ENERDIS®
CHAUVIN ARNOUX GROUP

Power Factor Correction

THE GUIDE

CONTENTS

General concepts
concerning Power Factor Correction and electrical networks

WHY IS POWER FACTOR CORRECTION NECESSARY?

Many devices consume reactive power to generate electromagnetic fields (motors, transformers, fluorescent lighting ballasts, etc.).
Compensating reactive power means supplying this power in place of the distribution network by installing a capacitor bank as a source of reactive power Q_c.

This offers a host of advantages:

- **savings on the sizing** of electrical equipment because less power is required
- **increase in the active power available** on the transformer secondary
- **reduced voltage drops** and line losses
- **savings on electricity bills** by preventing excessive reactive power consumption
- **payback in 18 months on average**

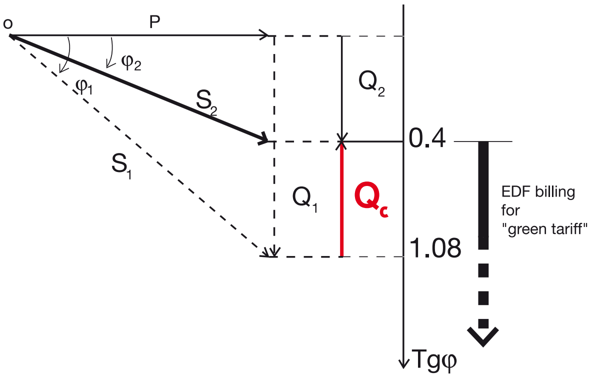
This is why you need to produce reactive power as close to the loads as possible, so that it is not drawn by the network. We use capacitors to supply the reactive power to the inductive receivers and to raise the displacement power factor (Cos φ).

Summary

When an energy supplier supplies reactive power, it overloads the lines and transformers. In France, there are two tariffs for which we can install power factor correction equipment:

- The "Yellow Tariff" (S between 36 and 252 kVA): reactive power is not billed but high consumption of reactive power by machines results in a bad Cos φ value leading to a poor apparent power value which may cause the installation to exceed the subscribed power value
- The "Green Tariff" (S > 252 kVA), EDF bills excessive reactive power from 1st November to 31st March (during normal and peak times, excluding Sundays) above the following thresholds:
  - tan φ > 0.40 so Cos φ < 0.928 on the primary of the transformer
  - tan φ > 0.31 so Cos φ < 0.955 on the secondary of the transformer

Power overview



P = Active power
Q_1 = Reactive power **without** power factor correction
S_1 = Apparent power **before** power factor correction
φ_1 = Phase shift **without** correction
Q_2 = Reactive power **with** power factor correction
S_2 = Apparent power **after** power factor correction
φ_2 = Phase shift **with** correction

$$Q_c = Q_1 - Q_2$$

$$Q_c = P\,(Tg\varphi_1 - Tg\varphi_2)$$

$$= P \times K$$

Example

Before

An installation with:

- a 630 kVA transformer
- 500 kW active power
- a power factor of 0.75

After

- Connection of a 275 kVAr capacitor bank

You obtain:

- a 21 % reduction in the apparent power for the power distributor
- a 16 % increase in the proportion of the rated power available as power from the transformer
- a 38 % reduction in the joule losses (out of the 3 % transformer losses)
- a 2.6 % reduction in voltage drops

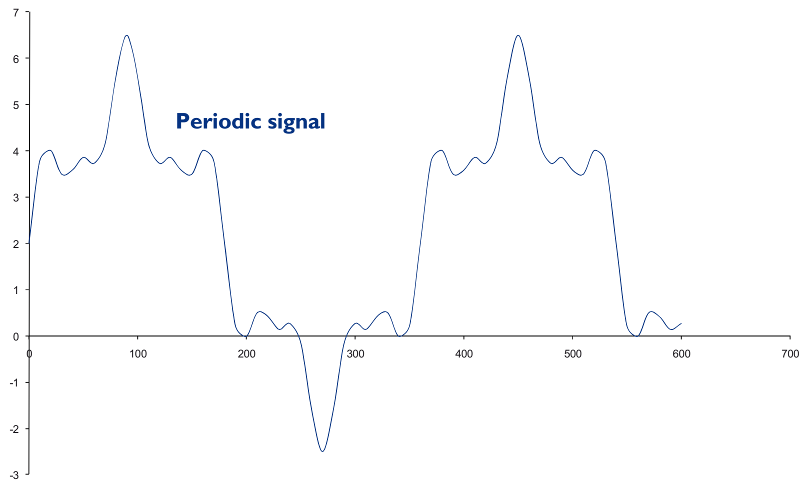
WHAT ARE HARMONICS?

Non-linear loads (rectifiers, frequency converters, arc furnaces, inverters, uninterruptible power supplies, etc.) inject non-sinusoidal currents into the network. These currents are formed by a 50 Hz or 60 Hz (depending on the country) fundamental component, plus a series of overlaid currents known as harmonics (as well as a DC component in some cases), with frequencies which are multiples of the fundamental. This decomposition is known as a Fourier Series.

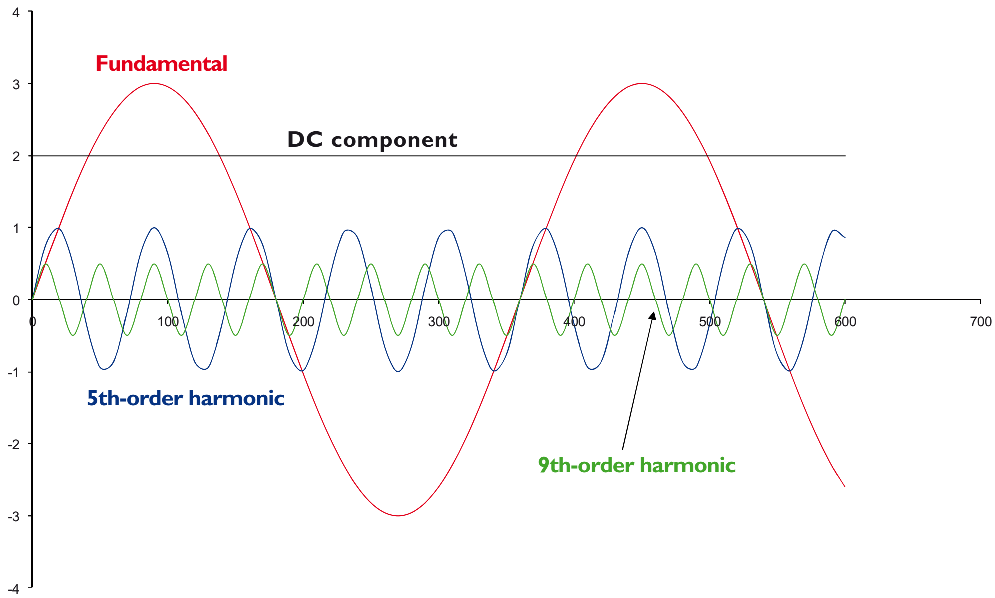
The result is distortion of the voltage and current causing a series of related secondary effects.
To measure the harmonics, you need to know a series of parameters as defined below.

$$\beta_{eff} = \beta_o + \sqrt{\beta_1^2 + \sum_{h=2}^{n} \beta_h^2}$$

$\sum$ = Sum of all the harmonic signals from the 2nd order through to the last order (50 Hz or 60 Hz x n).



Fourier Transform



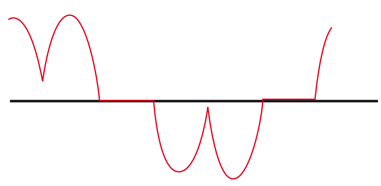
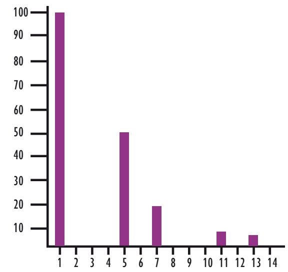
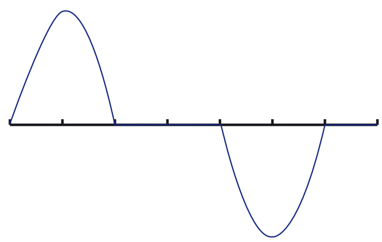
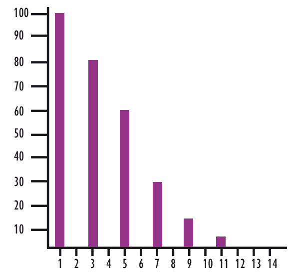
As electrical networks operate at 50 Hz, we will take that frequency as the fundamental (f_1).

$$f_n = n \times f_1$$

Harmonic order (n)

Harmonics are components whose frequency (f_n) is a multiple of the fundamental frequency (f_1 = 50 Hz).

These harmonics cause distortion of the sinusoidal wave. The table below identifies the most widespread harmonics in electrical networks containing non-linear loads.

