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Harmonic disturbances in networks, and their treatment

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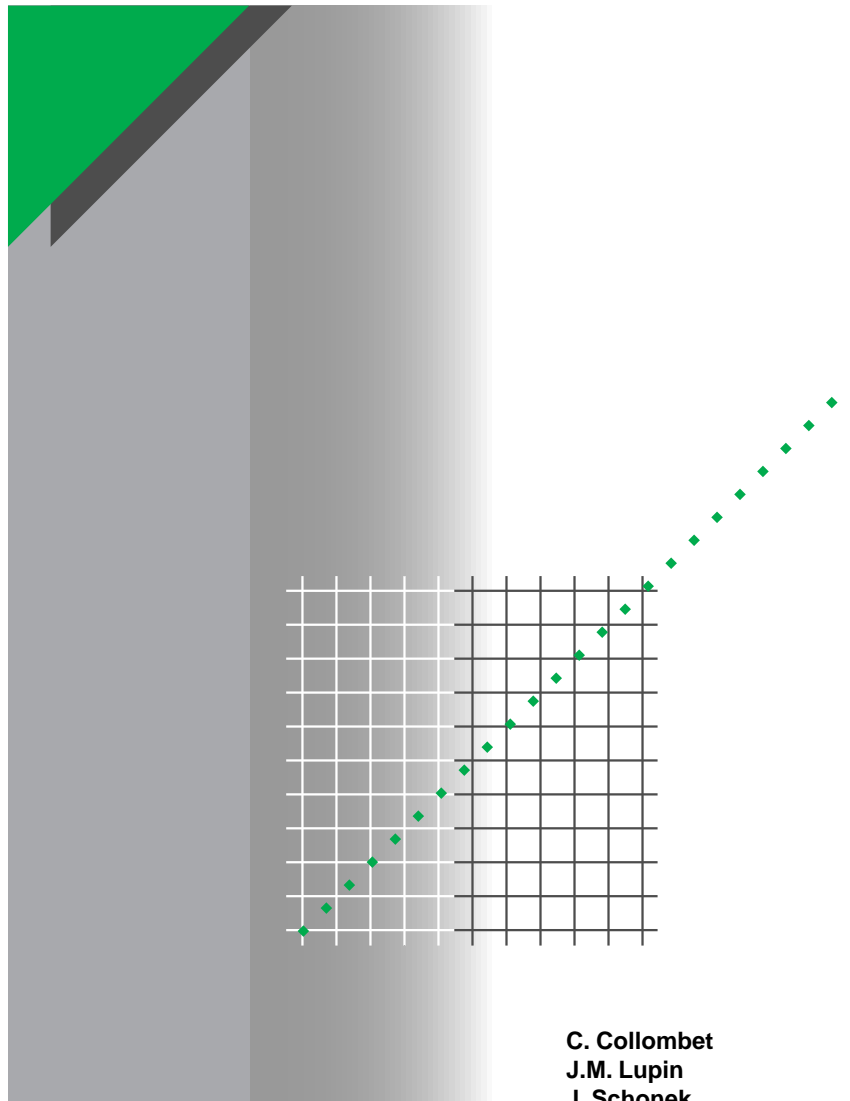
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no. 152

Harmonic disturbances in networks, and their treatment
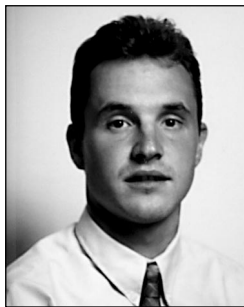
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Have also taken part in the 1999 edition of this document:
Noël QUILLION, author of the first edition, presently in the networks protection and control department;
Bruno LUSSON, harmonics specialist at "Support Services France".

