

UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA

## UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Ingegneria Industriale DII  
Corso di Laurea Magistrale in Ingegneria dell'Energia Elettrica

### Analysis and evaluation of harmonic distortion in industrial networks caused by HVAC air-conditioning systems

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**Badge Number:** 1183484

**Academic Year 2019/2020**

## **Abstract**

The topic of this research, conducted at Mitsubishi Electric Hydronics and IT Cooling Systems S.p.A., in the form of an internship, is the development of a simulation program for the calculation of the harmonic distortion of conditioning machines. The environment in which the simulation program will be implemented is the Neplan<sup>®</sup> software.

In the first place, a study will be carried out on the machines in use and their electrical characteristics, focusing on the harmonic distortion that these generate when they are connected to the proprietary network. After that, once we receive data from the companies that collaborate and work with Mitsubishi, there will be a characterisation phase of the machines. The implementation will follow certain steps, starting from the simplest and linear cases (single machines) up to the complete representation of the environment on software. As already introduced, in order to develop these topics, the Neplan<sup>®</sup>, associated with the Neplan Programming Library (NPL) which guarantees the possibility of storing a large number of components necessary for the analysis, has been identified as a suitable tool to simulate the phenomena described above, to assess any benefits derived from this analysis and possible changes to be implemented to obtain a lower harmonic distortion.

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# Introduction

The increasing use of technologies containing elements of power electronics, both domestic and industrial, leads both manufacturers and users to find a way to ensure that this technology does not reveal a problem but is correctly used.

It is known that these devices are very sensitive therefore they require a very high quality and reliability of the electric power [5].

This problem is not new since the purpose of an electrical energy system has always been to produce and distribute electricity to the various users. The novelty, instead, consists in considering the aforementioned interaction in terms of the quality of the power supplied to the loads and the quality of the impact of the utilities on the power supply system. For this reason it seems logical to talk about interaction between supplier and customer as well as interaction between the electrical system and the load: on the one hand the consumer of electricity is no longer a simple load but a customer and, as such, requires the product "electric power" with a certain quality; on the other hand customer loads can have a negative impact on the electrical system and therefore are also subject to an assessment in terms of quality.

The expression *Power Quality* it is therefore the most suitable to represent the described problem. The growing interest in *Power Quality* is linked to a series of factors:

- In recent years, some types of loads have spread, such as electronic loads, which are very sensitive to disturbances;
- The massive use of electronic power converters has led to a considerable increase in electromagnetic disturbances (*EMI*) and the introduction of current harmonics in the systems that power them;
- Currently there are available sophisticated measurement devices and powerful data processors that have facilitated the detection of various disturbances;
- In advanced countries (countries of Europe and North America) electrical systems are characterized by consistent availability and reliability, for which quality is an achievable goal.

The term *Power Quality*, *PQ*, therefore refers to a wide variety of electromagnetic phenomena that characterize the voltage and / or current in a given point of an electrical system. In general, the given definition is:

*Any power supply problem manifested in voltage, current or frequency deviations that lead to malfunctioning or failure of equipment owned by utilities or end users, [5].*

The purpose of this thesis will therefore be to develop a simulation program for the calculation of the harmonic distortion of conditioning machines, taking into account data obtained from actual measurements carried out by the manufacturer and by the user. The work, carried out at Mitsubishi Electric, will give way to verify the impact on the network deriving from the use of

certain machines and to minimize the causes of losses and malfunctions.

MEHITS (*Mitsubishi Electric Hydronics & IT Cooling System spa*) is a reality in which product quality, technological development and its environmental impact are some of the key points on which work and research are based and being able to make a contribution to everything is really important for me, both for that which concerns the professional experience that I will gain from working closely with professionals in the electricity sector, but above all because, as an electrical engineer, my main interest is to be able to contribute to the reduction of the harmful impact that technologies have on the environment without however stop its development.

The first period of internship will be aimed at studying Mitsubishi machines, to understand their composition, to identify the devices that will give rise to current distortion, therefore voltage, and to evaluate the results obtained. Once this is done, the data necessary for the construction of the industrial network in Neplan will be investigated, this will require knowledge of a large number of elements and parameters. In this phase it will be necessary to deal with the suppliers to obtain the greatest number of parameters that can facilitate the analysis and with the technical installers to be able to obtain the data of the constituent elements of the network and then implement it. Once this phase is concluded, checks and simulations will be made initially starting from elementary situations, in which there is only one unit connected to the network, to then be able to evaluate the case with multiple machines connected and the interactions that exist between them. The final part of the experience in the company will be dedicated to the measurement on real machines in the test room and to the verification of the goodness of the results obtained by the simulations with the software. Alongside the use of Neplan, it was decided to create using a Spice software, a model with which you can easily reproduce a Mitsubishi inverter whose characteristic parameters are known, so that you can then obtain the distortion characteristics more simply and independently of a certain machine.

# Chapter 1

## Harmonics and Harmonic Distortion

### 1.1 Influence of loads on current absorption

#### 1.1.1 Linear loads

When we power an electrical equipment in alternating current, we know that the supply voltage is sinusoidal in shape and we would therefore expect that the current absorbed by our load is also sinusoidal.

This however is valid only for some types of loads, those defined as *linear* in which in fact the current absorbed is sinusoidal and has the same frequency as the voltage. The current can be shifted (angle  $\phi$ ) with respect to the voltage. Ohm's law establishes a linear relationship between voltage and current ( $V = RI$ ) with a constant coefficient, the load impedance.

Possible examples are normal light bulbs, heating devices, resistive loads, motors, transformers. The elements that have this characteristic are those formed by basic components such as Resistance, Capacity and Inductance.

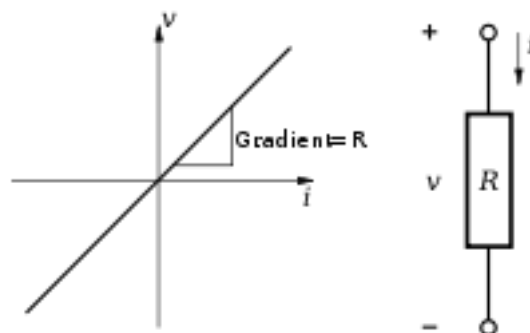


Figure 1.1: *V-I characteristic typical of a resistance*



### 1.1.2 Non Linear Loads

The main cause of the harmonics is the equipment with an electronics of power. To provide DC power to these components, the equipment is equipped with a switching power supply with a rectifier at the input that absorbs harmonic currents. Possible examples are computers, variable speed drives and so on. Other loads distort the current due to its operating principle, which generates harmonics. Possible examples are fluorescent lamps, discharge lamps, welding machines and devices with a magnetic core that can be saturated. All loads that distort the normal sinusoidal current generate harmonics and non-linear loads are defined, these devices contain, as already announced, elements of power electronics such as diodes and transistors.

The mains supply supplies 50/60 Hz of sinusoidal voltage to the loads. The waveform of the current supplied by the source in response to the load requirement depends on the type of load.

- The current absorbed by the load is periodic, but not sinusoidal: the waveform current is distorted by harmonic currents;
- The Ohm's law that defines the ratio between the total voltage and the current is no longer valid; here the relationship between current and voltage is not linear;
- The current absorbed by the equivalent load is the combination of:
  - a sinusoidal current called fundamental, at the frequency of 50 or 60 Hz;
  - harmonics, that is sinusoidal currents with an amplitude smaller than that of the fundamental, but a frequency which is a multiple of the fundamental and which defines the harmonic order.

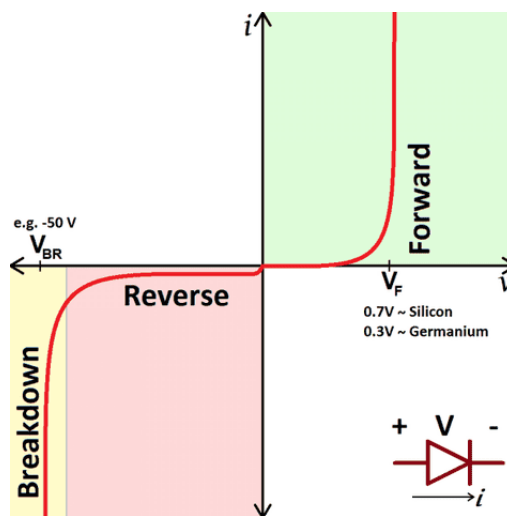


Figure 1.2:  $V$ - $I$  characteristic of a non-linear load, Diode

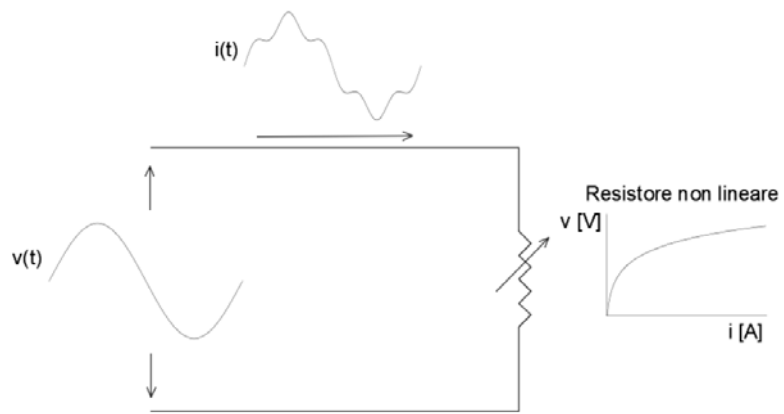


Figure 1.3: *Non-linear load and resulting distorted current*

## 1.2 Harmonics Characterization

### 1.2.1 Harmonic Order

Non-linear loads generate three types of harmonics:

- Harmonics  $h7 - h13 - \dots$  : positive sequence
- Harmonics  $h5 - h11 - \dots$  : negative sequence
- Harmonics  $h3 - h9 - \dots$  : homopolar (zero sequence)

There is no theoretical limit to the maximum order of a harmonic, but there is a practical one: in fact, the higher you go in order, the smaller the amplitude of the harmonic and therefore the contribution of high order harmonics becomes in fact negligible.

The sum of the fundamental and the harmonics determines a resulting periodic waveform, but not sinusoidal. If there were no harmonics, there would be only the fundamental, that is a perfect sine wave at 50 Hz.

It is important to note the jump of even-order harmonics since the distorted waves caused by non-linear devices, such as the PC, maintain the symmetry, (i.e. the positive half-period is equal and opposite to the negative one, as shown in the Fig.1.4) and for this type of waves, which are those with which we are dealing, all even harmonics are void.

The even order harmonics, if exceptionally present, are the sentinel of anomalies in the supply circuits, such as malfunctions of rectifiers or speed variators. The logical consequence of this is that the current absorbed by them is anything but sinusoidal, as can be seen in Fig.1.4, where a typical waveform affected by harmonics is observed, i.e. a periodic waveform, whose resulting can be thought of as the sum of many sinusoids at frequencies that are integer multiples of the frequency called fundamental or first order harmonic (50 Hz).

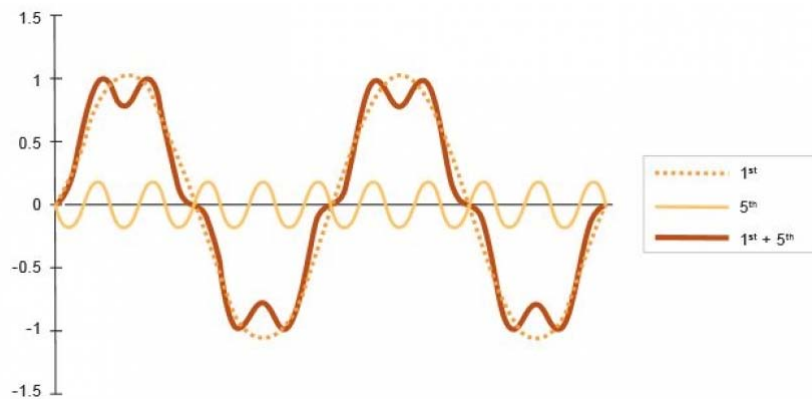


Figure 1.4: Breakdown of a periodic wave into the sum of the first and fifth harmonic

Essential in the study of harmonic distortion it is the property of periodic waves that allows to reconstruct the original wave by summing the sinusoidal components resulting from the Fourier series decomposition, the single components have a frequency that is an integer multiple of the fundamental frequency of the original distorted wave.

Thanks to this property the study of harmonic currents in the network can be carried out considering a single harmonic at a time, simplifying it considerably.

### 1.3 Fourier analysis for periodic waveforms

The following discussion is dealt with in Mohan's text on power electronics, [9].

In general, a non-sinusoidal wave  $f(t)$ , which is repeated with a pulsation  $\omega$ , can be expressed as follows:

$$f(t) = F_0 + \sum_{h=1}^{\infty} f_h(t) = \frac{1}{2}a_0 + \sum_{h=1}^{\infty} a_h \cos(h\omega t) + b_h \sin(h\omega t) \quad (1.1)$$

where  $F_0 = \frac{1}{2}a_0$  is the average value. In the eq.1.1

$$a_h = \frac{1}{\pi} \int_0^{2\pi} f(t) \cos(h\omega t) d(\omega t) \quad h = 0, \dots, \infty \quad (1.2)$$

and

$$b_h = \frac{1}{\pi} \int_0^{2\pi} f(t) \sin(h\omega t) d(\omega t) \quad h = 1, \dots, \infty \quad (1.3)$$

From 1.2 e 1.3, the average value is:

$$F_0 = \frac{1}{2} = \frac{1}{2\pi} \int_0^{2\pi} f(t) d(\omega t) = \frac{1}{T} \int_0^T f(t) d(t) \quad (1.4)$$

It can be seen that many alternating current waveforms have a zero mean value ( $F_0 = 0$ ).

Important to note that taking advantage of the symmetries of the waveforms simplifies the calculation of  $a_h$  e  $b_h$  in the eq. 1.2 e 1.3.

even	$f(-t) = f(t)$	$\Rightarrow b_k = 0, a_k = \frac{2}{\pi} \int_0^{\pi} f(t) \cos k\omega t d(\omega t)$
odd	$f(-t) = -f(t)$	$\Rightarrow a_k = 0, b_k = \frac{2}{\pi} \int_0^{\pi} f(t) \sin k\omega t d(\omega t)$
half-wave	$f(-t) = -f(t + \frac{\pi}{\omega}) = -f(t + \frac{T}{2})$	$\Rightarrow a_k = 0, b_k = 0$ per k even $a_k = \frac{2}{\pi} \int_0^{\pi} f(t) \cos k\omega t d(\omega t)$ $b_k = \frac{2}{\pi} \int_0^{\pi} f(t) \sin k\omega t d(\omega t)$
even & half-wave	$f(-t) = f(t) \wedge f(t) = -f(t + \frac{T}{2})$	$\Rightarrow b_k = 0 \forall k$ $a_k = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} f(\omega t) \cos k\omega t d(\omega t)$ per k odd $a_k = 0$ for even k
odd & half-wave	$f(-t) = -f(t) \wedge f(t) = -f(t + \frac{T}{2})$	$\Rightarrow a_k = 0 \forall k$ $b_k = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} f(\omega t) \sin k\omega t d(\omega t)$ for odd k $b_k = 0$ for even k

Table 1.1: Types of symmetry, required conditions and expressions of  $a_h$  e  $b_h$

### 1.4 Line Current Distortion

Figure 1.5 shows a line current  $i_s$  absorbed by an electronic power device that diverges from the sinusoidal shape. This current causes a distortion in the supply voltage, which is usually small.

Suppose that the supply voltage is perfectly sinusoidal and has a frequency equal to the fundamental frequency ( $\omega_1 = \omega$  e  $f_1 = f$ ), therefore we have:

$$v_s = \sqrt{2}V_s \sin(\omega_1 t) \quad (1.5)$$

The input current at steady state is the sum of its Fourier components, which can be expressed as:

$$i_s(t) = i_{s1}(t) + \sum_{h \neq 1} i_{sh}(t) \quad (1.6)$$

where  $i_{s1}$  it is the fundamental component to the network frequency  $f_1$  and  $i_{sh}$  is the component to the harmonic frequency  $h$ ,  $f_h = hf_1$ . The equation 1.6 can be expressed as:

$$i_s(t) = \sqrt{2}I_{s1} \sin(\omega_1 t - \phi_1) + \sum_{h \neq 1} \sqrt{2}I_{sh} \sin(\omega_h t - \phi_h) \quad (1.7)$$

where  $\phi_1$  is the phase angle between the input voltage  $v_s$ , supposed sinusoidal, and  $i_{s1}$ . We derive, by applying the definition, that the effective value  $I_s$  of the line current is:

$$I_s = \sqrt{I_{s1}^2 + \sum_{h \neq 1} I_{sh}^2} \quad (1.8)$$

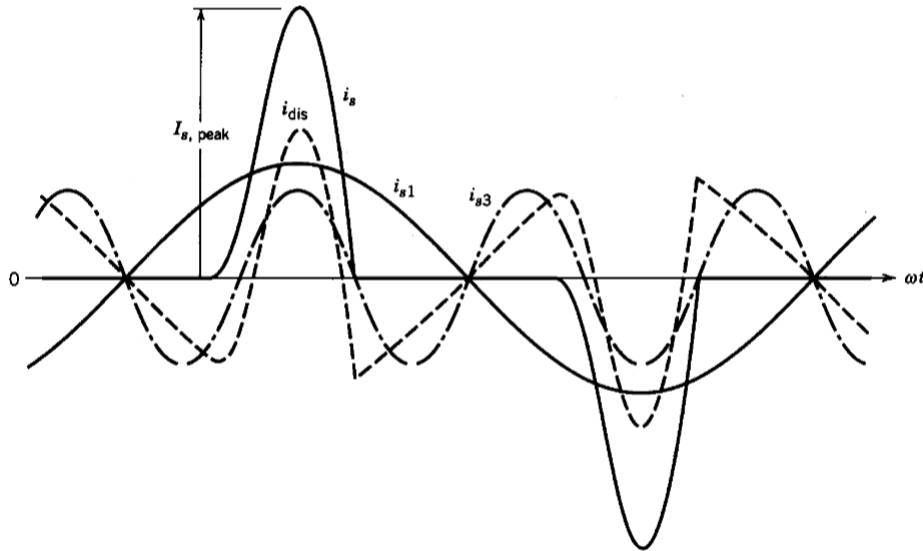


Figure 1.5: Line Current Distortion

#### 1.4.1 The essential indicators of harmonic distortion and measurement principles

The magnitude of the distortion in the voltage and current waveform is quantified with a index named *THD* (*Total Harmonic Distortion*)

From the equation 1.6 the current distortion component is:

$$i_{dis}(t) = i_s(t) - i_{s1}(t) = \sum_{h \neq 1} i_{sh}(t) \quad (1.9)$$

This current is shown in the Figure 1.5 and in terms of effective value it can be written as:

$$I_{dis} = \sqrt{I_s^2 - I_{s1}^2} = \sqrt{\sum_{h \neq 1} I_{sh}^2} \quad (1.10)$$

The current *THD* is defined as:

$$\begin{aligned} \%THD_i &= 100 \frac{I_{dis}}{I_{s1}} \\ &= 100 \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}} \\ &= 100 \sqrt{\sum_{h \neq 1} \left(\frac{I_{sh}}{I_{s1}}\right)^2} \end{aligned} \quad (1.11)$$

where the subscript *i* points out the *THD* for the current. For the voltage it is possible to compute an analogue *THD<sub>v</sub>* by entering the components of the voltage in the equation 1.11. In many applications it is important to understand the peak value, denoted with *I<sub>s,peak</sub>* in the Figure.1.5, of the current waveform *i<sub>s</sub>* so you can get the

$$CrestFactor = \frac{I_{s,peak}}{I_s} \quad (1.12)$$

For a sinusoidal signal the *Crest Factor* is equal to  $\sqrt{2}$ , whilst for a non-sinusoidal signal it can have more or less large values of  $\sqrt{2}$ . This factor is useful for drawing attention to much higher peak values than the effective value.

**Interpretation of the Crest Factor value:** a typical crest factor for the current absorbed by non-linear loads is much greater than  $\sqrt{2}$ . Its value can vary from 1.5 to 2 or even up to 5 in critical situations. A very high crest factor indicates that from time to time overcurrents occur. These overcurrents, detected by the protection devices, can cause disturbances.

