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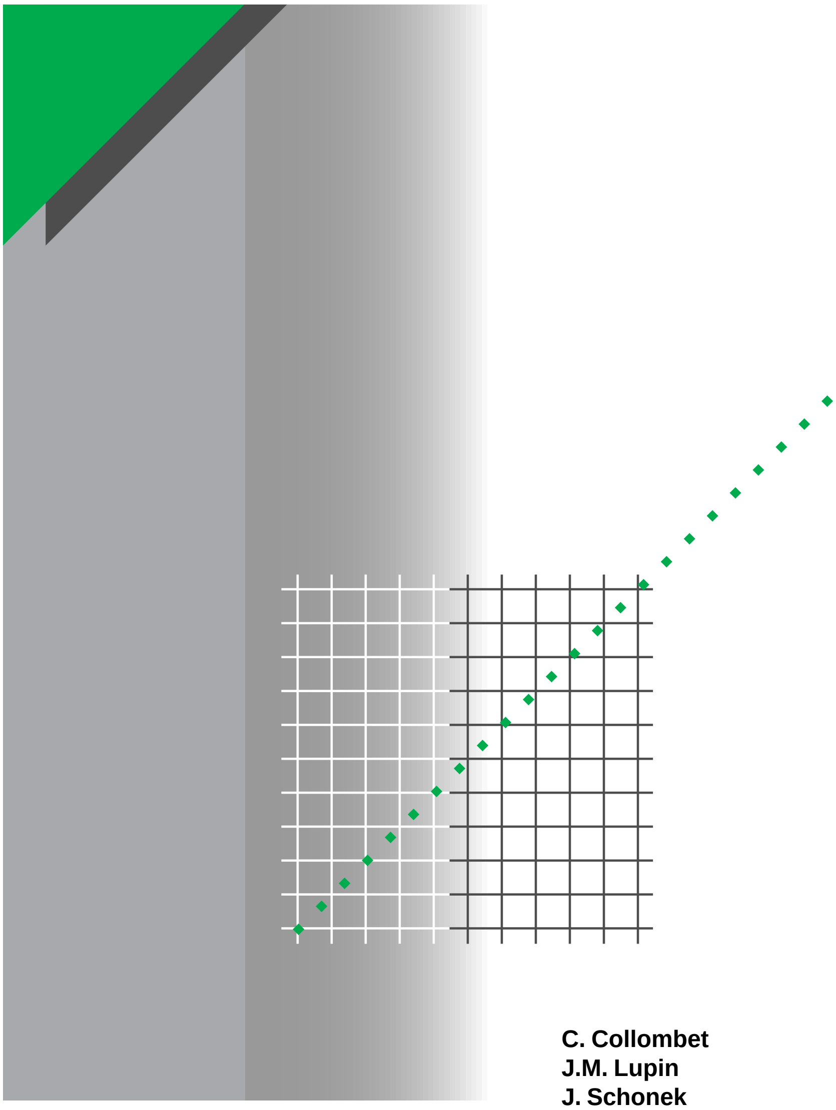
# Harmonic disturbances in networks, and their treatment



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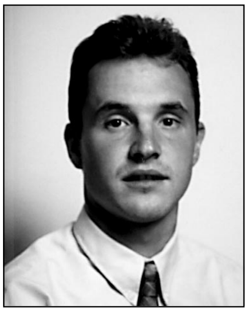
# no. 152

# Harmonic disturbances in networks, and their treatment

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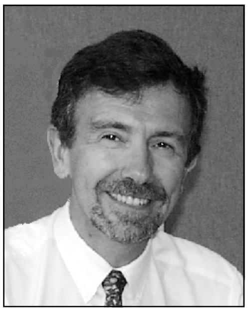

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**Have also taken part in the 1999 edition of this document:**
**Noël QUILLION, author of the first edition, presently in the networks protection and control department;**
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# Glossary

**Symbols:**

| | |
|---|---|
| C | capacitance or, more generally, the capacitors themselves |
| D (or THD) | total harmonic distortion |
| d | loss angle of a capacitor |
| $f_1$ | fundamental frequency |
| $f_{ar}$ | anti-resonance frequency |
| $f_n$ | frequency of the $n^{th}$ harmonic component |
| $f_r$ | resonance frequency |
| $j_n$ | phase angle of the $n^{th}$ harmonic component when t = 0 |
| $I_n$ | rms current of the $n^{th}$ harmonic component |
| j | complex operator such as $j^2 = -1$ |
| L | inductance or, more generally, the reactors, producing the inductance |
| Lsc | short-circuit inductance of a network, seen from a given point, as defined by Thevenin's theorem |
| n | the order of a harmonic component (also referred to as the harmonic number) |
| $n_{ar}$ | the order of anti-resonance, i.e. the ratio of the anti-resonance frequency to the fundamental frequency |
| $n_r$ | the order of resonance, i.e. the ratio of the resonance frequency to the fundamental frequency |
| k | a positive integer |
| p | number of rectifier arms (also referred to as the pulse number) |
| $p_1$ | filter losses due only to the fundamental current |
| $p_n$ | filter losses due only to the $n^{th}$ harmonic current |
| P (W) | active power |
| PB | pass-band of a resonant shunt filter |
| q | quality factor of a reactor |
| Q | quality factor of a filter |
| Q (var) | reactive power |
| r | resistance |
| R | resistance (or the real part of the impedance) |
| spectrum | the distribution, at a given point, of the amplitudes of the various harmonic components expressed relative to the fundamental |
| Ssc | short-circuit power of a network at a given point |
| T | period of an alternating quantity |
| U | phase-to-phase rms voltage |
| $V_n$ | phase-to-neutral rms voltage of the $n^{th}$ harmonic component |
| X | reactance |
| $X_0$ | characteristic inductance or impedance of a filter |
| Xsc | short-circuit reactance of a network, seen from a given point, as defined by Thevenin's theorem |
| $Y_0$ | amplitude of the DC component |
| $Y_n$ | rms value of the $n^{th}$ harmonic component |
| Z | impedance |

**Abbreviations:**

| | |
|---|---|
| **CIGRE** | Conférence Internationale des Grands Réseaux Electriques (International Conference on Large Electrical Networks) |
| **IEC** | International Electrotechnical Commission |

# Harmonic disturbances in networks, and their treatment

Electricity is generally distributed as three voltage waves forming a 3-phase sinusoidal system. One of the characteristics of such a system is its waveform, which must always remain as close as possible to that of a pure sine wave.

If distorted beyond certain limits, as is often the case on networks comprising sources of harmonic currents and voltages such as arc furnaces, static power converters, lighting systems, etc., the waveform must be corrected.

The aim of the present document is to provide a better understanding of these harmonics problems, including their causes and the most commonly used solutions.

## Summary

# 1 Harmonic quantities

To help the reader follow the discussion, we will first review the definitions of a number of terms related to harmonics phenomena. Readers already familiar with the basic terminology may proceed directly to the next chapter.

On AC industrial power supply networks, the variation of current and voltage with time is considerably different from that of a pure sine wave (see **fig. 1** ).

The actual waveform is composed of a number of sine waves of different frequencies, including one at the power frequency, referred to as the fundamental component or simply the "fundamental".

### Harmonic component

The term "harmonic component", or simply "harmonic", refers to any one of the above-mentioned sinusoidal components, the frequency of which is a multiple of that of the fundamental.

The amplitude of a harmonic is generally a few percent of that of the fundamental.

### Harmonic order

The harmonic order, also referred to as the harmonic number, is the ratio of the frequency $f_n$ of a harmonic to that of the fundamental (generally the power frequency, i.e. 50 or 60 Hz):

$$n = \frac{f_n}{f_1}$$

By definition, the harmonic order of the fundamental $f_1$ is equal to 1. Note that the harmonic of order n is often referred to simply as the $n^{th}$ harmonic.

### Spectrum

The spectrum is the distribution of the amplitudes of the various harmonics as a function of their harmonic number, often illustrated in the form of a histogram (see **fig. 2** ).

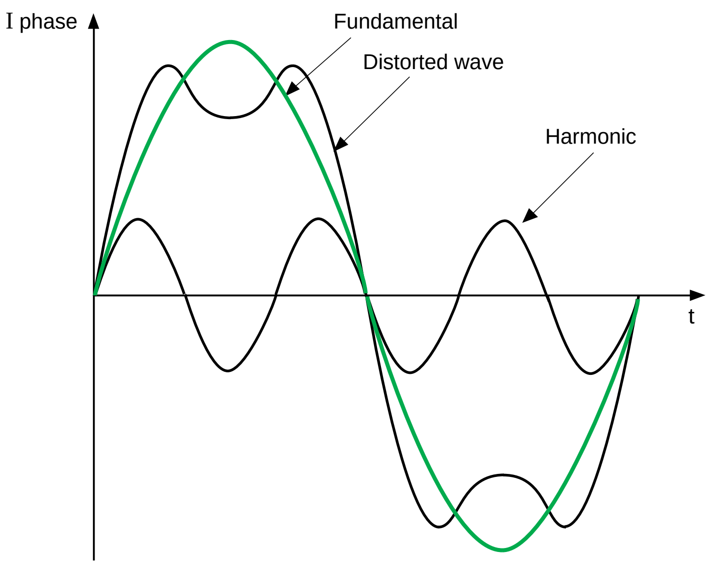


*Fig.1 : shape of a distorted wave.*

### Expression of the distorted wave

Any periodic phenomenon can be represented by a Fourier series as follows:

$$y(t) = Y_0 + \sum_{n=1}^{n=\infty} Y_n \sqrt{2} \sin(n\omega t - \varphi_n)$$

where:

- $Y_0$ = the amplitude of the DC component, which is generally zero in electrical power distribution (at steady state),
- $Y_n$ = the rms value of the $n^{th}$ harmonic component,
- $\varphi_n$ = phase angle of the $n^{th}$ harmonic component when t = 0.

Harmonic order amplitudes generally decrease as frequency increases. According to standards, harmonic orders above 40 are neglected.

### Rms value of a distorted wave

Harmonic quantities are generally expressed in terms of their rms value since the heating effect depends on this value of the distorted waveform. For a sinusoidal quantity, the rms value is the maximum value divided by the square root of 2. For a distorted quantity, under steady-state conditions, the energy dissipated by the Joule effect is the sum of the energies dissipated by each of the harmonic components:

$$RI^2t = RI_1^2t + RI_2^2t + \ldots + RI_n^2t$$

hence : $I^2 = I_1^2 + \ldots + I_n^2$

i.e. where : $I = \sqrt{\sum_{n=1}^{n=\infty} I_n^2}$ if the resistance can be considered to be constant.

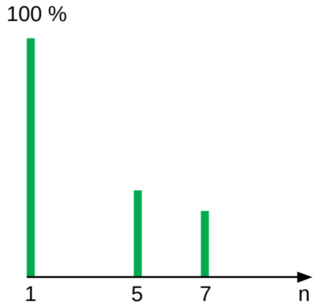


*Fig. 2 : the amplitude of a harmonic is often expressed with respect to that of the fundamental.*

The rms value of a distorted waveform can be measured either directly by instruments designed to measure the true rms value, by thermal means or by spectrum analysers.

### Individual harmonic ratio and total harmonic distortion

The industrial harmonic ratios and the total harmonic distortion quantify the harmonic disturbances present in a power supply network.

- Individual harmonic ratio (or harmonic percentage)

The harmonic ratio expresses the magnitude of each harmonic with respect to the fundamental (see fig. 2).

The $n^{th}$ harmonic ratio is the ratio of the rms value of the $n^{th}$ harmonic to that of the fundamental.

For example, the harmonic ratio of $I_n$ is $I_n/I_1$ or $100(I_n/I_1)$ if expressed as a percentage (note that here $I_n$ is not the nominal or rated current).

- Total harmonic distorsion (also referred to as THD, the total hamronic factor or simply as distorsion D)

The total harmonic distortion quantifies the thermal effect of all the harmonics. It is the ratio of the rms value of all the harmonics to that of one of the two following quantities (depending on the definition adopted):

- the fundamental (IEC 61000-2-2), which can give a very high value:

$$D = \frac{\sqrt{\sum_{n=2}^{n=\infty} Y_n^2}}{Y_1}$$

- or (occasionally) the measured disturbance quantity, in which case 0 < D < 1:

$$D = \frac{\sqrt{\sum_{n=2}^{n=\infty} Y_n^2}}{\sqrt{\sum_{n=1}^{n=\infty} Y_n^2}}$$

Unless otherwise indicated, we will use the definition adopted by IEC 61000-2-2, which corresponds to the ratio of the rms value of the harmonic content to the undistorted current at power frequency.

# 2 Principal disturbances caused by harmonic currents and voltages

Harmonic currents and voltages superimposed on the fundamental have combined effects on equipment and devices connected to the power supply network.

The detrimental effects of these harmonics depend on the type of load encountered, and include:
- instantaneous effects,
- long-term effects due to heating.

## 2.1 Instantaneous effects

Harmonic voltages can disturb controllers used in electronic systems. They can, for example, affect thyristor switching conditions by displacing the zero-crossing of the voltage wave (see IEC 146-2 and Schneider Electric "Cahier Technique" n° 141).

Harmonics can cause additional errors in induction-disk electricity meters. For example, the error of a class 2 meter will be increased by 0.3% by a 5th harmonic ratio of 5% in current and voltage.

Ripple control receivers, such as the relays used by electrical utilities for centralised remote control, can be disturbed by voltage harmonics with frequencies in the neighbourhood of the control frequency. Other sources of disturbances affecting these relays, related to the harmonic impedance of the network, will be discussed further on.

**Vibrations and noise**

The electrodynamic forces produced by the instantaneous currents associated with harmonic currents cause vibrations and acoustical noise, especially in electromagnetic devices (transformers, reactors, etc.).
Pulsating mechanical torque, due to harmonic rotating fields, can produce vibrations in rotating machines.

**Interference on communication and control circuits (telephone, control and monitoring)**

Disturbances are observed when communication or control circuits are run along side power distribution circuits carrying distorted currents.
Parameters that must be taken into account include the length of parallel running, the distance between the two circuits and the harmonic frequencies (coupling increases with frequency).

## 2.2 Long-term effects

Over and above mechanical fatigue due to vibrations, the main long-term effect of harmonics is heating.

**Capacitor heating**

The losses causing heating are due to two phenomena: conduction and dielectric hysteresis.
As a first approximation, they are proportional to the square of the rms current.

Capacitors are therefore sensitive to overloads, whether due to an excessively high fundamental or to the presence of voltage harmonics.

These losses are defined by the loss angle $\delta$ of the capacitor, which is the angle whose tangent is the ratio of the losses to the reactive power produced (see **fig. 3** ). Values of around $10^{-4}$ may be cited for $\tan\delta$. The heat produced can lead to dielectric breakdown.

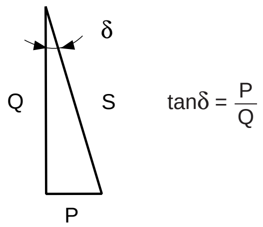


*Fig. 3 : triangle relating to the capacitor powers (active (P), reactive (Q), apparent (R)).*

**Heating due to additional losses in machines and transformers**

- additional losses in the stators (copper and iron) and principally in the rotors (damping windings, magnetic circuits) of machines caused by the considerable differences in speed between the harmonic inducing rotating fields and the rotor. Note that rotor measurements (temperature, induced currents) are difficult if not impossible,
- supplementary losses in transformers due to the skin effect (increase in the resistance of copper with frequency), hysteresis and eddy currents (in the magnetic circuit).

**Heating of cables and equipment**

Losses are increased in cables carrying harmonic currents, resulting in temperature rise. The causes of the additional losses include:

- an increase in the rms value of the current for an equal active power consumed;
- an increase in the apparent resistance of the core with frequency, due to the skin effect;
- an increase in dielectric losses in the insulation with frequency, if the cable is subjected to non-negligible voltage distortion;
- phenomena related to the proximity of conductors with respect to metal cladding and shielding earthed at both ends of the cable, etc.

Calculations for steady state can be carried out as described in IEC 60287.

Generally speaking, all electrical equipment (electrical switchboards) subjected to voltage harmonics or through which harmonic currents flow, exhibit increased energy losses and should be derated if necessary.

For example, a capacitor feeder cubicle should be designed for a current equal to 1.3 times the reactive compensation current. This safety factor does not however take into account the increased heating due to the skin effect in the conductors.
Harmonic distortion of currents and voltages is measured using spectrum analysers, providing the amplitude of each component.
It is important to use current or voltage sensors having a sufficient band width for the measured frequencies.

The rms value of the distorted current (or voltage) may be assessed in any of three ways:

- measurement using a device designed to give the true rms value,
- reconstitution on the basis of the spectrum provided by spectral analysis,
- estimation from an oscilloscope display.

# 3 Acceptable limits, recommendations and standards

## 3.1 General limits

- synchronous machines: permissible stator current distortion = 1.3 to 1.4%;
- asynchronous machines: permissible stator current distortion = 1.5 to 3.5%;
- cables: permissible core-shielding voltage distortion = 10%;
- power capacitors: current distortion = 83%, corresponding to an overload of 30% (1.3 times the rated current); overvoltages can reach up to 10%;
- sensitive electronics: 5% voltage distortion with a maximum individual harmonic percentage of 3% depending on the equipment.

## 3.2 Standardised limits

The series of standards (IEC 61000) for electromagnetic compatibility define certain limits concerning harmonics, mainly:

- IEC 61000-3-2 which define the limits of harmonic emissions for equipment consuming less than 16 A per phase (except for certain category of equipment indicated in the standards).
The case of equipment consuming over 16 A per phase is examined in the technical spec. IEC/TS 61000-3-4 and should finally be determined by the projected standards IEC 61000-3-12.
- IEC 61000-2-2 which defines compatibility levels for harmonic voltages in public LV power supply systems (see **fig.4** ).
- IEC 61000-2-4 which defines compatibility levels in industrial networks.

We would remind that compatibility level does not define an absolute limit. There remains some probability to be slightly beyond the fixed level.

Another standard, EN 50160, gives the characteristics of voltage supplied by a utility network.

In France, EDF proposes a contract for large consumers called "Emeraude" which consists in a reciprocal commitment: a quality commitment by EDF against limitation of pollution due to the consumer.

| **Odd harmonics non multiples of 3** | | **Odd harmonics multiples of 3** | | **Even harmonics** | |
|---|---|---|---|---|---|
| Harmonic order n | Harmonic voltage % | Harmonic order n | Harmonic voltage % | Harmonic order n | Harmonic voltage % |
| 5 | 6 | 3 | 5 | 2 | 2 |
| 7 | 5 | 9 | 1.5 | 4 | 1 |
| 11 | 3.5 | 15 | 0.3 | 6 | 0.5 |
| 13 | 3 | 21 | 0.2 | 8 | 0.5 |
| 17 | 2 | >21 | 0.2 | 10 | 0.5 |
| 19 | 1.5 | | | 12 | 0.2 |
| 23 | 1.5 | | | >12 | 0.2 |
| 25 | 1.5 | | | | |
| >25 | 0.2+0.5x25/n | | | | |

***Fig. 4*** *: compatibility level for individual harmonic voltages in low voltage distribution networks (IEC 61000-2-2).*

# 4 Harmonics generators

In industrial applications, the main types of equipment that generate harmonics are:

- static converters,
- arc furnaces,
- lighting,
- saturated reactors,
- other equipment, such as rotating machines which generate slot harmonics (often negligible).

## 4.1 Static converters on 3-phase networks

Rectifier bridges and, more generally, static converters (made up of diodes and thyristors) generate harmonics.

For instance, to deliver a perfect DC current, a Graetz bridge requires a rectangular pulsed AC current when the load is highly inductive (see **fig. 5** ), or tips when the bridge is followed by a capacitor (see **fig. 6** ).

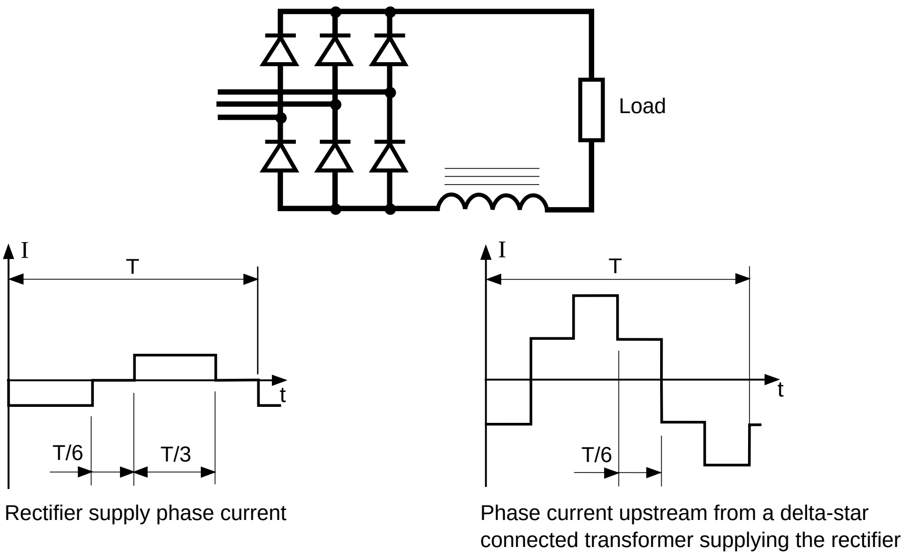


***Fig. 5** : alternating current upstream of a Graetz bridge rectifier delivering a perfect direct current on a highly inductive load.*

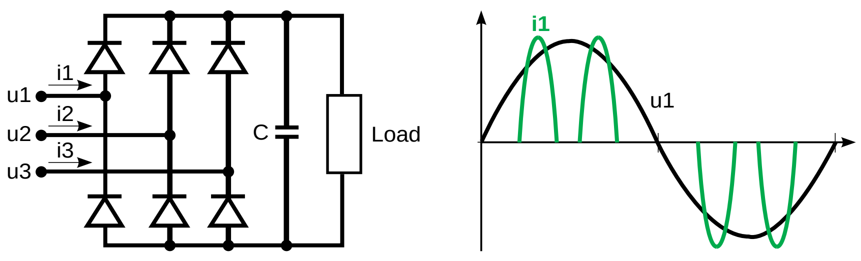


***Fig. 6** : alternating current upstream of a Graetz bridge rectifier followed by a capacitor.*

In spite of their different waveforms, the currents upstream and downstream from the delta-star connected transformer have the same characteristic harmonic components.
The characteristic harmonic components of the current pulses supplying rectifiers have harmonic orders n, such as n = kp ± 1, where:

- k = 1, 2, 3, 4, 5...
- p = number of rectifier arms, for example:
  - Graetz bridge p = 6,
  - 6-pulse bridge p = 6,
  - 12-pulse bridge p = 12.

Applying the formula, the p = 6 rectifiers cited above generate harmonics 5, 7, 11, 13, 17, 19, 23, 25, etc., and the p = 12 rectifiers generate harmonics 11, 13, 23, 25, etc.

The characteristic harmonics are all odd-numbered and their currents, when nearing the ideal case of figure 5, respect approximately the amplitude relation $I_n = I_1 / n$ where $I_1$ is the amplitude of the fundamental.

This means that $I_5$ and $I_7$ will have the greatest amplitudes. Note that they can be eliminated by using a 12-pulse bridge (p = 12).

In practice, the current spectrum is slightly different. New even and odd harmonics, referred to as non-characteristic harmonics, of low amplitudes, are created and the amplitudes of the characteristic harmonics are modified by several factors including:

- asymmetry,
- inaccuracy in thyristor firing times,
- switching times,
- imperfect filtering.

For thyristor bridges, a displacement of the harmonics as a function of the thyristor phase angle may also be observed.
Mixed thyristor-diode bridges generate even harmonics. They are used only at low ratings because the 2nd harmonic produces serious disturbances and is very difficult to eliminate.
Other power converters such as cyclo-converters, dimmers, etc. have richer and more variable spectra than rectifiers.

Note that they are sometimes replaced by rectifiers using the PWM (Pulse Width Modulation) technique. These devices operate at high chopping frequencies (around 20 kHz) and are generally designed to generate only low levels of harmonics.

The harmonic currents of several converters combine vectorially at the common supply busbars. Their phases are generally unknown except for the case of diode rectifiers. It is therefore possible to attenuate the $5^{th}$ and $7^{th}$ current harmonics using two equally loaded 6-pulse diode bridges, if the couplings of the two power supply transformers are carefully chosen (see **fig. 7** ).

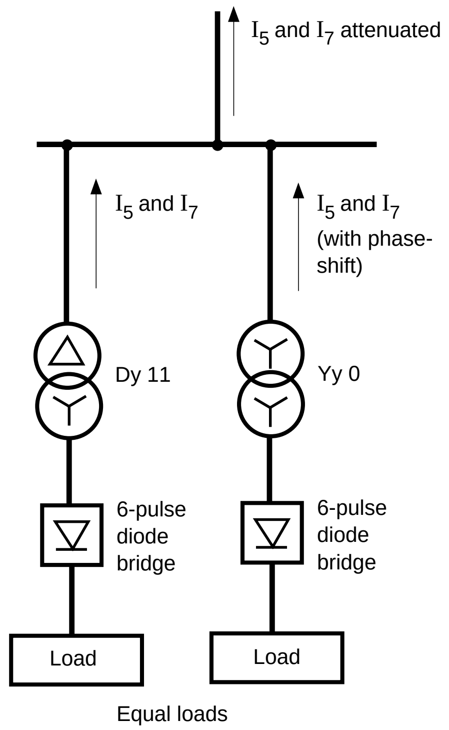


***Fig. 7** : attenuation circuit for $I_5$ and $I_7$.*

## 4.2 Lighting

Lighting systems made up of discharge lamps or fluorescent lamps are generators of harmonic currents.
A $3^{rd}$ harmonic ratio may even exceed 100% in certain cases of modern fluocompact lamps.

The neutral conductor then carries the sum of the $3^{rd}$ harmonic currents of the three phases, and may consequently be subjected to dangerous overheating if not adequately sized.

## 4.3 Arc furnaces

Arc furnaces used in the steel industry may be of the AC or DC type.

**AC arc furnaces** (cf. fig. 8 )

The arc is non-linear, asymmetric and unstable. It generates a spectrum including odd and even harmonics as was well as a continuous spectrum (background noise at all frequencies).
The spectrum depends on the type of furnace, its power rating and the operation considered (e.g. melting, refining). Measurements are therefore required to determine the exact spectrum (see fig. 9 ).

**DC arc furnaces** (cf. fig. 10 )

The arc is supplied via a rectifier and is more stable than the arc in AC furnaces.
The current drawn can be broken down into:

- a spectrum similar to that of a rectifier,
- a continuous spectrum lower than that of an AC arc furnace.

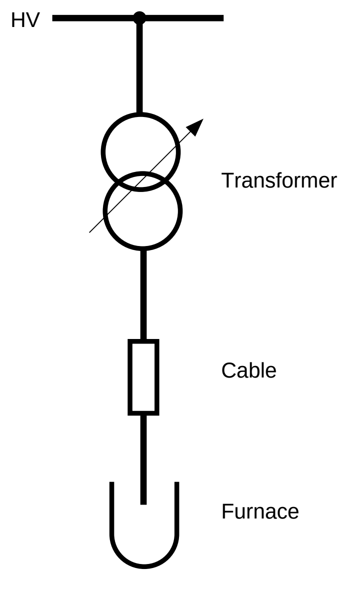


*Fig. 8 : arc furnace supplied by AC power.*

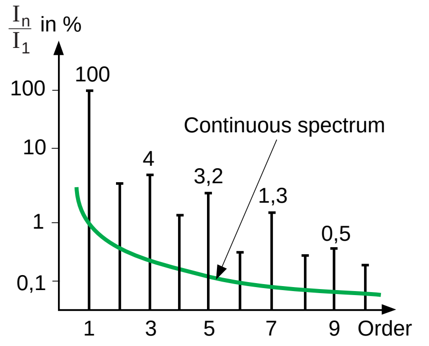


*Fig. 9 : current spectrum for an arc furnace supplied by AC power.*

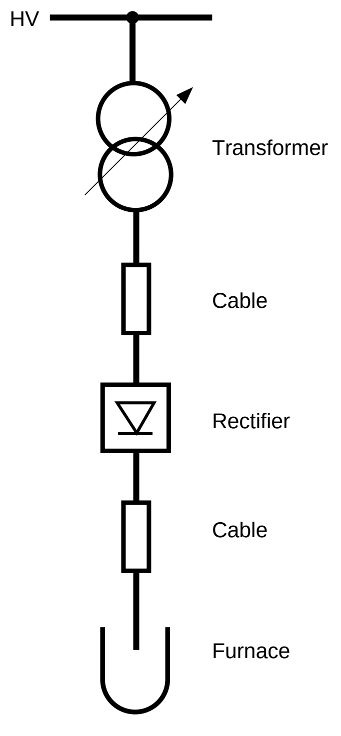


*Fig. 10 : arc furnace supplied by DC power.*

## 4.4 Saturated reactors

The impedance of a saturable reactor is varying with the current flowing through it, resulting in considerable current distortion.

This is, for instance, the case for transformers at no load, subjected to a continuous overvoltage.

## 4.5 Rotating machines

Rotating machines generate high order slot harmonics, often of negligible amplitude. However small synchronous machines generate 3rd order voltage harmonics than can have the following detrimental effects:

- continuous heating (without faults) of earthing resistors of generator neutrals;
- malfunctioning of current relays designed to protect against insulation faults.

## 4.6 Calculation model

When calculating disturbances, static converters and arc furnaces are considered to be harmonic current generators (see **fig. 11** ).

To a large extent, the harmonic currents drawn by the disturbing equipment are independent of the other loads and the overall network impedance. These currents can therefore be considered to be injected into the network by the disturbing equipment. It is simply necessary to arbitrarily change the sign so that, for calculation purposes, the disturbing equipment can be considered as current sources.

The approximation is somewhat less accurate for arc furnaces. In this case, the current source model must be corrected by adding a carefully selected parallel impedance.

It is also possible to take into consideration existent voltage harmonics at the connection to upstream network using the Norton equivalent model (see **fig. 12** ).

For each order of $U_H$, the current $I_H$ is calculated taking into account Z and the downstream network impedance.

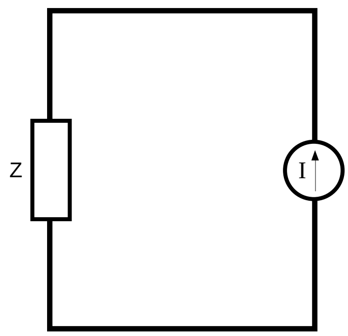


***Fig. 11** : harmonic current generators are modelled as current sources.*

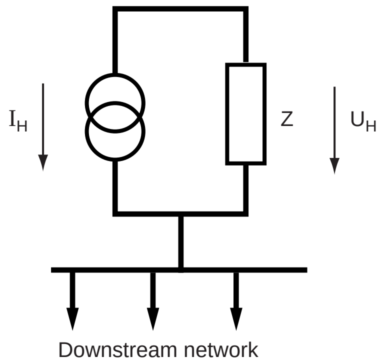


***Fig. 12** : Norton type equivalent model.*

## 4.7 Calculation method

When harmonic current arguments (phase-shifts) are known, vector processing may be used. For a number of single phase disturbing sources, it could be of interest to use unbalanced modelling.

When the harmonic currents produced by disturbing sources are known only for their amplitudes, the technical report IEC 61000-3-6 suggests a method of adding the effects of such sources.

# 5 Networks comprising disturbing equipment, the problem of amplification by resonance

We will consider the two following cases:

- networks without power capacitors;
- networks with power capacitors.

## 5.1 In the absence of capacitor banks, harmonic disturbances are limited and proportional to the currents of the disturbing equipment

In principle, in the range of frequencies concerned by harmonics, the network remains inductive.

Its reactance is proportional to the frequency and, as a first estimate, the effects of loads and resistance are negligible. The impedance of the network, seen from a network node, is therefore limited to the short-circuit reactance Xsc at the node considered.

The level of harmonic voltages can be estimated from the power of the disturbing equipment and the short-circuit power at the node (busbars) to which the disturbing equipment is connected, the short-circuit reactance considered to be proportional to the frequency (see **fig. 13** ).

In figure 13:

Lsc = the short-circuit inductance of the network, seen from the busbars to which the disturbing equipment is connected, $I_n$ = currents of the disturbing equipment,

therefore:

$Xsc_n = Lcc\ \omega_n = Lsc\ n(2\pi\ f_1)$

therefore $V_n = Xsc_n\ I_n = Lsc\ n(2\pi\ f_1)\ I_n$

The harmonic disturbances generally remain acceptable as long as the disturbing equipment does not exceed a certain power level. However, this must be considered with caution as resonance (see the next section) may be present, caused by a nearby network possessing capacitors and coupled via a transformer.

**Note** : In reality, the harmonic inductance of network X, without capacitors (essentially a distribution network), represented by Lsc, can only be considered to be proportional to the frequency in a rough approximation.

For this reason, the network short-circuit impedance is generally multiplied by a factor of 2 or 3 for the calculations, especially when there is a major doubt on network characteristics.

Therefore: $X_n = k\ n\ X_1$ with k = 2 or 3.

The harmonic impedance of a network is made up of different constituents such as the short circuit impedance of the distribution system as well as the impedance of the cables, lines, transformers, distant capacitors, machines and other loads (lighting, heating, etc.).

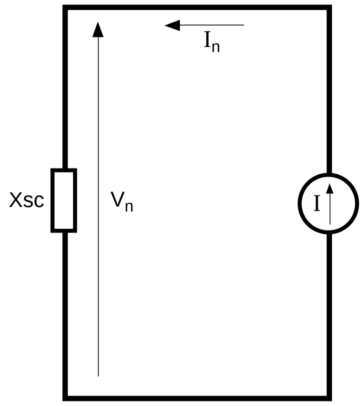


***Fig. 13** : the harmonic voltage $V_n$ is proportional to the current $I_n$ injected by the disturbing equipment.*

## 5.2 In the presence of a capacitor bank, harmonic disturbances may reach dangerous levels

At certain frequencies, resonance exists between the capacitor bank and the reactance of the network seen from the bank terminals.
The result is the amplification, with a varying degree of damping, of the harmonic currents and voltages if the order of the resonance is the same as that of one of the harmonic currents injected by the disturbing equipment. This amplified disturbance can be dangerous to the equipment. **This is a serious problem** and will be dealt with hereafter.
This phenomenon is referred to as parallel resonance.

**What is this parallel resonance and how can it cause dangerous harmonic disturbances?**

In so far as harmonic frequencies are concerned, and for a first approximation, the network may be represented as in **figure 14** .
In this diagram:

- Lsc = the short-circuit inductance of the upstream network seen from the busbars to which the capacitor bank and the disturbing equipment are connected,
- C = capacitors,
- $I_n$ = current of the disturbing equipment,
- Load = linear loads (JOULE effect, transmission of mechanical energy).

In principle, we consider the short-circuit harmonic reactance seen from the busbars, i.e. the node (A) to which the capacitors, the loads and the disturbing equipment are connected, giving $V_n = Z_{AO} I_n$.

The impedance versus frequency curves (see **fig.15** ) show that:

- for the resonance frequency $f_{ar}$, the inductive effect is compensated for exactly by the capacitive effect;
- the reactance of the rejector circuit:
  - ◻ is inductive for low frequencies, including the fundamental frequency,
  - ◻ increases with frequency, becoming very high and suddenly capacitive at the resonance frequency $f_{ar}$;
- the maximum impedance value reached is roughly $R = U^2/P$ where P represents the sum of the active power values of the loaded motors, other than those supplied by a static converter.

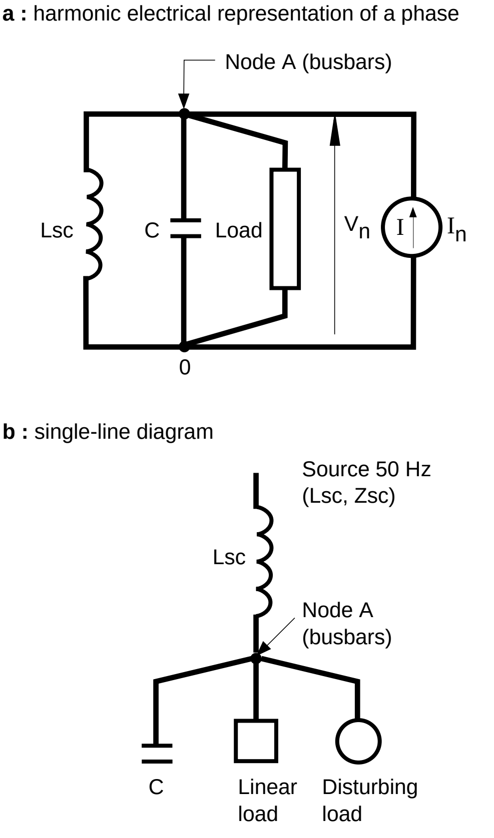


*Fig. 14 : equivalent diagrams for a circuit subject to harmonic currents and including a capacitor bank.*

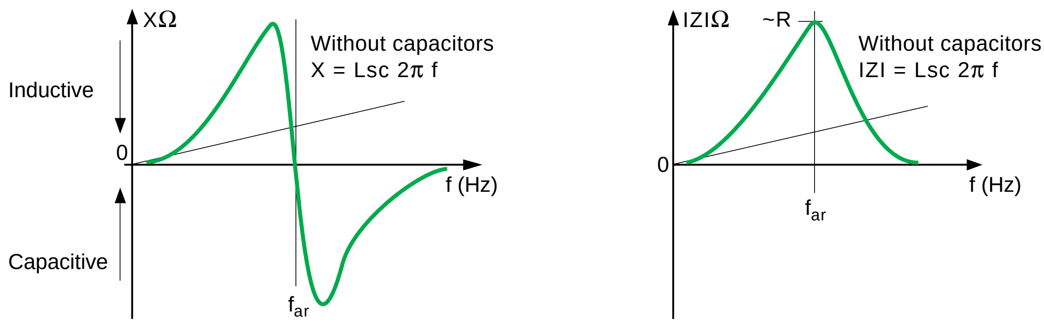


*Fig. 15 : curves showing the impedance due to the loads and due to the resistance of the conductors.*

If a harmonic current $I_n$ of order n, with the same frequency as the parallel resonance frequency $f_{ar}$, is injected by the disturbing equipment, the corresponding harmonic voltage can be estimated as $V_n = R\ I_n$ with $n = n_{ar} = f_{ar}/f_1$.

### Estimation of $n_{ar}$

The order $n_{ar}$ of parallel resonance is the ratio of the resonance frequency $f_{ar}$ to the fundamental frequency $f_1$ (power frequency).

Consider the most elementary industrial network, shown in the equivalent diagram in **figure 16** , including a capacitor bank C supplied by a transformer with a short-circuit inductance $L_T$, where Lsc represents the short-circuit inductance of the distribution network seen from the upstream terminals of the transformer,

$$f_{ar} = \frac{1}{2\pi \sqrt{(Lsc + L_T)\ C}}.$$

As $Lsc << L_T$, the order of the parallel resonance is roughly the same whether the network impedance is seen from point A or point B (e.g. the supply terminals).

In general, given the short-circuit power at the capacitor bank terminals,

$$n_{ar} = \sqrt{\frac{Ssc}{Q}} \quad \text{where:}$$

Ssc = short-circuit power at the capacitor bank terminals,

Q = capacitor bank power at the applied voltage.

Generally S is expressed in MVA and Q in Mvar.

Practical consequences:

- If the order of a harmonic current injected by disturbing equipment corresponds or is quite near the parallel resonance order, there is a risk of harmonic overvoltages, especially when the network is operating at low loads.

The harmonic currents then become intensively high in network constituents and undoubtedly present a danger to the capacitors.

- If the parallel resonance order corresponds to the frequency of the carrier-current control equipment of the power distribution utility, there is a risk of disturbing this equipment.