Type of load	Current waveform	Harmonic spectrum of current for a non-linear load
Three-phase transducer: ► variable speed drives ► Uninterruptible Power Supplies (UPS) ► rectifiers		
Single-phase transducer: ► variable speed drives ► discharge lamps (different signal but rich spectrum) ► inverters		

The main **generators of 3rd-order harmonics are single-phase diode rectifiers** with capacitive filtering.
Balanced **three-phase loads without connection to the neutral** which are symmetrical but non-linear **do not generate 3rd-order harmonics** or triplen harmonics (multiples of 3).
Balanced **three-phase loads with connection to the neutral** which are symmetrical but non-linear **do generate 3rd-order and triplen harmonics** in the conductor.
The RMS value of the neutral current may be greater than the value of the line current.
To rectify this, you need to choose a neutral conductor cross-section equal to twice the cross-section of a phase conductor.
Other solutions are possible too, such as the use of reactances with zigzag coupling or filters tuned to the 3rd order.

Total Harmonic Distortion

As the sinusoidal is distorted, the distortion has to be quantified using the formulae below:

Individual THD

$$\tau_n(\%) = \frac{A_n}{A_1} \times 100$$

A_1 = RMS value of the fundamental
A_n = RMS value of harmonic order n
The RMS values An may be voltages or currents

Global THD

$$THD\text{-}U(\%) = \frac{\sqrt{\sum_{n=2}^{n} U_n^2}}{U_1} \times 100 \qquad THD\text{-}I(\%) = \frac{\sqrt{\sum_{n=2}^{n} I_n^2}}{I_1} \times 100$$

Example		Fundamental	5th order	7th order	11th order	13th order	THD (%)
	I	327 A	224 A	159 A	33.17 A	9A	84.66 %
	U	440 V	20 V	17 V	6 V	2 V	6.75 %

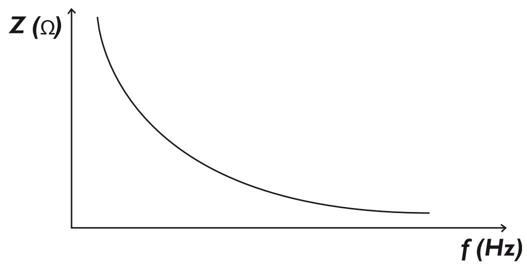
INFLUENCE OF HARMONICS ON POWER FACTOR CORRECTION AND FILTERING CABINETS

When harmonics overlay the fundamental signal, it causes:

- **premature ageing** or even destruction of the capacitors
- **electrical resonance**
- **heating** of machines
- **untimely tripping** of the protective devices
- **disturbance** of electrical equipment (control system, computer resources)
- **a power factor (PF) reduction**

Main phenomena encountered and related ENERDIS solutions

Eventual effects on capacitors



$$Z_C = \frac{1}{C\omega} = \frac{1}{C\,2\pi\,f}$$

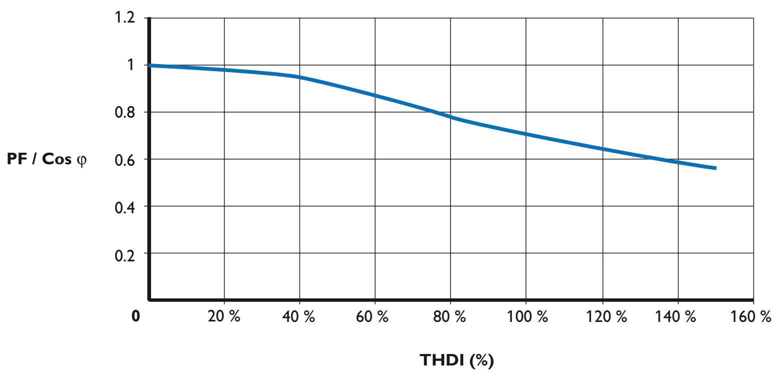
This curve shows that **a capacitor's impedance decreases with the frequency.** This causes **an increase in the intensity absorbed** by the capacitors, thus leading to **heating** which speeds up **capacitor ageing** and, in some cases, to **destruction**.

Main phenomena encountered and related **ENERDIS** solutions:

- an overvoltage of 1.1 Un (max. duration
  Un = 400 V (standard capacitors)
  Un = 440 V or 500 V (reinforced capacitors)
- a permanent overcurrent of 1.3 In at 50 Hz

These capacitors comply with the **IEC 831 and NFC C54-104 standards** (LV applications).

Influence of THD-I on the ratio PF/Cos φ



Variation of $\frac{PF}{\cos\varphi}$ according to **THD-I**

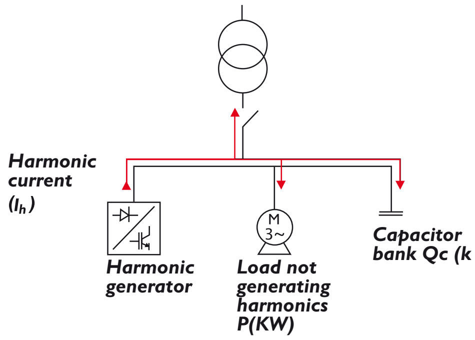
where **THD-U = 0 %**

$$PF \simeq \frac{\cos\varphi}{\sqrt{1 + THD\text{-}I^2}}$$

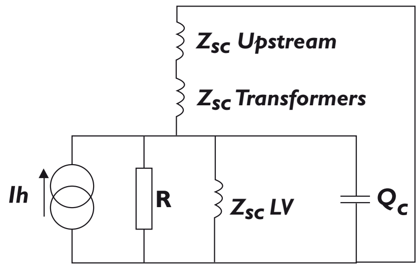
EFFECTS OF RESONANCE

When capacitor banks are installed in an electrical installation, it may cause amplification of the existing harmonics. In this context, amplification means increasing the harmonic distortion in both the voltage and the current. This amplification is due to electrical resonance between the bank's capacitance and the line and source inductances.

To understand this phenomenon, we will study a typical installation. The single-line diagram below, as modelled by an equivalent electrical circuit, can be used to study the effect of amplification on 3 types of receivers: harmonic generators, receivers not generating disturbances on the electrical network and capacitor banks.



Three-phase single-line diagram



Equivalent diagram of a single-phase model including a harmonic current generator modelling power electronics equipment

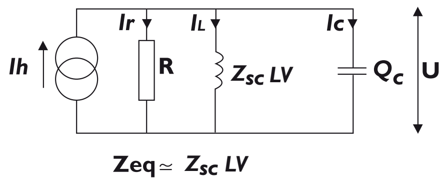
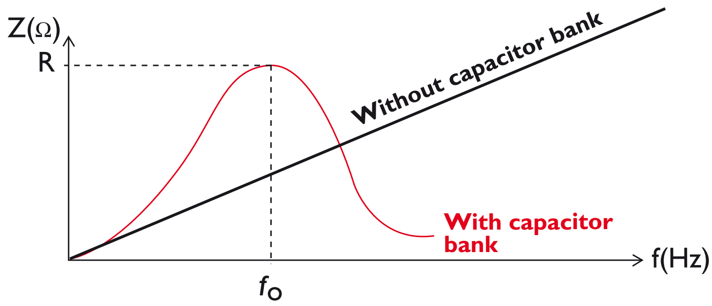


Diagram in the form of a parallel circuit (wave trap) with a single inductance equivalent to all the inductances in the circuit.

We can determine the impedance of this network as seen from the general low voltage switchboard by using:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{L\omega} - C\omega\right)^2}}$$

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



The amplification can be observed by studying the graph of the system's impedances as a function of the frequency. It shows the amplified value compared with the initial value of the network without capacitors.

At the resonance F_o, all the current I_o of order n generated by the circuit causing the disturbance flows into the resistance R, which means that almost all this current is absorbed by the loads consuming active power.

The direct consequence of this resonance is an increase in the harmonic voltages and therefore of the THD-U.

ESTIMATION OF PARALLEL RESONANCE

The possible resonance of the system depends on:

- The frequency of the harmonic order (f_n) at which the system resonates

$$f_n = f_1 \times \sqrt{\frac{S_{sc}}{Q_c}}$$

S_{SC} : short-circuit power of transformer
Q_C : reactive power of the capacitor bank
f_n : frequency of the harmonic order n at which the system resonates
f_1 : fundamental frequency (50 Hz)

The higher the short-circuit power (Ssc), the more the frequency deviates from the dangerous harmonic frequencies.

- The existence of harmonics at the resonance frequency
- The positions of the other loads on the network (active power consumed)

If the first 2 criteria are fulfilled, it is possible to calculate the harmonic current amplification factor Fa.

$$F_a = \frac{\sqrt{S_{sc} \times Q_c}}{P}$$

S_{SC} : short-circuit power of transformer
Q_C : reactive power of the capacitor bank
P : active power of loads not generating harmonics

The harmonic current amplification factor can be attenuated by increasing the number of non-polluting loads.

