HARMONICS: CAUSES, EFFECTS AND MINIMIZATION

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Contents

1.- INTRODUCTION

In recent years, with the increasing use of power electronics, the quality of electricity supply, together with energy efficiency, has become a key issue, and company energy responsibles are more and more aware of the benefits of paying attention to that.

The main representation of power quality is the harmonic distortion, which represents the deviation between the ideal sinusoidal waveform the network voltage or the load current should have, and what really it is.

Some of the effects the harmonic can cause, to the equipment, to the installation, or both, are:

- Added efficiency losses to the system composed by electrical installation and equipment.
- Unexpected resonances.
- Disturbances in electronic equipments, causing “logical” faults in digital circuits.
- Unwanted overload (or need to oversize) for transformers, wirings.
- Malfunctions of motors and generators.
- Unwanted Cicuit Breakers tripping or Fuses blowing.

The harmonics mitigation can report quantifiable benefits for industry critical processes, IT systems, datacenters, etc., in terms of overall installation cost, energy bill reduction, and protection against process interruptions and equipment faults.

2.- WHAT ARE THE HARMONICS ON HOW ARE THEY GENERATED?

The main cause of the harmonics generation are the “non-linear” loads. So, before talking about harmonics, we need to define what is a “linear” load and what a “non-linear” load.

Linear load

It is a load that draws instantaneously proportional current to the applied voltage, i.e., its impedance is maintained constant along the whole alternating period.

For public electricity supply of 50 or 60 Hz sinusoidal voltage, this will mean a pure sinusoidal current also.

Linear loads can be classified as resistive (electrical heaters, incandescence light bulbs), capacitive (capacitors usually found as part of systems or equipments), inductive (transformers, motors), or combinations of some of them.

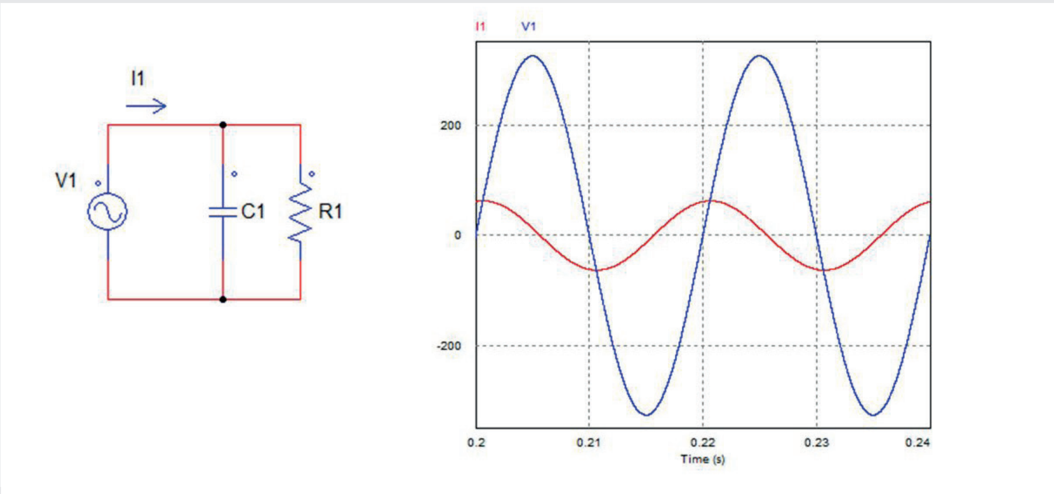

Fig.1 Linear load consisting in a combination of resistor and capacitor. In this case, the capacitor causes a leading power factor lower than 1.

Non-Linear load

In opposition to linear-loads, a non-linear load changes its impedance with instantaneous applied voltage, that will lead to a non-sinusoidal current draw when the applied voltage it’s so. In other words, this kind of load does not have a constant relation current vs. voltage along the alternating period. The simplest circuit to represent a non-linear load is a diode-rectifier, with its multiple variants (full-wave diode rectifier, half-wave diode rectifier, single-phase or three-phase). See fig.2.

Some examples of non-linear loads, capable of injecting harmonics into an electrical distribution, are: industrial equipments (welding, arc furnace), variable frequency drives (VFD), line-switched rectifiers, switch-mode power supplies, lighting ballasts … and also modern electronic equipments, at low load levels, even they could be designed to optimize efficiency around it’s rated working point. All these circuits can contain semiconductor power devices such as diodes, thyristors (SCR’s), transistors, and/or switching of loads or circuits.

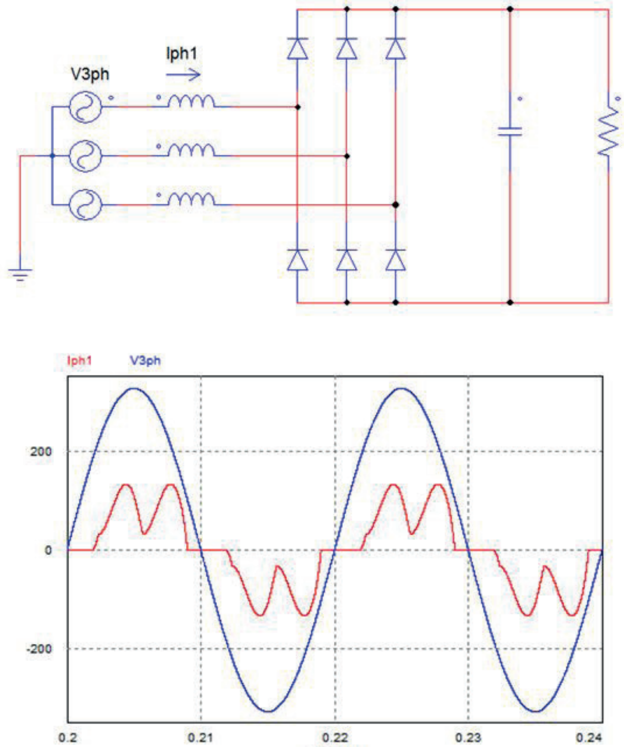

Fig.2 Example of non-linear load: circuit corresponding to a 6-pulse rectifier (or VFD input stage), and its highly distorted current draw (Iph1, similar for all 3 phases) not proportional to the 3-phase supply voltage V3ph.

To understand how distortion is transferred from current harmonics injection into harmonic voltage distortion, it's necessary to indroduce the concept of Point of Common Coupling (PCC). It is defined as the point where the distribution line (tipically public) reaches the end user, where the particular loads are going to be connected. So for industrial or commercial users, this point could be "serviced" via a distribution transformer (for example, MV to LV transformer), or a long distribution line, or combination of both. A series impedance can summarize the equivalent distribution circuit between the "ideal" power source and this PCC (represented in Fig.3 as Ls).

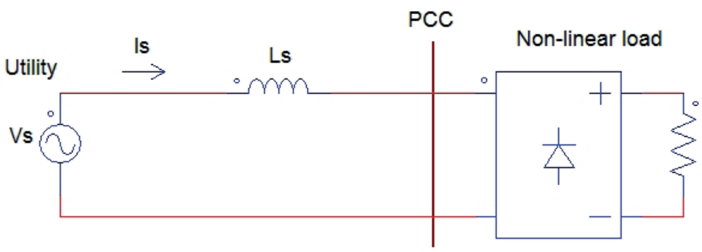

Fig.3 Equivalent circuit of utility distribution line and PCC.

The voltage at PCC can be deduced from voltage source Vs and voltage drop at Ls as:

$$V_{PCC}(t) = V_S(t) - L_S \cdot \frac{dI_S(t)}{dt}$$

Assuming a non-sinusoidal current draw (Is on Fig.4), hence a non-sinusoidal voltage waveform appears at PCC caused by the voltage drop at the distribuition impedance Ls (V_{PCC} on Fig.4). Note that, even non-sinusoidal, both current draw Is and voltage at PCC (V_{PCC}) are periodic signals.

That is, voltage at PCC now presents a significant harmonics content. The greater the current harmonics injection, the greater the voltage harmonics will appear at PCC, which also will depend on the distribution impedance Ls.

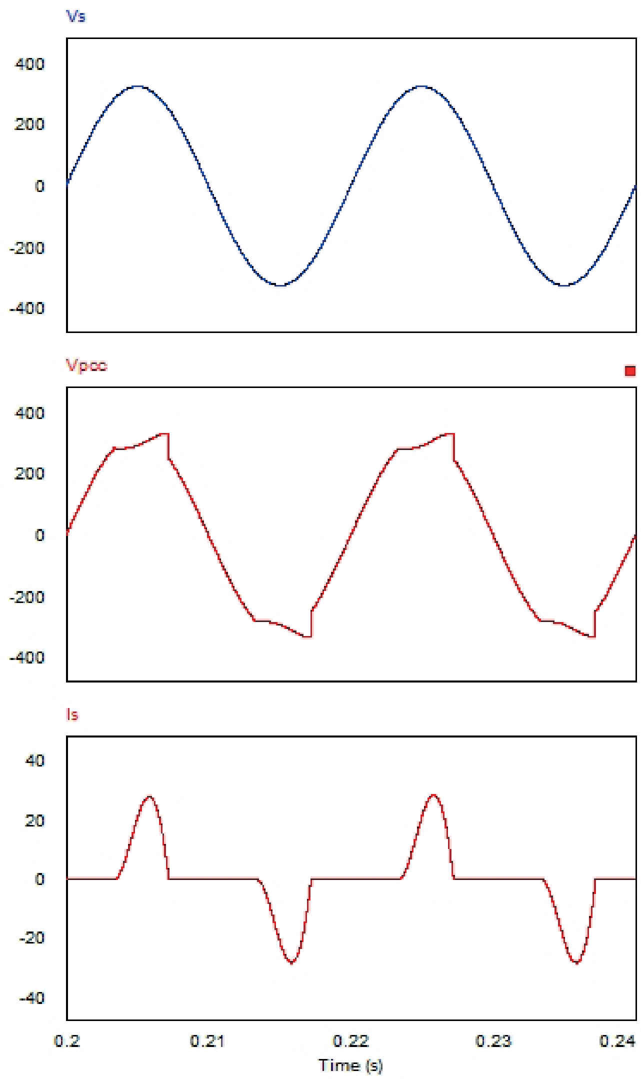

Fig.4 Waveforms for circuit represented in Fig.3. Voltage at PCC is affected by harmonic distortion (THD_v of around 9%).

