n° 160

harmonics upstream of rectifiers in UPS



Jean Noël Fiorina

Joined Merlin Gerin in 1968 as a laboratory technician in the ACS (Alimentations et Convertisseurs Statiques) department where he participated in the performance setting up procedures for static converters. In 1977 he obtained his ENSERG engineering degree following a 3 year evening course and rejoined the ACS department. Starting as development engineer he was soon afterwards entrusted with projets. He became later responsible for design projets in EPS department (Electricity Power Supplies). He is in some ways the originator of medium and high power inverters.

At present he is with the Supplies Division where, as responsible for innovations he works on the preparation on new UPS designs of tomorrow.

E/CT 160 first issued december 1993

glossary

$\cos j_1$	factor of phase shift $= \frac{P_1}{S_1}$
D %	global distortion rate $= 100 \frac{\sqrt{\sum_{n=2}^{\infty} Yn^2}}{Y_1}$
Hn %	individual rate of harmonics $= 100 \frac{Yn}{Y_1}$
l	power factor $= \frac{P}{S}$
P_1	active power of fundamental component
S_1	apparent power of fundamental component
n	distortion factor $= \frac{\lambda}{\cos \varphi_1}$
Y_1	effective value of fundamental (current or voltage)
Yn	effective value of harmonic of order n; for current: In (InIN according to standard spec. IEC 146-4)
Zn	impedance value for harmonic n (Un = Zn In)

harmonics upstream of rectifiers in UPS

summary

1. Harmonics in supply networks	Consequences due to harmonic currents	p. 4
	Need for standardization	p. 4
2. Thyristor Graetz bridge rectifier	Harmonic currents generated by a Graetz bridge rectifier	p. 6
	Influence of source impedance	p. 7
	Current distortion rate	p. 10
3. Minimisation of harmonic disturbances	Insertion of inductance at rectifier input	p. 11
	Use of double bridge rectifier	p. 12
	Rectifier circuit with more than two bridges	p. 15
	Utilization of a passive filter for harmonics	p. 16
4. Conclusions and prospects		p. 18
5. Bibliography		p. 20

UPS, like most static converters draw energy from an A.C. mains network through rectifiers.

Often, these rectifiers fitted with thyristors are generators of harmonics.

Merlin Gerin, manufacturers of UPS equipment are well acquainted with this problem and consequently have decided to share their knowledge in this «Cahier Technique».

In this treatise, the author highlights first the need for a standardized co-existence between polluting and polluted equipments.

He then recalls, which harmonic currents and voltages are produced by conventional (classic) rectifiers (thyristor Graetz bridge rectifier) and proceeds to offer various solutions designed to minimize harmonics.

Finally, in his conclusion, he alludes to the appearance in the near future of non-polluting UPS equipment and of de-polluting converters.

Note: harmonic problems occuring downstream of rectifiers which supply non-linear loads are fully discussed in Cahier Technique No 159. The latter provides also definitions and mathematical formulae relating to harmonics.

In the present booklet, only the principal definitions and formulae are listed in page 2.

1. harmonics in supply networks

consequences due to harmonic currents

Harmonic currents generated by certain equipment, such as static converters, discharge lamps, arc furnaces etc.. (providing there are many or providing they have of higher power rating compared with the power of the source) can adversely affect the operation of other equipment connected to the same network.

The effects of these harmonic currents are discussed in Cahier Technique No 152 «Harmonic disturbances in industrial supply networks and their treatment».

Let's recall the adverse effects of harmonic currents:
■ they cause additional heating especially in line conductors, transformers and condensers,
■ they induce vibrations and noises in electromagnetic equipment,
■ they can cause interference with communication and «low current» protection/signalling circuits.

A distorted voltage can, in addition, upset the operation of some receivers such as regulators, static converters (when the crossing through zero of the voltage waveform becomes indeterminate).
Thus, one of the factors highlighting the quality standard of electricity supply is its voltage distortion rate.

need for standardization

As electricity is today regarded as a product (in particular in Europe following the directive of 25 July 1985 under reference 85/374/CEE), the producer becomes fully liable for damages caused by excess of harmonics.

That is why electricity distributors in order to be able to guarantee a quality level acceptable to all consumers, do set or are compelled to set limits to disturbances produced by some consumers.
To achieve this, it is necessary to define:
■ first, a maximum distortion rate allowing correct functioning of most installations (level of compatibility),
■ second, a maximum disturbance rate, for each user so that the cumulative effects of various disturbances thus generated do allow an operational compatibility between all the installations (connected to the same network); all must operate correctly.
Thus' if this compatibility is needed to exist between subscribers, it is also needed to exist within the installation units of individual subscribers.

The end user is therefore burdened with a level of disturbances induced by equipment units that he has installed himself. That is why it is important that manufacturers clearly state the disturbance levels produced by their equipment.
Standards are therefore needed to set acceptable levels of harmonic disturbances for the supply networks as well as for polluters.

Level of operational compatibility
Levels of compatibility for Low Voltage (LV) public supply networks are defined in Standard Specification IEC 1000-2-2 of May 1990. As the levels retained in this standard specification are the same as those published in CIGREE periodicals (Electra No 77 of July 1991 and No 123 of March 1989), it is probable that levels specified for Medium Voltages (MV) and for High Voltages (HV) will also correspond to these recommendations (see table in fig. 1).

Emission Levels
Limits should be defined for each subscriber so as to avoid the necessity to carry out systematic controlled checks when the equipment is put into service.

It should be noted that for a same level of current disturbance, the voltage distortion ratio, at the point of connection, is dependent on the network impedance at that point.

A solution that is fair, is to authorise disturbance causing power sources that are proportional to the power contracted for by each user and for each range of voltage i.e. LV, MV and HV. Emission levels must be considered in domestic and industrial applications.

■ domestic applications
In the LV range, where the energy distributor is unable to control the situation, disturbance levels which have to be observed in equipment units are set in accordance with standards. As an example, standard specification IEC 555-2 referring to «Disturbances caused in supply networks by electro-domestic appliances and similar equipment» prescribes limiting values of current for each harmonic (in appliances drawing an effective current ≤ 16A - see table in fig. 2).

■ industrial applications
In this sector, there are so far no agreed international standards. However, a «consensus» appears to emerge on the concept of stages.
□ stage 1: automatic acceptance
This acceptance is dependent on the voltage level of network and applies to equipment of low power as compared with the power contracted for (subscribed). For example, the rule at «Electricité de France» (EDF) is to have a disturbance causing power that is inferior or equal to 1 % of minimum short-circuit power in a normal situation at the point of connection.
This tolerance can be extended if the total disturbing power is inferior to:
- 4 MVA in HV range,
- 500 kVA in MV range,
- 40 kVA in LV range.

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 %	
	LV/MV	HV		LV/MV	HV		LV/MV	HV
5	6	2	3	5	2	2	2	1.5
7	5	2	9	1.5	1	4	1	1
11	3.5	1.5	15	0.3	0.3	6	0.5	0.5
13	3	1.5	21	0.2	0.2	8	0.5	0.2
17	2	1	> 21	0.2	0.2	10	0.5	0.2
19	1.5	1				12	0.2	0.2
23	1.5	0.7				> 12	0.2	0.2
25	1.5	0.7						
> 25	$0.2 + \frac{12.5}{n}$	$0.1 + \frac{2.5}{n}$						

Global rate of distortion: 8 % in LV and MV networks - 3 % in HV networks

fig. 1: values indicative of levels (targets) of compatibility for harmonic voltages (in % of nominal voltage at fundamental frequency) in HV power networks (transports) and MV and LV networks (extracted from paper published in Electra No 123).

□ stage 2: acceptance with reservations
When, in the case of a given user, the limits stated previously are exceeded, the energy producer generally prescribes a maximum distortion rate at the point of connection. In cases where these levels were likely to be exceeded, the distributor/supplier would reserve the right to ask for complementary means of compensation to be resorted to if the distortion rate was exceeded.
□ stage 3: acceptance - exceptional and provisional.
When the limits stated in stage 2 are exceeded but without, however, causing the compatibility level to be exceeded - due to the non generation of harmonics by other users -, a provisional authorization permit may be granted.

Finally, in an effort to clarify the behaviour of harmonic producing equipment, some standards are now in the process of elaboration or modification.

harmonic order	max. permissible harmonic current (in Amperes)
odd harmonics	
3	2.3
5	1.14
7	0.77
9	0.4
11	0.33
13	0.21
$15 \leq n \leq 39$	$0.15 \times \frac{15}{n}$
even harmonics	
2	1.08
4	0.43
6	0.30
$8 \leq n \leq 40$	$0.23 \times \frac{8}{n}$

fig. 2: limits of harmonic components of current in domestic applications (In ≤ 16 A).

