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harmonics in industrial networks

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glossary

Symbols:	
C	capacitance or, more generally, the capacitors themselves
D	harmonic distortion
δ	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
φ _n	phase angle of the n th harmonic component when t = 0
In	rms current of the n th harmonic component
j	complex operator equal to the square root of $\sqrt{-1}$
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 radio of the anti-resonance frequency to the fundamental frequency
n _r	the order of resonance, i.e. the radio of the resonance frequency to the fundamental frequency
k	a positive integer
р	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
РВ	pass-band of a resonant shunt filter
q	quality factor of a reactor
Q	quality factor of a filter
Q (var)	reactive power
r	
R	resistance (or the real part of the impedance)
spectrum	fundamental
Ssc	short-circuit power of a network at a given point
Т	period of an alternating quantity
U	phase-to-phase rms voltage
V _n	rms voltage of the n th harmonic component
Х	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
Yn	rms value of the n th harmonic component
2	Impedance
Abbreviatio	ns:
CIGRE	Conférence Internationale des Grands Réseaux Electriques (International Conference on Large Electrical Networks)
IEC	International Electrotechnical Commission

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1. introduction

harmonic distortion is a problem that must often be dealt with in industrial power distribution networks

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.

2. 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).

Expression of the distorted wave

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

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

where:

• Y_0 = the amplitude of the DC component, which is generally zero in electrical power distribution;



fig.1: shape of a distorted wave.

• Y_n = the rms value of the nth harmonic component, • ϕ_n = phase angle of the nth harmonic component when t = 0. Harmonics with an order above 23 are often negligible.

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 steadystate conditions, the energy dissipated by the Joule effect is the sum of the energies dissipated by each of the harmonic components:

$$R I^{2} t = R I_{1}^{2} t + R I_{2}^{2} t + ... + R I_{n}^{2} t$$

where:

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

i.e. where:

$$I = \sqrt{\sum_{n=1}^{n=\infty} I_n^2}$$

if the resistance can be considered to be constant.

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 In is I_n/I_1 or 100 (I_n/I_1) if expressed as a percentage (note that here In is not the nominal or rated current);

■ total harmonic distortion (also referred to as THD, the total harmonic factor or simply as distortion 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 (CIGRE), which can give a very high value:

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

 \Box the measured rms quantity (IEC 555-1), 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 CIGRE (see the glossary) which corresponds to the ratio of the rms value of the harmonic content to the undistorted current at power frequency.



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

3. 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.

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 Merlin Gerin «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).

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 dielectricc hysteresis. As a first approximation, they are proportional to the square of the applied voltage for conduction and to the frequency for hysteresis. 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 δ . The heat produced can lead to dielectric breakdown.

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 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 can be carried out as described in IEC 287.

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.

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.



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

4. acceptable limits, recommendations and standards

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 % (see IEC 871-1, 931-1 and HD 525.1S1);

sensitive electronics: 5 % voltage distortion with a maximum individual harmonic percentage of 3 % depending on the equipment.

typical limits for distribution networks

The French electrical utility, EDF, considers that voltage distortion will not exceed 5 % at the supply terminals as long as each individual subscriber does not exceed the following limits:

■ 1.6 % voltage distortion;

■ individual harmonic percentages of: □ 0.6 % for even voltage harmonics,

 \Box 1 % for odd voltage harmonics.

The table in figure 4 lists typical percentages observed for the various voltage harmonics where:

low value = value likely to be found in the vicinity of large disturbing loads and associated with a low probability of having disturbing effects;

high value = value rarely exceeded in the network, and with a higher probability of having disturbing effects.

typical limits for industrial networks

It is generally accepted that industrial network without any sensitive equipment such as regulators, programmable controllers, etc. can accept up to 5 % voltage distortion. This limit and the limits for the individual harmonic ratios may be different if sensitive equipment is connected to the installation.

harmonic	low	high	
order	value (%)	value (%)	
2	1	1.5	
3	1.5	2.5	
4	0.5	1	
5	5	6	
6	0.2	0.5	
7	4	5	
8	< 0.2		
9	0.8	1.5	
10	< 0.2		
11	2.5	3.5	
12	< 0.2		
13	2	3	
14	< 0.2		
15	< 0.3		
16	< 0.2		
17	1	2	
18	< 0.2		
19	0.8	1.5	
20	< 0.2		
21	< 0.2		
22	< 0.2		
23	0.5	1	

fig. 4: individual voltage harmonic percentages measured in high voltage distribution networks.

