FRAKO Kondensatoren- und Anlagenbau GmbH

How to design capacitor banks in mains with harmonics

A guide issued by Hans-Georg Mall and Peter Riese

Reactive power compensation is still one of the most useful tools to optimise energy costs and provides a fast return of investment.

During the last few years capacitors have become smaller in size and the losses inside the dielectric were considerably reduced. This was achieved by using new materials and more efficient manufacturing processes. The reliability of a capacitor bank has also been greatly improved with the introduction of contactors developed especially for switching capacitors. Microprocessor-operated PF control relays assure an optimal response of the capacitor bank to the demand of the end user.

However, there are important reasons for consultants and customers to know more about the complex technical aspects of this subject.

Due to the increase of harmonic distortion in low and medium voltage networks the design and planning of capacitor banks have become increasingly more difficult. Rectifiers, electronic controlled motors, static frequency converters and other power electronic devices require capacitors to compensate the reactive power and simultaneously produce harmonic currents. A dangerous resonance can occur between transformer and capacitors when the resonant frequency of transformer and capacitors comes close to a harmonic frequency of the mains.

Already during the planning phase one has to find suitable means to avoid later problems and costs. Therefore it is highly recommended to consult an expert when dealing with mains with harmonics.

What are harmonics?

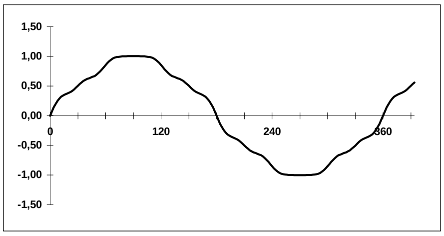
In modern low voltage networks there are increasing loads that take non-linear currents from the network. These load currents produce a voltage drop at the mains impedance, which distorts the original sinusoidal mains voltage.

These distortions can be analysed according to the Fourier-analyse as the basic oscillation (this is the mains frequency) and as the individual harmonic frequencies. The harmonic frequencies are whole number multiples of the basic oscillation and are designated with the ordinal number.

Examples:	Mains frequency = 50 Hz	5th harmonic = 250 Hz
	Mains frequency = 60 Hz	5th harmonic = 300 Hz

Linear loads :	**Non-linear loads = producers of harmonics :**
ohmic resistances (resistance heating, light bulbs, etc.) three phase a.c. motors, capacitors.	transformers and chokes, static converters, especially variable-speed induction motors, uninteruptable power supplies (UPS), power supplies for domestic appliances (TV, computer, compact energy-saving lamps, etc.)

An example for a line-voltage with superimposed harmonics:



Mains voltage with superimposition of

5 % of the 5th harmonic
4 % of the 7th harmonic
2.5 % of the 11th harmonic

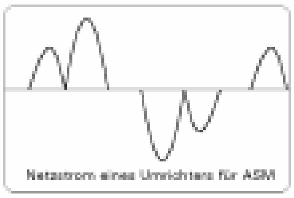
Harmonics are not only produced in industrial networks, but also with increasing quantity in private households. Normally only uneven numbered harmonics are produced by non-linear loads and therefore usually only 3rd, 5th, 7th, 11th, 13th etc. harmonic are present.

How do harmonics arise?

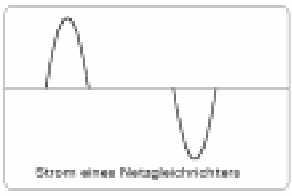
⇒ In your own low voltage network, especially when variable speed drives are installed.

⇒ In all households and office buildings: in all TV sets, computers and compact lamps with electronic ballast. Due to the multitude of these loads and their phase-balanced currents a high level of harmonic content occurs in the evening in some medium voltage networks.