ENERDIS solutions

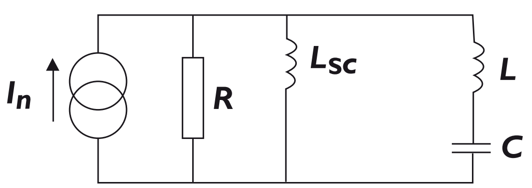
On the network, the resonance-order harmonic currents may be intense, representing a risk for the capacitors. ENERDIS offers solutions adapted to the level of pollution:

- Standard 400 V capacitors and reinforced 440V or 500 V capacitors recommended for networks with low or average pollution
- Capacitors with an anti-harmonic inductive circuit for polluted networks

Protecting capacitors with anti-harmonic inductive circuits

If there are significant harmonic overloads on the electrical network, ENERDIS equips the CYLINDRICAL capacitors with **anti-harmonic inductive circuits to protect them.**

In the previous paragraph, we saw that the presence of capacitances and inductances on an electrical network generates resonance. We therefore have the following equivalent electrical diagram:



- Parallel resonance frequency known as the anti-resonance frequency

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

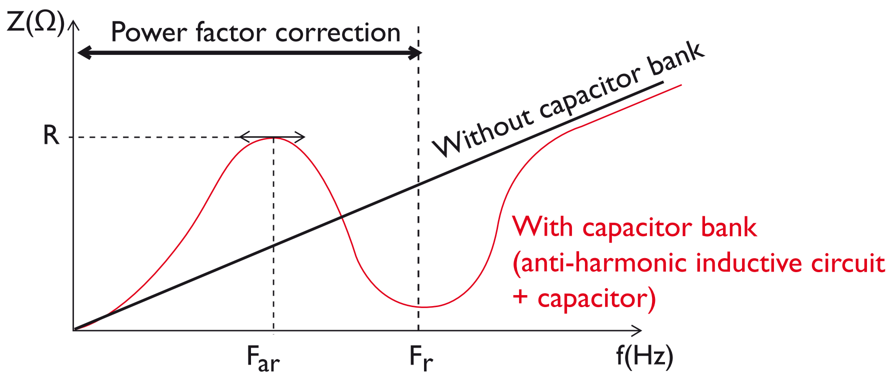
- Serial resonance frequency for the LC branch

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

The inductance of this anti-harmonic inductive circuit (L) must be calculated so that the resonance frequency does not match any of the harmonics present in the installation. This has the **advantage of preventing the risks of high harmonic currents in the capacitors** (increase in the impedance of the capacitor with regard to harmonic currents).

The choice of the anti-resonance frequency (f_{ar}) depends on the network's short-circuit impedance (L_{SC}) and on the circuit L-C, whereas the serial frequency (f_r) only depends on L and C.

The graph below shows the variation of the impedance as a function of the frequency, as seen from the busbars.



For a **frequency lower than f_r**, the assembly formed by the anti-harmonic inductive circuit and the capacitors acts as a capacitance and **allows reactive power correction**.
For a **frequency higher than f_r**, the assembly formed by the anti-harmonic inductive circuit and the capacitors acts as an inductance and **prevents amplification of the harmonics.**
The **serial frequency chosen (f_r)** will be below the first-order harmonics present in the circuit. This solution places the resonance outside the spectrum of the harmonic currents. ENERDIS has chosen the tuning frequency **f_r = 210 Hz** (order 4.03).

IMPORTANT

Avoid setting up an anti-harmonic inductance cabinet with a standard or type-H cabinet in parallel. This association causes parallel resonance which amplifies the existing harmonics in the electrical network and in the cabinets without anti-harmonic inductance.

Example of calculation

Transformer (S) = 630 kVA • **U_{sc}** = 6 % • **P** = 500 kW • **Q_c** = 275 kVAr

The short-circuit power is:

$$S_{sc} = \frac{S}{U_{sc}} \times 100 = \frac{630}{6} \times 100$$

$$S_{sc} = 10\,500 \text{ kVA}$$

The resonance frequency will therefore be:

$$f_n = 50 \times \sqrt{\frac{10\,500}{275}} \simeq 308.96 \text{ Hz}$$

The system will resonate at **order 6.18**

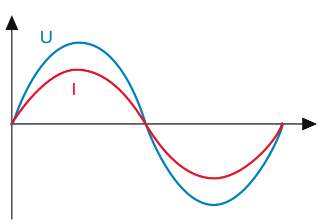
Amplification of the harmonics is as follows:

$$F_a = \frac{\sqrt{10\,500 \times 275}}{500} = 3.39$$

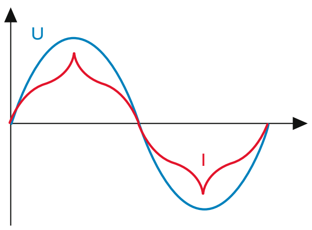
WHAT IS DISTORTING POWER?

When measuring electrical quantities, you may measure a reactive power with or without harmonics. This measurement influences the power factor. It should not be forgotten that, in non-sinusoidal AC systems, there is a difference between the power factor (PF) and the displacement power factor (DPF or Cos φ).

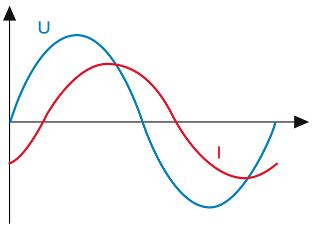
When harmonics are present, it is important to avoid confusing these two terms which are not equal when the voltage and the current are not sinusoidal.



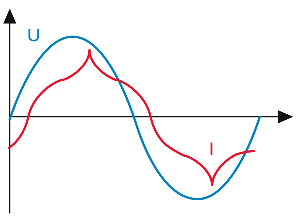
Cos φ = 1 PF = 1



Cos φ = 1 PF < 1



Cos φ = PF < 1



Cos φ < 1 PF < Cos φ

It is possible to quantify the power generated by the harmonics. This power value is better known as the **Distorting Power (D)** and it is linked to the distorting amperes. The unit is the distorting Volt-Ampere (VAd); This power has an immediate effect on the waveform and on the THD of the current. Power factor correction equipment will not be of any use because it only acts on the displacement power factor. Correcting reactive power generated by the harmonics will become more dangerous for power factor correction equipment. Indeed, the harmonics will displace the threshold, so the equipment will not compensate at the required moment and will be subjected to greater stress. To reduce the current harmonics (and therefore the distorting amperes), you must install filtering equipment. If a passive filter is used, it will short-circuit certain harmonic orders. If an active filter is used, a phase-opposition current will be injected to eliminate the harmonics observed on the network. Before installing filtering equipment, your site must be surveyed to determine the size of the filter according to the distorting amperes

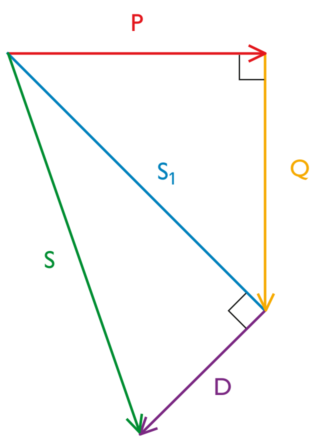
For passive filters, the inductances are totally different from the anti-harmonic inductances mounted in power factor correction cabinets which are not tuned to one of the harmonic orders and whose purpose is to protect the power factor correction cabinet against harmonic overloads.

In mathematical terms, the relation is as follows:

$$\mathbf{S} = \sqrt{\mathbf{P}^2 + \mathbf{Q}^2 + \mathbf{D}^2} = \sqrt{\mathbf{S_1}^2 + \mathbf{D}^2} \quad \text{where} \quad \mathbf{S_1}^2 = \mathbf{P}^2 + \mathbf{Q}^2$$

Q = reactive power without harmonics

This can be represented as shown in the diagram opposite.



Power Factor Correction
cabinet technology

TECHNOLOGY OF THE SAFETY CAPACITORS

Manufacturing principle

ENERDIS capacitors are made up of various capacitive elements connected in a triangular or star arrangement, depending on the rated voltage.

Life span of the capacitors

Because of their technology, ENERDIS capacitors offer an excellent life span. The capacitors' life span is calculated by extrapolating the results of an ageing test. The IEC 61049 standard serves as the reference. The following calculation method is used:

$$L = L_{Test}\left(\frac{U_{Test}}{U_n}\right)^K$$

with
- L: estimated life span in hours
- L_{Test}: number of hours tested
- U_{Test}: test voltage
- U_N: rated voltage
- K: this coefficient depends on the capacitor design

The ageing test involves submitting the capacitor to a test voltage greater than the rated voltage for a given period of time at the maximum operating temperature.