5. harmonics generators

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

- static converters;
- arc furnaces;
- lighting;
- saturated reactors;

■ other equipment, such as rotating machines which generate slot harmonics (often negligible).

static converters on 3-phase networks

Rectifier bridges and, more generally, static converters (made up of diodes and thyristors) generate harmonics. A Graetz bridge, for instance, requires a rectangular pulsed AC current (see fig. 5) to deliver a perfect DC current. 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 the following harmonic numbers n, with $n = kp \pm 1$, where:

■ k = 1, 2, 3, 4, 5...

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

The characteristic harmonics are all odd-numbered and have, as a first approximation, an amplitude of $I_{\text{n}}=I_{1}/\text{n}$ 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 opening 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 cycloconverters, dimmers, etc. have richer and more variable spectra than rectifiers. Note that they are increasingly replaced by converters using the PWM (Pulse Width Modulation) technique. These devices operate at high chopping frequencies (20 to 50 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. 6).

arc furnaces

Arc furnaces used in the steel industry may be of the AC (see fig. 7) or DC type.

AC arc furnaces

(see fig. 7) The arc is non-linear, asymmetric and unstable. It generates a spectrum



phase current upstream from a delta-star connected transformer supplying the rectifier

fig. 5: alternating current upstream from a Graetz bridge rectifier delivering a perfect direct current.

including odd and even harmonics as was well as a continuous component (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. 8).

DC arc furnaces

(see fig. 9)

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.

lighting

Lighting systems made up of discharge lamps or fluorescent lamps are generators of harmonic currents. A 3rd harmonic ratio of 25 % is observed in certain cases. 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.

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.

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.

calculation model

When calculating disturbances, static converters and arc furnaces are considered to be harmonic current generators. 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 (see fig. 10).

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.



equal loads









fig. 8: current spectrum for an arc furnace supplied by AC power.



fig. 9: arc furnace supplied by DC power.



fig. 10: harmonic current generators are modelled as current sources.

6. can capacitors cause a problem on networks comprising disturbing equipment?

We will consider the two following cases:

networks without power capacitors;

networks with power capacitors.

in the absence of capacitor banks, harmonic disturbances are limited and proportional to the currents of the disturbing equipment.

In principle, in so far as are concerned 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 shortcircuit 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. 11).

In figure 11:

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,

 $Xsc_n = Lsc \omega_n = Lsc n (2\pi f_1)$ 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 shortcircuit impedance is generally multiplied by a factor of 2 or 3 for the calculations.

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.).

in the presence of a capacitor bank parallel resonance can result in dangerous harmonic disturbances

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 in below.

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 12.



fig. 11: the harmonic voltage V_n is proportional to the current I_n injected by the disturbing equipment.



a: harmonic electrical representation of a phase.



b: single-line diagram.

fig. 12: equivalent diagrams for a circuit subject to harmonic currents and including a capacitor bank.

In this diagram:

□ Lsc = the short-circuit inductance of the network seen from the busbars to which the capacitor bank and the disturbing equipment are connected, □ C = capacitors,

 \Box I_n = currents of the disturbing equipment,

 \Box load = loads (Joule effect,

transmission of mechanical energy).

In principle, we consider the shortcircuit 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.13) show that: for the resonance frequency f_{ar}, the inductive effect is compensated for exactly by the capacitive effect; the reactance of the rejecter 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 = U²/P where P represents the sum of the active power values of the loaded motors, other than those supplied by a static converter.

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 14, 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,

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

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,

$$n_{ar} = \sqrt{\frac{Ssc}{Q}}$$

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 to 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.







fig. 14: the capacitor, together with the sum of the upstream impedances, forms a resonant circuit.

The rejecter circuit thus created is then represented by the diagram in figure 15 where $V_n = Z_{AO} I_n$.

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:

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

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 connections points = busbars A).

Series resonance

The branch made up of reactor L and capacitor C (see fig. 16), form a series resonance system of impedance $Z = r + j(L\omega - 1/C\omega)$ with:



fig. 15: the reactor, connected in series with the capacitor, forms a rejecter circuit.