#### 1.4.2 Power Factor and Displacement Power Factor

Starting from the basic definition of average power, in the Figure 1.5 one has:

$$P = \frac{1}{T_1} \int_0^{T_1} p(t) dt = \frac{1}{T_1} \int_0^{T_1} v_s(t) i_s(t) dt \quad (1.13)$$

Using the expressions of *v<sub>s</sub>* and *i<sub>s</sub>* respectively from the equations 1.5 e 1.6 we get:

$$P = V_s I_{s1} \cos \phi_1 \quad (1.14)$$

Note that the current components with frequencies beyond the fundamental do not contribute to the absorption of the average power of the sinusoidal voltage source  $v_s$ . The *Power Factor PF*, is:

$$\begin{aligned} PF &= \frac{P}{S} \\ &= \frac{V_s I_{s1} \cos \phi_1}{V_s I_s} \\ &= \frac{I_{s1}}{I_s} \cos \phi_1 \end{aligned} \quad (1.15)$$

The *Displacement Power Factor DPF* that corresponds to the *Power Factor* in a linear circuit with sinusoidal voltages and currents, is defined as the cosine of the angle  $\phi_1$ :

$$DPF = \cos \phi_1 \quad (1.16)$$

Therefore the PF for a *non sinusoidal* current is:

$$PF = \frac{I_{s1}}{I_s} DPF \quad (1.17)$$

Referring to the equations 1.11 and 1.17, the power factor can be expressed as:

$$PF = \frac{1}{\sqrt{1 + THD_i^2}} DPF \quad (1.18)$$

In the case of non-sinusoidal system the relationship between powers  $S, P$  and  $Q$ ,  $S = \sqrt{P^2 + Q^2}$ , is no longer valid because a new power  $D$  named *Distorting Power* come up, whose measurement unit is  $[VA]$ , which represents the contribution given by the product between the effective values of voltage and current at frequencies other than the fundamental and which therefore has no influence on the active power, [6].

Consequently, the relationship between powers becomes:

$$S = \sqrt{P^2 + Q^2 + D^2} \quad (1.19)$$

## Chapter 2

# Harmonics generators

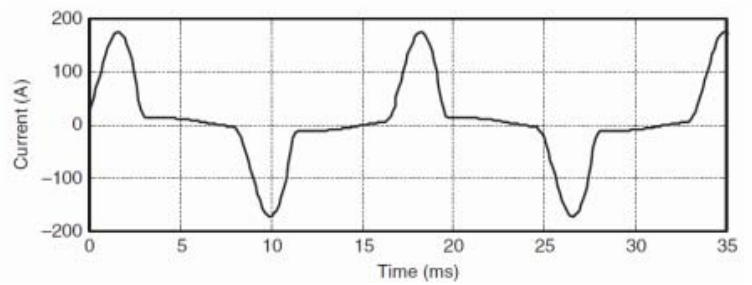
Commercial structures such as office complexes, department stores, hospitals and data centers are characterized by a large number of high efficiency fluorescent lamps operating via electronic ballasts, variable speed drives for heating, ventilation and air conditioning systems, lift units and equipment. electronic (sensitive) powered by a single-phase circuit. Commercial loads are therefore characterized by a high number of small "harmonic generator" loads. Depending on the diversity of load types, these small harmonic currents can add up (if they are in phase) or cancel each other out. The voltage distortion levels depend both on the impedances of the circuit and on the total harmonic distortion of current. As long as the power factor correction capacitors are not installed in the commercial structure, the impedance of the circuit is dominated by the impedances of the conductors and that of the transformers. The voltage distortion can therefore be estimated simply by multiplying the current by the impedance at the frequency considered. In industrial applications, the main types of equipment that generate harmonics are:

- Static converters;
- Arc furnaces;
- Lighting;
- Saturated reactors;
- Other equipment, such as rotating machines that generate harmonics.

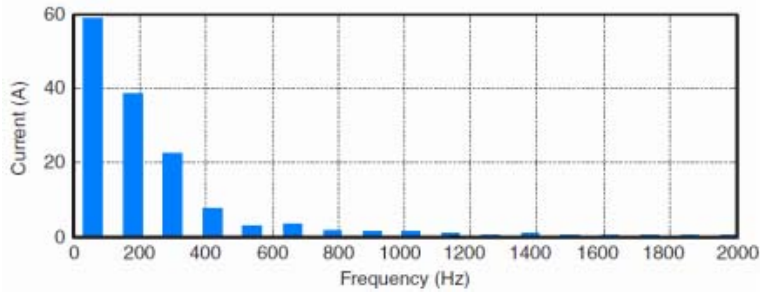
### 2.1 Single phase power supplies

Electronic power converters, with their "property" of producing harmonic currents, are currently the most important non-linear loads in the electrical system. This is "aggravated" if you think that power electronics is becoming more and more important year after year, as it is found in devices such as motor speed control drives, electronic ballasts and many high functioning equipment thanks to inverters and rectifiers. There are typically two types of single phase power supplies. The older one uses a voltage regulation on the alternating side, for example through transformers, to have a voltage control on the dc-bus. The advantage in this case lies in the fact that the transformer inductance reduces the harmonic content by smoothing the input current waveform.





(a)



(b)

Figure 2.2: Example of current and harmonic spectrum

The most recent one uses the switching converters which through a dc-dc conversion carry out a regulation directly on the direct current side with relatively small and light components, moreover the diode bridge is directly connected to the a.c. with the consequent elimination of the bulky and expensive transformer. The big disadvantage of this second technique is however linked to the fact that now the direct voltage is regulated approximately on the capacitor. This current is then reconverted to AC through a switch in high frequency of the switches and then rectified again. The main advantages related to power through switching are lightness, compact dimensions, efficient operation and, above all, the lack of the transformer. With reference to the circuit in figure 2.1, since there is no levelling inductance on the AC side, the input current to the power supply is supplied with very high pulses short.

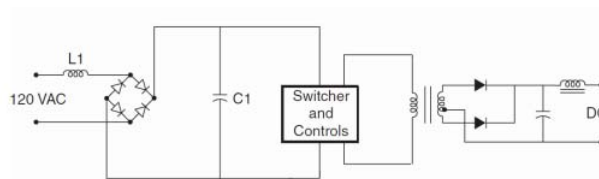


Figure 2.1: Power supply through switch

Fig.2.2 shows a typical waveform and the relative harmonic spectrum provided by a typical power supply circuit, with switching, of different electronic equipment.

An important feature of switching power supplies is the presence of a high third harmonic content in the current. Since third harmonic components add up to the neutral of a three phase system (Fig. 2.3), the continuous and growing demand for switching power supplies is bringing considerable concern for overloading the neutral conductor, especially in those long-standing buildings where the neutral may have been undersized. Furthermore, the situation of the transformer is aggravated due to its overheating due to a combination of harmonic current content, leakage flux, and high neutral currents.

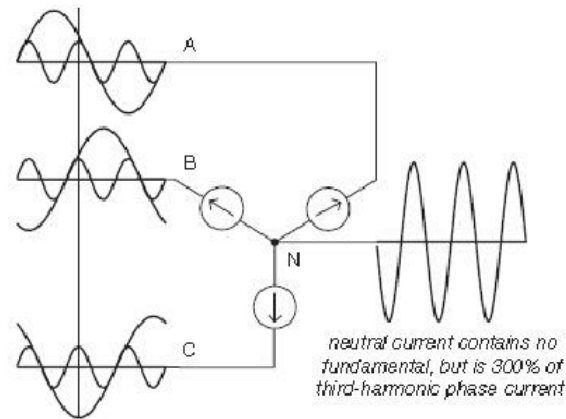


Figure 2.3: Behavior of the third harmonic in a three phase system with neutral

## 2.2 Static converters in three-phase networks

It has been seen that modern industrial plants are characterized by a widespread presence of non-linear loads that can inject harmonic currents into the power system, causing voltage distortion, a problem which is aggravated by the fact that normally this type of loads has a factor of relatively low power. As we will see later, the users use to install capacitor banks to improve the power factor to avoid incurring fines. However, the installation of power factor correction capacitors is potentially able to increase the harmonic currents due to non-linear loads thus meeting possible resonance conditions. Since it is customary to install capacitors on the lower voltage side, resonant currents can also lead to overheating of motors and transformers as well as an obvious malfunction of electronic equipment. In general, non-linear industrial loads can be divided into three categories which we will deal with separately. One is precisely that of three-phase converters, then there is that of arc furnaces and finally that of saturable devices. The rectifier bridges and, more generally, the static converters made up of diodes and thyristors, generate harmonics but unlike the single-phase converters addressed before, **have the great advantage of not generating third harmonic currents.**

For example, to provide a perfectly direct current, a Graetz bridge requires a rectangular ac current when the load is highly inductive,

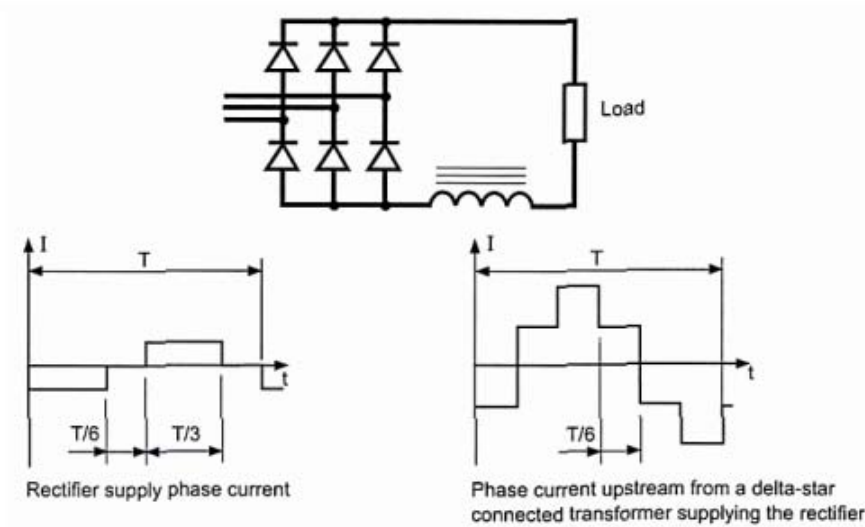


Figure 2.4: Alternating current upstream of a Graetz bridge which feeds a strongly inductive load

or "pointed" if the bridge is followed by a levelling capacitor.

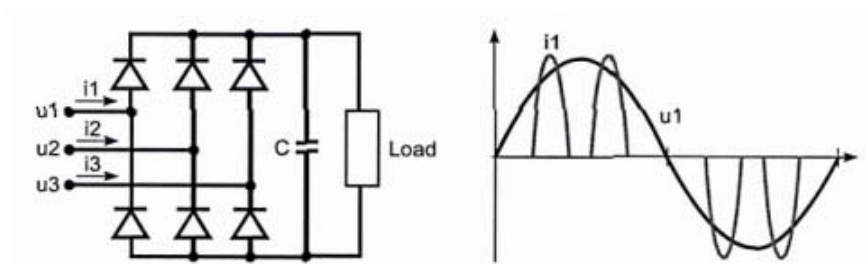


Figure 2.5: Alternating current upstream of a Graetz bridge which feeds a load preceded by a capacitor

Despite their different waveforms, the currents upstream and downstream of the star-delta transformer have the same characteristic harmonic components. The harmonic components characteristic of the current pulses supplied by the rectifier have a harmonic order  $h = np \pm 1$ , where:

- $n = 1, 2, 3, 4, 5, \dots$
- $p$  is the number of branches of the rectifier, for example:
  - graetz bridge  $\rightarrow p = 6$ ;
  - 6-pulse bridge  $\rightarrow p = 6$ ;
  - 12-pulse bridge  $\rightarrow p = 12$ ;

By applying the formula, bridges with  $p = 6$  mentioned above, generate harmonics of order 5, 7, 11, 13, 17, 19, etc., while bridges with  $p = 12$  generate harmonics of order 11, 13, 23, 25, etc. The characteristic harmonics are all of odd order and their currents, when approaching the ideal case of fig. 2.4, generally respect the amplitude ratio  $I_h = \frac{I_1}{h}$  where  $I_1$  is the amplitude of the

fundamental. This means that the most important harmonics, with greater amplitude, will be  $5^\circ$  and  $7^\circ$  but that we have seen can be eliminated thanks to the use of a 12-pulse bridge. In fact, the current spectrum is slightly different. New even and odd harmonics (referring to non-characteristic harmonics) of small amplitude are created and the amplitudes of the characteristic harmonics is modified by the following factors:

- asymmetry;
- inaccuracies in the firing times of the thyristor;
- switching times;
- imperfect filtering.

For thyristor bridges, harmonic displacement can also be observed as a function of the phase angle of the thyristor. Even a mixed diode-thyristor bridge generates harmonics and since the  $2^\circ$  harmonic can produce serious damage to disturbances that are difficult to eliminate, they are used only at low voltage levels. Other power converters such as cycle converters, dimmers, etc., are characterized by richer and more variable spectra than the rectifier bridges. Many times these converters are replaced by converters using the PWM technique which operate with very high switching frequencies (about 20kHz) and are generally designed to generate low harmonic levels.

### 2.2.1 DC units

For direct current devices and drives, the rectification of the mains current is essential. Motors operating in DC we know to have a much wider operating speed range than the corresponding AC powered motors. In addition to having a higher starting torque, however, they are characterized by a high maintenance and purchase cost which goes to a great disadvantage of these drives since the cost of the conversion devices has been gradually decreasing over the years. Most of the DC drives they use six-pulse rectifiers of the type of Fig. 2.6 but large units can also use 12-pulse rectifiers. This reduces the current in the thyristors and reduces some of the larger harmonics of the ac current: the two most important harmonics are the  $5^\circ$  and the  $7^\circ$  which with a twelve-pulse converter turns can think of reducing up to 90%. The two disadvantages of the twelve-pulse converter are the greater number and therefore cost of the electronic components and the presence of a transformer which is usually made necessary.

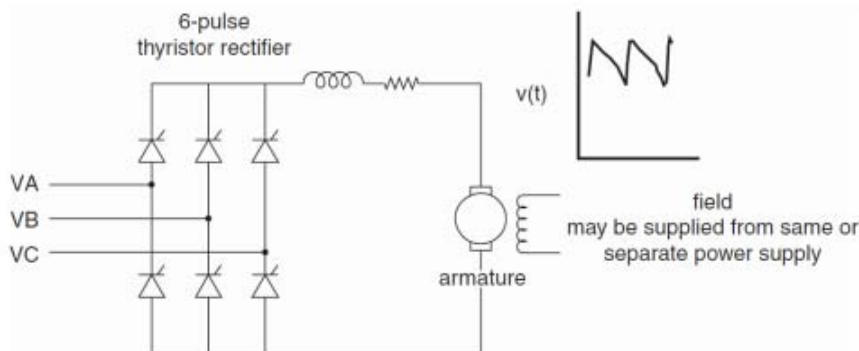


Figure 2.6: Six-pulse converter

## 2.2.2 AC units

In AC drives, the converter output is inverted to produce an alternating voltage for the variable frequency motor. Inverters are usually divided into inverters of voltage generators (VSI) or inverters of current generators (CSI). The first requires a continuous input voltage with a low ripple, which is obtained thanks to an LC filter; vice versa, for a CSI inverter you need a direct current input which is obtained by inserting an inductor in series. Usually the motors used in these cases are squirrel-cage asynchronous motors that have a relatively low cost, are robust and require little maintenance; synchronous motors are used instead where speed control is more critical. An example of a power supply diagram of an AC motor through a converter is shown in Fig. 2.7

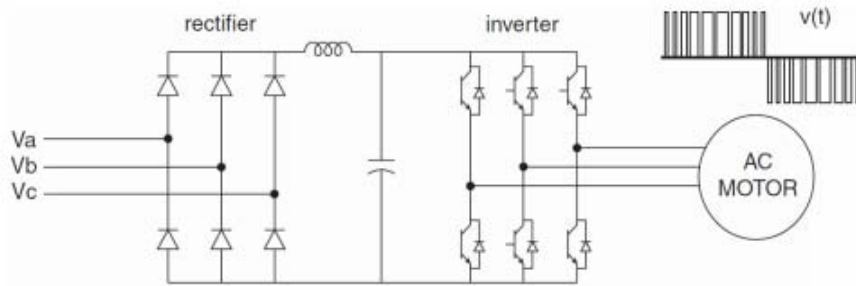


Figure 2.7: PWM control for a.c. motor

It is very important to note that the harmonic distortion in the speed control drives is not constant. In fact, the waveforms change significantly as the speed and torque vary. As shown in Fig. 2.8, the value of the harmonics changes with the variation of the speed.

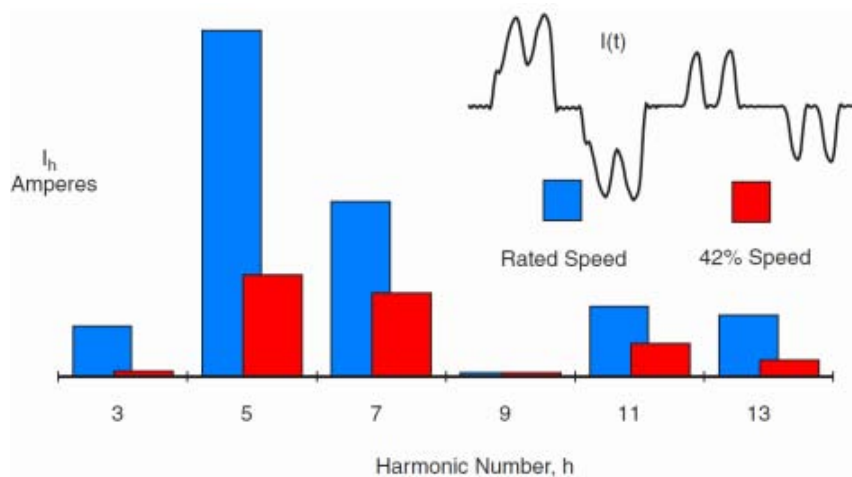


Figure 2.8: Effects of PWM modulation for speed variation on harmonic currents

## Chapter 3

# The System Response

In a power system affected by a noise, the response of the system is as important as the source of the noise itself. In fact, power systems tolerate currents injected fairly well by loads that produce harmonics unless there is some unfavorable interaction with the impedance of the system. The identification of the source of the disturbance is therefore only half of the work to be done in a harmonic analysis. There are 3 primary variables that influence the response of a system, i.e., the impedance of the system, the presence of capacitor banks and the set of resistive loads of the system.

### 3.1 The impedance of the system

At industrial frequency, power systems are mainly inductive and the equivalent impedance is usually called short circuit reactance. Capacitive effects are generally overlooked in power distribution and industrial systems. One of the most frequently used quantities in the harmonic analysis of an electrical system is the short circuit impedance at the point of connection of the capacitor bank with the network. If this is not directly available, it can be calculated from the results of a short-circuit study that gives me either the power or the short-circuit current, from which we obtain:

$$Z_{cc} = R_{cc} + jX_{cc} = \frac{kV^2}{MVA_{cc}} = \frac{kV1000}{\sqrt{3}I_{cc}} \quad (3.1)$$

where by  $kV$  we mean the concatenated voltage and by  $MVA_{cc}$  we mean the three-phase short-circuit power.  $Z_{cc}$  is a phasor quantity, formed by resistance and reactance; the inductive part of the impedance varies linearly with the frequency therefore the reactance to the  $h$ -th harmonic can then be determined from the reactance  $X_1$  to the fundamental, through:

$$X_h = hX_1 \quad (3.2)$$

An impedance trend as a function of frequency for an inductive system can be assessed from Fig. 3.1. In this simple model, capacities are neglected, which significantly worsen harmonic analysis.

