Harmonics and UPS

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Velimir Lackovic, Char. Eng.

CEDengineering.com
PDH FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.com

TABLE OF CONTENTS

List of Figures

List of Tables

Introduction

UPS equipment, like the majority of static converters, take energy from an AC network through rectifiers. Typically, these rectifiers are equipped with thyristors that generate harmonics. This course highlights the need for a standardized coexistence between polluting and polluted equipment. Additionally, the course elaborates on various harmonic currents and voltages that are generated by conventional (classic) rectifiers (thyristor Graetz bridge rectifier) and provides different solutions that are designed to minimize harmonic impact.

Power harmonics in electrical networks

Consequences caused by harmonic currents

Harmonic currents that are created by certain devices, such as static converters, discharge lamps, arc furnaces etc., can seriously affect the operation of other devices installed in the same electrical network. This is especially true when there is a significant number of harmonic currents or their rating is high in comparison with the power source.

Harmonics cause:

- extra heating particularly in line conductors, transformers, and condensers;

- vibrations and noises in electromagnetic devices; and

- interference with communication and protection/signalling devices.

Further, a distorted voltage can obstruct the service of some receivers such as regulators and static converters. Therefore, one of the factors describing the quality standard of electricity supply is its voltage distortion rate.

Requirement for standardization

Since electricity is treated as a product, the producer is completely responsible for any damage caused by high levels of harmonics. In order to guarantee a quality level that is acceptable to all customers, distributors of electricity need to set limits to disturbances generated by consumers. To accomplish this, it is critical to determine:

- the maximum distortion rate allowing proper functioning of most installations (compatibility level); and

- the maximum disturbance rate, for each user, so that the cumulative effects of different disturbances allow an operational compatibility between all the installations. Therefore, if this compatibility is required between consumers, it must also exist within the installation units of each consumer.

As such, the consumer is burdened with controlling the levels of disturbances generated by their own equipment, which is why it is important that manufacturers clearly declare the disturbance levels generated by their equipment. To that end, the appropriate standards must determine acceptable levels of harmonic disturbances for both the supply networks and for the polluters.

Operational compatibility and emission levels

Limits need to be defined for each consumer to avoid the need for systematic controlled verifications when equipment is placed into operation.

For the same level of current disturbance, the voltage distortion ratio at the interconnection point depends on the network impedance at that point. Disturbances that are proportional to the power taken by each user and for each range of voltage i.e. LV, MV and HV, need to be recognised. Additionally, emission levels have to be considered in domestic and industrial installations.

In *low-voltage domestic* applications, where the energy distributor is not able to control the installation, disturbance levels which have to be observed in equipment are set in line with standards.

Standard harmonic emission values are provided in Table 1 and Table 2.

Table 1.Compatibility levels for harmonics voltages (in % of nominal voltage at fundamental frequency) in HV power network and MV and LV networks

Odd harmonics non multiples of 3			Odd harmonics multiples of 3			Even harmonics		
	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+12.5/n	0.1+2.5/n						

Global distortion rate: 8% in LV and MV network – 3% in HV networks

Table 2. Current harmonic component limits in domestic installations (In≤16A)

Harmonic order	Max. permissible harmonic current (in A)
Odd harmonics	
3	2.3
5	1.14
7	0.77
9	0.4
11	0.33
13	0.21
15 ≤ n ≤ 39	0.15 x 15/n
Even harmonics	
2	1.08
4	0.43
6	0.3
8 ≤ n ≤ 40	0.23 x 8/n

In *industrial applications*, there are so far no agreed international standards. Nevertheless, an agreement emerges on the concept of stages.

- Stage 1: Automatic acceptance - This acceptance depends on the network voltage level and applies to equipment of low power in comparison with the contracted power. For example, one rule is to have a disturbance causing power that is less or equal to 1 % of minimum short-circuit power at the interconnection point, during normal operation.

This tolerance can be extended in the case the total disturbing power is lower than:

- 4 MVA in the HV range,

- 500 kVA in the MV range,

- 40 kVA in the LV range.

- Stage 2: Acceptance with reservations – In situations when the limits are surpassed, the energy producer typically defines a maximum distortion rate at the interconnection point. In situations when these levels are likely to be surpassed, the distributor/supplier would reserve the right to ask for complementary measures of compensation to be resorted to, if the distortion rate was surpassed.

- Stage 3: Provisional acceptance - When the limits presented in Stage 2 are surpassed but without exceeding the compatibility level - due to the non-generation of harmonics by other users - a provisional authorization permit may be allowed.

Thyristor Graetz bridge rectifier

UPS equipment 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). A typical UPS configuration is shown in Figure 1. Typically, as the input converter is expected to give a charge or to keep the charge of the battery at a constant voltage and to supply the required power to the inverter, it typically uses thyristors connected in the form of a Graetz bridge circuit. Other types of rectifier circuits exist, but the three-phase Graetz bridge configuration is the most typically used, especially in high powered UPS units.

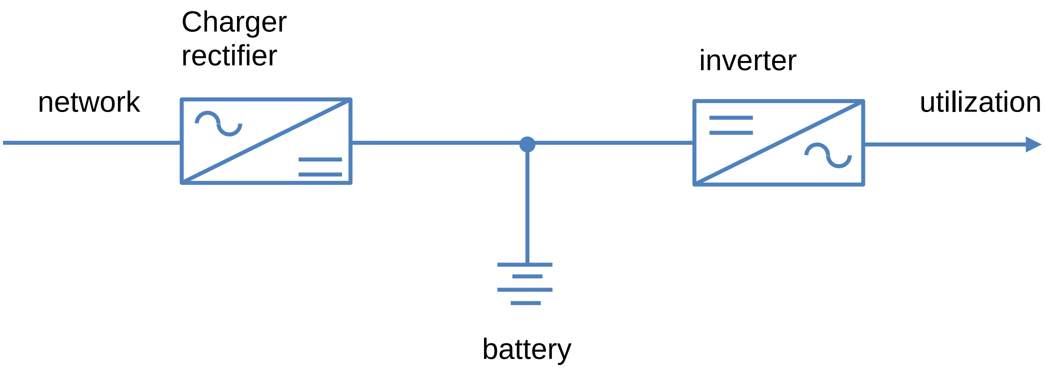


Figure 1. Circuit connection of a charger rectifier

Harmonic currents produced by a Graetz bridge rectifier

The rectifier presented in Figure 2 is connected to a high value inductance which serves as a filter to the DC current, I_d, to ensure that the latter is perfectly smooth. First, the source impedance is considered to be zero. The line currents I_1, I_2 and I_3 assume in turn the value (and the shape) of the DC current, I_d. Each thyristor provides current transfer during 1/3 of a period. Assuming that source impedance is zero, the current establishes itself instantaneously at its value I_d, as soon as one thyristor starts to transfer current.