Returning to the aim of this section, in defining what the harmonics are, we need to retreieve Fourier analysis for periodic signals: **any complex periodic signal can be obtained as the addition of different "pure" sinusoidal waves at different frequencies and amplitudes, multiple of the fundamental frequency. These multiples of the fundamental frequency are called harmonics.**

The mathematical expression of this definition, for a periodic signal I(t), is:

$$I(t) = I_0 + \sum_{n=1}^{N} [A_n \cdot \sin(n \cdot \omega t - \phi_n)]$$

In the decomposition into individual sinusoidal waveforms of above,the fundamental waveform will be the one for n=1, and the multiples of this are called harmonics of "n" order, for "n" ranging from 2 and above (it can be $N \rightarrow \infty$). I_0 represents the 0Hz component (DC, or mean value greater than 0). ϕ_n represents the phase displacement of each harmonic.

Assuming a signal with no DC component, we can write:

$$I(t) = I_1(t) + \sum_{n=2}^{N} I_n(t)$$

Being $I_1(t)$ the fundamental waveform of frequency f_1 ($\omega=2 \cdot \pi \cdot f_1$ in the original expression), and $I_n(t)$ the different harmonics at multiple frequencies $2 \cdot f_1$, $3 \cdot f_1$, …,$N \cdot f_1$.

For the case of distribution line and PCC circuit (Fig.3), the distorted signals Is(t) and $V_{PCC}(t)$ will have this similar composition, being $Is_1(t)$ and $VP_{CC1}(t)$ the 50Hz fundamentals, and $Is_n(t)$ and $V_{PCCn}(t)$ the harmonics of such signals.

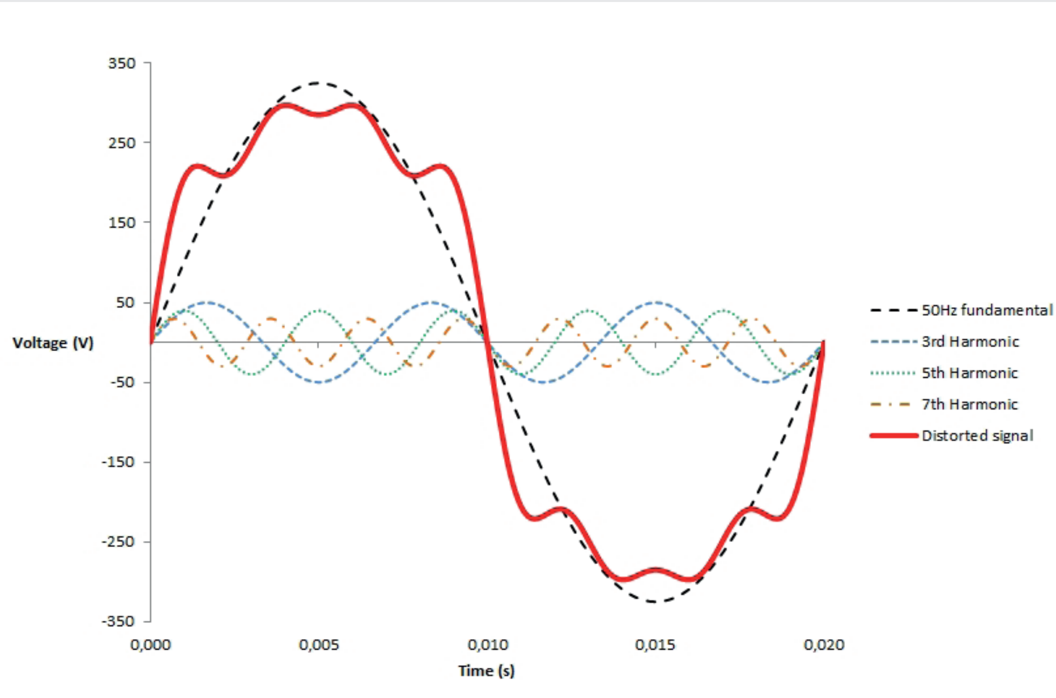

Fig.5 Decomposition example of a complex distorted signal, as addition of 50Hz fundamental and 3rd, 5th and 7th harmonics (150Hz, 250Hz, 350Hz respectively).

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Note:

- For symmetrical waveforms, only “odd” harmonics may appear (multiples 3rd, 5th, 7th, etc, of the fundamental frecuency), as in example of Fig.5.
- For asymmetrical waveforms, a part from “odd”, “even” multiples of the fundamental may appear (multiples 2nd, 4th, 6th, etc). Also DC components can appear in asymmetrical waveforms, which are represented as 0Hz signals.

3.- HARMONICS INDICATORS AND MEASUREMENTS

Individual harmonic percentage

The amplitude (or rms) value of a particular harmonic I_n can be expressed in relation to the fundamental I_1 , or to the rms value of the total current $I_{rms.}$

$$i_n(\%) = 100\frac{I_n}{I_1}; \quad i_n(\%) = 100\frac{I_n}{I_{rms}}$$

Harmonics spectrum

It is a graphical representation of previous concept, where decomposition of a distorted signal can be easily analyzed. Many Power Quality instruments can offer this representation. For the case of Fig.5., such representation will be as below.

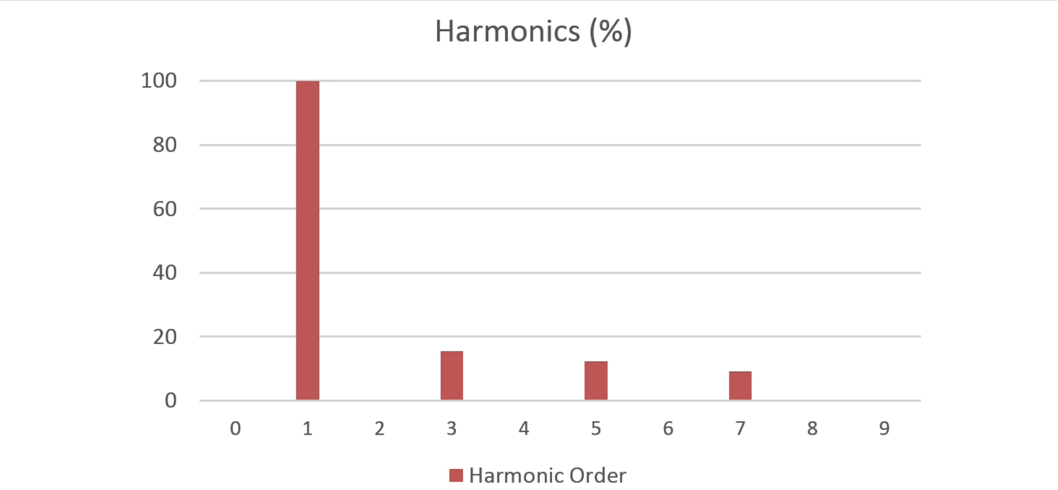


Fig.6 Harmonics spectrum for the sample signal represented in Fig.5 (100% at fundamental, 15% for 3rd harmonic, 12% for 5th, 9% for 7th).

Total Harmonic Distortion (THD)

It is defined as a ratio between the r.m.s. value of all the harmonics and the r.m.s. of the fundamental frequency.

- Current THD (THD_i) - according to the definition above, the Total Harmonic Distortion for current will be:

$$THD_i = \sqrt{\sum_{n=2}^{N}\left(\frac{I_n}{I_1}\right)^2}$$

… which is usually given as a percentage [%] (by multiplying previous result per 100).

Calculation Example for the distorted signal in Fig.5:

$$THD_i = \sqrt{(0{,}15)^2 + (0{,}12)^2 + (0.09)^2} = 0{,}2118 \rightarrow 21.18\%$$

If we want to express THD_i as function of total r.m.s. current, which is:

$$I_{rms} = \sqrt{\sum_{n=1}^{N} I_n^2}$$

… we can write:

$$THD_i = \sqrt{\left(\frac{I_{rms}}{I_1}\right)^2 - 1}; \qquad I_{rms} = I_1\sqrt{1 + THD_i^2}$$

- Voltage THD (THD_v) – similarly, the Total Harmonic Distortion of voltage is expressed as:

$$THD_v = \sqrt{\sum_{n=2}^{N} \left(\frac{U_n}{U_1}\right)^2}$$

Harmonics, Power Factor and Distortion Power

In the presence of harmonics the expressions of Active Power, Reactive Power and Apparent Power need to be defined carefully.

The Displacement Power Factor, cosφ, is due to the phase shift between voltage and current of the fundamental frequency f_1:

$$DPF = \cos\varphi = \frac{P_1}{S_1}$$

P_1 – Active Power of the fundamental

S_1 – Apparent Power of the fundamental.

But, in the presence of harmonics, previous equation is no longer valid as global Power Factor, since the power caused by the harmonics (voltage and current harmonics at different frequencies) need to be taken into account:

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

Where,

- P - Active Power, considering harmonics, and phase displacement φn between voltage and current for each:

$$P = \sum_{n=1}^{N} U_n \cdot I_n \cos\varphi_n$$

- S - Apparent Power, considering not only active (P) and reactive power (Q), but also distortion power (D), can be represented in a three-dimension axis, being the modulus:

$$S = \sqrt{P^2 + Q^2 + D^2}$$

In a system or installation where the most distorted signal is the current, and voltage is nearly sinusoidal at fundamental frequency, and retrieving I_{rms} as function of THD_i

$$P \approx P_1 \approx U_1 I_1 \cos\varphi_1 \ ; \quad I_{rms} = I_1 \sqrt{1 + THD_i^2}$$

… we can write a relationship between THD_i (current distortion) and Power Factor:

$$PF \approx \frac{\cos\varphi_1}{\sqrt{1 + THD_i^2}}$$

… that gives us an idea of the higher the THD_i the lower the PF (compared to DPF=cosφ), and when no harmonics are present, PF= cosφ.