■ 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 17 show the shape of the network inductance, 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



fig. 16: impedance of the rejecter circuit.

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).







7. 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 reactor-connected capacitor installations.

The reference diagram is once again figure 15.

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 fr 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 shortcircuit impedance.

The shape of the network impedance, seen from the busbars to which the LC branch is connected, is shown in figure 18.

There is no anti-resonance inside the current spectrum. The use of an antiharmonic 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 antiresonance, 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). The anti-harmonic reactor is tuned to an order of 4.5 to 4.8, giving a value of f_r between 225 to 240 Hz for a 50 Hz network, which is very near the ripple control frequency used on many distribution networks;

■ 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.



8. filters

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

- resonant shunt filters,
- damped filters.

resonant shunt filters

The resonant shunt filter (see fig. 16) 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 19 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:

 \blacksquare f_r = tuning frequency;

■ f_1 = fundamental frequency (generally the power frequency, e.g. 50 Hz). These characteristics are:

 \blacksquare the reactive power for compensation: $\mathsf{Q}_{var}.$

The resonant shunt, behaving capacitively 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:

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

(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;



$$X_0 = \sqrt{\frac{L}{C}};$$

■ the quality factor:

 $q = X_0/r$.

An effective filter must have a reactor with a large quality factor q, therefore: $r \ll X_0$ at frequency fr.

Approximate values of q:

□ 75 for air-cored reactors,

□ greater than 75 for iron-core reactors. ■ the pass-band (see fig. 20), in relative terms:

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

■ 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:

$$p_1 = \frac{Q_{var}}{q n_r}$$



fig. 20: Z versus f curve for a resonant shunt.



with:

 $\label{eq:qvar} \begin{array}{l} \square \ Q_{var} = reactive \ power \ for \\ compensation \ produced \ by \ the \ filter, \\ \square \ p_1 = filter \ losses \ at \ power \ frequency \\ in \ W; \end{array}$

■ 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).

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 21 shows one of the three phases of the filter. The 2nd order damped filter has zero reactance for a frequency f_r higher than

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

the frequency f where:

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 adsorb, to a certain extent, the spectrum lines greater than f_r , and in particular any continuous spectrum that may be present. However, antiresonance, 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:

$$X_0 = \sqrt{\frac{L}{C}};$$

■ 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.

Figure 22 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. 23) 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. 24) 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;



fig. 22: the impedance, seen from point A, of a network equipped with either a 2nd order damped filter or a resonant shunt.





■ damped double filter (see fig. 25) 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: type C damped filter.





9. measurement relays required for the protection of reactor-connected capacitors and filters

An anti-harmonic reactor must withstand the 3-phase short-circuit current at the common reactorcapacitor terminals.

Furthermore, both anti-harmonic reactors and filters must continuously withstand fundamental and harmonic currents, fundamental and harmonic voltages, switching surges and dielectric stresses.

In this chapter, anti-harmonic reactorconnected capacitor assemblies and filters will be referred to collectively as «devices».

basic protection against device failures

All the elements of these devices can be subject to insulation faults and shortcircuits, while the capacitor banks are mainly the source of unbalance faults caused by the failure of capacitor elements.

protection of these devices against insulation faults can be provided by residual current relays (or zero phase sequence relays).

Note:

□ the neutral is generally not distributed on such devices;

□ for higher sensing accuracy, it is better to use a toroidal type transformer, encircling all the live conductors of the feeder, rather than three step-down current transformers;

protection against short-circuits can be provided by overcurrent relays installed on the «filter» feeder. This protection must detect 2-phase short-circuits at the common reactorcapacitor terminals, while letting through inrush transients;

■ detection of unbalance currents in the connections between the neutrals of

the double star connected capacitor banks (see fig. 26).

In addition to the damage that can be caused by the resulting unbalanced stresses, the failure of a small number of capacitor elements is detrimental to filter performance.

This protection is therefore designed to detect, depending on its sensitivity, the failure of a small number of capacitor elements. Of the single-pole type, this protection must be:

□ insensitive to the harmonics,

 set to above the natural unbalance current of the double star connected capacitor bank (this unbalance depends on the accuracy of the capacitors),
set to below the unbalance current due to the failure of a single capacitor element, □ operate on a major fault causing an unbalance.