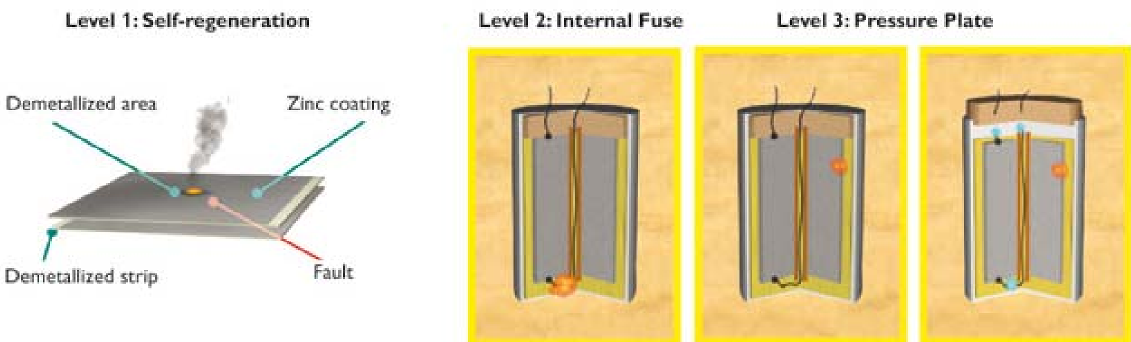
The IEC 60831 standard stipulates that the capacitors must be capable of operating for 1,500 hours with a voltage 25% higher than the rated voltage, without any short-circuits occurring and with a capacitance loss under 5%. For example, for a 400 V capacitor, the test is carried out with a voltage of 500 V.

With a 5% capacitance loss, it can be deduced that the estimated life span is 10 years. If the capacitor operates for less than 18 hours a day, the life span may be longer.

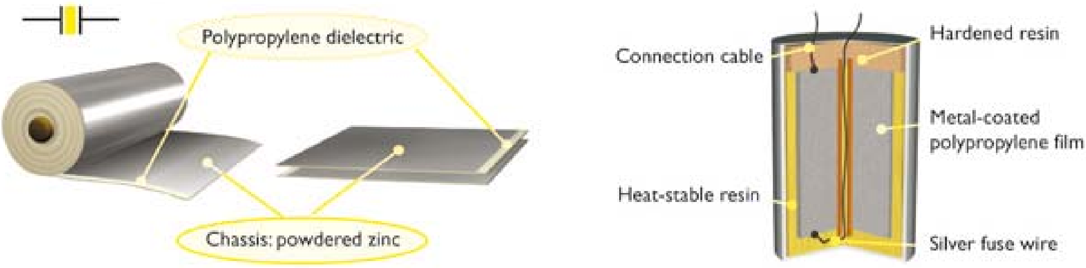
This calculation method implies a network in which the operating voltage is constant and an operating temperature within the range specified for the capacitor by the manufacturer.

If this is not the case, the life span is reduced. Indeed, some of these parameters are difficult to keep under control as time passes: quality of the power supply, changes to the users' power distribution systems and temperatures linked to those changes. Annual operating tests are recommended.

Level of protection



Technology



CHOOSING THE TYPE OF CORRECTION

Fixed correction

Used when:

- the reactive power to be compensated is constant, whatever the installation's reactive power consumption
- the amount of reactive power to be compensated is small
- there are large loads on the installation which need to be compensated individually to reduce the energy transported by the installation

This type of correction is generally used on the terminals of asynchronous motors and transformers.

Automatic correction

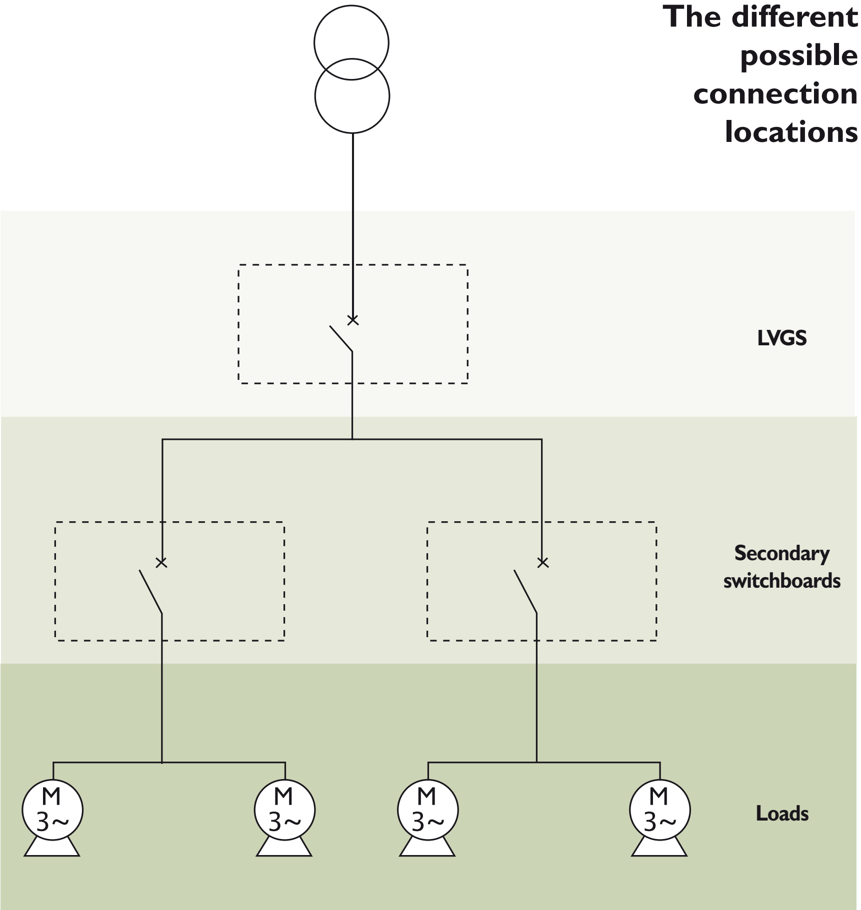
Used when the reactive power has to be adapted to the installation's reactive power consumption requirements.

The correction bank is then divided into several power steps controlled by a varmetric controller. The equipment must have a step connection response time matching the rate of variation of the powers on the installation.

If the power variation cycle is shorter than one second (lifts, welding units, etc.), the displacement power factor correction equipment will be fitted with "fast" static contactors. If this is the case, the steps will be connected by means of power thyristors (electronic switching). This type of contactor offers a host of advantages such as suppression of transients at start-up and an unlimited number of operations.

If the cycle of reactive power variation on the installation is around one second long, the displacement power factor correction equipment will be fitted with power contactors (electromechanical switching).

CHOOSING WHERE TO COMPENSATE



There are two criteria for choosing where to install your Power Factor Correction equipment:

Size of the installation:

- installation with a low-voltage general switchboard (LVGS) and a relatively small distance to the secondary switchboards,
- installation divided electrically into different zones, with large distances between them, i.e. with internal power distribution and large secondary switchboards.

Existence of large power-consuming loads

If this is the case, power consumption or harmonic filtering should be studied at the level of each load.

On the basis of these criteria, the diagram opposite summarizes the various possible locations for connection, along with the advantages of each location.

	LVGS	Secondary switchboards	Loads
ADVANTAGES	▸ no more billing of reactive power ▸ increase in available power on transformer secondary ▸ particularly economical solution because only one capacitor bank installed	▸ no more billing of reactive power ▸ increase in available power on transformer secondary if all the secondary levels of reactive power correction banks are installed ▸ economical solution	▸ no more billing of reactive power ▸ no voltage drops ▸ savings on electrical equipment sizing ▸ reactive power correction as close as possible to the equipment consuming reactive power
COMMENTS	▸ no reduction in line losses (voltage drops) ▸ no savings on electrical equipment sizing	▸ ideal solution for very extensive factory networks	▸ expensive solution

The ENER*phi* + (6 or 12 relays) reactive power controllers automatically control the connection and disconnection of the capacitors according to the network's power factor.

Logical operation is optimized to minimize the time and number of cycles necessary, as well as the active capacitors. This ensures that the capacitors are used evenly over the long term.

Backlit alphanumeric LCD screen for viewing the measurements, the status of the active capacitors and the alarms. The available measurements are the voltages and currents, active and reactive power, **THD on voltage and current,** internal temperature, number of operations and operating time of each capacitor, manual/automatic operating mode.

Alarm for: harmonic voltage overload, harmonic current overload, excessive temperature, under-correction, peak voltage overrun, RMS voltage overrun, immediate disconnection if voltage drop >10 ms and < 50% U_n

Disconnection time between two connections programmable from 5 to 300 s.

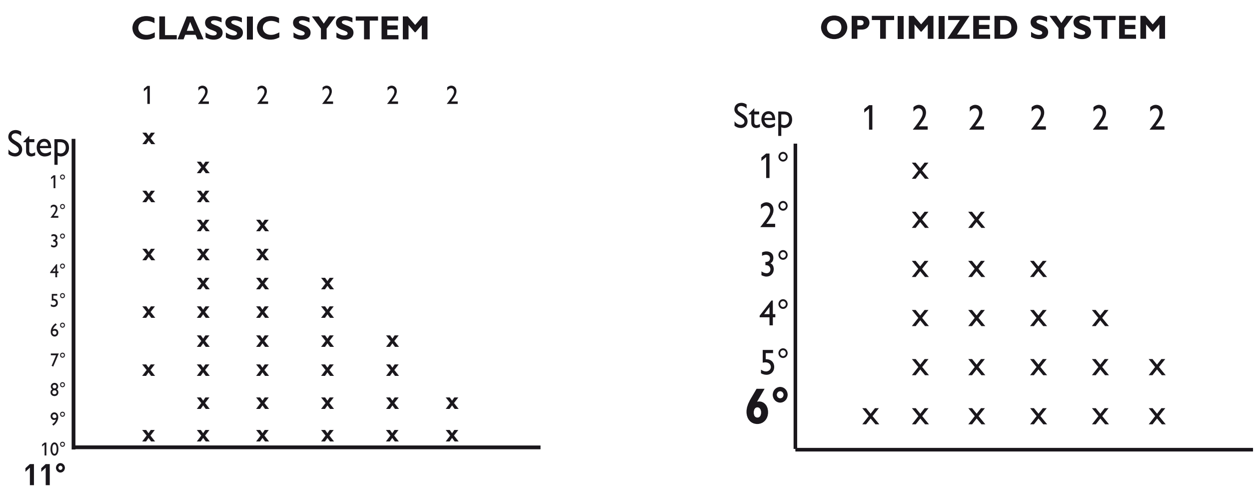
RS-485 communication, additional CT for measuring the current in the cabinet and the harmonic distortion. This measurement allows more detailed control of the reactive power and can be linked to an alarm.