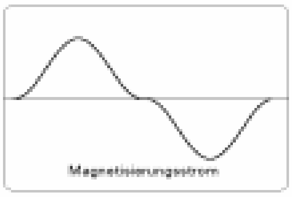
These are examples for the line-current of non-linear loads:



3-phase converter for ASM



Single phase rectifier



Reactive current of transformer

How high are these harmonics when no capacitor bank has been installed yet?

a) In their own low voltage network:

According to number and rating of variable speed drives and other power electronic devices.

⇒ If, for example, one large 6 pulse thyristor control is installed in a network, whose rating is 50% of the transformer's nominal rating , then about

4 % of the 5th harmonic (250 Hz) and
3 % of the 7th harmonic (350) Hz will occur.

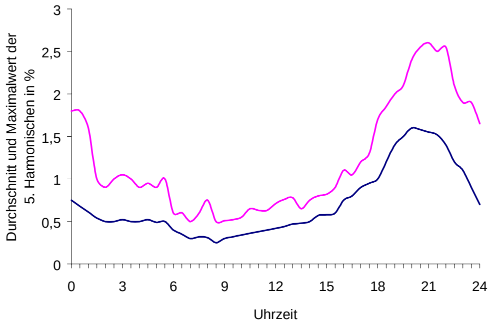
⇒ It is more usual that several small static converters are installed in a network. Due to the different phase lags of the currents of the individual converters the resulting harmonic voltages are lower. If, for example, several converters with a total rating of about 25 % of the transformer nominal rating are installed, then about

1 - 1.5 % of the 5th harmonic (250) Hz and
0.7 - 1 % of the 7th harmonic (350) Hz will occur.

These are only reference values for a first assessment of the expected level of the harmonic distortion.

b) In medium voltage networks

In most networks the harmonic distortion nowadays is influenced by non-linear loads in private households (mainly TV sets). This is clarified by the graph, showing the course of 24 hours of the 5th harmonic :



The harmonic level in the medium voltage network of a municipal utility in Germany with industrial and domestic users on week days.
Average value and maximum value of a series of measurements which were carried out during 1985 - 1987. These values are definitely higher nowadays. The rise during the evening is due to the multitude of TV sets and other non-linear loads in private households.

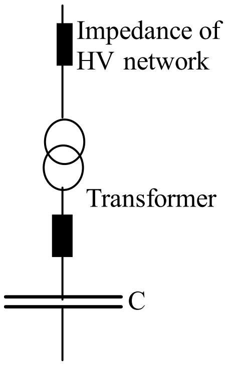
In large urban areas

more than 4 % of the 5th harmonic and up to approx. 1.5 % of the 7th harmonic

can be superimposed on the medium voltage during the evening hours. The 11th and higher harmonics can be disregarded in most cases.

What influence does a capacitor bank have on the harmonic level?

A capacitor bank without filter circuits forms a resonant circuit with the reactive mains impedance. There is a simple rule-of-thumb formula to calculate the resonant frequency:



$$f_r = 50Hz \cdot \sqrt{\frac{S_k}{Q_c}}$$

Sk = short circuit power of the mains
Q_c = rating of the capacitor bank

The short-circuit power Sk

- is defined mainly by the transformer
- is reduced by about 10 % due to the impedance of the medium voltage network,
- can be considerably reduced by a long supply line between transformer and capacitor bank.

For most applications a rough estimate is good enough:

$$S_k \approx 0.9 * \frac{Sn}{uk}$$

Sn = nominal power of transformer
uk = short circuit voltage of transformer.