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 nth harmonic component
f_r	resonance frequency
j_n	phase angle of the nth harmonic component when t = 0
I_n	rms current of the nth 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 nth 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 nth 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 nth 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 nth 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**).
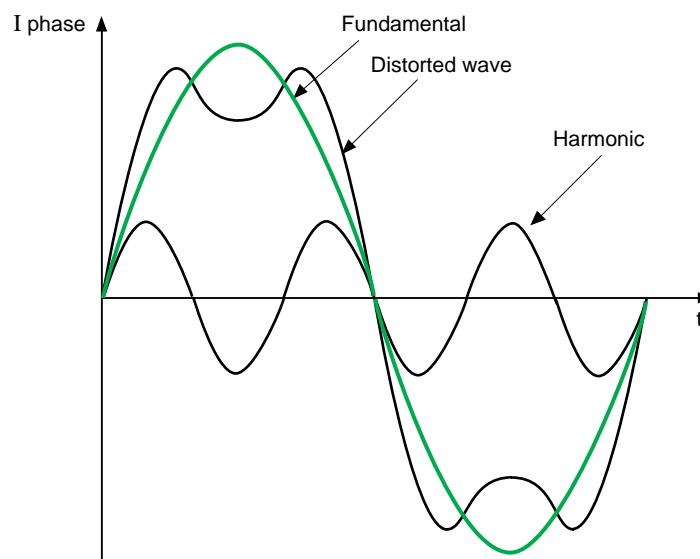

Fig.1 : shape of a distorted wave.

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 nth harmonic component,

■ φ_n = phase angle of the nth 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:

$$R I^2 t = R I_1^2 t + R I_2^2 t + \dots + R I_n^2 t$$

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

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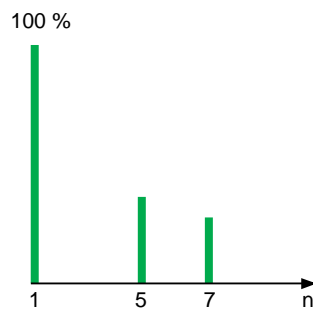

100 %

1   5   7   n

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 nth harmonic ratio is the ratio of the rms value of the nth 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 δ 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.

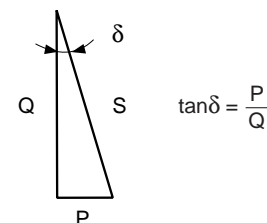$$\tan\delta = \frac{P}{Q}$$

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**).

Rectifier supply phase current

Phase current upstream from a delta-star connected transformer supplying the rectifier
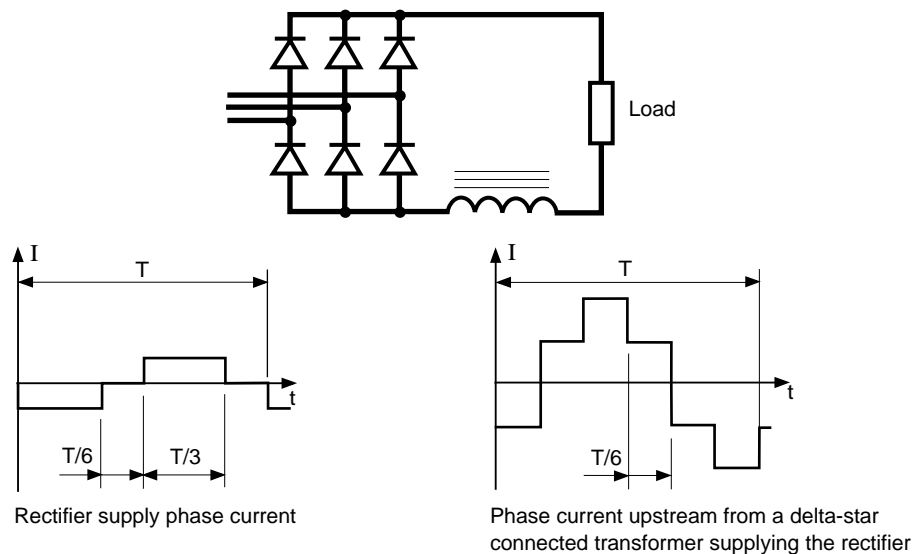
Fig. 5 : *alternating current upstream of a Graetz bridge rectifier delivering a perfect direct current on a highly inductive load.*
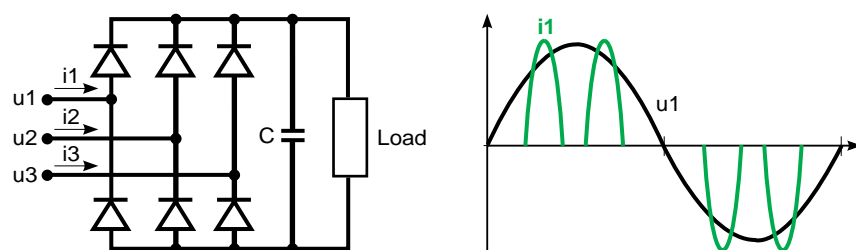
Fig. 6 : *alternating current upstream of a Graetz bridge rectifier followed by a capacitor.*