2. thyristor Graetz bridge rectifier

UPS equipments consist of an AC/DC converter (i.e. rectifier), a battery bank (which can be charged by the rectifier or with an appropriate current charger) and a DC/AC converter (i.e. inverter) (see fig. 3).

Generally as the input converter is expected to provide a charge or to maintain the charge of the battery at a constant voltage and to supply the required power to the inverter, it utilises usually thyristors arranged in the classic form of a Graetz bridge circuit. There are other types of rectifier circuits but the three-phase Graetz bridge arrangement is the most commonly used, in particular in high powered UPS units; hence the following study of harmonic currents generated by the three-phase Graetz bridge with a fully regulated circuit and of the means of minimising them.

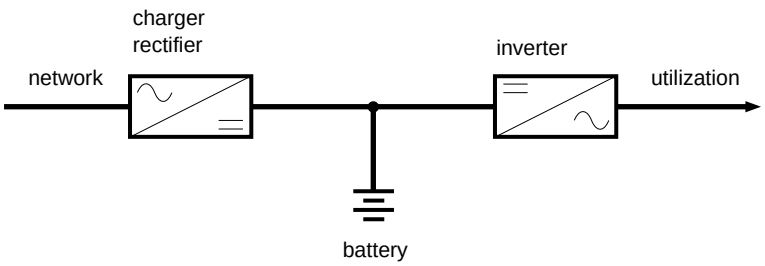


fig. 3: circuit diagram of a charger rectifier.

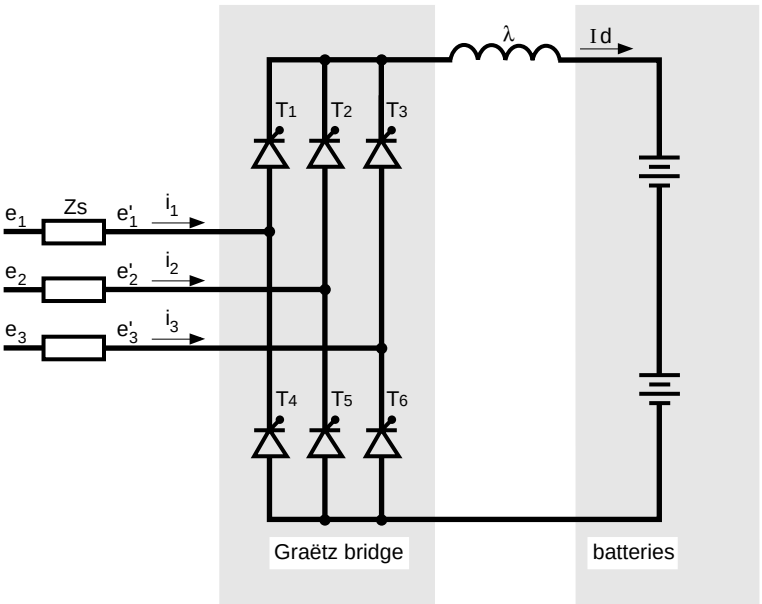


fig. 4: circuit diagram of charger rectifier.

harmonic currents generated by a Graetz bridge rectifier

The rectifier in figure 4 is assumed to be connected to a high value inductance acting as filter to the DC current Id to ensure that the latter is perfectly smooth. Initially, the source impedance is considered to be zero.

The line currents I1, I2 and I3 assume in turn the value (and the shape) of the DC current Id.
Each thyristor ensures current conduction during 1/3 of a period.

Having assumed a source impedance equal to zero, the current establishes itself instantaneously at its value Id as soon as one thyristor starts conducting.

Currents supplied by the source have a rectangular waveform (see fig. 5).
The spectrum is made up of current harmonics:

$$In = \frac{I1}{n}$$

where n = 6 k ± 1, k taking values 1, 2, 3... (whole numbers/integers) and I_1 being the effective value of fundamental, i.e. $I_1 = 0.78\ Id$.

For the first harmonics of current, the amplitudes vary therefore in function of I_1:

- I_5 = 20 % of I_1,
- I_7 = 14 % of I_1,
- I_{11} = 9 % of I_1,
- I_{13} = 8 % of I_1.

The global rate of distortion of this current is thus 30 %.

The global rate of distortion of the voltage is zero in this case, since the source impedance has been assumed to be zero (i.e infinite power).

influence of source impedance

Since the source is by nature inductive, its inductance precludes any instantaneous variations of current.

The phenomenon of overlap

When thyristor T_2 (see fig. 6a) is gated while thyristor T_1 is conducting, current I_2 establishes itself in thyristor T_2 while current I_1 in Thyristor T_1 decreases. Inductances L oppose sudden sharp variations of these currents.

During the time Δt of commutation (see fig. 6a) there is simultaneous conduction in two thyristors (this phenomenon is also called «overlap»).

The source is therefore in a state of interphase short-circuit (phases 1 and 2) limited only by the two inductances L.

The voltage v is such that:

$$v = e_1 + L \cdot \frac{d \cdot i_1}{dt} = e_2 + L \cdot \frac{d \cdot i_2}{dt},$$

hence

$$2v = e_1 + e_2 + L \cdot \frac{d \cdot i_1}{dt} + \frac{d \cdot i_2}{dt},$$

$$L \cdot \frac{d \cdot i_1}{dt} + \frac{d \cdot i_2}{dt} = L \cdot \frac{d(i_1 + i_2)}{dt}$$

$$= L \cdot \frac{d \cdot Id}{dt} = 0,$$

therefore:

$$2v = e_1 + e_2,$$

or

$$v = \frac{e_1 + e_2}{2}.$$

The same phenomenon occurs later between T_2 and T_3, then between T_3 and T_1 and also in the negative polarity of the rectifier between thyristors T_4, T_5 and T_6.

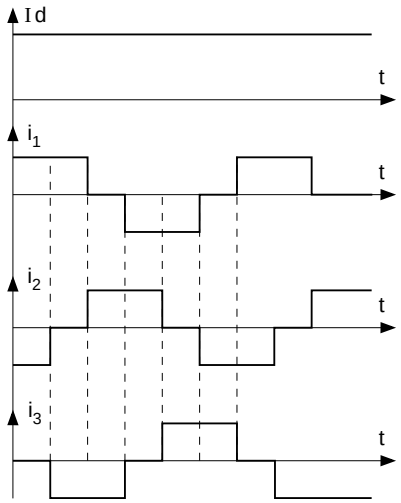
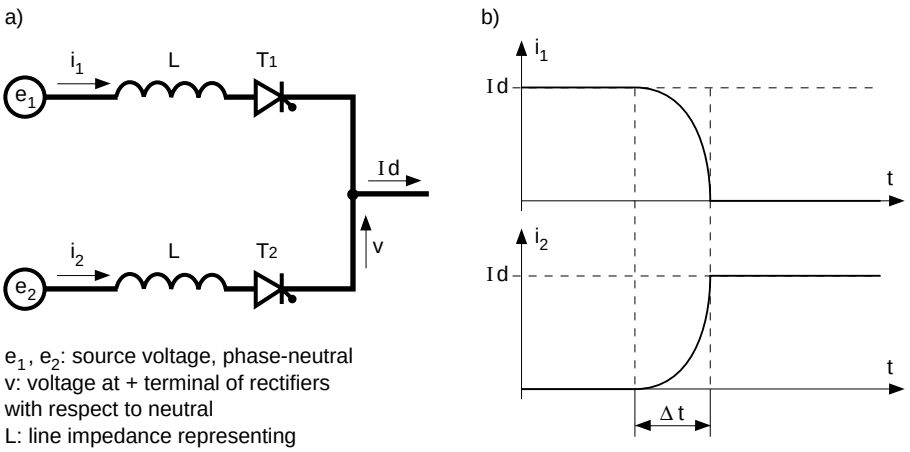


fig. 5: theoretical currents upstream of rectifier with infinite dowstream filter impedance and source impedance = 0.



e_1, e_2: source voltage, phase-neutral
v: voltage at + terminal of rectifiers with respect to neutral
L: line impedance representing source impedance

Δ t: commutation time

fig. 6: overlap phenomenon.

For an angle of lag α of 30° (which corresponds to a normal working point), voltages e'_1, e'_2 and e'_3 obtained at the input to the rectifier and also the line current i_1 are shown in fig. 7.

The angle of lag α is used for the regulation of the DC voltage supplied by the rectifier.
In the case of a rectifier/battery charger, this output voltage must be kept constant (see fig. 8) whatever the variations of the AC voltage or whatever the charging conditions of the rectifier.