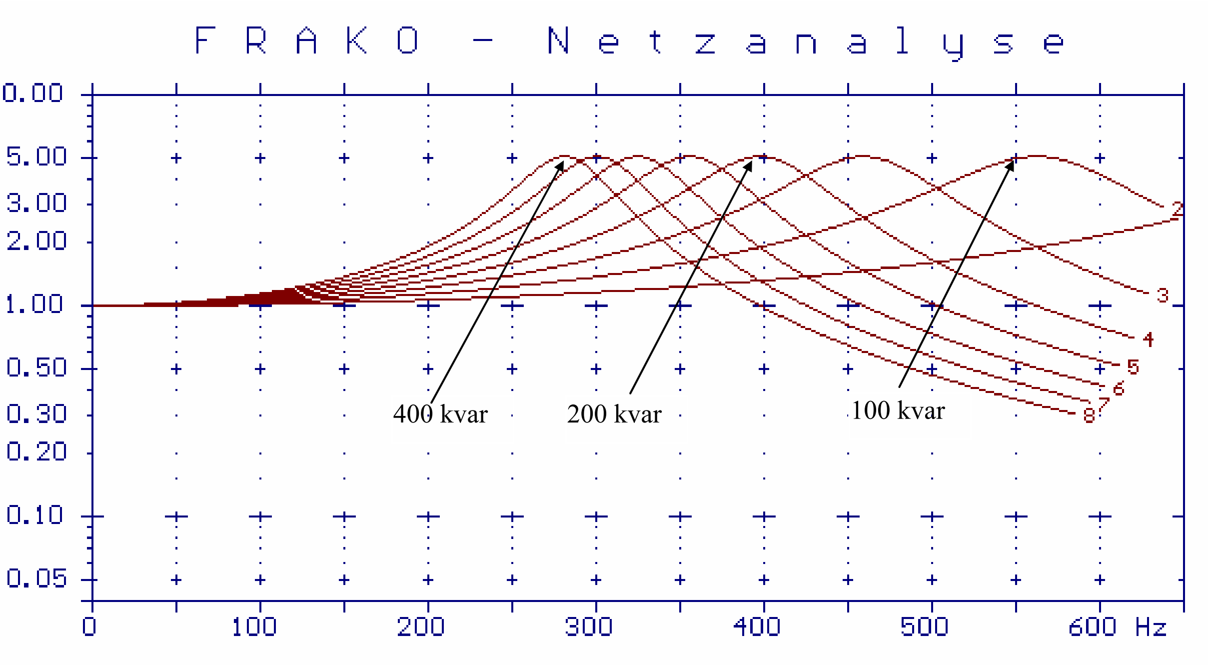
Example: Sn = 1000 kVA
uk = 6%
Sk = about 15 000 kVA

If i.e. **300 kvar** are installed, the resonant frequency is ca. **353 Hz** in a 50Hz-network.

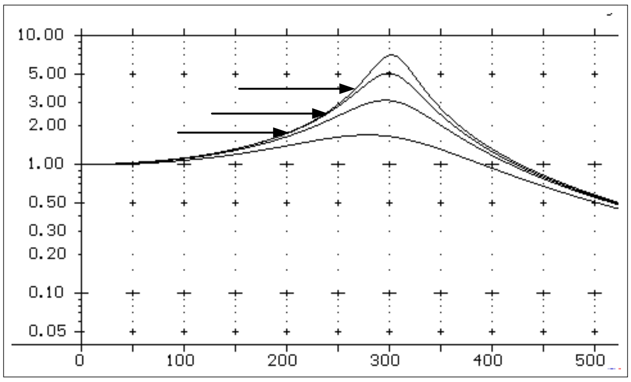
When switching the stages of the capacitor bank the resonant frequency of the network alters considerably and is often near a harmonic frequency.

If the resonant frequency is near the frequency of an harmonic voltage this harmonic voltage then increases due to the characteristic of the resonant circuit. It is possible that these can be multiplied by a factor of 5 or even more :

Resonant characteristic of a 400 kvar capacitor bank in a low voltage network with 1000 kvar transformer, drawn for each stage of the capacitor bank.



By using the multiplication factor of the harmonic voltages of a capacitor bank one can estimate whether problems with harmonics could occur. A few simple rules are available:



1. If the resonant frequency is

- **10 % below or above** the frequency of a harmonic voltage this could be increased by a **factor of above 4** in a network with low damping, i.e. in the evening or during the night.
- **20 % below or above** the frequency of a harmonic voltage this could be increased by a **factor of up to 2.5**.
- **30 % below or above** the frequency of a harmonic voltage this could be increased by a **factor of up to 1.7**.