**To prevent resonance from becoming dangerous, it must be forced outside the injected spectrum and/or damped.**

The short-circuit impedance of the network is seldom accurately known and, in addition, it can vary to a large extent, thereby resulting in large variations of the parallel resonance frequency.

It is therefore necessary to stabilise this frequency at a value that does not correspond to the frequencies of the injected harmonic currents. This is achieved by connecting a reactor in series with the capacitor bank.

The circuit thus created is then represented by the diagram in **figure 17** where $V_n = Z_{AO}\ I_n$.

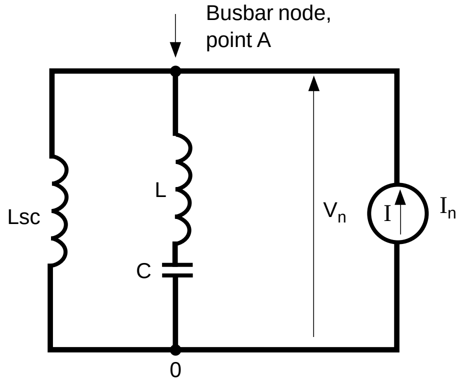


*Fig. 17 : reactor, connected in series with the capacitor.*

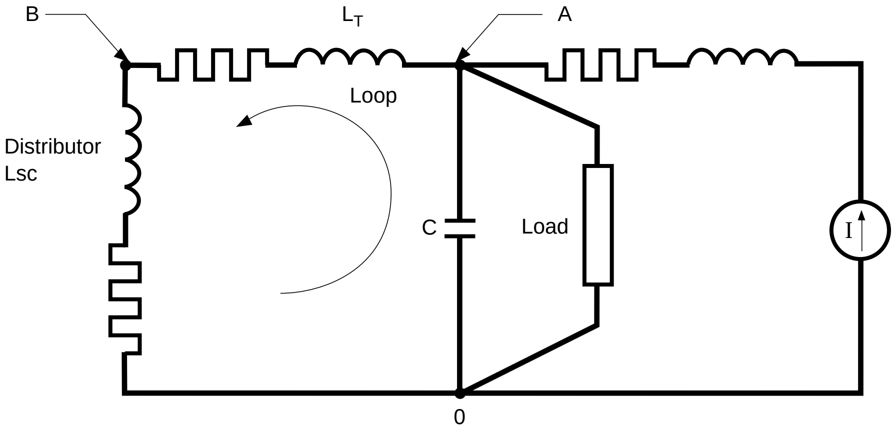


*Fig. 16 : the capacitor, together with the sum of the upstream impedances, forms a resonant circuit.*

A series resonance, between L and C, appears. As opposed to this resonance, which gives a minimum impedance, the parallel resonance is often referred to an anti-resonance.

The equation giving the frequency of the anti-resonance is: $f_{ar} = \dfrac{1}{2\pi\sqrt{(Lsc + L)\,C}}$

Lsc generally being small compared to L, the equation shows that the presence of reactor L, connected in series with the capacitors, renders the frequency $f_{ar}$ less sensitive to the variations of the short-circuit inductance Lsc (from the connection points = busbars A).

### Series resonance

The branch made up of reactor L and capacitor C (see **fig. 18** ), form a series resonance system of impedance: Z = r + j (Lω - 1/Cω) with:

- a minimum resistive value r (resistance of the inductance coil) for the resonance frequency $f_r$,
- a capacitive reactance below the resonance frequency $f_r$ ,
- an inductive reactance above the resonance frequency $f_r$, where

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

The curves in **figure 19** show the shape of the network impedance, including the short-circuit impedance and that of the LC branch, seen from busbars A.

The choice of $f_{ar}$ depends on Lsc, L and C, while that of $f_r$ depends only on L and C; $f_{ar}$ and $f_r$ therefore become closer as Lsc becomes small with respect to L. The level of reactive power compensation, and the voltage applied to the capacitors, depend partly on L and C.

The reactor L can be added in two different manners, depending on the position of the series resonance with respect to the spectrum. The two forms of equipment are:

- anti-harmonic reactors (for series resonance outside the spectrum lines);
- filters (for series resonance on a spectrum line).

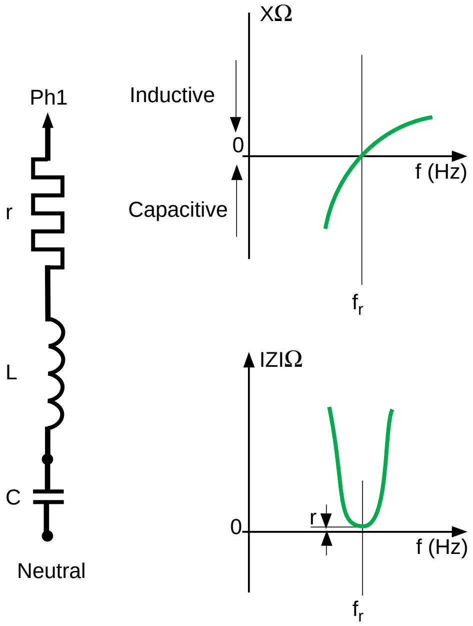


*Fig. 18 : impedance of the rejector circuit.*

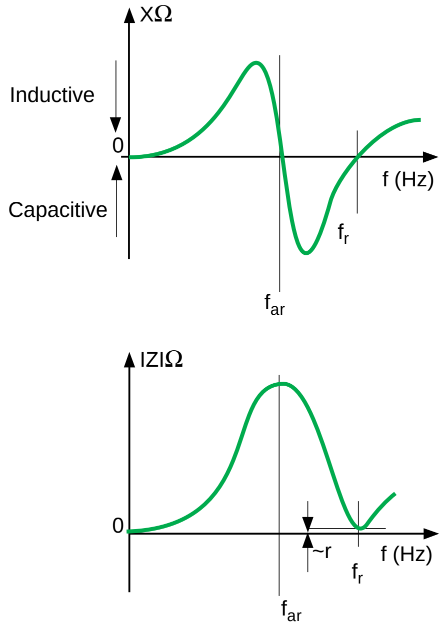


*Fig. 19 : network impedance at point A.*

# 6 Anti-harmonic reactors

An anti-harmonic reactor can be used to protect a capacitor bank against harmonic overloads. Such solutions are often referred to as detuned capacitor banks or detuned filters.

The reference diagram is once again figure 17.

In this assembly, the choice of L is such that the LC branch (where L is the reactor and C the reactive power compensation capacitors) behaves inductively for the harmonic frequencies, over the spectrum.

As a result, the resonance frequency $f_r$ of this branch will be below the spectrum of the disturbing equipment.

The LC branch and the network (Lsc) are then both inductive over the spectrum and the harmonic currents injected by the disturbing equipment are divided in a manner inversely proportional to the impedance. Harmonic currents are therefore greatly restricted in the LC branch, protecting the capacitors, and the major part of the harmonic currents flow in the rest of the network, especially in the short-circuit impedance.

The shape of the network impedance, seen from the busbars to which the LC branch is connected, is shown in **figure 20** .

There is no anti-resonance inside the current spectrum. The use of an anti-harmonic reactor therefore offers two advantages:

- it eliminates the danger of high harmonic currents in the capacitors;
- it correlatively eliminates the high distortions of the network voltage, without however lowering them to a specified low value.

Certain precautions are necessary:

- No other capacitor banks must be present that could induce, through anti-resonance, a capacitive behaviour in the initial network inside the spectrum;
- Care must be taken not to introduce an anti-resonance with a frequency used by the distribution utility for carrier-current control, since this would place an increased load on the high frequency generators (175 Hz, 188 Hz). Anti-harmonic reactors are generally tuned for $f_r$ between 135 to 225 Hz for a 50 Hz network.
- Due to the continuous spectrum, the use of anti-harmonic reactors on arc furnaces requires certain precautions which can only be defined after carrying out special studies.

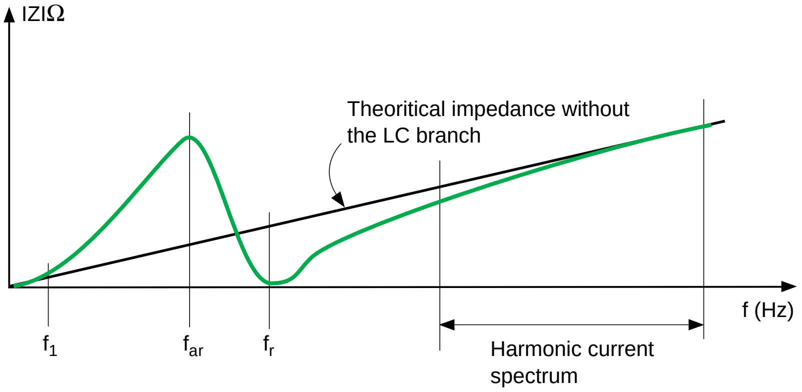


*Fig. 20 : the capacitors are protected when $f_r$ is well bellow the harmonic spectrum.*

# 7 Filters

Filters are used when it is necessary to limit harmonic voltages present on a network to a specified low value.
Three types of filters may be used to reduce harmonic voltages:

- resonant shunt filters,
- damped filters,
- active filters.

## 7.1 Resonant shunt filters

The resonant shunt filter (see fig. 18) is made up of an LC branch with a frequency of

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

tuned to the frequency of the voltage harmonic to be eliminated.

**This approach is therefore fundamentally different than that of reactor-connected capacitors already described.**

At $f_r$, the resonant shunt presents a low minimum impedance with respect to the resistance r of the reactor. It therefore absorbs nearly all the harmonic currents of frequency $f_r$ injected, with low harmonic voltage distortion (since proportional to the product of the resistance r and the current flowing in the filter) at this frequency.

In principle, a resonant shunt is installed for each harmonic to be limited. They are connected to the busbars for which harmonic voltage reduction is specified. Together they form a filter bank.

**Figure 21** shows the harmonic impedance of a network equipped with a set of four filters tuned to the $5^{th}$, $7^{th}$, $11^{th}$ and $13^{th}$ harmonics. Note that there are as many anti-resonances as there are filters. These anti-resonances must be tuned to frequencies between the spectrum lines. A careful study must therefore be carried out if it is judged necessary to segment the filter bank.

**Main characteristics of a resonant shunt**

The characteristics depend on $n_r = f_r/f_1$ the order of the filter tuning frequency, with:

- $f_r$ = tuning frequency,
- $f_1$ = fundamental frequency (generally the power frequency, e.g. 50 Hz).

These characteristics are:

- The reactive power for compensation: $Q_{var}$.

The resonant shunt, behaving as a capacitor below its tuning frequency, contributes to the compensation of reactive power at the power frequency.

The reactive power produced by the shunt at the connection busbars, for an operating voltage $U_1$, is given by the following equation:

$$Q_{var} = \frac{n_r^2}{n_{r-1}^2} U_1^2 \, C \, 2\pi f_1$$

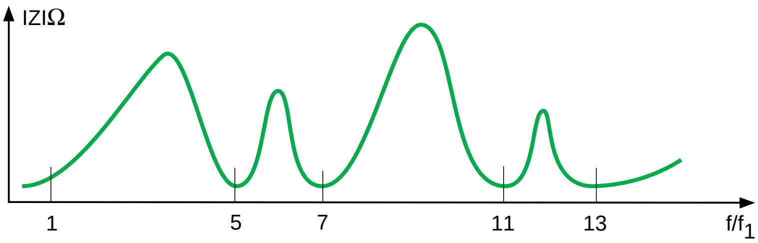


*Fig. 21 : impedance of a network equipped with shunt filters.*

(note that the subscript 1 refers to the fundamental); C is the phase-to-neutral capacitance of one of the 3 branches of the filter bank represented as a star.

At first glance, the presence of a reactor would not be expected to increase the reactive power supplied. The reason is the increase in voltage at power frequency $f_1$ caused by the inductance at the capacitor terminals.

- Characteristic impedance $X_0 = \sqrt{\frac{L}{C}}$
- The quality factor $q = X_0/r$

An effective filter must have a reactor with a large quality factor q, therefore $r << X_0$ at frequency $f_r$.

Approximate values of q:

- for air-cored reactors,
- greater than 75 for iron-core reactors.

- The pass-band (see **fig. 22** ) in relative terms:

$$BP = \frac{1}{q} = 2\frac{f - f_r}{f_r} = \frac{r}{X_0}$$

- The resistance of the reactor $r = X_0/q$

This resistance is defined at frequency $f_r$.
It depends on the skin effect. It is also the impedance when the resonant shunt is tuned.

- The losses due to the capacitive current at the fundamental frequency $p_1 = \frac{Q_{var}}{q\ n_r}$

with:

- $Q_{var}$ = reactive power for compensation produced by the filter,
- $p_1$ = filter losses at power frequency in W.

- The losses due to the harmonic currents cannot be expressed by simple equations; they are greater than: $p_n = \frac{U_{nr}^2}{r}$

in which $U_{nr}$ is the phase-to-phase harmonic voltage of order $n_r$ on the busbars after filtering.

In practice, the performance of resonant shunt filters is reduced by mis-tuning and special solutions are required as follows:

- adjustment possibilities on the reactors for correction of manufacturing tolerances;
- a suitable compromise between the q factor and filter performance to reduce the sensitivity to mis-tuning, thereby accepting fluctuations of $f_1$ (network frequency) and $f_r$ (caused by the temperature dependence of the capacitance of the capacitors).

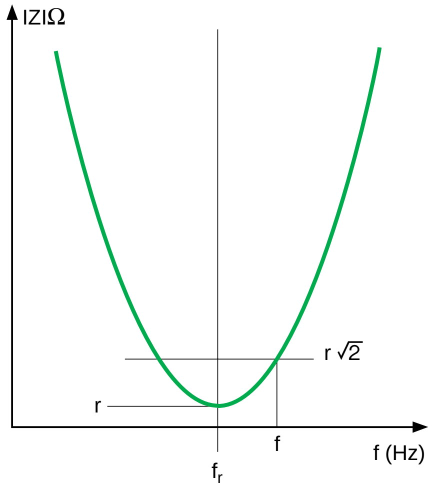


*Fig. 22 : Z versus f curve for a resonant shunt.*

## 7.2 Damped filters

**2nd order damped filter**

On arc furnaces, the resonant shunt must be damped. This is because the continuous spectrum of an arc furnace increases the probability of an injected current with a frequency equal to the anti-resonance frequency. In this case, it is no longer sufficient to reduce the characteristic harmonic voltages. The anti-resonance must also be diminished by damping. Moreover, the installation of a large number of resonant shunts is often costly, and it is therefore better to use a wide-band filter possessing the following properties:

- anti-resonance damping,
- reduced harmonic voltages for frequencies greater than or equal to its tuning frequency, leading to the name "damped high-pass filter",
- fast damping of transients produced when the filter is energised. The 2nd order damped filter is made up of a resonant shunt with a damping resistor R added at the reactor terminals.

**Figure 23** shows one of the three phases of the filter.
The 2nd order damped filter has zero reactance for a frequency $f_r$ higher than the frequency f where:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad \text{and} \quad f_r = \frac{1 + Qq}{2\pi q\sqrt{(Q^2 - 1)LC}}.$$

where:

Q = the quality factor of the damped filter,
q = the quality factor of the reactor.

The filter is designed so that $f_r$ coincides with the first characteristic line of the spectrum to be filtered. This line is generally the largest.
When Q (or R) take on high values, $f_r$ tends towards f, which means that the resonant shunt is a limiting case of the 2nd order damped filter.

It is important not to confuse Q, the quality factor, with $Q_{var}$, the reactive power of the filter for compensation.

The 2nd order damped filter operates as follows:

- Below $f_r$

The damping resistor contributes to the reduction of the network impedance at anti-resonance, thereby reducing any harmonic voltages.

- At $f_r$

The reduction of the harmonic voltage to a specified value is possible since, at this frequency, no resonance can occur between the network and the filter, the latter presenting an impedance of a purely resistive character.

However, this impedance being higher than the resistance r of the reactor, the filtering performance is less than for a resonant shunt.

- Above $f_r$

The filter presents an inductive reactance of the same type as the network (inductive), which lets it absorb, to a certain extent, the spectrum lines greater than $f_r$, and in particular any continuous spectrum that may be present. However, anti-resonance, if present in the impedance of the network without the filter, due to the existing capacitor banks, reduces the filtering performance. For this reason, existing capacitor banks must be taken into account in the design of the network and, in some cases, must be adapted.

The main electrical characteristics of a 2nd order damped filter depend on $n_r = f_r / f_1$, the order of the filter tuning frequency, with:

- $f_r$ = tuning frequency,
- $f_1$ = fundamental frequency (generally the power frequency, e.g. 50 Hz).

These characteristics are:

- The reactive power for compensation

For a 2nd order damped filter at operating voltage $U_1$ (the subscript 1 referring to the fundamental), the reactive power is roughly the same as for a resonant shunt with the same inductance and capacitance, i.e. in practice:

$$Q_{var} = \frac{n_r^2}{n_r^2 - 1} U_1^2 C 2\pi f_1$$

C is the phase-to-neutral capacitance of one of the 3 branches of the filter bank represented as a star.

- Characteristic impedance $X_0 = \sqrt{\frac{L}{C}}$

- The quality factor of the reactor $q = X_0/r$ where r is the resistance of the reactor, dependent on the skin effect and defined at frequency $f_r$.

- The quality factor of the filter $Q = R/X_0$ The quality factors Q used are generally between 2 and 10.

- The losses due to the fundamental compensation current and to the harmonic currents; these are higher than for a resonant shunt and can only be determined through network analysis.

The damped filter is used alone or in a bank including two filters. It may also be used together with a resonant shunt, with the resonant shunt tuned to the lowest lines of the spectrum.

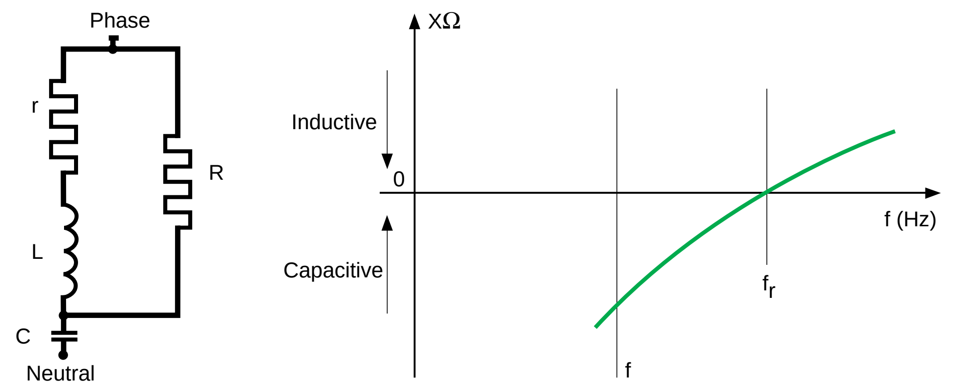


*Fig. 23 : 2nd order damped filter.*

**Figure 24** compares the impedance of a network with a 2nd order damped filter to that of a network with a resonant shunt.

### Other types of damped filters

Although more rarely used, other damped filters have been derived from the 2nd order filter.

- 3rd order damped filter (see **fig. 25a** )

Of a more complex design than the 2nd order filter, the 3rd order filter is intended particularly for high compensation powers.
The 3rd order filter is derived from a 2nd order filter by adding another capacitor bank C2 in series with the resistor R, thereby reducing the losses due to the fundamental.
C2 can be chosen to improve the behaviour of the filter below the tuning frequency as well, which favours the reduction of anti-resonance.
The 3rd order filter should be tuned to the lowest frequencies of the spectrum.
Given the complexity of the 3rd order filter, and the resulting high cost, a 2nd order filter is often preferred for industrial applications.

- Type C damped filter (see **fig. 25b** )

In this filter, the additional capacitor bank C2 is connected in series with the reactor. This filter offers characteristics roughly the same as those of the 3rd order filter.

- Damped double filter (see **fig. 25c** )

Made up of two resonant shunts connected by a resistor R, this filter is specially suited to the damping of the anti-resonance between the two tuning frequencies.

- Low q resonant shunt

This filter, which behaves like a damped wide-band filter, is designed especially for very small installations not requiring reactive power compensation. The reactor, with a very high resistance (often due to the addition of a series resistor) results in losses which are prohibitive for industrial applications.

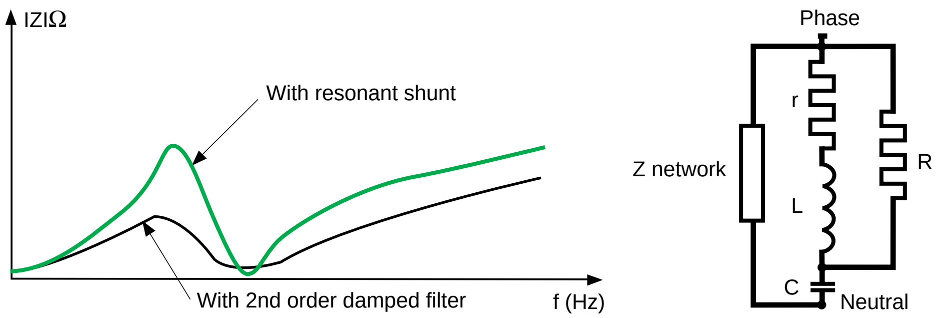


*Fig. 24 : the impedance, seen from point A, of a network equipped with either a 2nd order damped filter or a resonant shunt.*

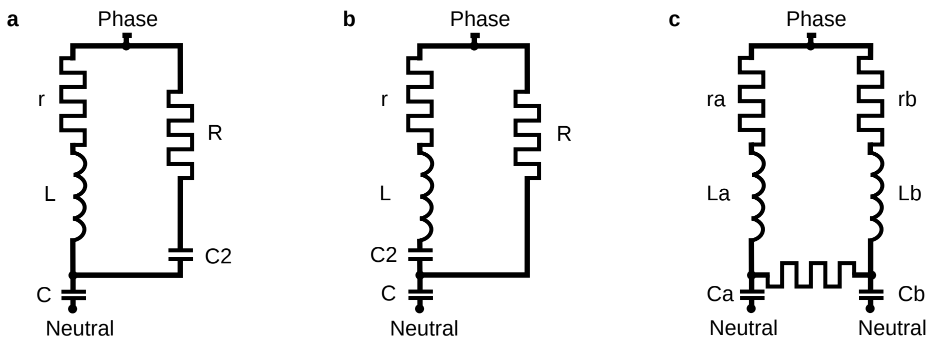


*Fig. 25 : other types of damped filters: **[a]** - 3rd order; **[b]** - C type; **[c]** - double filter.*

## 7.3 Active filters

An active filter enables neutralizing the effect of a disturbance by the injection of an equal signal but of opposite sign. Active filters are often used in complement with passive filters described in this chapter, thus forming hybrid filtering.
Such filters are described in Cahier Technique no. 183 entitled "Active harmonic conditioners and unity power factor rectifiers".

# 8 Example of the analysis of a simplified network

The diagram in **figure 26** represents a simplified network comprising a 2,000 kVA six-pulse rectifier, injecting a harmonic current spectrum, and the following equipment which will be considered consecutively in three different calculations:

- a single 1,000 kvar capacitor bank;
- anti-harmonic reactor-connected capacitor equipment rated 1,000 kvar;
- a set of two filters comprising a resonant shunt tuned to the $5^{th}$ harmonic and a $2^{nd}$ order damped filter tuned to the $7^{th}$ harmonic.

Note that:

- the 1,000 kvar compensation power is required to bring the power factor to a conventional value;
- the harmonic voltages already present on the 20 kV distribution network have been neglected for the sake of simplicity.

This example will be used to compare the performance of the three solutions, however the results can obviously not be applied directly to other cases.

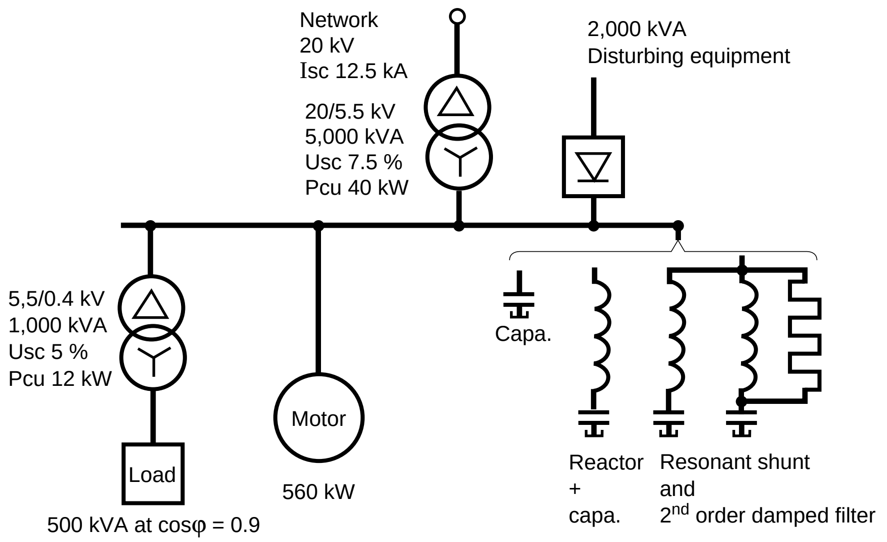


***Fig. 26** : installation with disturbing equipment, capacitors and filters.*

## 8.1 Capacitor bank alone

The network harmonic impedance curve (see **fig. 27** ), seen from the node where the harmonic currents are injected, exhibits a maximum (anti-resonance) in the vicinity of the $7^{th}$ current harmonic. This results in an unacceptable individual harmonic voltage distortion of 11% for the $7^{th}$ harmonic (see **fig. 28** ).

The following characteristics are also unacceptable:

- a total harmonic voltage distortion of 12.8% for the 5.5 kV network, compared to the maximum permissible value of 5% (without considering the requirements of special equipment);
- a total capacitor load of 1.34 times the rms current rating, exceeding the permissible maximum of 1.3 (see **fig. 29** ).

The solution with capacitors alone is therefore unacceptable.

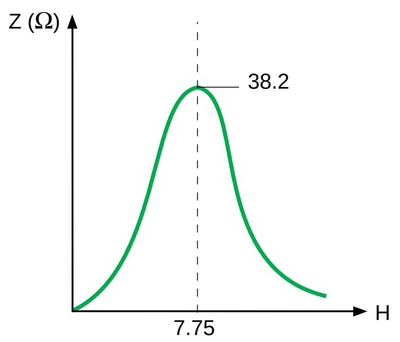


***Fig. 27** : harmonic impedance seen from the node where the harmonic currents are injected in a network equipped with a capacitor bank alone.*

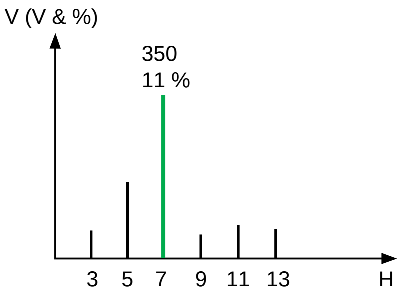


*Fig. 28* : *harmonic voltage spectrum of a 5.5 kV network equipped with a capacitor bank alone.*

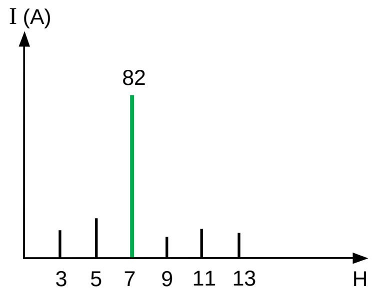


*Fig. 29* : *spectrum of the harmonic currents flowing in the capacitors for a network equipped with a capacitor bank alone.*

## 8.2 Reactor-connected capacitor bank

This equipment is arbitrarily tuned to 4.8 $f_1$.

**Harmonic impedance** (see fig. 30 )

The network harmonic impedance curve, seen from the node where the harmonic currents are injected, exhibits a maximum of 16 ohms (anti-resonance) in the vicinity of harmonic order 4.25. The low impedance, of an inductive character, of the $5^{th}$ harmonic favours the filtering of the $5^{th}$ harmonic quantities.

**Voltage distorsion** (see fig. 31 )

For the 5.5 kV network, the individual harmonic voltage ratios of 1.58% ($7^{th}$ harmonic), 1.5% ($11^{th}$ harmonic) and 1.4% ($13^{th}$ harmonic) may be too high for certain sensitive loads. However in many cases the total harmonic voltage distortion of 2.63% is acceptable.

For the 20 kV network, the total harmonic distortion is only 0.35%, an acceptable value for the distribution utility.

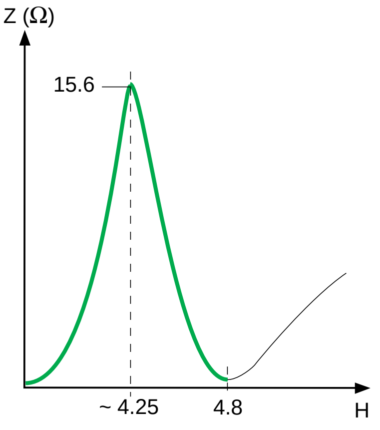


*Fig. 30* : *harmonic impedance seen from the node where the harmonic currents are injected in a network equipped with reator-connected capacitors.*

**Capacitor current load** (cf. fig. 32 )

The total rms current load of the capacitors, including the harmonic currents, is 1.06 times the current rating, i.e. less than the maximum of 1.3. This is the major advantage of rea ctor-connected capacitors compared to the first solution (capacitors alone).

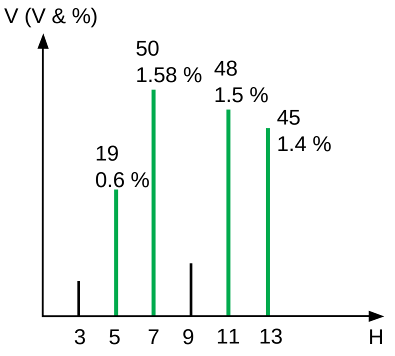


*Fig. 31* : *harmonic voltage spectrum of a 5.5 kV network equipped with reactor-connected capacitors.*

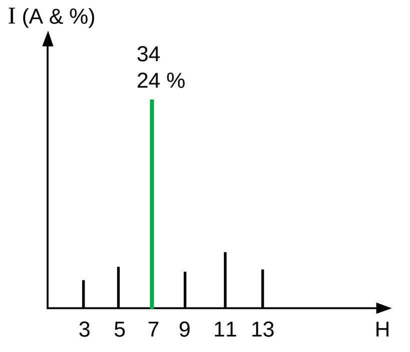


*Fig. 32* : *spectrum of the harmonic currents flowing in the capacitors for a network equipped with reactor-connected capacitors.*

## 8.3 Resonant shunt filter tuned to the 5th harmonic and a damped filter tuned to the 7th harmonic

In this example, the distribution of the reactive power between the two filters is such that the filtered 5th and 7th voltage harmonics have roughly the same value. In reality, this is not required.

**Harmonic impedance** (see **fig. 33** )

The network harmonic impedance curve, seen from the node where the harmonic currents are injected, exhibits a maximum of 9.5 ohms (anti-resonance) in the vicinity of harmonic 4.7.

For the 5th harmonic, this impedance is reduced to the reactor resistance, favouring the filtering of the 5th harmonic quantities.

For the 7th harmonic, the low, purely resistive impedance of the damped filter also reduces the individual harmonic voltage.

For harmonics higher than the tuning frequency, the damped filter impedance curve reduces the corresponding harmonic voltages.

This equipment therefore offers an improvement over the second solution (reactor-connected capacitors).

**Voltage distorsion** (see **fig. 34** )

For the 5.5 kV network, the individual harmonic voltage ratios of 0.96%, 0.91%, 1.05% and 1% for the 5th, 7th, 11th and 13th harmonics respectively are acceptable for most sensitive loads. The total harmonic voltage distortion is 1.96%.
For the 20 kV network, the total harmonic distortion is only 0.26%, an acceptable value for the distribution utility.

**Capacitor current load**

The capacitor rating must be adequately chosen considering the overvoltage at fundamental frequency, the harmonic voltages and currents.

This example demonstrates an initial approach to the problem. However in practice, over and above the calculations relative to the circuit elements (L, r, C and R), other calculations are required before proceeding with the implementation of any solution:

- the spectra of the currents flowing in the reactors connected to the capacitors;
- the total voltage distortion at the capacitor terminals;
- reactor manufacturing tolerances and means for adjustment if necessary;

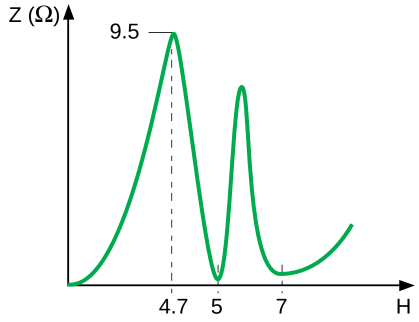


*Fig. 33 : harmonic impedance seen from the node where the harmonic currents are injected in a network equiped with a resonant shunt filter tuned to the 5th harmonic and a damped filter tuned to the 7th harmonic.*

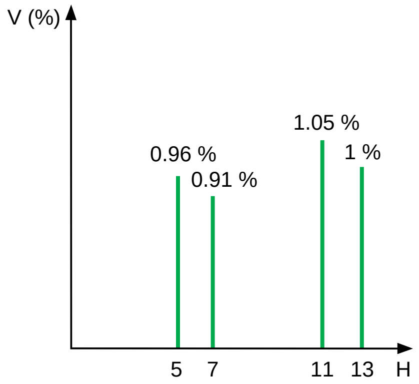


*Fig. 34 : harmonic voltage spectrum of a 5.5 kV network equipped qith a resonant shunt filter tuned to the 5th harmonic and a damped filter tuned to the 7th harmonic.*

- the spectra of the currents flowing in the resistors of the damped filters and their total rms value;
- voltage and energy transients affecting the filter elements during energisation.

These more difficult calculations, requiring a solid understanding of both the network and the equipment, are used to determine all the electro-technical information required for the filter manufacturing specifications.

# 9 Conclusion

Static power converters are increasingly used in industrial distribution. The same is true for arc furnaces in the growing electric-powered steel industry. All these loads produce harmonic disturbances and generally require compensation of the reactive power they consume, leading to the installation of capacitor banks.

If such capacitors are installed without precaution, they can cause resonance with the network reactors and amplify harmonic disturbances.

Installers and operators of industrial networks are thus often confronted with a complex electrical problem.

The main types of harmonic disturbances and the technical means available to limit their extent have been presented in this document. Without offering an exhaustive study of the phenomena involved or relating all acquired experience, this document should provide the necessary background to, if not solve the problems, at least facilitate discussions with specialists.

Schneider Electric has since 1970, a team of specialists to solve electrotechnical problems in electrical networks, at the Corporate Research and Development department, as well as a subsidiary specialized in implementing filters (Rectiphase).

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**Lampiran 2: Cahier Technique Merlin Gerin no. 183**

# n° 183

# active harmonic conditioners and unity power factor rectifiers

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**E/CT 183,** first issued January 1997

# active harmonic conditioners and unity power factor rectifiers

## contents



Electric loads are becoming increasingly non-linear in the industrial, tertiary and even household sectors. These loads absorb non-sinusoidal currents which, under the effect of circuit impedance, distort the purely sinusoidal voltage waveform. This is what is known as harmonic disturbance of power networks, currently a cause for concern as it gives rise to serious problems.

We recommend that harmonic non-specialist readers begin by reading the appendix where they will find the basic concepts required to understand the various standard and new solutions to limit or combat harmonics. Not only the characteristic quantities, but also the non linear equipment, influence of the sources and disturbing effects of harmonics need to be known. Last but not least, standards lay down levels of compatibility, i.e. the maximum permissible levels.

The purpose of this «Cahier Technique» is to describe the active harmonic conditioners. This attractive, flexible and self-adaptive solution can be used in a wide variety of cases to complete or replace other solutions. However chapter 1 of this «Cahier Technique» will review other «traditional» solutions which should also be taken into consideration.

# 1. the traditional solutions

Electricians need to be familiar with these solutions in order to take the right measures when installing polluting equipment or to take all factors into account when designing new installations.

The solutions described hereafter depend on the objective sought and on the non linear/sensitive equipment installed.
They use passive components: reactors, capacitors, transformers and/or carefully choose the installation diagram.

In most cases the aim is to reduce voltage total harmonic distortion at a load multi-connection point (in a distribution switchboard).

## reducing harmonic currents of non linear loads

Besides the obvious solution which consists of choosing non-disturbing equipment, the harmonic currents of some converters can be limited by inserting **a «smoothing» reactor** between their connection point and their input. This solution is particularly employed with rectifiers with front end capacitors: the reactor may even be proposed as an option by manufacturers.
A word of warning however! Although this solution reduces voltage total harmonic distortion upstream of the reactor, it increases it at the terminals of the non-linear load.

## lowering harmonic impedance of the source

In concrete terms this consists of connecting the disturbing equipment directly to the most powerful transformer possible, or of choosing a generator with a low harmonic impedance (see appendix and fig. 1).
Note that it is advantageous on the source side to use several parallel-connected cables of smaller cross-section rather than a single cable. If these conductors are far enough apart, apparent source impedance is divided by the number of parallel-connected cables.

## carefully choosing the installation structure

Sensitive loads should not be parallel-connected with non-linear loads (see fig. 2).

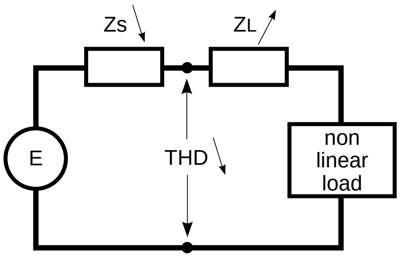



*fig. 1: addition of a downstream reactor or reduction in upstream source impedance reduces voltage THD at the point considered.*

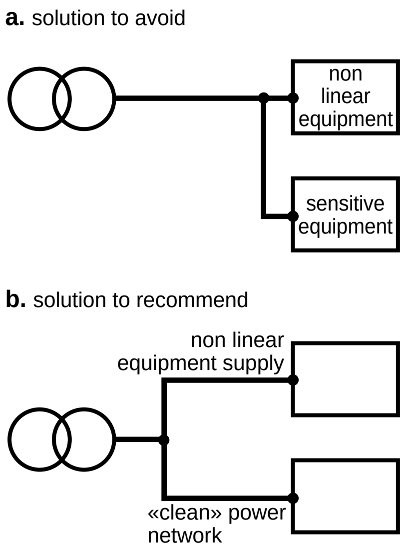



*fig. 2: a Y-shaped distribution enables decoupling by natural and/or additional impedances.*

Very powerful non-linear loads should preferably be supplied by another MV/LV transformer.

## harmonic isolation

The aim is to limit circulation of harmonic currents to as small a part as possible of the installation **using suitable coupling transformers**.

Use of Y-connected primary transformers (without neutral!) with zig-zag secondary is an interesting solution as it ensures minimum distortion at the secondary. In this case 3 k order harmonic currents do not flow at the transformer primary, and the impedance Zs depends only on the secondary windings. The inductive part of the impedance is very low:
Uccx ≈ 1%, and resistance is practically halfed compared with a ΔY transformer of identical power.

Figure 3 and the following calculation show why 3 k ω angular frequencies are not present at the transformer primary (zero sequence current is nil).