4.- ADVERSE EFFECTS OF THE HARMONICS

Power Factor

As already advanced in previous section 3., harmonics increase the Distortion Power (D), i.e., increase the Apparent Power (S) required by the sytem, while the "effective" real power at the fundamental frequency f_1 (P1) does not benefit from that. This means higher current needs to be drawn from the PCC, so added wire section, and higher rating protection and distribution circuits (yielding to transformers derating).

Conductor losses

Obviously, added current draw a part from the needed at the fundamental I_1, i.e. $I_{rms} = I_1\sqrt{1+THD_i^2}$ yield to added cable losses at the conductors, $I_{rms}{}^2 \cdot R$. In Fig.7 we can graphically observe these two phenomena.

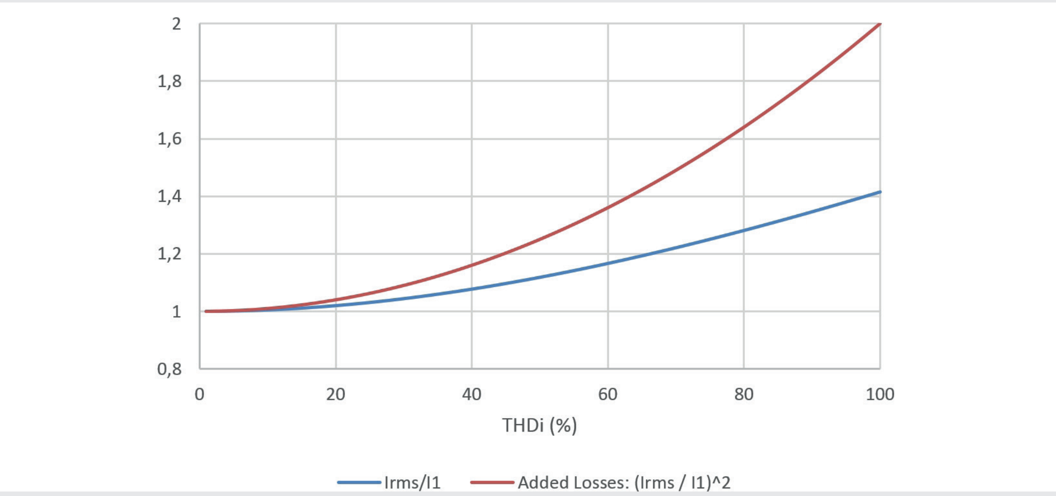


Fig.7 Increase of r.m.s. current due to harmonics (blue), and corresponding added losses for a given wire resistive losses R (red).

- Example of Fig.5 of THD_i=21.18%: we will get increased 2% current demand I_{rms}, and an extra 4% losses in conductors.
- High distorting non-linear load of THD_i=60% (for example VFD): the current draw will be 16% higher, and the conductor losses will be 36% higher than the fundamental I_1 would cause. This example will make rethink the installation (or apply corrective actions).

Skin Effect

Describes the magnetic property of confining alternating current towards the outer area of a conductor, the higher the frequency of that AC current. This "effective" reduced area (compared to real cross-sectional area of the conductor), will mean higher resistive losses directly proportional to frequency.

So, for higher order harmonics, the Skin Effect can cause added losses or need for oversizing of conductors.

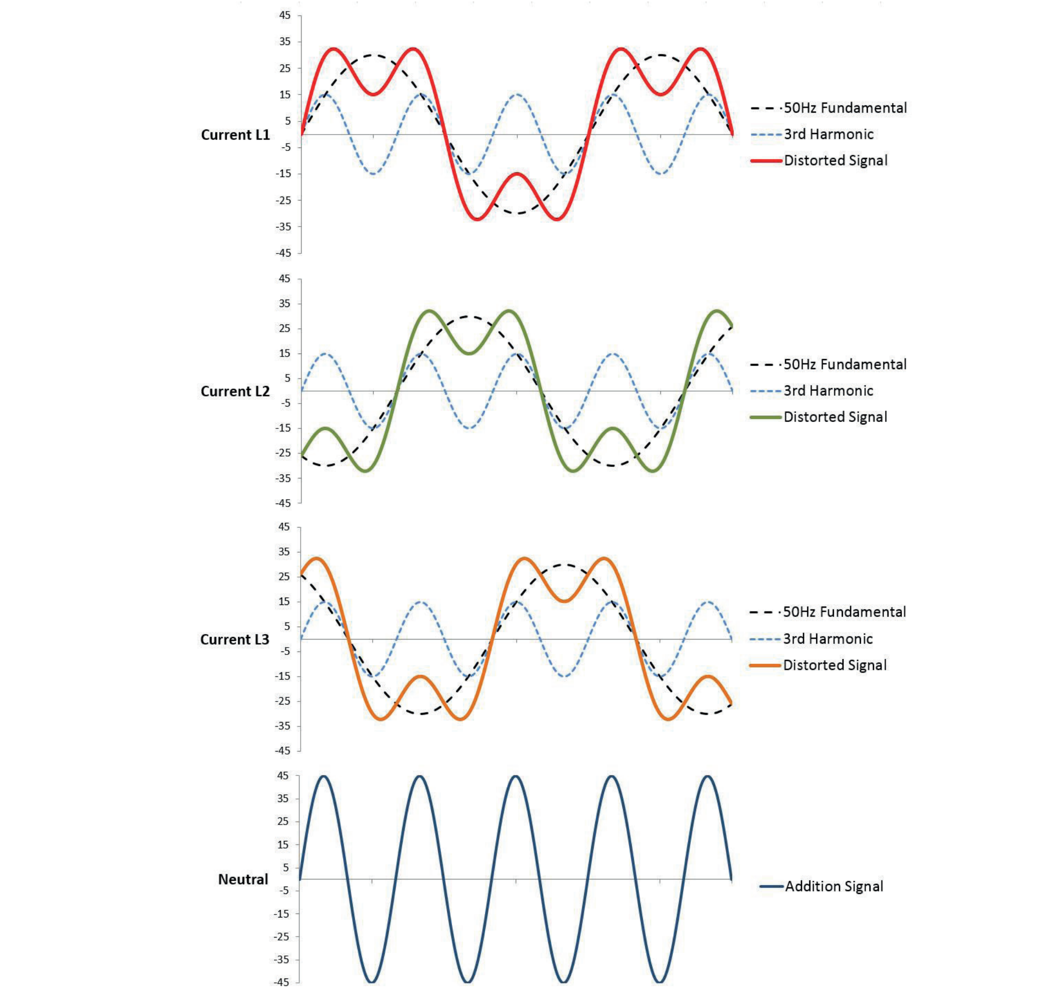


Fig.8 Effects of triplen harmonics addition into Neutral conductor, derived from three-phase distorted currents.

Triplen harmonics and neutral conductor

The harmonics in which a signal can be decomposed, as we saw before, are entire multiples of the fundamental. A part from the distinction between Odd (symmetrical) and Even (asymmetrical), they can be classified according its phase rotation with the fundamental:

- Positive sequence harmonics (4th, 7th, 10th,...): they do have the same phase rotation than the fundamental, and circulate between phases.
- Negative sequence harmonics (2nd, 5th, 8th,…): they have the opposite phase rotation than the fundamental, and circulate between phases.
- Zero sequence harmonics (3rd, 6th, 9th, …), also known as Triplen harmonics: these harmonics are on phase with the fundamental, and circulate between phases and neutral. What is the same, they do not cancel and add up directly in the Neutral conductor. For that reason, in the presence of significant components of such harmonics in a 3-phase installation, Neutral conductor will need to be oversized (compared to phase conductors) to carry out these extra-current. For example, in the presence of around 10 Arms 3rd order harmonic in each of the 3 phases, will mean an extra current of around 30 Arms in Neutral conductor (at 150Hz in a 50Hz installation), like in Fig.8. If no triplen harmonics were present, Neutral current will carry no current (no 50Hz component present in Fig.8).

Resonances

Especially in installations in presence of capacitors bank for power factor correction, in the case a load generating harmonics, such as a non-linear load, this combined circuit will contain following equivalent elements (see Fig. 9 as reference):

- L_s, equivalent inductance of the distribution installation (transformer, cables)
- C_{PF}, power factor capacitor bank.
- R_L, linear part of the load.
- V_s, Voltage source. In presence of non-linear load, voltatge harmonics may be present at PCC.

The equivalent complex impedance:

$$Z = \frac{jL_S\omega}{1 - L_S C_{PF}\omega^2}$$

… so for certain harmonic frequencies we can meet resonace frequencies when denominator is 0, i.e:

$$1 - L_S C_{PF}\omega^2 = 0 \rightarrow Resonance\ Frequency{:}\ f_r = \frac{1}{2\pi\sqrt{L_s C_{PF}}}$$

Motors and Generators

A part from being a possible cause of harmonics, generators themselves can be affected by other harmonic sources, in terms of efficiency losses, overheat, derating.

One of the main reasons is the high impedance of generators, that will transfer easily current harmonic distortion into voltage harmonic distortion (i.e., affecting other loads supplied from that source).

For the case of motors, we refer to them as loads of the electrical installation, more than voltage sources .

But the direct effects of harmonics both for motors and generators are mainly the same:

- Core losses (iron) increase with harmonics, caused by Eddy currents (loss increase with square of the frequency) and hysteresis.
- Copper losses, which are proportional both to THD_i ($I_{rms}^2 \cdot R$) and frequency (Skin Effect). Refer to previous description of both effects.
- Negative sequence harmonics, have the effect of force against torque rotation, so they can cause motor vibration, added heat, need for derating, etc.