During the night the damping of the power network is low, therefore the resonant faktor is high, about 5 to 7. During normal working time the resonant faktor is lower, usually about 2 to 3.

2. In a low voltage network without any power electronic device, but with more than 1.5 % of 5th or 7th harmonic content on the medium voltage side.

⇒ The 7th harmonic will be increased if the resonance frequency is below 400 Hz.

⇒ **The 5th harmonic will be increased by a factor of up to 4 if the resonant frequency is below 300 Hz**

If capacitors are already installed, the multiplication factor can be calculated by measuring the harmonic content of the 5th (and 7th) harmonic voltage with capacitors switched (u5 with cap) and with **all** capacitors switched off (u5 without cap).

The multiplication factor for the 5th harmonic is: $x_5 = \frac{u5withcap}{u5withoutcap}$

How does the network configuration influence the problem of harmonics?

The network short-circuit capacity determines the resonance frequency.

⇒ It could be problematic if the network short-circuit capacity is too low at the connection point of the capacitor bank, or

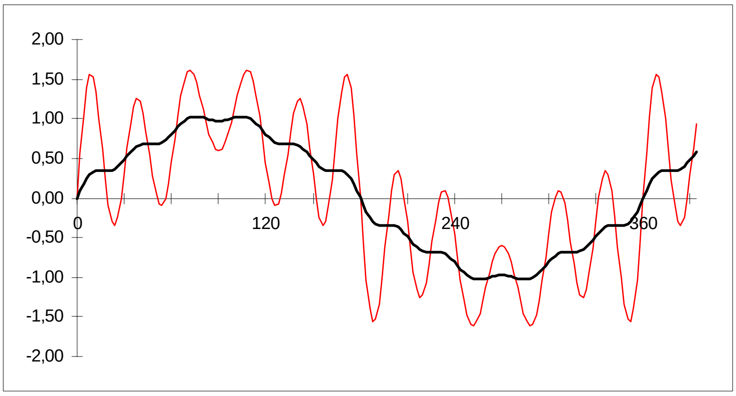
⇒ it could be problematic if the short-circuit capacity changes, i.e. due to transformers being switched on or off.

Example:

In many factories the low voltage stations are connected in a closed-loop circuit to have a higher safety margin. This kind of network has a very high short-circuit power. Even the use of big capacitor banks may not create problems with harmonics, as the resonant frequency is quite high.
If the loop is interrupted (e.g. during maintenance) the short-circuit power will drop considerably and consequently the resonant frequency can drop below 300 Hz.

Voltage and current load for capacitor banks without filter circuits

When a resonance occurs the effective value of the network voltage is increased only marginally.
The effective value of the capacitor current however is increased considerably.
A resonance with the 11th harmonic could increase it to 10 %. As a result :



the RMS. value of the mains voltage increases by 0.5 %,

the peak value of the mains voltage increases by 8-10 %,

but **the effective value of the capacitor current increases by approx. 50 %.**

THEREFORE A HIGH CURRENT CARRYING CAPACITY OF THE CAPACITOR IS ONE OF THE MOST IMPORTANT QUALITY FEATURES.

A nominal voltage of 440 V AC is absolutely sufficient in 400 V AC networks if the capacitor's current carrying capacity is

1.7 times the rated current at 400 VAC permanently and
at **least 200 times the rated current** for short time peak currents.

FRAKO capacitors fulfil this specification !

What has to be done if a resonance is possible, but unlikely to occur

This applies to a significant part of all capacitor banks to be designed. For example:

⇒ If there are no harmonic producers in the low voltage network and no harmonics in the medium voltage network, but the resonant frequency is below 400 Hz.

⇒ If the resonance frequency could drop below 400 Hz due to changes in the network configurations and if there are harmonics in the medium voltage network.