Currents provided by the source have a rectangular waveform as shown in Figure 3. The spectrum is composed of current harmonics:

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

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

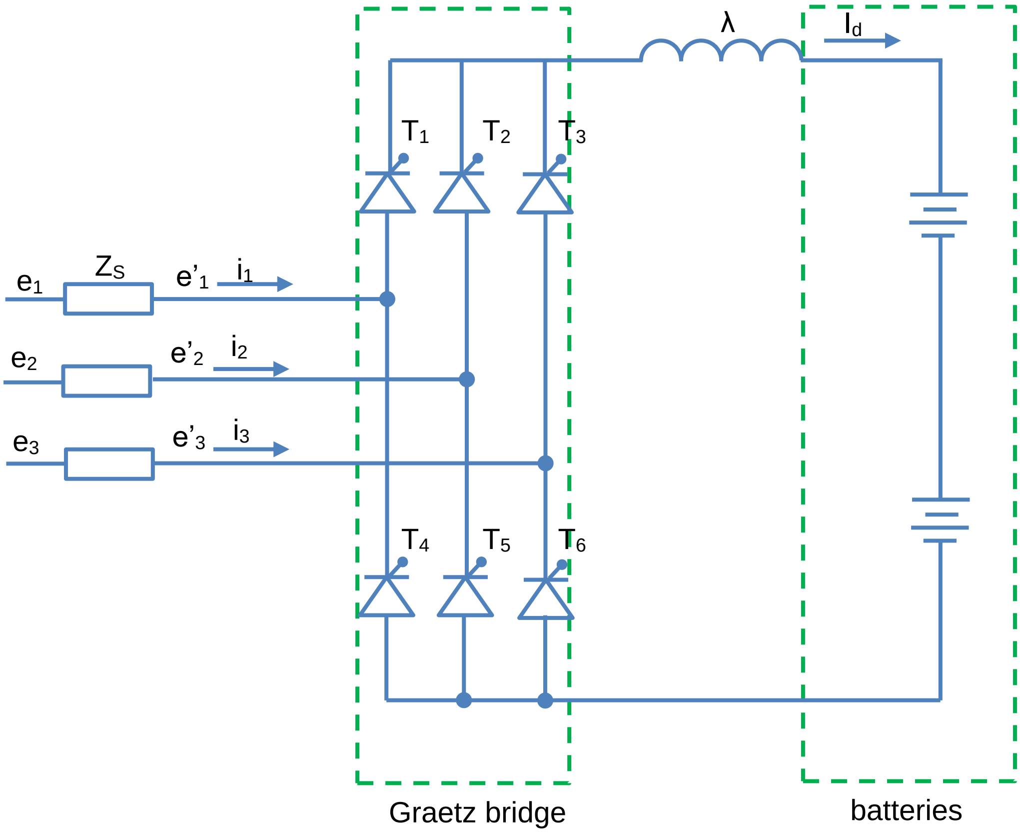


Figure 2. Circuit connection of charger rectifier

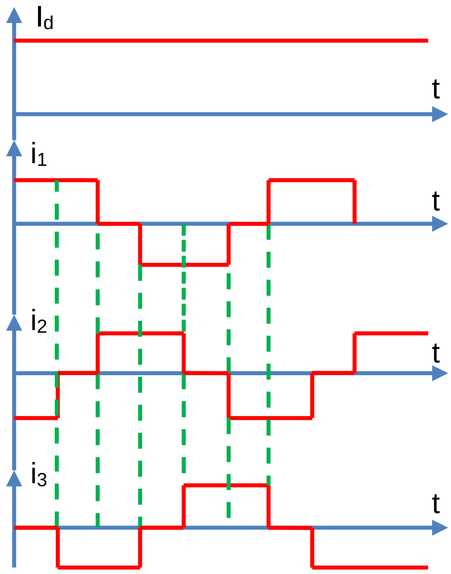


Figure 3. Theoretical currents upstream of rectifier with infinite downstream filter impedance and source impedance =0

For the current first harmonics, the amplitudes change as 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.

Therefore, the global rate of distortion of this current is 30 %. In this case, the voltage global distortion rate is zero, since the source impedance is assumed to be zero (e.g. infinite power).

Source impedance effect

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

Overlap phenomenon

When thyristor T_2 (shown in Figure 4a) is closed (gated) while thyristor T_1 is transferring, current I_2 establishes itself in thyristor T_2 while current I_1 in Thyristor T_1 decreases. Inductances L oppose instant, sharp changes of these currents. During commutation time Δt (Figure 4a) there is simultaneous conduction in two thyristors (this phenomenon is known as overlap). Therefore, the source is in a state of interphase short-circuit (phases 1 and 2) limited only by the two inductances L.

The voltage v is such that:

$$v = e_1 + L\frac{di_1}{dt} = e_2 + L\frac{di_2}{dt}$$

Hence:

$$2v = e_1 + e_2 + L\frac{di_1}{dt} + \frac{di_2}{dt}$$

$$L\frac{di_1}{dt} + \frac{di_2}{dt} = L\frac{d(i_1 + i_2)}{dt} = L\frac{dI_d}{dt} = 0$$

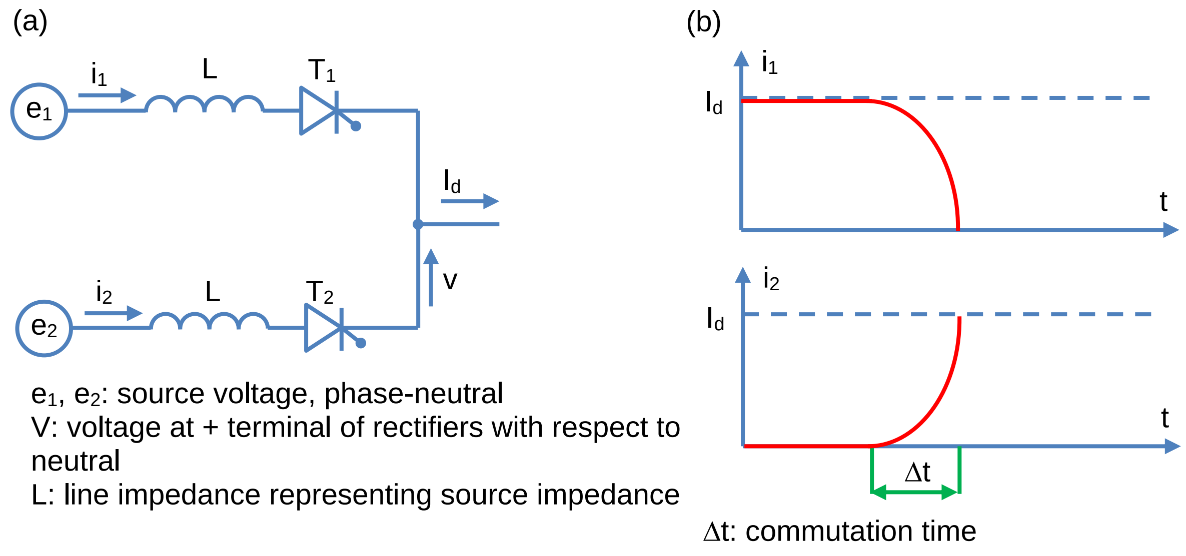


Figure 4. Overlap phenomenon

Hence:

$$2v = e_1 + e_2$$

Or

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

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

For an angle of lag α of 30° (which relates to a normal working point), voltages e'_1, e'_2 and e'_3 obtained at the rectifier input and line current i_1 are presented in Figure 5. The lag angle 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 constant (as shown in Table 3) regardless of the changes of the AC voltage or rectifier charging conditions.