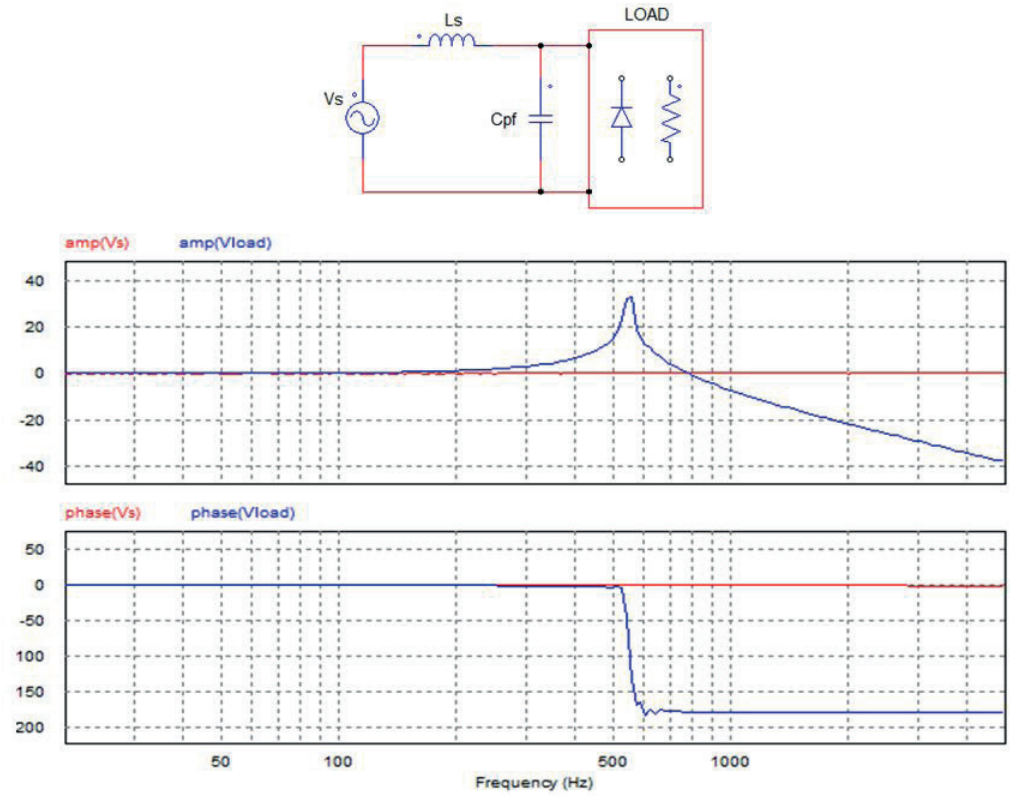


Fig.9 Resonance example circuit and its voltage Bode frequency diagram. Observe the resonance frequency at around 550Hz at the voltage applied to the load (Vload), corresponding to 11th harmonic of a 50Hz signal. Special care will need to be taken if there is a load generating this harmonic.

Transformers

The same effects of core losses and copper losses (windings) described for motors above, appear for the case of transformers.

Also triplen harmonics in the neutral conductor of a Delta-Wye distribuition transformer can dangerously overheat them.

There is also a potential risk of resonance between transformer inductance and supplied capacitive loads, at the harmonics frequencies.

Laminated transformers cores can also vibrate at certain harmonic frequencies, causing audible noise and overheat.

Transformer windings can be affected also by **Proximity Effect**: two close conductors carrying alternating current in the same direction, cause more magnetic flux in the area close to both conductors, causing the current distribution to the more distant areas of these two conductors. This effect of reduced “effective” area, similarly to Skin Effect, is proportional to frequency, so for higher order harmonics the AC resistance of winding conductors will be further increased, i.e., added losses.

For all the effects described above, transformers need to be derated in the presence of harmonics, or specially designed to handle harmonics, identifying them by a rating parameter called "K factor", function of the harmonics capability. The "k factor" transformers could be a more optimal solution (cost and weight), rather than derating (for example, can be designed with only oversizing neutral for triplen harmonics).

Circuit breakers and fuses

Since thermal-magnetic tripping mechanism in circuit breakers responds proportionally to rms current, a highly distorted current signal (I_{rms} much higher than the fundament I_1) can cause unwanted MCB's tripping, or need to oversize them. Also, circuit-breakers that are designed to interrupt current at zero current crossover, can meet in the case of very distorted current (with several zero crossovers within a fundament period) premature interruption of the circuit.

Similarly for fuses, the higher the rms current, the higher the heating effect of that current in the fuse, so the faster the fuse will act. Then, for the case of non-linear loads, it may be necessary to derate fuse selection. Moreover, higher order harmonics can cause skin-effect and proximity effect in the internal construction of the fuse, so additional unwanted overheat.

Flicker

Obviously, voltage harmonics and interharmonics supplying lighting circuits can cause fluctuations of light intensity, perceptible to the human eye. This phenomena may affect basically to incandescent and fluoresecent lamps.

Other effects of the harmonics

- Electronic equipment may be sensitive to the voltage distortion supplying it, due to higher voltage peaks, unexpected zero-crossing, affectation to protection circuits, etc.
- Digital circuits can be affected by misinterpretation of logical values in presence of harmonics.
- Reduced service life of components and equipment under continuous distorted supply voltage.
- Affectation to IT equipment such as memory losses, turn offs.
- UPS may need to handle with high distording loads, i.e., high current peaks may be over the range of the crest factor capacity of this UPS. In such case, the voltage distortion can even increase, if the inverter of the UPS is not capable enough.

5.- CORRECTIVE ACTIONS

While in this section we will make an overview of methods to reduce or cancel harmonics in installations or systems where harmonics already exist, by adding additional hardware, on next section 6. we will focus the problem from another point of view: avoid harmonic generation from the very beginning by means of active frond-ends.

Transformers

Transformers by themselves, or forming part of active front-ends (as we will see in next section for multi-pulse converters), can have the ability to cancel certain load harmonics. In fact, what they do is to discriminate certain harmonics to circulate upstream in the installation, rather than eliminate them.

- Delta-Star transformer: triplen harmonics in the secondary are not able to circulate in the primary of the distribution system, since they are confined in the Neutral of the star connection.
- Zig-zag transformer: can also be used to trap triplen harmonics, by placing them close to the distorting loads, and avoiding its propagation upstream.
- Delta-Star-Delta transformer: placing two similar non-linear loads on each of the transformer secondaries (one Delta, the other Star), will have the effect of cancel harmonics 5th and 7th in the Delta primary.

Reactors (AC line, or DC link)

Harmonics pollution of non-linear loads (for example a VFD, see Fig.10) can be minimized by placing series inductor (reactor), either to the AC line, to the DC link circuit, or both, with the ability of filtering upstream harmonic current, and also decoupling the line voltage distortion from that at the non-linear load side. Either of these added elements can limit also current peaks.

These reactors do have the drawback of added voltage drop, and what can be more important, they are designed for a certain working point (close to maximum current demand), away from which the THD_i minimization is not so effective (i.e, if THD_i on a VFD is reduced from more than 100% to 35% at full load, it may be quite possible to have THD_i higher than 50% below half load).

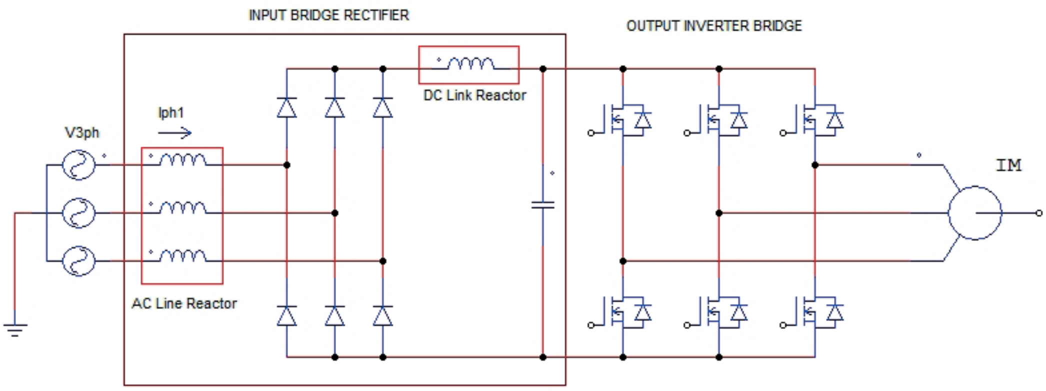


Fig.10 Complete circuit of a Variable Frecuency Drive for Motors. Observe location of AC line and DC link reactors.