⇒ If it is planned to install power electronic devices at a later stage.

The **FRAKO Network Analyser EMA 1100** is used to protect the capacitor banks against resonances which might occur occasionally. It monitors the network in all 3 phases and will shut down the capacitor bank if dangerous levels of harmonics are reached. When the harmonic level drops again it will restart the capacitor bank.
The maximum levels occurred will be stored and can be retrieved through the RS 485 bus connection of this unit.

In networks with symmetric loads the Reactive Power Control Relay **EMR 1100** can also be used. It monitors when resonances arise and calculates the RMS. current of the capacitor bank.
When exceeding the pre-programmed value the relay will shut down the capacitor bank. It will restart the capacitor bank once the values are again within the permissible limits.
In these cases it is recommended to use capacitor banks which can be equipped with harmonic filter circuits at a later time.

If the control relay switches the capacitor bank off very often, it should be considered to equip it with harmonic filters.

Designing capacitor banks for networks with harmonics

A combination of the following information will help to design a capacitor bank:

⇒ Measurement of the harmonic voltage and current over a period of a few days with the existing capacitor bank shut down.

⇒ Theoretical calculation of the resonant frequency in the network.

Following harmonic levels can be expected in the measured network:

⇒ maximum value of the measurement without capacitor bank, multiplied with the multiplication factor from the network analysis.
Example:

An average low voltage network with a 1000 kVA transformer (see diagram on page 4)

When the capacitor bank is fully switched on with 400 kvar the 5th harmonic will be increased by a factor of 3. At 250 kvar the 7th harmonic will be increased by the factor 4!

These values will be lower during daytime and higher during weekends and in the evenings.

Strong interference of other electronic equipment in the same network can occur if higher voltage levels of the harmonics than the below mentioned are expected:

4% of the 3rd harmonic (150 Hz)
5% of the 5th harmonic (250 Hz)
4% of the 7th harmonic (350 Hz)
3% of the 11th harmonic (550 Hz)
2.1% of the 13th harmonic (650 Hz)

In our example it is to be expected that the level of harmonic voltages will exceed the permitted levels if

without compensation
⇒ the level of the 5th harmonic is more than 2 % or
⇒ the level of the 7th or higher harmonic is more than 1 %.

In this case it is recommended to use capacitor banks which are equipped with harmonic filter circuits.

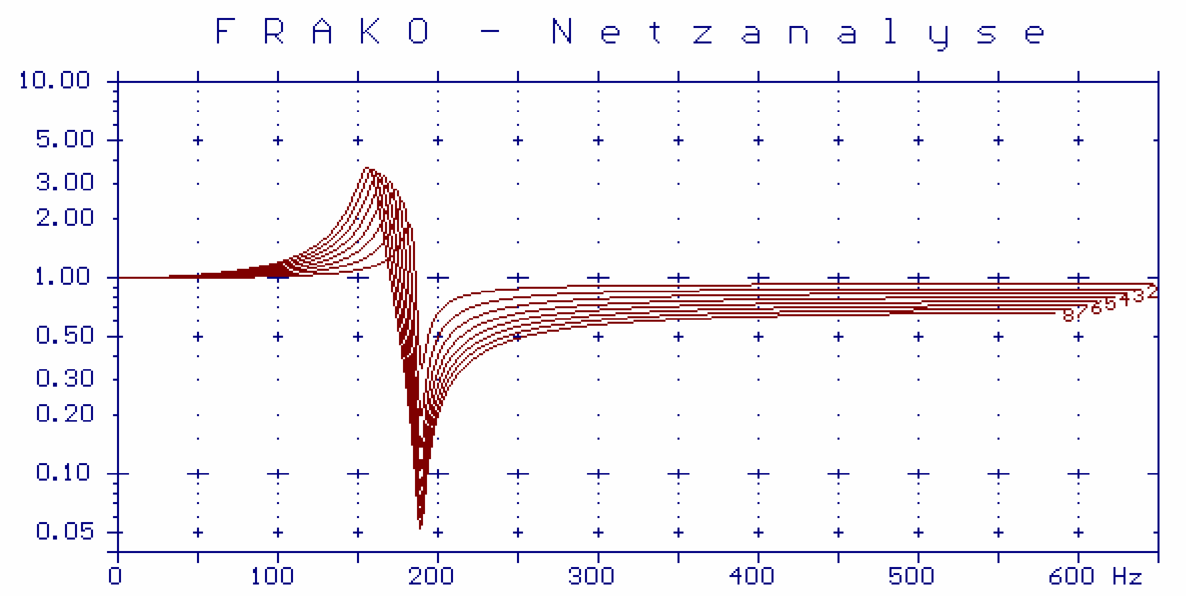
How does a capacitor bank with harmonic filters work?