The value of this DC voltage can be expressed by the approximate relation:

$$Ud = 1.35 \cdot Ueff \cdot \cos\alpha - \frac{1}{2} \cdot L \cdot \omega \cdot I_1$$

where Ueff: effective value of «composed resultant voltages»

$$(Ueff = e_1 \cdot \frac{\sqrt{3}}{\sqrt{2}}$$

if one refers to fig. 6a).

Disturbances due to overlap

It is evident that during each half-period, each of the simple fundamental voltages is disturbed twice and exhibits:
- a voltage drop when the corresponding thyristor is triggered into conduction,
- an overvoltage when the current in this thyristor is turned off.

The higher the inductance of line L, the longer is therefore the duration Δt of these disturbances.
As the line current no longer has a perfectly rectangular shape, its harmonic content decreases (strong attenuation of harmonics of high orders).

Consequently, the resulting distortion of the voltage increases when the line impedance increases, but this increase is not proportional to the impedance since the harmonic content of current decreases.
In addition, the time of commutation decreases when the angle of lag α increases which, as a result, brings about - for the same inductance value - an increase in the harmonic content of current and the voltage distortion.

Harmonic content of current

The figure 9 extracted from the standard specification IEC 146-4, shows how harmonic currents vary with respect to the source impedance for different angles of lag α.
The harmonic currents are represented in relative value with respect to their maximum theoretical value (I_{niN}):

I_{nN} = Ieff of harmonic of order n

$$I_{niN} = \frac{I_1}{n}$$

I_1 = effective value of fundamental

The source impedance is represented here by the term d_{XN} which corresponds to the relative voltage drop on the DC side. The latter is due to the effect of total inductance of line.

For this rectifier:

$$d_{xN} = \frac{1}{2} \cdot \frac{L \cdot \omega \cdot I_1}{V_1} \cdot 100$$

where V1: is the effective value of simple fundamental voltages.

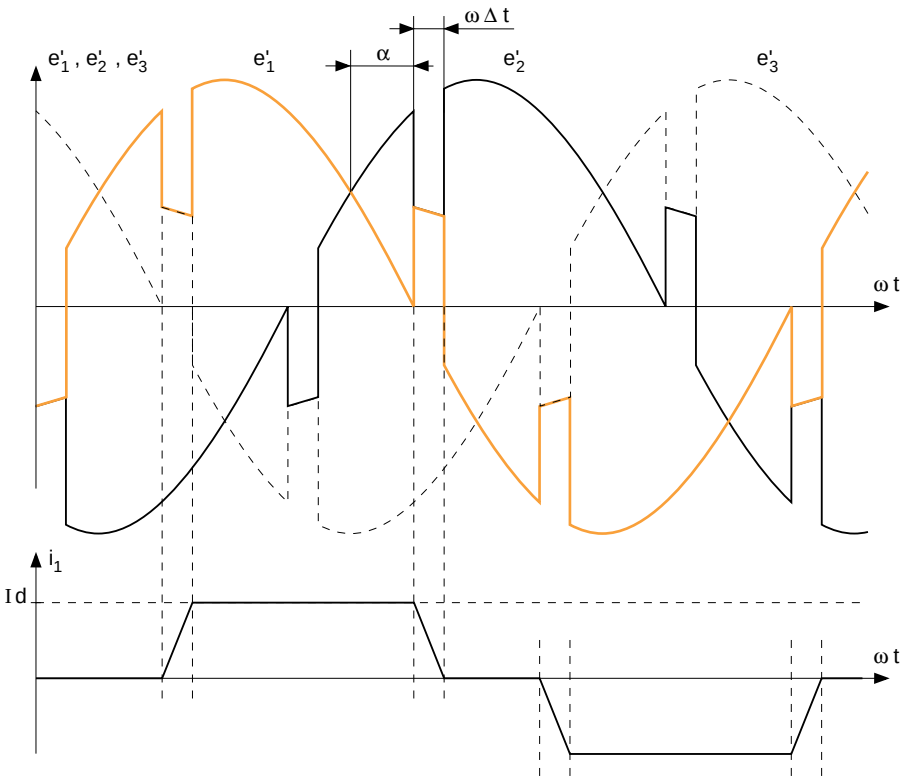
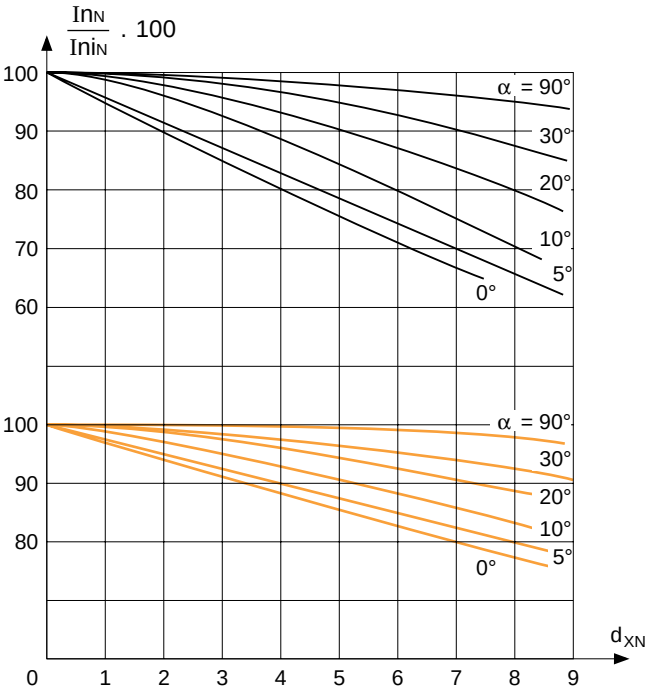


fig. 7: overlap for a thyristor rectifier with an angle of lag α of 30°.

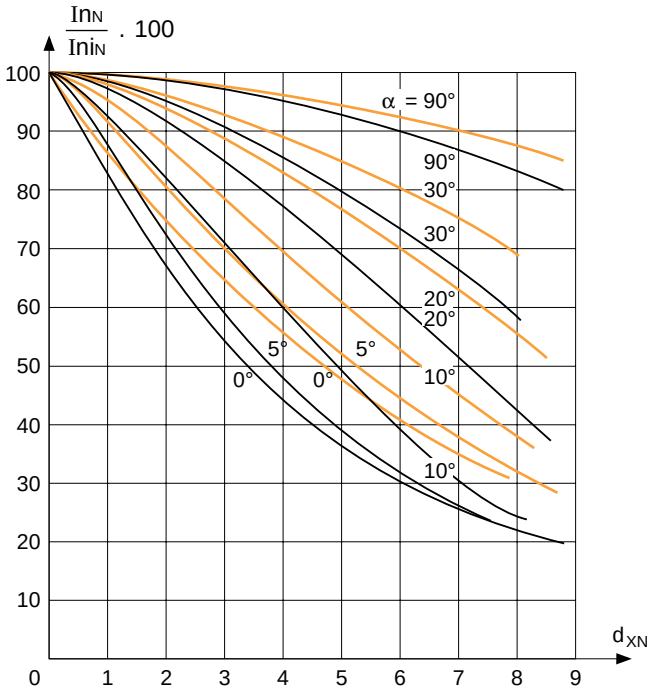
	lead storage cells "recombination"	open load cells	nickel-cadmium cells
charging voltage (high rate) (in V)	$2.30 < U_{charge} < 2.50$	$2.30 < U_{charge} < 2.50$	$1.42 < U_{charge} < 1.65$
floating voltage (low rate) (in V)	$2.23 < U_{floating} < 2.30$	$2.18 < U_{floating} < 2.25$	$1.38 < U_{floating} < 1.50$

Sealed batteries (recombination) are generally charged at low rate charge only.
Open batteries are charged in two successive voltage steps.

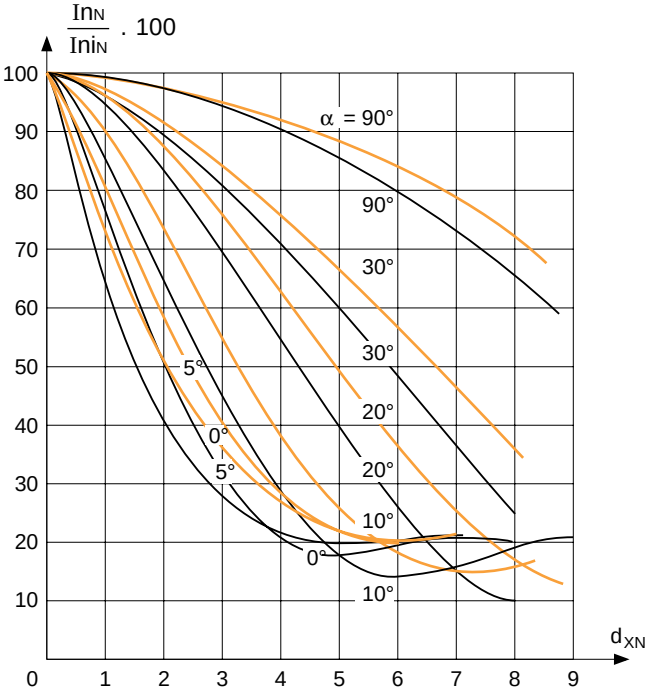
fig. 8: charge of UPS batteries at constant voltage and limited current (according to Gimelec recommendations).