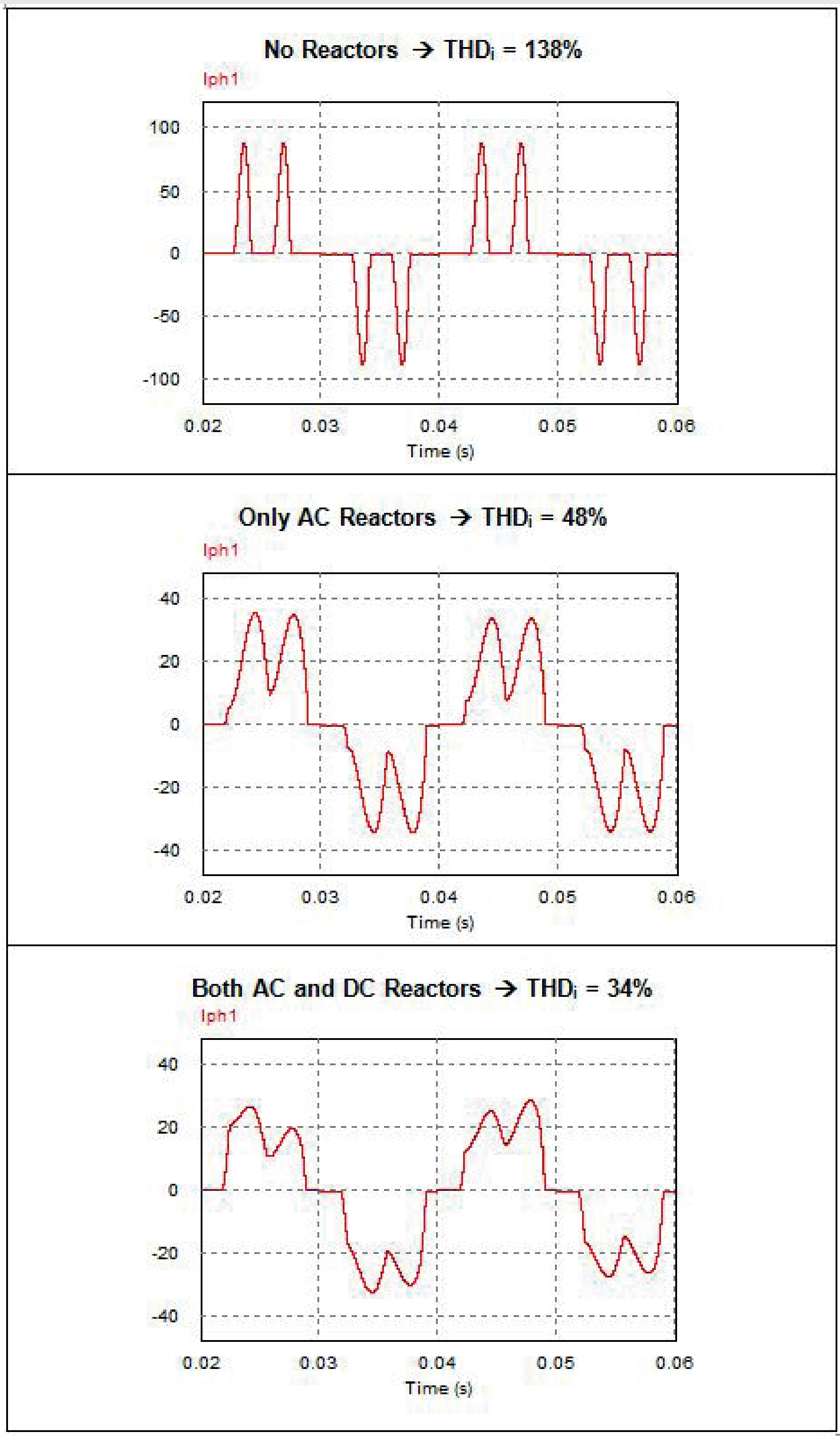
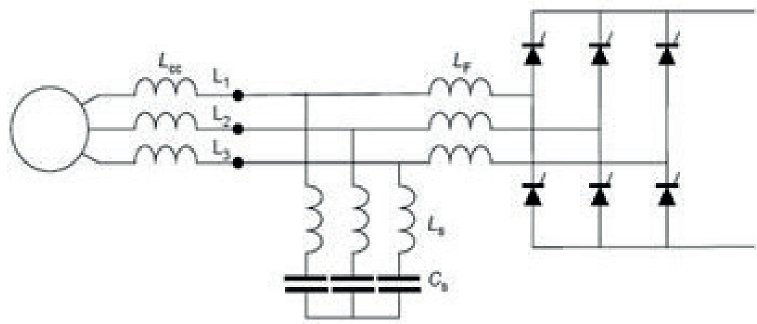


Fig.11 Different stages of THD_i minimization when placing reactors. Observe also current crest factor reduction.

Passive Harmonic Filters

Passive harmonic filters consist usually of resonant filters composed of Inductors and Capacitors (and sometimes damping resistors) tuned to cancel or trap a certain harmonic frequency, usually of low order (5^{th}, 7^{th}, 11^{th},..). Observe Fig.12: on a 6-pulse bridge rectifier input stage, generating high levels of 5^{th} harmonic, an Harmonic Passive Filter is added (inductors L_s, capacitors C_S), to minimize the current distortion at PCC. Such effect is obtained by tuning the resonance frequency of L_S-C_S at that 5^{th} harmonic. If other harmonic frequencies were needed to cancel in a same installation, additional passive filters (L,C) would need to be added, tuned at those different harmonics.



Resonance Frequency $\equiv 5^{th}$ *Harmonic*

$$f_r = \frac{1}{2\pi\sqrt{L_S C_S}}$$

Fig.12 Typical circuit for 5th harmonic reduction on a 6-pulse rectifier.

A part from being tuned only for a certain frequency harmonic, passive harmonic filters do have their harmonic mitigation functionality only at a certain working point (i.e., at a given load), which means that away from that point, usually lower load levels, the harmonic distortion is not minimized. Moreover, they do have the effect of reducing the power factor, if no additional circuit is added to compensate that (additional parallel inductors). Also, they introduce the possibility of resonance, as explained in section 4, and can be affected for each particular line or source impedance.

Even that, passive filters are an easy, robust and cost-effective solution for "closed" (repetitive working conditions) installations or systems.

Active Harmonic Filters

Active harmonic filters are power electronic equipments to cancel (or reduce) current harmonic pollution of an installation. The working principle consists in measuring the current harmonics of the load, and generate in real-time the same harmonics but in phase opposition, in such way that the addition of both currents seen from the electrical installation contains nearly no harmonics, but only the fundamental f_1 (see Fig.13) . This yields to THD_i lowering, at levels typically below 5%.

They also have the capability of reducing reactive power of the load, i.e., increasing power factor to nearly 1.

Due to its design and working principle, the distortion minimization is achieved for all load leves (within active filter capacity), and they are not affected by resonances nor line impedances.

So, compared to passive filters, they offer several advantages: can compensate several harmonics at the same time, correct also very high order harmonics, increase the power factor of the installation, offer more flexibility (not dependant on the load or source impedance).

On the other hand, they are a more complex and expensive equipment.

Note that the rating (kVA) of A.H.F. has to be chosen not for the total rating of the installation (total power demand of the load), but for the Distorting Power that has to be compensated (Example: an installation with a total power demand of S=60kVA, but with only 20kVA of them corresponding to distortion power D, would need an A.H.F. of around 25-30 kVA rated power).

For reasons given above, and taking into account the robust and low cost of Passive Filters in order to compensate strong presence of a given harmonic, the Hybrid Filters (combination of Passive and Active), could be a good choice in certain cases.

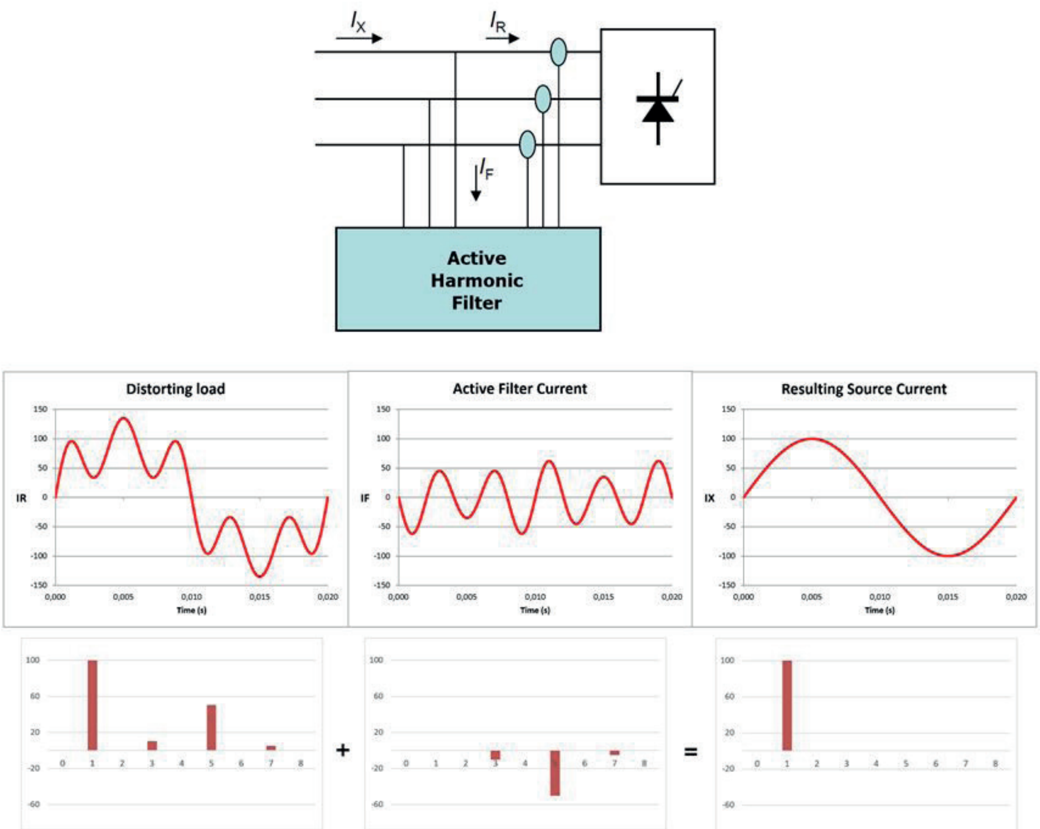


Fig.13 Active filter disposition, and its corrective behaviour over a non-linear load: the AHF generates the compensation current I_F, that once is added to the distorted current of the load I_R, composes a "clean" source current I_X with a a very low THD_i. Harmonic spectrum for each current is shown at the bottom, and the result of the equation $I_X=I_R+I_F$.

6.- LOW HARMONIC DISTORTION SYSTEMS

Clearly the best way to get rid off harmonics, is to not generate them. We will review in this section, some converters design that have in mind this idea from the very beginning, so no additional hardware is supposed to be added to them for harmonics reduction once they are installed and put on service.

Multi-pulse converter

The basic principle of multi-pulse converter is to transform the 3 input phases into 6, 9, or more phases, that will connect to 12-pulse, 18-pulse, or more pulse bridge rectifiers. The transformation to multiple of 3·n phases is achieved either by:

- Delta-Delta and Delta-Wye transformers.
- "Zig-zag" transformer.
- Auto transformer.