The harmonic filter will reduce the resonant frequency to a level below 250 Hz. All harmonics above this level will be reduced.

A capacitor bank with harmonic filters is a series connection of capacitors and filters chokes. The resonant frequency of the capacitor bank with harmonic filter has to be selected so that it will be below the 5th harmonic (250 Hz). This combination appears at all frequencies above the resonant frequency as inductive reactance.

A capacitor bank with harmonic filters partly absorbs harmonics.

The following diagram shows the reduction of harmonic voltages depending on the number of capacitor stages switched on:



Capacitor banks with harmonic filters are specified according to its resonant frequency or according to the relative voltage drop „p“ at the filter choke. „p“ is the voltage drop at the filter choke divided by the voltage drop at the capacitor. Both values are interrelated according to the following formula:

$$f_r = 50Hz \cdot \sqrt{\frac{1}{p}} \qquad \text{i.e.:} \quad p = 0.07\ (7\%) \quad fr = 189\ Hz$$

At 250 Hz the impedance of the capacitor <u>with</u> harmonic filter is equal to the impedance of a capacitor <u>without</u> harmonic filters <u>divided by the factor x</u>**.**

For the 5th harmonic the capacitor bank with harmonic filters has:

absorption characteristic	if x > 1
blocking characteristic	if x < 1

p =	5.7 %	fr = 210 Hz	x = 2.4	u250 max = 4 %
p =	7 %	fr = 189 Hz	x = 1.33	u250 max = 5 %
p =	8 %	fr = 177 Hz	x = 1.0	u250 max = 5 %
p =	13.5 %	fr = 136 Hz	x = 0.42	u250 max = 5 %

Example:

If 4 % of the 5th harmonic are superimposed on the mains voltage, a capacitor bank with harmonic filters will absorb the 5th harmonic as follows (In = 50 Hz rated current of the capacitor bank):

with p = 7% : 0.27 x In = (4% *(250/50 Hz)* 1.33 = 0.27)
with p = 5.7 % : 0.48 x In
with p = 13.5 % : 0.08 x In

Principally the following has to be observed when choosing a capacitor bank:

⇒ Capacitor banks with harmonic filters should never be used together with capacitor banks without harmonic filters in the same low voltage network.

⇒ Capacitor banks with harmonic filters with different resonant frequencies can be used in parallel. However the capacitor bank with the higher resonant frequency (= the lower „p“) can be overloaded especially if the harmonic levels are quite high.

The power distribution systems are more and more affected by harmonics. Therefore this guide gives information on what has to be considered. However, this subject cannot be dealt with in full within a short article. The best result for each application will be reached with the help of specialists with long experience in this field.

FRAKO agents and representatives are trained in all problems dealing with harmonics.

FRAKO itself is the leading capacitor and power factor correction company in Germany with vast experience in all harmonic matters.

We reduce the cost of energy
by Power Factor Correction and Energy Management

FRAKO Kondensatoren- und Anlagenbau GmbH
79331 Teningen Tscheulinstr. 21a
Telefon 07541 453 0 Telefax 07641 453 535
eMail info@frako.de Internet http://www.frako.de