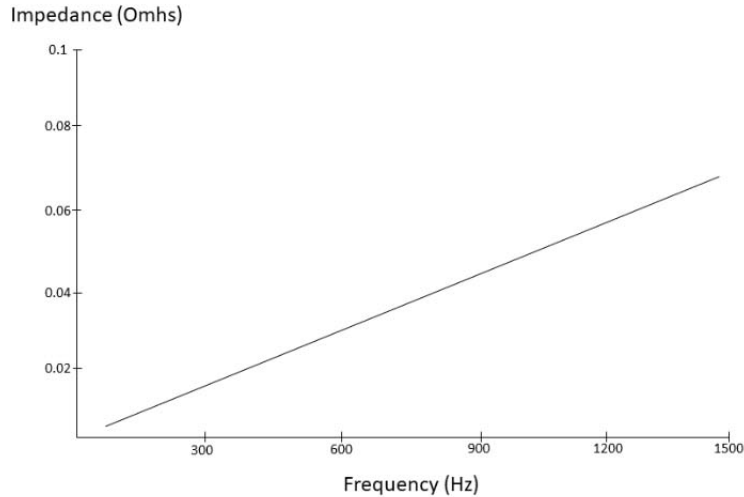


Figure 3.1: *Impedance as a function of frequency for an inductive system*

However, neglecting the resistive effects gives a more conservative forecast for the purposes of harmonic distortion. In an industrial electrical system the equivalent reactance is often approximated to that of the service transformer, therefore the approximation can be made:  $X_{sys} \approx X_{Tr}$ . Although not very precise, it is generally more than 90% of the total impedance, this approximation is sufficient to evaluate the possibility or not of resonance problems.

## 3.2 Capacitive impedance

Capacitive shunts, which can be installed by a consumer for power factor correction or in distribution systems for voltage correction, drastically alter the impedance of the system as the frequency changes. Capacitors do not generate harmonics, but important harmonic distortions can sometimes be attributed to their presence. While the reactance of an inductive component increases proportionally with the frequency, the capacitive reactance  $X_C$  proportionally decreases:

$$X_C = \frac{1}{2\pi fC} \quad (3.3)$$

where  $C$  is the capacity, in farad. Questa quantità è raramente disponibile direttamente per i condensatori di potenza, i quali vengono caratterizzati in termini di *kvar* o *Mvar* ad una determinata tensione. La reattanza capacitiva equivalente tra fase e neutro alla frequenza fondamentale per un banco di condensatori può essere determinata da:

$$X_C = \frac{kV^2}{Mvar} \quad (3.4)$$

### 3.2.1 Parallel Resonance

All circuits have both capacitance and inductances having one or more natural frequencies (denoted by  $f_0$  and is the frequency at which the capacitive reactance  $\frac{1}{\omega C}$  and the inductive reactance  $\omega L$  are of the same modulus, forcing the energy to oscillate between the magnetic field of an inductance and the electric field of a capacitor). When one of these frequencies coincides with a frequency

produced by the electrical system, a resonance can develop at which voltages and currents with very high values can occur. This is the origin of many harmonic distortion problems on power systems. Fig. 3.2 shows a distribution system with potential parallel resonance problems.

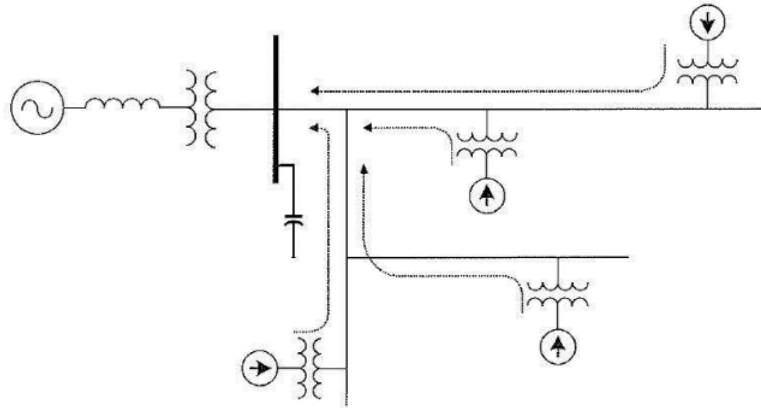


Figure 3.2: *System with potential parallel resonance problems*

If a source of harmonics is present, the shunt capacitors are in parallel with the system's inductance equivalent to the harmonic frequency, as shown more simply in Fig. 3.3. Furthermore, as long as the power system is represented as a voltage generator at only the fundamental frequency, the voltage source in the figure appears short-circuited. Parallel resonance occurs when the capacitive reactance  $X_c$  and that of the distribution system compensate each other. The frequency at which this phenomenon occurs is called parallel resonance frequency, which can be expressed by:

$$f_p \approx \frac{1}{2\pi} \sqrt{\frac{1}{L_{eq}C}} \quad (3.5)$$



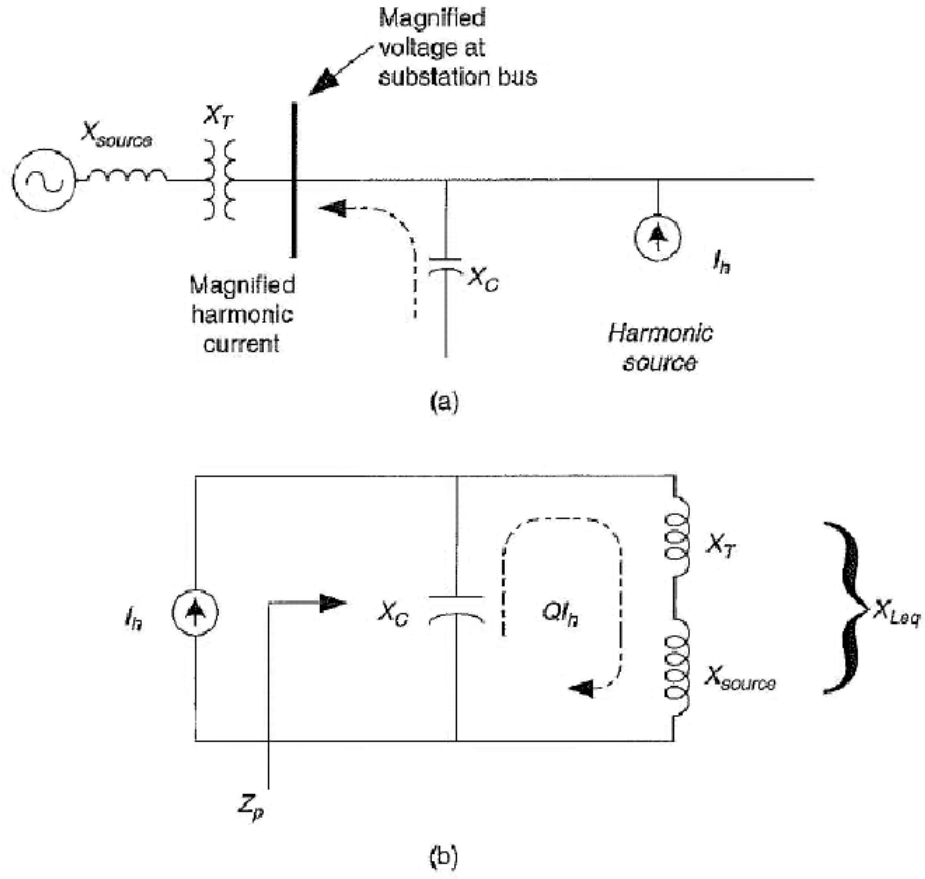


Figure 3.3: At the harmonic frequencies the capacitors are parallel to the inductance of the system  
a) simplified distribution circuit  
b) parallel resonant circuit seen from the harmonic source

At the resonance frequency, the impedance resulting from the parallel of the inductance and the capacity seen from the harmonic source is very large, therefore:

$$Z_p = \frac{X_C(X_{CLeq} + R)}{X_C + X_{Leq} + R} \approx \frac{X_{Leq}^2}{R} = \frac{X_C^2}{R} = QX_{Leq} \quad (3.6)$$

Where  $Q$  is known as **resonant circuit quality factor** and determines the shape of the frequency response. From the previous equation it is clear that in a parallel resonance condition even a small current harmonic can cause high voltage drops on the resulting impedance, namely:

$$V_P = QX_{Leq}I_h \quad (3.7)$$

The voltage near the capacitor bank can be very high and highly distorted. The behavior of the current during resonance. The current flowing either through the capacitor bank or in the electrical system is:

$$I_{Ris} = \frac{V_P}{X_C} = \frac{QX_C I_h}{X_C} = QI_h \quad (3.8)$$

It is therefore clear that the current flowing in the capacitors and in the electrical system (i.e. in the transformer) is increased  $Q$  times. This can cause the capacitor bank to go out of operation, the fuses to trip and the transformers to overheat. The amplitude of the voltage or current increase is determined by the size of the capacitor bank.

Fig. 3.4 shows the effects of various capacitance values in relation to the impedance of the transformer seen from the harmonic source, also considering the case in which there are no capacitors.

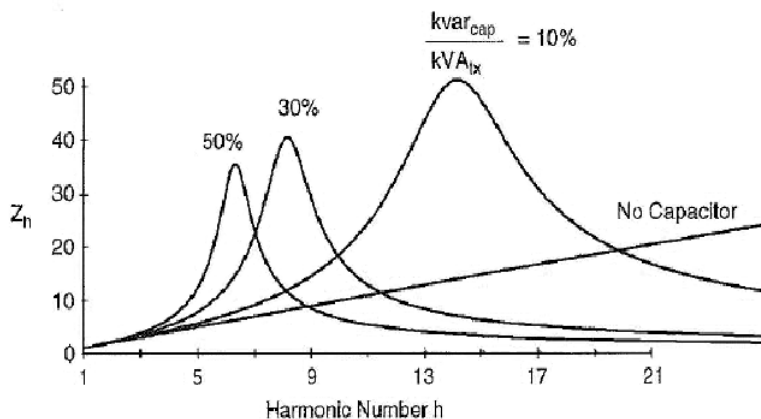


Figure 3.4: Frequency response of a system with different capacitance values in relation to the transformer

### 3.2.2 Series Resonance

There are certain cases in which a shunt capacitor and the inductance of a transformer or a distribution line appear in series with a current harmonic source. If the resonant frequency corresponds to the harmonic frequency characteristic of the non-linear load, the LC circuit drains a large part of the current circulating in the electrical system. A consumer does not have nonlinear loads, but often uses capacitors for power factor correction, and these can be home to large harmonic voltage distortions due to their proximity to harmonic sources. This situation is represented in Fig. 3.5

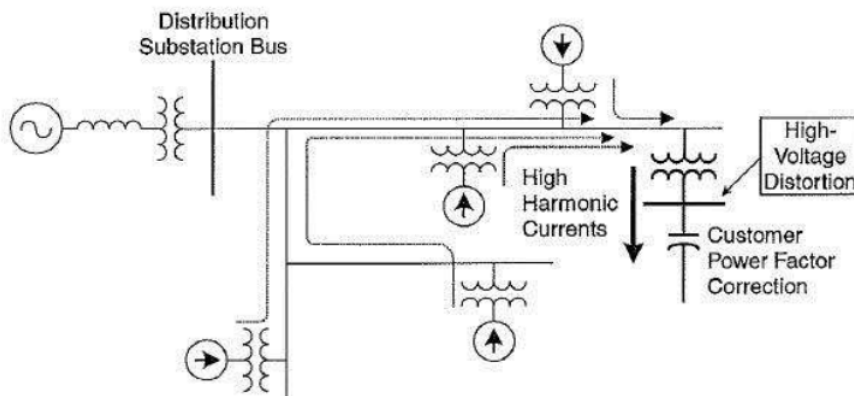


Figure 3.5: System with possible serious resonance problems

Capacitors are used for power factor correction, and can be home to large harmonic voltage distortions due to their proximity to harmonic sources. During resonance, the power factor correc-

tion capacitors form a series circuit with the transformer and the harmonic source. The simplified circuit is shown in Fig. 3.6

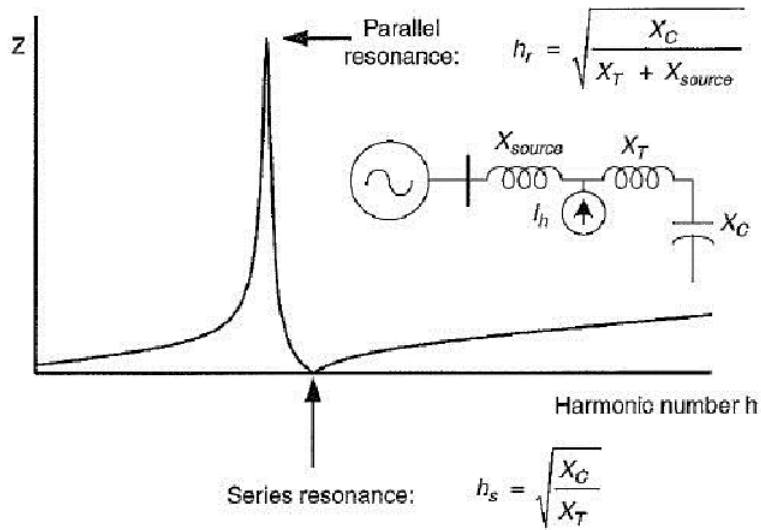


Figure 3.6: Frequency response of a circuit with series resonance

The harmonic source shown in the figure represents the totality of the harmonics produced by the other loads. The series of transformer inductance with the capacitor bank is very small (theoretically zero) and limited only by their resistances. Thus the current harmonic corresponding to the resonance frequency can circulate freely in the circuit. The voltage on the capacitors is very high and highly distorted, in fact:

$$V_s = \frac{X_C}{X_{Tr} + X_C + R} V_h \approx \frac{X_C}{R} V_h \quad (3.9)$$

where  $V_h$  = voltage harmonic corresponding to the current harmonic  $I_h$  and  $V_s$  = voltage across the capacitor bank. In many systems with potential serious resonance problems there are also parallel resonance problems due to the topology of the circuit, in the circuit shown above, the parallel resonance is formed by the parallel between  $X_{source}$  and the series  $X_T$  e  $X_C$ .

### 3.3 Effects of resistance and resistive loads

Damping due to system resistances is often sufficient to prevent critical voltage and current levels. Fig. 3.7 shows the impedance of a parallel resonant circuit for various resistive load values parallel to the capacitance. Even a small contribution, of the order of 10%, by the resistive load has significant benefits on the peak of the impedance. Lines and cables can therefore add significant portions of resistance to the equivalent circuit.

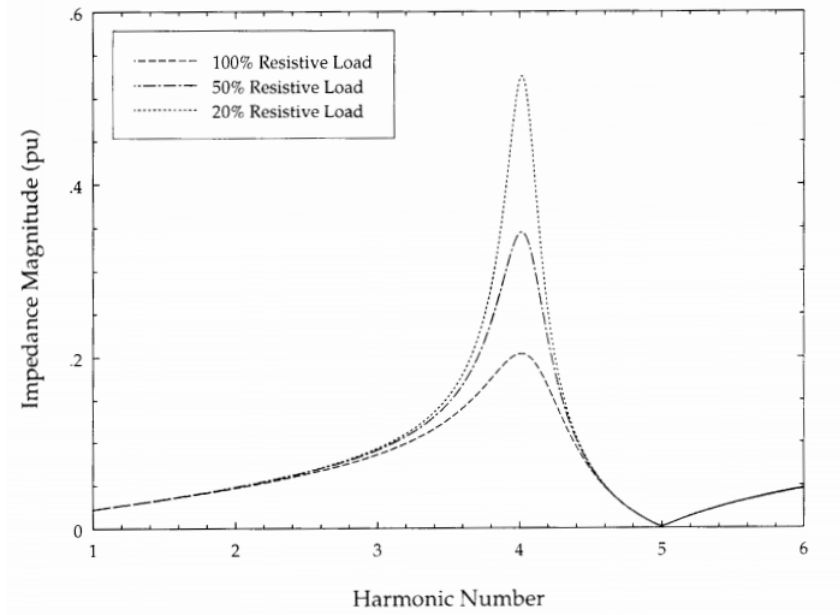


Figure 3.7: *Effects of resistive loads on parallel resonance*

# Chapter 4

## Harmonic effects

### 4.1 Need to detect and attenuate harmonics

#### 4.1.1 Disorders managed by harmonics

In distribution systems, the flow of harmonics reduces the quality of the power supply and consequently causes a series of problems, in particular it is necessary to take into account, as seen in the Schneider Electric article [4]:

##### Temperature rise in cables

The increase in temperature in the cables due to the harmonic currents adds up to the increase due to the fundamental current,

$$Losses = r \sum_{n=1}^{\infty} I_{hn}^2 \quad (4.1)$$

##### Neutral current

All the third harmonic currents and their odd multiples add up to the neutral and the current circulating there can reach values 1,7 times greater than those of the phase.

Homopolar harmonic currents ( $H3$  and odd multiples, written as  $3(2k+1)$  with integer  $k$ ) in three-phase systems add up in the neutral conductor. This is due to the fact that the order  $3(2k+1)$  is a multiple of the number of phases (3), that is, they coincide with the displacement (one third of a period) of the phase currents. Fig. 4.1 illustrates this phenomenon over a period. The currents of the three phases are shifted by a third of the period ( $\frac{T}{3}$ ), that is the respective harmonics  $I_{H3}$  are in phase and the instantaneous values add up.

Consequently:

- When there are no harmonics, the current in the neutral is equal to zero:  $I_n = I_1 + I_2 + I_3 = 0$
- When there are harmonics, the current in the neutral is equal to:  
 $I_n = I_1 + I_2 + I_3 = 3I_n$

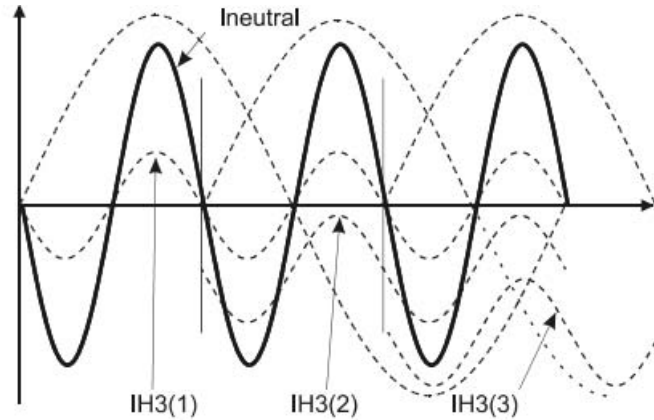


Figure 4.1: The harmonics of order 3 and their multiples add up in the neutral

→ Perdite significative nel neutro

→  $RI_{neutro}^2 = \text{aumento temperatura nel neutro}$

### Polluting loads

The current distortion  $THD_i$ , caused by the load, generates a voltage distortion  $THD_v$  caused by the harmonic currents that pass through the various impedances starting from the source. Fig.4.2 shows the different forms of distortion in a common electrical system.

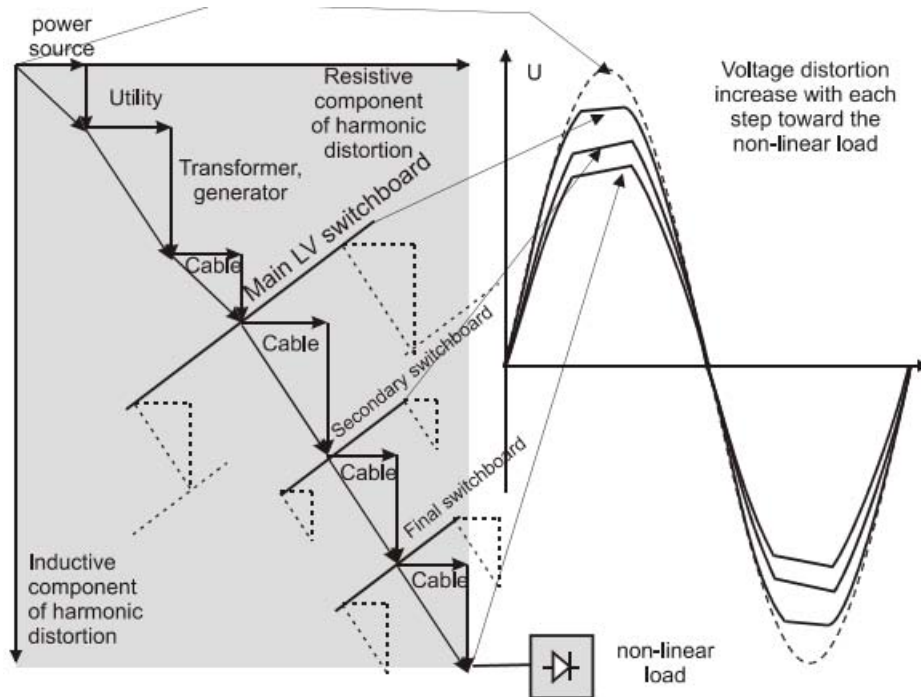


Figure 4.2: *Harmonic effects in a system*

### Breakage risk of the Capacitor

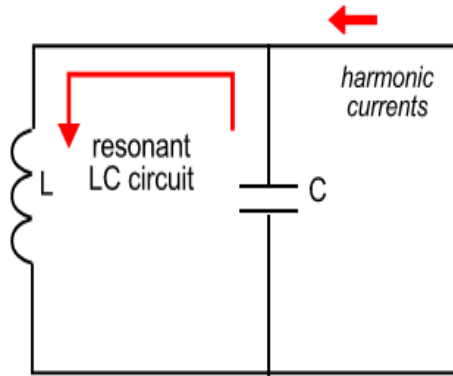
The current value increases with increasing harmonic order  $k$ ; Furthermore, a harmonic frequency can also involve a resonance between the capacitor (capacitance  $C$ ) and the equivalent inductance ( $L$ ) of the source (transformer, essentially inductive) in parallel with that of the other powered loads. This resonant circuit greatly amplifies the harmonic current of the corresponding order, with consequent worsening of the situation for the condenser.