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

$$U_d = 1.35\, U_{eff}\, \cos\alpha - \frac{1}{2} L\omega I_1$$

where U_{eff} is the effective value of composed resultant voltages

$$U_{eff} = e_1 \cdot \frac{\sqrt{3}}{\sqrt{2}}$$ - if one refers to Figure 4a

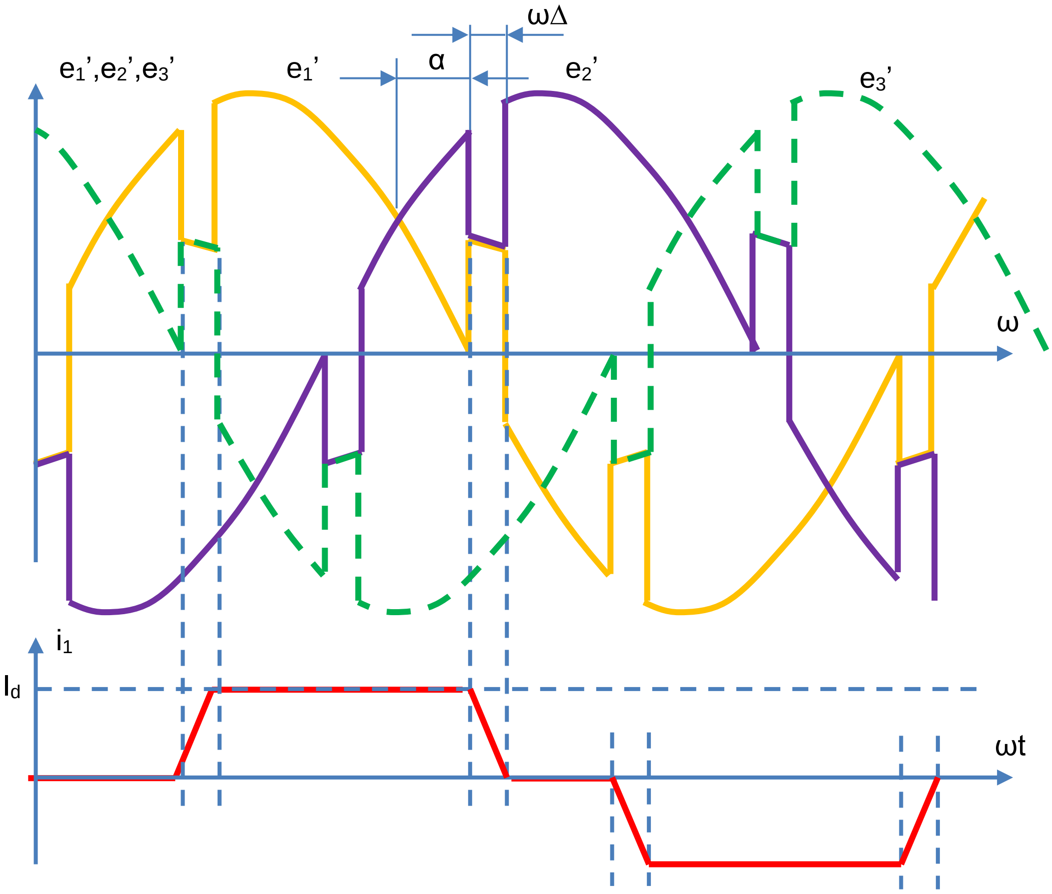


Figure 5. Thyristor rectifier overlap with an angle of lag α of 30°

Table 3. Charge of UPS batteries at constant voltage and limited current (Sealed batteries (recombination) are typically only charged at low rate charge. Open batteries are charged in two successive voltage steps)

	Lead storage cells “recombination”	Open load cells	Nickel-cadmium cells
Charging voltage (high rate) (in V)	$2.3<U_{charge}<2.5$	$2.3<U_{charge}<2.5$	$1.422<U_{charge}<.65$
Floating voltage (low rate) (in V)	$2.23<U_{floating}<2.30$	$2.18<U_{floating}<2.25$	$1.38<U_{floating}<1.5$

Disturbances caused by overlap

It is clear 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 for transfer; and
- An overvoltage when the current in this thyristor is switched off.

The bigger the inductance of line L, the longer the disturbances duration, Δt. Since the line current no longer has a perfectly rectangular shape, its harmonic content reduces (strong attenuation of harmonics of high orders). Therefore, the resulting voltage distortion increases when the line impedance increases. However, this increase is not proportional to the impedance since the harmonic content of current decreases. Also, the commutation time decreases when the lag angle, α, increases which brings about an increase in the current harmonic content and the voltage distortion for the same inductance value.

Current harmonic content

Figure 6 shows how harmonic currents change with respect to the source impedance for different lag angles, α. The harmonic currents are shown in relative value with respect to their maximum theoretical value (I_{niN}): I_{nN} = I_{eff} of harmonic of order n:

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

Where I_1 is the effective value of fundamental

The source impedance is expressed by the term d_{XN} which corresponds to the relative voltage drop on the DC side. The latter is due to the effect of the line's total inductance. For this rectifier:

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

where V_1 is the effective value of simple fundamental voltages.

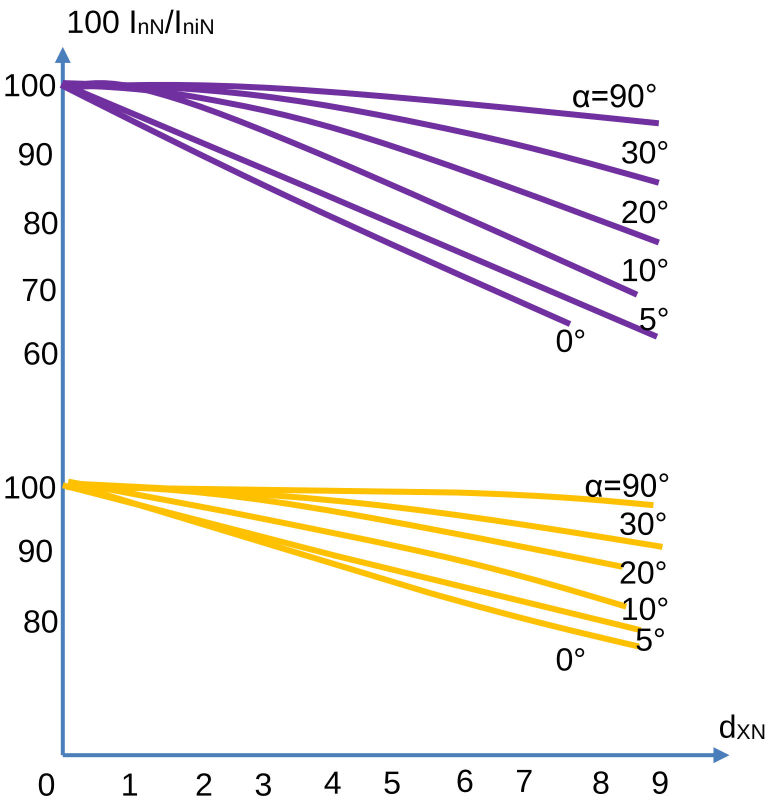


Figure 6. Harmonic currents amplitude changes with respect to source impedance for different lag angles (α) in a three phase Graetz bridge circuit

Harmonic of order n=5 (yellow), n=7 (purple)

In a balanced three-phase circuit, d_{XN} represents half of the relative voltage drop of the line. If this relative voltage drop (U'_{cc}) is likened to a short-circuit voltage, it is possible to write:

$$d_{xN} = \frac{1}{2} U'_{cc}$$

Current distortion rate

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

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

For example, the harmonic content does not depend on α (Δt = 0). The global rate of theoretical distortion is determined using the expression:

$$D\ \% = 100\,\frac{\sqrt{\sum_{k=1}^{\infty}\left(I_{6k+1}^{2} + I_{6k-1}^{2}\right)}}{I_1}$$

In reality, for calculation needs, 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 accomplished (as shown in Figure 7). Consequently, current harmonic content is slightly modified. In particular, it is noted that harmonics of order 6 k - 1 are increased whereas those of order 6 k + 1 are decreased.