For the case of the more common 12-pulse converter, the 6 phases are obtained by 30º phase displacement of the original phases. Then, by means of two 3-phase diode (or SCR controlled) bridges connected in parallel, up to 12 current pulses at the AC mains are obtained, and THD_i minimized, since current harmonics of orders 5^{th} and 7^{th} are significantly reduced. THD_i slightly below 10% can be obtained with this disposition, but only at chosen load working point. Observing Fig.14, a 12-pulse rectifier loaded with similar load than the simple 3-phase bridge in Fig.10 is evaluated, and the THD_i improvement can be clearly seen (using reactors, from 34% to 14%).

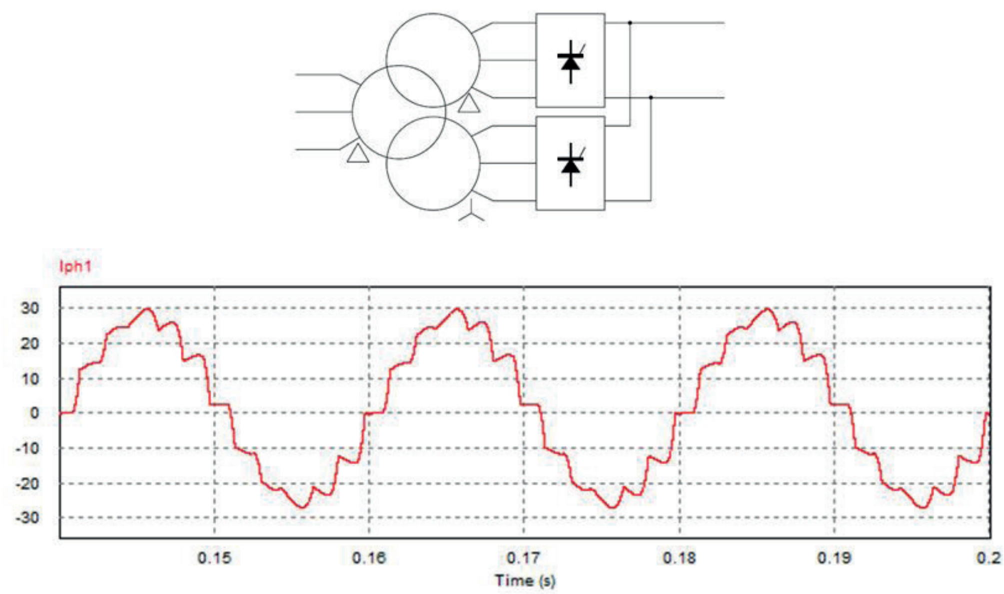


Fig.14. 12-pulse rectifier composed of Delta-Delta-Wye transformer and two 3-phase SCR bridges. The typical current waveform that can be obtained is shown below, with THD_i = 14%.

The basic principle of 18-pulse converter is similar, but now 9 phases need to be generated (transformer with three more windings) with 20º phase displacement, and three 3-phase bridges are going to be paralleled. The advantage is harmonic reduction extension to 5^{th}, 7^{th}, 11^{th} and 13^{th}, for a resulting THD_i even below 5% at nominal load.

No need to say are the disadvantages of these solutions: high weight and volume of transformers, efficiency losses, cost.

Sinusoidal Input Rectifier (Low Harmonic Drive)

To solve the typically high harmonics contents generation of VFD with diode/SCR input 6-pulse input bridge, the input stage here is substituted by an active front end consisting of a 3-phase IGBT (or MOSFET) half bridge, i.e., a symmetrical hardware architecture to the one that can be found for the inverter output bridge. The AC/DC rectification, then, is consigned (nowadays, by digital control) to absorve sinusoidal input current (or at least, an input current with the same shape than input voltage). The same than for the inverter output stage of VFD, the switching technique is served by AC PWM, in the magnitude order of kHz. A part of Input THD_i reduction, typ. <5% in the whole load range, other advantges of this active input rectifier can be power factor correction, current balancing, "four quadrant" operation (capable of energy regeneration, mains upstream, in case of motor braking).

The issues that this active front-ends have to deal with, compared to 6-pulse rectifiers, are the propagation of the switching frequency to the mains input voltage, in terms of some kHz ripple voltage, that in some input sensitive cases, like high-impedance lines, generators, transformers, will need some effort for minimization (T-filter at the input of the rectifier, for example, consisting of L-C-L).

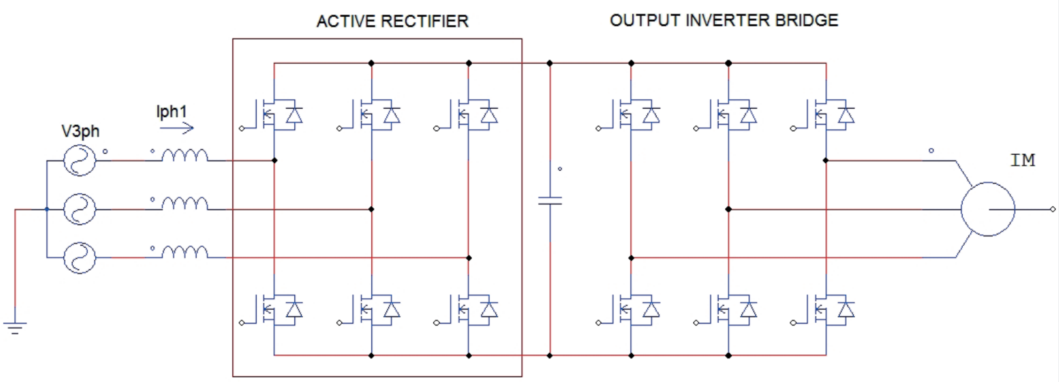


Fig.15 . Complete VFD hardware schemathic, with Active Input Rectifier.

As the principle of operation is the same than input rectifier of an UPS, more details are detailed in next section.

BENEFITS OF LOW DISTORTION UPS

As sources of Harmonic current injection, legacy and low-end UPS's have their negative influence. Even in designs where Input Power Factor is corrected (close to 1), these basic designs do not always take care of Input Current Harmonics minimization. For higher rating UPS's, electrotechnical solutions, such as passive filters and multi-pulse rectifiers, do their job at rated power, but do have the drawbacks before presented: no correction away from working point, efficiency losses, size and weight.

Other important issue, in terms of harmonics propagation to the whole installation, is the Output Voltage Distortion generated by the UPS. Basic UPS's and higher rating UPS with transformer can generate output THD_v easily higher than 10%, amplifying in some loads the current harmonics, with the adverse effects studied in section 4.

Nowadays, modern 3-phase UPS includes leading edge technology, in terms of powerful digital control and suitable topology, to undertake the higher performance challenges. In this section we will describe this kind of UPS, reporting high benefits in terms of low harmonics injection (lowering THD_i at the input, and THD_v at the output).

Fig.16. The Salicru CUBE3+ series, ranging from 10kVA to 200kVA.

Example of Digital Control for High-End UPS's:

- Digital Control implemented in Digital Signal Processor(s): in the range of >200MHz, floating-point.
- Advanced control techniques giving extremely good performance in terms of lowest Current Input Distortion and Output Voltage Distortion.
- As an example, the Adaptive Feed-forward Cancellation (AFC) is presented here:
  - » AFC technique, used in Inverter & PFC, consists of using parallel digital resonant cells in different frequencies where there are orders to follow or disturbances to refuse.
  - » Using this technique a perfect tracking of sine wave signals of the output voltage (in the inverter control loop) and the input current (in the PFC-Rectifier control loop) is done.
  - » Moreover, the resonators act as integrators, but for sinusoidal signal. That means that, similar than a PI for a DC steady-state error, resonators will achieve "0" error for AC signals (i.e, perfect sine wave).

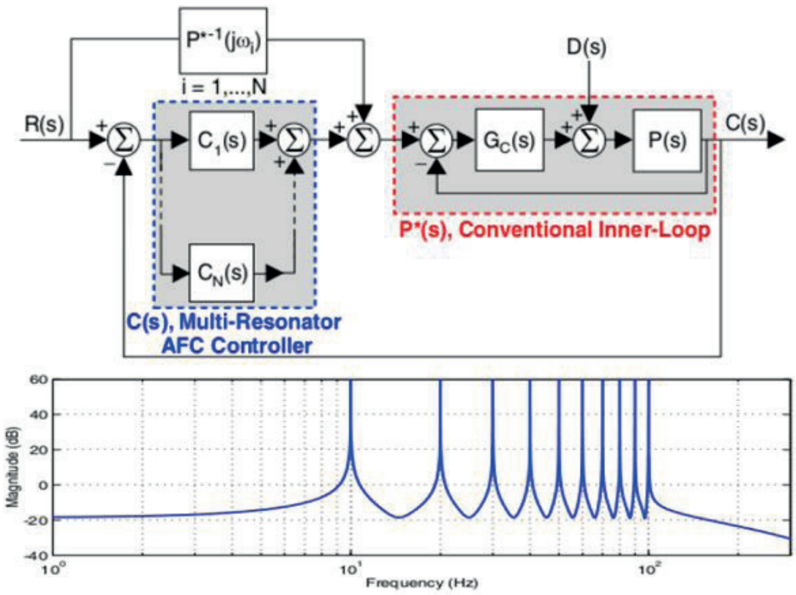


Fig.17. AFC Digital Control topology, and Bode gain diagram. The resonant cells (Ci(s)) are tunned to have high gain at harmonic frequencies. The aim is to refuse these harmonics as disturbances.

Electrical Performance of High-end UPS's:

- Low input current distortion for the whole load range. Some UPS achieve low THD_i in the load range >50%, but the challenge is to maintain low values at lower load levels. Desirable values:
  - » @ full load: THD_i <2%.
  - » @10%~50% load: THD_i <6%.

