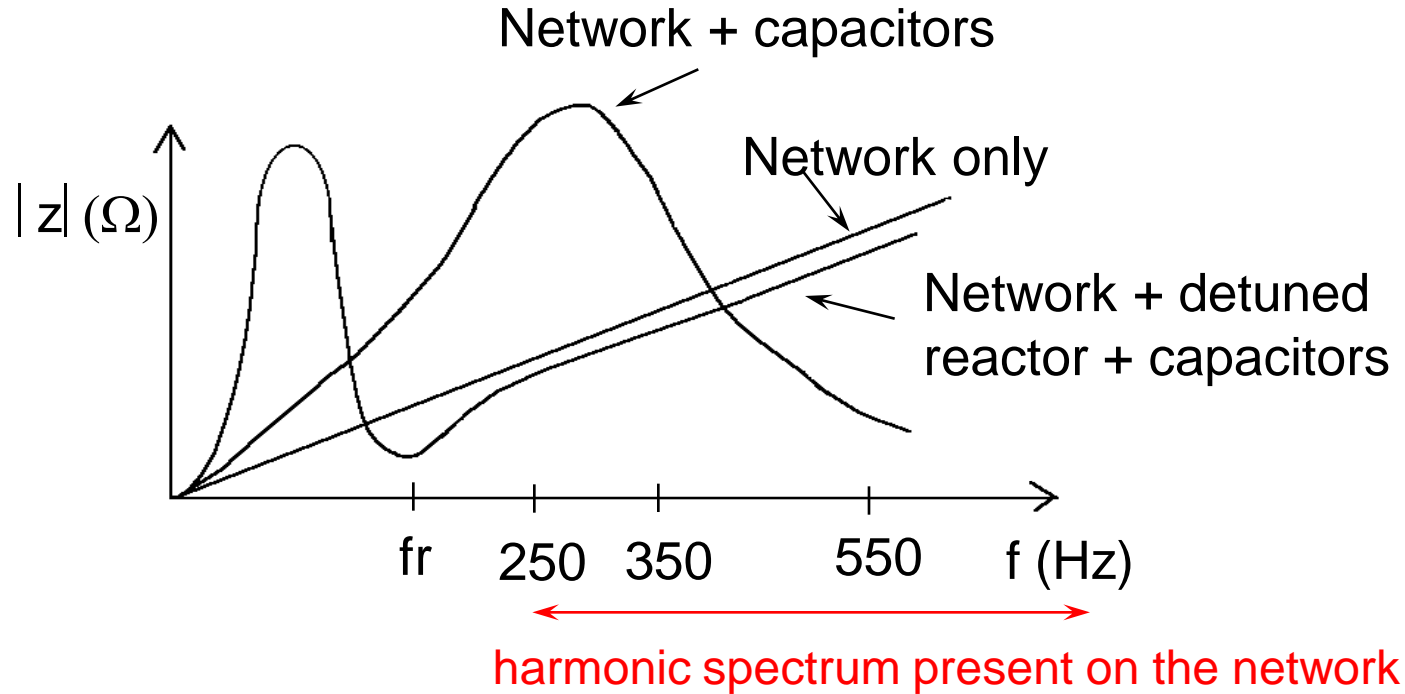
$$I_{11}=7A$$

$$I_{13}=3A$$



Capacitors on polluted networks

Solution with detuned reactor

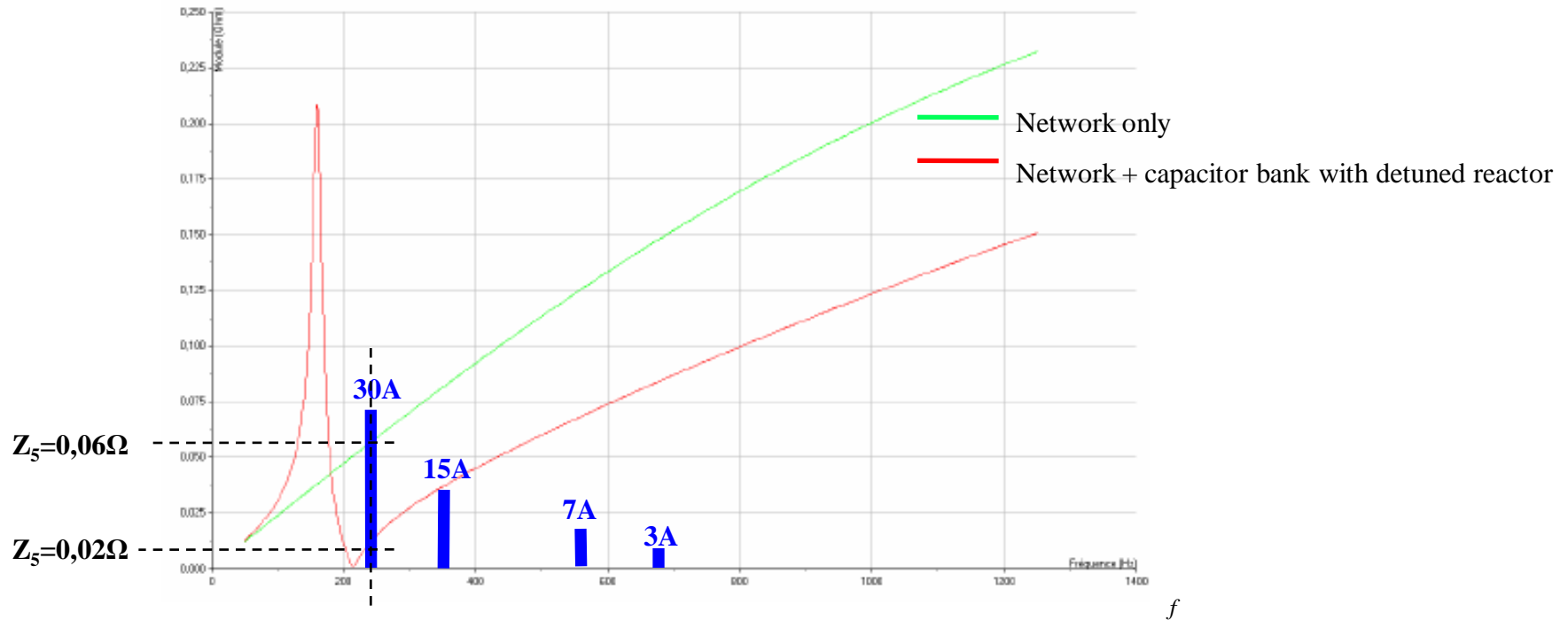


Resonance frequency

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Capacitors on polluted networks

Solution with detuned reactor



Without capacitor bank	$V_5 = Z_5 \times I_5 = 0,06 \times 30 = 1,8V$	} No resonance on rank 5 <u>GOOD SOLUTION</u>
With capacitor bank	$V_5 = Z_5 \times I_5 = 0,02 \times 30 = 0,6V$	