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 $n = kp \pm 1$, 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 5th and 7th 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**).
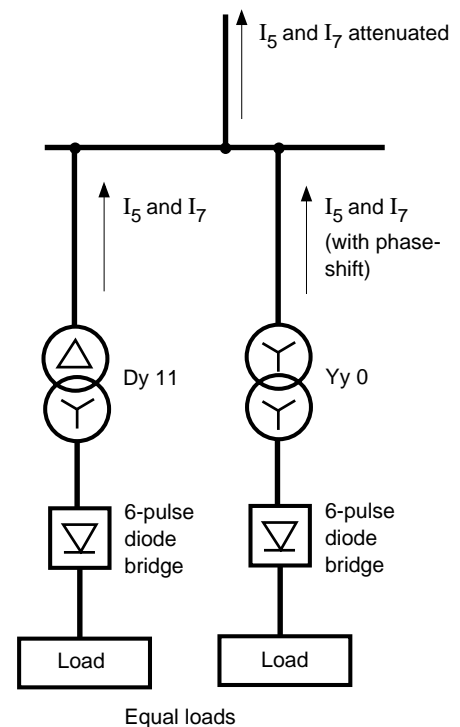

I_5 and I_7 attenuated

I_5 and I_7 I_5 and I_7 (with phase-shift)

Dy 11   Yy 0

6-pulse diode bridge   6-pulse diode bridge

Load   Load

Equal loads

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 3rd harmonic ratio may even exceed 100% in certain cases of modern fluocompact lamps.

The neutral conductor then carries the sum of the 3rd 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.
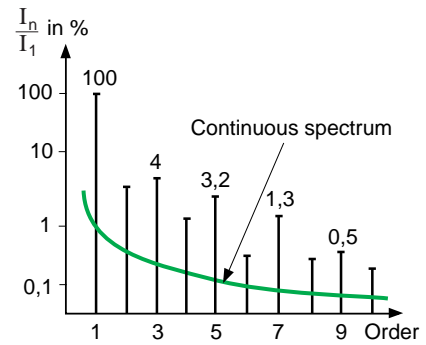
Fig. 9 : current spectrum for an arc furnace supplied by AC power.
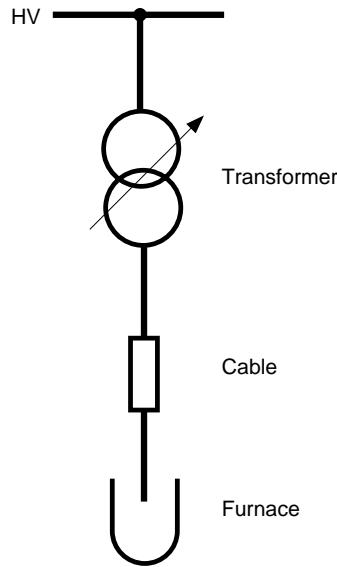
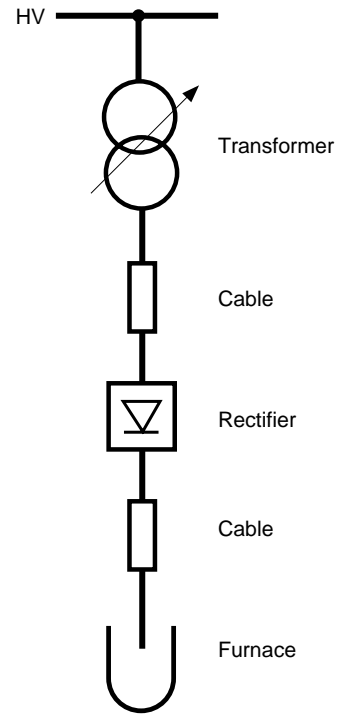*Fig. 8* : arc furnace supplied by AC power.