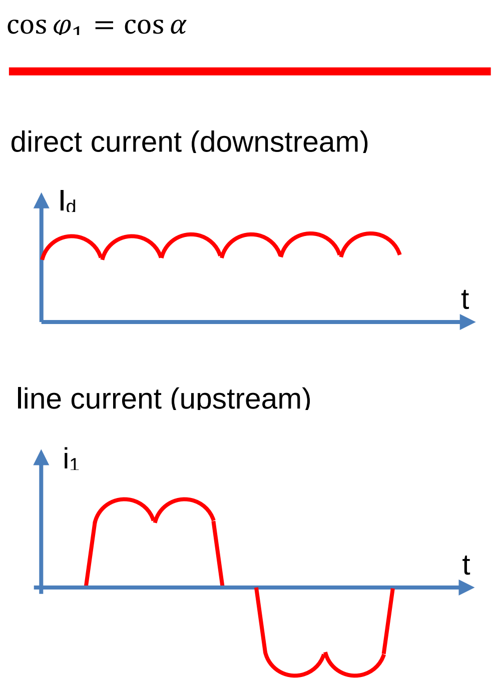


Figure 7. Currents upstream and downstream of rectifier

Voltage distortion rate

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 lag angle, α, set for thyristor control, is shown in Figure 8. Distortion rate increases quickly and it is difficult to keep it below a value of 5 %.

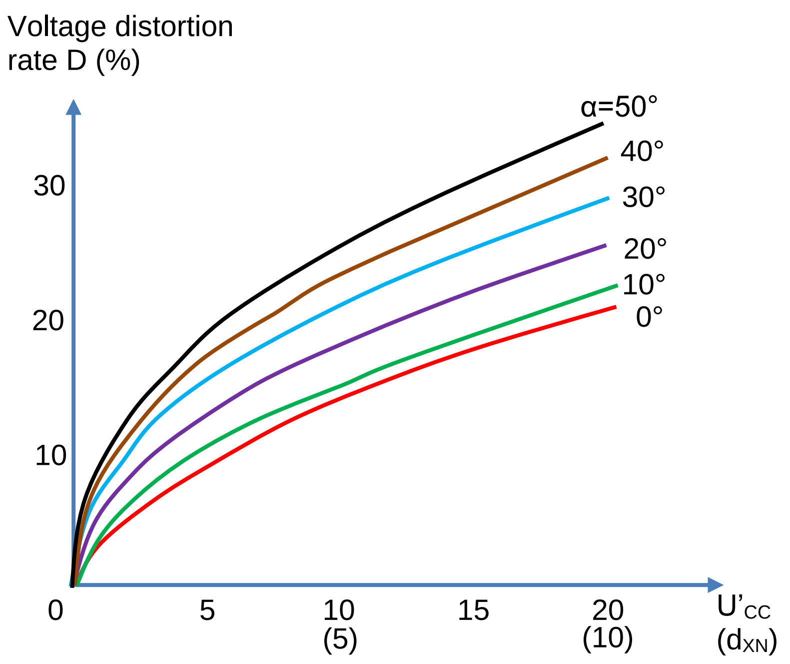


Figure 8. Voltage distortion variation rate with respect to source impedance for different values of lag angle α

Rectifier power factor

Since the current taken by the rectifier is highly distorted, the RMS current has a value superior to that of the fundamental. The current effective value can be calculated by using equation:

$$I_{eff} = \sqrt{I_1^2 + \sum_{k=1}^{\infty}(I_{6k+1}^2 + I_{6k-1}^2)}$$

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

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

Therefore:

$$I_{eff} = \sqrt{1 + \left(\frac{1}{5}\right)^2 + \left(\frac{1}{7}\right)^2 + \cdots}.$$

For instance:

$$I_{eff} = 1.05 I_1$$

Moreover, 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 ωΔt. As a first approximation, since the overlap angle is small in comparison to the lag angle, a phase shift equal to α can be retained, therefore:

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

If the effective voltage approaches close to the fundamental (which is true when the distortion rate is low), the power factor λ can be expressed with good approximation as: λ=0.95 cosα

Since:

$$\lambda = \frac{P}{S} = \frac{\sqrt{3} U_1 I_1 \cos \varphi_1}{\sqrt{3} U_{eff} I_{eff}}$$

Note - U_1 and Ueff represent line to line voltages.

$$\lambda = \frac{1}{1.05} \cos \alpha$$

Mitigation of harmonic disturbances

Curves shown in Figure 8 indicate that the voltage distortion rate at the rectifier input quickly increases in importance, even when the source impedance is very low. Hence, it is mandatory to decrease this distortion rate to allow the use of rectifiers of non-negligible power. Since harmonic currents are responsible for the voltage distortion when they go across the source impedance, reduction in their amplitude will introduce an improvement to the voltage waveform. To accomplish this, three classic techniques are used:

- The insertion of extra inductance in the rectifier input in order to attenuate the harmonics amplitude (particularly those of higher orders);

- Application of several rectifiers supplied by voltages appropriately phase shifted. Using this method, it is possible to eliminate - by combining currents – the most severe harmonics (harmonics of the lowest orders with the biggest amplitudes); and

- The retention of a single Graetz bridge rectifier to which a passive filter is added. This filter is designed to eliminate the most severe harmonics and to decrease the amplitude of other harmonics.

Certainly, it is possible to combine these techniques to optimize the results.

Insertion of inductance at rectifier input

The circuit diagram that refers to single phase is shown in Figure 9. The insertion of inductance L_F decreases the current distortion rate. The voltage distortion rate at point A decreases. Its value can be found from the value obtained at point B. Inductances L_s and L_F compose a divider for harmonic voltages.

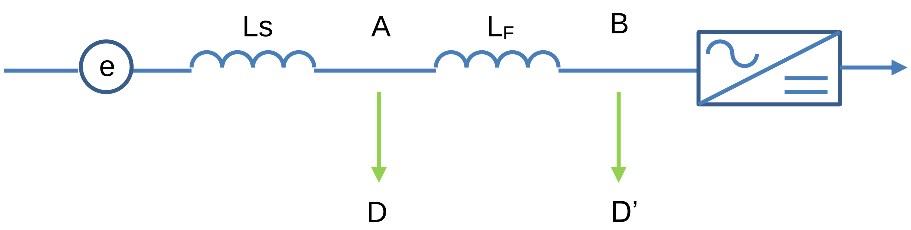


Figure 9.Harmonic separation (decoupling) through use of extra inductance

L_F – rectifier filtering inductance

LS – total inductance of source (generator +cabling)

E – perfect voltage source

D – D' – voltage distortion rates

Distortion rate theoretical calculation

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

$$V_n' = n(L_S + L_F)\omega I_n$$

Where ω - pulsation of fundamental

Voltage V_n measured at point A is:

$$V_n = nLs\omega ln$$

$$V_n = V'n \frac{L_s}{L_s + L_f}$$

By using this methodology for each harmonic and calculating the total distortion, it becomes clear that if the voltage distortion rate measured at point B is D', the voltage distortion rate at A is:

$$D = D' \frac{L_s}{L_s + L_F}$$

Using:

$$U_{ccs} = \frac{Ls\omega I_n}{V_n}$$

$$U_{ccF} = \frac{L_F\omega I_n}{V_n}$$

Where V_n is the effective value of the simple fundamental voltage.

For example, if L_s is such that U_{ccs} = 2 % and L_F is such that U_{ccF} = 6 %, then their sum U_{ccs} + U_{ccF} = 8 %. For lag angle α equal to 30°, the curve in Figure 8 gives a 19% distortion rate. Hence, the distortion rate at point A is:

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

Without the inductance L_F in the circuit, the distortion rate would have been referred only to L_s, that is U_{ccs} = 2 %, a value which gives D = 10 %, as shown on the curve in Figure 8. The insertion of inductance L_F has allowed decreasing the voltage distortion rate by a factor bigger than 2 in comparison with the rate level in other usages.

Example:

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. Hence, the apparent power taken by the rectifier is:

$$\frac{250\ x\ 0.8}{0.92\ x\ 0.82} = 265\ kVA$$

The rectifier is supplied from a transformer rated at 630 kVA, U_{ccs} = 4 % and is related to an inductance corresponding to U_{ccF} = 12 % and calculated for a rectifier power rating of 350 kVA.