As consequences:

- Breakage risk of the capacitor;
- Resonance risk due to the presence of inductors.

It is therefore necessary to respect some limitations:

1.  $V_{max} = 1,1V_n$
2.  $I_{max} = 1,3I_n$
3.  $THD_{V,MAX} = 0.08$
4. Choice of the type of capacitor, according to the circumstances, for example standard, class H (reinforced insulation), with harmonic inductors.



(a) Effects of harmonics on capacitors, risk of resonance.



(b) Collapse of a protection capacity against harmonic stress

Figure 4.3: Possible destructive effects of harmonics, especially of a high order, on capacitors

### Losses in asynchronous motors

Harmonics produce the following effects in asynchronous motors:

- increases in losses due to Joule and iron (losses in the stator);
- pulsating torque (losses in the rotor with a decrease in mechanical efficiency).

To limit these phenomena, the  $THD_v$  must be less than 0.1.

### Effects on other equipment

The harmonics can also disturb the operation of the following equipment:

- unwanted activation of circuit breakers;
- telephone auto-switches;
- alarms;
- sensitive electronic devices;
- remote control systems.

### Effect on latest UPS systems

Modern UPS systems have high cut-off frequencies (PWM) and an extremely low output impedance (equivalent to a transformer five times more powerful). Compared to non-linear loads, these UPSs offer:

- limited losses;
- operation with current limitation;
- extremely low voltage distortion,  $THD_v < 0.03$ .

UPSs are excellent tools for powering nonlinear loads.



### 4.1.2 Detection and reduction

The most frequently encountered harmonics (and consequently the most problematic) on three-phase distribution systems are odd order harmonics (3<sup>o</sup>, 5<sup>o</sup>, 7<sup>o</sup>, etc.) Beyond the 50<sup>o</sup> order, the harmonic currents are negligible and no measurements are required. Sufficient measurement accuracy is obtained taking into account harmonics up to 30<sup>o</sup> order. It follows that the conditioning of harmonics is indispensable up to order 13 and ideally should include harmonics up to order 25.

### 4.1.3 Contrast strategies

- accept harmonics, which basically involves the need to oversize the equipment in order to keep the effects of harmonics under control;
- eliminate harmonics, in part or in whole, by means of filters or active harmonic compensators.

#### Passive filters

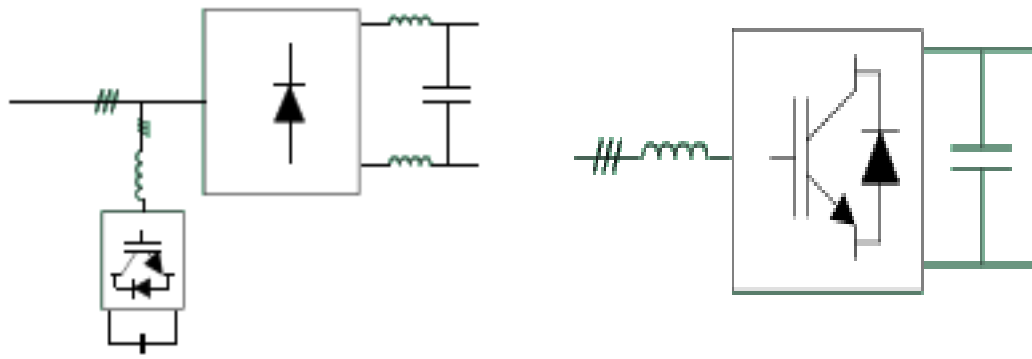
Passive LC filters are tuned to the frequency to be eliminated or attenuate a frequency band. Harmonic recombination systems (double bridge, phase translation) can also fall into this category. Passive filters have two main disadvantages:

- the elimination of harmonics is effective only for the specific system, therefore the addition or removal of loads can compromise the filtering system;
- it is often difficult to implement them in an existing plant.

#### Active filters or active harmonic compensators

Active filters, also called active harmonic compensators, are devices that are inserted in parallel, cancel the harmonics by injecting exactly equivalent harmonic currents when they occur. This type of filter reacts in real time (i.e. actively) to existing harmonics in order to eliminate them. More effective and flexible than passive filters, it overcomes its disadvantages and, in comparison, constitutes a solution that:

- Corrects the power factor and voltage imbalance;
- Provides energy savings by reducing losses in the system;
- offers better performance (allows the elimination of all harmonics, up to order 50);
- it is flexible, adaptable (the action can be configured) and reusable.



(a) Active filter/Low Harmonic Drive

(b) Active Front End

Figure 4.4: Harmonic elimination mode through Active Filters

The filters shown in fig. 4.4a and 4.4b work dynamically with the ability to react to changes in load, network and resonances.

# Chapter 5

## Mitigation methods

### 5.1 Solutions to avoid resonances

The main method to avoid resonance problems is to keep the resonance frequency as far away as possible from the harmonic frequencies which have considerable amplitudes. This can be achieved by changing the inductance or capacity of the network components. However, the possibilities are limited, if a particular network configuration is defined by the power supply and the reactive power compensation. In particular, when an automatic capacitor bank is to be used, many resonance conditions must be considered. The most common solution to avoid resonance problems is to connect a reactor in series with the capacitor and tune them to a series resonance frequency lower than the lowest frequency of the voltages and harmonic currents of the network. Below the tuning frequency, the impedance of the reactor-capacitor connection is capacitive, above the tuning frequency it is inductive. The interaction of the network inductance and the (inductive) impedance of the reactor-capacitor connection can no longer create resonance situations, neither serious resonance nor parallel resonance, at the frequencies of the voltages and harmonic currents present on the network.

### 5.2 Filter - electrical system interaction

For a correct design of a filter system, it is necessary to analyze what the consequences of inserting the filter into the network may be: given the complexity of the problem, this is generally done through a series of computer simulations using existing harmonic load-flow programs on the market, [3]. The simulations allow to establish with good reliability the quality of a filtering design solution: it is usually studied for the nominal values of capacitance, inductance and resistance; then it is necessary to check the response of the network to one or more variations of the characteristics of the filter within the pre-established tolerances for the individual elements. Typically the capacitance can vary in time by  $\pm 10\%$  and the inductances by  $\pm 5\%$ .

The insertion of the filter into the network can often create problems that were previously negligible or non-existent. The parallel resonance situation is particularly dangerous, because it presents itself easily when a filtering system has to be designed. As an example, suppose that an industrial user has a bank of power factor correction capacitors which creates 7<sup>o</sup> harmonic

resonance phenomena. The designer can then decide to convert the bank of capacitors into a bank of filters tuned to the same harmonic. This decision (Fig. 5.2) can cause, due to the relationships between the impedances of the filters and the network, a shift of the parallel resonance frequency from 7<sup>o</sup> to 5<sup>o</sup> harmonic; since generally currents of 5<sup>o</sup> harmonic are significantly present in electrical networks (think of the six-pulse converters), this can give rise to an unacceptable distortion of the voltage precisely because of the components of 5<sup>o</sup> harmonic.

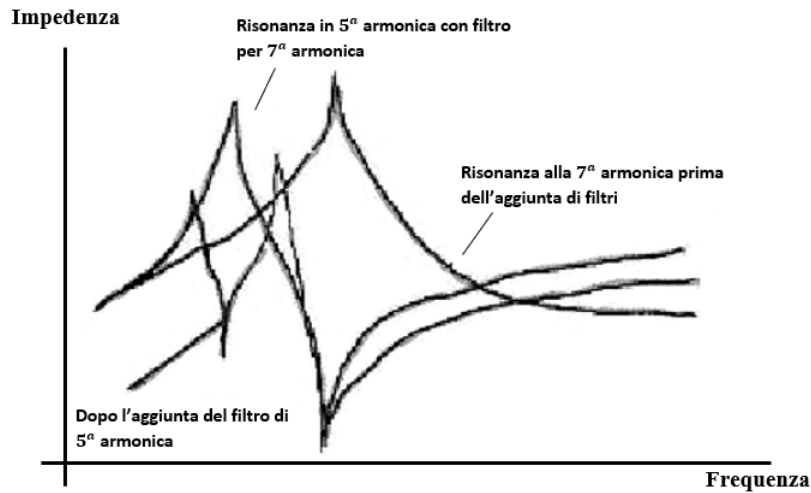


Figure 5.1: Example of frequency responses to highlight the filter-electrical system interaction

The solution then consists in providing the presence of a filter for the harmonic 5<sup>o</sup> which, in addition to filtering the harmonic 5<sup>o</sup>, further lowers the resonance frequency. The considerations made also indicate that, in general, the insertion of the filters must take place starting from those relating to the lowest harmonics, to prevent the parallel resonance frequency from coinciding with a lower frequency at which there is a disturbance in network. If, on the other hand, this disturbance has already been eliminated, the presence of a resonance at the corresponding frequency does not cause problems. Obviously, for the same reasons, when disconnecting the filters, it will be necessary to proceed from the filters for the highest harmonics. It often happens that the presence of harmonics in the network is due to resonance caused by the mainly inductive inductance of the network with the power factor correction capacitors. This problem can be remedied simply by remembering that the size or location of the capacitors can be changed, thus eliminating the problem. In particular, it has been observed that the capacitors used in industrial systems to improve the power factor cause resonances on the 5<sup>o</sup> harmonic. This occurs when the short-circuit power of the node is approximately 23-30 times greater than the reactive power generation required by the power factor correction system. Problems with the 3<sup>o</sup> harmonic, on the other hand, can occur frequently in the presence of large single-phase loads (up to 501% of the current absorbed by these loads can be of the third harmonic), which are often present in the distribution; the 3<sup>o</sup> harmonic, on the other hand, generally does not give problems with non-linear three-phase loads. If you do not want to resort, for example for economic reasons, to the use of multiple filters to avoid the onset of resonances, you can simply add a reactance in series to the power factor correction capacitor; this time the aim is not to create a wired filter, but to move only the resonance frequency and no longer match it with the harmonic frequency of a disturbance present in the network. This does not create particular difficulties in the project, but it must always be remembered that the LC branch thus created will produce more reactive power than the only power factor correction capacitor previously produced (due to the decreased impedance).

## 5.3 Basic composition of a filter

A filtering plant generally consists of:

- Capacitors;
- Reactors;
- Switches;
- Protection systems.

The sizing of these components is generally based on the stresses calculated in the most expensive operating situation, it is therefore necessary to take into consideration the harmonic currents produced by the loads and all the harmonic currents and voltages existing in the network. It must be checked that they do not cause unacceptable negative repercussions on the functioning of the filter: manufacturing tolerances, the influence of temperature and aging, the intervention of any internal or external fuses, the possible non-linearity of the filter components as well as the variation of the grid frequency.

### 5.3.1 Capacitor

Capacitive units or batteries constitute a fundamental part of the filtering system, therefore a careful study must be carried out to obtain an optimal realization. The current in the capacitor consists of a fundamental component and components at harmonic frequencies. Since the amplitude of the harmonic components can be high, especially in a tuned filter, it is necessary to take this into account when the nominal values of the capacitors are established. Of course, the increase in voltage on the capacitor due to the connection in series with the reactor must also be considered, [2].

### 5.3.2 Reactor

The current in the reactor consists of a fundamental component and its harmonics. It must be designed to withstand temperatures determined by the maximum current values of the fundamental component and its harmonics. In the design of a filter, the manufacturing tolerances of the reactor inductance must be considered; a tolerance of 3% is generally acceptable for most filter applications. The reactor must be able to withstand the short-circuit currents that can occur in the event of a fault and also the operating currents and voltages. The value of the reactor inductance must not show a variation greater than 5% between its value than at the rated current and that in the conditions of maximum load determined by the peak value of the current or voltage (induction caused by the arithmetic sum of the maximum values of fundamental and harmonic currents or voltages). When using iron core reactors (normal case of low voltage filters) precautionary measures must be taken to avoid saturation problems.

### 5.3.3 Switch

Switching these systems requires a switchgear with some special features. The following requirements must be considered:

- The contactor must not lead to arc re-priming and must be suitable for the operation of the capacitors;

- Its nominal voltage must be equal to or greater than the maximum voltage of the network with the service filter;
- It must be designed for a permanent current (including harmonics) that can pass through the filter at the maximum supply voltage, at the maximum frequency and considering the component tolerances;
- The breaking capacity must be equal to or greater than the short circuit current that can occur in the filter;

### 5.3.4 Short circuit protection (fuses)

The nominal voltage of the protection against short circuits must be equal to or greater than the maximum voltage of the network with the power factor correction system and/or filter in service. Protection against short circuits must be provided for a permanent current (including harmonics) which can pass through the power factor correction system and/or the filter at the maximum supply voltage, at the maximum frequency and at the extreme tolerance values of the components, especially condenser and reactor mode. The short-circuit protection must have a short-lasting seal sufficient to withstand the short-circuit currents and the insertion currents that can occur at power-up.

## 5.4 Passive filters

The generally most used method to limit the presence of harmonic voltages in the network is to use a passive filtering system. A passive filter must be able to:

- Reduce the harmonic content of currents or voltages within the limits established by the regulations;
- Produce reactive power useful for power factor correction;
- Do not suffer from network disturbances and must not create new ones;

They mainly consist of inductors and capacitors suitably connected for the purpose of:

- Create a high impedance in series with the load to ensure that the current harmonics are as low as possible. Of course this type of filter, given the nature of the connection with the load, must be sized to withstand the maximum line voltage and the maximum load current. It is not suitable if there are many distorting loads since in fact it would prevent the harmonic currents from flowing in ways with low impedance towards the network, and therefore causes a voltage distortion;
- Create a low impedance way that will short circuit undesired harmonic components to the ground. These filters are placed parallel to the load and must be sized for the harmonic currents that will result. For this reason, the parallel filters are generally less expensive than the series filters, and moreover these filters allow to supply reactive power at the fundamental frequency useful for power factor correction (while the series filters absorb reactive power at the fundamental frequency).

They are classified according to their bandwidth, therefore you can have:

1. Tuned filters;

2. Filters not tuned;
3. high-pass filters (or damped filters).

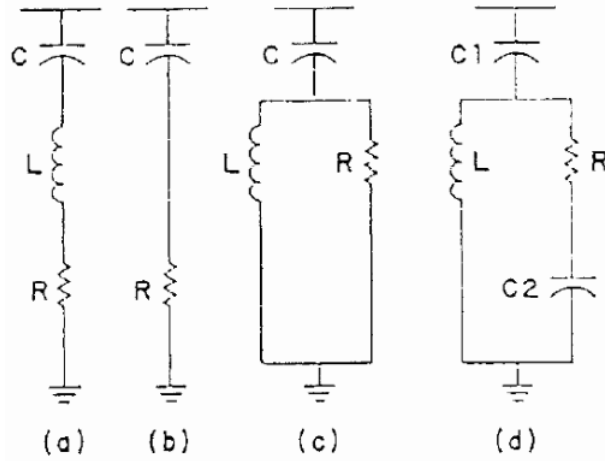


Figure 5.2: Schemes of different types of tuned and high-pass filters:  
a) tuned filter  
b) other-pass filter of the I<sup>o</sup> order  
c) other-pass filter of the II<sup>o</sup> order  
d) pass-other filter of the III<sup>o</sup> order

## 5.5 Power factor correction capacitors

This type of installation for power factor correction can be used when it is not necessary to resort to special measures to avoid problems due to resonance or to reduce harmonics. This generally occurs when the resonance frequency determined by the inductance of the network and the capacity of the power factor correction system is relatively high and the harmonic content of the network is low (i.e. harmonic voltages and currents in the network generated by the load). However, it should be borne in mind that the resulting total capacity of all power factor correction systems connected to the low voltage side of a distribution transformer determines the possibility of having harmonic resonance problems. Solving these problems, when the power factor correction system is already in service, can be much more difficult than not at the time of initial installation, in fact it is often not possible to reuse the capacitors, the support frames etc. , already existing.

## 5.6 Active filters

The diagram in Fig. 5.3 shows the single-line diagram relating to the operation of an active filter. The current absorbed by a non-linear load is composed of a component at the fundamental frequency  $i_{L1}$  and a distortion component  $i_{L,distortion}$ . The current in the load is measured and filtered to provide a signal proportional to the distortion component  $i_{L,distortion}$ . With a current control an inverter is operated to supply the system with current  $i_{L,distortion}$ . Then, with reference to an ideal case, the harmonics present in the mains current are eliminated. On the DC side of the converter only a capacitor that can store minimal energy is needed, since the voltage on it is maintained by the inverter which transfers only the active power necessary to compensate its losses from the electricity grid, through a small current  $i_{L,loss}$ .

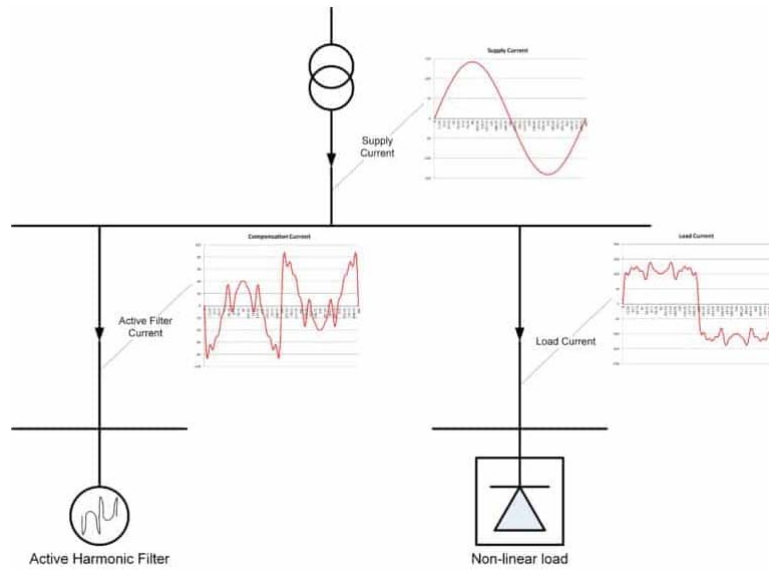


Figure 5.3: Single-line diagram of the connection of an active filter and related analysis of the currents in the circuit itself

The converter is called to deliver the distortion component  $i_{L,distortion}$ . The control system processes the currents necessary to compensate the reactive component (possibly also the harmonic content) of the current absorbed by the load. A minimum active power is required, necessary to keep the DC side capacitor charged at the voltage  $V_d$ . Given the operating mechanism of the active filter and the high dynamic performance it presents, the compensation of the distorted current occurs without delay and can be considered instantaneous. Furthermore, with modern harmonic filters it is possible to compensate up to 50<sup>o</sup> order and with the 4-conductor filter models, neutral currents can also be eliminated. Furthermore, given the operating characteristics of the active filter, it is independent of the  $\cos\phi$  of the network, the direction of the power and the type of load, as well as the impedance of the network, characteristics that make it easy to use without details precautions. The cost of active filters is a function of the effective current present.