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.
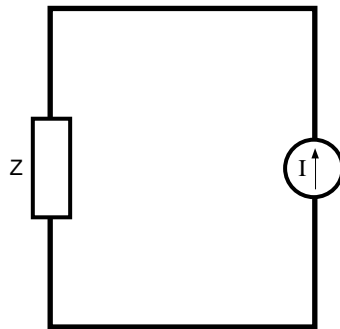

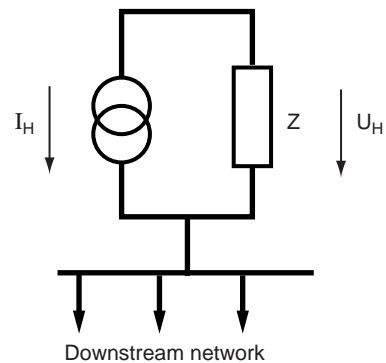**Fig. 11** : harmonic current generators are modelled as current sources.

Downstream network

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
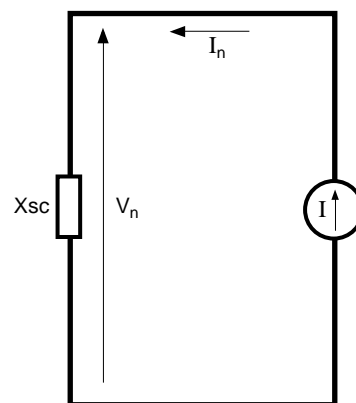

Fig. 13 : the harmonic voltage V_n is proportional to the current I_n injected by the disturbing equipment.

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.).

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.

a : harmonic electrical representation of a phase
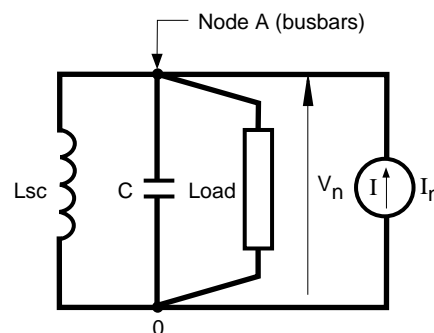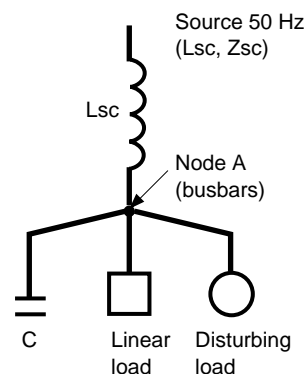

b : single-line diagram

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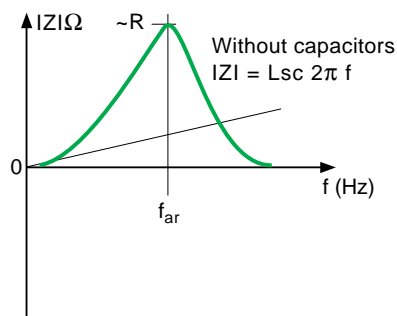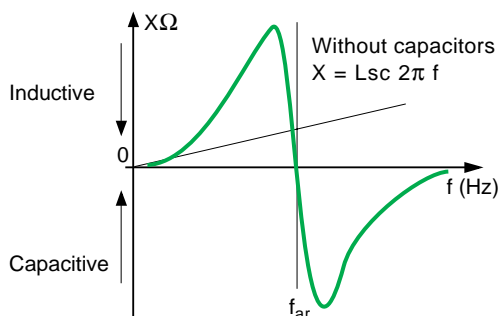

Fig. 15 : *curves showing the impedance due to the loads and due to the resistance of the conductors.*

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 $V_n = Z_{AO}\,I_n$.
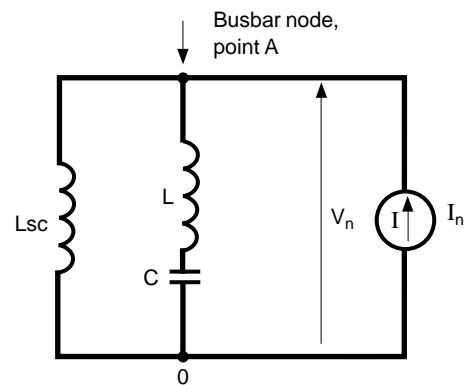
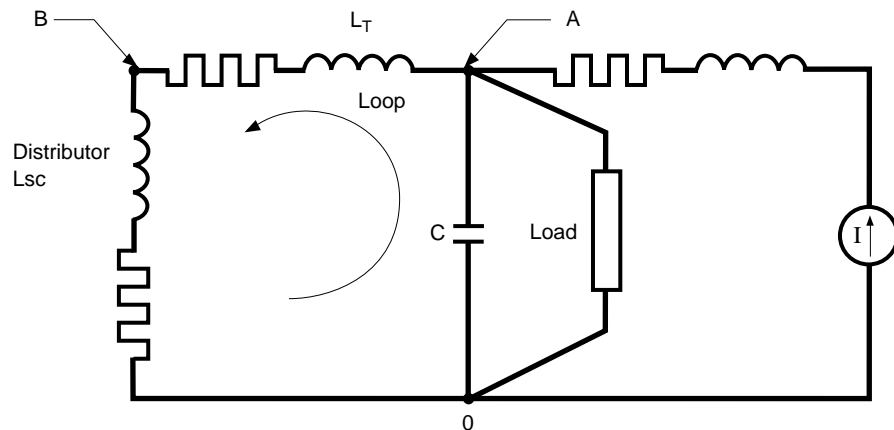*Fig. 17* : reactor, connected in series with the capacitor.