Considering the transformer and rectifier load rates:

$$U_{ccs}\, becomes\ 4\% \times \frac{265}{630} = 1.7\%$$

$$U_{ccL}\, becomes\ 12\% \times \frac{265}{350} = 9.1\ \%$$

In the case the thyristors operate with a lagging phase angle α of 20° on average, it is then possible to calculate the distortion rate from Figure 8:

$$D = 18.8\ \%$$

$$(\alpha = 20°, Ucc = 10.8\%)$$

Therefore, a distortion rate across the transformer terminals is:

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

Double bridge rectifier application

Double bridge rectifier, shown in Figure 10, consists of using a transformer with two secondary windings which provide voltages with a phase displacement of 30° between them. Each of those secondaries powers a Graetz bridge rectifier which provides a six-phase rectification. The rectifiers must supply identical DC currents to make sure that the AC currents taken from the transformer secondaries have the same value. Under those conditions, a recombining process happens. It happens between the harmonic currents generated by each rectifier in the transformer primary winding. Calculations show that harmonics of order 6 k±1 (k being an odd number) are eliminated.

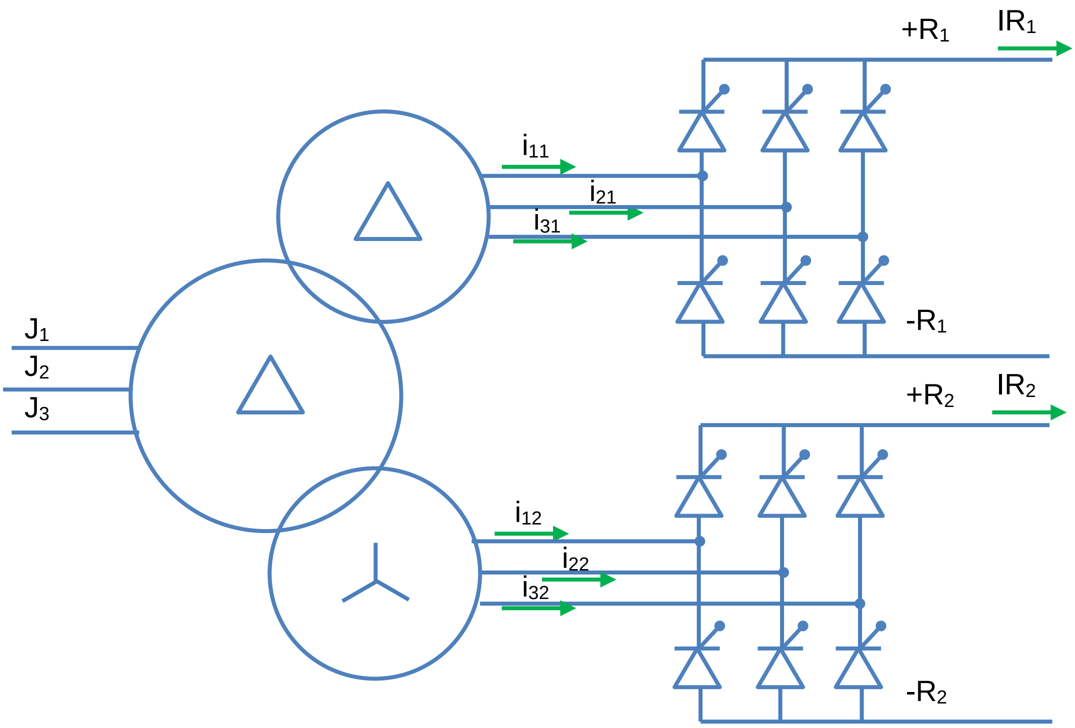


Figure 10.Basic arrangement of a rectifier with two phase staggered bridges

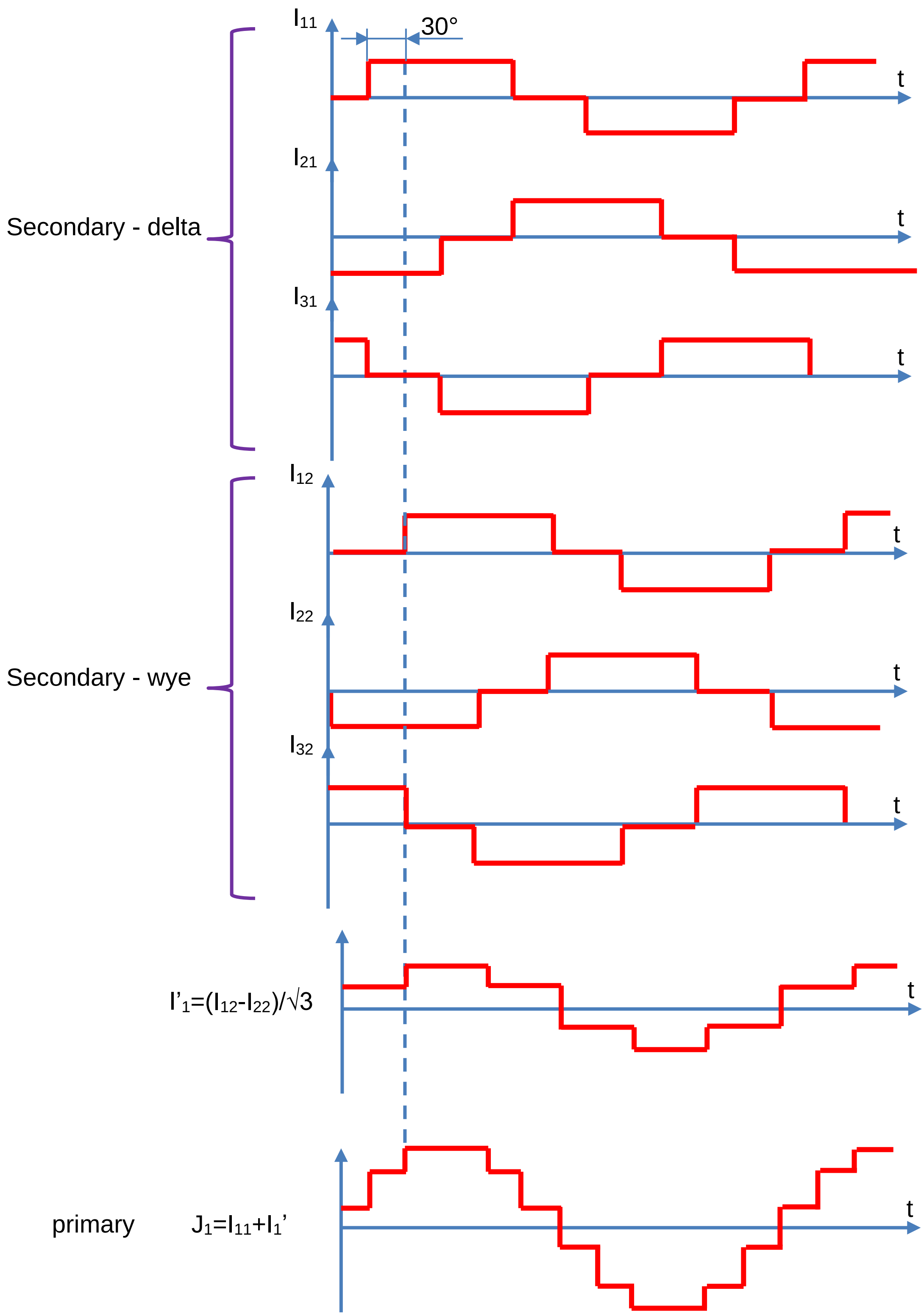


Figure 11. Current shapes taken by rectifier (transformer primary with two secondaries)

This is especially the case with 5th and 7th harmonics whose theoretical amplitudes are the most critical. 11th and 13th harmonics are retained but the 17th and 19th harmonics are cancelled. Hence, the remaining harmonics are of order 12 k±1 (k being a whole number). Figure 11 shows the current taken by the transformer primary and resulting from currents supplied by the two secondaries. The line current in shape is much closer to a sinusoidal waveform than that of the current obtained with a single rectifier. The two rectifiers can be put in series or in parallel (as shown in Figure 12). When the two circuits are connected in parallel and considering that the instantaneous voltages delivered by each one of the two rectifiers are not equal (there is phase displacement of 30°), it is mandatory to add an inductance with a centre tap in order to keep a permanent flow in each rectifier.