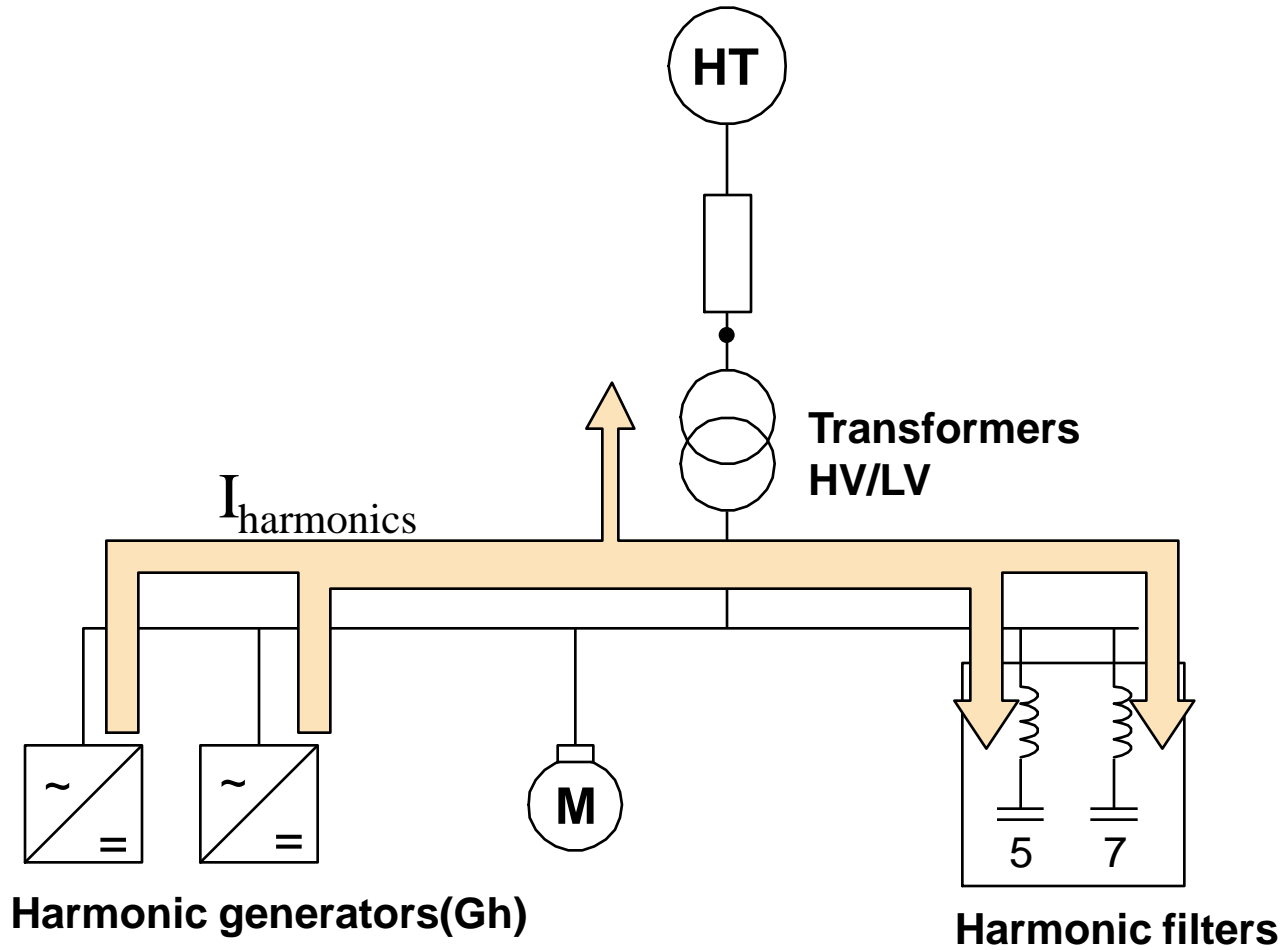
Capacitors on polluted networks

Passive filtering solutions

- When detuned reactors are not enough to decrease harmonic pollution, a filtering solution is needed.
- Principle: A short-circuit is created at an accurate frequency in order to trap the harmonic current generated at this frequency.