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: $Z = r + j (L\omega - 1/C\omega)$ 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

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

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);

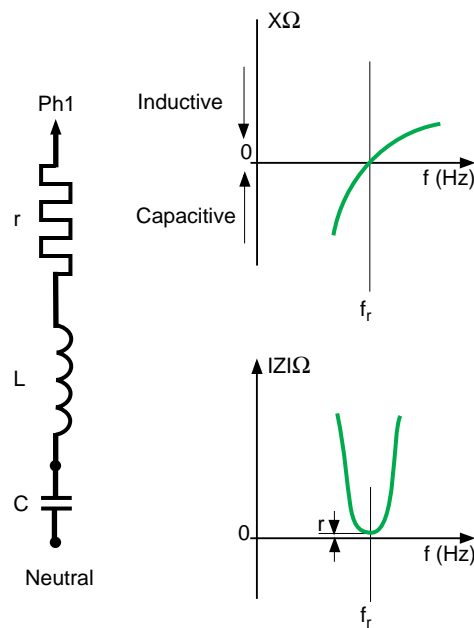■ filters (for series resonance on a spectrum line).

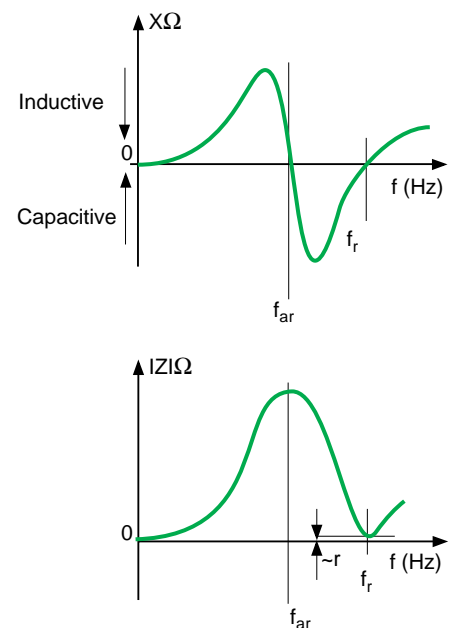*Fig. 18* : impedance of the rejector circuit.

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.
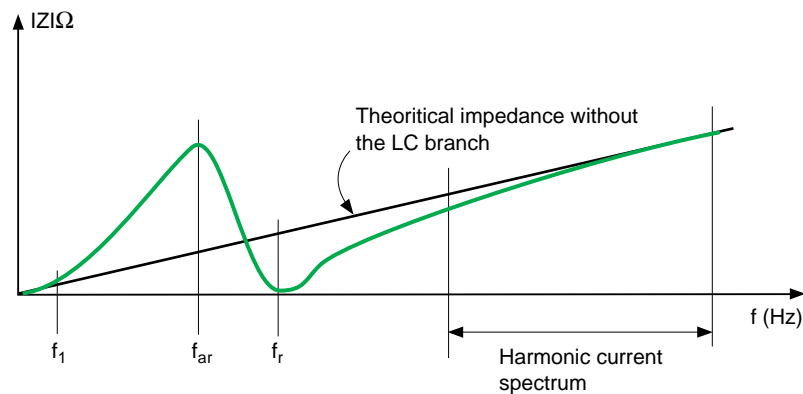

Fig. 20 : *the capacitors are protected when f_r is well bellow the harmonic spectrum.*

7 Filters

7.1 Resonant shunt filters

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

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

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 5th, 7th, 11th and 13th 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:

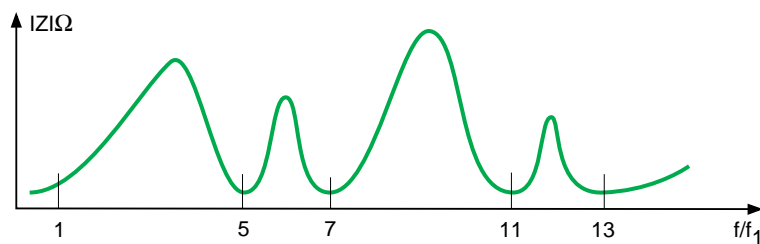$$Q_{var} = \frac{n_r^2}{n_r^2 - 1}\, U_1^2\, C\, 2\pi\, f_1$$

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 $X_0 = \sqrt{\dfrac{L}{C}}$

■ The quality factor $q = X_0/r$

An effective filter must have a reactor with a large quality factor q, therefore $r \ll X_0$ 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 $p_1 = \dfrac{Q_{var}}{q\, n_r}$

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: $p_n = \dfrac{U_{nr}^2}{r}$

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).
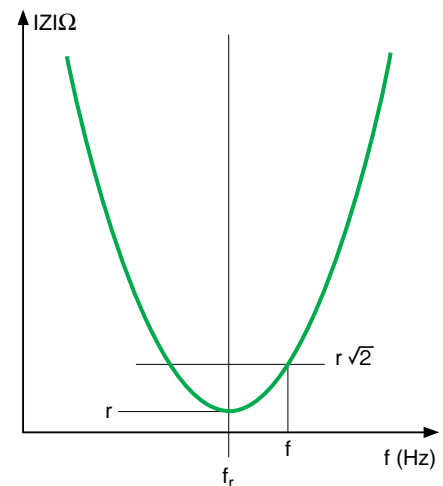

Fig. 22 : Z versus f curve for a resonant shunt.

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:

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

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:

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

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

■ Characteristic impedance $X_0 = \sqrt{\dfrac{L}{C}}$

■ 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.
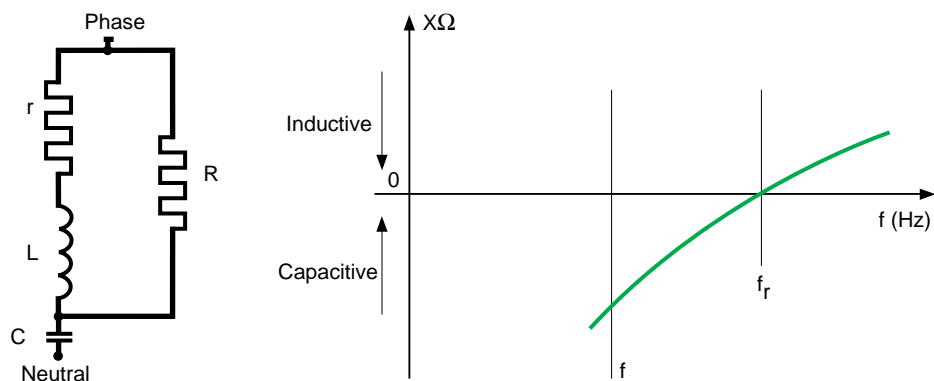

Fig. 23 : 2nd order damped filter.

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.
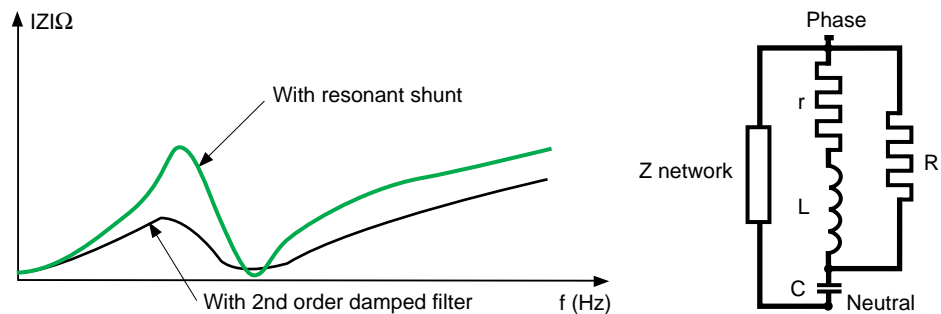