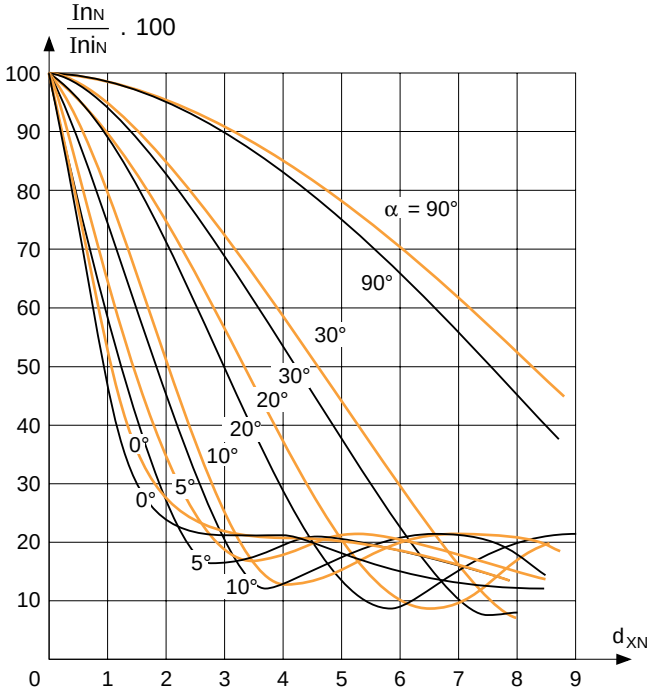
a) harmonics of order: n = 5; n = 7



b) harmonics of order: n = 11; n = 13



c) harmonics of order: n = 17; n = 19



d) harmonics of order: n = 23; n = 25

fig. 9: amplitude variation of harmonic currents with respect to source impedance for various angles of lag α in a three-phase Graetz bridge circuit.

In a balanced three-phase circuit, d_{XN} represents half the relative voltage drop of the line.
By calling U'cc this relative voltage drop that can be likened to a short-circuit voltage, it is possible to write:

$$d_{XN} = \frac{1}{2} . U'cc$$

current distortion rate

Assuming a source impedance equal to zero and a perfectly filtered DC current, the effective value of each current harmonic can be expressed as:

$$In = \frac{I_1}{n}$$

In this instance, the harmonic content is independent of α ($\Delta t = 0$).

The global rate of theoretical distortion is given by the expression:

$$D\,\% = 100 . \frac{\sqrt{\sum_{k=1}^{\infty} (I^2_{6k+1} + I^2_{6k-1})}}{I_1}$$

that is = 30 %.

Note: in practice, for calculation purposes, the line current does not strictly assume the theoretical shape taken as a basis for the calculations, since perfect smoothing of DC current cannot be achieved (see fig. 10).
As a result, the harmonic content of current is slightly modified; in particular it is observed that harmonics of order 6 k - 1 are increased whereas those of order 6 k + 1 are decreased.

Voltage distortion rate

The figure 11 shows the variation of the voltage distortion rate at the rectifier input with respect to the total source impedance referred to the short-circuit voltage U'cc and the angle of lag α set for thyristor control. It is clearly seen that this distortion rate increases very rapidly and that it is difficult as originally anticipated to remain below a value of 5 %.

Power factor of rectifier

■ as the current drawn by the rectifier is highly distorted, the RMS current has therefore a value superior to that of the fundamental. The effective value of current can be calculated by applying the basic formula:

$$Ieff = \sqrt{I^2_1 + \sum_{k=1}^{\infty} (I^2_{6k+1} + I^2_{6k-1})}$$

with a theoretical value of current (source being of infinite power) equal to:

$$I_{6k\pm1} = \frac{I_1}{6k \pm 1}$$

hence

$$Ieff = \sqrt{1 + \left(\frac{1}{5}\right)^2 + \left(\frac{1}{7}\right)^2 + \ldots\ldots}$$

i.e.

$$Ieff = 1.05 . I_1$$

■ in addition, the phase shift between the current and the voltage has a minimum value equal to α, to which must be added approximately half the overlap angle $\omega \Delta t$.

As a first approximation, since the overlap angle is small compared with the angle of lag, a phase shift equal to α can be retained, hence:

$$\cos \varphi_1 = \cos \alpha .$$

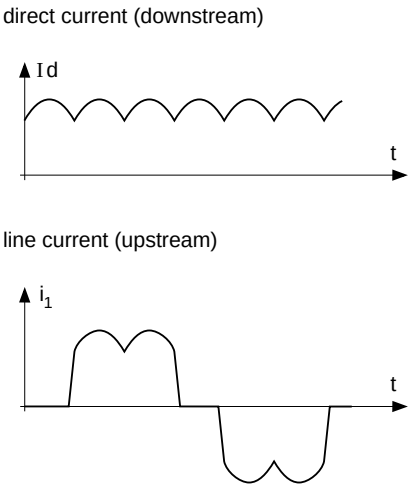


fig. 10: factual currents upstream and downstream of rectifier.

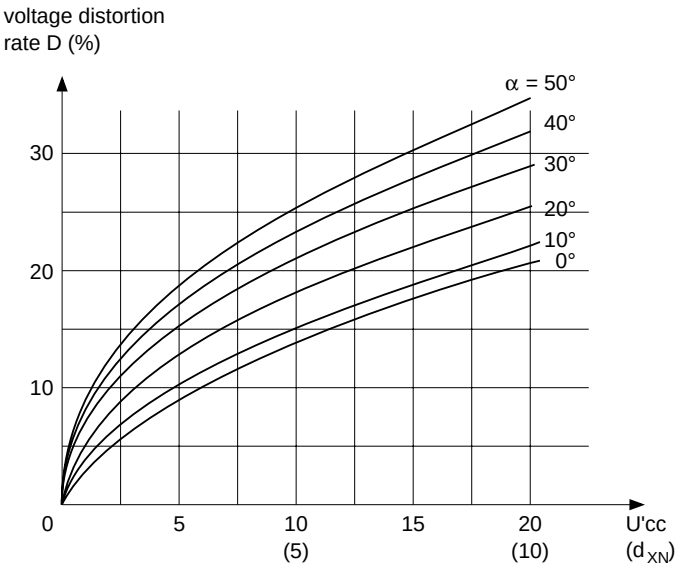


fig. 11: variation of voltage distortion rate with respect to source impedance for different values of lag angle α .

■ allowing that the effective value of voltage approaches very closely that of the fundamental (which is true when the distortion rate is low), the power factor λ can be expressed with good approximation as:

$$\lambda = 0.95 \cdot \cos\alpha$$

since:

$$\lambda = \frac{P}{S} = \frac{\sqrt{3} \cdot U_1 \cdot I_1 \cdot \cos\varphi_1}{\sqrt{3} \cdot Ueff \cdot Ieff}$$

(U_1 and Ueff. representing line to line voltages)

that is: $\lambda = \frac{1}{1\,05} \cdot \cos\alpha$

Note: for more details refer to standard IEC 146-4 § 424.

3. minimisation of harmonic disturbances

Curves in figure 11 clearly show that the voltage distortion rate at the rectifier input grows rapidly in importance even when the source impedance is very low. It is therefore necessary to reduce this rate of distortion so as to allow the use of rectifiers of non-negligible power compared with the contracted for power.

Since harmonic currents are responsible for the voltage distortion when they flow across the source impedance, reduction in their amplitude will bring about an improvement to the voltage waveform.

To achieve this, three classic methods are utilized:

■ the insertion of an additional inductance in the rectifier input in order to attenuate the amplitude of harmonics (especially those of higher orders),

■ the use of several rectifiers fed by voltages appropriately phase shifted. It is possible, with this method to eliminate - by combining currents - the most troublesome harmonics (that is harmonics of the lowest orders for they have the highest amplitudes).

■ the retention of a single Graetz bridge rectifier to which is added a passive filter designed to eliminate the most troublesome harmonics and to reduce the amplitude of other harmonics.

It is, of course, possible to combine these methods so as to optimize the results.

insertion of inductance at rectifier input

The circuit diagram corresponding to one phase is shown in figure 12.