- **Minimization of the number of step switching operations** by adjusting the connection time
- **Increase in the life span** of the components constituting the step (including the switching system)
- **Increase in the response time** of the power factor correction cabinet
- **Uniform ageing of the equipment**

The programme stores the connection time of each step in its memory. When there is a power factor variation, it orders connection to the step which has remained unconnected for the longest. In this way, the MTBF (Mean Time Between Failures) is equal for all the equipment steps.

Example

Operations necessary for a 100 % demand starting from zero on equipment set to 6 steps.



Total number of operations = 16

Total number of operations = 6

All the controllers are equipped with alarms displayed on the screen. The ENER*phi* + controller has a RUNTIME function making it possible to change the controller's parameters while the power factor correction cabinet is operating.

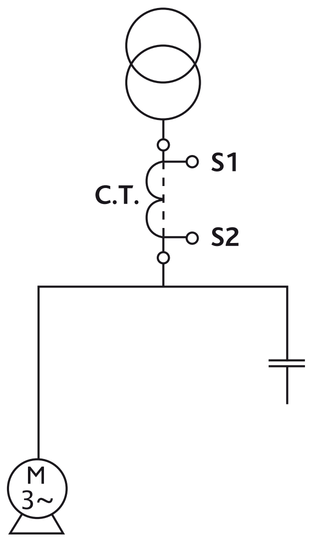
CONNECTING THE VARMETRIC CONTROLLER

The control system for the switching devices is prewired by ENERDIS. The installer only has to wire in the power supply for the circuits:

- 230 Vac power supply of the contactors circuit (depending on the type of capacitor bank, see specifications)
- Connection of the current transformer on phase 1

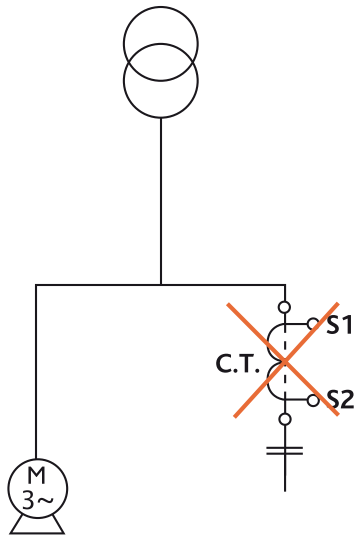
This arrangement enables the controller to calculate the power factor. The current transformer will be installed at a point in the circuit through which all the installation's current flows, including the current specific to the capacitors.

CORRECT

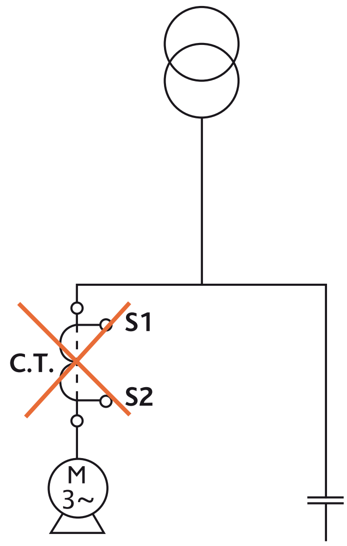


- The current transformer must necessarily be positioned before the capacitor bank and the receivers (motors, etc.).

INCORRECT



- No capacitors will be connected because the current transformer does not supply any type of signal.
- Check that the CT is not short-circuited or installed to bypass the loads.

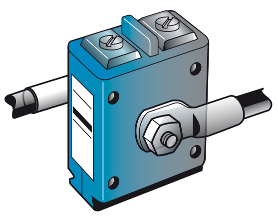


- All the capacitors in the bank are connected, but they are not disconnected after reducing the load. Risk of overcompensating the network without any load being present.

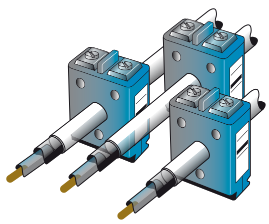
For commissioning, a current transformer (normally I_n/5 A) **must be installed which matches the total current of the receivers installed.** The current transformer's secondary line must have an appropriate cross-section depending on the distance between the transformer and the controller.

Type of cable/busbar primary and current intensity

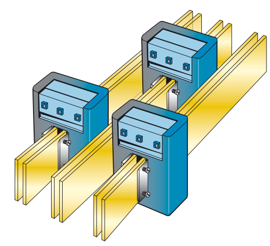
The choice depends on the types of cables or busbars on the installation and the intensity of the currents flowing through them:



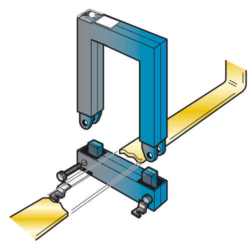
WOUND PRIMARY
for currents under 60 A



CABLE PRIMARY
for currents between 60 A and 2,500 A



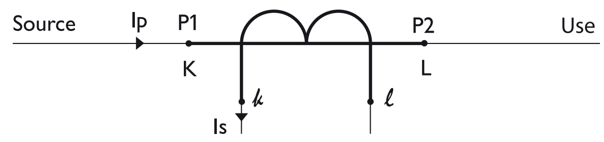
BUSBAR PRIMARY
for currents from 750 to 5,000 A



SPLIT-CORE PRIMARY
for easy incorporation into an existing installation, on a bar or cable.

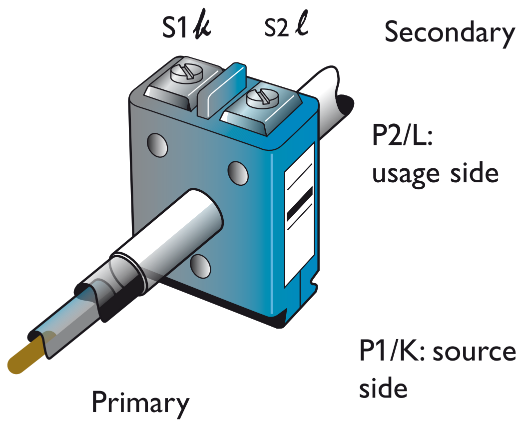
CONNECTING YOUR CURRENT TRANSFORMER

The transformer connection direction must always be respected, particularly in three-phase systems, to avoid reversing the phase shift between the current and the voltage on one or more phases.