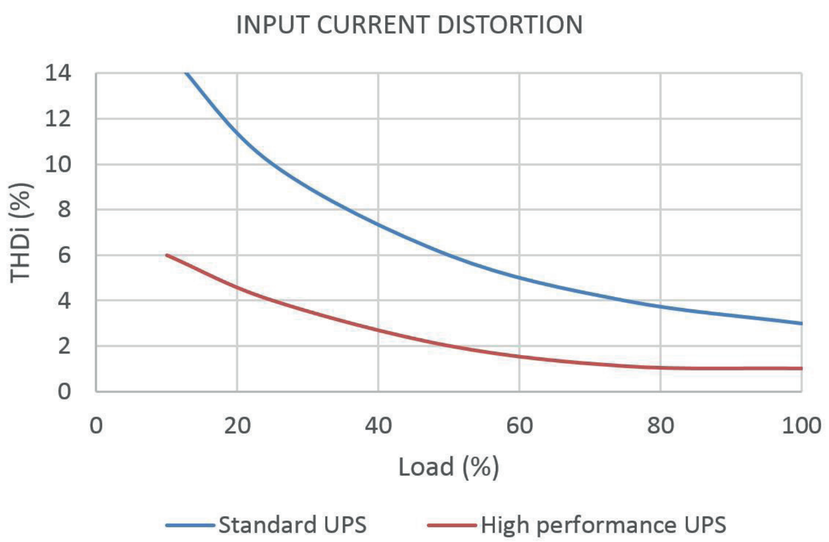


Fig.18. Input Current Distortion should be kept low even at low load (in red).

- Input current balancing, when completely unbalanced output load.
- Unity Input Power Factor for the whole load range:
  - » 1.0 @50%-100%.
  - » 0,99 starting at @10% load.

- Low Output Voltage Distortion:
  - » THD_v<1%, full resistive load.
  - » THD_v<2%, diode-bridge non-linear load (CF=3).
- "Four quadrant" topology is desirable: the UPS can manage regenerating loads, by injecting energy comming from the load to the mains.This feature is specially suitable for supplying elevators or industrial machines including motors (absorving energy when braking).
- Abovementioned features should be achieved with good global efficiency (above 93%) in double-conversion mode (VFI-SS-111, according to IEC-62040-3 classification).

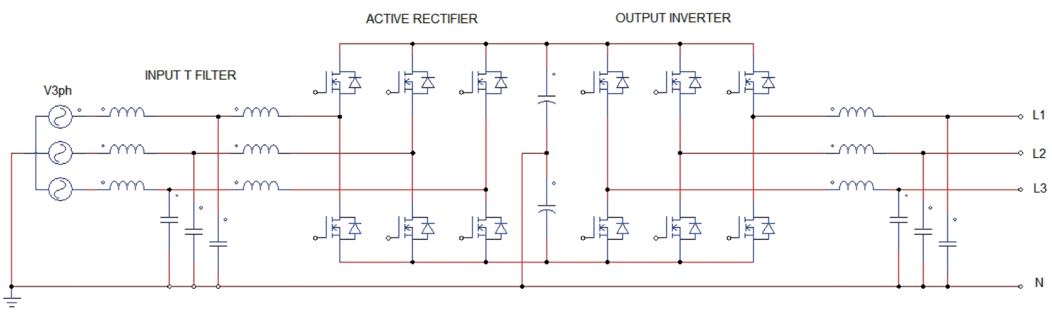


Fig.19. Sample schemathic for the active converters in a high-end modern UPS. "Back-to-back" topology, consisting of symmetrical Rectifier and Inverter, allows "Four Quadrant" functionality. Observe Input T Filter (L-C-L), for upwards voltage ripple filtering.

Modern UPS Real Examples of Operation:

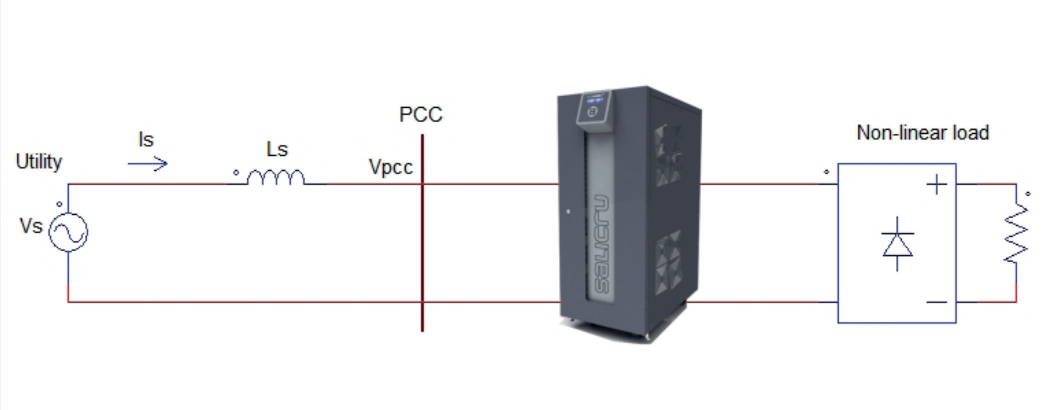


Fig.20. A Salicru Cube3+ UPS supplying a non-linear load, fed on a PCC with certain distribution impedance Ls.

1) Mains Harmonics Mitigation

On image below (Fig.21), observe Input Harmonics mitigation with a UPS: in this example, a UPS, fed at a PCC with certain impedance (see Fig.20 for reference), is supplying a non-linear load.

- On the left (corresponding to scope window zoom1, bottom left), Input Voltage (yellow) and Input Current (pink) with the UPS on Static Bypass, equivalent to load supplied directly by mains:
  - » Distortion affecting mains: THD_v =8%, THD_i =63%.

- On the right (scope window zoom2, bottom right), once the Active Rectifier of the UPS is running, the Input Current is transformed into sinusoisdal, and hence the voltage distortion at PCC is also corrected.
  - » Distortion correction for mains: THD_v =2%, THD_i =2%.

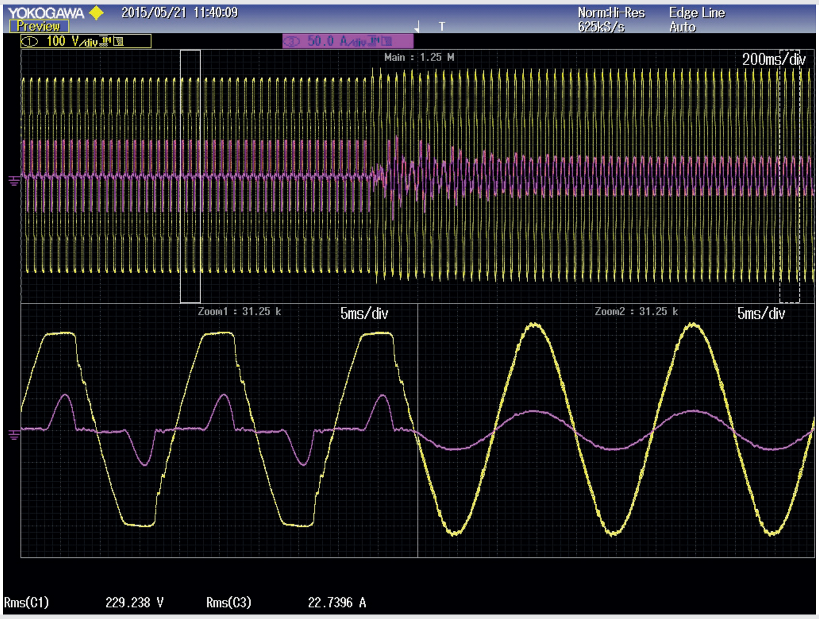


Fig.21. Observation of mains at PCC (CH1, yellow) and UPS input current (CH3, pink), during the unit start-up process.

2) Solution to voltage distortion affecting the loads

Taking as reference the same installation than on previous example (same mains distribution, UPS and non-linear load), now we will take a look at the voltage supplied by the UPS, i.e., voltage distributed to the loads (see Fig.22).

- On the left (corresponding to scope window zoom1, bottom left), Output Voltage and Current, with the UPS on Static Bypass, equivalent to load supplied directly by mains:
  - » Voltage Distortion affecting other loads: THD_v =8.5%.
  - » Crest factor (ratio between current peak value and rms value) for the non-linear load: CF=2.2.
- On the right (scope window zoom2, bottom right), once the Inverter of the UPS is running, the Voltage distortion supplying other loads is significantly corrected, which can avoid malfunction of other devices (described along this Whitepaper).
  Additionally, the Crest Factor demanded by the load is highly increased.
  - » Voltage Distortion correction for other loads: THD_v =1.8%.
  - » Crest factor for the non-linear load: CF=3.5.

Fig.22. Observation of UPS output waveforms, supplying a non-linear load, during the transfer process from static bypass to inverter. Output voltage distributed to loads on CH2 (green) and loads current demand on CH4 (blue).

3) Current balancing, Neutral harmonics cancellation, Power Factor correction

Let's consider now a star 3-phase non-linear load. On first image below (Fig.23), this 3-phase load directly supplied by mains (or UPS on bypass). One can observe distorted currents on each phase, and what is more, 3rd harmonic current addition on the neutral wire (see "Triplen Harmonics" on section 4.), of higher rms value than phase currents.