Fig. 24 : the impedance, seen from point A, of a network equipped with either a 2nd order damped filter or a resonant shunt.
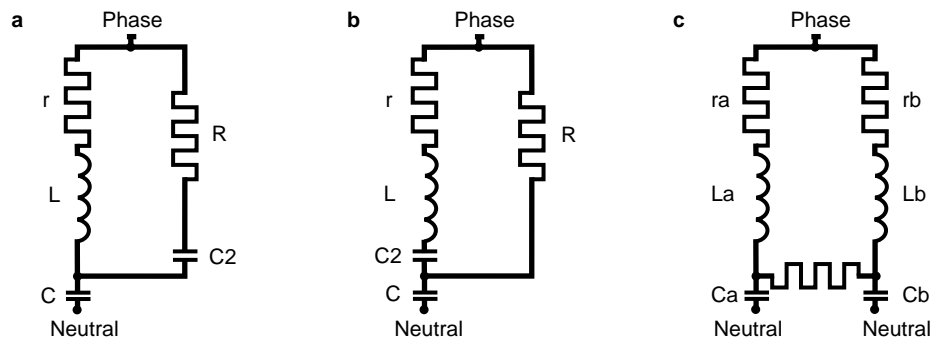

Fig. 25 : other types of damped filters: *[a]* - 3rd order; *[b]* - C type; *[c]* - double filter.

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 5th harmonic and a 2nd order damped filter tuned to the 7th 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.
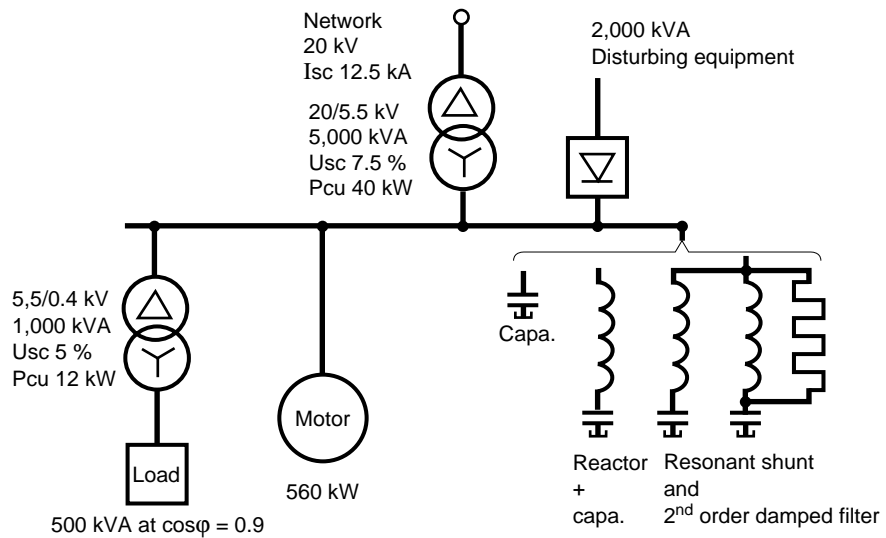

Fig. 26 : installation with disturbing equipment, capacitors and filters.

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 7th current harmonic. This results in an unacceptable individual harmonic voltage distortion of 11% for the 7th 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**).

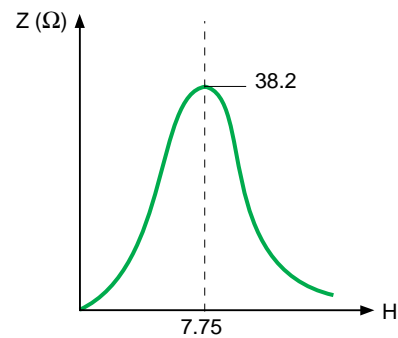The solution with capacitors alone is therefore unacceptable.