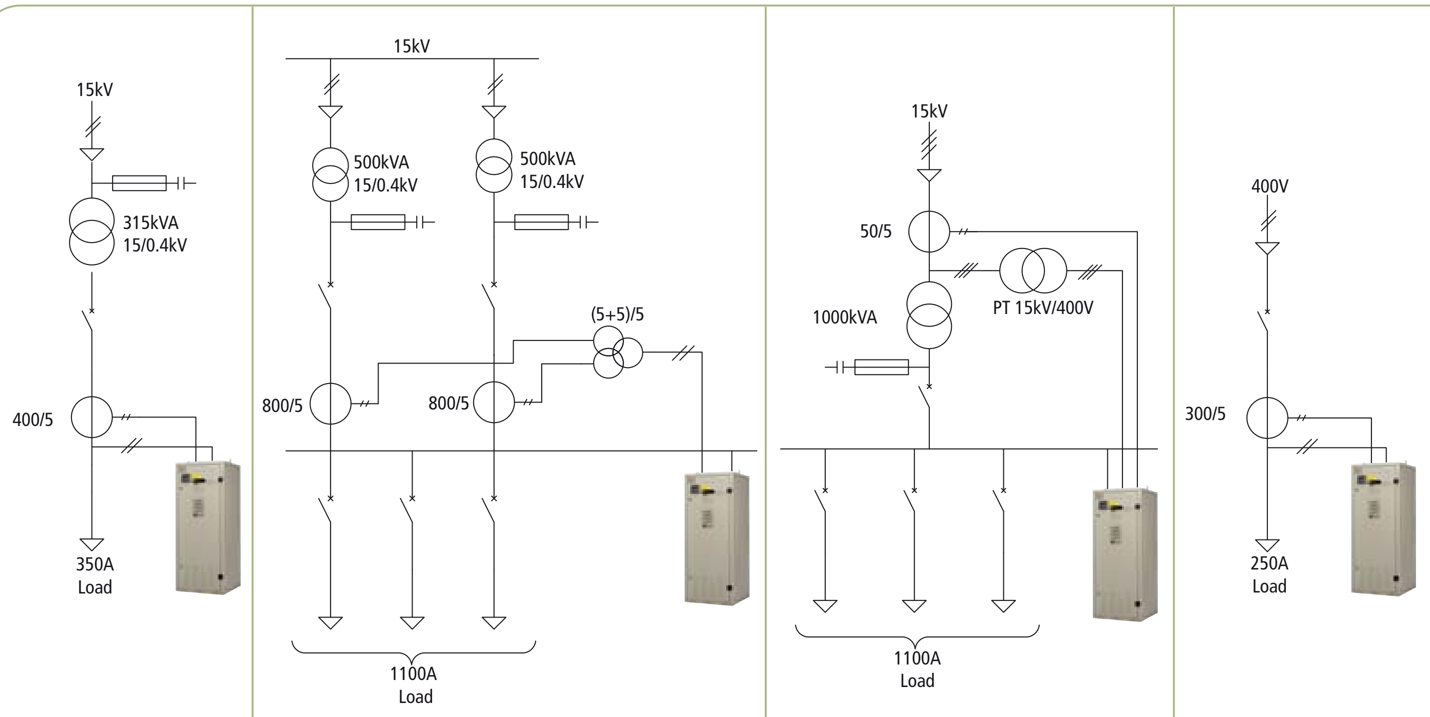


The accuracy class

The accuracy class is the result of all the measurement errors on each element in the chain. **A CT's accuracy class must be less than or equal to the class of the measurement instrument which it powers,** particularly for energy metering where accuracy has a direct impact on billing.



Examples of connection



Advantages of ENERDIS cabinets

Excess reactive power and harmonic pollution not only generate significant financial costs, they also cause heating and noise disturbance, as well as interfering with the operation of the protective systems.

Power factor correction to compensate the reactive power and harmonic filtering are both excellent investments for reducing energy costs, usually achieving payback within three years.

Defining your Power Factor Correction cabinet

3 STEPS FOR DEFINING YOUR POWER FACTOR CORRECTION CABINET

1 / Calculation of power "Qc"

The reactive power $\mathbf{Q_c}$, which is necessary for correction, is calculated on the basis of the measured active power **P** and the tan φ value measured on the installation. The measurements are made downstream of the transformer.

The table opposite indicates the factor **K** to be applied to the active power **P** on the installation in order to calculate the reactive power $\mathbf{Q_c}$ of the capacitor bank to be installed. It also shows the correspondence between tan φ and Cos φ.

$$Q_c = P \times \underbrace{(\tan \varphi_{measured} - \tan \varphi_{required})}_{K} = P \times K$$

2 / Fixed or automatic correction

At low voltages, two equipment systems can be used for reactive power correction:

- fixed correction system using capacitors with fixed values delivering a constant reactive power.
- automatic correction system involving a capacitor bank divided into steps and commanded by a controller. This controller adapts the reactive power supplied to suit the installations' requirements, on the basis of the power factor (Cos φ).

Q_c: reactive power of the correction equipment in kVAr

S_n: apparent power of the installation's transformer in kVA.

$Q_c / S_n <$ 15 % ► fixed correction
$Q_c / S_n \geq$ 15 % ► automatic correction

3 / Type of reinforcement

S_h: apparent power (kVA) of the receivers producing harmonics (variable-speed motors, power electronics, etc.)

S_n: apparent power of the installation's transformer in kVA

$S_h / S_n <$ 15 %	► standard type (voltage 400 V)
$S_h / S_n =$ 15 à 25 %	► H type (reinforced voltage 440 V or 500 V)
$S_h / S_n >$ 25 %	► SAH type (reinforced voltage + anti-harmonic inductive circuit)

Because of the growing presence of harmonic currents, it is now necessary to use power factor correction cabinets specifically designed to deal with such overloads.

Four "types of capacitors" are proposed, depending on the level of harmonic pollution (S_h / S_n) :

- Standard type: voltage 400 V
- H type: reinforced voltage 440 V or 500 V
- SAH type: reinforced voltage + anti-harmonic inductive circuit
- FH type: harmonic filter. Survey of the installation by the Audit & Troubleshooting Department.

Example

Active power of the installation	**P** = 614 kW
Cos φ measured on the installation	**Cos φ** = 0.68 so **Tan φ** = 1.08
Cos φ required after correction	**Cos φ** = 0.93 so **Tan φ** = 0.40
Coefficient indicated by the table	**K** = 0.684
Reactive power to be compensated	$\mathbf{Q_c}$ = 614 x 0.684 = 420 kVAr

DEFINITION OF THE K FACTOR

required ◄

measured ▼	tan φ	0.46	0.43	0.40	0.36	0.33	0.29	0.25	0.20	0.14	0
tan φ	**Cos φ**	**0.91**	**0.92**	**0.93**	**0.94**	**0.95**	**0.96**	**0.97**	**0.98**	**0.99**	**1**
2.29	**0.40**	1.832	1.861	**1.895**	1.924	1.959	1.998	2.037	2.085	2.146	2.288
2.16	**0.42**	1.709	1.738	**1.771**	1.800	1.836	1.874	1.913	1.961	2.022	2.164
2.04	**0.44**	1.585	1.614	**1.647**	1.677	1.712	1.751	1.790	1.837	1.899	2.041
1.93	**0.46**	1.473	1.502	**1.533**	1.567	1.600	1.636	1.677	1.725	1.786	1.929
1.83	**0.48**	1.370	1.400	**1.430**	1.464	1.497	1.534	1.575	1.623	1.684	1.826
1.73	**0.50**	1.276	1.303	**1.337**	1.369	1.403	1.441	1.481	1.529	1.590	1.732
1.64	**0.52**	1.188	1.215	**1.249**	1.281	1.315	1.353	1.393	1.441	1.502	1.644
1.56	**0.54**	1.103	1.130	**1.164**	1.196	1.230	1.268	1.308	1.356	1.417	1.559
1.48	**0.56**	1.024	1.051	**1.085**	1.117	1.151	1.189	1.229	1.277	1.338	1.480
1.40	**0.58**	0.949	0.976	**1.010**	1.042	1.076	1.114	1.154	1.202	1.263	1.405
1.33	**0.60**	0.878	0.905	**0.939**	0.971	1.005	1.043	1.083	1.131	1.192	1.334
1.27	**0.62**	0.809	0.836	**0.870**	0.902	0.936	0.974	1.014	1.062	1.123	1.265
1.20	**0.64**	0.744	0.771	**0.805**	0.837	0.871	0.909	0.949	0.997	1.058	1.200
1.14	**0.66**	0.682	0.709	**0.743**	0.775	0.809	0.847	0.887	0.935	0.996	1.138
1.08	**0.68**	**0.623**	**0.650**	**0.684**	0.716	0.750	0.788	0.828	0.876	0.937	1.079
1.02	**0.70**	0.564	0.591	0.625	0.657	0.691	0.729	0.769	0.811	0.878	1.020
0.96	**0.72**	0.507	0.534	0.568	0.600	0.634	0.672	0.712	0.754	0.821	0.963
0.91	**0.74**	0.453	0.480	0.514	0.546	0.580	0.618	0.658	0.700	0.767	0.909
0.86	**0.76**	0.399	0.426	0.460	0.492	0.526	0.564	0.604	0.652	0.713	0.855
0.80	**0.78**	0.347	0.374	0.408	0.440	0.474	0.512	0.552	0.594	0.661	0.803
0.75	**0.80**	0.294	0.321	0.355	0.387	0.421	0.459	0.499	0.541	0.608	0.750
0.70	**0.82**	0.242	0.269	0.303	0.335	0.369	0.407	0.447	0.489	0.556	0.698
0.65	**0.84**	0.190	0.217	0.251	0.283	0.317	0.355	0.395	0.437	0.504	0.645
0.59	**0.86**	0.140	0.167	0.198	0.230	0.264	0.301	0.343	0.390	0.450	0.593
0.54	**0.88**	0.085	0.112	0.143	0.175	0.209	0.246	0.288	0.335	0.395	0.538
0.48	**0.90**	0.031	0.058	0.089	0.121	0.155	0.192	0.234	0.281	0.341	0.484

DEFINITION OF THE CABINET ON THE BASIS OF REAL MEASUREMENTS OF THE HARMONICS

1. Identify the harmonic pollution on the network

2. Take measurements

1. Identifying the harmonic pollution on the network

It is not easy to determine the global apparent power of the receivers producing harmonics, so we are providing the table below to help you choose the type of correction according to the measurements on site.
It is not easy to determine the global apparent power of the receivers producing harmonics, so we are providing the table below to help you choose the type of correction according to the measurements on site.