## Chapter 6

# Job description and type of unit

### Abstract

The first phase of the work in the company allowed us to get to know the unit being analyzed by making evaluations on its components and drawing the first conclusions regarding the distortion values. This first frame of the machine was purely theoretical, without the aid of any calculation software, taking advantage of the theoretical notions reported in the chapter 1. To know the quantities relating to the components of the unit, also considering its operation at different load percentages, refer to databases, made available by the manufacturers, which collect their work points and characteristic values.

### 6.1 Machine 1

In this phase of the study we focus on the type of machines presented in fig.6.1; it is an outdoor unit for the production of chilled/heated water with compressors driven by fixed speed and variable speed motors (Inverter Driven) in a single-circuit configuration, with the use of R410A refrigerant, condensing coil with copper pipes and aluminum fins, brazed plate heat exchanger and standard electronic expansion valve. The machine is flexible and reliable and adapts to the most diverse load conditions thanks to the accurate thermoregulation combined with the use of inverter technology. The careful design and use of innovative fixed speed motors together with variable speed motors (inverters) ensure a high level of energy efficiency both at full and partial load [7].



Figure 6.1: *Machine 1*

Two versions are produced, the basic one and the **super silenced version SL**.

⇒ FEATURES:

- *HIGH EFFICIENCY*: very high efficiency both at full load and at partial loads. Energy consumption is reduced, thanks also to the use of inverter technology;
- *VARIABLE FLOW*: correctly adjusting the speed of the pumps controlled by the inverter according to the load required by the system allows you to reduce electricity consumption and ensure unit operation even in critical conditions;
- *TWO LEVELS OF SILENCE*: it is possible to choose between two distinct levels of silence, to meet the requirements required on the basis of plant design and final use.

Using the data collected from measurements and those provided by the databases, it was possible to implement a spreadsheet with the aim of obtaining the  $THD_i$  of the unit starting from that characteristic of the individual components which constitute it.

### 6.1.1 Interpretation of database and software results

#### Machine 1 data analysis

- Compressor

Compressor 1: variable speed	Compressor 2: fixed speed	Configuration: tandem
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Table 6.1: *Compressor features*

As you can see in Tab.6.1 this unit consists of two compressors in tandem mode;

- **Fan**

N° Fans	EC fan type
---------	-------------

Table 6.2: *Fan features*

In Tab.6.2 the indications regarding the machine are given

- **Pump**

Pump Model 1	Pump Type 1
--------------	-------------

Table 6.3: *Pump features*

In Tab.6.3 there are the indications concerning the machine

### 6.1.2 Considerations

A purely theoretical calculation like the one done in this first phase gives me an indication of the distortion value of a unit but can tell me nothing about what happens when other functioning machines and their distortion characteristics are connected to the network. We can therefore say that it is useful but an end in itself when I get information that is not absolute but related to the specific unit.

## Chapter 7

# Comparison of the software utilised

### Abstract

After getting an idea about the units, focusing in particular on the *Machine 2* which is the first case study, the phase of data research, screening and use of different software began. The various phases were carried out in parallel since the initial lack of the elements necessary for the implementation of Neplan required to look for them elsewhere; hence the use of various platforms, some requiring a license, others free, in order to simulate the behavior of the machine which is the main cause of distortion in the current injected into the network, the inverter, and therefore have the opportunity to obtain, at least in part, useful numbers. In this chapter we will analyze the ways in which these software have been used for the purpose of our study and we will provide comments and considerations related to pros and cons observed in the simulations.

Since it is not always immediate to obtain such detailed information from suppliers, it has been hypothesized to build a model of this machine using different software in order to obtain its harmonic characterization. To simulate the distorting load, platforms such as:

- Matlab, in particular the Simscape Electrical tool, and Simulink;
- NI Multisim (National Instruments software);
- LTSpice;
- Infineon Designer (powered by TinaCloud);
- Harmonic Calculation Software.

The potential of each of these software has been analyzed through simulations and verification of the results, which will then be presented in the chapter; all this with the aim of finding the best method, the one that can bring results closer to the real ones, also taking into account the cost of using the platform, and then being able to use it in conjunction with Neplan.

## 7.1 Multisim<sup>TM</sup>, Matlab e Simulink

The first simulations on Neplan have brought to light the need to have a precise amount of data in order to better implement the network that you have the will to study; in particular, the harmonic characterization of the components connected to the networks and which behave like distorting loads is needed. We therefore refer to power electronics to describe the complex *rectifier bridge + inverter*, its effects and the distortion it introduces into the network. In this analysis we compare two software for which a license is required (therefore for a fee).

### 7.1.1 Multisim<sup>TM</sup>

Multisim<sup>TM</sup> software integrates industry standard SPICE simulation features with an interactive schematic environment to view and analyze the behavior of electronic circuits in real time. Its intuitive interface helps understanding circuit theory and improving its learning in engineering courses. By adding powerful circuit analysis and simulations to the design flow, Multisim<sup>TM</sup> helps researchers and designers reduce iterations of printed circuit board (PCB) prototypes and save on development costs. Thanks to this software, it was possible to implement the same rectifier + inverter model, however, being able to make a much more accurate choice on all the components involved; also in this case the intent was to obtain as much data as possible in order to characterize the harmonic behavior of the components studied. The cost features of the software and the fact that it was never used during the university course led me to discard it, albeit excellent for the resolution and composition of circuits of power electronics.

### 7.1.2 Matlab & Simulink

This Matlab tool allows you to recreate the connection of the inverter to the grid, first passing through a suitable rectifier, and to obtain its harmonic characterization through the FFT ('Fast Fourier Transform') function. Simulink is a software for modeling, simulation and analysis of dynamic systems, developed by the American company MathWorks, a software that presents a graphical interface, predefined blocks (which you can customize) only to be connected and a high flexibility in the variation of the project .

It was not difficult to implement the model as the platform is very intuitive and user friendly making the block construction linear and schematic, as will be seen in the 7.4 section.

The only drawback was found in the when you tried to insert more precise data in the components that make up the inverter for a more accurate simulation and, with the predefined IGBT model in the library, you do not have the possibility to do so beyond a certain limit.

The output is the desired one but to obtain a more precise result, it is therefore advisable to turn to another software that lends itself only to simulations inherent to power electronics.

## 7.2 Software open license, LTSpice e

### Infineon Designer

These are SPICE software, ie software entirely focused on circuit design using the elements of power electronics, in order to build the model of the inverter in detail and to evaluate the distortion it causes. These two platforms both allow SPICE simulations but the substantial difference lies in the fact that Infineon, which allows you to build the scheme to be simulated entirely online, has a very large library of examples and explanations, as well as the possibility of using predefined real

products for your own simulations. For this reason, it was initially preferred to use this second possibility. In fact, the analysis and the work done with LTSpice proved to be very useful towards the end of the experience in the company, when it was necessary to connect the simulation and implementation work of a detailed circuit representative of the inverter its less accurate representation on Neplan (see chap.9).

## 7.3 Harmonic Calculation Software

Mitsubishi uses Supplier inverters on a certain type of machine, this has allowed us to get in touch more easily with the suppliers who recommended the use of these two software. Therefore, as regards the tools that Supplier makes available, the Harmonic Calculation Software rely on different platforms:

- works on a very extensive database of actual tests carried out. Intermediate values are extrapolated and come very close to the real case;
- is based on a core engine that realizes a high precision mathematical simulation.

In order to have a simulated result that was as far as possible not conditioned by the power supply, it would be possible to set the data of an ideal power transformer, much larger than the load. However, the tools available are sized to provide real data, therefore they allow you to insert only finished power transformers with values that are reflected in reality.

In fact, the Harmonic Calculation Software have been created specifically to help the end user to evaluate the effect of using frequency converters in their system in terms of harmonic distortion, returning the values of current and voltage harmonics in percentage terms with respect to the fundamental. It also gives us the possibility to make simulations for different load percentages and to obtain the indications of distortion of the current injected into the network, therefore the *harmonic characterization* that we need.

## 7.4 Simulation Results

### Matlab & Simulink

This section presents the results obtained using the block diagram with which the diode bridge and the inverter have been modeled. The focus of the simulation was to evaluate the distortion of the current injected into the network, for a certain fixed load value and according to the variability of the size of the equivalent impedance  $RL$  AC side.



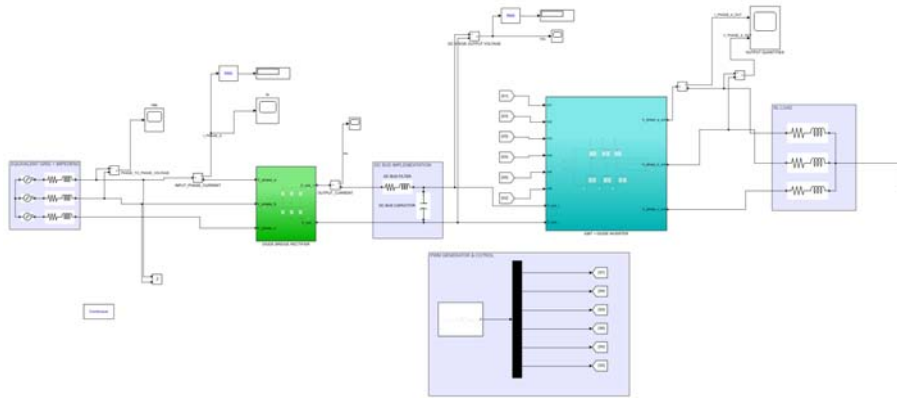


Figure 7.1: diode bridge model and inverter in Matlab simulation

### L=1 mH case analysis

Looking at the tension between the phases a-b, we notice that it has a quasi-trapezoidal shape with the square peak. The value of input voltage and that of the output voltage from the rectifier bridge do not respect the characteristic relationship of this type of converter, that is  $V_{dc,out} = 1.35V_{ac,avg,in}$ .

The problem identified concerns the input impedance  $RL$  (the internal impedance) which, although small, due to resonance problems (input voltage cut off at the ends), especially in relation to the inductance  $L$ ; this in fact resonates with Capacity  $C$  and this entails a voltage drop at the end of  $RL$  and therefore a voltage output value different from what is expected.

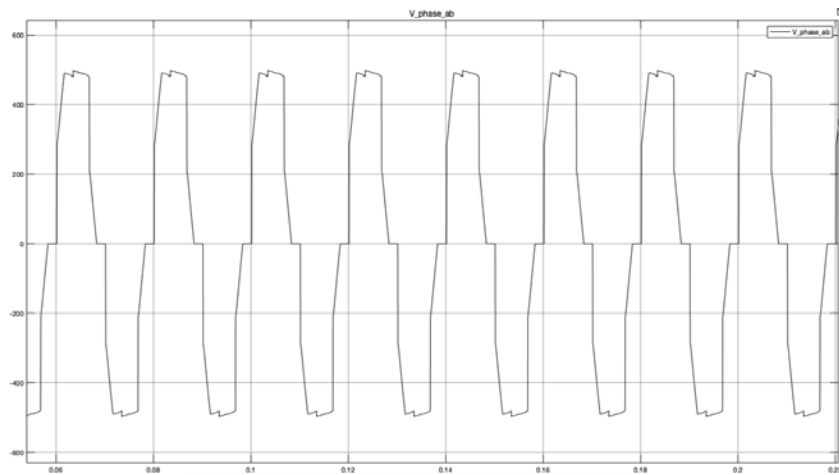


Figure 7.2: Line voltage between phases a and b, case  $L = 1mH$

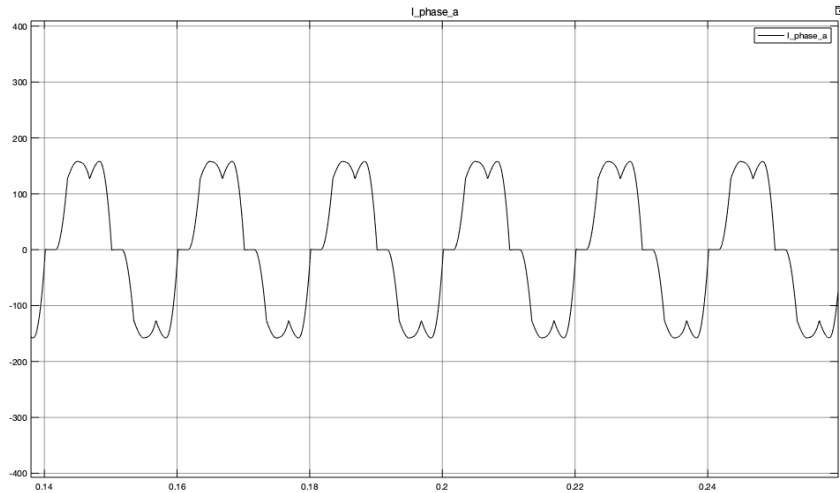


Figure 7.3: Current injected into the grid of phase a, case  $L = 1mH$

By analyzing the current that is injected into the network, using Simulink's *FFT* tool that returns the harmonic analysis of the wave, we obtain a visible spectrum in fig. 7.7

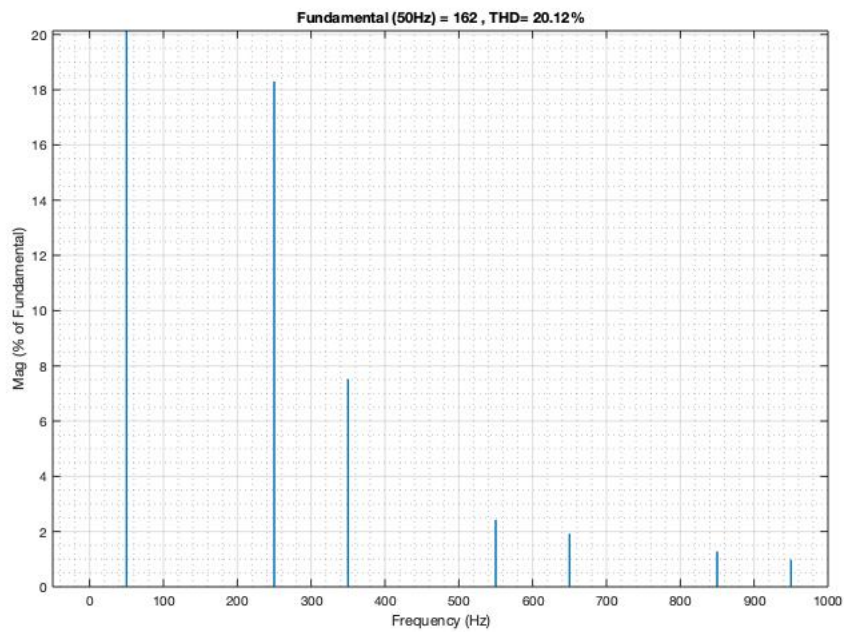


Figure 7.4: Current spectrum injected into the network of phase a

### **L=1 uH case analysis**

By remaking the simulation we now obtain a better result, as regards the voltage waveform between the phases a and b which has, apart from some spikes, a sinusoidal shape, as visible in fig. 7.5

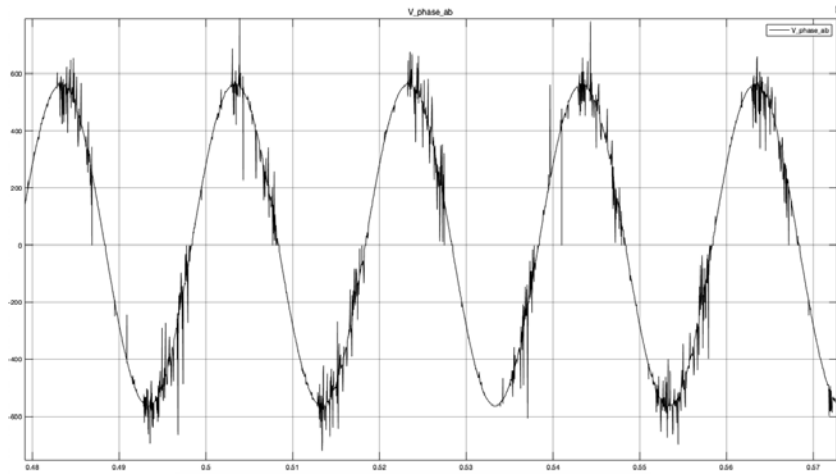


Figure 7.5: Concatenated voltage between phases a and b, case  $L = 1\mu H$

As for the current injected into the network, the shape we obtain is different from that obtained previously, with also a different harmonic content.

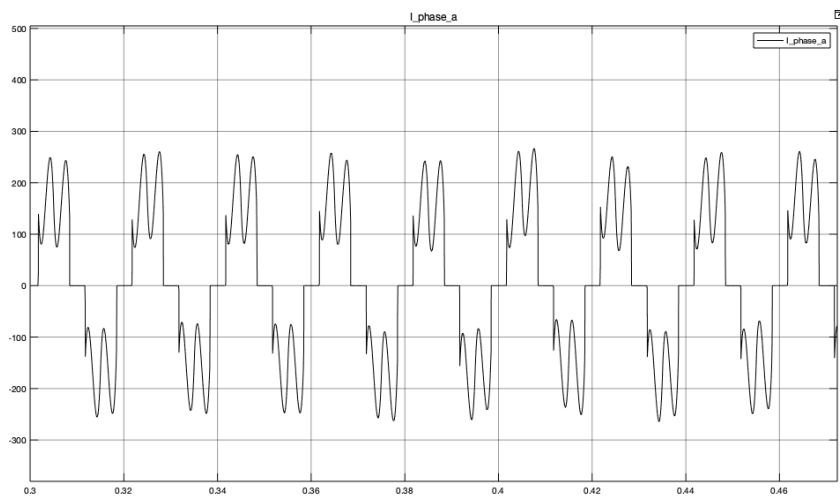


Figure 7.6: Current injected into the grid of phase a, case  $L = 1\mu H$

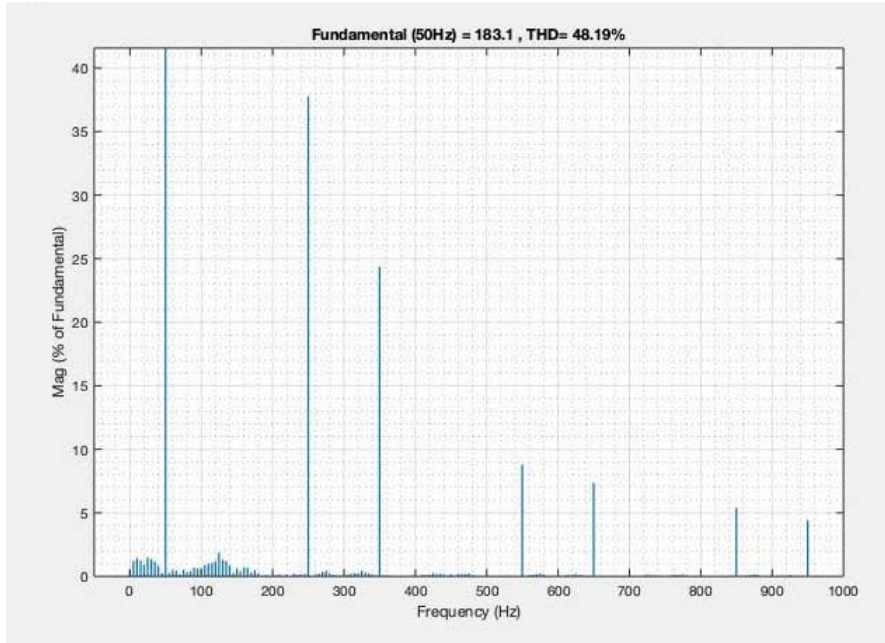


Figure 7.7: Current spectrum injected into the network of phase a

## Infineon Designer

As for what has been done previously, we focus on the characterization of the harmonic spectrum, using a simpler configuration, that is, taking into account only the diode bridge connected to the network. This is because the characteristic form of current of the configuration that is injected into the network is the one we are interested in. Clearly it is a very simplified analysis which however allows us to understand what happens when the quantities of the incoming  $RL$  branch vary, keeping the other conditions unchanged and the behavior to load variations.