The fluctuation of the supply voltage must be taken into account in the calculation of all these currents.

basic protection against abnormal stresses on the devices

These abnormal stresses are essentially due to overloads. To protect against them, it is necessary to monitor the rms value of the distorted current (fundamental and harmonics) flowing in the filter.

It is also necessary to monitor the fundamental voltage of the power supply using an overvoltage relay.



fig. 26: unbalance detection for a double star connected capacitor bank.

10. example of the analysis of a simplified network

The diagram in figure 27 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 1000 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. The capacitor bank implemented in this manner is rated 1,000 kvar.

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.

capacitor bank alone

The network harmonic impedance curve (see fig. 28), seen from the node where the harmonic currents are injected, exhibits a maximum (antiresonance) 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. 29).

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. 30).

The solution with capacitors alone is therefore unacceptable.

reactor-connected capacitor bank

This equipment is arbitrarily tuned to 4.8 $\ensuremath{f_1}$.

Harmonic impedance (see fig. 31)

The network harmonic impedance curve, seen from the node where the harmonic currents are injected, exhibits a maximum of 16 ohms (antiresonance) in the vicinity of harmonic order 4.25. This unfortunately favours the presence of 4th voltage









fig. 28: harmonic impedance seen from the node where the harmonic currents are injected in a network equipped with a capacitor bank alone.

fig. 29: harmonic voltage spectrum of a 5.5 kV network equipped with a capacitor bank alone.

harmonic. However, the low impedance, of an inductive character, of the 5th harmonic favours the filtering of the 5th harmonic quantities.

Voltage distortion

(see fig. 32)

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 loads. However in many cases the total harmonic voltage distortion of 2.63 % is acceptable.



fig. 30: spectrum of the harmonic currents flowing in the capacitors for a network equipped with a capacitor bank alone.



fig. 31: harmonic impedance seen from the node where the harmonic currents are injected in a network equipped with reactor-connected capacitors.

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

Capacitor current load (see fig. 33)

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 reactor-connected capacitors compared to the first solution (capacitors alone).



fig. 32: harmonic voltage spectrum of a 5.5 kV network equipped with reactorconnected capacitors.



fig. 33: spectrum of the harmonic currents flowing in the capacitors for a network equipped with reactor-connected capacitors.

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. 34)

The network harmonic impedance curve, seen from the node where the harmonic currents are injected, exhibits a maximum of 9.5 ohms (antiresonance) 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).



fig. 34: harmonic impedance seen from the node where the harmonic currents are injected in a network equipped with a resonant shunt filter tuned to the 5th harmonic and a damped filter tuned to the 7th harmonic.

Voltage distortion

(see fig. 35) For the 5.5 kV network, the individual harmonic voltage ratios of 0.96 %, 0.92 %, 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 total rms current load of the resonant shunt filter capacitors (see fig. 36) is greater than 1.3 time the current rating. The capacitance must therefore be increased, which will improve the filtering performance,



fig. 35: harmonic voltage spectrum of a 5.5 kV network equipped with a resonant shunt filter tuned to the 5th harmonic and a damped filter tuned to the 7th harmonic.

reducing the 5th harmonic ratio to less than 1 %.

The result is of course an increase in the reactive power compensation capacity.

To avoid overcompensating, a compromise must be found for the size of these capacitors. The calculation is therefore repeated with this new data. For the damped filter tuned to the 7th harmonic, the total rms current load of the capacitors (see fig. 37) is within the tolerance of 1.3 times their current rating.

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:

■ 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 electrotechnical information required for the filter manufacturing specifications.



fig. 36: spectrum of the harmonic currents flowing in the capacitors of a resonant shunt filter tuned to the 5th harmonic on a network equipped with a damped filter tuned to the 7th harmonic.



fig. 37: spectrum of the harmonic currents flowing in the capacitors of a damped filter tuned to the 7th harmonic on a network equipped with a resonant shunt filter tuned to the 5th harmonic.

11. conclusion

Static power converters are increasingly used in industrial distribution. The same is true for arc furnaces in the growing electricpowered steel industry. All these loads produce harmonic disturbances and require compensation of the reactive power they consume, leading to the installation of capacitor banks. Unfortunately these capacitors, in conjunction with the inductances in the network, can cause high frequency oscillations that 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.