Current circulating for example in the primary winding 1 equals:

$$\frac{N_2}{N_1}(i_1 - i_3)$$

where

$$i_1 = I_{1\,(3k)} = I \sin(3k\ \omega t)$$

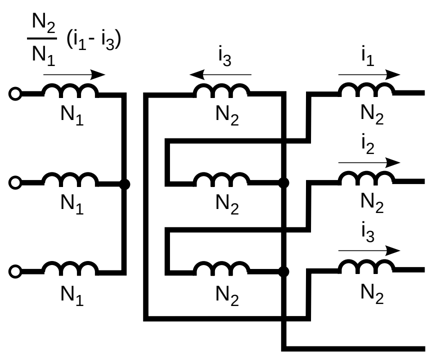



*fig. 3: zig-zag secondary transformer and attenuation of 3 k orders.*

$$i_3 = I_{3\,(3k)} = I \quad \sin 3k \left(\omega t - \frac{4\pi}{3}\right),$$

$$i_3 = I \quad \sin\left(3k \quad \omega t\right) = i_1$$

hence

$$\frac{N_2}{N_1}\,(i_1 - i_3) = 0$$

As regards three-phase loads, some harmonic orders can be removed by using transformers or autotransformers with a number of displaced secondaries, a solution particularly adopted for powerful rectifiers. The best known of these circuit assemblies is the rectifier consisting of two serial or parallel-connected bridges, supplied by a transformer with two secondaries, one Y and the other delta connected. This assembly produces a 30 degree phase displacement between the voltages of the two secondaries. The calculation shows that the 6k±1 order harmonics where k is odd are removed from the transformer primary. The first harmonics removed, which are also the highest in amplitude, are for k = 1, harmonics 5 and 7. The first harmonics present are then 11 and 13.
This property can be generalised by increasing the number of rectifiers and the number of transformer secondaries or the number of transformers by choosing the appropriate phase displacement for each secondary.
This solution is commonly employed in the case of very high power rectifiers where current distribution in the various bridges presents no problems. It is frequently used by electrolytic rectifiers (up to 72 phases!).
Parallel-connected uninterruptible power supplies (UPS) are of special interest, as the inverters share the output currents and the rectifiers supplying them absorb identical currents.

## using detuning reactors

This solution consists of protecting the capacitors, designed to improve the displacement power factor by installing a serial reactor. This reactor is calculated so that resonance frequency matches none of the harmonics present. Typical tuning frequencies are for a 50 Hz fundamental: 135 Hz (order 2.7), 190 Hz (order 3.8) and 255 Hz (order 4.5). Thus for the fundamental, the battery can perform its displacement power factor improvement function, while the high impedance of the reactor limits amplitude of the harmonic currents.

The switched-steps capacitors must allow for the priority of certain resonance frequencies.

## passive harmonic filters

This case differs from the above in that a capacitor is used in series with a reactor in order to obtain tuning on a harmonic of a given frequency. This assembly placed in parallel on the installation has a very low impedance for its tuning frequency, and acts as a short-circuit for the harmonic in question.
A number of assemblies tuned on different frequencies can be used simultaneously in order to remove several harmonic orders.

Passive filters contribute to reactive energy compensation of the installation.

This apparently simple principle nevertheless calls for thorough study of the installation since, although the filter acts as a short-circuit for the required frequency, there is a possibility of resonance risks with other power network reactors on other frequencies and thus of increased previously non-troublesome harmonic levels prior to its installation (see «Cahier Technique» n° 152).

# 2. unity PF rectifiers and active harmonic conditioners

## introduction

The previous chapter reviewed the techniques and corresponding passive systems used to reduce harmonic disturbances.
These systems all modify impedances, impedance ratios or cause the opposition of certain harmonic currents.
Other impedance monitoring means are available (which we shall not dare to term «intelligent»!), which use static converters of ever increasing effectiveness due to the steady increase in semiconductor power component possibilities (see table fig. 4).
IGBT's made possible the industrial development of power converters able to guarantee non-disturbance at the point of common coupling (unity PF rectification), and harmonic compensation of power networks (active harmonic compensation).

■ unity PF rectification is a technique enabling static converters to absorb a current very similar to a sinusoidal waveform with, in addition, a displacement power factor close to the unit: this highly interesting technique should be used with increasing frequency.

■ active harmonic compensation
An active harmonic conditioner is a device using at least one static converter to meet the «harmonic compensation» function.
This generic term thus actually covers a wide range of systems, distinguished by:

- ☐ the number of converters used and their association mode,
- ☐ their type (voltage source, current source),
- ☐ the global control modes (current or voltage compensation),
- ☐ possible association with passive components (or even passive filters).

The only common feature between these active systems is that they all generate currents or voltages which oppose the harmonics created by non-linear loads. The most instinctive achievement is the one shown in figure 5 which is normally known as «shunt» (or «parallel») topology.
It will be studied in detail in paragraph 3.
The «serial» type active harmonic conditioner (see fig. 6) will be mentioned merely as a reminder as it is seldom used. Its function is to enable connection of a sensitive load on a disturbed power network by blocking the upstream harmonic voltage sources. However, in actual practice, this «upstream» harmonic compensation technique is of little interest since:

- ☐ the «quality» of the energy at the point of common coupling is satisfactory in the majority of cases,
- ☐ insertion of a component in the «serial» mode is not easy (for example short-circuit current withstand),
- ☐ it is more useful to examine the actual causes of voltage distortion within a power network (the harmonic current sources).

Out of the numerous «hybrid» alternatives we shall concentrate on the «serial/parallel» type combining active and passive filtering (see fig. 7) which is a very effective solution for harmonic cancellation close to high power converters.

| technology | | V | A | F (kHz) |
|---|---|---|---|---|
| **transistor** | | | | |
| | MOS | 500 | 50 | 50 |
| | Bipolar | 1200 | 600 | 2 |
| | IGBT | 1200 | 600 | 10 |
| **thyristor** | | | | |
| | GTO | 4500 | 2500 | 1 |

*fig. 4: typical characteristics of use of power semiconductors in static converters.*

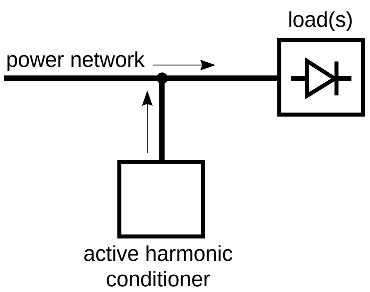



*fig. 5: «shunt type» active harmonic conditioner generates an harmonic current which cancels current harmonics on the power network side.*

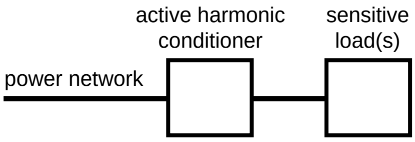



*fig. 6: «serial type» active harmonic conditioner generates an harmonic voltage which guarantees a sinusoidal voltage on the load terminals*

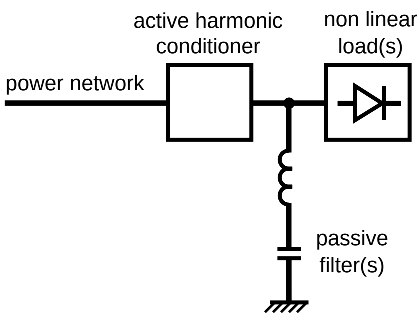



*fig. 7: «serial/parallel» type hybrid filter*

However this «Cahier Technique» does not aim to be complete and deliberately chooses not to treat many topologies. This is because all the other systems are merely variations on a theme and because the basic solutions are described in this document.
Before going on to describe unity PF rectifiers and active harmonic conditioners in detail, it should be noted that there is a certain technological resemblance between these two devices, namely:

■ when the control strategy of a rectifier bridge (integrating, for example, a BOOST stage) imposes circulation of a current reduced merely to its fundamental, **this is called unity PF rectification** and the rectifier is said to be **«clean»**,

■ when the current reference applied to this control is (for example) equal to the harmonic content of the current absorbed by a third-party non linear load, the rectifier cancels all the harmonics at the point of common coupling: **this is known as active harmonic conditioner**.

Thus the same power topology is able to meet the two separate needs which are non-disturbance and harmonic compensation. Only the control strategy differs (see fig. 8).

## unity PF rectifiers

Whether for rectifiers, battery chargers, variable speed drives for DC motors or frequency converters, the device directly connected with the power network is always a «rectifier». This component, and more generally the input stage (power and control) determines the harmonic behaviour of the complete system.

### Unity PF rectification principle (in single-phase)

This consists of forcing the absorbed current to be sinusoidal. Unity PF rectifiers normally use the PWM (Pulse Width Modulation) switching technique.
Two main categories are identified according to whether the rectifier acts as a voltage source (most common case) or a current source.

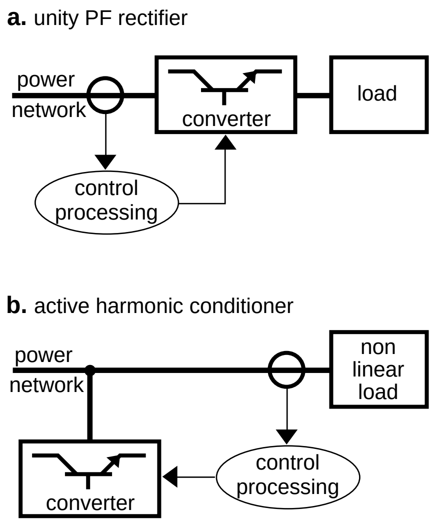



*fig. 8: unity PF rectifier and active harmonic conditioner*

■ voltage source converter
In this case the converter acts as a back-electromotive force (a «sinusoidal voltage generator») on the power network (see fig. 9), and the sinusoidal current is obtained by inserting a reactor between the power network and the voltage source.
Voltage is modulated by means of a control loop designed to maintain current as close as possible to the required sinusoidal voltage waveform.
Even if other non-linear loads raise the power network's voltage total harmonic distortion, regulation can be used to draw a sinusoidal current.
The frequency of low residual harmonic currents is the frequency of modulation and of its multiples.
Frequency depends on the possibilities of the semiconductors used (see fig. 4).

■ current source converter
This converter acts as a chopped current «generator». A fairly large passive filter is required to restore a sinusoidal current on the mains side (see fig. 10).
This type of converter is used in specific applications, for example to supply an extremely well regulated DC current.

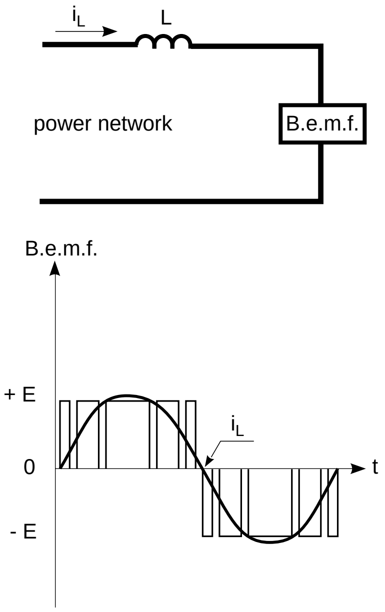



*fig. 9: single-phase diagram equivalent to a voltage PWM converter.*

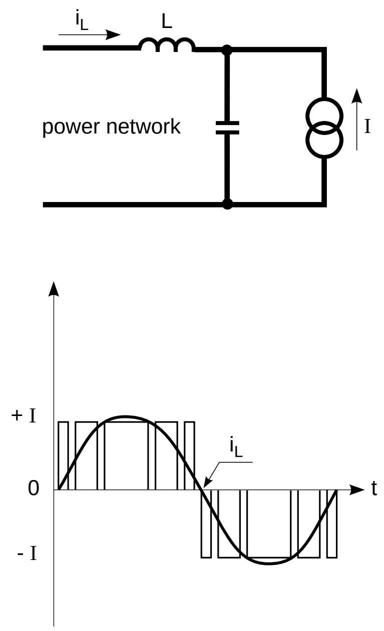
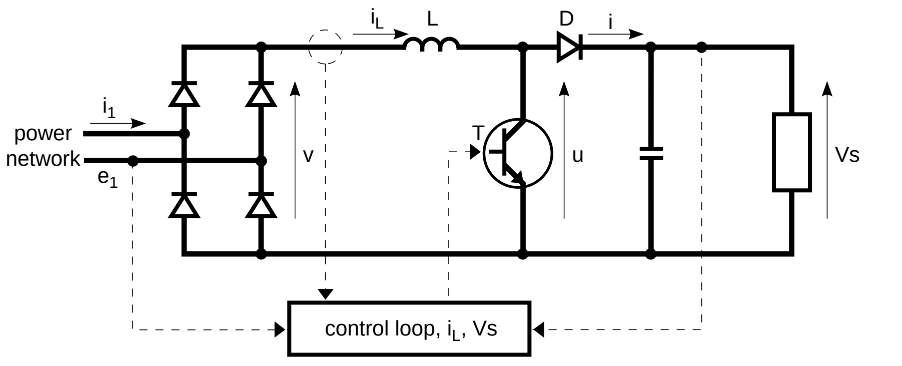


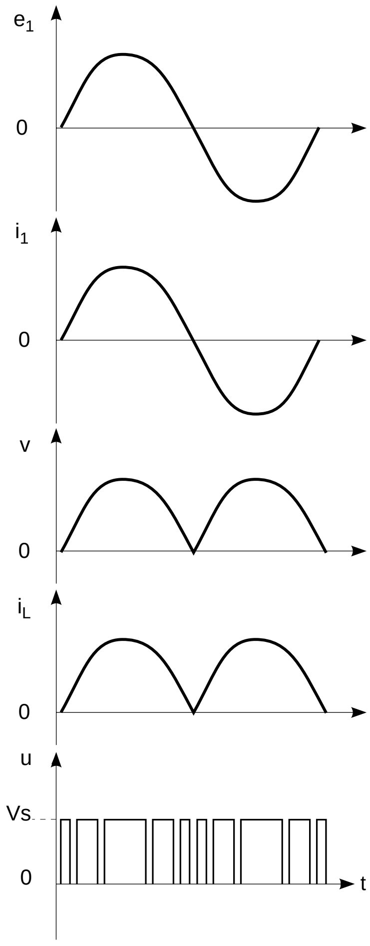

*fig. 10: single-phase diagram equivalent to a current PWM rectifier*

**«Voltage converter» implementation principle**

Its ease of implementation means that the diagram in figure 11 is the one most often chosen (see certain Merlin Gerin UPS).

This diagram uses the voltage generator principle.




From the source viewpoint, the converter must act like a resistance: (sinusoidal) $i_1$ and in phase with $e_1$ (DPF = 1). By controlling transistor T, the controller forces $i_L$ to follow a sinusoidal type current reference with double wave rectification. The shape of $i_1$ is thus necessarily sinusoidal and in phase with $e_1$. Moreover, to keep voltage Vs at its nominal value at the output, the controller adjusts the mean value of $i_L$.

*fig. 11: circuit diagram showing a single-phase rectifier with unity PF rectifier.*

Transistor T (normally using MOS technology) and diode D make up the voltage modulator. The voltage (u) thus moves from 0 to Vs according to whether transistor T is in the on or off state.

When transistor T is conductive, the current in reactor L can only increase as voltage v is positive and u = 0.

The relationship is then:

$$\frac{di}{dt} = \frac{e}{L} > 0$$

When transistor T is off, the current in L decreases, provided that Vs is greater than v, so that:

$$\frac{di}{dt} = \frac{e - Vs}{L} < 0$$

For this condition to be fulfilled, voltage Vs must be greater than the peak voltage of v, i.e. the rms value of the ac voltage, multiplied by $\sqrt{2}$.

If this condition is fulfilled, the current in L can be increased or decreased at any time. The time evolution of current in L can be forced by monitoring the respective on and off times of transistor T.

Figure 12 shows the evolution of current $i_L$ with respect to a reference value.

The closer the switching moments of T (i.e. switching frequency is high), the

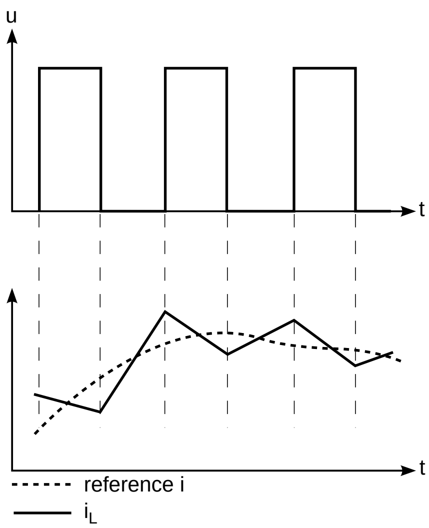



*fig.12: evolution of current $i_L$ compared with the reference i.*

smaller the errors of $i_L$ compared with the reference sine wave. In this case the current $i_L$ is very close to the rectified sinusoidal current, and the line current $i_1$ is necessarily sinusoidal.

Figure 13 shows the time curve and the harmonic spectrum of the current drawn by a unity PF rectifier of a 2.5 kVA UPS. In this case the transistor is a MOS, and the switching frequency equals 20 kHz.

The harmonics of the current absorbed are highly attenuated compared with a switch mode power supply which does not use the «unity PF rectification» control strategy, and their level is below standard requirements.

Filtering of ≥ 20 kHz orders is easy and inexpensive.

### Three-phase circuits

The basic circuit arrangement is shown in figure 14.

We recognise the arrangement in figure 11 where the reactor is placed upstream of the rectifiers. The operating principle is the same.

The monitoring system controls each power arm, and forces the current absorbed on each phase to follow the sinusoidal reference.

There are currently no three-phase unity PF rectifiers on the market as additional cost is high. Changes in standards may however stipulate their use.

## the «shunt type» active harmonic conditioner

### Operating principle

The «shunt type» active harmonic conditioner concept can be illustrated by means of an electro-acoustic analogy (see fig. 15). The observer will no longer hear the noise source S if a secondary noise source S' generates a counter-noise. The pressure waves generated by the loudspeaker have the same amplitude and are in opposition of phases with those of the source: this is the destructive interference phenomenon. This technique is known as ANR (Active Noise Reduction).

This analogy is a perfect illustration of the «shunt type» active harmonic conditioner: the aim is to limit or even remove the current (or voltage)

a) time form

b) spectral breakdown

| order | max. contrib. as a % of I1 as in IEC 1000-3-2 | typical values without unity PF rectifier (Uccx = 1%) | measured value |
|---|---|---|---|
| 3 | 14.65% | 81% | 8.03% |
| 5 | 7.26% | 52% | 2.94% |
| 7 | 4.90% | 24% | 3.15% |
| 9 | 2.55% | 6% | 1.65% |
| 11 | 2.10% | 7% | 1.09% |
| 13 | 1.34% | 6% | 1.07% |

*fig. 13: current upstream of a « clean » single-phase rectifier (2.5 kVA UPS - PULSAR-PSX type).*

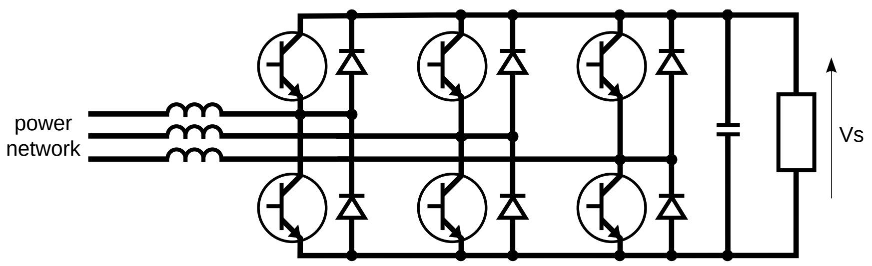



*fig. 14: three-phase rectifier with unity PF rectifier.*

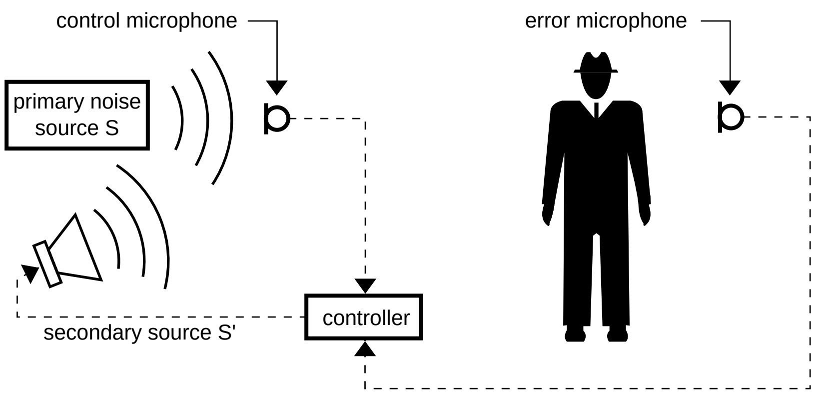



*fig. 15: principle of acoustic active noise reduction.*

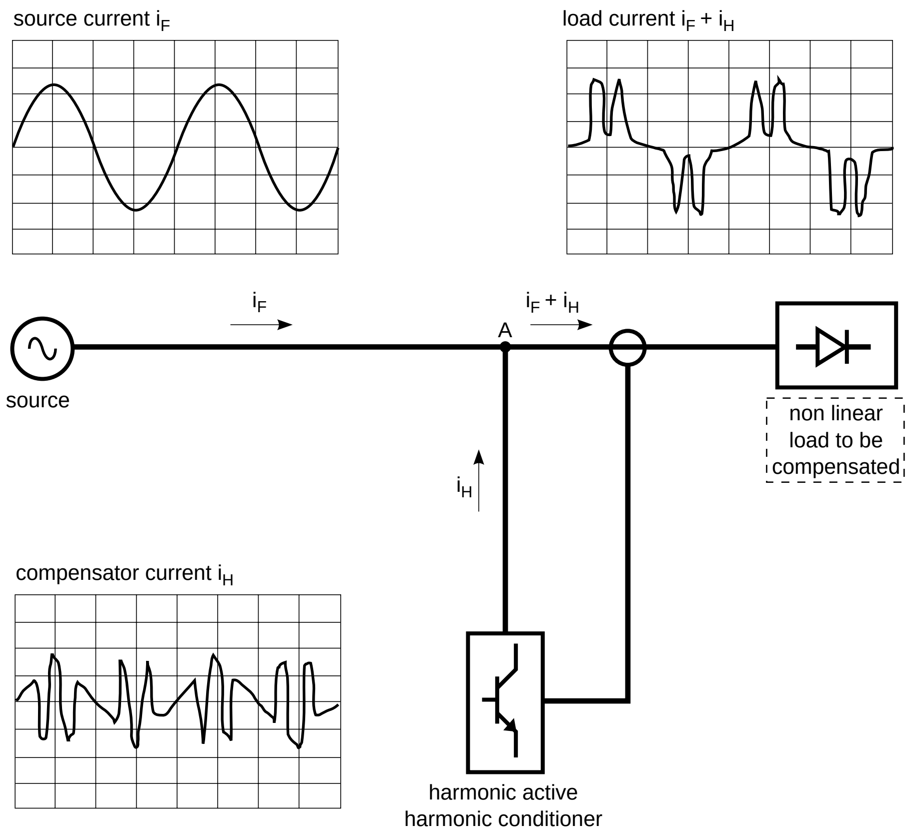



*fig. 16: principle of compensation of harmonic components by «shunt type» active harmonic conditioner.*

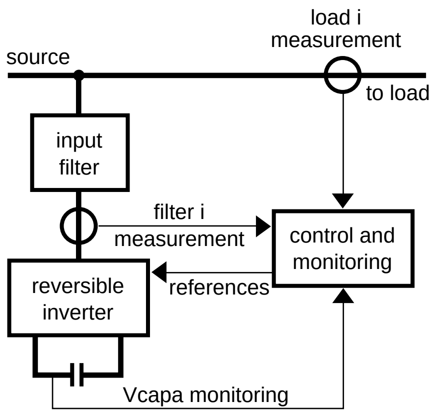



*fig. 17: schematic diagram showing the structure of the «shunt type» active harmonic conditioner.*

harmonics at the point of common coupling by injecting an appropriate current (or voltage) (see fig. 16).
Provided that the device is able to inject **at any time** a current where each harmonic current has the same amplitude as that of the current in the load and is in opposition of phases, then Kirchoff's law at point A guarantees that the current supplied by the source is purely sinusoidal. The combination of «non linear loads + active harmonic conditioner» forms a linear load (in which current and voltage are linked by a factor k). This kind of device is particularly suited for harmonic compensation of LV networks irrespective of the chosen point of coupling and of the type of load (the device is self-adaptive).
The following functions are thus performed according to the level of insertion:

- local harmonics compensation: if the active harmonic conditioner is associated with a single non linear load,
- global harmonics compensation: if the connection is made (for example) in the MLVS (Main Low Voltage Switchboard) of the installation.

The «shunt type» active harmonic conditioner thus forms a current source independent of power network impedance, and with the following intrinsic characteristics:

- its band-width is sufficient to guarantee removal of most harmonic components (in statistical terms) from the load current. We normally consider the range $H_2$ - $H_{23}$ to be satisfactory, as the higher the order, the lower the harmonic level.
- its response time is such that harmonic compensation is effective not only in steady state but also in «slow» transient state (a few dozen ms),
- its power enables the set harmonic compensation objectives to be met. However this does not necessarily mean total, permanent compensation of the harmonics generated by the loads.

Provided that these three objectives are simultaneously achieved, the «shunt type» active harmonic conditioner forms an excellent solution as it is self-adaptive and there is no risk of interaction with power network impedance. It should also be noted that this device does not aim to rephase the fundamental U and I components: insertion of an active harmonic conditioner has no effect on the displacement power factor.
Nevertheless, if the load treated is of the «multiphase rectifier» kind, then the global power factor is indeed considerably improved as the distortion factor is closer to the unit and the displacement power factor of a rectifier

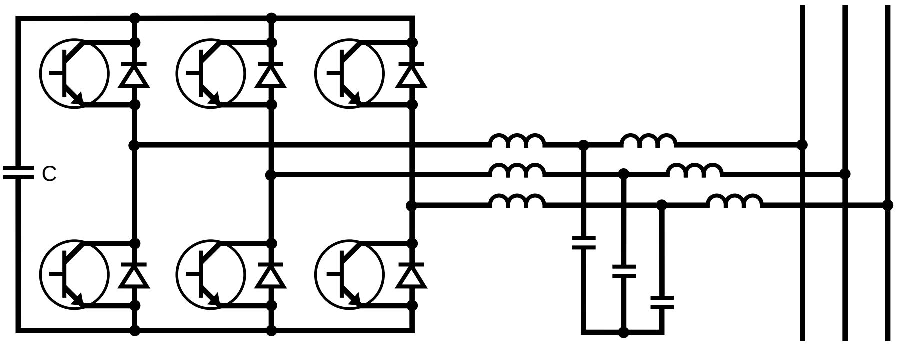



*fig. 18: diagram showing the «shunt type» active harmonic conditioner with VSI.*

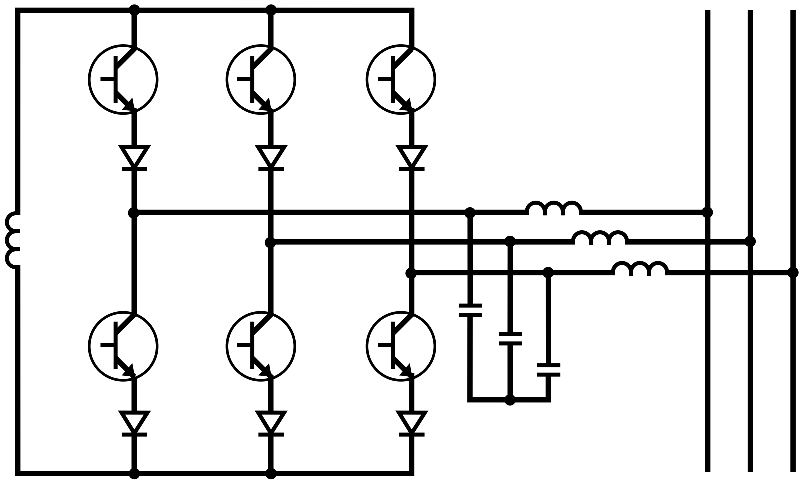


*fig. 19: diagram showing the «shunt type» active harmonic conditioner with CSI .*

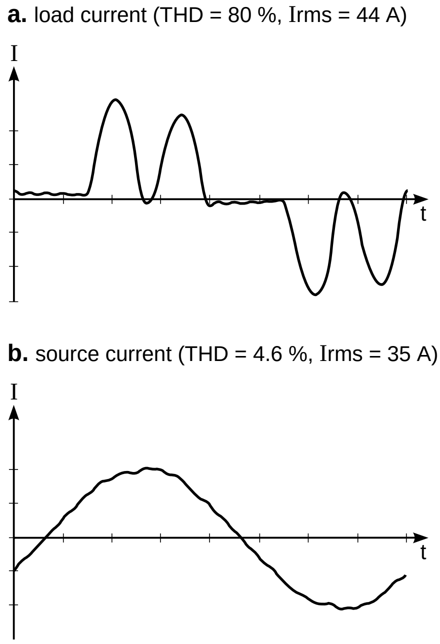



*fig. 20: «shunt type» active harmonic conditioner associated with a UPS - time waveforms of currents (20% load).*

(not controlled) is close to the unit. However this is more a «secondary effect» than an actual objective!

**Structure of the «shunt type» active harmonic conditioner**

This device is broken down into the following two subassemblies (see fig. 17).

■ power: input filter, reversible inverter, storage components,

■ control: reference processing, U/I controls, converter low level control.

The main difference between a converter and a unity PF rectifier, described in the previous chapter, lies in the control and monitoring (as the setpoint is no longer a 50 Hz sine wave). If the «storage» component is a capacitor or battery, the converter has a similar structure to that of the input stage of the converter with unity PF rectifier (see fig. 18).

A reactor can also be used (see fig. 19). Merlin Gerin has chosen Voltage Source Inverter -VSI- for its SINEWAVE range because of its added value in technical and economic terms: wider pass-band, simpler input filter. Moreover the VSI structure technically resembles inverter structure.

**Control and monitoring electronics**

Its main function is to control the power semiconductors. As such it must:

■ control capacitor load (c) on energising,

■ regulate voltage at the terminals of c,

■ generate « rectifier » on/off patterns when it has an inverter function so that the active harmonic conditioner permanently supplies a current compensating the non linear harmonic currents (see fig. 16).

There are 2 signal processing methods, namely:

■ the real time method, which is particularly suitable for loads with ultra-fast variations in their harmonic spectrum. It can use the «synchronous detection» method or use Clark transformations.

■ the non real time method, used for loads where the harmonic content of the current absorbed varies slightly in 0.1 s. This method uses the frequency analysis principle and is based on the Fast Fourier Transform (FFT). It enables global or selective treatment of harmonic orders.

**Examples of performances obtained using non-linear loads**

In these examples the loads do not operate on full load, as the THD (I) is at its lowest on full load. In the example below, the THD (I) is 30% on full load, whereas it is 80% with a 20% load.

■ case of a UPS

A « shunt type » active harmonic conditioner is parallel-connected on a three-phase uninterruptible power supply of a power of 120 kVA. The current time waveforms are shown in figure 20. The spectrum of the current

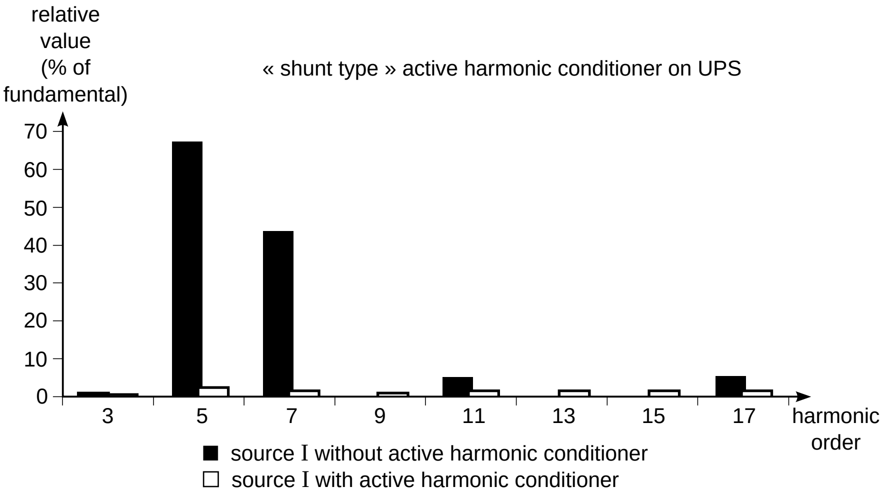



*fig. 21: source currents spectrum.*

| current characteristics | without active harmonic conditioner | with active harmonic conditioner |
|---|---|---|
| Irms (A) | 44.1 | 35.2 |
| Peak factor | 1.96 | 1.52 |
| THD (I) as a % | 80.8 | 4.6 |
| Power factor | 0.65 | 0.86 |
| DPF | 0.84 | 0.86 |
| Harmonic Irms (A) | 27.7 | 1.6 |

*fig. 22: «shunt type» active harmonic conditioner on UPS: measured values.*

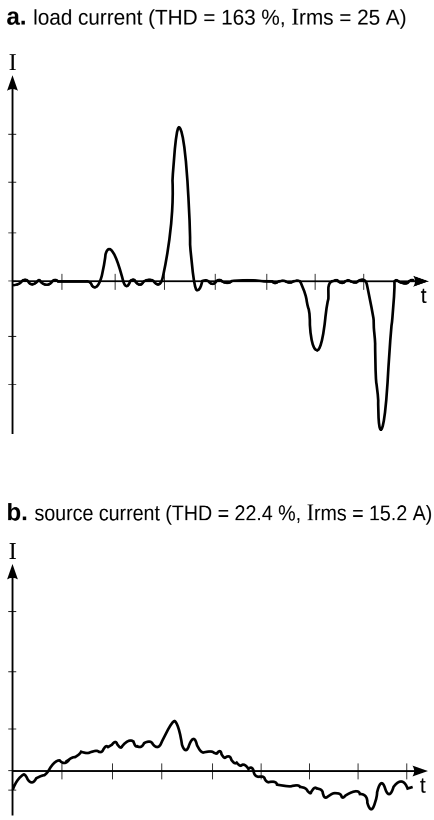



*fig. 23: «shunt type» active harmonic conditioner on variable speed drive: waveforms of currents on half-load.*

absorbed by the load is given in figure 21 and corresponds to an harmonic distortion of 80 %. Use of the « shunt type » active harmonic conditioner considerably attenuates the THD (I) which drops from 80% to 4.6%.
The rms current drops by nearly 20%, and the power factor increases by 30%. (see fig. 21 and 22).

■ case of a VSD (frequency converter type)

An active harmonic conditioner is parallel-connected to a variable speed drive for asynchronous motor of a power of 37 kW operating on half-load. The current time waveforms are shown in figure 23 and correspond to an harmonic distortion of 162% for the load current. Figure 24 shows the harmonic spectrum of the source and load currents.
Use of the «shunt type» active harmonic conditioner considerably attenuates the THD (I) which drops to 22.4%. The rms current drops by nearly 40% (see fig. 24 and 25).
Performance is lower than in the first case (UPS) since line current fluctuations are much faster. In this cases addition of a 0.3 mH smoothing reactor is recommended. The table in figure 26 illustrates the resulting increase in effectiveness.
We can conclude that the «shunt type» active harmonic conditioner is an excellent means for removing harmonics on a feeder or non-linear load. However:

■ removal of all disturbances, even if it is possible, is not necessarily the aim,
■ it is not suited to voltage power networks exceeding 500 V,
■ it has no effect on disturbances upstream of the current sensor,
■ technical and economic considerations may require use combined with a passive component; for example a reactor (see fig. 26) or a passive filter to remove the 3rd or 5th harmonic (considerable decrease in «shunt type» active harmonic conditioner power rating).

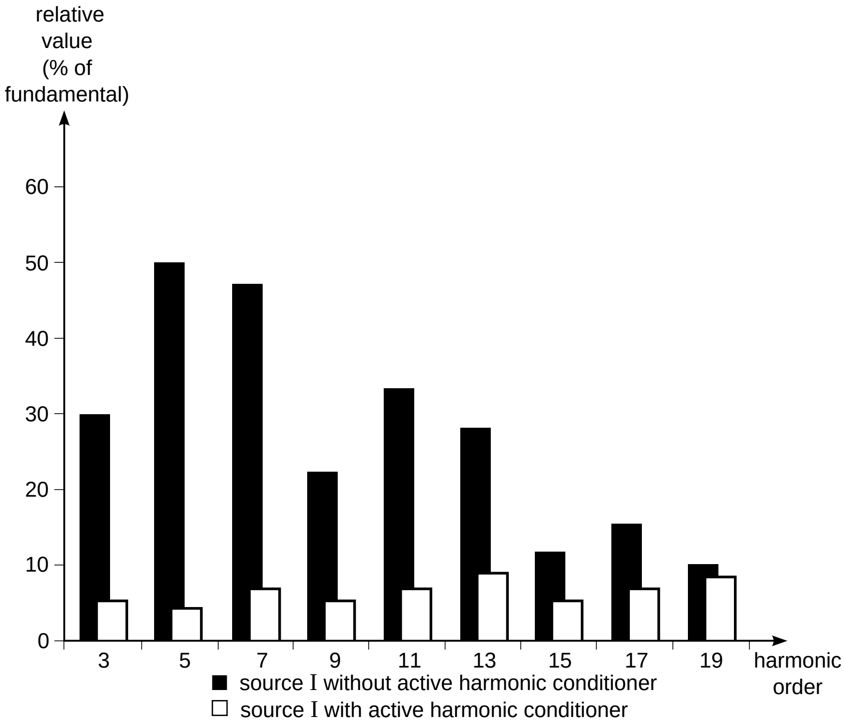



*fig. 24: «shunt type» active harmonic conditioner associated with a variable speed drive: harmonic spectrum of the source current.*

| characteristics of current on half-load | without active harmonic conditioner | with active harmonic conditioner |
|---|---|---|
| Irms (A) | 25.9 | 15.2 |
| Peak factor | 3.78 | 1.95 |
| THD (I) as a % | 163 | 22.4 |
| Harmonic Irms (A) | 21.7 | 3.3 |

*fig. 25: «shunt type» active harmonic conditioner associated with a variable speed drive: current characteristics.*

| characteristics of current on full load | with active harmonic conditioner and smoothing reactor |
|---|---|
| Irms (A) | 57.6 |
| Peak factor | 1.46 |
| THD (I) as a % | 3.4 |
| Harmonic Irms (A) | 2 |

*fig. 26: «shunt type» active harmonic conditioner associated with a variable speed drive with smoothing reactor: current characteristics.*

# 3. hybrid active harmonic conditioners

Harmonic compensation needs are many and varied, since we may need to guarantee:

■ non-disturbance of a «clean» power network by a disturbing load,

■ or proper operation of a sensitive load (or power network) in a disturbed environment,

■ or both these objectives simultaneously!

The problem of harmonic compensation can thus be handled at two levels (exclusive or combined):

■ parallel compensation by current source downstream of the point in question: this is the «shunt type» solution described in the previous chapter,

■ serial compensation by implementing an upstream voltage source.

The structures that we shall refer to as «hybrid» hereafter in this document are those which simultaneously implement both solutions, as shown for example in figure 27.

They use passive filters and active harmonic conditioners.

We have chosen to describe three of the many alternatives available.

## the «serial» hybrid structure

The diagram in figure 28 illustrates the main subassemblies of this structure, namely:

■ one (or more) bank (s) of resonant passive filters (Fi), parallel-connected with the disturbing load(s),

■ an active harmonic conditioner, made up of:

□ a magnetic coupler (Tr), the primary of which is inserted in series with the passive filter(s),

□ an inverter (MUT) connected to the secondary of the magnetic coupler. The active harmonic conditioner is controlled so that:

$Vfa = K \times I_{SH}$

where:

Vfa: voltage at the magnetic coupler terminals,

K: value in «ohm» fixed for each order,

$I_{SH}$: harmonic current from the source.

In this configuration the active harmonic conditioner only acts on the harmonic currents and increases the effectiveness of the passive filters:

□ it prevents amplification of upstream harmonic voltages at the anti-resonance frequencies of the passive filters,

□ it considerably attenuates harmonic currents between load and source by «lowering» global impedance (passive filters plus active harmonic conditioner).

Since not all the power network current flows through the active harmonic conditioner, the components of the latter can be downsized (and in particular the magnetic coupler).

This structure is thus ideal for treating high voltage and power networks, while at the same time ensuring rephasing of fundamental components.