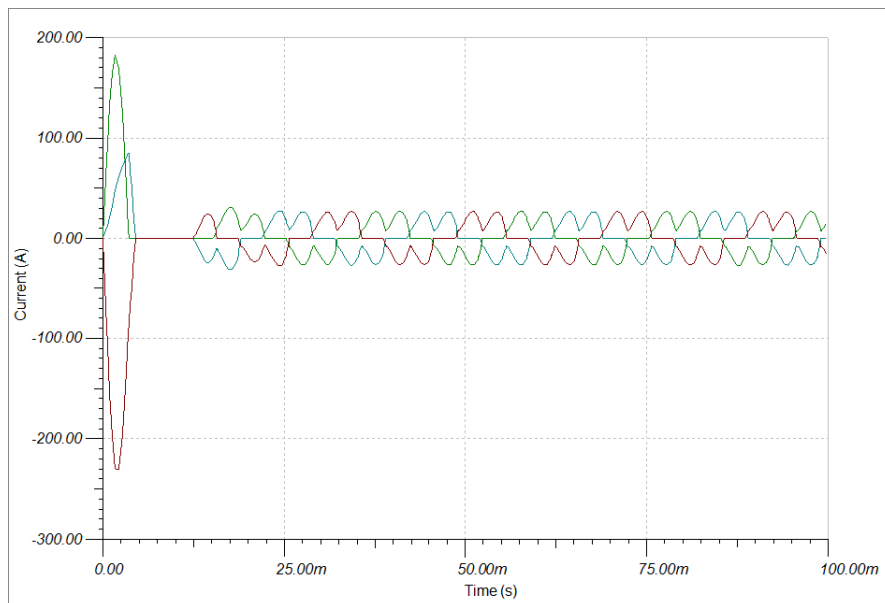


Figure 7.8: Phase current waveform a, case  $L = 1mH$

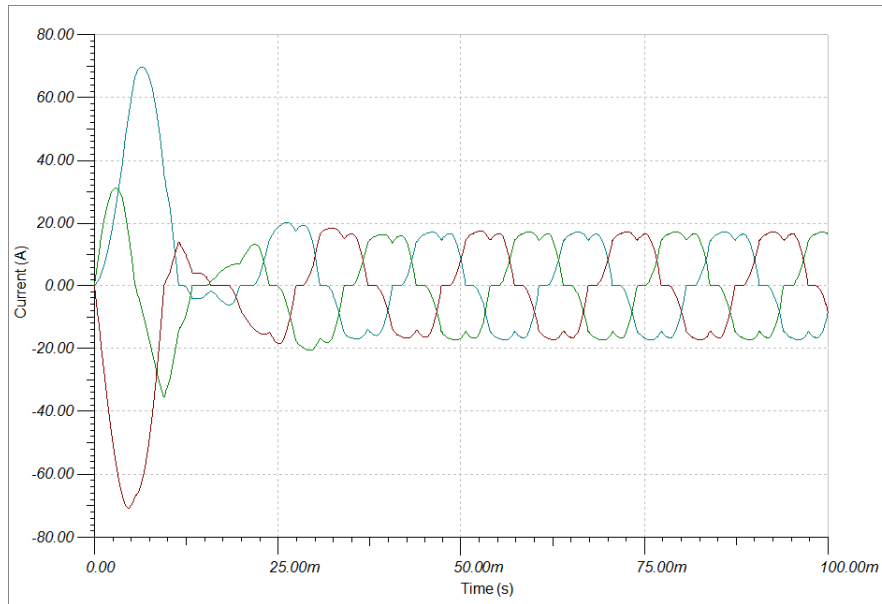


Figure 7.9: Phase current waveform a, case  $L = 10mH$

From the results of the simulations, therefore from the curves shown, it is clear that the higher the  $L$  value, the less the current that is injected into the network is distorted. In other words, when a *network is stronger* it is less affected by impurities and distortions caused by nonlinear loads.

## Harmonic Calculation Software

As previously introduced, through this platform we are able to obtain the harmonic current characterization according to the component used and the degree of load partialisation. Since units of this type are used in the Mitsubishi machines considered in our analysis, the possibility of obtaining the data necessary for the implementation of Neplan is fundamental since it is data supplied directly by the manufacturer therefore certainly more results can be obtained accurate than those of the simulations.

## 7.5 Comments and considerations

Each of the software presented has its usefulness but for the purpose of our analysis we will basically use two of them, a Spice software, which can allow us to represent the electrical circuit of the inverter so that we can analyze it in its fundamental components, and the Supplier Harmonic Calculation Software in order to have precise indications on the effects of connecting the inverter to the busbar and to obtain its current characteristic.

These two options have been evaluated and compared with the solutions proposed in the previous chapters, both free license and paid, and identified as the best both because they have already been tested and used in the company (Harmonic Calculation Software) and because with the same potential they are free license and easy to use.

## Chapter 8

# Evaluation of harmonic distortion in

## NEPLAN<sup>®</sup>

### 8.1 Introduction to software and analysis

NEPLAN<sup>®</sup> “Electricity” is a tool for analyzing, planning, optimizing and simulating electricity grids. The strength of the software is the extremely intuitive graphical interface with large libraries for network elements, protection devices and control circuits, which allows the user to perform case studies very efficiently. The software has a modular concept, is based on international standards, such as IEC, ANSI, IEEE, etc. and is customizable for the European and American market. It is used in transmission, distribution, generation/industrial networks, among other things for network and investment planning, power quality, multi-period optimization, protection setting and evaluation, dynamic simulation (RMS/EMT), [10].

Through this software it was possible to easily reconstruct the electrical diagram of the network of the Mitsubishi plant where the largest conditioning machines are tested and therefore where you are most interested in quantifying imbalances, distortions and possible malfunctions. The aim is precisely to simulate the behaviour of the network when one or more units are tested and therefore quantify the current and voltage distortions that occur and evaluate whether they fall within the limits of the law and within the limits required by the buyers. The first step was precisely to rebuild the network starting from the electrical diagrams provided by the installers, with the aim of representing the system layout on the software so as to be able to observe the positioning of the cabins where the tests take place and, in particular thus, to be able to highlight the ways in which these are connected to the primary distribution cabinet.

In this chapter we will initially review the ways in which we will implement the network in Neplan, in order to also leave a brief guide to the future user, and then analyze simpler cases in order to verify the correct functioning of the software.

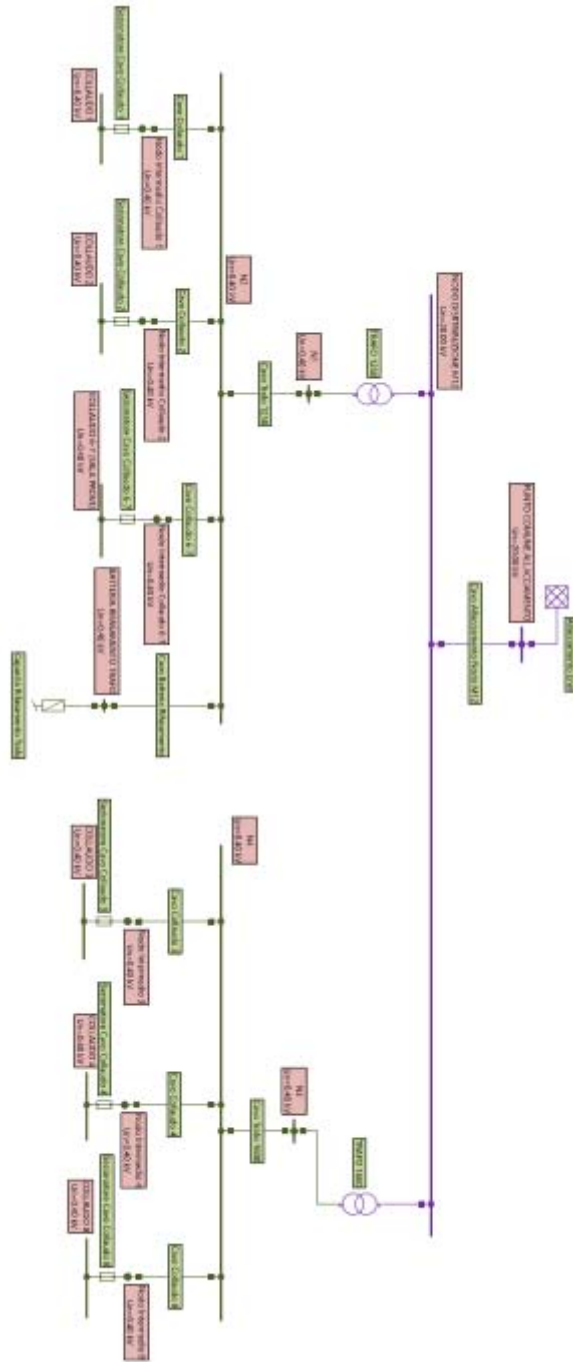


Figure 8.1: MEHITS plant electrical diagram implemented on NEPLAN

From fig.8.1 the complexity of the layout of the plant and the need to have a method to evaluate what happens when one or more test cabins are in operation can be seen. Two transformers are derived from the "Nodo di Distribuzione", each of which underlies the test cabins:

→ **1250 kVA Transformer** to which they are connected: Cabina Collaudo 1, Cabina Collaudo 2 and Testing Room;

→ **1600 kVA Transformer** to which they are connected: Cabina Collaudo 3, Cabina Collaudo



4 e Cabina Collaudo 8;

The wiring diagram allows to obtain the quantities related to the power transformers and cables used for the connection. In particular, the characterization of the connection cables required a more in-depth work since NEPLAN wants input quantities that are not explicitly stated in the data sheets.

## 8.2 Components library

### 8.3 Cable lines

This paragraph presents the calculation methods for cable parameters, as studied in the Electrical Systems class [11], to be included in the program.

#### 8.3.1 Calculation of primary constants of cable conduits

The calculation of the primary constants always refers to the single-phase scheme equivalent to the direct sequence and therefore presupposes both the perfect structural symmetry of the phase conductors and the absence of passive conductors with shields and armors.

##### Calculation of the longitudinal kilometric resistance $r$

The calculation of the direct current resistance is immediate through the use of:

$$r_{cc20^\circ} = 10^3 \frac{\rho_{20^\circ}}{S} \quad (8.1)$$

expressed in  $[\frac{\Omega}{km}]$ , where  $\rho_{20^\circ}$  is the electrical resistivity at  $20^\circ C$  and  $S$  the effective section of the cable.

Once the resistance has been calculated at  $20^\circ C$  it is necessary to bring it back to the maximum operating temperature passing through the temperature coefficient  $\alpha$ :

$$r_{cc\theta_c} = r_{cc20^\circ} [1 + \alpha(\theta_c - 20^\circ)] \quad (8.2)$$

Depending on the type of conductor and insulation, corrective factors are obtained. As is well known, the alternating current resistance  $r_{ca}$  differs from the direct current one in terms of skin effect or proximity effect; generally for LV and MV cables, reference will always be made to the tables supplied by the manufacturers and it will be possible to have:

$$\frac{r_{ca}}{r_{cc}} = 1, 2 \div 1, 6 \quad (8.3)$$

##### Calculation of the operating inductance $L_e$

In the hypothesis that the current distribution is uniform over the whole section of the phase conductor and there are no currents in the metal shields, the longitudinal operating inductance in kilometers can be calculated using the formula:

Reattanza a 50 Hz		
Sezione nominale mm2	Conduttore flessibile di rame non stagnato	
	Unipolari Ohm/km	Multipolari Ohm/km
1,5	0,144	0,100
2,5	0,132	0,094
4	0,122	0,087
6	0,114	0,083
10	0,105	0,078
16	0,098	0,075
25	0,093	0,074
35	0,089	0,072
50	0,085	0,071
70	0,084	0,070
95	0,083	0,069
120	0,080	0,069
150	0,080	0,069
185	0,080	0,069
240	0,078	0,069
300	0,076	0,068

Figure 8.2: Inductance table 50Hz Tratos

$$L_{es} = 0.46 \log_{10} \left( \frac{Ks}{GMR} \right) \quad (8.4)$$

expressed in  $\frac{mH}{km}$  where  $Ks$  corresponds to the geometric mean distance and  $GMR$  to the geometric mean radius.

In our analysis we will use the indications provided by the Tratos [1] cable catalog, in which the inductance value at  $50Hz$  is shown in the following table:

### Calculation of exercise capacity $c_e$

The transverse kilometric capacity of a cable is the capacity between phase and metal screen and is calculated using:

$$c_e = \frac{\epsilon_r}{18 \ln \frac{d_0}{d_1}} \quad (8.5)$$

where  $\epsilon_r$  is the relative dielectric constant of the insulating material,  $d_0$  the outer diameter of the insulating medium excluding the semiconductive state and  $d_1$  diameter of the phase conductor including the semiconductive layer if present.

### 8.3.2 Sequence behavior of cable power lines

For cable conduits the approximation of perfect structural symmetry is more stringent than for overhead lines especially because the active and concentric conductors are strongly coupled with them metallic shields and armor.

In our analysis it is possible to use the following approximations,

$$Z_0 \approx 4Z_{direct} \quad (8.6)$$

regarding inductance; for resistance we have that

$$R_0 = 7R_C. \quad (8.7)$$

From the calculation of these parameters it is possible to fill in the mask of values requested by Neplan,

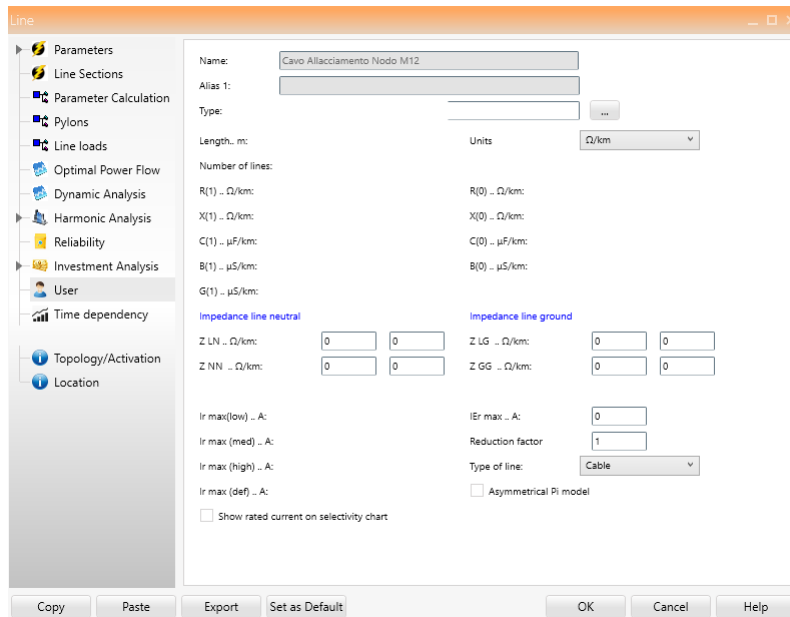


Figure 8.3: Mask cable lines parameters

With the numbers obtained in par.8.3.1, given the large number of cables used and their differences, it was decided to build a library of lines, called *caviMEHITS*, so that you can have them all available within the program.

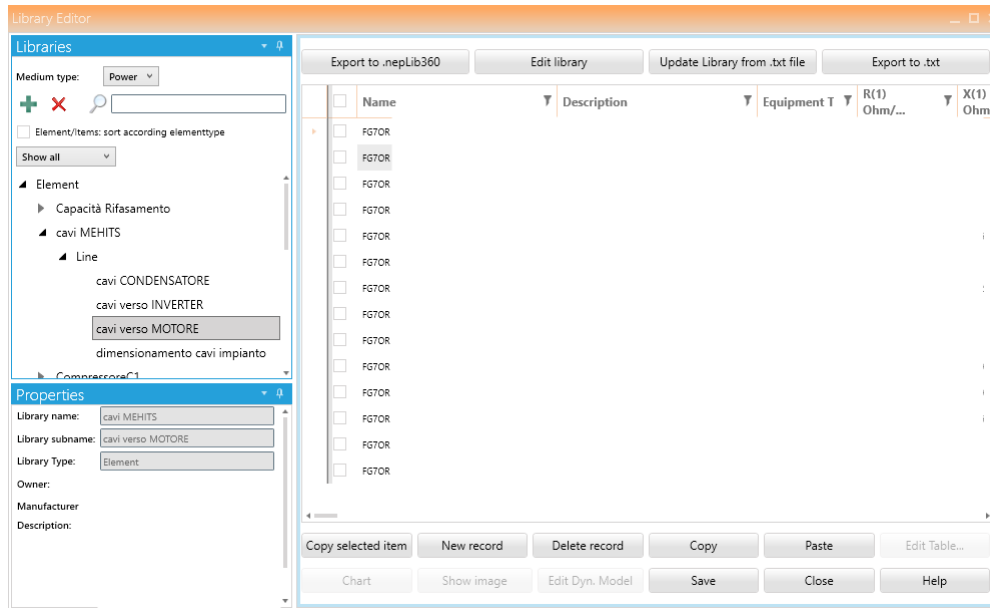


Figure 8.4: cable lines library: *caviMEHITS*

As visible in fig.8.4, it was preferred to distinguish between connection cables to the Condenser, to the Motor and to the Inverter to further simplify the decision when the line is to be characterized.

### 8.3.3 Distorting Load: Inverter

A good characterization of the inverter is the crucial point in order to obtain reliable and truthful results from the simulations. Fig.8.5 shows that such a load requires to enter the data relating to the *harmonic distortion in current*, obtainable from a previous analysis using the Harmonic Calculation Software software or from a Spice simulation.

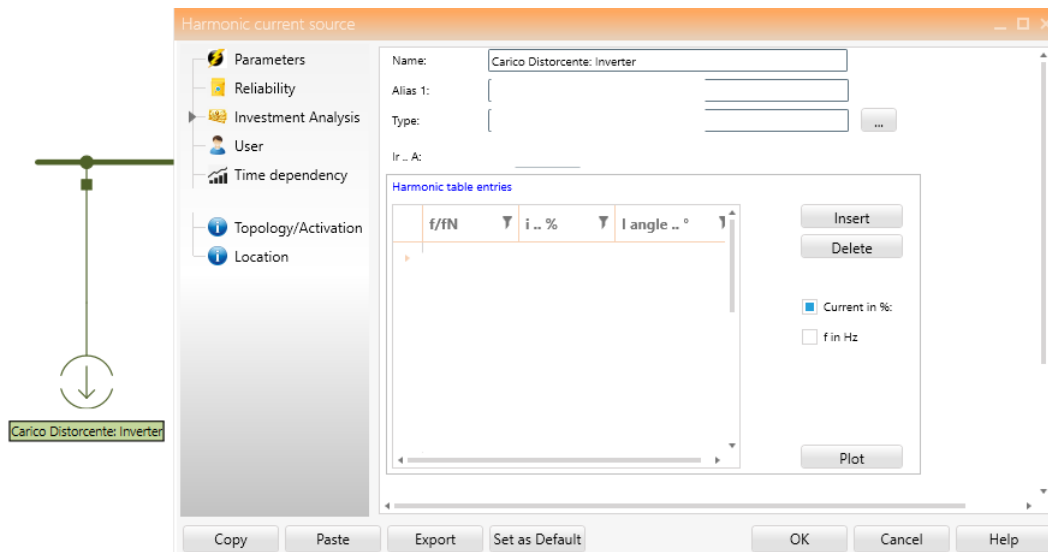


Figure 8.5: Parameterization of a Distorting Load

It is important to note that, in our case, the data relating to the harmonic characterization must be entered as:

- frequency, expressed in harmonic order with respect to the fundamental;
- current in % value, with respect to the value of the fundamental current.

The boxes above the table show the information relating to the element, in particular for the inverter considered, we see that it is connected to the *Collaudo 1*.

Through the command *Plot* it is also possible to view the distorted waveform of current that will be injected into the system, the result is represented in fig.8.6.