The insertion of inductance L_F reduces the distortion rate of current. The voltage distortion rate at point A decreases.
Its value can be calculated from the value obtaining at point B.
Inductances Ls and L_F form a divider for harmonic voltages.

Theoretical calculation of distortion rate

For each harmonic of order n, there is a voltage component V'n at the point B, such that:

$$V'n = n \cdot (Ls + L_F) \cdot \omega \cdot In$$

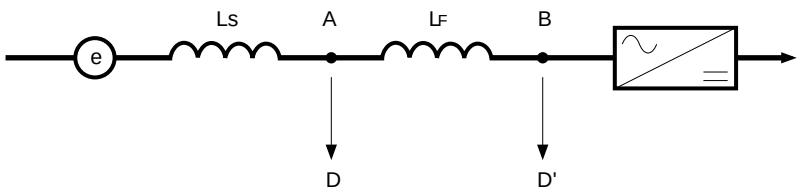
where ω: pulsation of fundamental.

Voltage Vn measured at point A is:

$$Vn = n \cdot Ls \cdot \omega \cdot In$$

$$Vn = V'n \cdot \frac{Ls}{Ls + L_F}.$$

By applying this reasoning for each harmonic and calculating the total distortion, it becomes evident that, if the voltage distortion rate measured at



L_F: filtering inductance of rectifier
Ls: total inductance of source (generator + cabling)
e: source of perfect voltage
D, D': voltage distortion rates

fig. 12: harmonic separation (decoupling) through use of additional inductance.

point B is D', the voltage distortion rate at A is:

$$D = D' . \frac{Ls}{Ls + LF}$$

Remembering that:

$$Uccs = \frac{Ls . \omega . In}{Vn}$$

$$UccF = \frac{LF . \omega . In}{Vn}$$

where Vn = effective value of the simple fundamental voltage.
As an example, if Ls is such that Uccs = 2 % and LF such that UccF = 6 %, then their sum Uccs + UccF = 8 %.

For an angle of lag α equal to 30°, the curve in figure 11 gives a distortion rate of 19 %. The distortion rate at point A is therefore:

$$D = 19\ \% \times \frac{2}{8} = 4.75\ \%.$$

Without the inductance LF in the circuit, the distortion rate would have been that referred to Ls alone, that is Uccs = 2 %, value which gives on the curve in figure 11

D = 10 %.

The insertion of inductance LF has made it possible, in this case, to reduce the voltage distortion rate by a factor greater than 2 compared with the rate level in other utilizations.

Application

An UPS unit, rated at 300 kVA, supplies a load of 250 kVA with a cos φ = 0.8; its efficiency is 0.92 and the power factor of its rectifier is λ = 0.82.

The apparent power drawn by the rectifier is therefore:

$$\frac{250 \times 0.8}{0.92 \times 0.82} = 265\ \text{kVA}.$$

The rectifier is fed from a transformer rated at 630 kVA; Uccs = 4 % and is related to an inductance corresponding to a UccF value of 12 % and calculated for a rectifier power rating of 350 kVA.

Taking into account, the load rates of transformer and of the rectifier:

$$\text{Uccs becomes: } 4\ \% \times \frac{265}{630} = 1.7\ \%$$

$$\text{UccL becomes: } 12\ \% \times \frac{265}{350} = 9.1\ \%$$

If, on average, the thyristors operate with a lagging phase angle α of 20°, it is then possible to determine the distortion rate from figure 11:

D = 18.8 %
(α = 20°; Ucc = 10.8 %)

hence a distortion rate across the transformer terminals amounting to:

$$D = 18.8\ \% \times \frac{1.7\ \%}{10.9\ \%} = 2.9\ \%$$

use of double bridge rectifier

(see fig. 13)

This principle consists in utilizing a transformer with two secondary windings which supply voltages with a phase displacement of 30° between them; each of those secondaries supplies a Graetz bridge rectifier which provides a six-phase rectification.

The rectifiers must supply identical DC currents to ensure that the AC currents drawn from the transformer secondaries have the same value.

Under those conditions, there occurs a recombining process between the harmonic currents generated by each one of the rectifiers in the primary winding of transformer and calculations show that harmonics of order 6 k ± 1 (k being an odd number) are eliminated.

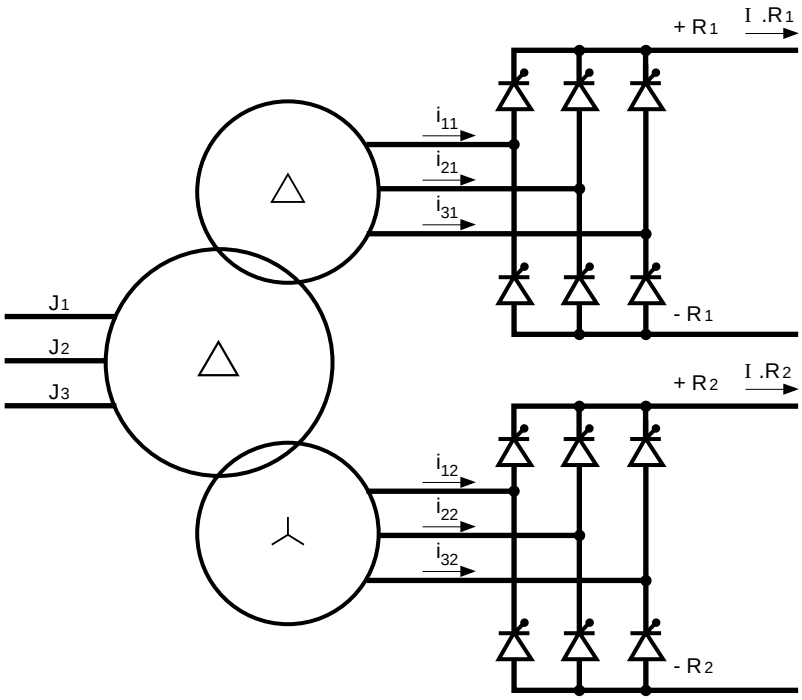


fig. 13: basic diagram of a rectifier with two phase staggered bridges.

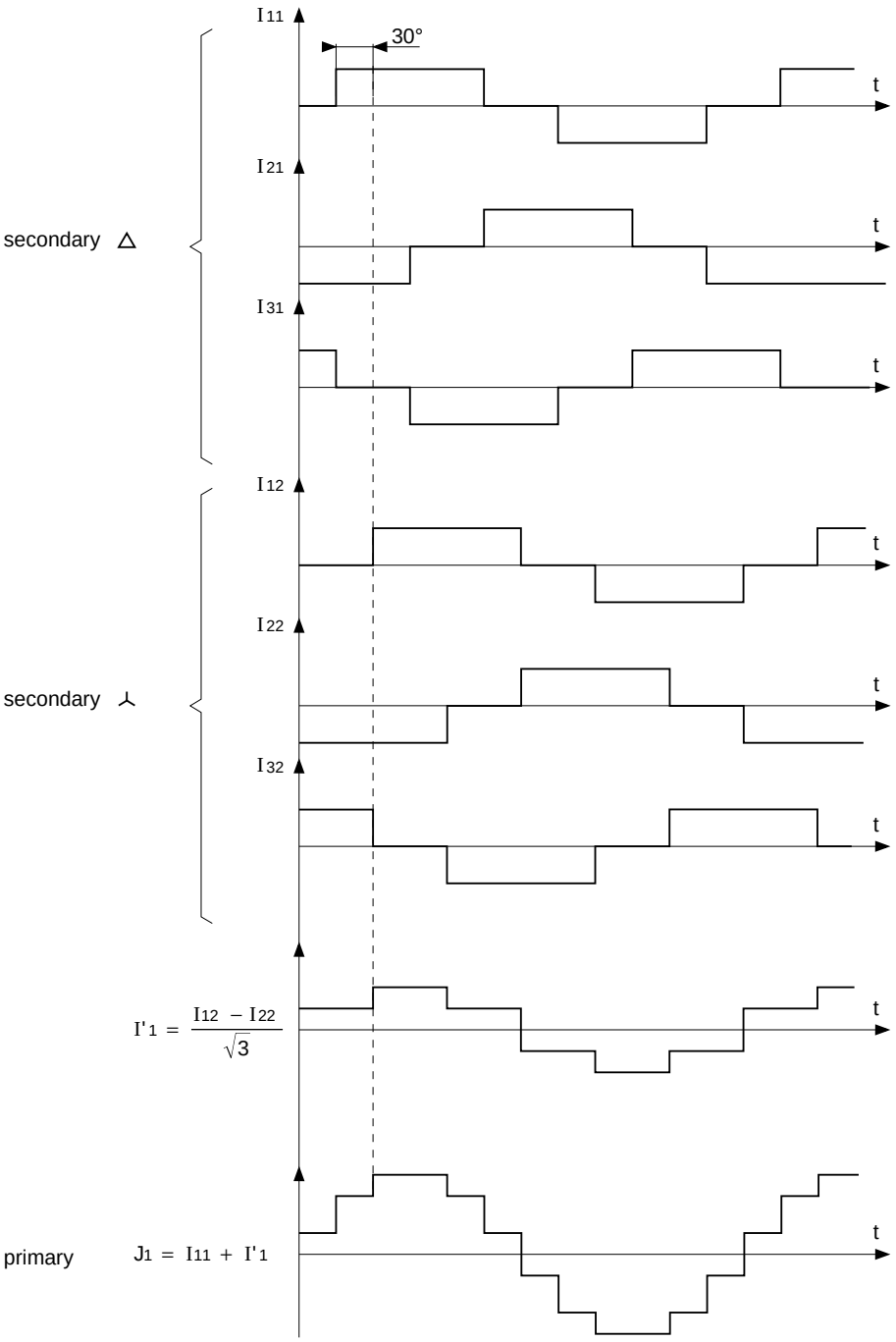
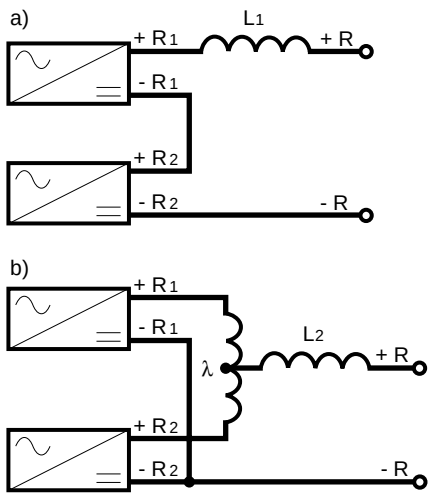