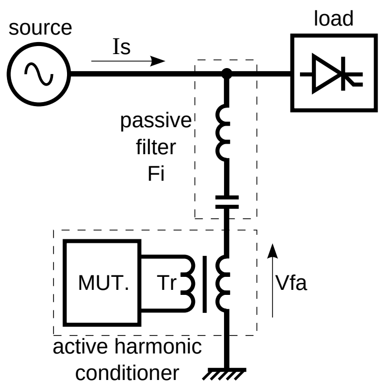



*fig. 28: «serial/serial type» hybrid conditioners - one-line diagram.*

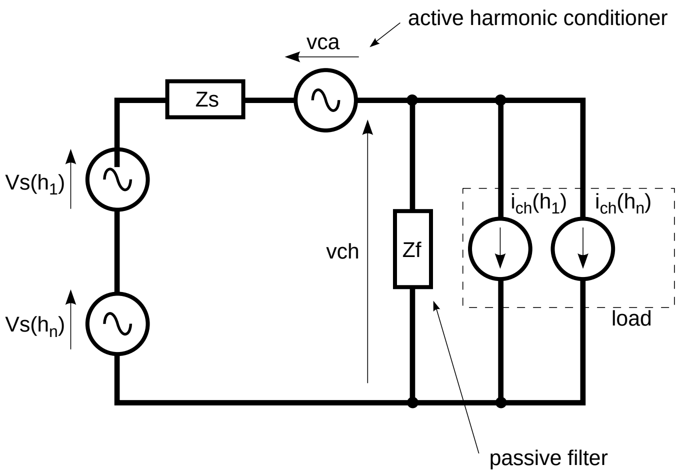



*fig. 27: active/passive hybrid conditioners - example.*

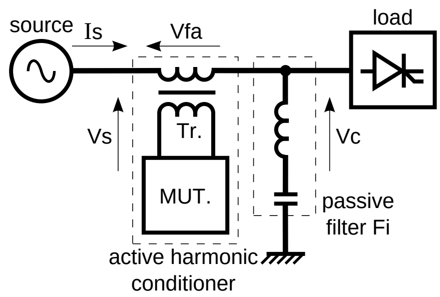



*fig. 29 : «serial/parallel type» hybrid conditioners.*

Its main drawback is that the passive filters depend on the type of load, thus requiring a preliminary study.
Finally, virtually all the pre-existing harmonic voltages (on the source) are present on the load side. This configuration can therefore be compared with the «shunt type» active harmonic conditioner.

## the «serial/parallel» hybrid structure

The diagram in figure 29 shows that this structure contains the main subassemblies of the previous structure, the only difference being in the connection point of the coupler primary (in series between source and load).
The active harmonic conditioner control law is the same: its aim is for the active harmonic conditioner to develop a voltage which opposes circulation of harmonic currents to the source. It therefore acts as an impedance (of value K fixed for each order) for harmonic frequencies.
Passive filtering is thus more efficient (as the presence of this serial «impedance» forces circulation of the harmonic load currents to the passive filters). Moreover, the serial filter isolates the load of the harmonic components already existing on the source and prevents passive filter overload. This topology is thus most often referred to as an «harmonic isolator» since, in some respects, it isolates the source of a disturbing load, and, reversely, prevents overload of a passive filter by upstream disturbance.
It should be noted that this topology generates sizing and protection problems for the magnetic coupler, since:
■ total load current flows through this coupler,
■ a very high current wave is applied in the event of a short-circuit.
A possible solution to both problems may be to use a transformer with secondary winding (see fig. 30).
Compensation then takes place «magnetically» by directly acting on the flow.

## «parallel» combination of passive filters and active harmonic conditioner

The principle consists of «parallel» connection of one (or more) tuned passive filter(s) and a «shunt type» active harmonic conditioner (see fig. 31).
In this case also, the active harmonic conditioner and the passive filter prove the ideal combination. It may prove useful to limit (by the FFT technique), the action of the active harmonic conditioner to the orders not treated by the passive filters.
This structure is used (as applicable) to:
■ improve the harmonic cancellation obtained using only passive filters,
■ limit the number of orders of passive filters,
■ improve the effectiveness of the active harmonic conditioner only (for the same power effectiveness of the active harmonic conditioner).
Nevertheless, this combination does not prevent passive filter overloads or the effects of anti-resonance with power network impedance.

**In short**

These hybrid structures do not possess the «universal» character of the «shunt type» active harmonic conditioner as passive filters need to be chosen (in terms of type, number of orders and tuning frequencies) according to the kind of harmonic currents generated by the load. The presence of the active harmonic conditioner downsizes the passive filters and reinforces their effect. Vice versa, the addition of an active harmonic conditioner of reduced power to an existing installation increases the efficiency of existing passive filters.

## the performances of hybrid structures

Prototypes have been designed, produced and tested in partnership with Electricité de France (which is the largest and almost the only power utility in France). These models comprised two banks of resonant passive filters tuned on orders 5 and 11 (harmonic compensation of a UPS-type load) or 5 and 7 (variable speed drive load).
The result of the tests combining two types of hybrid filters with a frequency converter (variable speed drive for asynchronous motor) is given below:

**«Serial» configuration**
(see fig. 28)
The test circuit characteristics are defined in the table in figure 32.

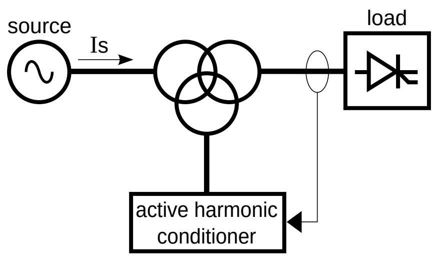



*fig. 30: hybrid conditioner with injection by transformer.*

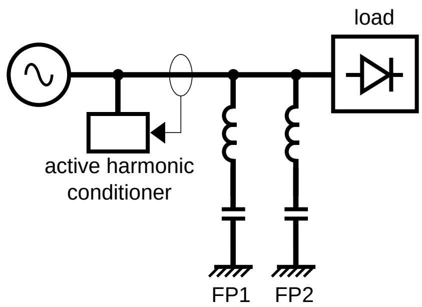



*fig. 31 : «parallel» connection of active harmonic conditioner and passive filters - principle.*

| | | |
|---|---|---|
| **circuit characteristics** | | |
| | source | 400 V, three-phase, 600 kVA, 5 %, THD (Vs) < 1.5 % |
| | load | 130 kW, 70 % load, 0.15 mH smoothing reactor. |
| **measurements taken** | | |
| | THD (Ich) | 35 % |
| | THD (Is) | 9 % |
| | THD (Vch) | 2 % |

*fig. 32: «serial type» conditioner - characteristics and results*

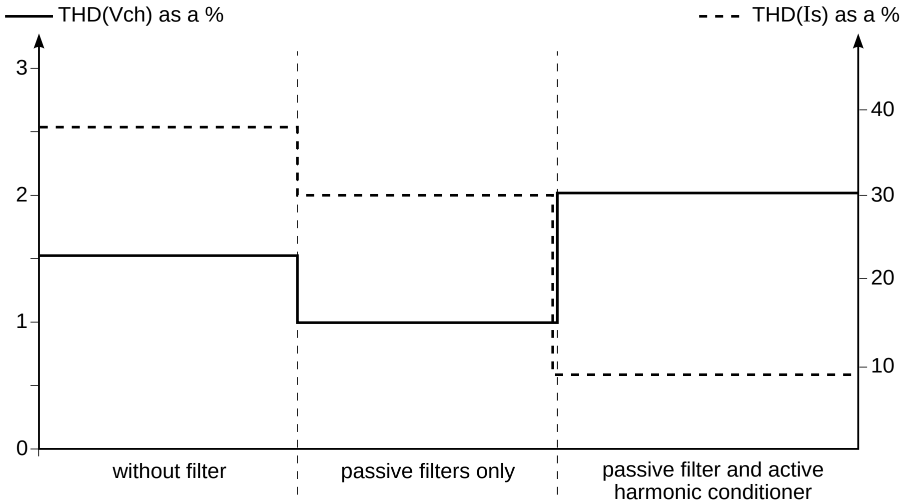



*fig. 33: «serial type» hybrid conditioner associated with a variable speed drive - evolution of THD (Vch) and THD (Is).*

**Comments:**

This topology is not suitable for treating power networks with a high upstream voltage THD. However, its « current » performances are totally respectable (the THD (I) is reduced from over 35% to 9%) (see fig. 33).
It is thus particularly well suited for treating power networks with low upstream THD, or for which serial insertion of a device is particularly problematic.

| | | |
|---|---|---|
| **circuit characteristics** | | |
| | source | 400 V, three-phase 600 kVA, 5 %, THD (Vs) < 1.5 % |
| | load | 130 kW, 70% load, 0.15 mH smoothing reactor. |
| **measurements taken** | | |
| | THD (Ich) | 35 % |
| | THD (Is) | 11 % |
| | THD (Vch) | 2.1 % |

*fig. 34: «serial/parallel type» hybrid conditioner: characteristics and result.*

**«Serial/parallel type» configuration**

(see fig. 29)
The test circuit characteristics are defined in the table in figure 34.

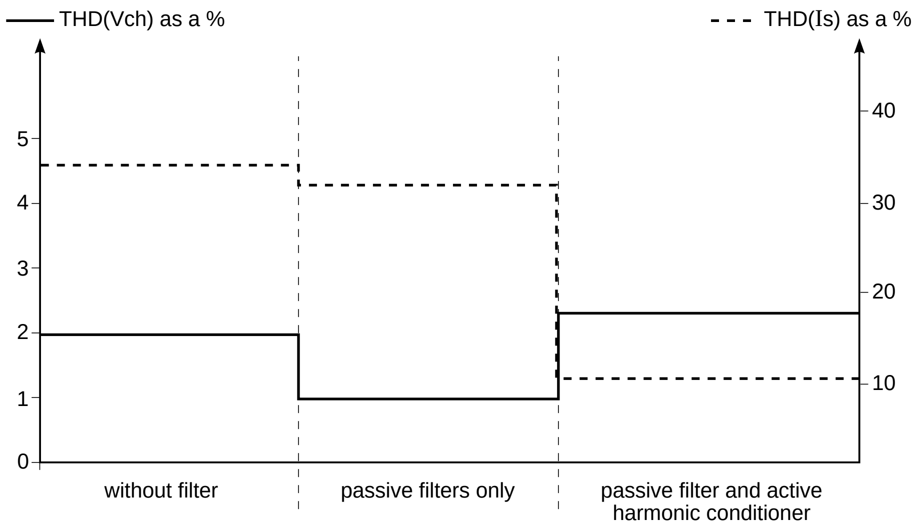



*fig. 35: «serial/parallel type» hybrid conditioner associated with a variable speed drive - reading of THD (Vch) and THD (Is).*

**Comments:**

The performances are in this case also totally satisfactory even if the quality of the source voltage (THD (u) very low) does not let us appraise performance in terms of isolation. The source current THD is however reduced from more than 35% to 11% (see fig. 35). Passive filter current remains constant and is thus representative of isolation from the source. Additional tests proved that for very high upstream distortion (THD (U) = 11%), voltage quality at the load terminals continued to be good (THD ($U_{CH}$) = 4.7%).

**Characteristics of the active solutions**

We have now dealt with serial and parallel type active harmonic conditioners and with hybrid structures.
To round off this chapter, we propose to summarise the qualities of these various «active solutions» used to combat harmonic disturbance. The table in figure 36 shows that, except for a few special cases, the «shunt type» active harmonic conditioner and the parallel-connected structure are the solutions to be preferred in low voltage.

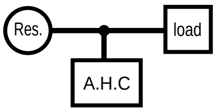
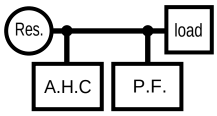
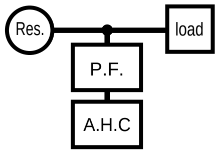
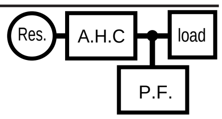
| **type of filter** ⇒ <br>**criterion** ⇓ | **«serial»** | **«shunt»** | **«parallel» hybrid** | **«serial» hybrid** | **«serial/parallel type» hybrid** |
|---|---|---|---|---|---|
| schematic diagram<br><br>A.H.C.: Active Harmonic Conditioner |  |  |  |  |  |
| action on | Uh/source | Ih/load | Ih/load | Ih/load | Ih/load,<br>Uh/source |
| performance | +++ | +++ | +++ | ++ | ++ |
| active harmonic conditioner sizing | fund + harm | harm. | harm. | harm. | fund + harm |
| short-circuit impact | great | none | none | none | great |
| insertion | difficult | easy | easy | easy | difficult |
| improvement of DPF | no | possible | yes | yes | yes |
| open-endedness | no | yes | yes | no | no |
| resonance risk | NA (not applicable) | NA (not applicable) | yes | no | no |

*fig. 36: summary of the various «active solutions» to combat harmonic disturbance.*

# 4. implementing a «shunt type» active harmonic conditioner

We would first like to emphasise that our aim is not to act as a «selection guide» between the various types of harmonic compensation techniques (both active and passive), but rather to present the criteria used to size and insert the active harmonic conditioners. Furthermore, a selection guide would imply that the various solutions given are available in product form.
At present, given that both the «traditional» solutions and the hybrid solutions require in-depth study and suitable solutions, only the shunt type active harmonic conditioners are available on the market (they require merely a simple study).
We shall thus concentrate on identifying the main parameters that «potential» active harmonic conditioner users need to know in order to make the right choice.

## objective and context

**Knowing the «mechanisms»**
The main problem of harmonic phenomena is undeniably linked to their very weak visibility. Although it is usually easy to observe deterioration in wave quality (voltage and/or current) at one or more points, the combinational function between the various sources (self-sufficient or not), loads and topology of the power network is no simple matter!
Moreover, the association between harmonic phenomena (often overlooked) and the malfunctions observed in the power network components (often random) is not instinctive.

**Knowing the power network and its topology**
The first preliminary requirement thus concerns the power network environment: implementation of an harmonic compensation technique requires knowledge of the entire power network (sources, loads, lines, capacitors) and not just a fragmented view limited merely to the zone concerned. This single-line diagram is in some respects the first component of our «tool box».

**Carrying out an «inventory»**
We have first placed an harmonic distortion analyser in this «tool box», vital for quantifying disturbance at various points of an existing installation.

**Identifying and characterising disturbing equipment**
We need to identify the main disturbing equipment(s) and their respective spectra. The latter can be obtained either by measurements or by consulting the technical specifications provided by each manufacturer.

**Defining the harmonic compensation objective**
The second preliminary requirement concerns the actual objective of the action considered: the method used differs considerably according to whether you wish to correct malfunctioning observed, or to ensure compliance with the specifications of power utility or a non-linear load manufacturer. Short term power network changes must also be taken into consideration.
For example this stage must enable identification of at least:

- ■ the type of compensation (global or local),
- ■ the power rating at the node considered,
- ■ the type of correction required (on voltage and/or current distortions),
- ■ the reactive energy compensation need,

....
Once the above analyses are complete, the most advantageous technical and economic solution must be chosen. The same objective often has several technical possibilities, and the problem is in most cases to make a choice according to the individual difficulties of each electrical installation. For example, isolation or decoupling by impedance of disturbing loads is easily carried out on new installations provided it is considered in the design phase. However it frequently generates unacceptable difficulties on existing power networks.
It is thus obvious that no «active» solutions (regardless of the type) can be systematically chosen, but that an analytical approach is required in which active harmonic conditioner cost alone is not necessarily the most important factor.
Although Active harmonic conditioners have undeniable advantages over passive filters, they are not necessarily preferred particularly for existing installations already equipped with passive filters. The insertion of a serial or parallel type active harmonic conditioner, after study, is a good solution.
We shall now use experience acquired on site to describe the implementation of a «shunt type» active harmonic conditioner which is the simplest solution.

## the insertion point of a shunt type active harmonic conditioner

The connection principle of a «shunt type» active harmonic conditioner is shown in figure 37. In our example it is inserted in parallel mode in the LV switchboard of an installation, and the only interaction with the power network to be treated, is the insertion of the current sensors.
As regards insertion of the active harmonic conditioner, harmonic compensation can be considered at each level of the tree structure shown in figure 38.

The compensation mode may be termed global (position «A»), semi-global (position «B») or local (position «C») according to the point of action chosen. Although it is hard to lay down hard and fast rules, it is obvious that if disturbance is caused by a large number of small loads, the «mode» preferred will be global, whereas if it is caused by a single high power disturbing load, the best result will be achieved using the local «mode».

**Local harmonic compensation**

The «shunt type» active harmonic conditioner is directly connected to the load terminals. This mode is the most efficient provided that the number of loads is limited and that the power of each load is significant compared with global power. In other terms, the loads treated must be the main generators of the harmonic disturbances.

Circulation of harmonic current in the power network is avoided, thus reducing losses by Joule effect in upstream cables and components (no oversizing of cables and transformers) as well as reducing disturbances of sensitive loads.

It is worth pointing out, however, that the «shunt type» active harmonic conditioner lowers source impedance at the connection point, and thus slightly increases current total harmonic distortion between the connection point and the load.

**Semi-global compensation**

The active harmonic conditioner, connected to the input of the LV subdistribution switchboard, treats several sets of loads. The harmonic currents then flow between the MLVS and the loads of each feeder. This type of compensation is ideal for multiple disturbing loads with low unitary power, e.g. on floors in service sector buildings (office equipment and lighting systems).

It also makes it possible to benefit from non-algebraic summing between loads, at the cost of a slight increase in losses by Joule effect on each feeder treated.

NB: this type of compensation can also be applied to a single feeder, thus limiting harmonic compensation to a single type of load (see fig. 37).

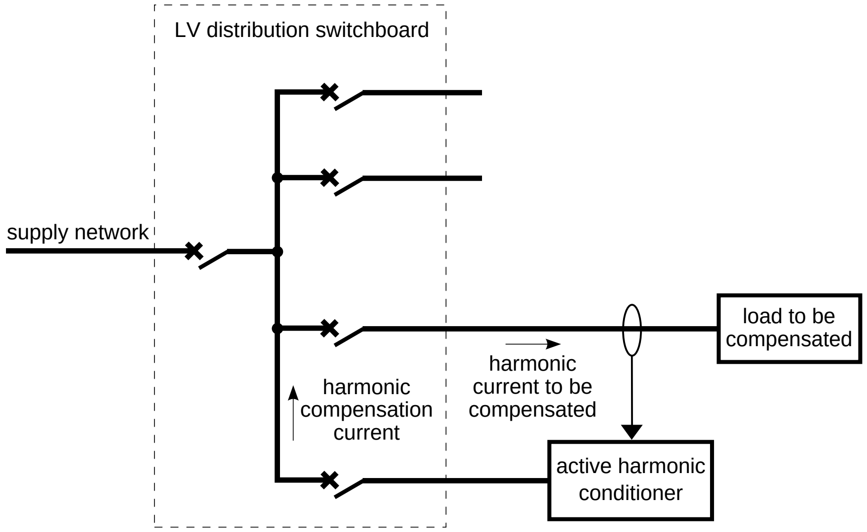



*fig. 37: connection of a «shunt type» active harmonic conditioner : principle.*

**Global compensation**

This form of compensation contributes rather to compliance with the point of common coupling according to «power utility» requirements, than to the reduction of internal disturbances in the customer's power network. Only the power transformer(s) actually derive direct advantage from harmonic compensation. Nevertheless, this form has a serious advantage for operation in autonomous production mode as a result of the numerous interactions between disturbing loads and generator sets with high harmonic impedance. However, compared with local compensation, this compensation technique results in a reduction in active harmonic conditioner power rating which benefits from the non-algebraic summing of the disturbing loads throughout the power network.

## sizing a «shunt -type» active harmonic conditioner

The main factor to consider when sizing a «shunt type» active harmonic conditioner is its power rating (**or more precisely its rms current**):

the rms curren $I_{CA\ RMS}$ is the current that can be permanently generated by the active harmonic conditioner.

Other characteristic active harmonic conditioner factors are its **bandwith** and **its dynamic capacity**:

■ the active harmonic conditioner bandwith is defined by $n_{min}$ and $n_{max}$, the (minimum and maximum) action orders of the active harmonic conditioner.

The following can be written:

$$I_{CA\ RMS}(A) = \sqrt{\sum_{n=n_{min}}^{n=n_{max}} \left(I^2_{CA(n)}\right)}$$

■ the active harmonic conditioner current tracking dynamic capacity (expressed by $\frac{di}{dt}$) is the capacity of the active harmonic conditioner to «track» rapidly varying references.

NB: these last two factors are not considered to affect size, since they form a characteristic inherent in the active harmonic conditioner and not an adjustable parameter.

Choosing nominal rating:

Provided that the spectrum of the current to be treated $I_{CH}$ is known, the nominal current of the active harmonic

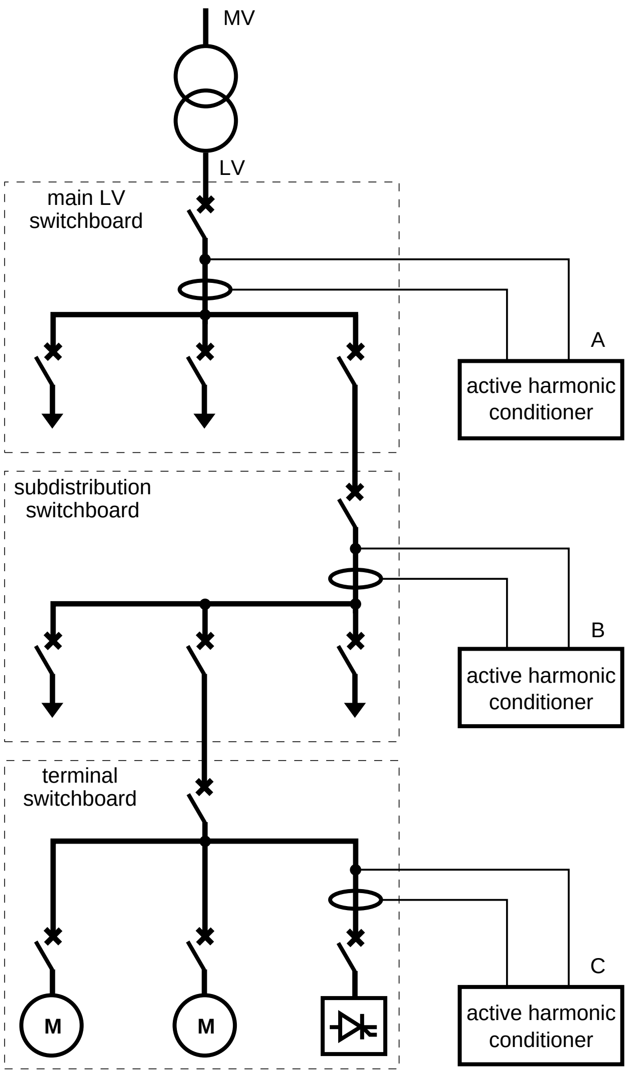



*fig. 38: the various insertion points of a «shunt type» active harmonic conditioner: principle.*

conditioner $I_{N\,CA\,RMS}$, can be determined such that:

$$I_{N\,CA\,RMS}(A) \geq \sqrt{\sum_{n=n_{min}}^{n=n_{max}} I^2_{CH(n)}}$$

Provided that the above condition is met, the « new » current total harmonic distortion (upstream) can be calculated once the active harmonic conditioner is put into operation:

$$THD\ I(\%) = \frac{\sqrt{\sum_{n=2}^{n=n_{min}} I^2_{CH(n)} + \sum_{n=n_{max}+1}^{n\to\infty} I^2_{CH(n)}}}{I_{CH(1)}}$$

This formula is used to determine whether the maximum theoretical performance of the active harmonic conditioner is compatible with the target objective. It can be simplified still further, if we consider the specific cas of Merlin Gerin products for which $n_{min}$ = 2 and $n_{max}$ = 23:

$$THD\ I(\%) = \frac{\sqrt{\sum_{n=24}^{n\to\infty} I^2_{CH(n)}}}{I_{CH(1)}}$$

Furthermore, the above nominal rating selection rule must be weighted by the following practical considerations:

- the harmonic spectrum of most loads is significant only in the band h3 to h13,
- the purpose of inserting the active harmonic conditioner is not to cancel the THD (I) but to limit it below a predefined level (e.g. 8%),
- An active harmonic conditioner can be chosen with a rating lower than $I_{N\,CA\,RMS}$, and then operate in permanent saturation (by permanent, automatic limitation of its rms current).

Finally, parallel-connection of a number of active harmonic conditioners at the same insertion point is technically feasible, a solution which may prove of interest for upgrading of a pre-equipped network.

## application examples

**Reduction of line distortions**

As regards high rise buildings or buildings occupying a large ground surface area, the main problem concerns the lengths of the lines between the point of common coupling (MV/LV transformer) and the loads.
This is because, irrespective of voltage wave quality at the origin of the installation and of the precautions taken for the lines (choice of cable diameter, splitting,...), voltage total harmonic distortion increases at the same time as «altitude» or distance!
As from a specific point, therefore, voltage distortion can be considered unacceptable in permanent mode, and the «shunt-type» active harmonic conditioner provides an interesting alternative to traditional solutions (e.g. isolation by suitable LV/LV coupling transformers).
Let us consider the example of a three-phase UPS supplying a set of «computer» loads at the end of a 60 m line. We then observe a voltage distortion of 10.44% (phase to phase) and of 15.84% (phase to neutral) at load level. This deterioration is the result of a combination of two factors, namely:

- UPS sensitivity (with non-PWM control) to the non-linear characteristic of the downstream current,
- the mainly inductive characteristic of the line which amplifies distortions.

The proposed solution is illustrated in figure 39 and is based on insertion of a «shunt type» active harmonic conditioner as close as possible to loads. Performances are then totally satisfactory with respect to the objective: the THD (U) drops to 4.9% phase to phase and to 7.2% phase to neutral.

**Combination of «shunt type» active harmonic conditioner and passive components**
**Effect on tariffs**

A pumping station is designed to maintain constant water pressure on the drinking water distribution network (see fig. 40). The motor-driven pump P1 is thus controlled by a variable speed drive with frequency converter.
In this particular instance, the main objective was compliance of the source current spectrum with the power utility's requirements. With no filtering device, the authorised harmonic emission level was:
■ greatly exceeded on order 5,
■ more or less reached on orders 7 and 11.
The choice made is a combination of smoothing reactors and a «shunt type» active harmonic conditioner: performances are shown in figure 41:
■ all the harmonic orders are well below authorised emission limits,
■ the current total harmonic distortion is reduced by 89%.

An advantage particularly appreciated by the customer is the reduction of his contracted power (in kVA).
This example also shows that the combination of an active harmonic conditioner + smoothing reactor is particularly suitable in view of the high degree of disturbance.

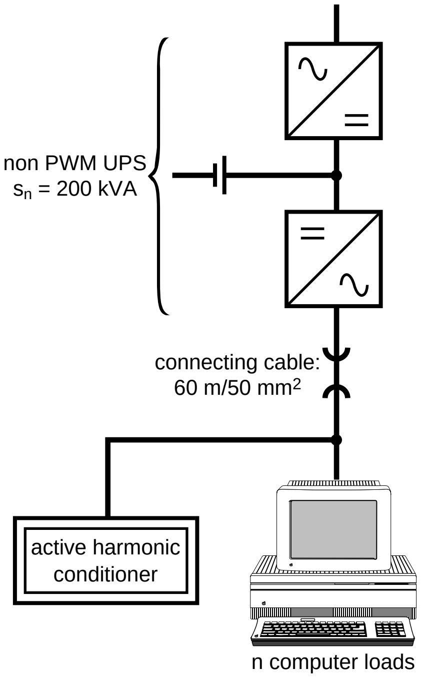



*fig. 39: using an active harmonic conditioner to treat voltage total harmonic distortion at the end of a 60 m cable.*

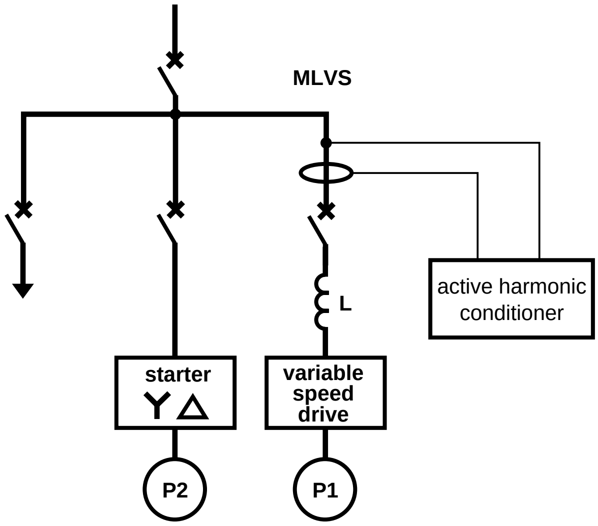



*fig. 40: pumping station diagram.*

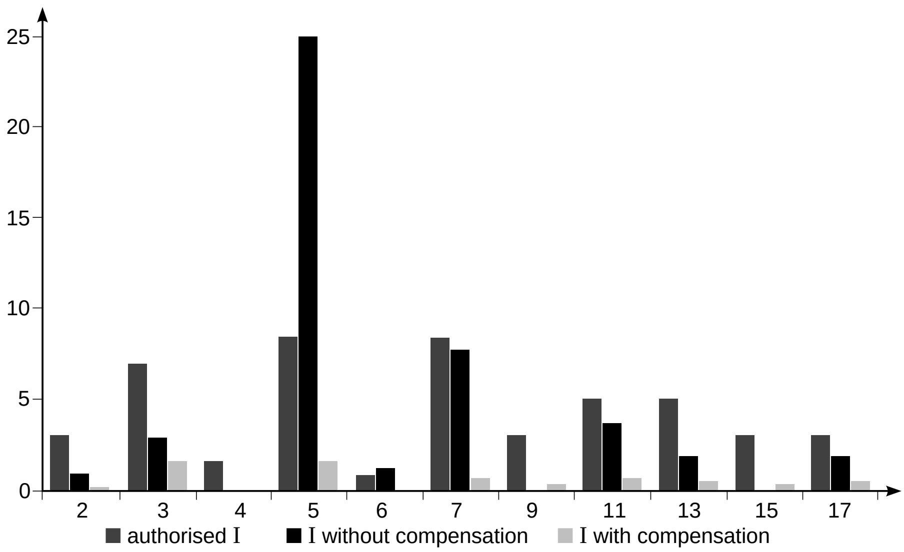



*fig. 41: spumping station - spectral representation of harmonic currents.*

# 5. conclusion

The profusion of non-linear loads makes harmonic distortion of power networks a phenomenon of increasing amplitude, the effects of which cannot be ignored since almost all the power network components are in practice affected.
Up to now the most popular solution was passive filtering. However an attractive alternative to this complex, non risk-free solution, is now commercially available in the form of active harmonic conditioners.
These devices use a structure of the static power converter type.
Consequently, semiconductor progress means that converters, which are normally harmonic disturbers, now form efficient, self-adaptive harmonic compensation devices .

The easy to use, self-adaptive «shunt type» active harmonic conditioner, which requires virtually no preliminary studies prior to use, is the ideal solution for harmonic compensation on a non-linear load or LV distribution switchboard. However it does not necessarily replace passive filters with which it can be combined advantangeously in some cases.

# appendix: review of harmonic phenomena

## definition and characteristic quantities

Joseph FOURIER proved that all non-sinusoidal periodic functions can be represented by a sum of sinusoidal terms, the first one of which, at the recurrence frequency of the function, is said to be fundamental, and the others, at multiple frequencies of the fundamental, are said to be harmonic. A DC component may complete these purely sinusoidal terms.

**FOURIER's formula:**

$$y(t) = Yo + \sum_{n=1}^{n=\infty} Yn\,\sqrt{2}\,\sin(n\,\omega\,t - \varphi_n),$$

where:

- Yo: DC component value, generally nil and considered hereafter to be nil,
- Yn: rms value of the nth harmonic component,
- $\omega$: angular frequency of the fundamental,
- $\varphi_n$: displacement of the nth harmonic component.

The notion of harmonics applies to all periodic phenomena irrespective of their nature, and particularly to AC current.

### rms value of a non-sinusoidal alternating quantity

There is similarity between the normal expression of this rms value calculated from the time evolution of the alternating quantity (y(t)) and the expression calculated using its harmonic content:

$$Yrms = \sqrt{\frac{1}{T}\int_0^T y^2(t)dt} = \sqrt{\sum_{n=1}^{n=\infty} Yn^2}$$

Note that when harmonics are present, the measuring instruments must have a wide bandwidth (> 1 kHz).

### Total harmonic distortion

Total harmonic distortion is a parameter globally defining distortion of the alternating quantity:

$$THD(\%) = 100\,\frac{\sqrt{\sum_{n=2}^{n=\infty} Yn^2}}{Y_1}$$

There is another definition which replaces the fundamental Y1 with the total rms value Yrms. This definition is used by some measuring instruments.

### Individual harmonic ratio

This quantity represents the ratio of the value of an harmonic over the value of the fundamental (Y1), according to the standard definition or over the value of the alternating quantity (Yrms).

$$Hn\% = 100\,\frac{Yn}{Y_1}$$

### (Frequency) spectrum

Representation of harmonic amplitude as a function of their order: harmonics value is normally expressed as a percentage of the fundamental.

### Power factor (PF) and Displacement Power Factor (DPF)

It is important not to confuse these two terms when harmonics are present, as they are equivalent only when currents and voltages are completely sinusoidal.

■ the power factor ($\lambda$) is the ratio between active power P and apparent power S:

$$\lambda = \frac{P}{S}$$

■ the displacement power factor ($\cos\varphi_1$) relates to fundamental quantities, thus:

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

In pure sinusoidal waveform:
$\cos\varphi_1 = \cos\varphi = \lambda$

### Distortion factor

The IEC 146-1-1 defines this factor as the ratio between the power factor and the displacement power factor

$$\cos\varphi_1 : \ \nu = \frac{\lambda}{\cos\varphi_1}$$

It is always less than or equal to 1.

### ■ Peak factor

The ratio of peak value over rms value of a periodic quantity.

$$Fc = \frac{Ypeak}{Yrms}$$

## origin and transmission

### Linear and non-linear loads

A load is said to be linear when there is a linear relationship (linear differential equation with constant factors) between current and voltage. In simpler terms, a linear load absorbs a sinusoidal current when it is supplied by a sinusoidal voltage: this current may be displaced by an angle $\varphi$ compared with voltage.
When this linear relationship is not verified, the load is termed non-linear. It absorbs a non-sinusoidal current and thus harmonic currents, even when it is supplied by a purely sinusoidal voltage (see fig. 42).

### Voltage and current total harmonic distortion

A non-linear load generates harmonic voltage drops in the circuits supplying it. In actual fact all upstream impedances need to be taken into consideration right through to the sinusoidal voltage source.
Consequently a load absorbing harmonic currents always has a non-sinusoidal voltage at its terminals. This is characterised by the voltage total harmonic distortion:

$$THD\% = 100\,\frac{\sqrt{\sum_{n=2}^{n=\infty}(Zn\ In)^2}}{U_1}$$

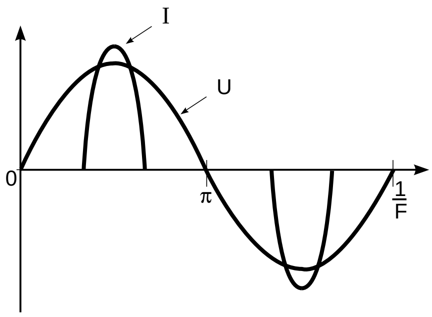



*fig. 42: current absorbed by a non-linear load.*

where Zn is the total source impedance at the frequency of harmonic n, and In the rms value of harmonic n.

The greater the non-linearity of the load, the larger the voltage distortion and the higher the order of the harmonic currents (inductive source impedance $2\pi\ f_1\ n\ L$).
Remember that current total harmonic distortion is:

$$100\frac{\sqrt{\sum_{n=2}^{n=\infty} In^2}}{I_1}$$

In order to illustrate the main types of behaviour of the main sources, figure 43 shows the evolution of their impedances as a function of frequency.

For further details, readers can consult «Cahier Technique» n° 159.

Do not forget that large diameter cables are mainly inductive and that small diameter cables have a non-negligible resistance.

## deforming loads

Most deforming loads are static converters. They may be powerful and few in number, or low-power and plentiful. Some examples are:

- fluorescent lamps, dimmers,
- computers,
- electrical household appliances (television sets, microwaves, induction plates).

Nowadays the proliferation of low power devices is chiefly responsible for increased voltage harmonic distortion in power networks.
Figure 44 illustrates the current absorbed by a few loads, and figure 45 the matching harmonic spectra (typical values).

## harmful effects of harmonics

### Effects on low current appliances and systems

Harmonic distortion may cause:

- malfunctioning of certain appliances which use voltage as a reference to generate semiconductor controls or as a time base to synchronise certain systems.
- disturbances by creating electromagnetic fields. Thus when «data transmission lines » circulate in the vicinity of power lines through which harmonic currents flow, they may be subjected to induced currents able to cause malfunctioning of the equipment to which they are connected.
- finally circulation of harmonic currents in the neutral provokes a voltage drop in this conductor: thus in the case of the TN-C earthing system, the frames of the various devices are no longer at the same potential, which may well interfere with information exchange between «intelligent» loads.

Moreover current circulates in the metallic structures of the building and creates disturbing electromagnetic fields.

### Effects on capacitors

Capacitor impedance decreases as frequency increases. Consequently if voltage is distorted, relatively strong harmonic currents flow in these capacitors whose aim is to improve the DPF. Furthermore the presence of reactors in the different parts of the installation reveals a risk of resonance with the capacitors which may considerably increase the amplitude of an harmonic in the capacitors. In practice, capacitors should never be connected on installations with a voltage total harmonic distortion greater than 8%.