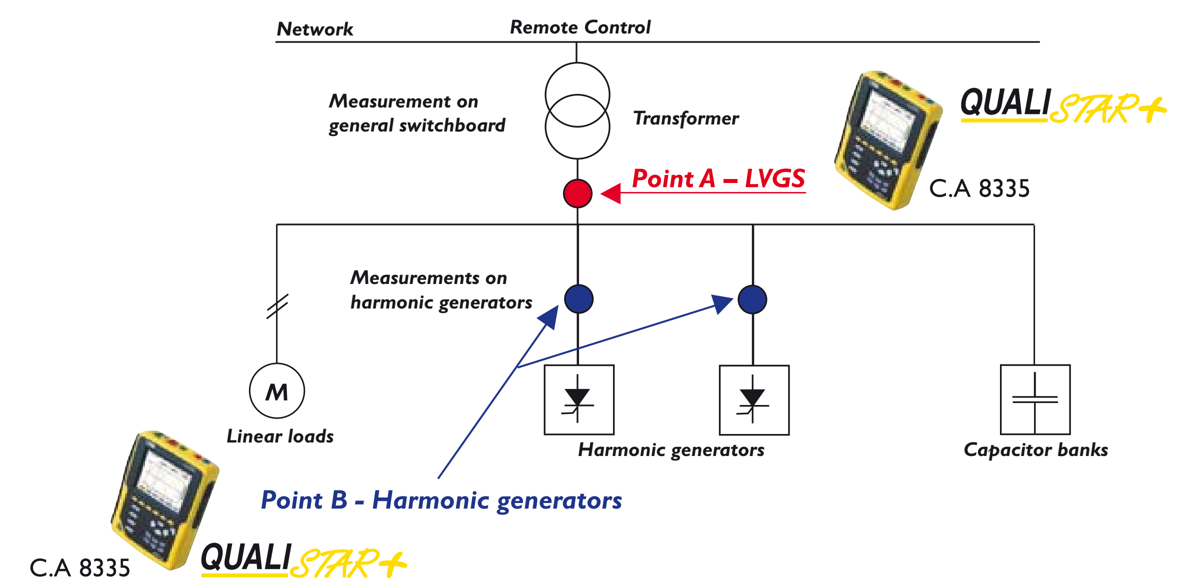
THD-U (%)	THD-I (%)	Type of reinforcement to use	Comments
< 2	< 15	standard type (400 V)	check the resonance
2 < THD-U < 3	15 < THD-I < 30	reinforced type (440 or 500 V)	inductive circuit tuned to 210 Hz
> 3	< 15	440 V or 500 V reinforced type + anti-harmonic inductive circuit	inductive circuit tuned to 210 Hz
> 3	> 30	harmonic filter	detailed study of the installation

For installations heavily polluted by harmonics, ENERDIS proposes on-site measurements via a network of experts capable of sizing the compensation and harmonic filtering cabinets.

2. Taking measurements

a. The diagram below shows:

- the points where measurements must be taken with a C.A 8335 three-phase network analyzer
- the distribution of the loads



b. General data concerning the installation:

- Identification of the measurement points
- Type of industrial process

Number of transformers	
S_n (transformer power)	kVA
U_n (rated voltage)	V
U_{sc} (short-circuit voltage)	%

Harmonic order	1	3	5	7	11	13	THD
THD-U							
THD-I							
I_n(A)							

c. General switchboard (point A)

- Measurement of the active and reactive power values
- Measurement of harmonics

With bank connected		Without bank connected	
THD-I	%	THD-I	%
THD-V	%	THD-V	%
Q (bank)			kVAr
P (installation)			kW

- Is there a capacitor bank?

Harmonic order	1	3	5	7	11	13	THD
THD-V							
THD-I							
I_n(A)							

d. Loads (point B)

- Measurements on the terminals of power-converter loads

Harmonic order	1	3	5	7	11	13	THD
THD-V							
THD-I							
I_n(A)							

- Measurements on the terminals of loads generating harmonics

Description of the type of load:

- discharge lamps
- welding units
- inverters
- variable speed drives
- rectifiers
- uninterruptible power supplies (UPS)

ENERDIS would be pleased to carry out a harmonic survey for you.
Do not hesitate to contact the Sales Department.

Specific applications of Power Factor Correction

Compensating an asynchronous motor

When a motor drives a load with significant inertia and there is a power supply outage, it may continue to rotate due to the kinetic energy in the system (energy proportional to the square of the speed).
The presence of capacitor banks may then cause "self-excitation" of the motor, which means that they may supply it with sufficient reactive power to function as an asynchronous generator.
This self-excitation causes overvoltages which may be significantly higher than the network voltage.
Whenever a capacitor bank is installed on the terminals of a motor, **you must make sure that the power of the capacitor bank is lower than the power necessary for self-excitation of the motor.**

In any installation incorporating motors with high inertia and capacitor banks, the control equipment for the capacitor banks must be designed so that, in the absence of any voltage, no electrical links subsists between these motors and the capacitors.

The Cos φ of the motors is very poor when there is no load or only a light load. It may therefore be useful to install capacitors for this type of receiver.

Case of capacitors mounted on the terminals of the motor

To avoid dangerous overvoltages due to self-excitation, make sure that the power of the battery complies with the following equation:

$$Q_c \leq 0.9 \times \sqrt{3} \times U_n \times I_o$$

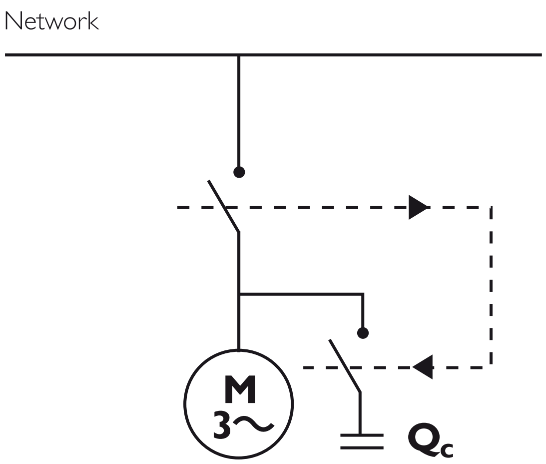
I_O: No-load current of motor

I_O can be estimated using the following equation: $I_o = 2I_n \times (1 - \cos\varphi_n)$

I_n: Rated current of motor

Cos φ_n: Cos φ of the motor at the rated power

U_n: Rated phase-to-phase voltage



In this case, if $Q_c \geq 0.9 \times \sqrt{3} \times U_n \times I_o$, then the equipment can be connected as shown.

Example

An asynchronous motor has the following nameplate values:

- $P_u = 37$ kW
- 220/380 V
- f = 50 Hz
- N' = 1440 rpm
- $\eta = 0.91$
- $\cos \varphi_n = 0.85$

We need to calculate the maximum power of the capacitor bank.
The rated current is given by the following equation:

If $P_u = 3U_nI_n\cos\varphi_n$ ► $I_n = \dfrac{P_u}{\sqrt{3}U_nI_n\cos\varphi_n}$ $\qquad I_n = \dfrac{37 \times 10^3}{\sqrt{3} \times 380 \times 0.85} = 66.14$ A

To calculate the power of the capacitor bank, we need to know the no-load current of the motor:

Therefore $I_0 = 2I_n \times (1 - \cos\varphi_n)$

$I_0 = 2 \times 66.14 \times (1 - 0.85) = 19.84$ A

$Q_c \leq 0.9 \times \sqrt{3} \times 380 \times 19.84$

$Q_c \leq 11\,752$ VAr

$\mathbf{Q_c \leq 11.752}$ **kVAr**

A capacitor bank rated 11 kVAr (maximum) should be installed for a 37 kW motor at a rotation speed of 1,500 rpm in order to avoid self-excitation of the motor.

Necessary precautions:

- When the motor is started up: if the motor is started with the help of a special device (resistor, inductance, star/triangle set-up, auto-transformer), the capacitor bank should only be activated after starting the motor.
- For special motors: you are advised not to compensate these motors (step-by-step motors, two-way motors, etc.).

400 V THREE-PHASE MOTOR					
Rated power		Max. power (kVAr)			
		Max. rotation speed (rpm)			
kW	**horsepower**	**3,000**	**1,500**	**1,000**	**750**
8	11	2	2	3	
11	15	3	4	5	
15	20	4	5	6	
18	24	5	7	7.5	
22	30	6	8	9	10
30	41	7.5	10	11	12.5
37	50	9	11	12.5	16
45	61	11	13	14	17
55	75	13	17	18	21
75	102	17	22	25	28
90	122	20	25	27	30
110	149	24	29	33	37
132	179	31	36	38	43
160	217	35	41	44	52
200	272	43	47	53	61
250	340	52	57	63	71
280	380	57	63	70	79
355	482	67	76	86	98
400	543	78	82	97	106
450	611	87	93	107	117

Compensating a transformer

A transformer consumes reactive power to ensure that its windings are magnetized. The table below shows the normal consumption levels.

Example

If Cos φ = 0.7, 30 % of the transformer's power is unavailable because of the reactive power which it has to produce.