fig. 14: shape of currents drawn by rectifier and resultant in primary of transformer with two secondaries.

This is, in particular the case of 5 th and 7 th harmonics whose theoretical amplitudes are the most important.
11 th and 13 th harmonics are retained but the 17 th and 19 th harmonics are eliminated.
The remaining harmonics are therefore of order 12 k ± 1 (k being a whole number).

The figure 14 indicates the current drawn by the transformer primary and resulting from currents supplied by the two secondaries.
The line current has a shape which is much closer to a sinusoidal waveform than that of the current obtained with a single rectifier. The two rectifiers can be connected in series or in parallel (see fig. 15).

When the two circuits are put in parallel and considering that the instantaneous voltages delivered by each one of the two rectifiers are not equal (since they are displaced from each other by 30°), it is necessary to add an inductance with a centre tap in order to maintain a continuous flow in each rectifier.



L1, L2: inductances of DC current filtering
λ: separation (decoupling) inductance with centre tap point

fig. 15: connection in series (a) or in parallel (b) of two rectifiers.

In the absence of this inductance, conduction would be ensured at each instant only by that rectifier that delivers the highest voltage.
There are several variants (patented by Merlin Gerin) of the circuit diagram shown in figure 13 (see fig. 16) which lead to the same result as regards level of harmonics.

Distortion rate of current

Assuming zero impedance upstream of rectifier and a perfectly smoothed DC current, the effective value of each current harmonic is of the following form: $I_n = \frac{I_1}{n}$

where $n = 12k \pm 1$

The theoretical rate of distortion is thus:

$$D\% = \frac{\sqrt{\sum_{k=1}^{\infty} (I^2_{12k+1}) + (I^2_{12k-1})}}{I_1} \cdot 100$$

that is D ≈ 15 % which represents half the value obtained with a single rectifier (see start of paragraph 2).

Distortion rate of voltage

The voltage distortion rate is dependent on the source impedance.

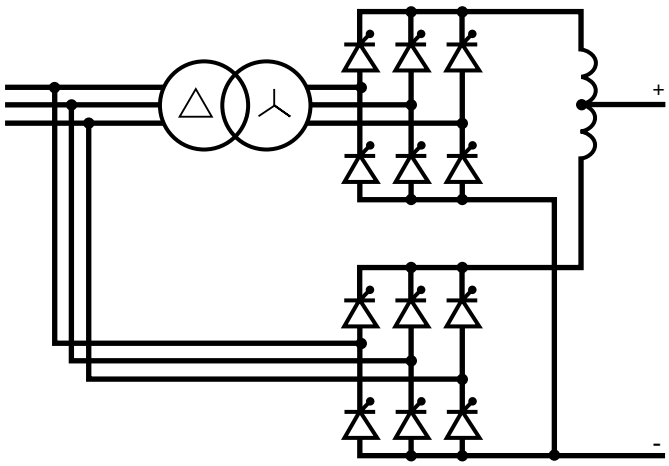
For a very low source impedance, (sum of impedances upstream of rectifier(s)), the ratio between the distortion rates obtained with a two-rectifier circuit to that obtained with a single rectifier is:

$$\frac{1}{\sqrt{2}} \approx 0.7.$$

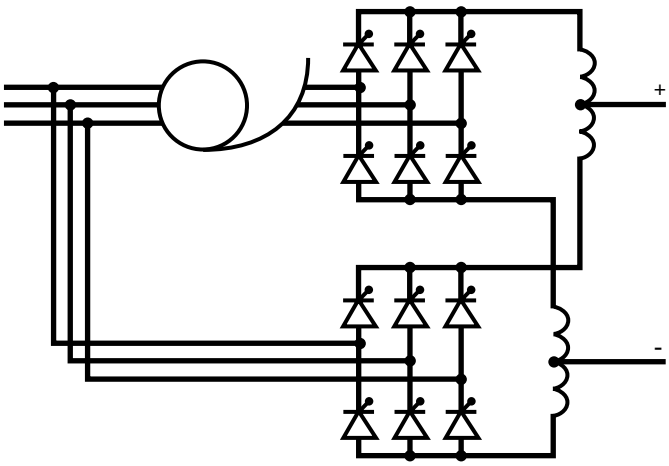
For a higher source impedance, the gain is more substantial since higher order harmonics decrease rapidly as the source impedance increases. However, the gain remains rather «modest» and in practice a ratio of 0.5 in favour of the double bridge circuit is to be retained.

Example:

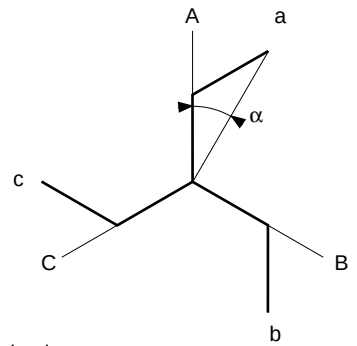
■ for an angle of lag α of 30°, the ratio between the two distortion rates



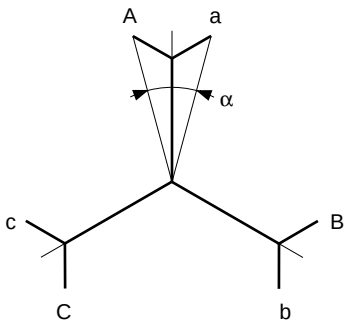
a) circuit connection with power transformer



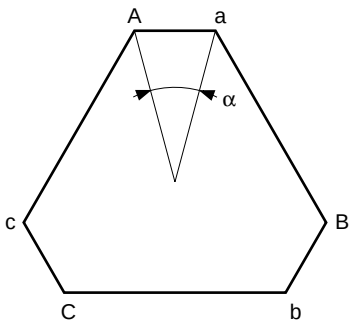
b) circuit connection with autotransformer



simple star



double star



polygonal

c) various connection circuits for autotransformer

fig. 16: circuit connections to obtain a phase shift of 30° and various connection methods for autotransformer.

amounts to 0.66 with U'cc = 8 %
and 0.55 with U'cc = 16 %;
■ for angle $\alpha = 0$, the ratios are 0.53 and 0.37 respectively.

This ratio between the distortion rates takes no account of the inductance of the phase shifting system.

rectifier circuit with more than two bridges

(see fig. 17)
The basic idea here is to increase the number of transformer secondaries with respective phase displacements depending on the number of secondaries retained for the purpose of eliminating other harmonics of current.

Three rectifier circuit arrangement
For this form of arrangement, the phase displacement must be such that:
■ $\alpha_1 = 0°$,
■ $\alpha_2 = 20°$,
■ $\alpha_3 = 40°$.

In this case, the only harmonics remaining are those of order 6 k ± 1 (where k = multiple of 3) that is 18 k ± 1.