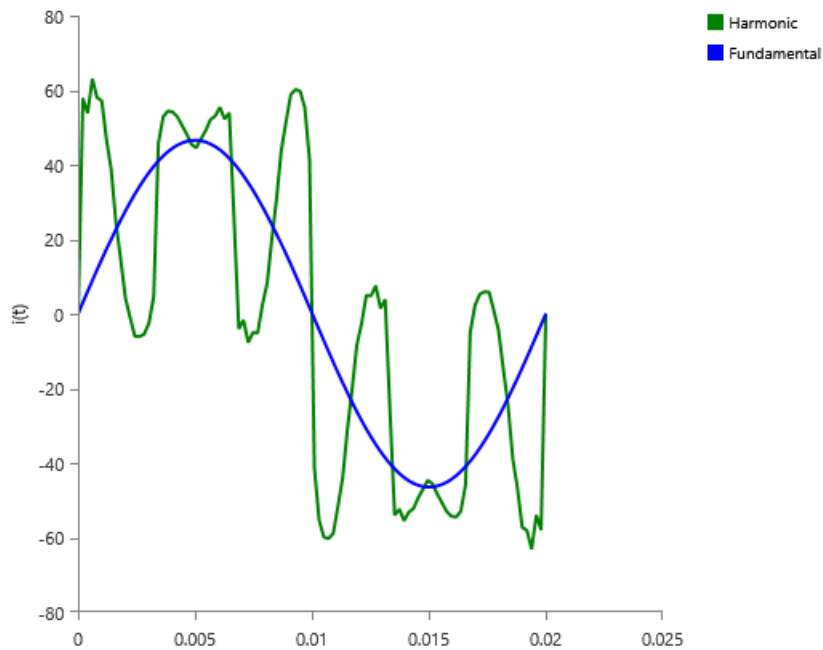


Figure 8.6: *Distorted current in relation to the fundamental at 50Hz*

As done for the lines, also in this case we have chosen to create a library called **CURRENT HARMONICS**, containing all the inverters used in the simulations, as shown in fig.8.7.

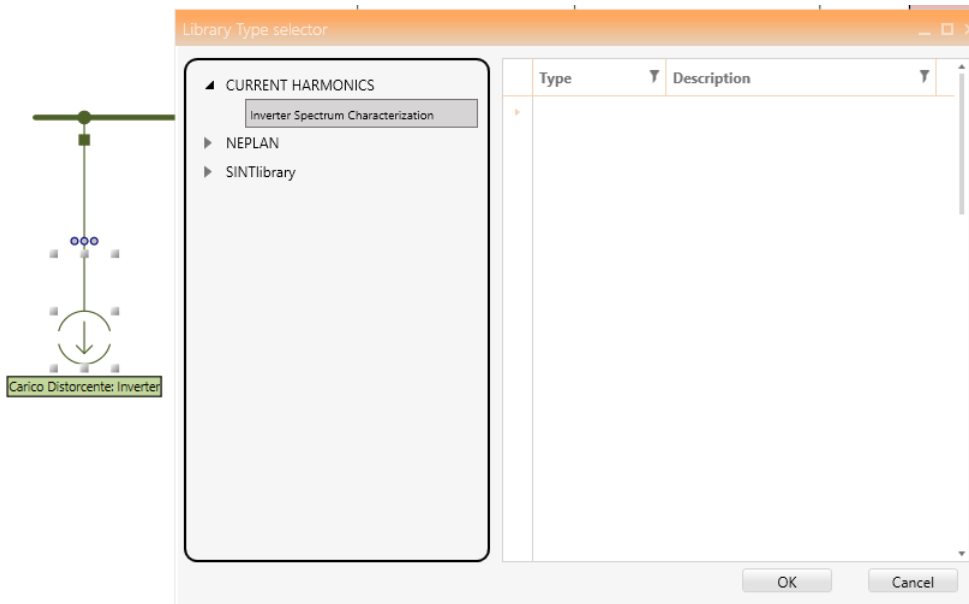


Figure 8.7: Distorted Load Library

In the window relating to the “ Library Type selector ” you can find the various sizes of Inverter and their percentage of operation; each machine has its own harmonic characterization and the current to which it refers, as already shown in fig.8.5.

### 8.3.4 Variable speed compressor: *CMP1*

The *Variable speed compressor*, as far as our simulation is concerned, is described as a simple load since it is not considered for *Harmonic Analysis* as it does not introduce any distortion.

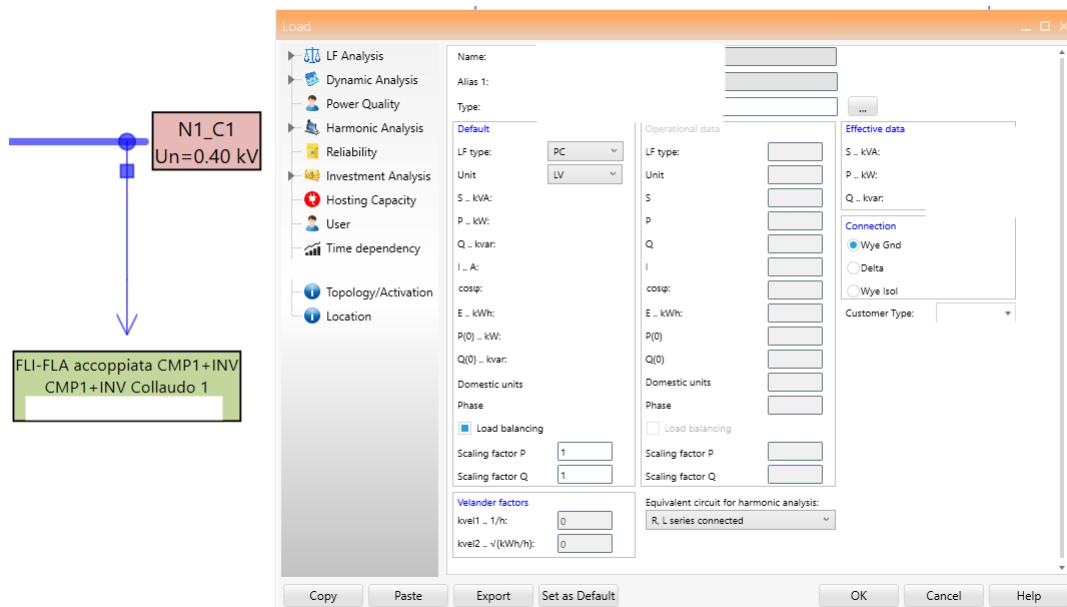


Figure 8.8: *CMP1* Parametrization

For the loads it is possible to enter the data for the analysis of *Load Flow* according to some

modalities, in this case what we had obtained through the Harmonic Calculation Software was the value of the power  $P$  in  $kW$  and the Power Factor  $\cos\phi$ .

$\Rightarrow$  *LF type: PC*

So, by inserting only these two information in the load mask, NEPLAN will automatically calculate the rest. Since there are numerous sizes and work percentages, a library of variable speed compressors is featured, containing all the information necessary for the simulations.

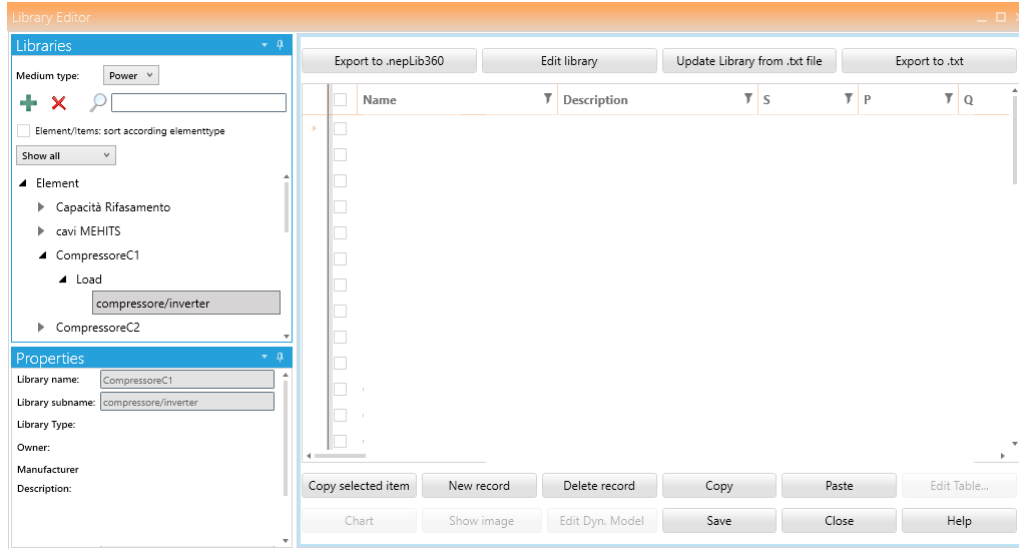


Figure 8.9: Variable speed compressor library

### 8.3.5 Fixed speed compressor library: *CMP2*

The *Fixed speed compressor*, as far as our simulation is concerned, is described as a simple load since it is not considered for *Harmonic Analysis* as it does not introduce any distortion.



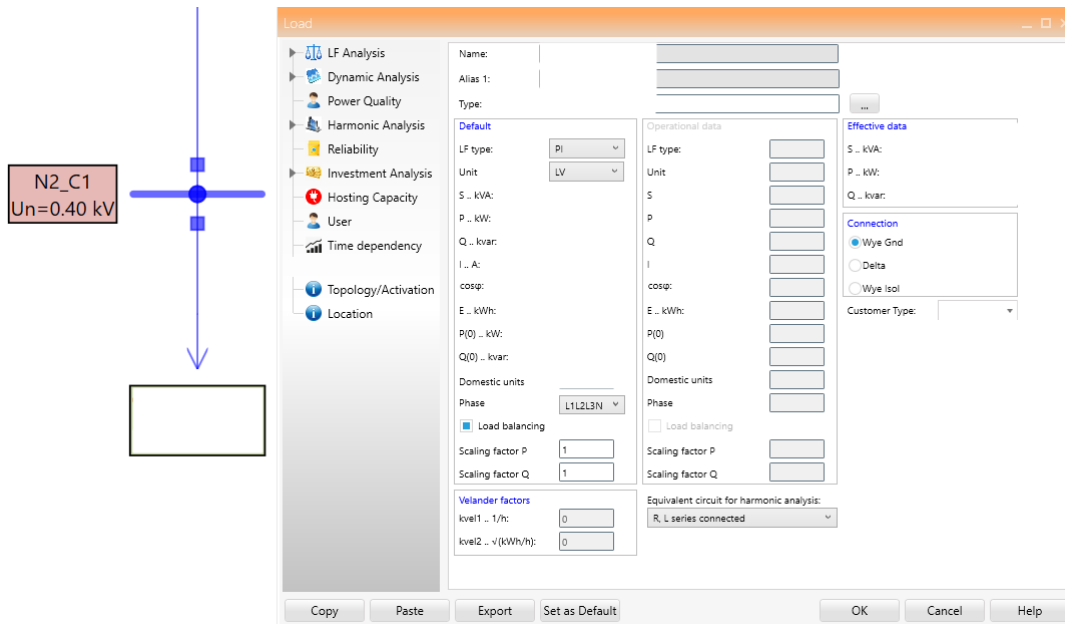


Figure 8.10: *CMP2* Parametrization

For the loads it is possible to enter the data for the analysis of *Load Flow* in some ways, in this case what we had obtained through the Harmonic Calculation Software was the power value  $P$  in  $kW$  and the value of streams  $I$  into  $A$ .

⇒ *LF type: PI*

So, by inserting only these two information in the load mask, NEPLAN will automatically calculate the rest. Since there are numerous sizes and work percentages, a library of variable speed compressors is featured, containing all the information necessary for the simulations.

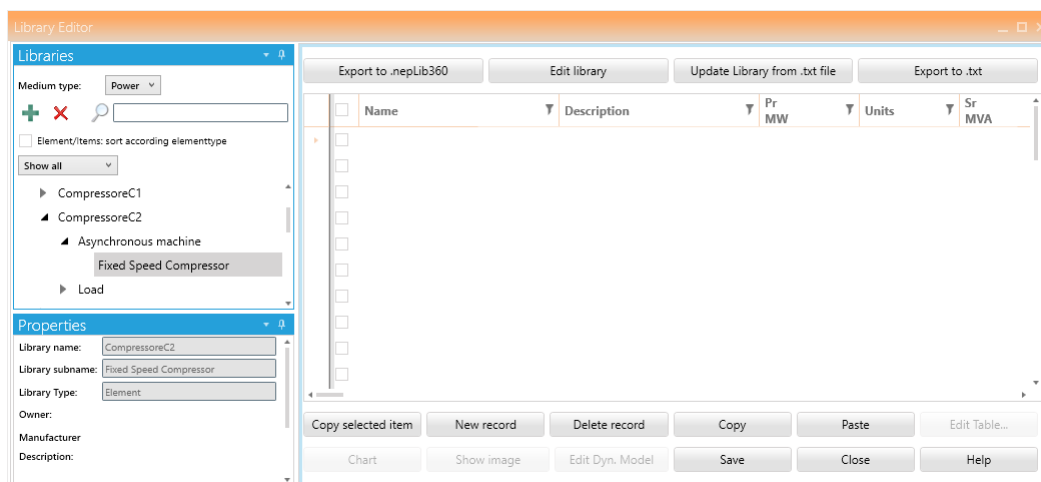


Figure 8.11: *Fixed speed compressor library*

## 8.4 Task Overview

The purpose of the simulations was, in principle, to prove the veracity of the results proposed by the software; for this purpose two Case Studies have been designed, each of them with a goal to be confirmed. Subsequently, a comparison will be made between the values obtained by the software previously used for these analyzes, such as the Harmonic Calculation Software, in order to verify the goodness of what is obtained from NEPLAN and the correctness of the results that have always been used for sizing the unit.

### 8.4.1 Description of the unit in analysis

*Machine 2* is used for this job.

These machines, represented in fig.8.12, are described in the Mitsubishi online page [8] as single-circuit indoor unit for the production of chilled water with screws optimized to work with low compression ratios driven by fixed speed and variable speed motors (Inverter Driven), with the use of R134a refrigerant, electronic expansion valve, tube bundle condenser and flooded tube bundle evaporator with high heat transfer coefficients, both designed and manufactured by Mitsubishi Electric Hydronics & IT Cooling Systems SpA.



Figure 8.12: *Machine 2*

This machine is represented in the NEPLAN environment according to the scheme proposed in fig.8.13

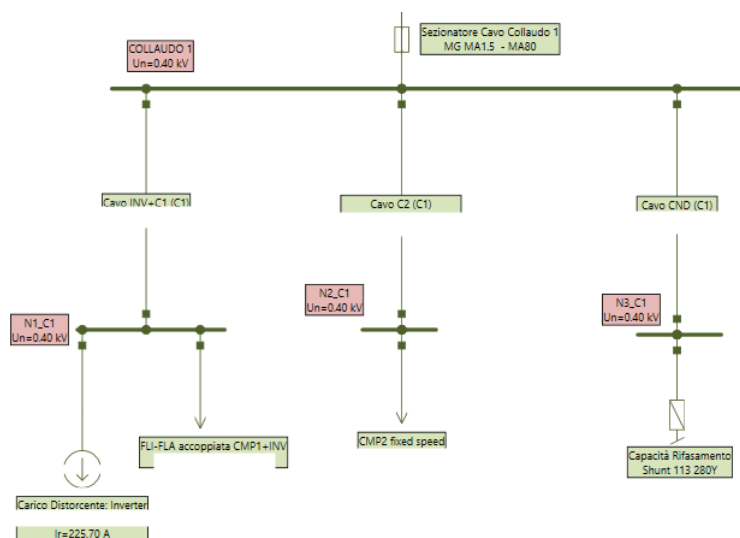


Figure 8.13: *Characterization of Machine 2 in NEPLAN*

The components that stand out are:

- *Variable speed compressor + Inverter*, described through the two loads connected to **N1\_C1**;
- *Fixed speed compressor*, represented by the load connected to **N2\_C1**;
- *Power factor correction capacity*, described by the Shunt located in **N3\_C1**.

## 8.5 Scenario 1

M12 electrical diagram is modified by inserting *Machine 2*, of different size, at each test booth, obtaining a first variant composed by:

1. *Cabina Collaudo 1 e Cabina Collaudo 3* → operating at 100%;
2. *Cabina Collaudo 2 e Cabina Collaudo 4* → working at 100%;
3. *Sala Prove e Cabina Collaudo 8* → operating at 100%.

### Case Study 1 Target

In this first scenario we want to calculate and graph the values of  $THD_v\%$ ,  $THD_i\%$  and  $PowerFactor(PF)$  which are obtained at nodes *NODO DISTRIBUZIONE* and *COLLAUDO 1*.

Assuming now to keep constant the units inside the test cabins underlying the  $1250kVA$  transformer and to vary, according to a certain logic, the partialisations of the various units under test under the  $1600kVA$  transformer in order to verify the first study hypothesis:

*As the load percentage of the machines under test changes in Cabins 3, 4, 8 we will notice marked variations in the values of  $THD_v\%$ ,  $THD_i\%$  and  $PowerFactor(PF)$  to the NODO DISTRIBUZIONE M12 while the same values obtained for the NODO COLLAUDO 1 will not vary.*

To obtain a significant number of data and therefore more reliable results, it was decided to do iterations  $n$  starting from the situation of **minimum load** on the  $1600kVA$  transformer up to get a condition of **maximum load**, on the same transformer, according to the steps:

**iter 0** → *unit at 50%* on all test cabins

**iter 1** → *unit working at MAX* on all test cabins

↓

**iter n-1** → *unit at 50%* on all test cabins

**iter n** → *unit operating at MAX* on all test cabins

### 8.5.1 Results and Considerations

From the simulations in NEPLAN, starting with *Load Flow* and then *Harmonic Analysis*, the desired results are obtained which can be easily exported to Excel to be able to visualize them

graphically.

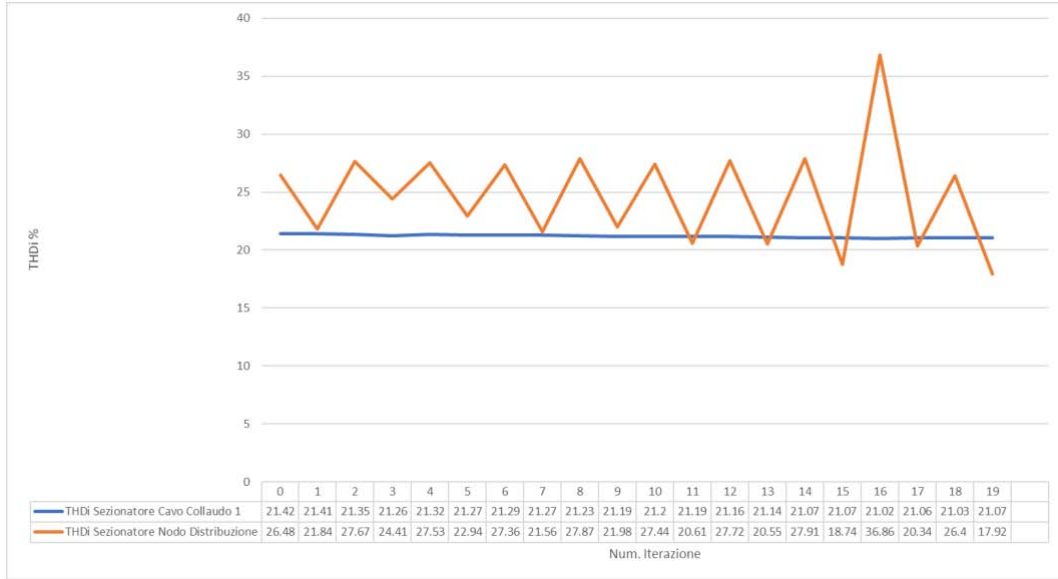


Figure 8.14:  $THD_i\%$  variation nearby the nodes under observation

From fig.8.14 it can be seen that for load variations on a network branch subtended by the  $1600kVA$  transformer the value of  $THD_i\%$  measured in the proximity of the NODO DISTRIBUZIONE varies at each iteration while the value of  $THD_i\%$  measured closed to the COLLAUDO 1 node remains constant throughout the analysis.

⇒ this outcome **confirms the hypothesis made for the first scenario!**

It should be noted that we are talking about the measurement made "in the proximity of the node" since the  $THD_i\%$  is a property of the element and not of the node, in this regard a switch element has been inserted (*Circuit Breaker*) on which current flows to obtain the desired measurement. From the graph proposed above, the presence of a peak in the distortion values in correspondence with iteration 16 immediately catches the eye, that is when the machine (*working at 50%*) is working without the contribution of the fixed speed compressor.