### Effects on transformers

Harmonics generate additional losses in the transformers:

- losses due to Joule effect in the windings, accentuated by the skin effect,
- losses by hysteresis and eddy current in the magnetic circuits. To take these losses into consideration, a standardised empirical formula (NFC 52-114) is used to calculate the derating factor k to be applied to a transformer.

$$k = \frac{1}{\sqrt{1+0.1\sum_{n=2}^{n=\infty} H_n^2\ n^{1.6}}} \quad \text{where } H_n = \frac{In}{I_1}$$

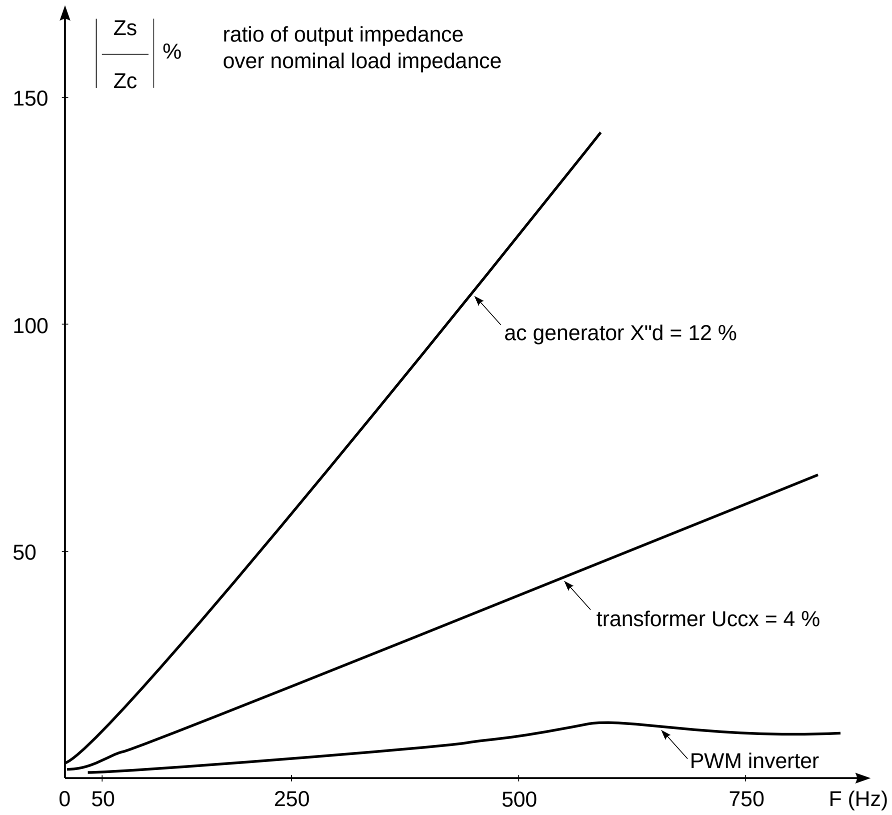



*fig. 43: output impedance of the various sources as a function of frequency.*

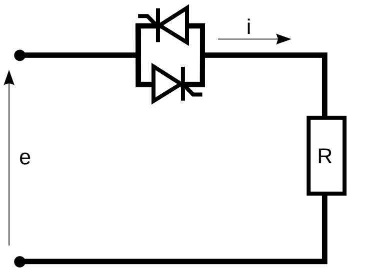
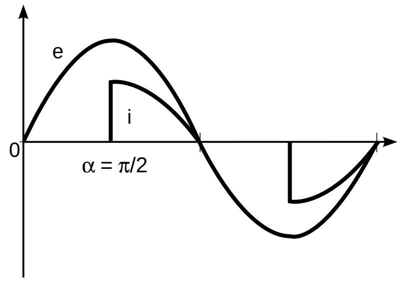
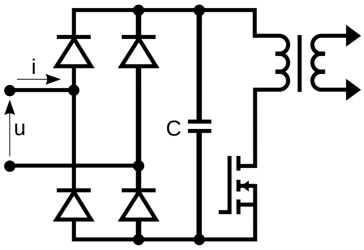
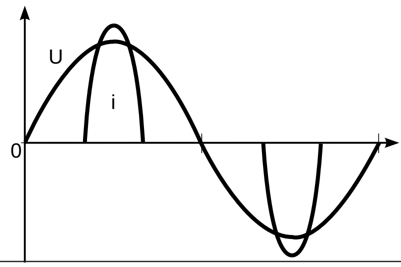
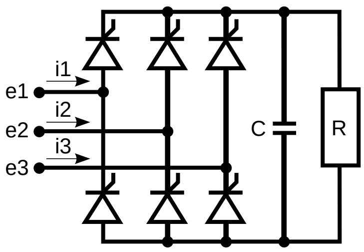
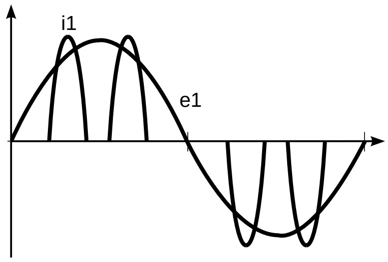
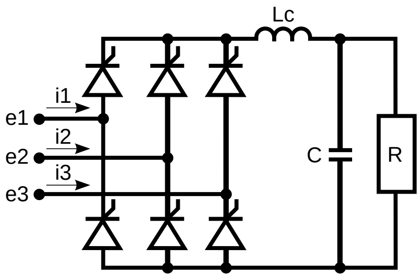
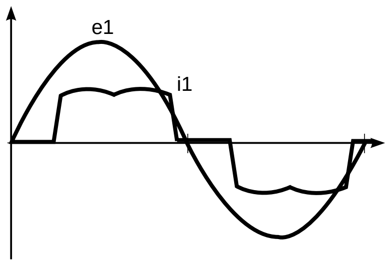
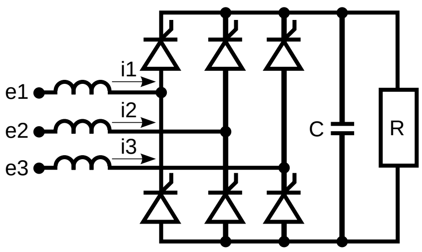
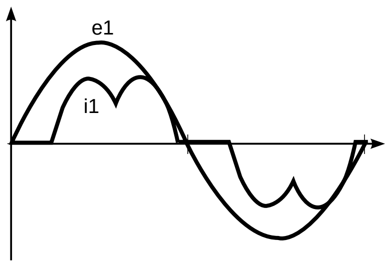
| CONVERTER | DIAGRAM | CURRENT WAVEFORM |
|---|---|---|
| 1: Light dimmer or heating regulator |   |   |
| 2: Switch mode power supply rectifier, for example:<br>■ computer<br>■ electrical household appliances |   |   |
| 3: Three-phase rectifier with front end capacitor, for example: variable speed drive for asynchronous motors |   |   |
| 4: Three-phase rectifier with DC filtering reactor, for example: battery charger. |   |   |
| 5: Three-phase rectifier with AC smoothing reactor, for example: high power UPS |   |   |

*fig. 44: curve of the current absorbed by some non-linear loads.*

For example where
$H_5$ = 25 % ; $H_7$ = 14 % ; $H_{11}$ = 9 % ; $H_{13}$ = 8 %,
the factor k is 0.91.

**Effect on ac generators**

In the same way as for the transformer, the harmonics create additional losses in the windings and magnetic circuit.
Furthermore the harmonics create pulsating torques which generate vibrations and additional overheating in the damping windings. Finally as the subtransient reactance is relatively large, the voltage total harmonic distortion quickly rises with the increase in harmonic currents.
In practice, limitation of the current total harmonic distortion to a value less than 20% is accepted, with a limit of 5% for each harmonic order. Beyond these values, manufacturers must be consulted as to the spectrum of current really absorbed by the loads.

**Effect on power lines and in particular on the neutral conductor**

Harmonic currents create additional losses in conductors accentuated by the skin effect.
Losses are even more serious when single-phase loads absorb harmonic currents 3 and multiples of 3. These currents are in phase and are added together in the neutral conductor.
With, for example, an harmonic 3 of 75%, the current flowing in the neutral is 2.25 times the fundamental. The current in each phase is only
$\sqrt{1+0.75^2}$ = 1.25 times the fundamental.
Special attention must thus be paid to the sizing of the neutral conductor when non linear loads are present. The TN-C earthing system is strongly advised against.

## standards and recommendations

Electricity is today regarded as a product, especially in Europe with the directive of July 25th 1985.
The EN 50160 standard defines its main characteristics at the customer's point of common coupling for a low voltage public supply network, and in particular the harmonic voltage levels (class 2 levels in the table in figure 47). These are the levels of compatibility in terms of electromagnetic compatibility (see fig. 46).
In addition to this European standard, the maximum levels of the various harmonic orders are defined in IEC 1000.
■ **for low voltage public supply networks:** IEC 10 000-2-2 and CIGRE recommendations.
■ **for medium and high voltage public supply networks:** IEC draft standard for medium voltage and CIGRE recommendations.
■ **for low voltage and medium voltage industrial installations:** IEC 1000-2-4.
By way of illustration, the table taken from this standard gives the harmonic levels of compatibility in three standard situations (classes) (see fig. 47).

To ensure these levels are not reached, **limits must be set for the disturbances emitted (emission level)** by devices either considered separately, or for a group of devices as regards their point of connection to the power network.
**IEC 1000-3-2 deals with low voltage and devices absorbing current of less than 16 A, and the IEC 1000-3-4 draft guide deals with devices absorbing current greater than 16 A.**
Although there is no standard for industrial applications, there is a sort of «consensus» concerning the notion of stages for authorisation of connection to the public supply network: stage 1 means automatic acceptance for low powers with respect to contracted power, stage 2 means acceptance with reservations (a single consumer must not exceed a level representing half the level of compatibility) and stage 3 means exceptional and provisional acceptance when the previous level is exceeded.
Finally, to guarantee proper operation of devices, **these devices must be able to withstand levels of disturbance greater than the levels of compatibility** given in figure 47 should these levels be overshot (permissible temporarily): this is their level of immunity.

| N° | $H_3$ | $H_5$ | $H_7$ | $H_9$ | $H_{11}$ | $H_{13}$ | $H_{15}$ | $H_{17}$ | $H_{19}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 54 | 18 | 18 | 11 | 11 | 8 | 8 | 6 | 6 |
| 2 | 75 | 45 | 15 | 7 | 6 | 3 | 3 | 3 | 2 |
| 3 | 0 | 80 | 75 | 0 | 40 | 35 | 0 | 10 | 5 |
| 4 | 0 | 25 | 7 | 0 | 9 | 4 | 0 | 5 | 3 |
| 5 | 0 | 33 | 3 | 0 | 7 | 2 | 0 | 3 | 2 |

*fig. 45: example of the harmonic spectrum of currents absorbed by the loads in figure 44.*

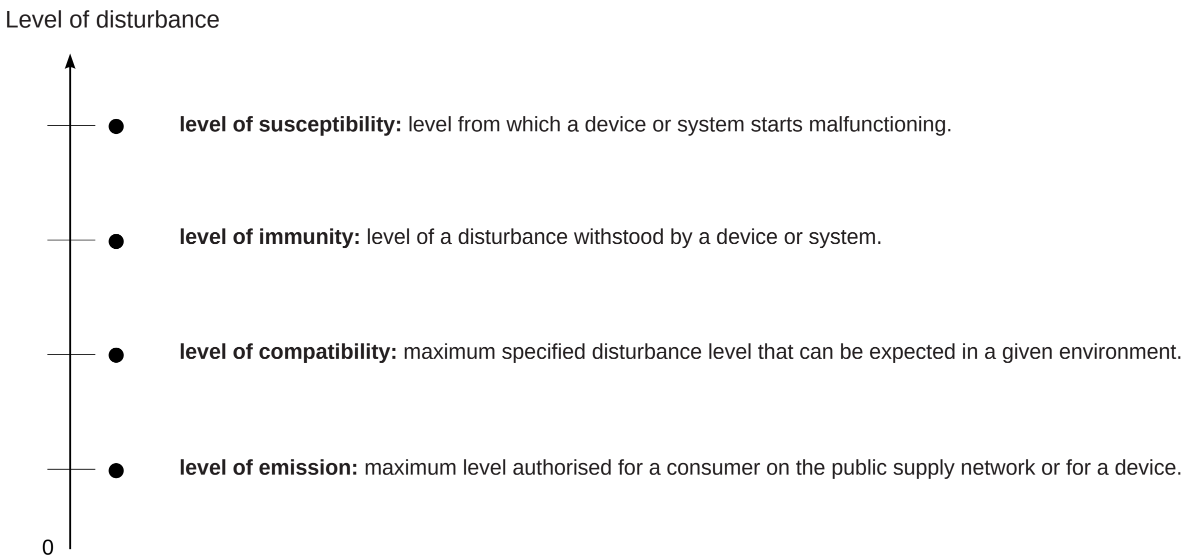



*fig. 46: the various levels of disturbance for compatibility of non linear/sensitive equipment.*

| harmonic order | class 1 (sensitive devices and systems) | class 2 (public and industrial supply networks) | class 3 (for connection of large non-linear loads) |
|---|---|---|---|
| 2 | 2 | 2 | 3 |
| 3 | 3 | 5 | 6 |
| 4 | 1 | 1 | 1.5 |
| 5 | 3 | 6 | 8 |
| 6 | 0.5 | 0.5 | 1 |
| 7 | 3 | 5 | 7 |
| 8 | 0.5 | 0.5 | 1 |
| 9 | 1.5 | 1.5 | 2.5 |
| 10 | 0.5 | 0.5 | 1 |
| 11 | 3 | 3.5 | 5 |
| 12 | 0.2 | 0.2 | 1 |
| 13 | 3 | 3 | 4.5 |
| TDH | 5% | 8% | 10% |

*fig. 47: ratio (as a %) of acceptable harmonic voltages (compatibility).*

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## Power Quality

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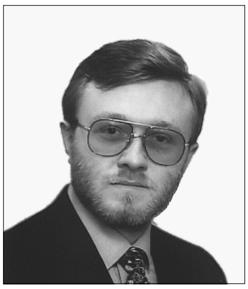
## Power Quality



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**He joined Schneider Electric in 1996, where he now conducts advanced research into the area of electrotechnical and electrical power systems.**

**ECT 199(e)** october 2001

# Power Quality

One of the properties of electricity is that some of its characteristics depend not only on the electricity producer/distributor but also on the equipment manufacturers and the customer. The large number of players combined with the use of terminology and definitions which may sometimes be imprecise partly explain why this subject area is so complex.

This "Cahier Technique" aims to facilitate exchanges on this topic between specialists and non-specialists, as well as customers, manufacturers, installers, designers and distributors. The clear terminology used should help avoid confusion. It describes the main phenomena causing degradation in Power Quality (PQ), their origins, the consequences for equipment and the main solutions. It offers a methodology for measuring the PQ in accordance with differing aims. Illustrated with practical examples for the implementation of solutions, it shows that only by observing best practice and by applying strict methodology (diagnostics, research, solutions, implementation and preventive maintenance) can users obtain the right quality of power supply for their requirements.

## Contents

# 1 Introduction

## 1.1 Context

The quality of electricity has become a strategic issue for electricity companies, the operating, maintenance and management personnel of service sector and industrial sites, as well as for equipment manufacturers, for the following main reasons:

- the economic necessity for businesses to increase their competitiveness,
- the widespread use of equipment which is sensitive to voltage disturbance and/or generates disturbance itself,
- the opening up of the electricity market.

**The economic necessity for businesses to increase their competitiveness**

- Reduction of costs linked to loss of supply continuity and problems of non-quality

The cost of disturbance (interruptions, voltage dips, harmonics, lightning overvoltages, etc.) is substantial. These costs must take into account losses in production and raw materials, restarting of production facilities, non-quality of production and delivery delays. The malfunction or shutdown of vital equipment such as computers, lighting and safety systems may put lives at risk (e.g. in hospitals, airport lighting systems, public and high-rise buildings, etc.).

Costs also include high quality, targeted preventive maintenance measures for anticipating possible problems. There is an increasing transfer of responsibility from the industrial user to the equipment manufacturer for the provision of site maintenance; manufacturers are now becoming electricity suppliers.

- Reduction of costs linked to oversized installations and energy bills

Other less obvious consequences of PQ degradation are:

- A reduction of installation energy efficiency, leading to higher energy bills
- Overloading of the installation, causing premature ageing and increasing the risk of breakdown, leading in turn to oversizing of distribution equipment

This is why professional users of electricity are keen to optimise the operation of their electrical installations.

**The widespread use of equipment which is sensitive to voltage disturbance and/or generates disturbance itself**

As a consequence of their numerous advantages (flexible operation, excellent efficiency, high performance levels, etc.), we have seen the development and widespread use of automated systems and adjustable speed drives in industry, information systems, and fluo-compact lighting in the service and domestic sectors. These types of equipment are both sensitive to voltage disturbance and generate disturbance themselves.

Their multiple use within individual processes requires an electrical power supply which can provide ever increasing performance in terms of continuity and quality. The temporary shutdown of just one element in the chain may interrupt the whole production facilities (manufacture of semi-conductors, cement works, water treatment, materials handling, printing, steelworks, petrochemicals, etc.) or services (data processing centres, banks, telecommunications, etc.).

Consequently, the work of the IEC on electromagnetic compatibility (EMC) has led to stricter and stricter standards and recommendations (limitations on disturbances emission levels, etc.).

**The opening up of the electricity market**

The rules governing the electricity sector are undergoing radical change: electricity production has opened up to competition, production is decentralised, and (large) electricity consumers now have the opportunity to choose their supplier.

In 1985, the Commission of the European Communities states (directive 85/374) that electricity is to be considered a product and as a consequence made it necessary to define its essential characteristics clearly.

In addition, in the context of liberalising energy markets, the search for competitiveness by electricity companies now means that quality has become a differentiating factor. A guarantee of quality is a potential criterion of choice for industrial users when looking for an energy supplier.

## 1.2 Objectives of Power Quality measurement

The measurement parameters and accuracy may differ depending on the application.

**Contractual application**

Within the context of a deregulated market, contractual relations may exist not only between the electricity supplier and the end user, but also between the power production company and transmission company or between the transmission company and distribution company. A contractual arrangement requires that terms are defined jointly and mutually agreed upon by all parties. The parameters for measuring quality must therefore be defined and the values compared with predefined, i.e. contractual limits.
This arrangement frequently requires the processing of significant quantities of data.

**Corrective maintenance**

Even where best practice is observed (single-line diagram, choice of protective devices and neutral point connection, application of appropriate solutions) right from the design phase, malfunctions may occur during operation:

■ Disturbances may have been ignored or under-estimated.

■ The installation may have changed (new loads and/or modification).

Troubleshooting is generally required as a consequence of problems of this nature.
The aim is frequently to get results as quickly as possible, which may lead to premature or unfounded conclusions.
Portable measurement systems (for limited periods) or fixed apparatus (for continuous monitoring) make it easier to carry out installation diagnostics (detection and archiving of disturbances and triggering of alarms).

**Optimising the operation of electrical installations**

To achieve productivity gains (operational economies and/or reduction of operating costs) correct operation of processes and sound energy management are required, both of which are factors dependent on PQ.
Operating, maintenance and management personnel of service sector and industrial sites all aim for a PQ which matches their requirements.

Complementary software tools to ensure control-command and continuous monitoring of the installation are thus required.

**Statistical surveys**

Such research requires a statistical approach on the basis of wide-ranging results from surveys generally carried out by the operators of transmission and distribution power systems.

■ Benchmark the general performances of a power system

These can be used, for example, to:

□ Plan and target preventive actions by mapping disturbance levels on a network. This helps reduce operating costs and improve control of disturbance. An abnormal situation with respect to an average level can be detected and correlated with the addition of new loads.
Research can also be carried out into seasonal trends or excessive demand.

□ Compare the PQ of various distribution companies in different geographical areas.
Potential customers may request details of the reliability of the electricity supply before installing a new plant.

■ Benchmark performances at individual points on the power system

These can be used to:

□ Determine the electromagnetic environment in which a future installation or a new piece of equipment may have to operate. Preventive measures may then be taken to improve the distribution power system and/or desensitise the customer power system.

□ Specify and verify the performance levels undertaken by the electricity supplier as part of the contract. This information on the electricity quality are of particular strategic importance for electricity companies who are seeking to improve competitiveness, satisfaction of needs and customer loyalty in the context of liberalising energy markets.

# 2 Degradation of PQ: origins - characteristics - definitions

## 2.1 General

Electromagnetic disturbances which are likely to disturb the correct operation of industrial equipment and processes is generally ranked in various classes relating to conducted and radiated disturbance:

- low frequency (< 9 kHz),
- high frequency (⩾ 9 kHz),
- electrostatic discharge.

Measurement of PQ usually involves characterising low frequency conducted electromagnetic disturbances (the range is widened to include transient overvoltages and transmission of signals on a power system):

- voltage dips and interruptions,
- harmonics and interharmonics,
- temporary overvoltages,
- swell,
- transient overvoltages,
- voltage fluctuations,
- voltage unbalance,
- power-frequency variations,
- DC in AC networks,
- signalling voltages.

It is not generally necessary to measure each type of disturbance.

The types can be placed in four categories, affecting the magnitude, waveform, frequency and symmetry of the voltage. Several of these characteristics may be modified simultaneously by any one type of disturbance. Disturbances can also be classified according to their permanent, semi-permanent or random nature (lightning, short-circuit, switching operations, etc.).

## 2.2 Voltage dips and interruptions

**Definitions**

A voltage dip is a sudden reduction of the voltage at a point in an electrical power system followed by voltage recovery after a short period of time from a few cycles to a few seconds (IEC 61050-161 ). A voltage dip is normally detected and characterised by the calculation of the root mean square value "rms (1/2)" over one cycle every half-cycle -each period overlaps the prior period by one half-cycle- (see **fig. 1**).

There is a dip to x % if the rms (1/2) value falls below the dip threshold x % of the reference value Uref. The threshold x is typically set below 90 (CENELEC EN 50160, IEEE 1159). The reference voltage Uref is generally the nominal voltage for LV power systems and the declared voltage for MV and HV power systems. A sliding reference voltage, equal to the voltage before the beginning of the disturbance is useful to study transference factor between different voltage systems.

A voltage dip is characterised by two parameters (see fig. 1b for x equal to 90):

- depth: ΔU (or its magnitude U),
- duration ΔT.

In case of a non-rectangular envelope, the duration is dependent on the selected dip threshold value (set by the user according to the objective). The duration is typically defined as the time interval during which the rms (1/2) is lower than 90 %. The shape of the envelope (for example in case of complex multi-step and not simple one step dip) may be assessed using several dip thresholds set and/or wave form capture. Time aggregation techniques may define an equivalent dip characterised by the smallest rms (1/2) value measured during the dip and the total duration of the dip. For three-phase systems phase aggregation techniques (mainly used for contractual applications) may define a single phase equivalent dip (characterised for example by the greatest depth on the three phases and the total duration).

Interruptions are a special type of voltage dip to a few percentage of Uref (typically within the range 1-10 %). They are characterised by one parameter only: the duration. Short interruptions last less than one minute (extended to three minutes depending on network operating conditions) and often result from tripping and automatic reclosure of a circuit breaker designed to avoid long interruptions which have longer duration. Short and long interruptions differ in both their origins and the solutions required to prevent or reduce their occurrence.

Voltage disturbances lasting less than a half-cycle T (ΔT < T/2) are regarded as transient. Different terms are used in the USA depending on the length of the dips (sags) and interruptions:

- instantaneous (T/2 < ΔT < 30 T),
- momentary (30 T < ΔT < 3 s),
- temporary (3 s < ΔT < 1 min),
- sustained interruption and undervoltage (ΔT > 1 min).

Depending on the context, the measured voltages may be between live conductors (between phases or between phase and neutral), between live conductors and earth (Ph/earth or neutral/earth), or between live conductors and the protective conductor.

In a 3-phase system, the characteristics ΔU and ΔT in general differ for each of the three phases. This is why a voltage dip must be detected and characterised separately on each phase.

A voltage dip is regarded as occurring on a 3-phase system if at least one phase is affected by the disturbance.

## Origins

- Voltage dips and short interruptions are mainly caused by phenomena leading to high currents, which in turn cause a voltage drop across the network impedances with a magnitude which decreases in proportion to the electrical distance of the observation point from the source of the disturbance.

Voltage dips and short interruptions have various causes:

- Faults on the transmission (HV) or distribution (LV and MV) networks or on the installation itself

The occurrence of faults causes voltage dips for all users. The duration of a dip is usually conditioned by the operating time of the protective devices. The isolation of faults by protective devices (circuit breakers, fuses) will produce interruptions (long or short) for users feeded by the faulty section of the power system. Although the power source is no longer present, network voltage may be maintained by the residual voltage provided by asynchronous or synchronous motors as they slow down (0.3 to 1 s) or voltage due to the discharge of capacitor banks connected to the power system.

Short interruptions are often the result of the operation of automated systems on the network such as fast and/or slow automatic reclosers, or changeover of transformers or lines. Users are subjected to a succession of voltage dips and/or short interruptions caused by intermittent arc faults, sequence of automatic reclosing (on overhead or mixed radial networks) intended to extinguish transient and semi-permanent faults or voltage feedback intended to locate the fault.

- Switching of large loads (asynchronous motors, arc furnaces, welding machines, boilers, etc.) compared to the short-circuit power.

- Long interruptions are the result of the definitive isolation of a permanent fault (requiring to repair or to replace any component before re-energising) by means of protective devices or by the intentional or unintentional opening of a device.

Voltage dips and interruptions are propagated to lower voltage levels via transformers. The number of phases affected and the depth of the voltage dips depend on the type of fault and the transformer coupling.

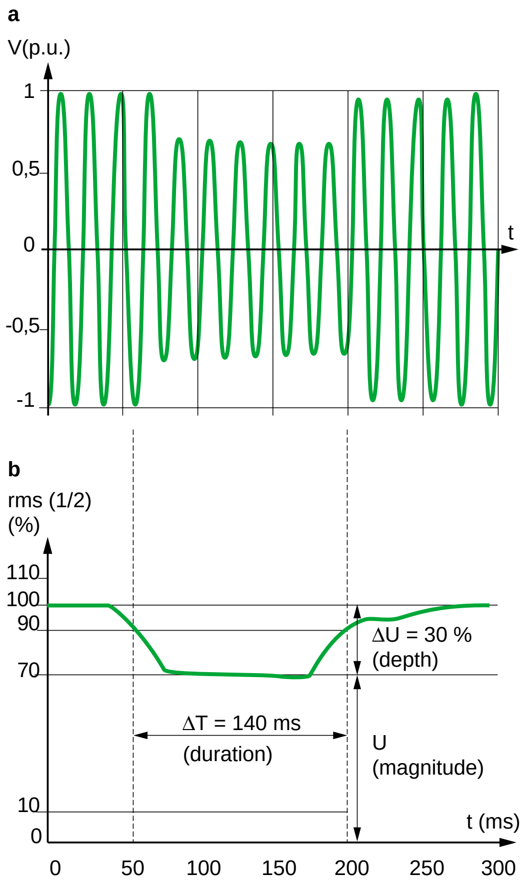



***Fig. 1**: Characteristic parameters of a voltage dip **[a]** waveform **[b]** rms (1/2).*

Overhead networks, which are exposed to bad weather, are subject to more voltage dips and interruptions than underground networks. However, an underground feeder connected to the same busbar system as overhead or mixed networks will suffer voltage dips which are due to the faults affecting overhead lines.

■ Transients ($\Delta T < T/2$) are caused, for example, by the energisation of capacitor banks, the isolation of a fault by a fuse or a fast LV circuit breaker, or by commutation notches from polyphase converters.

## 2.3 Harmonics and interharmonics

**Summary:**

All periodic functions (of frequency f) can be broken down into a sum of sinusoidal waves of frequency h x f (h is an integer). h is the harmonic order (h > 1). The first order component is the fundamental component.

$$y(t) = Y_0 + \sum_{h=1}^{\infty} Y_h \sqrt{2}\,\sin(2\,\pi\,h\,f + \varphi_h)$$

The rms is:

$$Y_{eff} = \sqrt{Y_0^2 + Y_1^2 + Y_2^2 + Y_h^2 + \ldots}$$

The THD (Total Harmonic Distortion) factor measures the signal distortion:

$$THD = \sqrt{\sum_{h=2}^{\infty} \left(\frac{Y_h}{Y_1}\right)^2}$$

Harmonics are mainly produced by non-linear loads which draw current of a different wave form from the supply voltage (see **fig. 2**). The spectrum of the harmonics depends on the nature of the load. Harmonic voltages occur across network impedances resulting distorted voltages which can disturb the operation of other users connected to the same supply. The value of the supply impedance at different harmonic frequencies thus has a vital role in limiting the voltage distortion. Note that if the source impedance is low (Scc is high), voltage distortion is low.

### Main sources of harmonics

These are loads which can be distinguished according to their domain, i.e. industrial or domestic.

■ Industrial loads

□ Power electronic equipment: drives, rectifiers (diode or thyristor), inverters or switching power supplies;

□ Loads using electric arcs: arc furnaces, welding machines, lighting (discharge lamps, fluorescent tubes). Starting motors using electronic starters and power transformers energisation also generates (temporary) harmonics.

Note that because of its multiple advantages (operating flexibility, excellent energy efficiency, high performance levels, etc.), the use of power electronic equipment is becoming more widespread.

■ Domestic loads with power inverters or switching power supplies such as television, microwave ovens, induction hotplates, computers, printers, photocopiers, dimmer switches, electrodomestic equipments, fluorescent lamps.

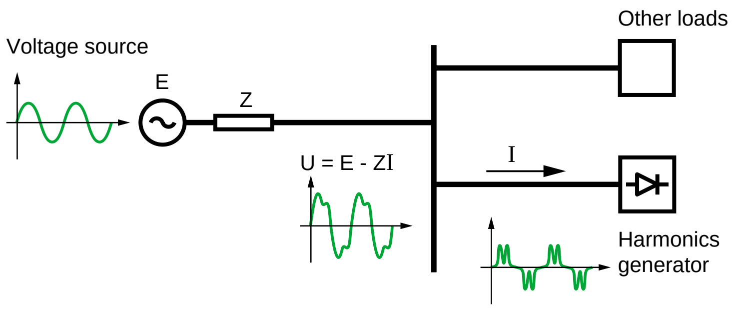



***Fig. 2**: Degradation of network voltage caused by a non-linear load.*

Although their individual power ratings are much less than for industrial loads, the combination of large numbers and simultaneous use over long periods creates significant sources of harmonic distortion. Note that the use of this type of equipment is increasing, as in some cases is the power rating.

### Harmonic levels

These generally vary according to the operating mode of the device, the hour and the season (heating and air conditioning).
The sources usually generate odd harmonic components (see **fig. 3**). Power transformer energisation, polarised loads (half-wave rectifiers) and arc furnaces generate even harmonics in addition to odd harmonics components.

Interharmonics are sinusoid components with frequencies which are not integer multiples of the fundamental component (they are located between harmonics). They are due to periodic or random variations in the power drawn by various devices such as arc furnaces, welding machines and frequency inverters (drives, cycloconverters). The remote control frequencies used by the power distributor are also interharmonics.

The spectrum may be discrete or continuous and vary randomly (arc furnaces) or intermittently (welding machines).
To study the short, medium and long term effects, the various parameters must be measured at time intervals which are compatible with the thermal time constant of the devices.

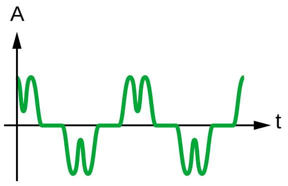
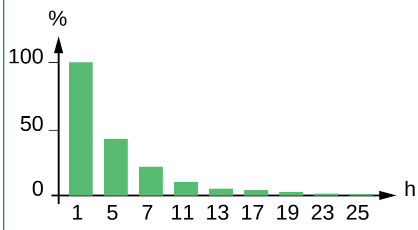
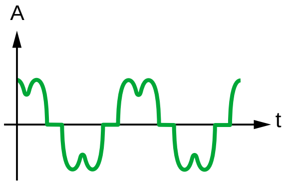
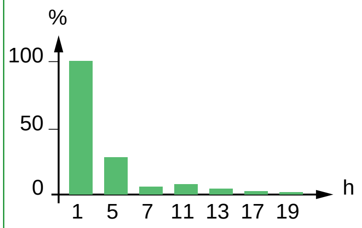
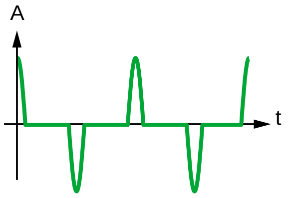
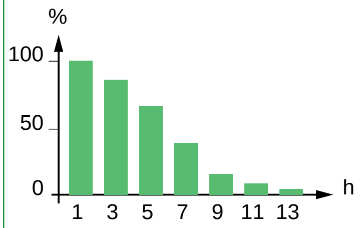
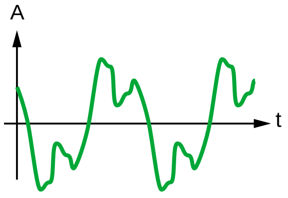
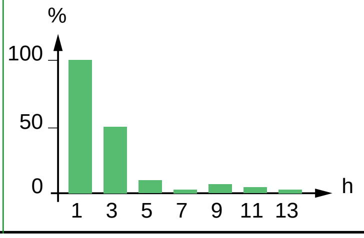
| Non-linear loads | Current waveform | Spectrum | THD |
|---|---|---|---|
| Adjustable speed drive |   |   | 44 % |
| Rectifier/charger |   |   | 28 % |
| Data processing load |   |   | 115 % |
| Fluorescent lighting |   |   | 53 % |

*Fig. 3: Characteristics of certain harmonics generators.*

## 2.4 Overvoltages

Where voltage is applied to a device and the peak value exceeds the limits defined in a standard or specification, this is an overvoltage (see "Cahiers Techniques" nos. 141, 151 and 179).

Overvoltages are of three types:

- temporary,
- switching,
- lightning.

They can appear:

- in differential mode (between live conductors: ph/ph – ph/neutral),
- in common mode (between live conductors and the exposed-conductive-part or earth).

**Temporary overvoltages**

By definition, these occur at power frequency (50/60 Hz). They have various origins:

- An insulation fault

When an insulation fault occurs between phase and earth in an isolated neutral system or impedance earthed neutral system, the voltage of the healthy phases to earth may reach the phase to phase voltage. Overvoltages on LV installations may come from HV installations via the earth of the HV/LV station.

- Ferroresonance

This is a rare non-linear oscillatory phenomenon which can often be dangerous for equipment and which is produced in a circuit containing a capacitor and a saturable inductance. Ferroresonance is often the apparent cause of malfunctions or the destruction of devices (see "Cahier Technique" no. 190).

- Break of the neutral conductor

Devices powered by the phase with the least load witness an increase in voltage (sometimes up to the phase to phase voltage).

- Faults on alternator regulators or tap changer transformer

- Overcompensation of reactive power

Shunt capacitors produce an increase in voltage from the source to their location.
This voltage is especially high during periods of low load.

**Switching overvoltages**

These are produced by rapid modifications in the network structure (opening of protective devices, etc.). The following distinctions are made:

- switching overvoltages at normal load,
- overvoltages produced by the switching on and off of low inductive currents,
- overvoltages produced by the switching of capacitive circuits (no-load lines or cables, capacitor banks). For example, the energisation of a capacitor bank produces a transient overvoltage in which the first peak may reach $2\sqrt{2}$ times the rms value of the nominal voltage and a transient overcurrent with a peak value of up to 100 times the rated current of the capacitor (see "Cahier Technique" no. 142).

**Lightning overvoltages**

Lightning is a natural phenomenon occurring during storms. A distinction is made between direct lightning strike (on a line or structure) and the indirect effects of lightning (induced overvoltages and increase in earth potential) (see "Cahiers Techniques" nos. 151 and 179).

## 2.5 Voltage variations and fluctuations

Voltage variations are variations in the rms value or the peak value with an amplitude of less than 10% of the nominal voltage.

Voltage fluctuations are a series of voltage changes or cyclical or random variations in the voltage envelope which are characterised by the frequency of variation and the magnitude.

- Slow voltage variations are caused by the slow variation of loads connected to the network.
- Voltage fluctuations are mainly due to rapidly varying industrial loads such as welding machines, arc furnaces or rolling mills.

## 2.6 Unbalance

A 3-phase system is unbalanced if the rms value of the phase voltages or the phase angles between consecutive phases are not equal. The degree of unbalance is defined using the Fortescue components, comparing the negative sequence component ($U1_i$) (or zero sequence component ($U1_o$)) of the fundamental to the positive sequence component ($U1_d$) of the fundamental.

$$\Delta Ui = \frac{\left|\overline{U1_i}\right|}{\left|\overline{U1_d}\right|} \text{ and } \Delta Uo = \frac{\left|\overline{U1_o}\right|}{\left|\overline{U1_d}\right|}$$

The following approximate formula can also be used: $\Delta Ui = \max_i \frac{V_i - Vavg}{Vavg}$

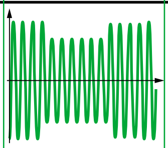
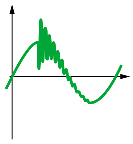
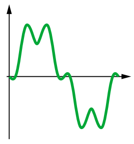
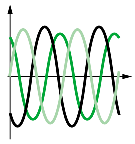
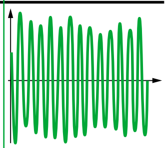
where Vi = phase voltage i and

$$V_{avg} = \frac{V1 + V2 + V3}{3}$$

The negative sequence (or zero sequence) voltage is produced by voltage drops along the network impedances due to negative sequence (or zero sequence) currents produced by unbalanced loads leading to non-identical currents on the three phases (LV loads connected between phase and neutral, or single-phase or 2-phase MV loads such as welding machines and induction furnaces).

Single-phase or 2-phase faults produce unbalance until tripping of the protective devices.

## 2.7 Summary

| **Disturbances** | Voltage dips | Overvoltages | Harmonics | Unbalance | Voltage fluctuations |
|---|---|---|---|---|---|
| **Characteristic waveforms** |  |  |  |  |  |
| **Origin of disturbance** | | | | | |
| ■ **Power system** | | | | | |
| □ Insulation fault, break of the neutral conductor... | Occasional | | | Occasional | |
| □ Switching, ferroresonance | | Occasional | | | |
| □ Lightning | | Occasional | | | |
| ■ **Equipment** | | | | | |
| □ Asynchronous motor | Occasional | | | | |
| □ Synchronous motor | Occasional | | Frequent | | |
| □ Welding machine | Occasional | | Frequent | Frequent | Frequent |
| □ Arc furnace | Occasional | | Frequent | Frequent | Frequent |
| □ Converter | | Frequent | Frequent | | |
| □ Data processing loads | | | Frequent | | |
| □ Lighting | | | Frequent | | |
| □ Inverter | | | Frequent | | |
| □ Capacitor bank | Occasional | Frequent | Frequent | | Occasional |

: Occasional phenomenon    : Frequent phenomenon

# 3 Effects of disturbance on loads and processes

Generally speaking, the effects of all disturbances can be classified in two ways:

- Instantaneous effects: unwanted operation of contactors or protective devices, incorrect operation or shutdown of a machine. The financial impact of the disturbance can be estimated directly.
- Deferred effects: energy losses, accelerated ageing of equipment due to overheating and additional electro-dynamic stress caused by the disturbance.

The financial impact (e.g. on productivity) is more difficult to quantify.

## 3.1 Voltage dips and interruptions

Voltage dips and interruptions disturb many types of devices connected to the network. They are the most frequent cause of Power Quality problems. A voltage dip or interruption of a few hundred milliseconds may have damaging consequences for several hours.

The most sensitive applications are:

- complete continuous production lines where the process cannot tolerate any temporary shutdown of any element in the chain (printing, steelworks, paper mills, petrochemicals, etc.),
- lighting and safety systems (hospitals, airport lighting systems, public and high-rise buildings, etc.),
- computer equipment (data processing centres, banks, telecommunications, etc.),
- essential auxiliary plant for power stations.

The paragraphs below cover the main consequences of voltage dips and interruptions on equipment used in the industrial, service and domestic sectors.

### Asynchronous motors

When a voltage dip occurs, the torque of an asynchronous motor (proportional to the square of the voltage) drops suddenly which slowdowns the motor. This slowdown depends on the magnitude and duration of the dip, the inertia of the rotating masses and the torque-speed characteristics of the driven load. If the torque developed by the motor drops below the resistant torque, the motor stops (stalls). Following an interruption, at the time of voltage recovery, the motor tends to re-accelerate and absorb current whose value is nearly its starting current, the duration of which depends on the duration of the interruption. Where there are several motors in an installation, the simultaneous restarting may produce a voltage drop in the upstream impedances on the network which will increase the duration of the dip and may make restarting difficult (long restarts with overheating) or even impossible (motor torque lower than the resistive torque).

Rapidly reconnecting (~ 150 ms) the power to an asynchronous motor which is slowing down without precautionary measures may lead to reclosing in opposition to the phase between the source and the residual voltage in asynchronous motors. In this case the first current peak may reach three times the start-up current (15 to 20 In) (see "Cahier Technique" no. 161).

The overcurrents and consequent voltage drops have consequences for the motor (excessive overheating and electro-dynamic force in the coils, which may cause insulation failures and torque shocks with abnormal mechanical stress on the couplings and reducers, leading to premature wear or even breakage) as well as other equipment such as contactors (wear or even fusion of the contacts). Overcurrents may cause tripping of the main general protective devices of the installation causing the process to shutdown.

### Synchronous motors

The effects are almost identical to those for asynchronous motors. Synchronous motors can however withstand deeper voltage dips (around 50 %) without stalling, owing to their generally greater inertia, the possibilities of overexcitation and the fact that their torque is proportional to the voltage. In the event of stalling, the motor stops and the entire complex start-up process must be repeated.

### Actuators

The control devices (contactors, circuit breakers with voltage loss coils) powered directly from the network are sensitive to voltage dips whose depth exceeds 25 % of Un. Indeed, for a standard contactor, there is a minimum voltage value which must be observed (known as the drop-out voltage), otherwise the poles will separate and transform a voltage dip (lasting a few tens of milliseconds) or a short interruption into a long interruption until the contactor is reenergized.