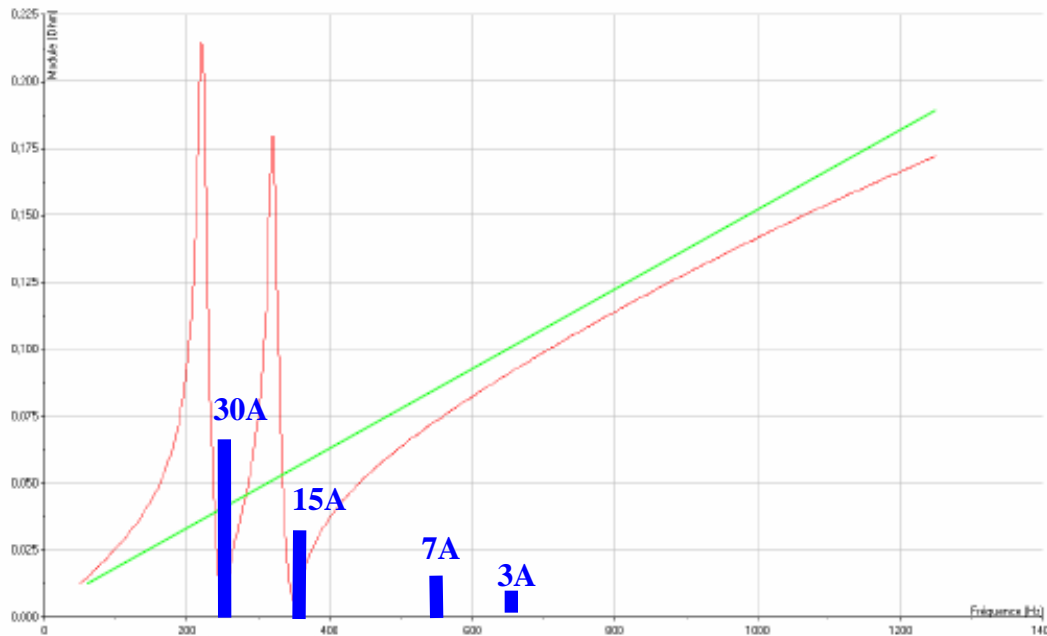
Capacitors on polluted networks

Passive filtering solutions



Capacitors on polluted networks

Passive filtering solutions



H5

$f_r=250\text{Hz}$

H7

$f_r=350\text{Hz}$

With filter

$$V_5 = Z_5 \times I_5 = 0,01 \times 30 = 0,3\text{V}$$

$$V_7 = Z_7 \times I_7 = 0,01 \times 15 = 0,15\text{V}$$

$$f_r = \frac{1}{2 \times \pi \times \sqrt{LC}}$$

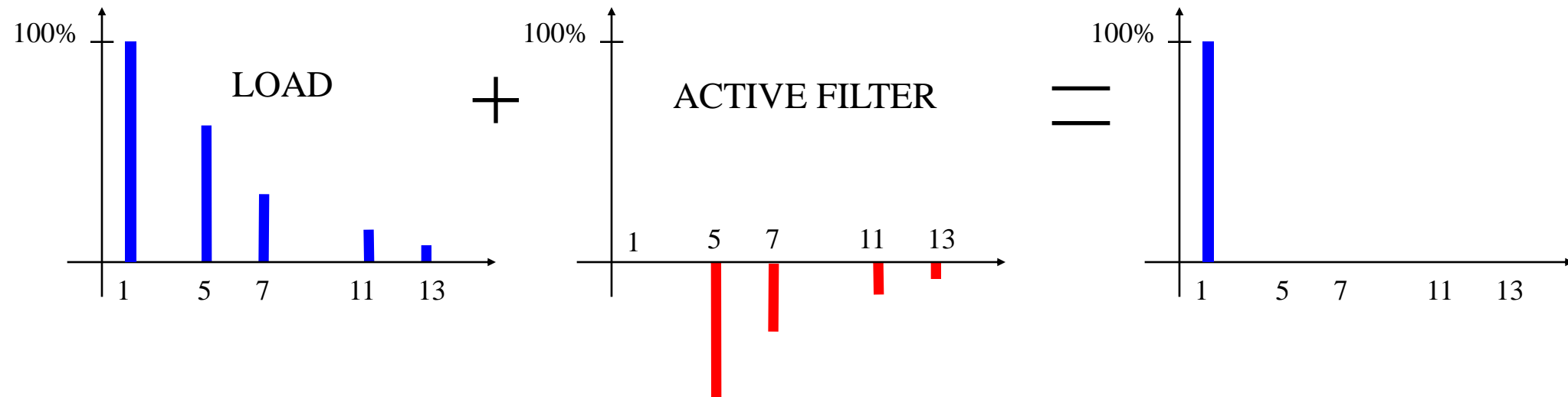
f_r: tuning frequency of the passive filter

Capacitors on polluted networks

Active filtering solutions

■ PRINCIPLE

- Active Harmonic Filter injects anti-phase harmonic current which cancels the existing harmonic currents.
- Provides Harmonic current or reactive current or any combination of both



Capacitors and polluted networks

Filtering solutions: Advantages and drawbacks

	Passive filter	Active filter
Advantages	<ul style="list-style-type: none">• high power• simultaneous power factor correction	<ul style="list-style-type: none">• wide spectrum• easy commissioning• flexibility
Drawbacks	<ul style="list-style-type: none">• study by a specialist is necessary• filter adapted to only a few orders of harmonics	<ul style="list-style-type: none">• high price

Bibliography

- Technical book n°199: Power quality
- Guide design of the industrial electrical supply networks vol 1&2
- Expert guides low tension N°6