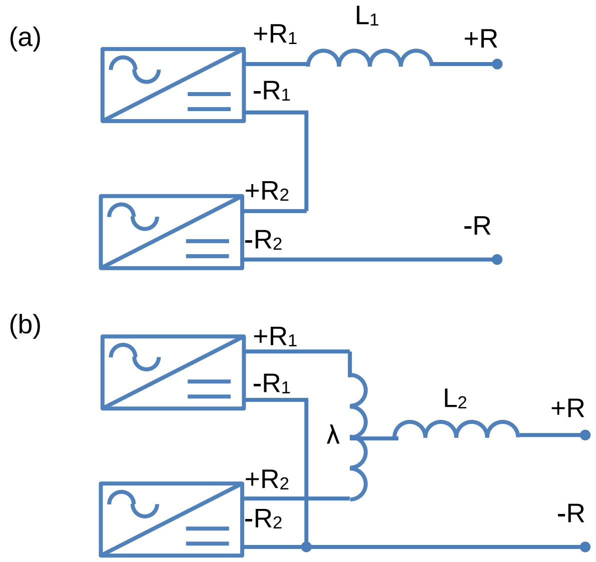
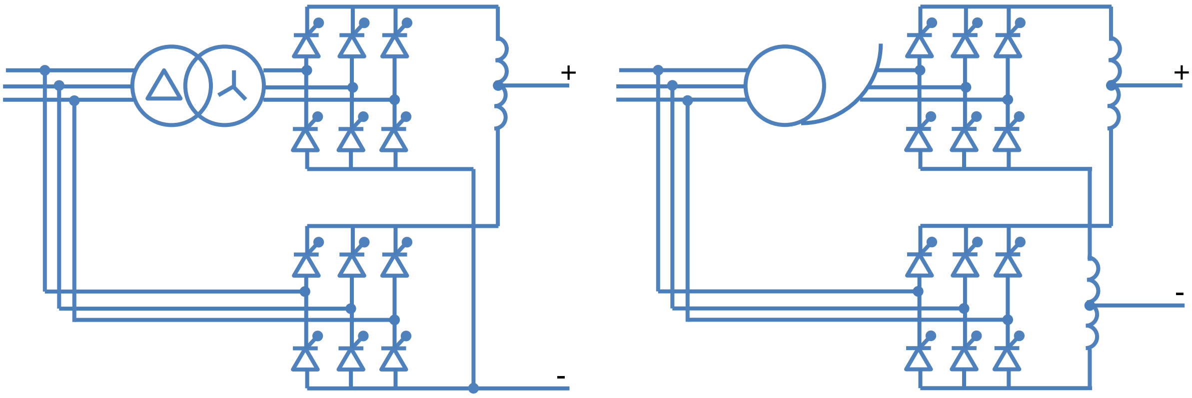


Figure 12. Two rectifier connection (a) series (b) parallel

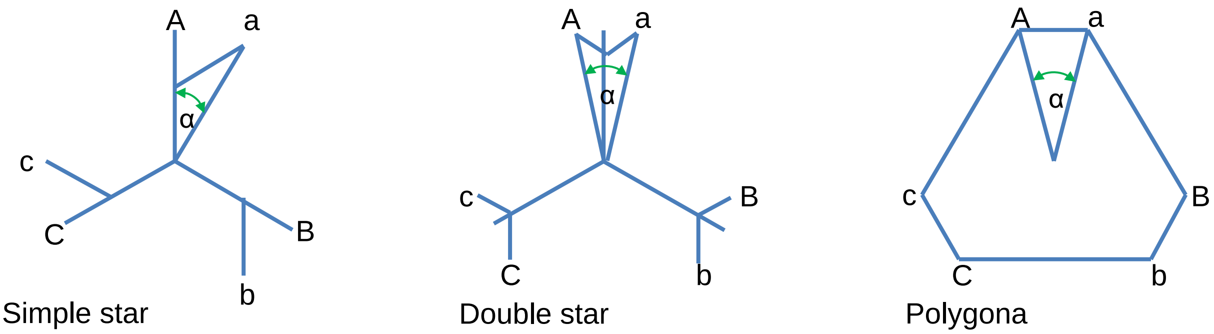
L_1, L_2: inductances of DC current filtering λ: separation (decoupling) inductance with center tap point

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 of the arrangement presented in Figure 10 (as presented in Figure 13) which produce the same harmonic levels.



(a) circuit arrangement with power transformer

(b) circuit arrangement with autotransformer



Simple star Double star Polygona

Figure 13. Circuit arrangement to obtain 30° phase shift and different connection arrangements for autotransformer

(c) different connection arrangements for autotransformer

Simple star	Double star	Polygonal
(c) different connection arrangements for autotransformer		

Current distortion rate

Assuming zero impedance upstream of rectifier and ideally smoothed DC current, the effective value of each current harmonic can be calculated using formula:

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

Where n=12k ±1

Therefore, the theoretical rate of distortion is:

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

Hence, D~15 % which represents half the value obtained with a single rectifier.

Voltage distortion rate

The voltage distortion rate depends 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 higher source impedances, the gain is larger since higher order harmonics decrease rapidly as the source impedance increases. Nevertheless, the gain stays moderate and in reality, a ratio of 0.5 in favour of the double bridge circuit is to be retained.

Example:

- For a lag angle α = 30°, the ratio between the two distortion rates amounts to 0.66 with U'_{cc} = 8 % and 0.55 with U'_{cc} = 16 %.

- For a lag angle α = 0, the ratios are 0.53 and 0.37 respectively. The ratio between the distortion rates does not take account for the inductance of the phase shifting system.

Rectifier circuit with multiple bridges

A rectifier with multiple bridges is shown in Figure 14. The basic idea is to increase the number of transformer secondaries with respective phase displacements depending on the number of secondaries retained in order to eliminate other current harmonics.