### Computer equipment

Computer equipment (computers, measurement apparatus) today occupy a dominant position in the monitoring and control-command of installations, management and production. All of this equipment is sensitive to voltage dips with depth greater than 10 % Un.

The ITIC (Information Technology Industry Council) curve – formerly CBEMA curve – shows on a duration-amplitude scale, the typical withstand of computer equipment to voltage dips, interruptions and overvoltages (see **fig. 4**).

Operation outside these limits leads to loss of data, incorrect commands, and shutdown or malfunction of equipment. The consequences of the loss of equipment functions depend in particular on the restart conditions when voltage is restored. Certain equipment, for example, has its own voltage dip detection devices which enable data to be backed up and ensure safety by interrupting calculation processes and any incorrect commands.

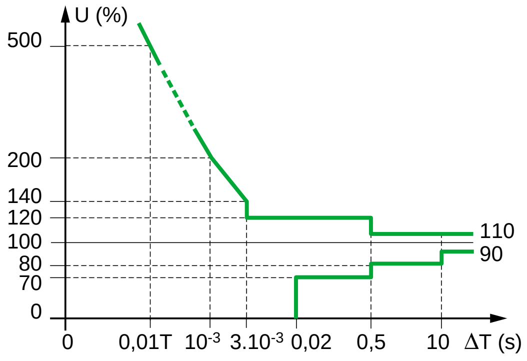



***Fig. 4**: Typical withstand as defined by the ITIC curve.*

### Adjustable speed machines

The problems of voltage dips applied to variable speed drives are:

- It is not possible to supply sufficient voltage to the motor (loss of torque, slowdown).
- The control circuits supplied directly by the network cannot function.
- There is overcurrent when voltage recovers (the drive filter capacitor is recharged).
- There is overcurrent and unbalanced current in the event of voltage dips on a single phase.
- There is loss of control of DC drives functioning as inverters (regenerative braking).

Adjustable speed drives usually trip out when a voltage dip deeper than 15 % occurs.

### Lighting

Voltage dips cause premature ageing of incandescent lamps and fluorescent tubes.

Voltage dips deeper than or equal to 50 % with a duration of around 50 ms will extinguish discharge lamps. The lamp must then be left off for several minutes to cool the bulb before it is turned on again.

## 3.2 Harmonics

The consequences of harmonics are linked to the increase in peak values (dielectric breakdown), rms values (excessive overheating) and to the frequency spectrum (vibration and mechanical stress) of voltages and currents.

The effects always have an economic impact resulting from the additional costs linked to:

- degradation in the energy efficiency of the installation (energy loss),
- oversizing of equipment,
- loss of productivity (accelerated ageing of equipment, unwanted tripping).

Malfunctions are probable with a harmonic distortion factor of greater than 8 % of the voltage. Between 5 and 8 %, malfunctions are possible.

- Instantaneous or short term effects

□ Unwanted operation of protective devices: harmonics have a harmful influence mainly on thermal control devices. Indeed, when protective devices of this type calculate the rms value of the current from the peak value, there is a risk of error and unwanted operation even during normal operation with no overload.

□ Disturbances induced by low current systems (remote control, telecommunications, hi-fi systems, computer screens, television sets).

□ Abnormal vibrations and acoustic noise (LV switchboards, motors, transformers).

□ Destruction of capacitors by thermal overload
If the actual frequency of the upstream capacitor-network system is similar to a harmonic order, this causes resonance and amplification of the corresponding harmonic.

□ Loss of accuracy of measurement instruments
A class 2 induction energy meter will produce in current and voltage, a 0.3 % additional error in the presence of 5 % of harmonic 5.

- Long term effects

Current overload produces excessive overheating and leads to premature ageing of equipment:

□ Overheating of sources: transformers, alternators (through increased joule and iron losses).

- Mechanical stress (pulse torque in asynchronous machines).
- Overheating of equipment: phase and neutral conductors through increased joule and dielectric losses. Capacitors are especially sensitive to harmonics as their impedance decreases in proportion to the harmonic order.
- Destruction of equipment (capacitors, circuit breakers, etc.).

Overload and excessive overheating of the neutral conductor may result from the presence of third harmonic (and multiples of 3) currents in the phase conductors which add in the neutral. The TNC neutral earthing system uses the same conductor for neutral and protection purposes. This conductor interconnects the installation earth, including the metal structures of the building. Third harmonic (and multiples of 3) currents will flow through these circuits and produce variations in potential with the following results:

- corrosion of metal parts,
- overcurrent in the telecommunication links between the exposed-conductive-part of two devices (for example, printer and computer),
- electromagnetic radiation causing screen disturbance (computers, laboratory apparatus).

The table in **figure 5** summarises the main effects of harmonics and the normal permitted levels.

Interharmonics affect remotely-controlled devices and produce a phenomenon known as flicker.

| Equipment | Effects | Limits |
|---|---|---|
| **Power capacitors** | Overheating, premature ageing (breakdown), resonance. | I < 1.3 In, (THD < 83 %)<br>or U < 1.1 Un<br>for 12 hrs/days at MV<br>or 8 hrs/days at LV |
| **Motors** | Losses and excessive overheating.<br>Reduction of capacity for use at full load.<br>Pulse torque (vibrations, mechanical stress)<br>Noise pollution. | HVF ⩽ 2 %<br>for usual asynchronous motors |
| **Transformers** | Losses (ohmic-iron) and excessive overheating.<br>Mechanical vibrations. Noise pollution. | |
| **Circuit breakers** | Unwanted tripping (exceeding voltage peak values, etc.). | $U_h / U_1 \leqslant$ 6 to 12 % |
| **Cables** | Additional dielectric and ohmic losses (especially in the neutral conductor if third harmonic currents present). | THD ⩽ 10 %<br>$U_h / U_1 \leqslant 7$ % |
| **Computers** | Operating problems. | $U_h / U_1 \leqslant 5$ % |
| **Power electronics** | Problems related to waveform (commutation, synchronisation). | |

$HVF = \sqrt{\sum_{h=2}^{13} U_h^2 / h}$ (Harmonic Variation Factor according to IEC892)

*Fig. 5: Effects of harmonics and practical limits.*

## 3.3 Overvoltages

The consequences are extremely varied according to the period of application, repetitivity, magnitude, mode (common or differential), gradient and frequency:

- Dielectric breakdown, causing significant permanent damage to equipment (electronic components, etc.).
- Degradation of equipment through ageing (repetitive rather than destructive overvoltages).
- Long interruptions caused by the destruction of equipment (loss of sales for distribution company, loss of production for industrial companies).
- Disturbance in control system and low current communication circuits (see "Cahier Technique" no. 187).
- Electrodynamic and thermal stress (fire) caused by:
  - Lightning (usually)

Overhead networks are most vulnerable to lightning, but installations supplied by underground networks may also be affected by stress due to high voltage if lightning strikes close to the site.

□ Switching overvoltages: these are repetitive and their probability of occurrence is considerably higher than that of lightning, with a longer duration.

They can lead to degradation as serious as that caused by lightning.

## 3.4 Voltage variations and fluctuations

As fluctuations have a magnitude no greater than ± 10 %, most equipment is not affected.
The main effect of voltage fluctuations is a fluctuation in the luminance of lamps (flicker).
The physiological strain (visual and nervous fatigue) depends on the magnitude of the fluctuations, the repetition rate of the variations, the composition of the spectrum and the duration of the disturbance.
There is however a perceptibility threshold (the amplitude as a function of the variation frequency) defined by the IEC below which flicker is no longer visible.

## 3.5 Unbalance

The main effect is the overheating of 3-phase asynchronous machines.
In fact, the zero sequence reactance of an asynchronous machine is equivalent to its reactance during the start-up phase. The current unbalance factor will thus be several times that of the supply voltage. Phase currents can thus differ considerably. This increases the overheating of the phase(s) which the highest current flows through and reduces the operating life of the machine.
In practice, a voltage unbalance factor of 1 % over a long period, and 1.5 % over a few minutes is acceptable.

## 3.6 Summary

| **Equipment** | **Sensitivity to disturbance** | | | | | |
|---|---|---|---|---|---|---|
| | Voltage dips < 0.5 s | Voltage dips > 0.5 s | Overvoltages | Harmonics | Unbalance | Voltage fluctuation |
| ■ Asynchronous motor | | ■ | | ■ | ■ | |
| ■ Synchronous motor | | ■ | | ■ | ■ | |
| ■ Actuator | | ■ | | | | |
| ■ Speed drive | ■ | ■ | ■ | ■ | ■ | |
| ■ Data processing load, numerical control | ■ | ■ | ■ | ■ | ■ | |
| ■ Induction furnace | | | ■ | | | |
| ■ Lighting | | | ■ | ■ | | ■ |
| ■ Capacitor bank | | | ■ | ■ | | |
| ■ Transformer | | | ■ | ■ | | |
| ■ Inverter | ■ | ■ | | | ■ | |
| ■ Circuit breaker | | | ■ | ■ | | |
| ■ Cable | | | ■ | ■ | | |

# 4 Level of Power Quality

## 4.1 Evaluation methodology

**Contractual application**

The contract must state:

- Its duration.
- The parameters to be measured.
- The contractual values.
- The measurement point(s).
- The voltages measured: these voltages (between phases and/or between phase and neutral) must be the equipment supply voltages.
- For each parameter measured the choice of measurement method, the time interval, the measurement period (e.g. 10 minutes and 1 year for the voltage amplitude) and the reference values; for voltage dips and interruptions, for example, the reference voltage, detection thresholds and the distinction between long and short interruptions must be defined.
- The measurement accuracy.
- The method of determining penalties in the event of one party failing to honour the terms of the contract.
- Clauses in the event of disagreement concerning the interpretation of the measurements (intervention of third parties, etc.).
- Data access and confidentiality.

**Corrective maintenance**

This is generally the consequence of incidents or malfunctions during operation requiring troubleshooting in order to apply corrective measures.
The usual steps are:

- Data collection

This involves the collection of information such as the type of load, the age of the network components and the single-line diagram.

- Search for symptoms

This involves identifying and locating the equipment subject to disturbance, determining the time and date (fixed or random) when the problem occurred, any correlation with particular meteorological conditions (strong winds, rain, storm) or recent modification of the installation (installation of new machines, modification of the power system).

- Examination of the installation

This phase is sometimes sufficient for quickly determining the origin of the malfunction. Environmental conditions such as humidity, dust and temperature must not be overlooked.
The installation, especially the wiring, circuit breakers and fuses, have to be checked.

- Monitor the installation

This step consists in equipping the site with measurement apparatus to detect and record the event where the problem originated. It may be necessary to place instruments at several points in the installation, especially (where possible) close to the equipment subject to disturbance.

The apparatus detects events when the thresholds of the parameters used to measure the Power Quality are exceeded, and records the data characterising the event (for example date, time, depth of voltage dip, THD). The waveforms just before, during and after the disturbance can also be recorded. The threshold settings must match the sensitivity of the equipment.

When using portable apparatus, the duration of the measurements must be representative of the operating cycle of the factory in question (e.g. one week). It must always be assumed that the disturbance will recur.

Fixed apparatus can be used for continuous monitoring of the installation. If the apparatus settings are correct, it will carry out prevention and detection by recording each occurrence of disturbance. The data can be displayed locally or remotely via an Intranet or Internet connection. This can be used to diagnose events as well as to anticipate problems (preventive maintenance). This is the case with apparatus in the Power Logic System range (Circuit Monitor - Power Meter), Digipact and the latest generation of Masterpact circuit breakers fitted with Micrologic P trip release (see **fig. 6**).

Records of disturbance from the distributor's power system which have caused damage (destruction of equipment, production losses, etc.) may also prove useful when negotiating compensation claims.

■ Identification of origin

The signature (waveform, profile of rms value) of the disturbance can in general be used by experts to locate and identify the source of the problem (fault, motor starting, capacitor bank energisation, etc.).
The simultaneous recognition of the signature for the voltage and the current can be used to determine if the disturbance is sourced upstream or downstream of the measurement point. The disturbance may come from either the installation or the distribution power system.

■ Definition and choice of mitigation solutions

A list of solutions and costings is prepared. The choice of solution is often made by comparing the cost with the potential lost earnings in the event of disturbance.
After implementing a solution, it is important to verify, via measurement, that it is effective.

### Optimising the operation of electrical installations

The operation of electrical installations can be optimised through three complementary actions:

■ Saving energy and reducing energy bills:

□ making users aware of costs,

□ assigning costs internally (by site, department or product line),

□ locating potential economies,

□ managing peaks in consumption (load shedding, standalone sources),

□ optimising the power contract (reduction in subscribed power demand),

□ improving the power factor (reduction in reactive power).

■ Ensuring the Power Quality:

□ displaying and monitoring the measurement parameters for Power Quality,

□ detecting problems in advance (monitoring of harmonics and neutral current, etc.) for preventive maintenance purposes.

■ Ensuring continuity of service:

□ optimising maintenance and operation,

□ becoming acquainted with the network in real time,

□ monitoring the protection plan,

□ diagnosing faults,

□ reconfiguring a network following a fault,

□ ensuring an automatic source transfer.

Software tools are used for the control-command and monitoring of the installation. They can be used for example to detect and archive events, monitor circuit breakers and protection relays in real time, control circuit breakers remotely, and generally make use of the possibilities of communicating devices (see fig. 6).

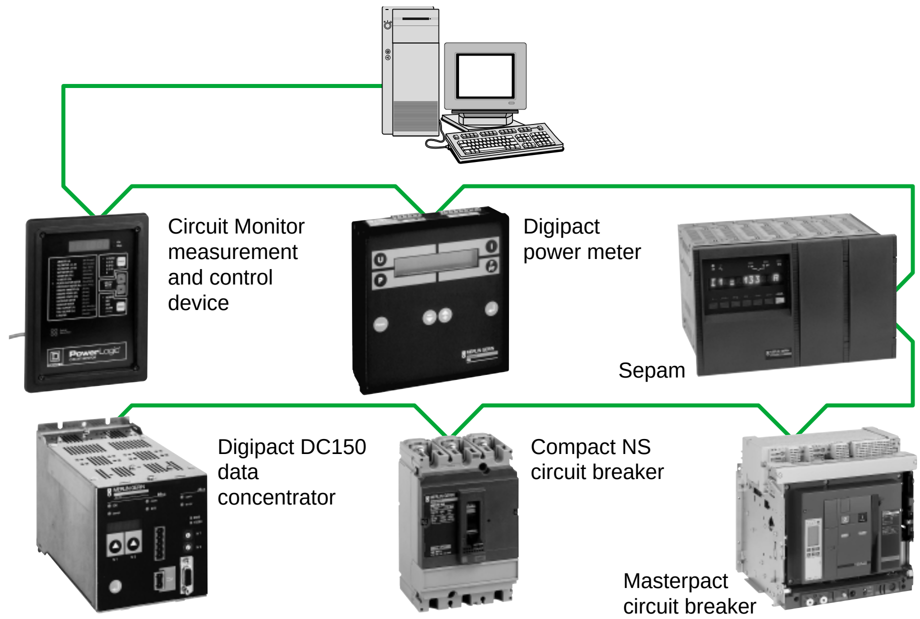



*Fig. 6: Some communicating products (Merlin Gerin brand).*

## 4.2 EMC and planning levels

### Electromagnetic compatibility (EMC)

Electromagnetic compatibility is the ability of an equipment or system to fonction satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment (IEC 60050-161).

The aim of electromagnetic compatibility is to ensure that:

- The emission of disturbances from each separate source is such that the combined emission from all sources does not exceed the expected levels of disturbance in the environment.
- The immunity level of the equipment gives the appropriate level of performance for the expected disturbance in three classes of environment (see **fig. 7**).

Note that the environment is also determined by the characteristics specific to the user installation (single-line diagram, types of load, etc.) and by the characteristics of the supply voltage.

One way of ensuring compatibility levels is to specify the emission limits of user installations with a sufficient margin below the compatibility level. In practice this is possible for large installations (IEC 61000-3-6, IEC 61000-3-7). For other installations (e.g. LV) the "product" standards specify emission limits for families of equipment (e.g. standard IEC 61000-3-2 imposes emission limits on current harmonics for loads under 16 A).

In certain cases, technical solutions must be applied to keep the emission levels below the prescribed levels.

### Voltage characteristics

The method used to evaluate the actual voltage characteristics at a given point on the network and to compare them to the predefined limits is based on a statistical calculation over a given measurement period. For example, for the harmonic voltage the measurement period is one week: 95 % of the rms values calculated over successive periods of 10 minutes must not exceed the specified limits.

### Planning levels

These are the internal quality objectives specified by the network operator which are used to evaluate the impact of all disturbance-producing loads on the network. They are usually equal to or below the compatibility levels.

### Summary

**Figure 8** summarises the relations between the various levels of disturbance.

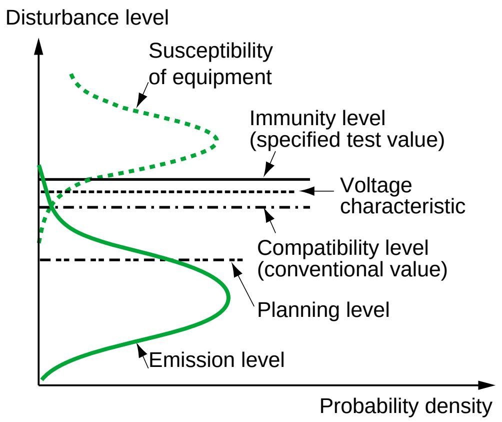



*Fig. 8: Relations between the various levels of disturbance.*

| Disturbances | Class 1 | Class 2 | Class 3 |
|---|---|---|---|
| Voltage variations $\Delta U/U_N$ | ± 8 % | ± 10 % | +10 % -15 % |
| Voltage dips(1)<br>$\Delta U / U_N$<br>$\Delta T$ (number of half-cycle) | <br>10 % to 100 %<br>1 | <br>10 % to 100 %<br>1 to 300 | <br>10 % to 100 %<br>1 to 300 |
| Short interruption (s) | none | – | ⩽ 60 |
| Voltage unbalance $U_i / U_d$ | 2 % | 2 % | 3 % |
| Frequency variations $\Delta f / f_N$ | ± 1 % | ± 1 % | ± 2 % |

(1) These values are not compatibility levels: they are given for indicative purposes only.

*Fig. 7: Compatibility levels according to IEC 61000-2-4.*

# 5 Solutions for improving PQ

A degradation of quality may lead to a change in behaviour, performance or even the destruction of equipment and dependent processes with possible consequences for the safety of personnel and additional economic costs.
This assumes three elements:

- one or more generators of disturbance,
- one or more loads sensitive to the disturbance,
- a channel for the disturbance to be propagated between them.

The solutions consist in taking action with regard to all or part of the three elements, either globally (the installation) or locally (one or more loads).
The solutions can be implemented to:

- correct a malfunction in an installation,
- take preventive action when polluting loads are to be connected,
- ensure the installation conforms to a standard or to the power distributor's recommendations,
- reduce energy bills (reduction of subscribed power in kVA, reduction in consumption).

Loads are not sensitive to the same disturbance and have different levels of sensitivity, the solution adopted, as well as being the best from a technical and economic point of view, must ensure an appropriate level of PQ which meets actual requirements.
It is vital that specialists carry out a prior diagnosis to determine the nature of the disturbance to be prevented (e.g. remedies may differ depending on the duration of an interruption). This determines the effectiveness of the chosen solution. The definition, choice, implementation and maintenance (to ensure long-term effectiveness) of solutions must also be carried out by specialists.
The value of the choice and implementation of a solution depends on:

- The required level of performance

Malfunction is not permitted if it would put lives at risk (e.g. in hospitals, airport lighting systems, lighting and safety systems in public buildings, auxiliary plant for power stations, etc.).

- The financial consequences of malfunction

Any unprogrammed stop, even when very short, of certain processes (manufacture of semi-conductors, steelworks, petrochemicals, etc.) results in loss or non-quality of production or even restarting of production facilities.

- The time required for a return on the investment

This is the ratio of financial losses (raw materials, production losses, etc.) caused by the non-quality of electrical power and the cost (research, implementation, operation, maintenance) of the solution.

Other criteria such as practices, regulation and the limits on disturbance imposed by the distributor must also be taken into account.

## 5.1 Voltage dips and interruptions

The network architecture, automated power restart systems, the reliability of equipment, the presence of a control-command system and maintenance policy all play an important role in the reduction and elimination of interruptions.

Correct diagnosis is vital before choosing an effective solution. For example, at the point of common coupling (the customer's electricity input), it is important to determine whether the voltage dip is coming from the customer's installation (with a corresponding increase in current) or from the distribution power system (no increase in current).
Different types of solution exist.

**Reducing the number of voltage dips and interruptions**

Distributors can take certain measures such as making their infrastructure more reliable (targeted preventive maintenance, modernisation, underground installation) or restructuring power systems (shortening feeders). For impedance earthed neutral power systems, they can also replace auto-reclosing circuit breakers with shunt circuit breakers which present the major advantage of not causing interruptions on a damaged feeder in the event of a transient earth fault (reducing the number of short interruptions).

These circuit breakers allow the extinction of transient earth faults by cancelling the voltage to the fault terminals for at least 300 ms by earthing the single faulty phase at the substation busbars. This does not alter the voltage between phases supplying the customer.

**Reducing the duration and depth of voltage dips**

■ At power system level

□ Increasing the possibilities of ring connections (new substations, ring closing switch)

□ Improving the performance of electrical protective devices (selectivity, automatic power restart, remote control devices on the network, remote management, replacement of spark gaps with surge arresters, etc.)

□ Increasing the network short-circuit power

■ At equipment level

Decrease the power consumed by the switched large loads with real time reactive compensators and soft starters which limit current peaks (and mechanical stress).

**Increasing immunity of industrial and service installations**

The general principle for ensuring that equipment is immune to voltage dips and interruptions is to compensate for a lack of power with an energy storage device between the distribution power system and the installation. The availability of the storage device has to be greater than the duration of the disturbances to which the system has to be immune to.
The information required when choosing mitigation solutions is:

■ the quality of the source (maximum level of existing disturbances),

■ the load requirements (voltage sag ride-through capability in the duration-depth scale).

Only by careful analysis of the process and of the technical and financial consequences of disturbances can these two elements be reconciled. There are various possible solutions to provide immunity depending on the power required by the installation and the duration of the voltage dip or interruption. It may well be helpful to study solutions by making a distinction between power supplies for control systems and regulation systems and those for motors and large power consumers. Indeed, a voltage dip or interruption (even of short duration) may be sufficient to open all of the contactors whose coils are supplied by the power circuit. Loads controlled by the contactors are thus no longer supplied when the voltage is restored.

**Increasing immunity of the control system**

The increase of immunity of a process is in general based on providing immunity to the control system.
In general, the control system is not of high power and is thus extremely sensitive to disturbances. It is therefore often more economical to immunise only the control system rather than the equipment power supply.
Maintaining control of machines assumes:

■ There will be no risk to the safety of personnel or equipment when the voltage is restored.

■ The loads and processes tolerate a short interruption in the power circuit (high inertia or slowdown is tolerated) and can be restarted on the fly when the voltage is restored.

■ The source can ensure that all of the equipment can be supplied simultaneously (in the case of a replacement source) and provide the inrush current caused by the simultaneous restart of several motors.

The solutions consist in powering all of the contactor coils from a reliable auxiliary source (battery or rotating set with flywheel), or in using an off-delay relay, or in using a rectifier and a capacitor connected in parallel with the coil.

**Increasing immunity of the equipment power supply**

Certain loads cannot withstand the expected disturbance levels, i.e. neither voltage dips nor interruptions. This is the case for "priority" loads such as computers, lighting and safety systems (hospitals, airport lighting systems, public buildings) and continuous production lines (manufacture of semi-conductors, data processing centres, cement works, water treatment, materials handling, paper industry, steelworks, petrochemicals, etc.).
The following different technical solutions are possible depending on the power required by the

installation and the duration of the voltage dip or interruption.

■ Solid state uninterruptible power supply (UPS)

A UPS consists of three main elements:

□ a rectifier-charger, powered from the main supply, to convert AC voltage to DC,

□ a flywheel and/or battery (kept charged) which on interruption provide the necessary power for the load via the inverter,

□ a DC-AC inverter.

Two technologies are currently in use: on-line and off-line.

□ On-line technology

During normal operation, power is supplied continuously via the inverter without drawing on the battery. This, for example, is the case for MGE-UPS brand Comet and Galaxy UPS units. They ensure continuity (no changeover delays) and quality (voltage and frequency regulation) of the power supply for sensitive loads ranging from a few hundred to several thousand kVA.

Several UPS can be connected in parallel to obtain more power or to provide redundancy.

In the event of overload, power is provided by the static contactor (see **fig. 9**) from network 2 (which may be combined with network 1).

Power is maintained without interruption via a maintenance by-pass.

□ Off-line (or stand-by) technology

This is used for applications of no more than a few kVA. During normal operation, power is supplied from the network. In the event of loss of network power or if the voltage exceeds the prescribed tolerances, use is transferred to the UPS. The changeover causes an interruption of 2 to 10 ms.

■ Sources transfer

A device is used to control transfer between the main source and a replacement source (and vice versa) for supply to priority loads and if necessary orders the shedding of non-priority loads.

There are three types of transfer depending on the duration of transfer ($\Delta t$):

□ synchronous ($\Delta t = 0$),

□ delayed ($\Delta t = 0.2$ to 30 s),

□ pseudo-synchronous ($0.1 \text{ s} < \Delta t < 0.3 \text{ s}$).

The devices require special precautions (see "Cahier Technique" no. 161). For example, if there are several motors in the installation, simultaneous restart may produce a voltage drop which could prevent restart or lead to excessively long restarts (with the risk of overheating). It is therefore prudent to install a PLC which will restart the priority motors at intervals, especially with a replacement (backup) source with a low short-circuit power.

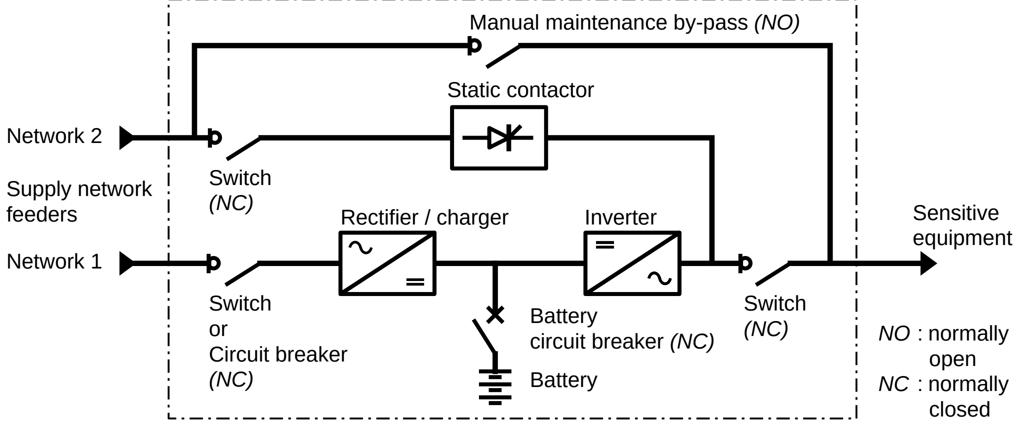



*Fig. 9: Schematic diagram of an on-line uninterruptible power supply (UPS).*

This solution is selected where the installation cannot withstand a long interruption of more than a few minutes, and/or requires a large amount of power. It can also be used in conjunction with a UPS.

- Zero-time set

In certain installations, the autonomy required in the event of interruption makes it necessary to install a generating set (large batteries would be too expensive, or cause technical or installation problems). Here, in the event of any loss of power supply, the battery or flywheel is used to provide sufficient time for starting and running up the stand-by engine generator, load shedding (if necessary) and interruption-free coupling by means of an automatic source changeover.

- Electronic conditioners

These are modern electronic devices to compensate voltage dips and interruptions to a certain extent with a short response time: for example the real time reactive compensator compensates the reactive power in real time and is especially well suited to loads with rapid, large variations (welding machines, lifts, presses, crushers, motor starting, etc.).

### Clean stop

If a stoppage is acceptable, it is especially advisable to prevent uncontrolled restarting if an unwanted restart would present a risk for the machine operator (circular saws, rotating electrical machines) or for the equipment (compression chambers while still under pressure, staggered restarts of air-conditioning compressors, heating pumps or refrigeration units) or for the application (necessity of controlling production restart). The process may be automatically restarted by a PLC using a predetermined restart sequence when conditions return to normal.

**Summary** (see table below)

| Installation power | Duration (indicative values) and technical requirements | | | | | | Immunisation solution |
|---|---|---|---|---|---|---|---|
| | 0 to 100 ms | 100 ms to 400 ms | 400 ms to 1 s | 1 s to 1 min | 1 min to 3 min | > 3 min | |
| A few VA | | | | | | | Time-delayed contactors |
| | | | | | | | DC power with capacitor storage |
| < 500 kVA | | | | | | | Rotating set with flywheel |
| < 1 MVA | | | | | | | Transfer source with diesel set |
| < 300 kVA | Between 15 minutes and several hours depending on battery capacity | | | | | | DC power with battery storage |
| < 500 kVA | Transfer time to a backup source may cause a short interruption | | | | | | Rotating set with flywheel and thermal motor or backup source |
| < 500 kVA | Between 15 minutes and several hours depending on battery capacity | | | | | | DC motor connected to battery and alternator |
| < 1 MVA (up to 4800 kVA with several UPS in parallel) | Between 10 minutes (standard) and several hours UPS depending on battery capacity | | | | | | |

Effective mitigation solution

Ineffective mitigation solution

## 5.2 Harmonics

There are three possible ways of suppressing or at least reducing the influence of harmonics. One section will examine the question of protective devices.

- Reducing generated harmonic currents

- Line choke

A 3-phase choke is connected in series with the power supply (or integrated into the DC bus for frequency inverters). It reduces the line current harmonics (especially high number harmonics) and therefore the rms value of the current consumption and the distortion at the inverter connection point. It is possible to install the choke without affecting the harmonics generator and to use chokes for several drives.

- Using 12-phase rectifiers

Here, by combining currents, low-order harmonics such as 5 and 7 are eliminated upstream (these often cause the most disturbance owing to their large amplitude). This solution requires a transformer with two secondary windings (star and delta), and only generates harmonics numbered 12 k ± 1.

- Sinewave input current devices

(see "Cahier Technique" no. 183)

This method consists in using static converters where the rectifier uses PWM switching to absorb a sinusoidal current.

- Modifying the installation

- Immunise sensitive loads with filters

- Increase the short-circuit power of the installation

- Derate equipment

- Segregate polluting loads

As a first step, the sensitive equipment must be connected as close as possible to the power supply source.

Next, the polluting loads must be identified and separated from the sensitive loads, for example by powering them from separate sources or from dedicated transformers. These solutions involve work on the structure of the installation and are, of course, usually difficult and costly.

- Protective devices and oversizing of capacitors

The choice of solution depends on the installation characteristics. A simple rule is used to choose the type of equipment where Gh is the apparent power of all generators of harmonics supplied from the same busbar system as the capacitors, and Sn is the apparent power of the upstream transformer(s):

- If Gh/Sn ⩽ 15 %, standard equipment is suitable
- If Gh/Sn > 15 %, there are two possible solutions.

**1 -** For polluted networks

(15 % < Gh/Sn ⩽ 25 %): the current rating of the switchgear and in-series links must be oversized, as must the voltage rating of the capacitors.

**2 -** For very polluted networks

(25 % < Gh/Sn ⩽ 60 %): anti-harmonic chokes must be connected to the capacitors and set to a frequency lower than the frequency of the lowest harmonic (for example, 215 Hz for a 50 Hz network) (see **fig. 10**). This eliminates any risk of resonance and helps to reduce harmonics.

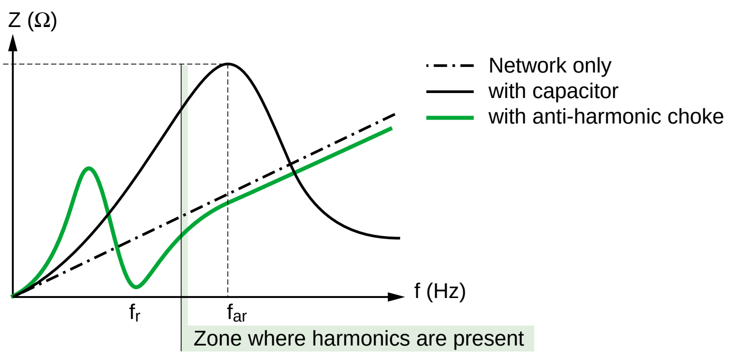



***Fig 10**: Effects of an anti-harmonic choke on network impedance*

■ Filtering

Where Gh/Sn > 60%, specialists must calculate and install the harmonics filter (see **fig. 11**).

□ Passive filtering (see "Cahier Technique" no. 152)

This involves connecting a low impedance by-pass to the frequencies to be attenuated using passive components (inductor, capacitor, resistor). Several passive filters connected in parallel may be necessary to eliminate several components. Careful attention must be paid to the sizing of harmonic filters: a poorly designed passive filter may lead to resonance and amplify frequencies which did not cause disturbance before installation of the filter.

□ Active filtering (see "Cahier Technique" no. 183)

This consists in neutralising the harmonics induced by the load. First an analysis of the current identifies them in amplitude and phase. Then the same but opposite harmonics are produced by the active filter. It is possible to connect several active filters in parallel. An active filter may for example be connected to a UPS to reduce harmonics which have been injected upstream.

□ Hybrid filtering

This consists of an active filter and a passive filter set to the order of the dominant harmonic (e.g. 5) which supplies the necessary reactive power.

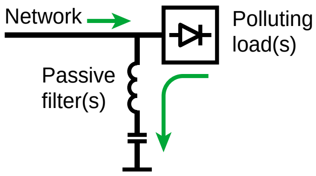
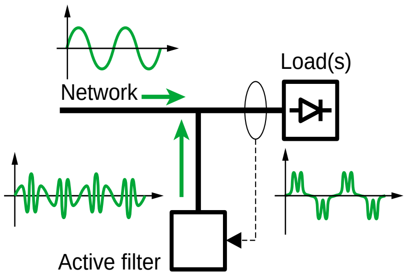
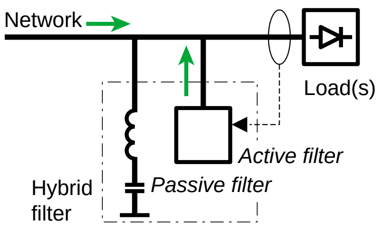
<table>
<tr><th>Filter</th><th>Principle</th><th>Characteristics</th></tr>
<tr><td>Passive</td><td>By-pass series LC circuit tuned to each harmonic frequency to be eliminated.<br>
</td><td>■ No limits in harmonic current.<br>■ Compensation of reactive power.<br>■ Elimination of one or more harmonic orders (generally 5, 7, 11). One filter for one or two orders to be compensated.<br>■ Risk of amplification of harmonics in the event of network modification.<br>■ Risk of overload caused by external pollution.<br>■ "Network" filter (global).<br>■ Case by case engineering study.</td></tr>
<tr><td>Active</td><td>Generation of current cancelling out all harmonics created by the load.<br>
</td><td>■ Solution particularly suited to "machine" filtering (local).<br>■ Filtering on a wide frequency band (elimination of harmonic orders 2 to 25).<br>■ Self-adapting:<br>□ network modification has no effect,<br>□ adapts to all variations in load and harmonic spectrum,<br>□ open-ended, flexible solution for each type of load.<br>■ Simple engineering study.</td></tr>
<tr><td>Hybrid</td><td>
</td><td>Offers the advantages of passive and active filtering solutions and covers a wide range of power and performance:<br>■ filtering on a wide frequency band (elimination of harmonics numbered 2 to 25),<br>■ compensation of reactive power,<br>■ large capacity for current filtering,<br>■ good technical-economic solution for "network" filtering.</td></tr>
</table>

***Fig. 11**: Principles and characteristics of passive, active, and hybrid filtering.*

■ Special case: circuit breakers (see "Cahier Technique" no. 182)

Harmonics may cause unwanted tripping of protective devices: care must be taken when choosing protective devices to avoid this. Circuit breakers can be fitted with two types of trip device, thermal-magnetic or electronic. The heat sensors of thermal-magnetic circuit breakers are particularly sensitive to harmonics and can identify the actual load on the conductors caused by the presence of harmonics. They are thus well suited to use on low current circuits, essentially in domestic or industrial applications. The method used by electronic circuit breakers to calculate the current being carried may present a risk of unwanted tripping and care must therefore be taken when choosing these devices that the true rms value of the current is measured. These devices have the advantage of being better able to track changes in the temperature of cables, particularly in the case of cyclical loads, as their thermal memory is superior to that of indirectly heated bimetallic strips.

■ Derating

This solution is applicable to some equipment and is a simple and frequently adequate response to disturbance caused by harmonics.

## 5.3 Overvoltages

Correct insulation co-ordination involves ensuring the protection of personnel and equipment against overvoltages, with the best balance between technical and economic considerations.
This requires (see "Cahier Technique" no. 151):

■ knowledge of the level and energy of the overvoltages which may occur on the network,

■ selection of the level of overvoltage withstand of the power system components to meet constraints,

■ use of protective devices where necessary, in fact, the appropriate solutions depend on the type of overvoltage encountered.

**Temporary overvoltages**

■ Switch off all or some of the capacitors during periods of low load.

■ Avoid configurations susceptible to ferroresonance or introduce losses (reducing resistors) to damp the phenomenon (see "Cahier Technique" no. 190).

**Switching overvoltages**

■ Limit the capacitors energisation transients by installing a fixed reactor and pre-insertion resistors. Static automatic reactive compensators which control closing instant are especially suitable for LV applications which cannot withstand transient overvoltages (PLCs, computer systems).

■ Connect line chokes upstream of the frequency inverters to limit the effects of transient overvoltages.

■ Use main residual current circuit breakers of discriminatory type (type "**S**") for LV and circuit breakers of type "**si**" ($I\Delta n$ = 30 mA and 300 mA). Their use avoids unwanted tripping due to transient leakage currents : lightning and switching overvoltages, energisation of circuits with a high capacitance to earth (capacitive filters connected to earth, extended cable networks, etc.) which flow through the network downstream of the RCD (residual current device) via the network capacitance to earth.

**Lightning overvoltages**

■ Primary protection

This protects the building and its structure from direct lightning strikes (lightning conductors, Faraday cages, overhead earth wire/earthing wire).

■ Secondary protection

This protects equipment against the overvoltages which follow lightning.
Surge arresters (spark gaps are now used less and less) are installed on the particularly exposed points of HV and MV networks and at the input to MV/LV installations (see "Cahier Technique" no. 151).
On LV installations, they are installed as far upstream as possible (to offer maximum protection) and as close as possible to the load. It is sometimes necessary to cascade surge arresters: one at the head of the installation, and one close to the load (see "Cahier Technique" no. 179). An LV surge arrester is always connected to a disconnection device. In addition, the use of main residual current circuit breakers of discriminatory type on LV installations avoids any current flow to earth via the surge arrester tripping the circuit breaker at the head of the installation, which would be incompatible with some equipment (freezers, controllers, etc.).
Note that overvoltages can be propagated to the equipment by other routes than the electrical power supply: telephone lines (telephone, fax), coaxial cables (computer links, TV aerials). Suitable protective devices are commercially available.

## 5.4 Voltage fluctuations

Fluctuations produced by industrial loads may affect a large number of consumers supplied from the same source. The fluctuation magnitude depends on the ratio between the impedance of the device generating the disturbance and the impedance of the power supply. The solutions are:

- Changing the type of lighting

Fluorescent lamps are less sensitive than incandescent lamps.

- Installing an uninterruptible power supply

This may be a cost-effective solution if users subject to disturbance are identified and grouped together.

- Modify the device generating the disturbance

Changing the starting mode of motors which have to start frequently, for example, can reduce overcurrents.