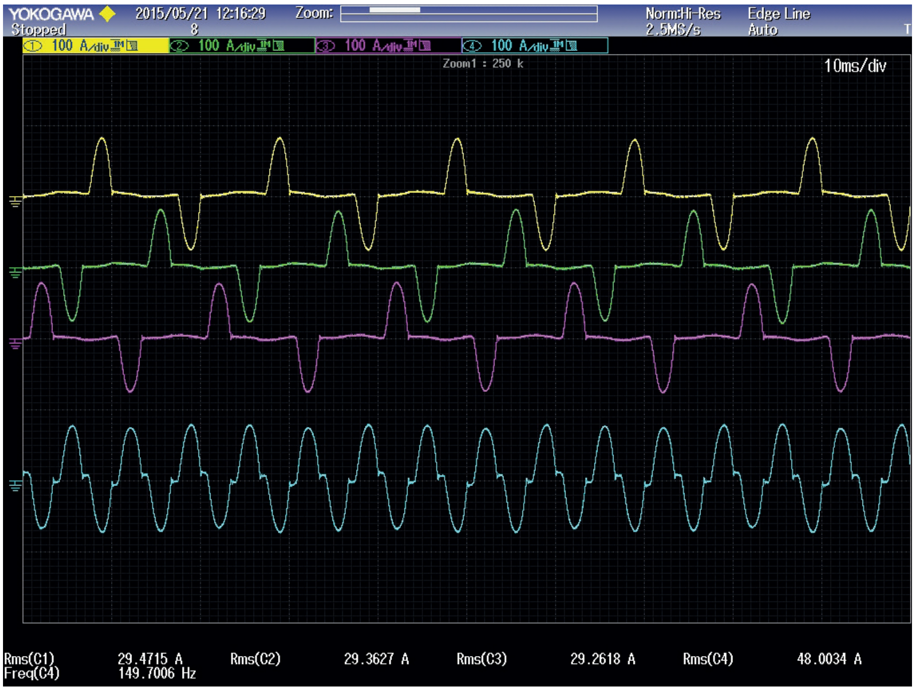


Fig.23. Current waveforms supplying a 3-phase non-linear load in star configuration (Neutral connected). CH1 to CH3 corresponding to phase currents, CH4 corresponds to Neutral current.

Now, let's observe current waveforms (Fig.24) when the UPS is put on normal mode (Rectifier and Inverter running), and supplying this same load. The objectives of neutral current cancellation, current harmonics mitigation, power factor correction, and current balancing are achieved.

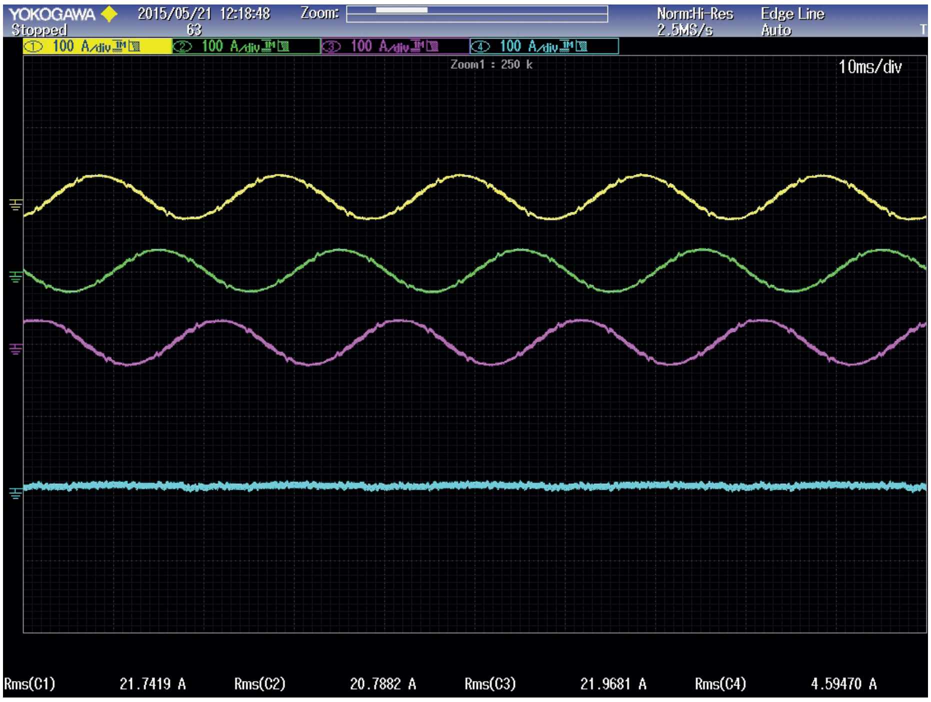


Fig.24. Mains current waveforms (UPS input), once the unit is supplying the star 3-phase non-linear, and it is working in double-conversion mode. CH1 to CH3 phase currents, CH4 Neutral current.

Comparision of both configurations in example 3 (fig. 23, 24):

- Loads would induce a 3rd harmonic component to Neutral (~48 Arms, 150Hz), nearly double rms value than the phases require, that the UPS will cancel. The neutral wire could need oversizing for the first case.
- Power Factor is corrected: loads have a low PF (around 0.6~0.7), that the UPS transforms into 1.0 seen for the mains. Observe rms phase current, that change from 29 Arms per phase to 21 Arms per phase with the UPS running. This could mean wiring and/or installation optimization.
- UPS achieves sinusoidal input current (THD_i ~1%), a part from current balancing between phases, even loads are unbalanced at the output.

ANNEX: HARMONICS STANDARDS

There are several regulatory standards covering harmonics, which could be grouped in three categories:

- Standards (or parts of them) defining the compatibility between distribution network and equipments.
- Standards (or part of them) specifying the quality the utility should meet, in terms of voltage distortion.
- Standards (or parts of them) defining harmonics emission limits for equipments.

We will review in this section, an example of each, probably the best well-known.

1) IEC 61000-2-2: Compatibility standard for products in public Low Voltage distribution network

Among other perturbations (overvoltages, flicker, voltage sags, etc), harmonics and interharmonics are covered in this standard, defining the levels a device should not exceed in order to not disturb the public network, but also under which levels of perturbations a device should operate normally .

In brief (in fact, individual harmonics levels are defined), for permanent or long term perturbations, the compatibility level is set at a maximum of Total Voltage Harmonic Distortion $THD_v = 8\%$.

For short term perturbations, the compatibility level is set at a maximum of $THD_v = 11\%$.

2) IEEE 519: Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

This document sets the quality of power that is to be provided at the point of common coupling. It is a joint approach between utilities and customers to limit harmonics generation, and recommend preventive actions. The objective for the utilities would be charge the customers in the electricity bill for harmonics generation.

For the utilities, the voltage harmonics limits are defined, which for LV distributions, and 2014 revision of IEEE-519, are:

	Individual harmonic limit (%)	Total harmonic distortion THDv (%)
Bus voltage at PCC ≤1.0 kV	5.0	8.0

For the end-customers, the current harmonics limits are defined, depending on the short-circuit capability of the distribuition network (ratio I_{sc}/I_L), which in fact is an indirect measure of distribution impedance at PCC. The limits are given for individual harmonics, and for Total Demand Distortion indicator (TDD), which is a relation similar to THD_i, but instead of relating the harmonics content to the current value of the fundamental I_1, the relation is made with the fundamental value at full load, taking an average of 15 or 30 mins. So TDD will only equal THD_i, at full load condition, in other cases TDD will always be an indicator of lower value than THD_i. Such limits, for distribuition networks <69kV are:

I_{sc}/I_L	Individual Harmonic limits (%), order ‘h’					TDD (%)
	h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h< 35	35 ≤ h	
<20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

3) IEC 61000-3-2: Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)
   IEC 61000-3-12: Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase

These 2 standards define current harmonics limits for the equipments, at the specified rated current each of them.

For the IEC 61000-3-2 (2014), input current ≤ 16A, the specification is only considered for public networks 220/380V, 230/400V, and 240/415V, for 50Hz or 60Hz. In this standard, limits depen on the equipment Classification (A, B, C, or D), and values are given in terms of absolute harmonic currents in Ampers (except for Class D). Harmonics up to 40th are specified, values up to 11th given below:

Harmonic order	Current limit				
	Class A	Class B	Class C	Class D	
h	[A]	[A]	Percentage of the input current at the fundamental frequency [%]	Permissible current per watt [mA/W]	Permissible harmonic current [A]
2	1.08	1.62	2	–	–
3	2.30	3.45	3*λ	3.4	2.30
4	0.43	0.64	–	–	–
5	1.14	1.71	10	1.9	1.14
6	0.30	0.45	–	–	–
7	0.77	1.15	7	1.0	0.77
8	0.23	0.34	–	–	–
9	0.40	0.60	5	0.5	0.40
10	0.18	0.27	–	–	–
11	0.33	0.49	3	0.35	0.33
...	...	...	...	...	...

λ, power factor of the circuit.

For the IEC 61000-3-12 (2012), input current > 16 A and ≤ 75 A, the rated voltages considered are up to 240V single-phase, up to 690V three-pase, frequency 50Hz or 60Hz. The tables of harmonic limits are specified as function of the parameter Short-circuit Relation ($R_{sce} = S_{sc} / S_{equ}$, relation between short-circuit power and equipment rated apparent power), and also as function of reference current Iref , average rms input current measured according specification given in this IEC 61000-3-12. A part from THD_i limit, a Partial Weighted Harmonic Distortion (PWHD) indicator is given, which is the ratio of a selected group of harmonics to the rms value of the fundamental (for this standard, the group considered is from 14th to 40th harmonics).

Current emission limits for non-balanced three-phase equipment.

R_{sce} min	Admissible individual harmonic current I_n/I_{ref} (%)						Admissible harmonic current distortion factors (%)	
	I_3	I_5	I_7	I_9	I_{11}	I_{13}	THD_i (I_{ref})	PWHD (I_{ref})
33	21.6	10.7	7.2	3.1	3.1	2	23	23
66	24	13	8	5	4	3	26	26
120	27	15	10	6	5	4	30	30
250	35	20	13	9	8	6	40	40
≥ 350	41	24	15	12	10	8	47	47

Current emission limits for balanced three-phase equipment (1).

R_{sce} min.	Admissible individual harmonic current I_n/I_{ref} (%)				R_{sce} min.	
	I_5	I_7	I_{11}	I_{13}	THD_i (I_{ref})	PWHD (I_{ref})
33	10.7	7.2	3.1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
≥ 350	40	25	15	10	48	46

(1) In certain conditions (specified in IEC 61000-3-12), such as quite lower emission of 5th and 7th harmonics (<5%), for balanced three-phase equipments, individual harmonic emissions of higher order harmonics are allowed to be higher.