Transformer rated power	**Compensation power in kVAr**		
	Transformer operating with		
kVA	**No load**	**75% load**	**100% load**
100	3	5	6
160	4	7.5	10
200	4	9	12
250	5	11	15
315	6	15	20
400	8	20	25
500	10	25	30
630	12	30	40
800	20	40	55
1000	25	50	70
1250	30	70	90
2000	50	100	150
2500	60	150	200
3150	90	200	250
4000	160	250	320
5000	200	300	425

Compensation and attenuation
of harmonics

The harmonics flowing in the electrical network reduce the quality of the power supply. The main effects are as described on page 6. Alongside these effects, there is also a significant economic impact.

- **Energy losses:** extra joules lost.
- **Extra cost of subscription:** the distorting power created by the harmonics increases the overall apparent power, requiring a higher subscribed power level.
- **Oversizing of equipment:** downgrading of the sources and oversizing of the cables to allow the harmonics to flow.
- **Reduced equipment life spans:** a THD-U of approximately 10 % significantly reduces equipment life spans.
- Untimely tripping and shutdown of the installation.

There are various standards and regulations covering harmonic emissions (compatibility standards adapted to networks, emission standards applicable to equipment generating harmonics, recommendations from power distributors).

For example, for the quality of the energy supplied by the medium and low-voltage public networks, the EN 50160 standard specifies the threshold values to be respected at the point of supply in normal operating conditions. The THD-U must not exceed 8 %.

Odd harmonics				Even harmonics	
Non-triplen harmonics		Triplen harmonics			
H order	Relative voltage	H order	Relative voltage	H order	Relative voltage
5	6.0 %	3	5.0 % (1)	2	2.0 %
7	5.0 %	9	1.5 %	4	1.0 %
11	3.5 %	15	0.5 %	6…24	0.5 %
13	3.0 %	21	0.5 %		
17	2.0 %				
19	1.5 %				
23	1.5 %				
25	1.5 %				

Harmonic voltage values at the point of supply up to the 25th order, expressed as a percentage of the rated voltage (Uc)

(1) Depending on the network design, the value of the 3rd order harmonic may be much lower.
NOTE: as the values corresponding to harmonics above the 25th order are usually low but are difficult to forecast due to the resonance effects, they are not shown in this table.

WHERE TO INSTALL YOUR FILTER

To choose the most suitable location to connect a filter in an installation, you must take into account:

- The type of disturbance present on the installation, which defines the type of filter to be installed.
- The configuration of the installation:
  - Existence of capacitor banks
  - Existence of major loads causing disturbances
  - Power and location of the lighting or computer lines

There are 3 points in an installation where you can connect filtering equipment in order to eliminate disturbances:

- **On the low-voltage general switchboard (LVGS)**
  When the disturbances have been eliminated or attenuated directly at the level of the loads or at the level of the secondary switchboards, **the remaining residual disturbances can be eliminated by connecting filtering equipment on the general switchboard.** In this way, it is possible to ensure that the electrical signal is in a satisfactory state at the point of connection with the energy supplier.
- **On the secondary switchboard**
  When there are various low-power loads connected to the secondary distribution switchboard. Elimination of the disturbances prevents discharging of the lines connected to the general switchboard.
- **On the terminals of the load generating harmonics**
  This is the best solution for **eliminating the disturbance directly** at the point where it is generated, thus **preventing propagation to all the lines** in the electrical installation.

Technology

In cases where preventive action is insufficient (e.g. grouping polluting loads or changing the earthing system), the polluted installation must be fitted with filtering equipment. There are 3 types of filters:

- **Passive filter**

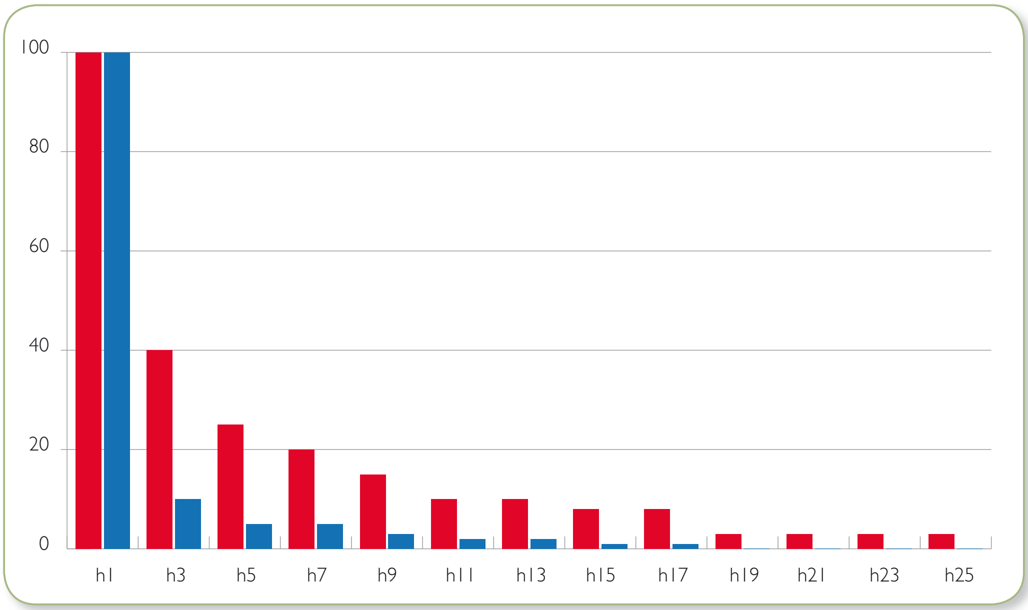
This is an LC circuit tuned to a harmonic frequency to be filtered. This filter, mounted on a bypass circuit, absorbs the harmonics and prevents them from flowing in the power supply. However, for a significant reduction of the THD-I (Sn < 200 kVA) on several harmonic orders, several branch filter circuits will be necessary.

- **Active filter**

This is an electronic power system designed to compensate either the harmonic voltage or the harmonic currents generated by the load. This filter reinjects, in phase-opposition, the harmonics present on the load's power supply so that the current in the line becomes sinusoidal (Sn < 200 kVA).

- **Hybrid filter**

This involves a combination of the two technologies described above for a broad power range.

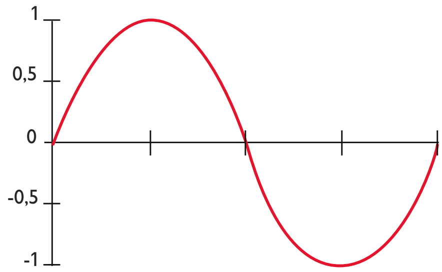


The harmonic spectrum opposite shows an installation before and after fitting an active harmonic compensator. This improvement of the spectrum is accompanied by improvement of the voltage and current waveforms.

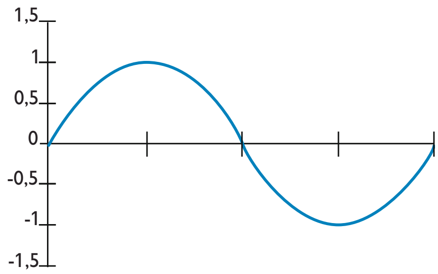
Harmonic order

Before active compensation

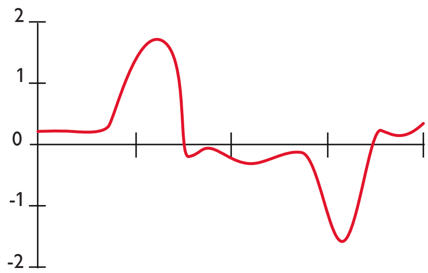
After active compensation



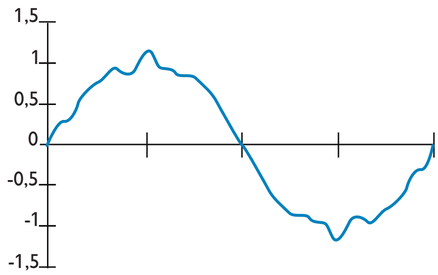
Voltage waveform before filtering



Voltage waveform after filtering



Current waveform before filtering



Current waveform after filtering

The effect of the active compensator can be seen very clearly on the current waveform: **reduced RMS value, reduced crest factor after correction and improved power factor.** The graphs show the impact of the active compensator with **very significant attenuation of the THD-I.**

THE ENERDIS RANGE

Green-tariff compensation

Fixed compensation

ENER*pack* **range**

H and SAH types

Automatic compensation

ENER*cap* **range**

230 V, standard and H types

SAH type

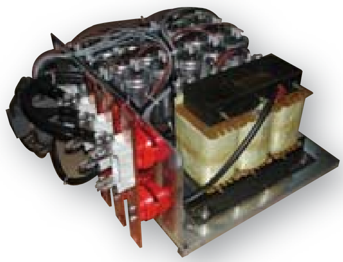
Sociated equipment

CONDO range

ENERPHI+ 6 and 12

Capacitors

Accessories



NOTES

NOTES

ENERDIS SUPPORTS YOUR ENERGY EFFICIENCY APPROACH

Enerdis is positioned as a **provider of global solutions focusing on active energy efficiency, complementing its offering of fixed equipment** for measuring, metering, analysing, supervising and managing energy use.

Brochures on our software, products and services to help you work out sustainable energy-saving strategies.

A collection of Case Studies based around energy efficiency.

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