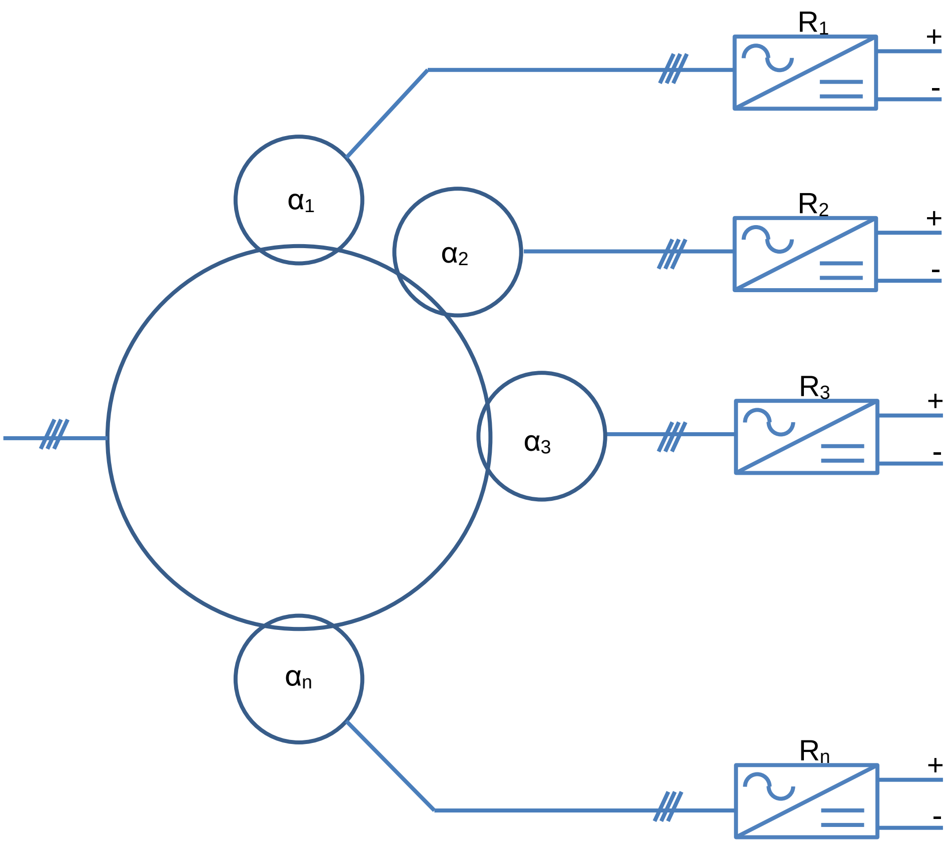


Figure 14. Rectifier with multiple bridges

Three rectifier circuit configuration

For this configuration, the phase displacement needs to be such that:

- $\alpha_1 = 0°$;
- $\alpha_2 = 20°$; and
- $\alpha_3 = 40°$.

In this configuration, the only harmonics remaining are those of order 6k±1 (where k = multiple of 3) that is 18k±1. Hence, the first current harmonics are 17th and 19th followed by 35th and 37th harmonics.

Four rectifier circuit configuration

In this configuration, the phase displacements are as follows:

- $\alpha_1 = 0°$;
- $\alpha_2 = 15°$;

- α_3 = 30°; and
- α_1 = 45°.

The only harmonics that remain are those of order 24k±1.

Therefore, the first harmonics are the 23rd and 25th followed by 47th and 49th.

These configurations are important since they make it possible to achieve relatively low current and voltage distortion rates. They have the drawback of being complex and costly. Finally, their application is reserved for high power rating devices. For example, aluminium electrolysis process, which uses DC current supplied from power sources of several MW, needs circuit configuration that consists of up to 72 phases!

Phase shifting circuit configuration

Phase shifting circuit configuration is shown in Figure 15. When several UPS units work in parallel, they share the load current between them and the currents taken by each rectifier have identical amplitudes. Therefore, it is possible to supply the rectifiers from auto-transformers which generate the required phase shifts according to the number or rectifiers (instead of using circuit configurations with transformers).

The auto-transformers that are used can be of the same type as those presented in Figure 13. The polygonal circuit configuration is typically used for economic reasons. The principal drawback of this configuration is due to the fact that harmonic rates increase when one of the UPS units is switched off. Table 4 presents the harmonic content in circuit connections in which all the rectifiers , except one, are in service.

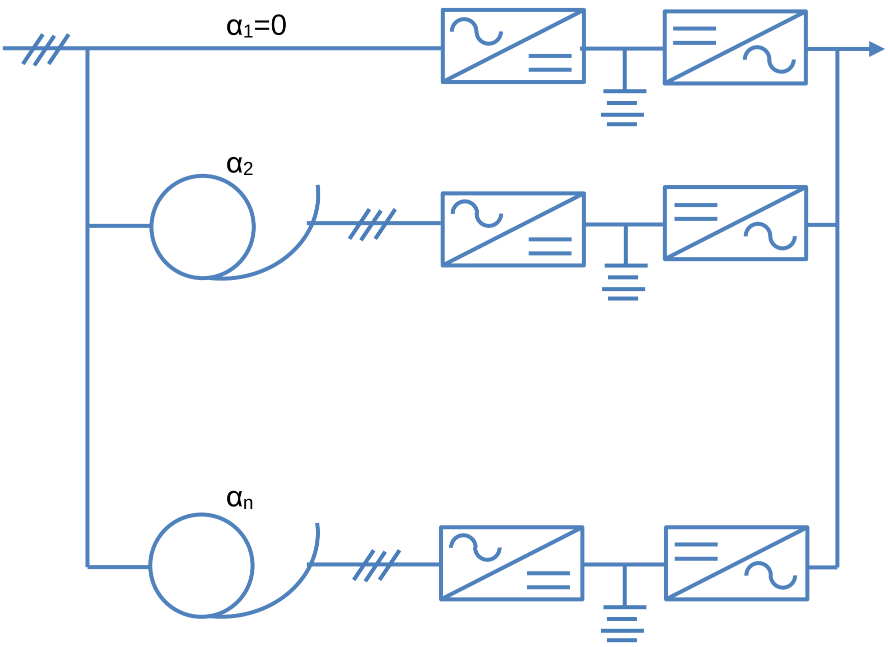


Figure 15. Phase shifting principle

Table 4. Current harmonic content change in principal connection systems

Connection arrangement	No. of rectifiers in operation	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	½	½	½	½	1	1	½	½
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

Harmonic passive filters

A harmonic passive filter is tuned to a specific frequency. Its effectiveness is highest at this frequency, but few filters may be needed to strongly attenuate several harmonics. Installation of passive filters is always critical due to the risk of resonance.

Filters for high power rating UPS devices

Figure 16 presents the equivalent circuit for one phase. The parallel arm of the filter consists of a circuit tuned to the 5th harmonic which is the most critical. The series arm of the filter contains an inductance whose function is to provide separation of the parallel arm from the source.

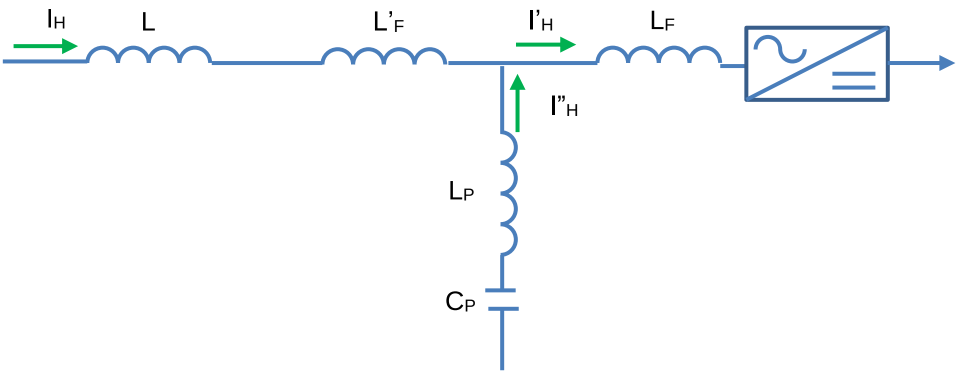


Figure 16. Passive harmonic filter

Impedances of filter parallel (Z_{pn}) and series (Z_{sn}) arms are tuned to nth order harmonic. If the current generated by the rectifier for this order is $I'H_n$, then the current generated by the source is:

$$I_{H\eta} = I'_{H\eta}\frac{Z_{pn}}{Z_{pn}+Z_{sn}} \quad \text{(as shown in Figure 17)}$$

Regarding 5th harmonic, the parallel impedance is equal to zero. The 5th harmonic current travels through the filter parallel arm and no longer affects other users.