For further information or assistance, feel free to contact the Network Studies department of the Central R&D organisation of Merlin Gerin, a group of specialised engineers with more than twenty years of experience in this field.

12. bibliography

Standards

■ IEC 146: Semi-conductor converters.

■ IEC 287: Calculation of the continuous current rating of cables.

■ IEC 555-1: Disturbances in supply systems caused by household appliances and similar electrical equipment - Definitions.

■ IEC 871-1 and HD 525.1-S-T: Shunt capacitors for AC power systems having a rated voltage above 660 V.

■ NF C 54-100.

■ HN 53 R01 (May 1981): EDF general orientation report. Particular aspects concerning the supply of electrical power to sensitive electronic equipment and computers.

Merlin Gerin's Cahier Technique

Residual current devices
Cahier Technique nº 114
R. CALVAS

■ Les perturbations électriques en BT Cahier Technique n° 141 R. CALVAS

Other publications

Direct current transmission, volume 1
E. W. KIMBARK

published by: J. WILEY and SONS.

■ Le cyclo-convertisseur et ses influences sur les réseaux d'alimentation (The cyclo-converter and its effects on power supply networks T. SALZAM and W. SCHULTZ - AIM Liège CIRED 75.

■ Perturbations réciproques des équipements électroniques de puissance et des réseaux - Quelques aspects de la pollution des réseaux par les distorsions harmoniques de la clientèle (Mutual disturbances between power electronics equipment and networks - Several aspects concerning network pollution by harmonic distortion produced by subscribers). Michel LEMOINE - DER EDF RGE T 85 n° 3 03/76.

Perturbations des réseaux industriels et de distribution. Compensation par procédés statistiques. Résonances en présence des harmoniques créés par les convertisseurs de puissance et les fours à arc associés à des dispositifs de compensation. (Disturbances on industrial and distribution networks. Compensation by statistical processes. Resonance in the presence of harmonics created by power converters and arc furnaces associated with compensation equipment.) Michel LEMOINE - DER EDF RGE T 87 n° 12 12/78.

■ Perturbations des réseaux industriels et de distribution. Compensation par procédés statistiques. Perturbations de tension affectant le fonctionnement des réseaux fluctuations brusques, flicker, déséquilibres et harmoniques. (Disturbances on industrial and distribution networks. Compensation by statistical processes. Voltage disturbances affecting network operation - fluctuations, flicker,

operation - fluctuations, flicker, unbalances and harmonics. M. CHANAS - SER-DER EDF RGE T 87 n° 12 12/78.

 Pollution de la tension (Voltage disturbances).
P. MEYNAUD - SER-DER EDF RGE T 89 n° 9 09/80.

■ Harmonics, characteristic parameters, methods of study, estimates of existing values in the network.

(ELECTRA) CIGRE 07/81.

 Courants harmoniques dans les redresseurs triphasés à commutation forcée.
(Harmonic currents in forced commutation 3-phase rectifiers)
W. WARBOWSKI
CIRED 81. Origine et nature des perturbations dans les réseaux industriels et de distribution.

(Origin and nature of disturbances in industrial and distribution networks). Guy BONNARD - SER-DER-EDF RGE 1/82.

Problèmes particuliers posés par létude du phénomène de distorsion harmonique dans les réseaux. (Particular problems posed by the study of harmonic distortion phenomena in networks).

P. REYMOND

CIGRE Study Committee 36 09/82.

 Réduction des perturbations électriques sur le réseau avec le four à arc en courant continu (Reduction of electrical network disturbances by DC arc furnaces).
G. MAURET, J. DAVENE IRSID SEE LYON 05/83.

■ Line harmonics of converters with DC motor loads.

A. DAVID GRAHAM and EMIL T. SCHONHOLZER. IEEE transactions on industry applications. Volume IA 19 n° 1 02/83.

 Filtrage dharmoniques et compensation de puissance réactive -Optimisation des installations de compensation en présence d'harmoniques.
(Harmonic filtering and reactive power compensation - Optimising compensation installations in the presence of harmonics).
P. SGARZI and S. THEOLERE, SEE Seminar RGE n° 6 06/88.