The first harmonics of current are therefore 17 th and 19 th followed by 35 th and 37 th harmonics.

Four rectifier circuit arrangement
In this case, the phase displacement are as follows:
■ $\alpha_1 = 0°$,
■ $\alpha_2 = 15°$,
■ $\alpha_3 = 30°$,
■ $\alpha_1 = 45°$.

The only harmonics remaining are then those of order 24 k ± 1.

The first harmonics are therefore the 23 rd and 25 th following by 47 th and 49 th.

These arrangements are of interest in so far as they make it possible to obtain relatively low distortion rates of current and voltage.

They have the disadvantage of being complex and expensive. Consequently, their utilization is reserved for equipment of high power rating.

For instance, aluminium electrolysis process, which utilizes DC current supplied from power sources of several MW, requires circuit arrangements consisting of up to 72 phases!

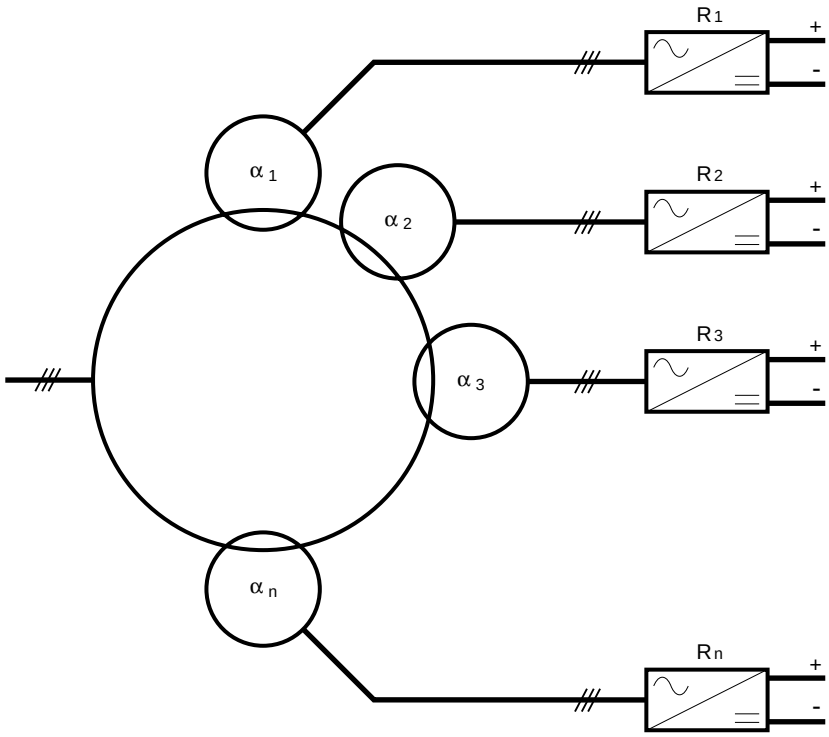


fig. 17: example using n rectifiers.

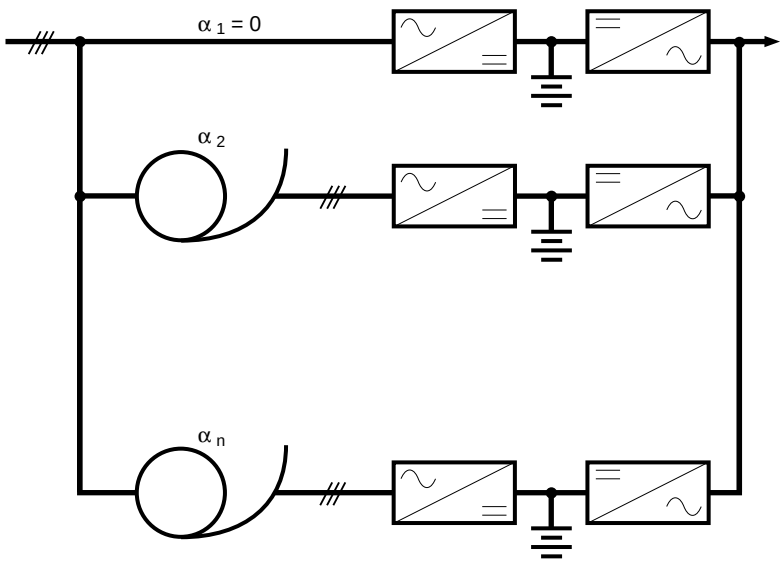


fig. 18: principle of phase shifting.

Special case of circuit connection called «phase shifting»
(see fig. 18)
When several UPS units are operated in parallel, they share the load current between them and the currents drawn by each rectifier have identical amplitudes.
It is then possible to supply the rectifiers from auto-transformers which

produce the required phase shifts according to the number or rectifiers (instead of utilizing circuit arrangements with transformers).

The auto-transformers utilized can be of the same type as those shown in figure 16.
The polygonal circuit arrangement is mostly utilized for economic reasons.
The principal disadvantage of this system is due to the fact that harmonic rates increase when one of the UPS units is shut down.
Table in figure 19 gives the harmonic content in principal circuit connections in which all the rectifiers - except one - are operational.

connection type	number of rectifiers in service	harmonics							
		H5	H7	H11	H13	H17	H19	H23	H25
2 rectifiers	2	0	0	1	1	0	0	1	1
	1	1	1	1	1	1	1	1	1
3 rectifiers	3	0	0	0	0	1	1	0	0
	2	1/2	1/2	1/2	1/2	1	1	1/2	1/2
4 rectifiers	4	0	0	0	0	0	0	1	1
	3	1/3	1/3	1/3	1/3	1/3	1/3	1	1

fig. 19: variation of harmonic content of current in principal connection systems.

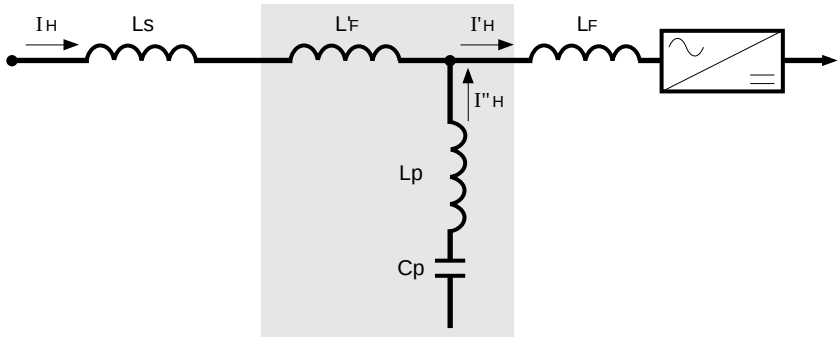


fig. 20: basic circuit of passive filter for harmonics.

utilization of a passive filter for harmonics

The filter is tuned to a particular frequency.
Its effectiveness is highest at this frequency, but several filters are needed to strongly attenuate several harmonics.
The introduction of passive filters is always critical because of risk of resonance.

(Refer on this subject to Cahier Technique No 152: «Les perturbations harmoniques dans les réseaux industrielles, et leur traitement»).

Filter utilized by Merlin Gerin for UPS units of high power rating

The figure 20 shows the equivalent basic circuit for one phase.

The parallel arm of the filter consists of a circuit tuned to the 5 th harmonic which is the most important. The series arm of the filter comprises an inductance whose function is to achieve separation of the parallel arm from the source.

Calling Zpn and Zsn the impedances of parallel and series arms of the filter tuned to harmonic of order n and assuming that the current generated by the rectifier for this order is I'Hn, then the current supplied by the source is:

$$I_{Hn} = I'_{Hn} \cdot \frac{Zpn}{Zpn + Zsn}$$

(see fig. 21).

■ as regards 5 th harmonic, the parallel impedance is equal to zero.
All the current of 5 th harmonic flows thus through the parallel arm of the filter and this harmonic no longer affects other users.

■ as regards 7 th harmonic, because of its proximity to the tuned frequency, the parallel impedance is still low and consequently a large proportion of this harmonic is also eliminated.

■ finally, as regards harmonics of higher orders, the parallel impedance of the filter is very close to that of its inductance Lp: the filter thus functions as a current divider.