- Modify the network

□ Increase the short-circuit power by connecting lighting circuits to the nearest power supply point.

□ Increase the "electrical distance" between the disturbance-generating load and lighting circuits by powering the disturbance-generating load from an independent transformer.

- Use a reactive compensator

This device provides real time reactive compensation for each phase. Flicker can be reduced from 25 % to 50 %.

- Connect a reactance in series

By reducing the inrush current, a reactance downstream from the connection point of an arc furnace can reduce flicker by 30 %.

## 5.5 Unbalance

The solutions are:

- balancing single phase loads on all three phases,
- reducing the power system impedance upstream of the devices causing the unbalance by increasing the transformer rated power and the cable cross-section,
- fitting the appropriate protective device for the machines,
- using carefully connected LC loads (Steinmetz connection).

## 5.6 Summary

| Type of disturbance | Origins | Consequences | Examples of mitigation solutions (special equipment and modifications) |
|---|---|---|---|
| **Voltage variations and fluctuations** | Large load variations (welding machines, arc furnaces, etc.). | Fluctuation in the luminance of lamps (flicker). | Electromechanical reactive power compensator, real time reactive compensator, series electronic conditioner, tap changer. |
| **Voltage dips** | Short-circuit, switching of large loads (motor starting, etc.). | Disturbance or shutdown of process: loss of data, incorrect data, opening of contactors, locking of drives, slowdown or stalling of motors, extinguishing of discharge lamps. | UPS, real time reactive compensator, dynamic electronic voltage regulator, soft starter, series electronic conditioner.<br>Increase the short-circuit power (Scc).<br>Modify the discrimination of protective devices. |
| **Interruptions** | Short-circuit, overloads, maintenance, unwanted tripping. | | UPS, mechanical source transfer, static transfer swtich, zero-time set, shunt circuit breaker, remote management. |
| **Harmonics** | Non-linear loads (adjustable speed drives, arc furnaces, welding machines, discharge lamps, fluorescent tubes, etc.). | Overloads (of neutral conductor, sources, etc.), unwanted tripping, accelerated ageing, degradation of energy efficiency, loss of productivity. | Anti-harmonic choke, passive or active filter, hybrid filter, line choke.<br>Increase the Scc.<br>Contain polluting loads.<br>Derate the equipment. |
| **Inter-harmonics** | Fluctuating loads (arc furnaces, welding machines, etc.), frequency inverters. | Interruption of metering signals, flicker. | Series reactance. |
| **Transient overvoltages** | Operation of switchgear and capacitors, lightning. | Locking of drives, unwanted tripping, destruction of switchgear, fire, operating losses. | Surge arrester, surge diverter, controlled switching, pre-insertion resistor, line chokes, static automatic compensator. |
| **Voltage unbalance** | Unbalanced loads (large single-phase loads, etc.). | Inverse motor torque (vibration) and overheating of asynchronous machines. | Balance the loads.<br>Shunt electronic compensator, dynamic electronic voltage regulator. Increase the Scc. |

# 6 Case studies

## 6.1 Hybrid filtering

### Description of the installation

Ski-lifts are powered by an MV/LV transformer (800 kVA).
The connected loads are the chair lifts together with other loads such as payment booths, ski-pass validation systems, the official timing system for competitions and a telephone network.

### Problems encountered

When the chair lifts are running, the low voltage network powered by the MV/LV transformer is subject to disturbance.
The measures taken at the site pinpointed a high pre-existing harmonic distortion factor in the voltage (THD ≈ 9 %) from the MV power system as well as harmonic pollution from the chair-lift feeder. The resulting distortion of the supply voltage (THD ≈ 12 %) disturbed sensitive equipment (payment booths, timing system, etc.).

### Solutions

The aim of the device is to ensure the simultaneous reactive compensation when harmonics are present and neutralisation of harmonics likely to disturb the installation.
The solution chosen (see **fig. 12**) was to install a hybrid filter (see **fig. 13**) consisting of a passive filter tuned to the order of the dominant harmonic (H5) which provides the required reactive power (188 kvar), and an active filter rated at 20 A is dedicated to the elimination of all other harmonics.

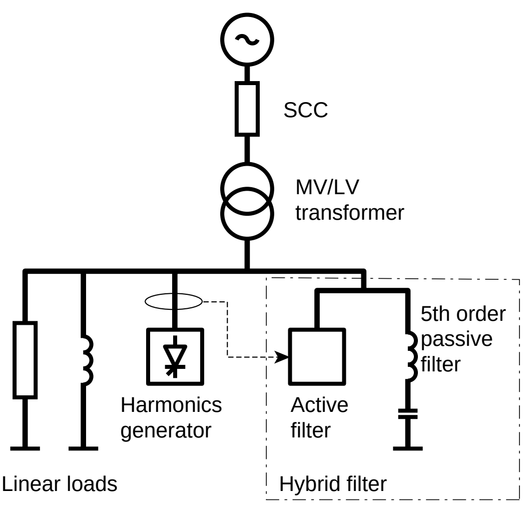



*__Fig. 12__: Implementation of the solution.*

After commissioning, measurements show that the device reduces the magnitude of the harmonics over a wide frequency spectrum in both current and voltage (see **fig. 14**) and reduced the voltage distortion factor from 12.6 % to 4.47 %. It also increased the power factor of the installation from 0.67 to 0.87. This solution solved all of the problems as no malfunction was subsequently detected.

*__Fig. 13__: Rectiphase hybrid filter device (Merlin Gerin brand).*

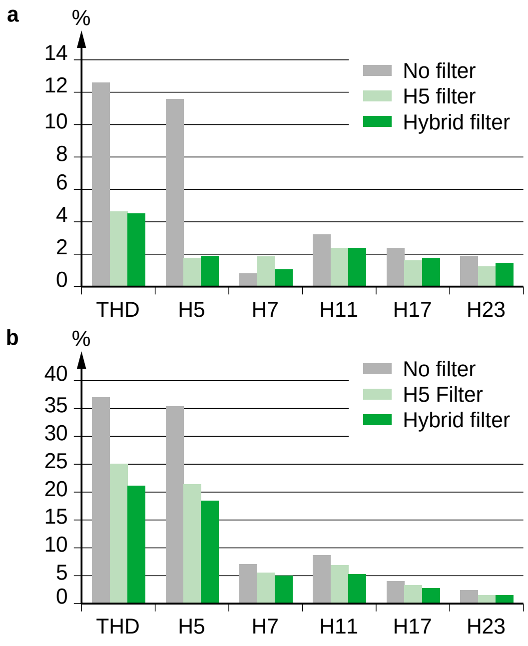



*__Fig 14__: Spectrums showing the effectiveness of a hybrid filter: __[a]__ in voltage __[b]__ in current.*

## 6.2 Real time reactive compensation

### Description of the installation

A car equipment manufacturer's plant in Concord (Ontario - Canada) is supplied by a transformer rated at 2000 kVA - 27.6 kV / 600 V - Yy - Ucc = 5.23 %.
It manufactures exhaust assemblies from steel plate using spot welders and seam welders.

### Problems encountered

- Visual and nervous fatigue in personnel, due to the fluctuation in brightness of lamps (flicker) when welding equipment was in operation.
- Noise pollution and premature mechanical ageing of equipment caused by vibrations mainly in the transformer and the main switchgear when welding equipment was in operation.
- Inability to add equipment for fear that the installation would be overloaded (peak currents when welders were fired were greater that the nominal current of the main circuit breaker). Expansion of the installation would thus require substantial investment, either to upgrade the existing installation or to build a new power supply facility.
- Annual penalties of 5 k€ for exceeding the reactive power consumption limit (0.75 power factor).
- Defective parts caused by welding faults appeared at the end of the manufacturing process when the tubes are bent into shape.

All these factors reduced company productivity.

### Solutions

The measures taken during the operation of the welding equipment showed a nominal voltage of 584 V, voltage dips of 5.8 %, current peaks of 2000 A, and reactive power peaks of 1200 kvar (see **fig. 15**).

| | **Before** | **After** |
|---|---|---|
| **Voltage** (V) | 584 | 599 |
| **Voltage dip** | | |
| ■ Depth (%): | 5.8 | 3.2 |
| ■ Duration (cycle) | 20 to 25 | 10 to 15 |
| **Current** | | |
| ■ Average | 1000 | 550 |
| ■ Peak | 2000 | 1250 |
| **Reactive power** (kvar) | 600 to 1200 | 0 to 300 |
| **Power factor** | 0.75 | > 0.92 |

*Fig. 15: Improvements due to the real time reactive compensator.*

The problems clearly stemmed from voltage fluctuations caused by the operation of welders with loads which vary rapidly and frequently and which consume significant reactive power.

A voltage dip of 6 % produces a reduction of 12 % ($1-0.94^2$) in the power available for welding. This was the reason for the large number of defective welds.

Standard devices for reactive power compensation use electromechanical contactors which cannot achieve the required response times; the operation of capacitor steps is deliberately time delayed to reduce the number of operations and avoid reducing the service life of the contactors through premature wear, as well as to enable the capacitors to discharge.

The solution chosen was to connect a real time reactive compensator (see **fig. 16**). This innovative device offers:

- ultra-rapid compensation of the variations in reactive power within one cycle (16.6 ms at 60 Hz), which is especially suitable for loads with rapid, large variations (welding machines, lifts, presses, crushers, motor starting, etc.);
- transient-free switch through controlled switching, which is especially useful with loads which cannot withstand transient overvoltages (PLCs, computer systems, etc.);
- increased service life of capacitors and contactors owing to the absence of moving mechanical parts and overvoltages

With compensation of 1200 kvar it would be possible to minimise voltage dips, but 800 kvar was deemed sufficient to maintain the voltage at

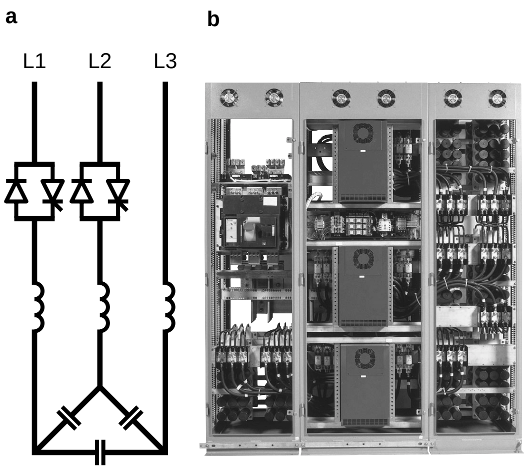



*Fig. 16: Real time reactive compensator **[a]** principle, **[b]** practical implementation.*

an acceptable level for all processes in the plant under all load conditions.
The results of implementing the solution are (see **fig. 17**):

- a reduction in current peaks to 1250 A and the addition of loads without modification of the installation, with improved installation efficiency through reduction of joule losses;
- a reduction in reactive power peaks to 300 kvar and an increase in the power factor to over 0.92, thus avoiding power factor penalties;
- an increase in the nominal voltage to 599 V and a reduction in voltage dips to 3.2 % (see fig. 16). This is a consequence of the increase in the power factor and reduction in the current amplitude (see **fig. 18**). Visual and nervous fatigue in personnel due to the flicker was also eliminated. Welding quality improved, as did productivity.

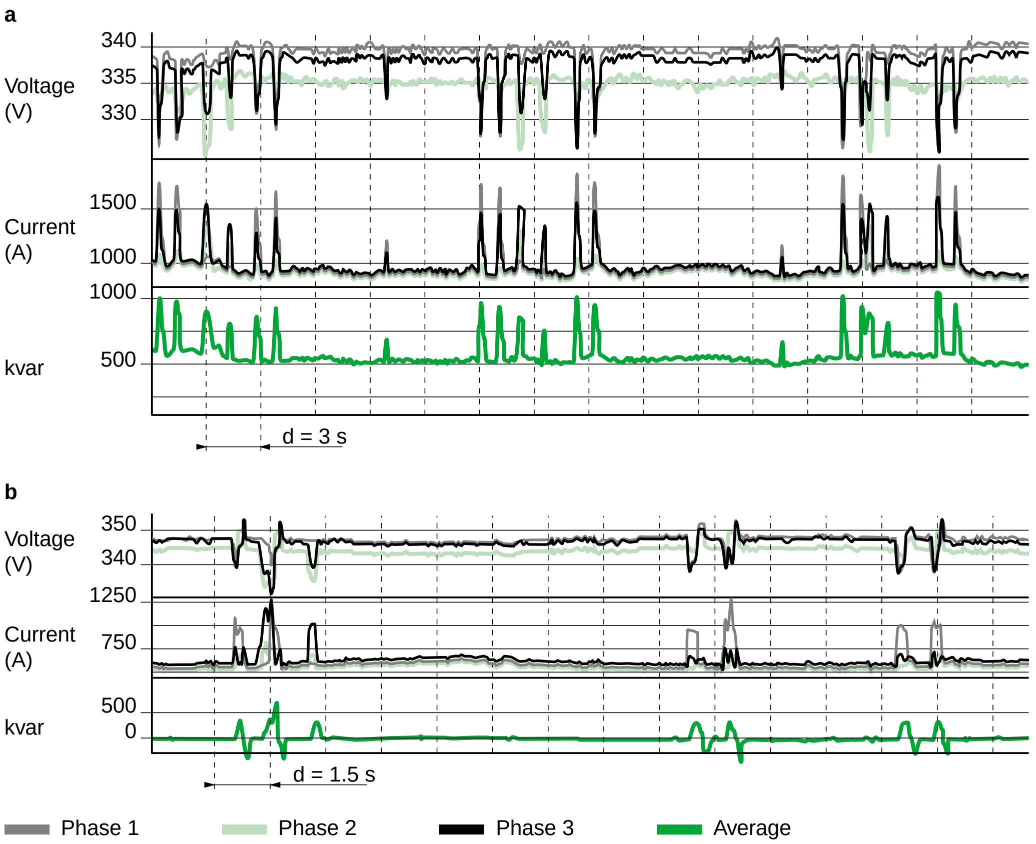



*Fig. 17: Measurement of current, voltage and reactive power: **[a]** without compensation **[b]** with compensation.*

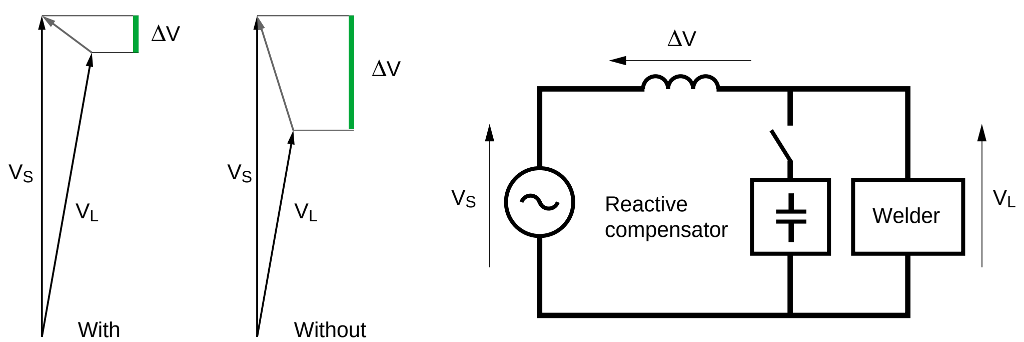



*Fig. 18: Reduction in voltage drop obtained using a real time reactive compensator.*

## 6.3 Protection against lightning

### Description of the installation

The site consists of offices (computer hardware, lighting and heating unit), a security post (fire alarm, burglar alarm, access control, video surveillance) and three buildings for the manufacturing process on 10 hectares in the Avignon region of France (probability of lightning is 2 strikes per $km^2$ per year).
There are trees and metal structures (pylons) in the vicinity of the site. All of the buildings are fitted with lightning conductors. The MV and LV power supplies are underground.

### Problems encountered

A storm struck the site, destroying the LV installation in the security post and causing 36.5 k€ of operating losses. The presence of lightning conductors prevented the structure from catching fire, but the electrical equipment which was destroyed was not protected by surge arresters, contrary to the recommendation in standards UTE C-15443 and IEC 61024.

### Solutions

After analysing equipotentiality and earthing of the power system, followed by verification of the installation of lightning conductors and checking of the values of the earth electrodes, the decision was taken to install surge arresters.

Surge arresters were installed at the head of the installation (main LV distribution board) and in cascade in each manufacturing building (see **fig. 19**). As the neutral point connection was TNC, protection would only be provided in common mode (between phases and PEN).

In conformity with guide UTE C-15443 regarding operation in the presence of lightning conductors, the characteristics of the Merlin Gerin PF65 and PF8 surge arresters (see **fig. 20**) are as follows:

- At the head of the installation

In = 20 kA – Imax = 65 kA – Up = 2 kV

- In cascade (at least 10 m apart)

In = 2 kA – Imax = 8 kA – Up = 1.5 kV

In cascade, good protection is provided for the secondary distribution boards (offices and security post).

As the neutral point connection was converted to TNS, protection had to be provided in common mode (between phase and PE) and differential mode (between phases and neutral). The disconnection devices in this case are circuit breakers with a breaking capacity of 22 kA.

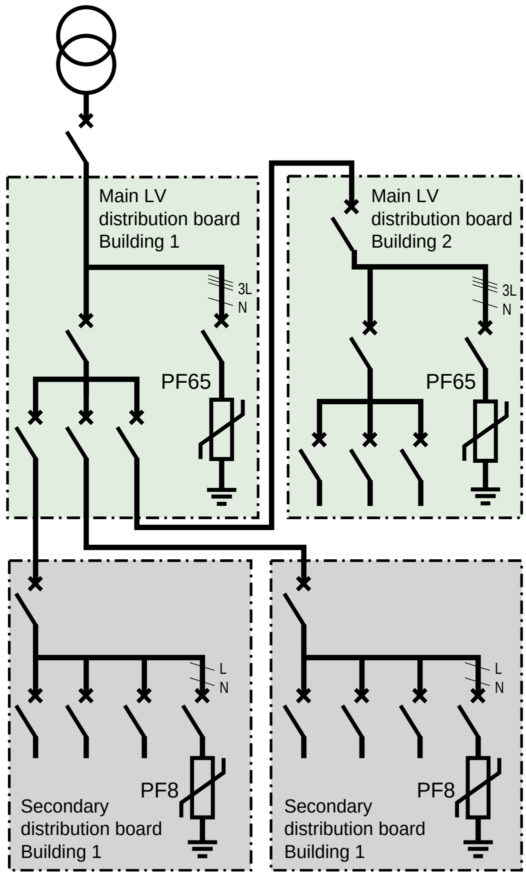



*Fig. 19: Installation diagram for several surge arresters in cascade.*


*Fig. 20: Low voltage surge arresters (Merlin Gerin PF65 and PF8).*

# 7 Conclusion

Electrical disturbance may originate in the distribution power system, in the installation of the user who is subject to disturbance or in the installation of a nearby user.

The consequences of the disturbance vary according to the economic context and the area of application: from inconvenience to shutdown of production facilities - it can even put lives at risk.

The search to improve company competitiveness and the deregulation of the electricity market mean that the quality of electricity has become a strategic issue for electricity companies, the operating, maintenance and management personnel of service sector and industrial sites, as well as for equipment manufacturers.

However, problems of disturbance should not be regarded as insurmountable, as solutions do exist. Employing specialists to define, implement and maintain these solutions while observing best practice will provide users with the right quality of power supply for their requirements.

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# A Hybrid Active Filter for Damping of Harmonic Resonance in Industrial Power Systems

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***Abstract*—This paper proposes a hybrid active filter for damping of harmonic resonance in industrial power systems. The hybrid filter consists of a small-rated active filter and a 5th-tuned passive filter. The active filter is characterized by detecting the 5th-harmonic current flowing into the passive filter. It is controlled in such a way as to behave as a negative or positive resistor by adjusting a feedback gain from a negative to positive value, and vice versa. The negative resistor presented by the active filter cancels a positive resistor inherent in the passive filter, so that the hybrid filter acts as an ideal passive filter with infinite quality factor. This significantly improves damping the harmonic resonance, compared with the passive filter used alone. Moreover, the active filter acts as a positive resistor to prevent an excessive harmonic current from flowing into the passive filter. Experimental results obtained from a 20-kW laboratory model verify the viability and effectiveness of the hybrid active filter proposed in this paper.**

***Index Terms*—Active filters, harmonic resonance, power quality, power systems, PWM inverters, voltage harmonics.**

## I. Introduction

NON-LINEAR loads such as diode or thyristor rectifiers and cycloconverters draw non-sinusoidal currents from utility grids, thus contributing to the degradation of power quality in utility or industrial power systems. Notably, voltage distortion or voltage harmonics in the power systems are becoming so serious that 5th- and 7th-harmonic voltages are barely acceptable at the customer-utility point of common coupling [1].

Oku, et al., have reported a serious status of harmonic pollution in Japan [2], [3]. The maximum value of 5th-harmonic voltage in the downtown area of a 6.6-kV power distribution system exceeds 7% under light-load conditions at night. The 5th-harmonic voltage increases on the 6.6-kV bus in the secondary of the primary distribution transformer installed in a substation, whereas it decreases on the 77-kV bus in the primary under light-load conditions at night. These facts based on the actual measurement suggest that the increase of 5th-harmonic voltage on the 6.6-kV bus at night is due to harmonic resonance between line inductors and shunt capacitors for power factor correction installed on the distribution system. This harmonic resonance may occur, not only in utility power systems, but also in industrial power systems for factories, plants, office buildings and so on. Harmonic damping, therefore, would be as cost-effective in mitigating harmonic voltages and currents as harmonic compensation [4], [5].

Hybrid filters consisting of active and passive filters connected in series or parallel with each other combine the advantages of both filters, thus leading to the best effectiveness in cost/performance [6]–[12]. Control schemes for the active filters have been presented to provide the required functions such as harmonic compensation, harmonic damping and/or harmonic isolation [1].

This paper proposes a hybrid active filter consisting of a small-rated active filter and a specially designed passive filter. The active and passive filters are connected in series with each other. The hybrid filter is connected in parallel with other loads in the vicinity of the secondary of a distribution transformer installed at the utility-consumer point of the common coupling (PCC). It is, therefore, different in the point of installation from pure active filters and hybrid active filters which have been installed in the vicinity of harmonic-producing loads. The purpose of installing the hybrid filter proposed in this paper is to damp the harmonic resonance in industrial power systems, as well as to mitigate harmonic voltages and currents. This paper describes the principle of operation of the hybrid filter and discusses three different harmonic detection methods for the active filter used in the hybrid filter. Experimental results obtained from a 20-kW laboratory model verify the viability of the hybrid filter and its effectiveness in harmonic damping and mitigation.

## II. Harmonic Resonance

Fig. 1 shows an industrial power system, in which linear and nonlinear loads, capacitors for power factor correction and passive filters are connected on a common bus. The primary of a distribution transformer installed by the consumer is connected to the PCC, while the secondary supplies the liner and nonlinear loads through the common bus. The power system may cause harmonic propagation as a result of series and/or parallel resonances between the power capacitors and the leakage inductor of the distribution transformer.

Fig. 2 shows a single-phase circuit equivalent to the power system under the assumption that only a 5th-harmonic voltage exists at the PCC. Here, $L_T$ is the leakage inductance of the transformer; $C$ is the capacitance of the capacitors for power factor correction; $R_L$ is the resistance equivalent to the loads. The common bus voltage $V_{\rm BUS}$ includes a 5th-harmonic voltage $V_{\rm BUS5}$ which is given by

$$V_{\rm BUS5} = \frac{1}{1-(5\omega)^2 L_T C + \frac{j5\omega L_T}{R_L}} V_{S5} \qquad (1)$$

where $\omega$ is the angular frequency of the line voltage.

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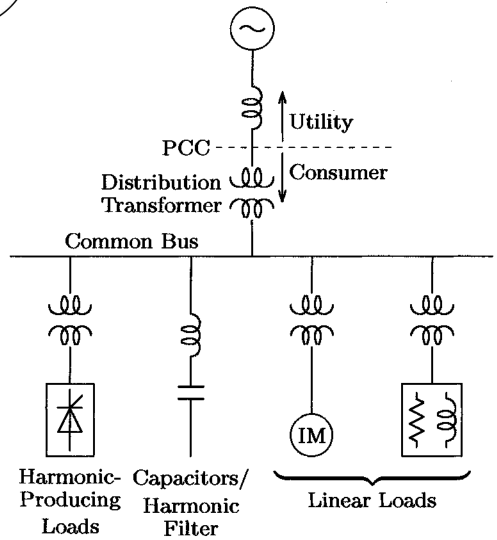


Fig. 1. Industrial power system.

A no-load condition of $R_L = \infty$ yields a relationship of $V_{\text{BUS5}} > V_{S5}$. This implies that harmonic propagation occurs in the industrial power system. When the resonant frequency between $L_T$ and $C$ coincides with the 5th-harmonic frequency, (1) is simplified as follows:

$$V_{\text{BUS5}} = \frac{R_L}{j5\omega L_T} V_{S5}. \tag{2}$$

The harmonic resonance may magnify the 5th-harmonic voltage by 4–10 times even in a full-load condition because $L_T$ has an inductance value of 2–5%.

## III. Hybrid Active Filter

### *A. Experimental System*

Fig. 3 shows a system configuration developed for this experiment. Table I summarizes the circuit constants in Fig. 3. The industrial power system is rated at 200 V, 60 Hz and 20 kVA, assuming no-load conditions under which the severest harmonic propagation occurs. The active filter consists of three single-phase voltage-source PWM inverters using twelve power MOSFETs. Each inverter is connected in series with the 5th-tuned passive filter via a single-phase matching transformer with a turns ratio of 1:10. Note that the rating of the active filter is 0.14 kVA, which is only 0.7% of 20 kVA, while the rating of the passive filter is 0.43 kVA or 2%. An inductor $L_T$ (=7%) is connected in series downstream of the PCC, in order to represent a leakage inductor of a distribution transformer. A shunt capacitor $C$ (=70%) is connected in parallel on the common bus. Combination of the inductor and capacitor forms a series and/or parallel resonant circuit, the resonant frequency of which is around the 5th-harmonic frequency. A 5th-harmonic generator consisting of a three-phase voltage-source PWM inverter is used to simulate a 5th-harmonic voltage existing upstream of the PCC.

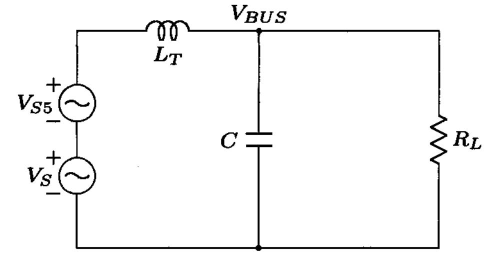


Fig. 2. Single-phase equivalent circuit.

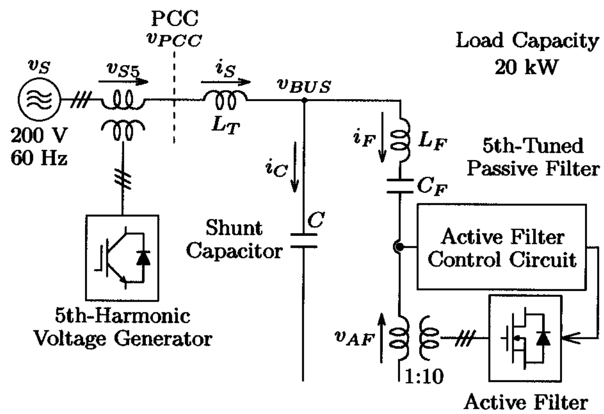


Fig. 3. Experimental system.

TABLE I
CIRCUIT CONSTANTS

| | |
|---|---|
| 5th-Tuned Passive Filter | $L_F = 12$ mH, $C_F = 24$ $\mu$F, $Q = 10$, 0.43 kVA (2%) |
| Active Filter | 0.14 kVA (0.7%) |
| Shunt Capacitor | $C = 900$ $\mu$F, 14 kVA (70%) |
| Leakage Inductance | $L_T = 360$ $\mu$H (7%) |

$3\phi$, 200-V, 60-Hz, 20-kVA base

### *B. Operating Principle of the Active Filter*

Fig. 4 shows a single-phase equivalent circuit for the industrial power system installing the hybrid filter on the common bus. The active filter detects the 5th-harmonic current flowing into the passive filter, $i_{F5}$, and then amplifying $i_{F5}$ by a gain $K$ determines its voltage reference as follows:

$$v_{\text{AF}}^* = K \cdot i_{F5}. \tag{3}$$

As a result, the active filter acts as a pure resistor of $K$ [$\Omega$] for the 5th-harmonic voltage and current. The impedance of the hybrid filter at the 5th-harmonic frequency, $Z_5$ is given by

$$Z_5 = j5\omega L_F + \frac{1}{j5\omega C_F} + r_F + K. \tag{4}$$

Here, $r_F$ is a resistance value of a resistor inherent in the passive filter, and $L_F$ and $C_F$ are inductance and capacitance values. When the gain $K$ is controlled in a range of $K < 0$, the active filter presents a negative resistor to the external circuit, thus improving the quality factor of the passive filter, $Q$. Assuming that the passive filter is well tuned at the 5th-harmonic frequency, the impedance of the passive filter is equal to $r_F$.

Fig. 5 shows an equivalent circuit with the focus on the 5th-harmonic frequency. It is clear that $Z_5$ is 0 as long as $K = -r_F$. This implies that no 5th-harmonic voltage appears on the common bus. In general, $V_{\mathrm{BUS5}}$, which is the 5th-harmonic voltage appearing on the common bus voltage, and $I_{S5}$, which is the 5th-harmonic current present in the supply current, are given by

$$V_{\mathrm{BUS5}} = \frac{1}{1-(5\omega)^2 L_T C + j5\omega L_T \left(\frac{1}{R_L} + \frac{1}{r_F+K}\right)} V_{S5} \quad (5)$$

$$I_{S5} = \frac{j5\omega C + \frac{1}{R_L} + \frac{1}{r_F+K}}{1-(5\omega)^2 L_T C + j5\omega L_T \left(\frac{1}{R_L} + \frac{1}{r_F+K}\right)} V_{S5}. \quad (6)$$

Assuming that $K = -r_F$ yields

$$V_{\mathrm{BUS5}} = 0 \quad (7)$$

$$I_{S5} = \frac{1}{j5\omega L_T} V_{S5}. \quad (8)$$

When an overcurrent flows into the passive filter, the active filter controls the gain $K$ to be a positive value. Thus, the active filter acts as a positive resistor, preventing the passive filter from absorbing an excessive 5th-harmonic current. The 5th-harmonic current flowing into the passive filter, $I_{F5}$ is given by

$$I_{F5} = \frac{\frac{1}{r_F+K}}{1-(5\omega)^2 L_T C + j5\omega L_T \left(\frac{1}{R_L} + \frac{1}{r_F+K}\right)} V_{S5}. \quad (9)$$

Assuming no-load conditions of $R_L = \infty$ simplifies the above equation as follows:

$$I_{F5} = \frac{1}{(1-(5\omega)^2 L_T C)(r_F+K) + j5\omega L_T} V_{S5}. \quad (10)$$

This indicates that adjusting the gain $K$ is effective in reducing $I_{F5}$.

## IV. Theoretical Considerations of Harmonic Detection Methods

### A. Stability Analysis

Three different harmonic detection methods for the active filter are considered and compared in view of system stability.

a) Detecting the harmonic current flowing into the passive filter, $I_{Fh}$

$$V_{\mathrm{AF}}^* = K \cdot I_{Fh}. \quad (11)$$

b) Detecting the harmonic voltage appearing across the passive filter, $V_{Fh}$

$$V_{\mathrm{AF}}^* = K \cdot V_{Fh}. \quad (12)$$

c) Detecting the harmonic voltage appearing on the common bus voltage, $V_{\mathrm{BUS}\,h}$

$$V_{\mathrm{AF}}^* = K \cdot V_{\mathrm{BUS}\,h}. \quad (13)$$

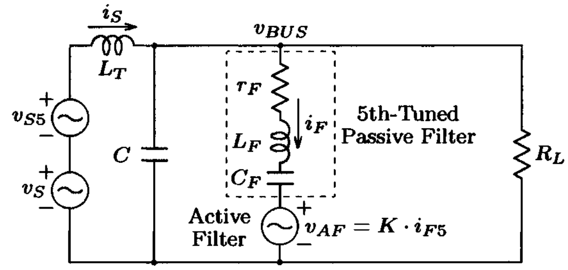


Fig. 4. Single-phase equivalent circuit.

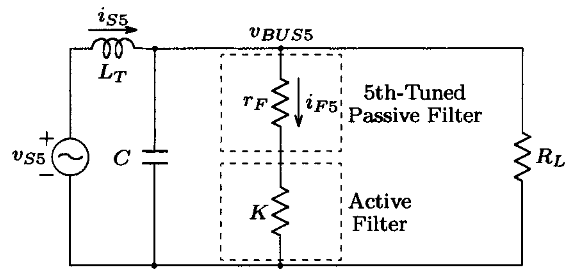


Fig. 5. Single-phase equivalent circuit for 5th harmonics.

In the following analysis, the harmonic-extracting circuit of the active filter is assumed to be ideal without time delay, so that the transfer function of the control circuit is simplified as the gain $K$. Fig. 6 shows a single-phase equivalent circuit from which the supply harmonic voltage is removed. The total impedance of the passive filter, $Z_F(s)$ is given by

$$Z_F(s) = r_F + sL_F + \frac{1}{sC_F}. \quad (14)$$

The external impedance seen from the installation point of the hybrid filter, $Z(s)$ is given by

$$Z(s) = \frac{1}{\frac{1}{R_L} + \frac{1}{sL_T} + sC}. \quad (15)$$

At first, it is necessary to calculate a loop transfer function of each harmonic detection method.

a) $I_F$-detecting method

Fig. 6 allows us to calculate the transfer function from $V_{\mathrm{AF}}$ to $I_{Fh}$ as follows:

$$\frac{I_{Fh}}{V_{\mathrm{AF}}} = -\frac{1}{Z_F(s) + Z(s)}. \quad (16)$$

The product between (16) and the gain $K$ offers the loop transfer function, $G_{I_{Fh}}(s)$

$$G_{I_{Fh}}(s) = K \cdot \frac{I_{Fh}}{V_{\mathrm{AF}}} = -\frac{K}{Z_F(s) + Z(s)} \quad (17)$$

b) $V_F$-detecting method

The loop transfer function of this method, $G_{V_{Fh}}(s)$ is also given by

$$G_{V_{Fh}}(s) = K \cdot \frac{V_{Fh}}{V_{\mathrm{AF}}} = -\frac{K \cdot Z_F(s)}{Z_F(s) + Z(s)}. \quad (18)$$

Moreover, the harmonic voltage appearing on the common bus, $V_{\mathrm{BUS}\,h}$ is given by

$$V_{\mathrm{BUS}\,h} = V_{Fh} + V_{\mathrm{AF}} = (1+K)V_{Fh}. \quad (19)$$

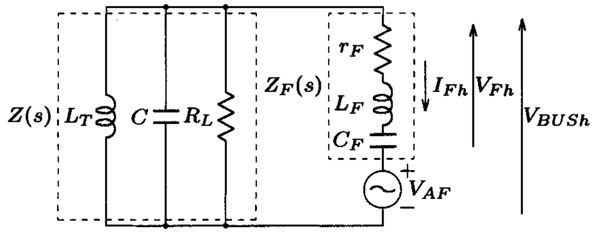


Fig. 6. Single-phase equivalent circuit when no harmonic voltage exists in the supply voltage.

Setting the gain to $K = -1$ yields an ideal condition of $V_{\text{BUS}\,h} = 0$.

c) $V_{\text{BUS}}$-detecting method

The loop transfer function of this method, $G_{V_{\text{BUS}\,h}}(s)$ is given by

$$G_{V_{\text{BUS}\,h}}(s) = K \cdot \frac{V_{\text{BUS}\,h}}{V_{\text{AF}}} = \frac{K \cdot Z(s)}{Z_F(s) + Z(s)}. \tag{20}$$

The harmonic voltage on the common bus, $V_{\text{BUS}\,h}$ is given by

$$V_{\text{BUS}\,h} = \frac{V_{Fh}}{1 - K}. \tag{21}$$

An ideal gain of $K = -\infty$ results in a condition of $V_{\text{BUS}\,h} = 0$. However, such a realistic gain as $K = -100$ is taken in the following analytical results.

## *B. Analytical Results*

Fig. 7 illustrates the Bode plots of the loop transfer functions obtained from (17), (18) and (20), where the circuit constants summarized in Table I are used for the analysis. A load resistor of $R_L = 2\ \Omega$, which is rated at 20 kW, is connected on the common bus. Since each harmonic detection method is based on a positive-feedback system, the system is stable as long as the magnitude plot is below 0 dB at the phase crossover frequency of $\angle G(s) = 0$.

The $I_F$-detecting method with a gain of $K = -r_F$ has a gain margin of −6 dB at the phase crossover frequency around 300 Hz, as shown in Fig. 7(a), so that the system is stable. When the tuned frequency of the passive filter is 300 Hz, this system theoretically falls into being marginally stable under no-load conditions. A realistic system, however, is stable even in no-load conditions due to existing line resistors.

The $V_F$-detecting method with a gain of $K = -1$ has the magnitude of 0 dB and the phase angle of 0 in a frequency range of less than 200 Hz and of more than 400 Hz, as shown in Fig. 7(b), so that this system is marginally stable. Therefore, the gain should be set in a range of $0 > K > -1$, to provide a gain margin.

As shown in Fig. 7(c), the $V_{\text{BUS}}$-detecting method with a gain of $K = -100$ has a phase margin of more than 20° although the magnitude is over 0 dB in a frequency range of 150–600 Hz, so that this system is stable.

It is assumed in the above analysis that the transfer function of the harmonic-extracting circuit in the control circuit is a constant gain $K$, independent of frequency. If it is implemented to amplify only the extracted 5th-harmonic current or voltage by the gain $K$ and to lower the gain for other frequencies, the system stability of the three harmonic detection methods can be improved. In addition, the $I_F$-detecting method is superior in harmonic detection accuracy to the other methods because the ratio of the extracted harmonic component with respect to the fundamental component is the highest among the three methods. This experimental system, therefore, takes the $I_F$-detecting method from the viewpoint of stability and harmonic detection accuracy.

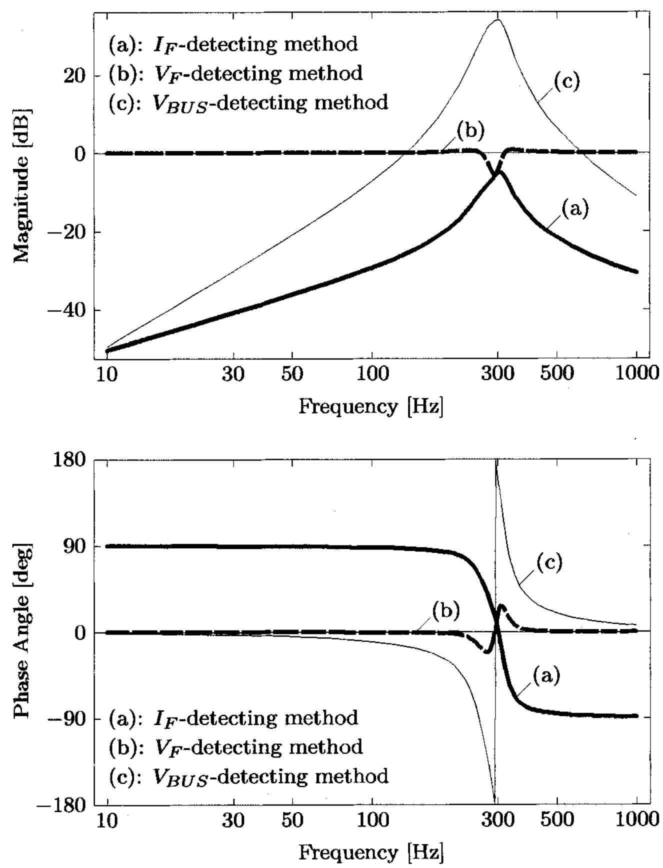


Fig. 7. Bode plots of each harmonic-extracting method under full-load conditions.