Fig. 27 : harmonic impedance seen from the node where the harmonic currents are injected in a network equipped with a capacitor bank alone.
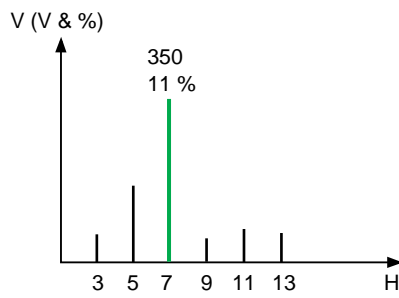
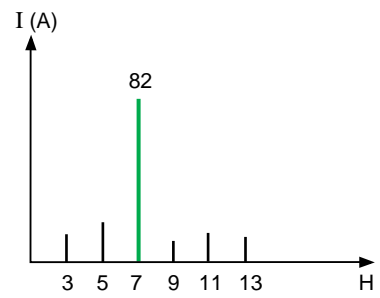**Fig. 28** : *harmonic voltage spectrum of a 5.5 kV network equipped with a capacitor bank alone.*

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 5th harmonic favours the filtering of the 5th harmonic quantities.

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

For the 5.5 kV network, the individual harmonic voltage ratios of 1.58% (7th harmonic), 1.5% (11th harmonic) and 1.4% (13th 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.
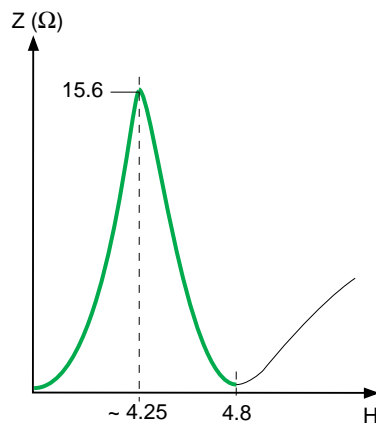
Capacitor current load (cf. **fig. 32**)

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).
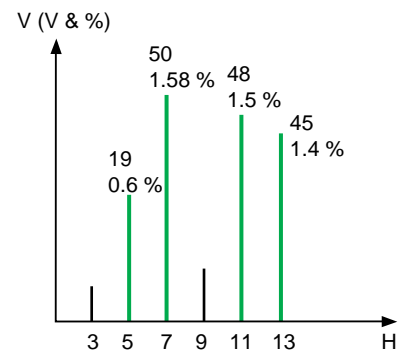

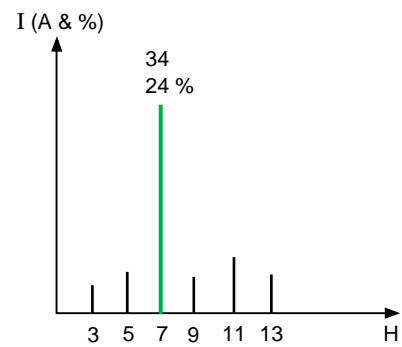**Fig. 31** : *harmonic voltage spectrum of a 5.5 kV network equipped with reactor-connected capacitors.*

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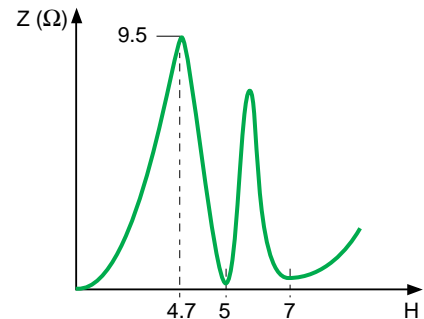

Fig. 33 : harmonic impedance seen from the node where the harmonic currents are injected in a network equiped with a resonant shunt filter tuned to the 5th harmonic and a damped filter tuned to the 7th harmonic.
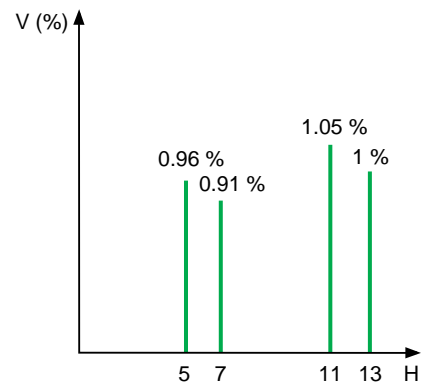

Fig. 34 : harmonic voltage spectrum of a 5.5 kV network equipped qith a resonant shunt filter tuned to the 5th harmonic and a damped filter tuned to the 7th harmonic.

■ 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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■ IEC 61000-2-2: Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems.

■ IEC 61000-2-4: Compatibility levels in industrial plants for low-frequency conducted disturbances.

■ IEC 61000-3-2: Limits for harmonic current emissions for equipment with input current not exceeding 16 A per phase.

■ IEC 61000-3-4: Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A.

■ IEC 61642: Industrial a.c. networks affected by harmonics - Application of filters and shunt capacitors.

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