For harmonics of higher orders:

$$I_{Hn} = I'_{Hn} \cdot \frac{Lp}{Lp + Ls + L'_F}$$

if Lp is chosen so that

$$Lp \approx Ls + L_F \text{ then}$$

$$I_{Hn} = \frac{1}{2} \cdot I'_{Hn}$$

Global distortion rate of voltage

Detailed calculations of the voltage distortion rate obtained at the source output, are beyond the terms of reference for this technical booklet.
Let's however consider an example:
■ if $L'_F = L_F$ with Ucc_F = 12 % and
■ if Lp corresponds to Uccp = 15 %,

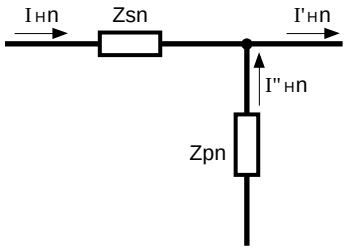


fig. 21: equivalent circuit diagram of filter for harmonics.

the gain following the insertion of inductance L'_F alone, is at least 3 whatever the value of the source impedance.
The figures 22 and 23 illustrate the shape of line currents with and without the presence of a filter, as well as the spectra of these currents for a rectifier comprising an input inductance and a filter inductance such that:

$$L'_F = L_F \text{ with } Ucc_F = 10\ \%$$

The rectifier is supplied from a source such that Uccs = 2 %.
For a current harmonic of order n, the voltage V_{Hn} developed across the source impedance is:

$$V_{Hn}\ \% = Uccs\ \% \cdot n \cdot \frac{I_{Hn}}{I_1}$$

since,

$$D\,\% = \sqrt{\sum_{n=2}^{\infty} V_{Hn}^2}$$

hence

$$D\,\% = U_{ccs}\,\% \cdot n \cdot \sqrt{\sum_{n=2}^{\infty} \left(\frac{I_{Hn}}{I_1}\right)^2}$$

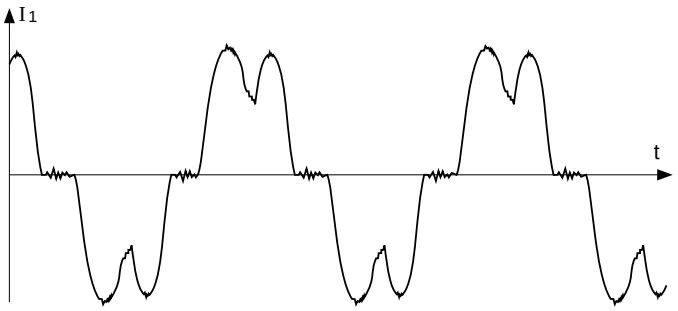
By taking the values listed in figure 22, the distortion rates at the source output are 4 % without filter, and 1 % with filter respectively.

For comparison purposes, it is to be noted that in the case of a two-bridge rectifier having the same input inductance, harmonics of orders 5, 7, 17 and 19 are eliminated, which results in a distortion rate at the source output equal to 1.9 %.

The harmonic filter is in this case, practically twice as effective compared with the use of a two-bridge circuit arrangement.
Furthermore, this is a less costly solution which can be resorted to after the equipment has been put in service.

Additional characteristic of harmonic filter

The presence of the parallel arm of the filter tuned to 5 th harmonic causes the appearance of a capacitive current at fundamental frequency. This capacitive current improves the power factor cos φ of the rectifier.

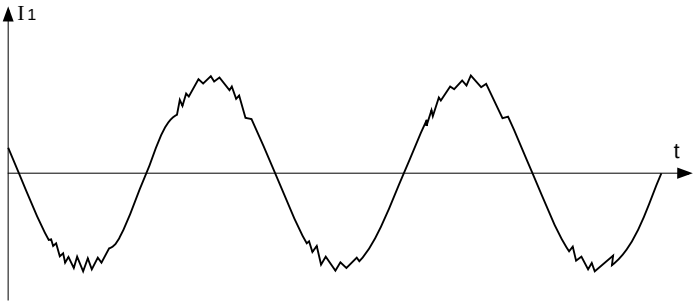


current spectrum

order	I_{Hn} / I_1
H5	33 %
H7	2.7 %
H11	7.3 %
H13	1.6 %
H17	2.6 %
H19	1.1 %
H23	1.5 %
H25	1.3 %

global rate of distortion of current ≈ 35 %

fig. 22: line current of rectifier without harmonic filter.



current spectrum

order	I_{Hn} / I_1
H5	2.1 %
H7	1.4 %
H11	3.6 %
H13	0.7 %
H17	1 %
H19	0.7 %
H23	0.6 %
H25	0.5 %

global rate of distortion of current < 5 %

fig. 23: line current of rectifier with harmonic filter.

4. conclusions and prospects

Thyristor rectifiers of classic types utilized in UPS equipments are sources of harmonic disturbances and adversely affect the power factor of the installation.

These pollutions are acceptable as long as the power rating of an UPS equipment is low compared with the short-circuit power rating of the network.

When the voltage distortion rate exceeds acceptable values (in the order of a few %), corrective measures must then be taken.

The simplest solution and the most common consists in inserting a series inductance which achieves harmonic decoupling.

When this measure is found to be insufficient, the use of phase staggered rectifiers or passive filters makes it possible to bring these disturbances down to an acceptable level.
These solutions are nowadays perfectly «mastered» and widely applied.

The figure 24 gives a synthesis of advantages and disadvantages for various solutions.

In the not too distant future, the multiplication of polluting equipments, the changes in standards and the requirements of energy distributors should lead to the use of «clean» rectifiers (this has already been achieved in single phase equipment thanks to the technique of sinusoidal sampling).

Furthermore, a converter utilising the technique of PWM (pulse width modulation) can, by making use of appropriately adapted regulation control, behave as an active filter intended to deal with a particular polluting load or with the whole of the installation; this principle can be compared to the one adopted for effecting «acoustic de-pollution» (i.e. emission of «sounds» in phase opposition to the sounds to be neutralised).

By utilizing a different regulation strategy, the same converters can also achieve self compensation of the power factor cos φ of the installation.

In order to make these devices, which are technically feasible, available to industry, it is necessary to ensure that their production costs are acceptable compared with those of classic solutions.

The principles of such converters and of their possibilities will be developed in a future Cahier Technique.

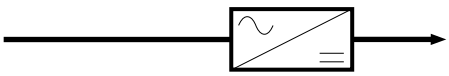
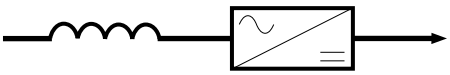
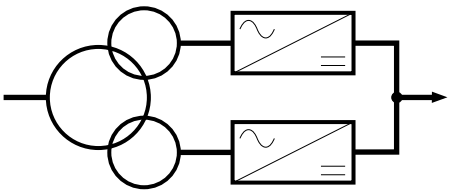
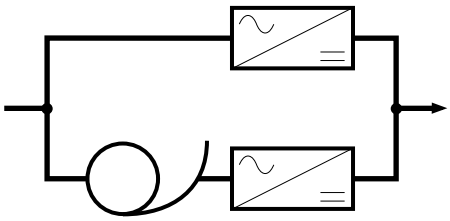
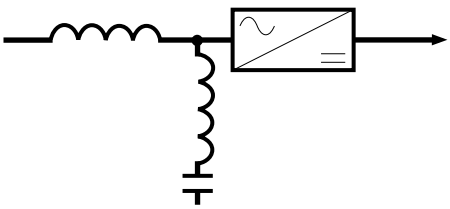
circuit type	diagram	observations
a) no reducing interface		■ acceptable if power required is low compared with short-circuit power of network
b) series inductance		■ simple, reliable ■ can be used in most cases ■ inductance can be added after equipment has been put in service ■ economic
c) double bridge and transformer with two secondaries		■ complicated (requires balancing of voltages, of Icc's, of currents in rectifiers) ■ to be considered at design start ■ expensive
d) double bridge with autotransformer		■ the solution for parallel connection of UPS units in active redundancy ■ compared with circuit C □ same effectiveness and drawbacks □ smaller losses □ more economic
e) passive filter		■ simple, reliable ■ best persorming ■ can be inserted after equipment has been put in service ■ more economic than solution with two rectifiers

fig. 24: comparison of anti-harmonics solutions.

5. bibliography

Standard specifications

■ IEC 146-4: semi-conductor converters part 4: Method for specifying performances of and test procedures with UPS.

■ IEC 552-2: Disturbances caused in supply networks by electro-domestic equipment and similar equipment.

■ IEC 1000-2-2: Electromagnetic compatibility (CEM) part 2: Environment.
Section 2: Levels of compatibility.

Merlin Gerin Cahier Technique publications

■ Les perturbations harmoniques dans les réseaux industrielles, et leur traitement : Cahier Technique No 152 by P. ROCCIA and N. QUILLON.

■ Inverters and Harmonics (case studies of non-linear loads): Cahier Technique No 159 by J.N. FIORINA.

Other publications

■ Directive of 25 July 1985 under reference 83/374/CEE.

■ Electra No 77 - July 1991.

■ Electra No 123 - March 1989.

Réal. : Illustration Technique Lyon -
DTE - 12/93 - 2500 - Imp. : Léostic Seyssinet-Pariset