## V. Control Circuit

Fig. 8 shows a block diagram of the control circuit for the active filter. It consists of two parts; a circuit for extracting the 5th-harmonic current from the passive filter current $i_F$ and a circuit for automatically adjusting the gain $K$. The reference voltage for the active filter, $v_{\text{AF}}^*$ is given by

$$v_{\text{AF}}^* = K \cdot i_{F5}. \tag{22}$$

where the gain $K$ is determined in the gain-adjusting circuit.

## *A. Harmonic-Extracting Circuit*

The extracting circuit detects three-phase currents flowing into the passive filter through three ac-CTs, and then the two-phase currents on the $\alpha$-$\beta$ coordinates are transformed to those on the $d$-$q$ coordinates by using a unit vector $(\cos 5\omega t, \sin 5\omega t)$ with a rotating frequency of five times as

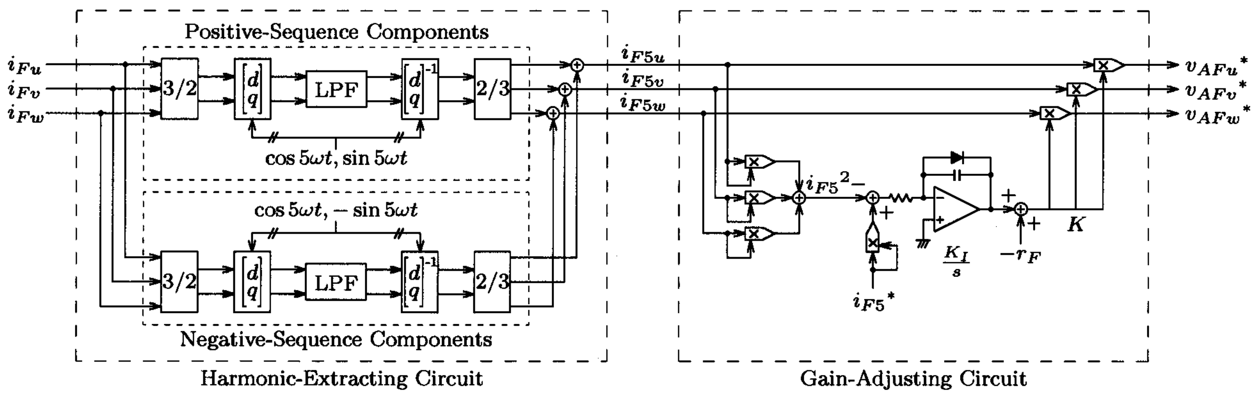


Fig. 8. Block diagram of control circuit.

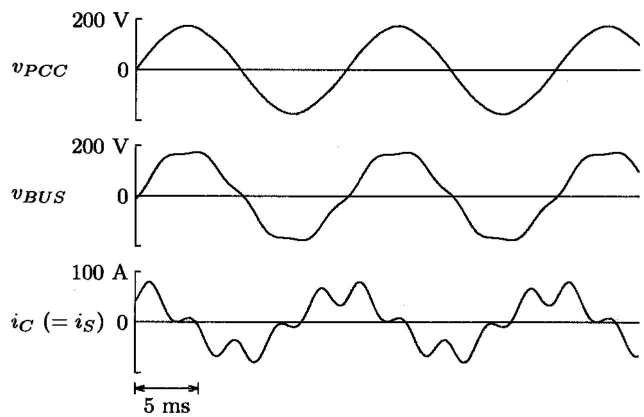


Fig. 9. Experimental waveforms when the hybrid filter is disconnected.

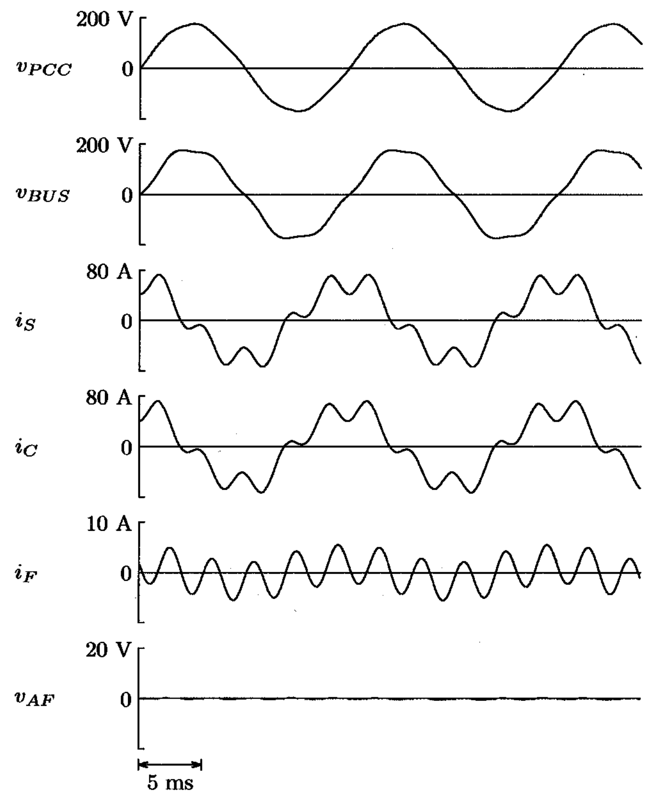


Fig. 10. Experimental waveforms when only the passive filter is installed.

high as the line frequency. As a result, only 5th-harmonic positive-sequence currents on the $d$-$q$ coordinates are converted into two dc components, and the fundamental current and other harmonic currents into ac components. Therefore, the 5th-harmonic positive-sequence currents can be extracted from the currents on the $d$-$q$ coordinates through two first-order low-pass filters (LPFs) with a corner frequency of 0.1 Hz. The inverse $d$-$q$ transformation is applied to the extracted 5th-harmonic positive-sequence currents, producing three-phase positive-sequence 5th-harmonic currents. To extract 5th-harmonic negative-sequence currents, the same signal processing as the 5th-harminc positive-sequence currents is performed except for employing another unit vector $(\cos 5\omega t, -\sin 5\omega t)$ with the opposite rotating direction. Finally, the extracted positive- and negative-sequence currents in each phase are added to obtain three-phase 5th-harmonic currents.

### *B. Gain-Adjusting Circuit*

The gain-adjusting circuit calculates a square of the extracted 5th-harmonic current every phase, and then sums all of the three, producing $i_{F5}^2$ as follows:

$$i_{F5}^2 = i_{F5u}^2 + i_{F5v}^2 + i_{F5w}^2. \tag{23}$$

The circuit compares $i_{F5}^2$ with a square of a limitation value $i_{F5}^*$. When $i_{F5}^2$ is smaller than the square of $i_{F5}^*$, the circuit sets the gain in such a way as $K = -r_F$. When $i_{F5}^2$ is larger, an integral feedback controller in the circuit adjusts the gain in such a way as to make $i_{F5}^2$ equal $i_{F5}^*$. The purpose of the gain-adjusting circuit is to prevent the passive filter and the active filter from overheating and overcurrent, and therefore the circuit requires a control response as slow as 1–4 seconds. The integral gain is set to $K_I = 0.4\ \Omega/(\mathrm{A}^2\mathrm{s})$ in the following experiment. This implies that it takes about 2 seconds to adjust the gain $K$ from $-2\ \Omega$ to 0, when an overcurrent being two times as large as the rated current of $i_{F5}$ flows into the passive filter.

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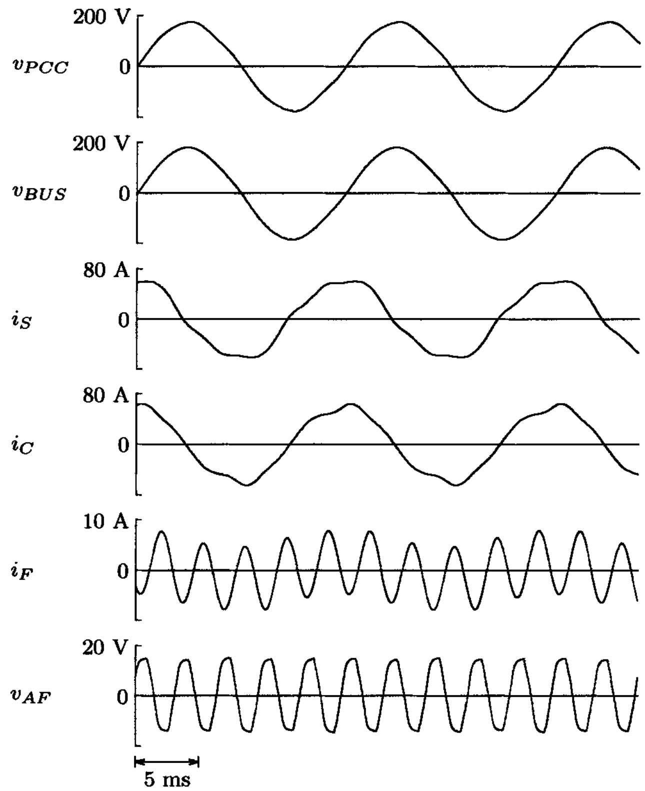


Fig. 11. Experimental waveforms when the hybrid active filter is installed.

TABLE II
FFT ANALYSIS OF WAVEFORMS IN FIGS. 9, 10, AND 11.

| [%] | 5th-harmonic voltages and currents | | |
|---|---|---|---|
| | Fig. 9 | Fig. 10 | Fig. 11 |
| $v_{PCC}$ | 1.3 ( 2.3) | 2.3 | 2.3 |
| $v_{BUS}$ | 8.1 (15.0) | 6.3 | 1.1 |
| $i_S$ | 27.0 (49.0) | 23.0 | 4.4 |
| $i_C$ | 27.0 (49.0) | 22.0 | 3.7 |
| $i_F$ | — | 4.7 | 7.8 |
| $v_{AF}$ | — | — | 9.4 |

( ) : values referred to $v_{PCC} = 2.3\%$
$3\phi$, 200-V, 60-Hz, 20-kVA base

## VI. Experimental Results

### A. Damping Effect of Harmonic Resonance

Figs. 9–11 show experimental waveforms obtained from Fig. 3. Table II summarizes FFT results of 5th-harmonic voltages and currents, where $v_{\rm PCC}, v_{\rm BUS}$ and $v_{\rm AF}$ are given as the ratio of the 5th-harmonic voltage with respect to the rated phase voltage of $200/\sqrt{3}$ V, and $i_S, i_C$ and $i_F$ are as the ratio of the 5th-harmonic current with respect to the rated load current of 60 A. In Figs. 10 and 11, a 2.3% 5th-harmonic voltage is injected upstream of the PCC by the harmonic voltage generator, whereas a 1.3% 5th-harmonic voltage is intentionally injected in Fig. 9, in order to reduce the 5th-harmonic current flowing into the capacitor for power factor correction.

When the hybrid filter is disconnected, that is, neither the passive filter nor the active filter is installed, the 5th-harmonic voltage on $v_{\rm BUS}$ is magnified by 6.3 as a result of the harmonic resonance between $L_T$ and $C$, as shown in Fig. 9. In other words, a 5th-harmonic voltage of 15% would appear on $v_{\rm BUS}$ if that of 2.3% existed on $v_{\rm PCC}$.

When only the passive filter is installed, a 5th-harmonic voltage of 6.3% appears on $v_{\rm BUS}$ with a magnification factor of 2.7, as shown in Fig. 10 and Table II. Note that a much larger amount of 5th-harmonic current flows in the passive filter than the fundamental current because the capacity of the passive filter is as small as 2%.

Fig. 11 shows the experimental waveforms when the hybrid filter is installed. No harmonic voltage magnification occurs even under the same conditions as Fig. 10, so that $v_{\rm BUS}$ is almost sinusoidal. The 5th-harmonic voltage and currents are reduced to one-sixth as small as those in Fig. 10. This indicates that the active filter connected in series with the passive filter makes a significant contribution to damping the harmonic resonance. The output voltage of the active filter, $v_{\rm AF}$ is opposite in phase to the 5th-harmonic current present in $i_F$. This implies that the active filter acts as a negative resistor for the 5th-harmonic voltage and current. Therefore, the 5th-harmonic current in $i_F$ in Fig. 11 is 1.7 times as large as that in Fig. 10. The required peak rating of the active filter is 0.14 kVA, which is only 0.7% of the load rated at 20 kW.

Invoking equivalent transformation between a voltage source and a current source gives us that series connection of the 2.3% 5th-harmonics voltage source upstream of the PCC is equivalent to parallel connection of a 5th-harmonic current source on the common bus under the disconnection of the 5th-harmonic voltage source. The following relationship between the 2.3% 5th-harmonic voltage source $V_{S5}$ and the 5th-harmonic current sources $I_{\rm BUS5}$ exists:

$$I_{\rm BUS5} = \frac{V_{S5}}{5\omega L_T} = \frac{200\ {\rm V}/\sqrt{3} \times 0.023}{5 \times 2\pi \times 60\ {\rm Hz} \times 0.00036\ {\rm H}} = 3.9\ {\rm A}.$$

### B. Experimental Results Against Overcurrent

Figs. 12 and 13 show experimental waveforms when the gain $K$ is kept as a constant value of $-2\ \Omega$, and when the gain is automatically controlled with the function of the gain-adjusting circuit, respectively. Figs. 14–16 illustrate close-up waveforms of periods A, B and C in Figs. 12 and 13. Note that the waveform of $v_{S5}$ in Figs. 14, 15 or 16 includes a fundamental voltage component in addition to a 5th-harmonic voltage. The reason is that a fundamental current component of $i_S$, flowing through the matching transformer for connecting the 5th-harmonic voltage generator in series with the utility, induces the fundamental voltage component across the matching transformer due to the presence of a non-negligible leakage inductor. To realize overcurrent conditions in this experiment, the amplitude of the 5th-harmonic voltage injected by the harmonic voltage generator is increased at a constant rate of 0.5 V/s, and the limitation value of the 5th-harmonic current flowing into the passive filter is set to be 1.0 A. In Fig. 12, the 5th-harmonic current flowing into the passive filter finally reaches 4.3 A as the injected 5th-harmonic voltage is increased. The increased

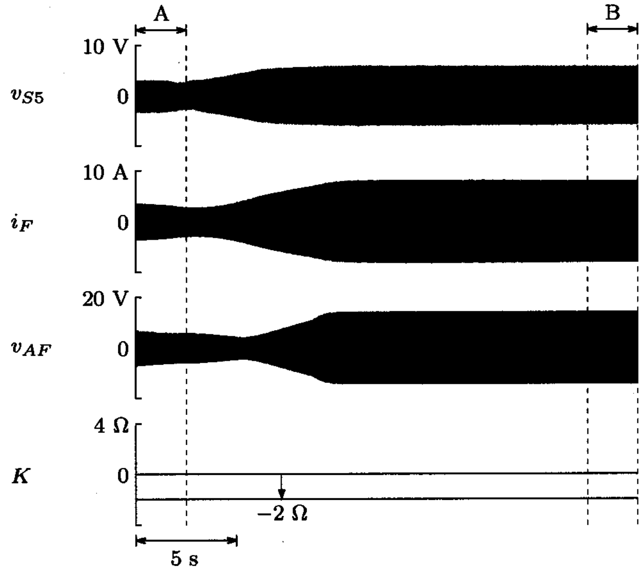


Fig. 12. Waveforms when $K$ is constant.

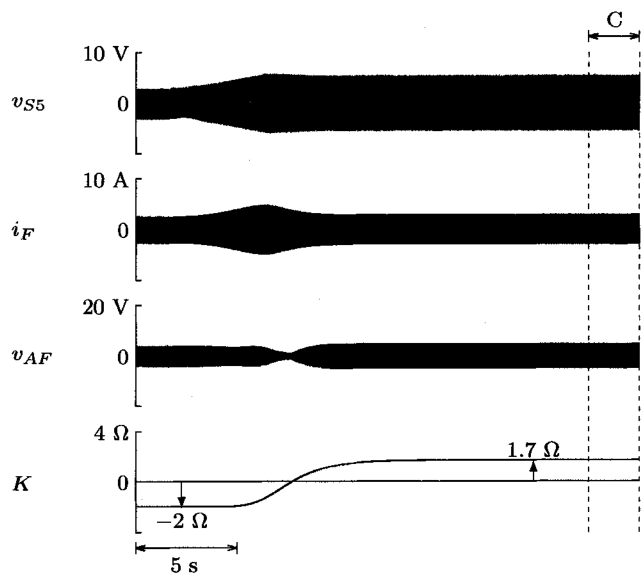


Fig. 13. Waveforms when $K$ is adjusted.

5th-harmonic current is accompanied by the increased output voltage of the active filter.

In Fig. 13, when the 5th-harmonic current $i_{F5}$ is over the limitation value, the gain-adjusting circuit starts to vary the gain from a negative to positive value, finally approaching 1.7 Ω. As a result of adjusting the gain, $i_{F5}$ is eventually limited within 1.0 A. Note that a time delay of 1.3 s exists between the maximum point of the 5th-harmonic current in $i_{F5}$ and the maximum point of a gain-rising rate of 1.2 Ω/s, because the first-order low-pass-filters with a corner frequency of 1.6 s are used in the harmonic-extracting circuit. In Fig. 16, the 5th-harmonic current in $i_{F5}$ is in phase with the output voltage of the active filter $v_{\mathrm{AF}}$, and thus the active filter acts as a positive resistor of 1.7 Ω at the 5th-harmonic frequency.

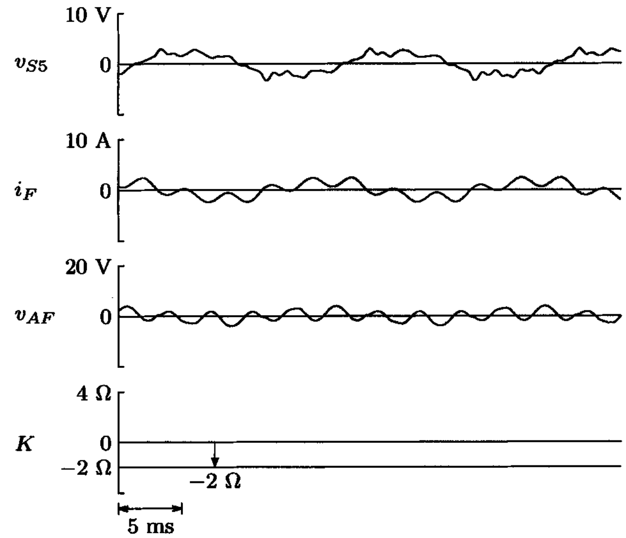


Fig. 14. Close-up of period A in waveforms in Fig. 12.

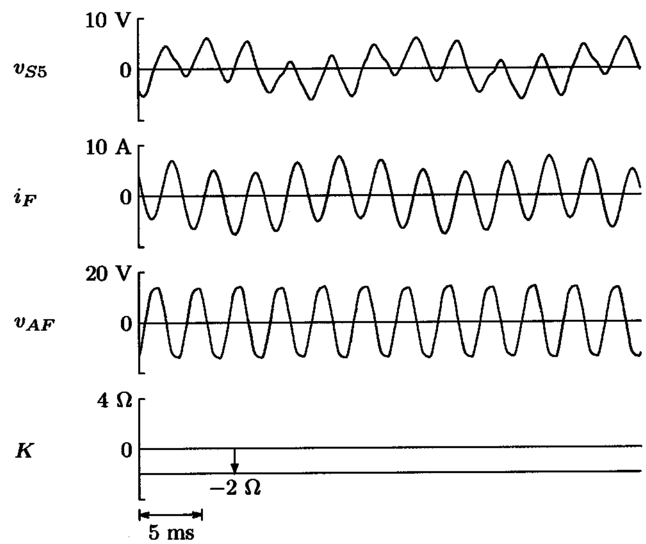


Fig. 15. Close-up of period B in waveforms in Fig. 12.

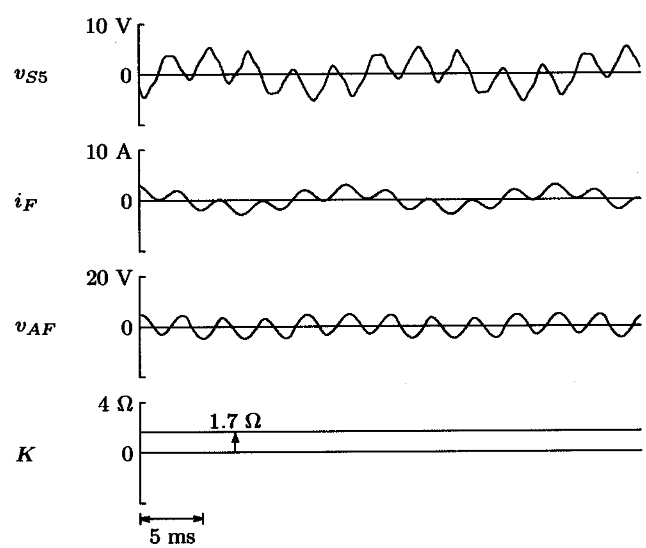


Fig. 16. Close-up of period C in waveforms in Fig. 13.

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## VII. Conclusion

This paper has proposed a hybrid active filter intended for damping of harmonic resonance in industrial power systems. The theoretical analysis and experiment developed in this paper have verified the viability and cost-effectiveness in the hybrid filter. This paper has led to the following conclusions.

1) The $I_F$-detecting method is much better in stability and detection accuracy than the other methods.
2) The hybrid filter can reduce the 5th-harmonic voltage appearing on the common bus to one-sixth as low as the passive filter used alone.
3) The required rating of the active filter is less than 1% of the rated load.
4) The active filter acting as a positive resistor at the 5th-harmonic frequency prevents the passive filter from overcurrent.

The hybrid active filter is expected to be installed in an industrial power system which is subjected to harmonic resonance.

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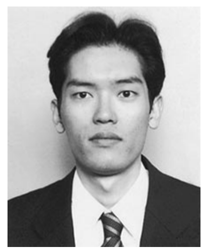

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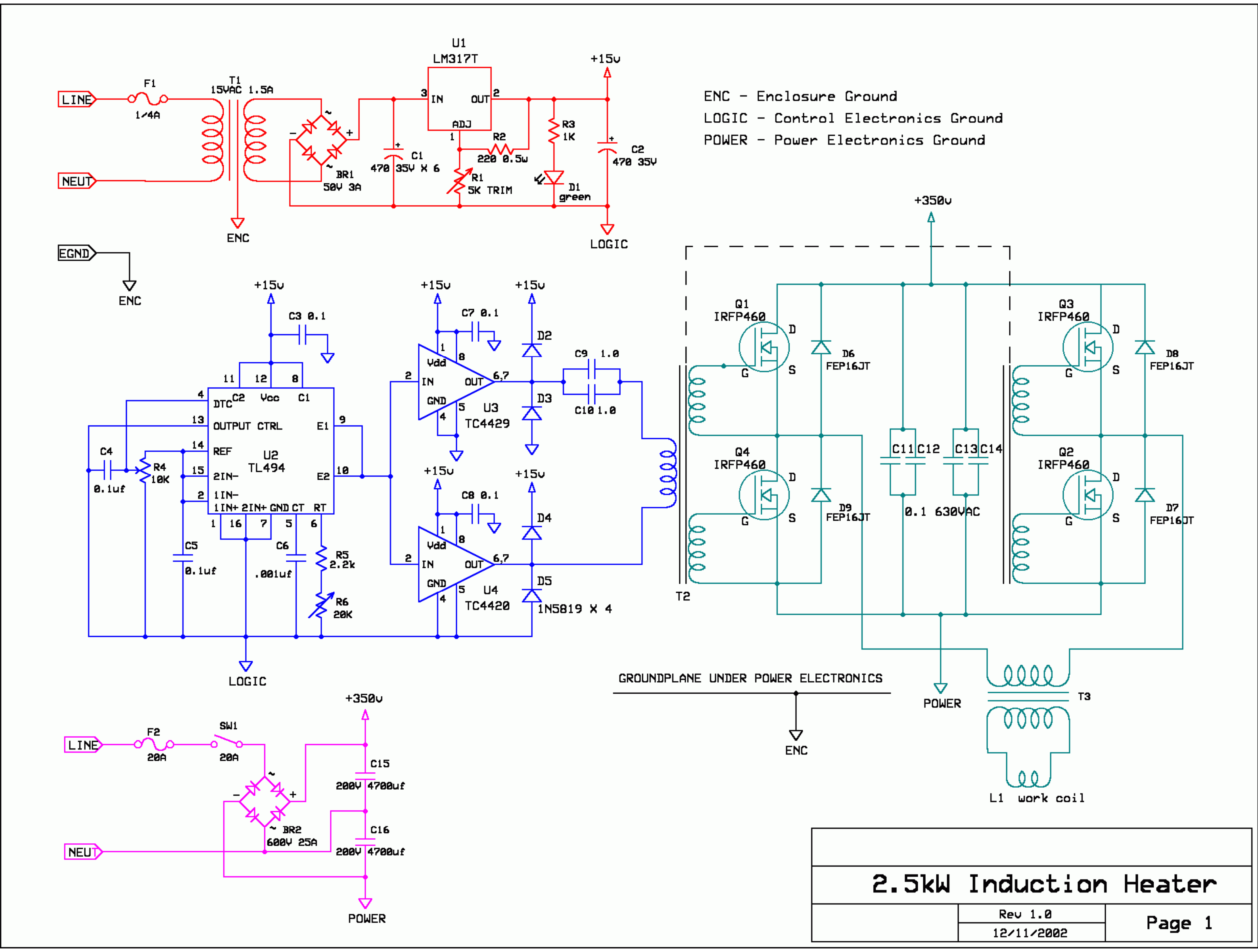

U1
LM317T
+15v
LINE
F1
1/4A
T1
15VAC 1.5A
IN
OUT
ADJ
R3
1K
R2
220 0.5w
C1
470 35V X 6
R1
5K TRIM
D1
green
C2
470 35V
BR1
50V 3A
NEUT
ENC
LOGIC
ENC - Enclosure Ground
LOGIC - Control Electronics Ground
POWER - Power Electronics Ground
+350v
EGND
C3 0.1
C7 0.1
C8 0.1
DTC
C2
Vcc
C1
OUTPUT CTRL
E1
REF
U2
TL494
2IN-
E2
1IN-
1IN+ 2IN+ GND CT RT
C4
0.1uf
R4
10K
C5
0.1uf
C6
.001uf
R5
2.2k
R6
20K
Vdd
IN
OUT
GND
U3
TC4429
U4
TC4420
D2
D3
D4
D5
1N5819 X 4
C9 1.0
C10 1.0
T2
Q1
IRFP460
Q2
IRFP460
Q3
IRFP460
Q4
IRFP460
D6
FEP16JT
D7
FEP16JT
D8
FEP16JT
D9
FEP16JT
C11 C12 C13 C14
0.1 630VAC
GROUNDPLANE UNDER POWER ELECTRONICS
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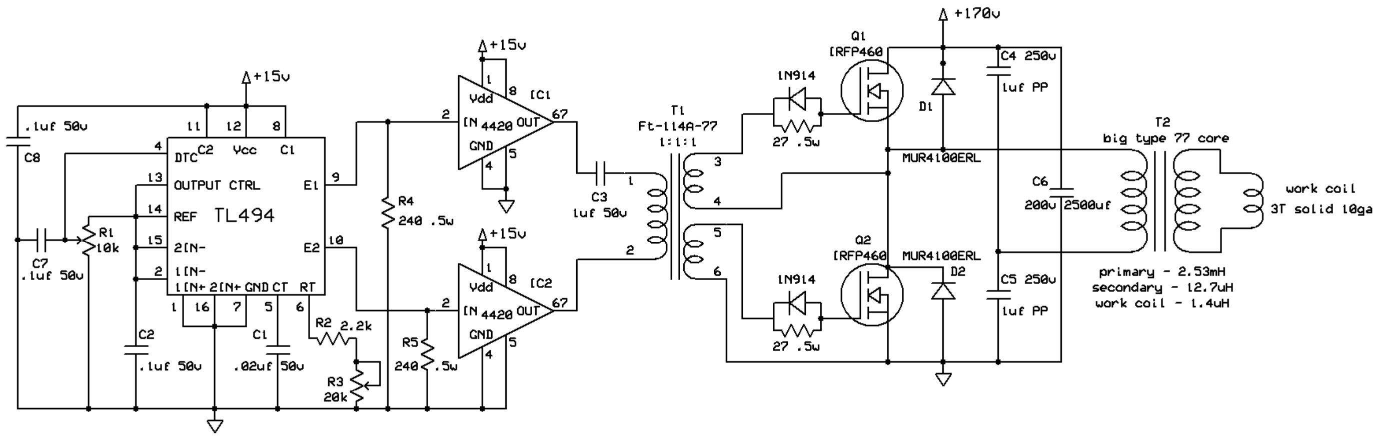


# MOSFET Induction Heater

Rev 1.0

12/11/2002

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**Lampiran 6: Proposal Tugas Akhir**

**JURUSAN TEKNIK ELEKTRO**
**FAKULTAS TEKNOLOGI INDUSTRI**
**UNIVERSITAS KRISTEN PETRA**

## PROPOSAL TUGAS AKHIR

| | |
|---|---|
| Nama | : RATNA SHINTA DEWI |
| NRP | : 23400150 |
| Bidang Studi | : Teknik Energi Listrik |
| Judul Tugas Akhir | : **Studi Simulasi Hybrid Active Filter Seri-Seri Untuk Meredam Harmonisa Pada Induction Furnace Dengan Menggunakan Program PSim** |
| Pembimbing I | : Ir. Limboto Limantara, M.T |
| Pembimbing II | : Yusak Tanoto, S.T |
| Dilaksanakan | : Semester Ganjil 2005-2006 |
| Kata Kunci | : Hybrid Active Filter Seri-Seri dan Harmonisa |

Surabaya, 20 Juli 2005
Yang mengusulkan,

(Ratna Shinta Dewi)

Mengetahui :

Pembimbing 1 Pembimbing 2

(Ir. Limboto Limantara, M.T) (Yusak Tanoto,ST)

Koordinator Tugas Akhir

(Petrus Santoso,S.T., M.Sc)

**1. Judul Tugas Akhir**

Studi Simulasi Hybrid Active Filter Seri-Seri Untuk Meredam Harmonisa Pada Induction Furnace Dengan Menggunakan Program PSim.

**2. Latar Belakang Masalah**

Banyaknya kebutuhan manusia terhadap peralatan listrik saat ini terutama dalam bidang industri. Peralatan-peralatan yang banyak digunakan adalah beban-beban non linier. Beban-beban listrik non linier pada peralatan industri yaitu antara lain mesin las, *arc furnace*, converter, UPS (Uninterruptible power sources), komputer, dan sebagainya. Beban non linier juga dapat merupakan peralatan-peralatan yang mempunyai komponen diode atau thyristor rectifier. Peralatan-peralatan non linier tersebut ternyata membawa dampak pada bentuk gelombangnya. Perubahan bentuk ini juga dapat diartikan peralatan telah timbul harmonisa.

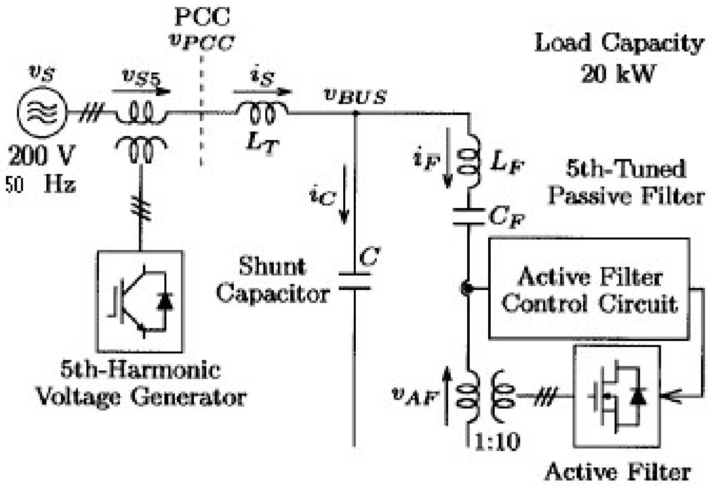
Harmonisa merupakan suatu fenomena yang timbul atau terjadi akibat dioperasikannya beban listrik non linier, yang merupakan sumber terbentuknya gelombang pada frekuensi-frekuensi tinggi yang merupakan kelipatan dari frekuensi fundamentalnya seperti 100 Hz, 150 Hz, 200 Hz, 250 Hz, 300 Hz, dan seterusnya. Hal ini dapat mengganggu sistem listrik pada frekuensi fundamentalnya yaitu 50 Hz, sehingga bentuk gelombang arus maupun tegangan yang idealnya adalah sinusoidal murni akan menjadi cacat akibat distorsi harmonisa yang terjadi. Dengan makin banyaknya alat-alat non linier yang dipakai, distorsi harmonisa dari bentuk gelombang tegangan merupakan persoalan yang perlu mendapat perhatian. Distorsi tegangan harmonisa pada sistem tenaga menjadi sangat serius dengan terjadinya harmonisa ke 5 dan ke 7 yang jarang bisa diterima di konsumen listrik di industri. Dimana Hybrid filter terdiri dari aktif dan pasif filter yang dirangkai seri atau paralel, filter pasif digunakan meredam harmonisa ke 5 dan filter aktif digunakan untuk meredam harmonisa ke 7. Peredaman harmonisa merupakan pilihan yang tepat untuk mengurangi harmonisa tegangan dan arus. Pada studi ini sebuah hybrid active filter digunakan untuk meredam harmonisa.

### 3. Perumusan Masalah

Dalam tugas akhir ini, penulis akan membahas :

- Sistem tenaga pada industri

  Sistem tenaga pada industri dinilai pada 200 V, 50 Hz dan 20 kVA.




- Filter Pasif

  Penggunaan filter pasif untuk meredam harmonisa ke 5 yang sangat besar, harmonisa ke 5 mempunyai frekuensi pada 5 x 50 Hz = 250 Hz.

  Peranan filter pasif dalam meredam hamonisa ke 5.

- Filter Aktif

  Penggunaan filter aktif untuk meredam harmonisa ke 7 yang mempunyai frekuensi 7 x 50 Hz = 350 Hz,

  Peranan filter aktif dalam meredam harmonisa ke 7.

- Harmonisa ke 5 dan ke 7

  Harmonisa ke 5 mempunyai frekuensi kerja 5 x 50 Hz = 250 Hz

  Harmonisa ke 7 mempunyai frekuensi kerja 7 x 50 Hz = 350 Hz

  Pengaruh harmonisa yang membuat distorsi pada tegangan sistem tenaga.

- Induction furnace sebagai beban

  Beban induction furnace yang menghasilkan harmonisa ke 5 dan ke 7. dengan daya 9 kW, 13.8 kVA, 200 V, 3 Ph , 50 Hz

- Pengukuran diindustri dengan mengambil data-data yang diperlukan sebagai bahan pembanding.

- Simulasi pemodelan sIstem dengan menggunakan program PSim.
- Hasil dari data-data yang didapat dari pengukuran di industri dibandingkan data-data yang didapat dari simulasi dengan menggunakan program PSim.
- Simulasi kelayakan penggunaan hybrid active filter pada sIstem untuk meredam harmonisa ke 5 dan ke 7.

**4. Tujuan Tugas Akhir**

Tujuan dari tugas akhir ini adalah untuk mempelajari dan memahami Studi Simulasi Hybrid Active Filter seri-seri dan sistem kerja rangkaian dalam meredam harmonisa pada Induction Furnace yang mempunyai daya 9 kW, 13.8 kVA, 200V, 3 Ph , 50 Hz, dengan Menggunakan Program PSim. Dan juga membandingkannya dengan yang ada di industri.

**5. Tinjauan Pustaka**

Penggunaan Hybrid Active Filter Seri-Seri pada Indution Furnace sangat efektif dalam meredam harmonisa dimana harmonisa ini dapat menyebabkan distorsi pada tegangan system. Karena didalam hybrid aktif filter seri-seri mempunyai filter aktif dan pasif. Filter aktif bekerja sebagai inverter yang mempunyai sifat anti harmonisa ke 7, sedangkan filter pasif berguna untuk meredam harmonisa ke 5 yang sangat besar.

Dimana Filter aktif selain berfungsi untuk meredam harmonisa dapat juga berfungsi menginjeksikan arus untuk membatalkan harmonisa yang terkandung pada arus beban.

Struktur Hibrid Filter Seri-Seri adalah seperti terlihat pada gambar di bawah ini, dimana rangkaiannya tersusun dari:

- Satu rangkaian atau lebih filter resonant pasif (Fi), yang terhubung paralel dengan beban non linier.
- Pengatur harmonisa aktif (filter aktif), terdiri atas:
  - *Coupler* magnetic (Tr), yang primer dihubungkan seri dengan filter pasif
  - Inferter (MUT) dihubungkan dengan sekunder *coupler* magnetic.

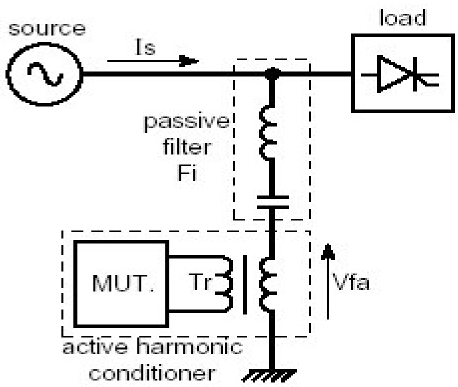
Pengaturan filter aktif dapat dikendalikan sehingga:

$$Vfa = K \times I_{SH}$$

Dimana : Vfa : Tegangan pada terminal coupler magnetic.

K : Nilai dalam (Ohm).

$I_{SH}$ : Arus harmonisa pada sumber.




Gambar. Duagram Satu Phasa Pengaturan FilterHibrid Seri-Seri

**6. Metodologi Penelitian**

Metode penelitian yang digunakan dalam tugas akhir ini meliputi :

- Studi Literatur

  Penulis mempelajari literatur-literatur mengenai harmonisa, resonansi, filter harmonisa, Hybrid Active Filter Seri-Seri, sistem peralatannya dan penggunaannya untuk meredam harmonisa.

  Mempelajari data beban Induction Furnace, mempelajari data Single Line Diagram Sistem, dan literatur-literatur lainnya yang berhubungan dengan Hybrid Active Filter Seri-Seri.

- Pengambilan Data

  Penulis melakukan pengambilan data nilai tegangan, arus, power factor (cosφ), sumber-sumber harmonisa, dan beberapa hal yang berhubungan dengan analisa data.

- Analisis Data

  Setelah memperoleh data, maka penulis menganalisa data-data tersebut. Selain itu, penulis juga melakukansimulasi pemodelan dengan menggunakan program Psim dengan dan tanpa Hybrid Active Filter.

  Pengukuran tanpa filter dengan filter diindustri.

- Kesimpulan

  Dengan menggunakan simulasi program PSim akan dibandingkan dengan pengukuran dilapangan, maka akan diambil kesimpulan.

## 7. Relevansi

Studi simulasi Hybrid Active Filter Seri-Seri untuk meredam harmonisa pada Induction Furnace dengan menggunakan program PSim dapat bermanfaat untuk masukan dalam mempercepat proses perencanaan hybrid active filter diindustri.

## 8. Jadwal Kegiatan

| Kegiatan | Bulan Ke | | | |
|---|---|---|---|---|
| | I | II | III | IV |
| Studi Literatur | ■ | ■ | ■ | |
| Pengambilan Data | | ■ | ■ | |
| Analisa Data | | | ■ | ■ |
| Pembuatan Laporan | | | | ■ |

## 9. Daftar Pustaka


Almanda, Deni. *Peranan Kapasitor dalam Penggunaan Energi Listrik*. Elektro Indonesia, Nomor 30, TahunVI, April 2000 <http://www.elektroindonesia.com/elektro/ener30a.html>.

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