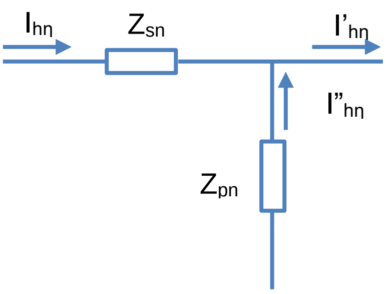


Figure 17. Harmonic filter equivalent circuit

Regarding the 7th harmonic, the parallel impedance is low and consequently a large part of this harmonic is eliminated, due to its proximity to the tuned frequency.

Regarding higher order harmonics, the filter parallel impedance is very close to its inductance L_p. Therefore, the filter works as a current divider. For higher order harmonics:

$$I_{H\eta} = I'_{H\eta}\frac{L_P}{L_P + L_S + L'_F}$$

In theis case, L_P is selected so that:

$$L_P \approx L_S + L_F \ then$$

Then:

$$I_{H\eta} = \frac{1}{2}I'_{H\eta}$$

Voltage global distortion rate

Let us consider an example:

- if $L'_F = L_F$ with U_{ccF} = 12 %,

and

- if L_p corresponds to U_{ccp} = 15 %,

the gain after the insertion of inductance L'_F alone is at least 3 regardless of the source impedance value. Figure 18 and Figure 19 present shapes of current with and without the filter, as well as current spectra for a rectifier. It consists of input inductance and a filter inductance such that:

$L'_F = L_F$ with U_{ccF} = 10 %

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

$$V_{H\eta}\% = U_{ccs\%}\, n\, \frac{I_{H\eta}}{I_1}$$

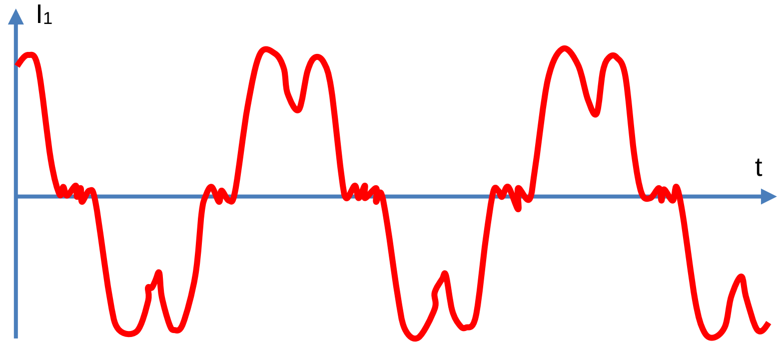


Figure 18. Rectifier line current without harmonic filter

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 current distortion rate ~35%	

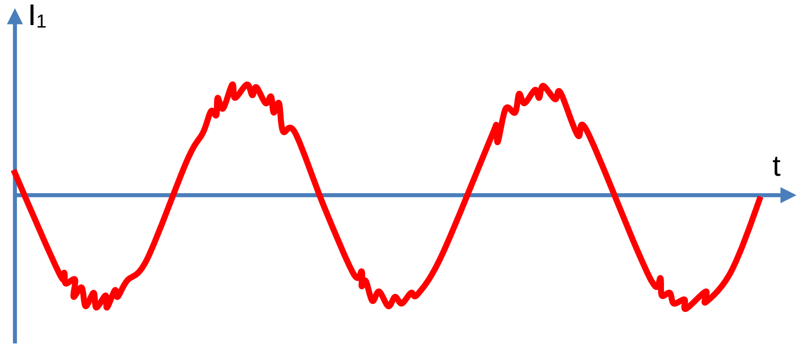


Figure 19. Rectifier line current with harmonic filter

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 current distortion rate <5%	

Since,

$$D\ \% = \sqrt{\sum_{n=2}^{\infty} V_H \eta^2}$$

Therefore,

$$D\ \% = U_{CCS}\ \%\ n \sqrt{\sum_{n=2}^{\infty} \left(\frac{I_{H\eta}}{I_1}\right)^2}$$

By taking the values from the Figure 18, the distortion rates at the source output are 4 % without the filter and 1 % with the filter.

For comparison, in the case of a two-bridge rectifier with the same input inductance, harmonics of orders 5, 7, 17 and 19 are cancelled, which results in a distortion rate at the source output equal to 1.9 %. In this particular case, the harmonic filter is practically twice as effective in comparison with the use of a two-bridge circuit configuration. Also, this is a less expensive solution which can be resorted to after the equipment has been placed into operation.

Additional features of harmonic filter

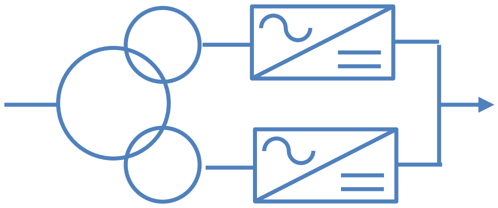
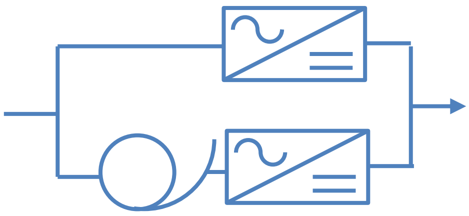
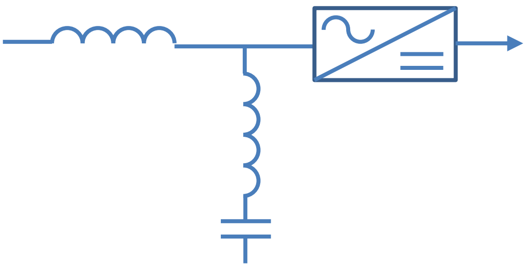
The existence of the filter parallel arm tuned to the 5th order harmonic causes the appearance of a capacitive current at the fundamental frequency. Capacitive current improves the rectifier's power factor, cos φ.

Conclusion

Classic thyristor rectifiers used in UPS devices are sources of harmonic disturbances and affect the power factor of an installation. These power quality disturbances may be acceptable as long as the UPS equipment power rating is low in comparison to the short-circuit power rating of the network. As soon as the voltage distortion rate surpasses acceptable values (in the order of a few %), mitigation measures must be taken. The simplest and most common solution is inserting a series inductance which achieves harmonic decoupling. When this measure is not sufficient, application of phase staggered rectifiers or passive filters, allows bringing disturbances down to an acceptable level. Nowadays, these solutions are widely applied. Figure 20 gives a synthesis of benefits and drawbacks for different solution techniques. In the distant future, the multiplication of polluting devices, the changes in standards and the demands of energy distributors will lead to the use of clean rectifiers (this has already been accomplished in single phase devices thanks to the sinusoidal sampling technique).

Table 5. Anti-harmonics solution comparison

Circuit configuration	Diagram	Notes
(a) no reducing interface		Acceptable if required power is low in comparison with short-circuit power of network
(b) series inductance		Simple, reliable Can be used in most

		situations Inductance can be added after devices have been put in service Economic
(c) Double bridge and transformer with two secondaries		Complicated (demands balancing of voltages, of ICC of currents in rectifiers To be considered at design stage Costly
(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 performing - Can be inserted after equipment has been put in operation - Less expensive than solution with two rectifiers

Moreover, a converter using PWM techniques can, by using an appropriate regulation control, behave as an active filter programmed to deal with a particular polluting load or with the complete installation. This technique can be compared to the one adopted for acoustic de-pollution. (i.e. emission of sounds in phase opposition to the sounds that need to be cancelled).

By using a different regulation strategy, the same converters can also accomplish self-compensation of the installation's power factor, cos φ. In order to make this technically feasible equipment, available to industry, it is important to make sure that their production costs are acceptable in comparison to classic solutions.

References

- Cahier Technique Merlin Gerin n° 160
- Directive of 25 July 1985 under reference 83/374/CEE
- Electra No 77 - July 1991
- Electra No 123 - March 1989
- 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