### THDi% variations upstream and downstream of the transformer

The transformers used in the MEHITS plant network, therefore reported in NEPLAN, are of the *Dyn11* type and have a primary and secondary transformation ratio equal to:

$$K_{Dy} = \frac{V_{1n}}{V_{2ny}} = \frac{I_{2ny}}{I_{1n}} \quad (8.8)$$

and since the value  $THD_i\%$  refers to the current circulating respectively at the primary and secondary of the transformer, the value obtained upstream and downstream of it will be almost unchanged since both the line current and the current distorted take into account the transformation ratio. In our case we have a  $V_{1n} = 20kV$  and a  $V_{2n} = 400V$  this means that the  $K_{Dy} = 50$ , as already said, however, both the quantities that define the current distortion are multiply by this index, confirming that the  $THD_i\%$  will not change significantly.

To take into account the *hour index*, that is the phase shift between primary and secondary of the transformer since this allows to obtain a little less distortion, in fact in the case in which third harmonics of currents or their multiples were present, these would cancel each other out. This can be seen in fig.8.15.

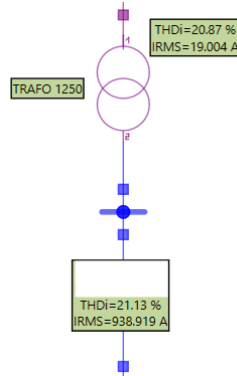


Figure 8.15: THD variation of Dyn11 time group transformer

## 8.6 Scenario 2

M12 electrical diagram is modified, as already done in par.8.5, by inserting *Machine 2*, of different size, at each test cabin, obtaining a first variant consisting of:

1. *Cabina Collaudo 1 and Cabina Collaudo 3* → operating at 100%;
2. *Cabina Collaudo 2 and Cabina Collaudo 4* → working at 100%;
3. *Sala Prove and Cabina Collaudo 8* → operating at 100%.

### Case Study 2 Target

In this second scenario we still want to calculate and graph the values of  $THD_v\%$ ,  $THD_i\%$  and *PowerFactor(PF)* which are obtained to the *NODO DISTRIBUZIONE* and *COLLAUDO 1* nodes as already done in 8.5 and, in addition, to the *SALA PROVE* and *COLLAUDO 2* nodes and to the heads of both transformers.

Since **the first hypothesis has been confirmed**, the part of the network underlying the 1600kVA transformer is neglected and attention is paid to the network part under the 1250kVA transformer. Assuming now to keep constant the unit present inside the *CABINA COLLAUDO 1* and to vary, according to a certain logic, the partializations of the various units in testing the *CABINA COLLAUDO 2* and in *SALA PROVE* in order to verify a second hypothesis of study:

*As the load percentage of the machines being tested in "Cabina 2" and in the "Sala Prove" changes, it is expected to obtain marked variations in the values of  $THD_v\%$ ,  $THD_i\%$  and PowerFactor(PF) at the "NODO DISTRIBUZIONE" and at the "COLLAUDO 2" and "SALA PROVE" nodes while waiting for a more modest variation, of the same values, near the "COLLAUDO 1" node.*

As done for the previous scenario, iterations  $n$  are simulated starting from the situation of **minimum load** on the nodes "COLLAUDO 1" and "SALA PROVE" until you get a condition

of **maximum load**, according to the steps :

**iter 0** → *unit working at 50% COLLAUDO 1 and SALA PROVE cabins*

**iter 1** → *unit operating at MAX COLLAUDO 1 and SALA PROVE cabins*

⇓

**iter n-1** → *unit working at 50% COLLAUDO 1 and SALA PROVE cabins*

**iter n** → *unit operating at MAX COLLAUDO 1 and SALA PROVE cabins*

### 8.6.1 Results and Considerations

From the simulations in NEPLAN, starting with *Load Flow* and then *Harmonic Analysis*, the desired results are obtained which can be easily exported to Excel to be able to visualize them graphically.

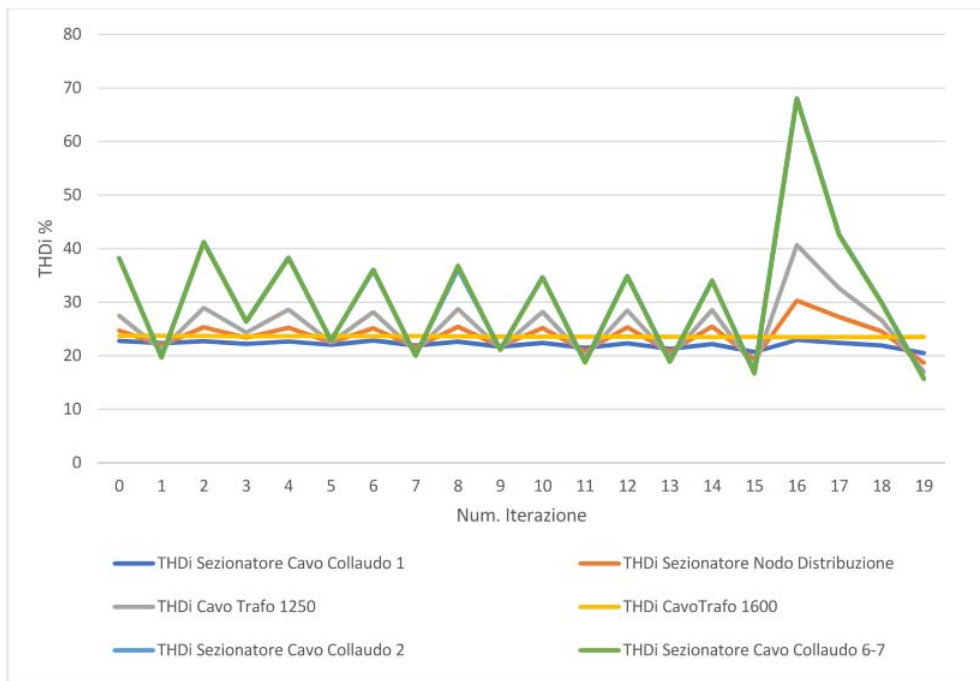


Figure 8.16: *THDi% variation near the nodes under observation*

Fig.8.16 gives us further confirmation that load variations on a network branch subtended by a transformer, in this case the one from  $1250kVA$ , do not involve variations of  $THD_i\%$  on the other branch of the network (connected through the  $1600kVA$  transformer) while more or less high variations are found in the other measurement points.

The most significant variations of  $THD_i\%$  are measured near the "COLLAUDO 1" and "SALA PROVE" nodes where, at each iteration, a different load and partialisation is taken into account; the slightest variations in distortion in the current are recorded in the vicinity of the "COLLAUDO 1" node which seems to be affected in an unimportant way by the changes on the nearest cabins.

⇒ these results **confirm the hypothesis for the second scenario!**

## 8.7 Machine 3 Simulation

Also this type of study wants to evaluate the goodness of Neplan's results starting from simulations of units of which we know all sizes; in particular we want to see the variations that occur in the distortion value when an active harmonic filter, "AHF" is installed, compared to the value of  $THD_i\%$  that is obtained when it is not in function.

### 8.7.1 Unit Features

The unit in question is made up of 2 compressors and 10 pairs of fans; since we do not have the individual absorption and distortion measurements of the machines that form it, we are forced to simulate the unit in a Neplan environment, characterizing it as a single distorting load, which takes into account the distortions of all the components, with the relative absorption.



Figure 8.17: Machine 3

### 8.7.2 Simulation Targets

From this case study, we want to achieve multiple objectives:

- Check, starting from measurements carried out on site, the variation of the distortion according to the testing room in which the unit was tested, since each room refers to a different transformer:

- Since the active harmonic filters, "AHF", have been installed in the units, both the case in which they are operating and when they are off will be evaluated in order to see how the THDi values vary;
- Check the truthfulness of the results obtained by Neplan and the goodness of the same.

Data are proposed here with whom the distorting loads and the absorption of the unit were characterized and, subsequently, the results of the Neplan simulations in each room and for the filter conditions in off and on were reported.

## **Sala Collaudo 2**

⇒ **AHF OFF**



⇒ AHF ON

Testing Center

⇒ AHF OFF

⇒ **AHF ON**

#### **Sala Collaudo 4**

In the case of testing in Sala 4, unlike what was done in the other rooms, more tests were made;

- Unit electrically and physically in Sala 4,

⇒ **AHF OFF**

⇒ AHF ON

- Unit physically in Sala 4 but electrically in Sala Prove,

⇒ **AHF OFF**

⇒ AHF ON

### 8.7.3 Comments and Considerations

The results obtained from Neplan simulations *are aligned* with the real measurements on the machines, in fact we see how the values of  $THD_i$  and those of  $THD_v$  do not differ much from the ones reported in the screens of the network analyzer; the few percentage points of which the results differ may derive from two different reasons:

1. Not knowing which other units are present in the network at the time of testing, we are unable to verify the possible influences that these may have on the same measurements;
2. By inserting the harmonic spectrum values reported by the network analyzer (i.e. current harmonics up to 15° order) to characterize the distorting load, it is possible that some harmonic components with important distorting value have been left out.

→ in support of this, the fact that, in the cases described in par. 8.7.2 the distorting loads have been characterized up to the harmonic of order 30 and the results obtained from the simulations are even closer to the real ones.

3. By comparing the tests made with the same machine, which was initially physically and electrically located in Sala 4 and subsequently physically located in Sala 4 and electrically in Sala Prove, we obtain variations on the  $THD_i$  as we expected.

## 8.8 Machine 4 Simulation

Let's now consider a smaller unit than the one analyzed in par. 8.7, of which all the values necessary for the analysis are known and, moreover, it is possible to take into account the presence of another working machine in a cabin connected to the same transformer.

### 8.8.1 Unit Characterization

The unit in question is made up of 2 *compressors* and 10 *pairs of fans*; since we do not have the individual absorption and distortion measurements of the machines that form it, we are forced to simulate the unit in a Neplan environment, characterizing it as a single distorting load, which takes into account the distortions of all the components, with the relative absorption.



Figure 8.18: *Machine 4*

### 8.8.2 Simulation Targets

The main objective we want to obtain from this case study is to verify the validity of the network analyzer measurements, now taking into consideration the influence that another machine has in a test room connected to the same transformer. The configuration therefore, is shown in fig. 8.19, is given by:

- **Machine 4** in Sala Collaudo 2 → powered by a  $1250kVA$  transformer;
- **Machine 5** in Sala Collaudo 1 → supplied by a  $1250kVA$  transformer.

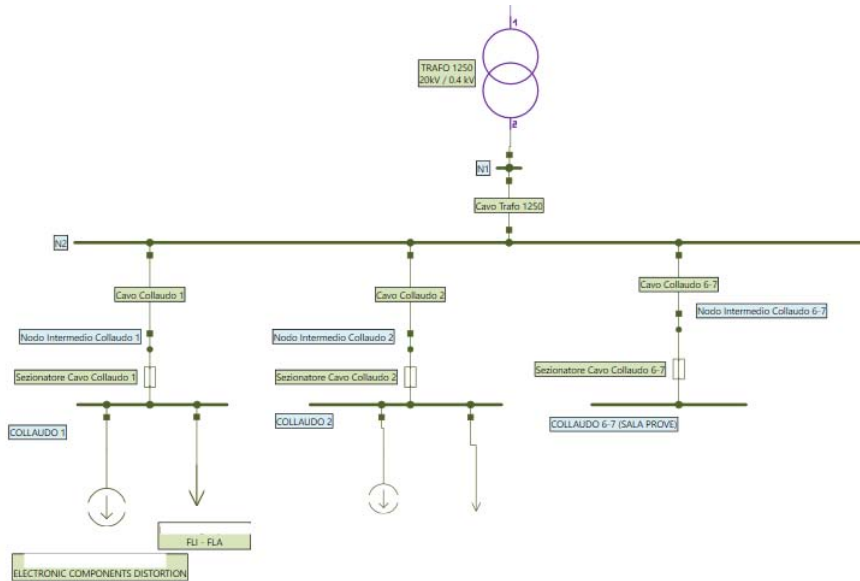


Figure 8.19: Modeling of the network scheme on Neplan in the case of two units under test

### 8.8.3 Machine 5

what we know about this unit:

- absorption.
- we are assuming a 1% distortion due to the presence of power electronics.

The data with which the distorting loads and the absorptions of the unit have been characterized are proposed here, and subsequently the results of the simulations in Neplan in each room and for the filter conditions in off and on are reported.

### 8.8.4 AHF OFF Case



### 8.8.5 AHF ON Case

### 8.8.6 Conclusion

The results obtained from Neplan simulations are in line with the real measurements on the machines, in fact we see how the values of  $THD_i$  and those of  $THD_v$  do not differ much from those shown in the screens of the network analyzer; the interaction with the unit connected in Collaudo 1 causes the distortion to vary but also in this case nothing more can be said than what was already known about the two units and their interactions. Up to now Neplan has not been able to give me more information than what I already know and whose measures I already have!

⇒ you will need to find a way to make Neplan work better!

## Chapter 9

# Spice software Simulations

### Introduction

In this last chapter we report the considerations and results of the study carried out in LTSpice, born from the need to reproduce the variations of  $THD_i\%$ , which are obtained by connecting several distorting devices in parallel to the same bar, of which on the Harmonic Calculation Software can be taken into account. The first step will therefore be to bring us back to the same situation as in the Harmonic Calculation Software and to do this, the LTSpice software was chosen in which it is possible to reconstruct the network and circuit diagram of the inverter device and reproduce its effects.

This is a "**reverse engineering**" procedure which allows us, starting from the result of the phenomenon described on the Harmonic Calculation Software, to go backwards to obtain an operating mode, using Spice software, in order to be able to see the same results on Neplan and take Neplan's potential and use possibilities to a higher level.

Knowing the values of the internal components of the inverters used in the units, it is possible to simulate their behaviour and subsequently use the Spice instrument coupled with Neplan. In particular with this study we want to try to find a general method that allows to characterize the inverter in its components  $L, C, R$  so that it can reproduce the model in the Neplan network. First we will start with the characterization of the network upstream of the rectifier bridge so that it is the same in all our simulations and therefore the starting point; to do this it is necessary to know the values related to the equivalent network and relative to the transformer used inside the Harmonic Calculation Software.

### 9.1 Harmonic Calculation Software input data

The Harmonic Calculation Software allows to obtain the harmonic characterization in current and voltage of an inverter, as well as its distortion index, and works on a very extensive database of actual tests carried out; characterizing the network to which the device is connected, the desired values of  $THD_i\%$  are obtained. In our study we will start from standard network values, which however do not differ much from the real ones of an industrial network, which can then be adapted to the specific case; in particular the Harmonic Calculation Software for the upstream network

uses as input:

MV short circuit power	9999MVA
Transforme size	1000kVA
Nominal secondary	400V
Transformer impedance	5.5%
Frequency	50Hz

Table 9.1: *Data relating to the network used in the Harmonic Calculation Software*

As for the inverter, it is possible to choose the size and characteristics of the machine in an internal library of the program, in our case we used an inverter with these characteristics:

### 9.1.1 Harmonic Calculation Software results

Starting from the values presented in par.9.1 we simulated various situations and reported below the first two in which the decrease in the distortion value already stands out:

- connection of only 1 inverter to the busbar;
- connection of 2 inverters to the same bus, in parallel.

The two scenarios are shown respectively in fig.9.1 and in fig.9.2.

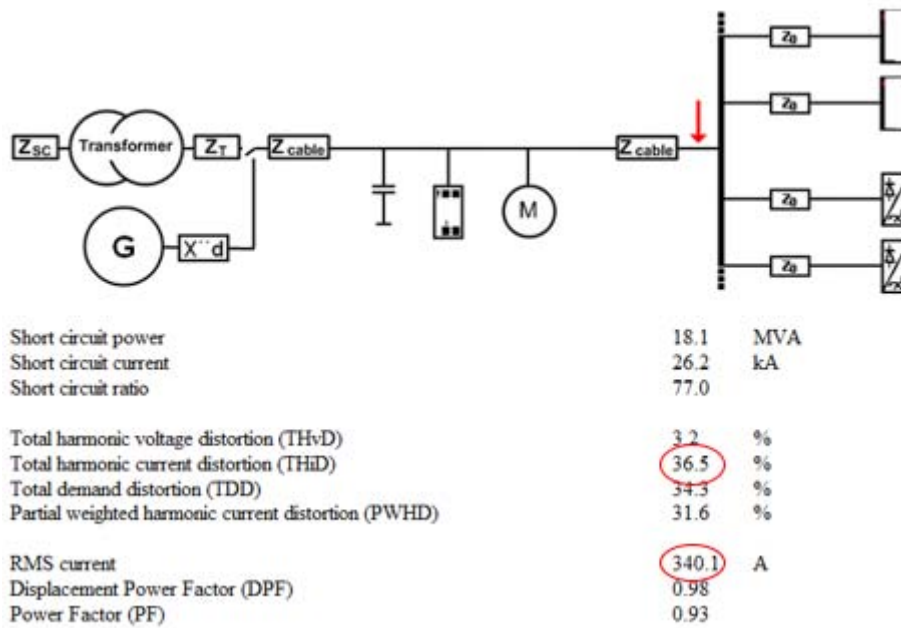


Figure 9.1: Harmonic Calculation Software simulation results, case 1 inverter

The results that interest us most in case there is 1 inverter are:

- $THD_i = 36.5\%$
- $RMS_{current} = 340.1A$

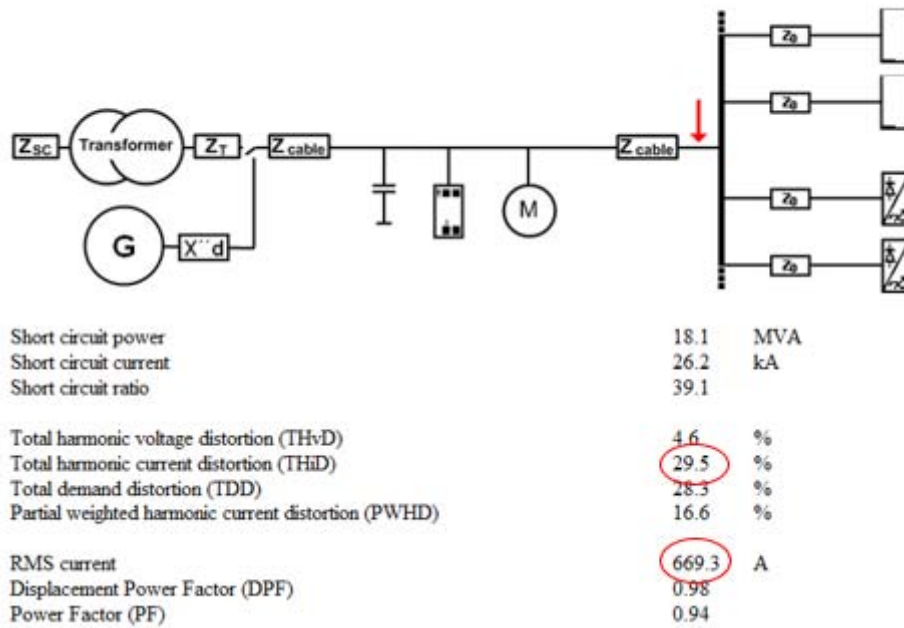


Figure 9.2: Harmonic Calculation Software simulation results, case 2 inverters in parallel

If instead there are 2 inverters:

- $THD_i = 29.5\%$
- $RMS_{current} = 669.3A$

⇒ therefore we notice how inserting more inverters in parallel to the same bus the value of  $THD_i\%$  tends to decrease!

One parameter that can be seen to vary between the two configurations is the "Short circuit ratio", defined as the ratio  $Z_{cc} = \frac{Z_{seq.zero}}{Z_{directseq}}$ ; we want to understand what this variation can entail and what parameters it refers to.

### Short circuit ratio variation analysis

Consider the presence of multiple inverters connected to the same busbar to see how the Short circuit ratio value varies;

Inverter number	Short Circuit Ratio
1	77
2	39.1
3	26.2
4	19.6
5	15.6
6	13
7	11.1
8	9.6
9	8.5
10	7.6
11	6.9
12	6.3
13	5.7
14	5.3
15	4.9

Table 9.2: Short circuit ratio variation as the number of inverters increases

We note that the value of the short circuit ratio parameter undergoes a decrease of about half of its previous value with the increase in the number of inverters that are connected to the same busbar and therefore with the increase of the  $Z_0$  of the connection cables.

→ we want to try to understand if it is possible to determine the contribution part of the inverter; taking as reference the  $Z_0$  for  $\approx 0$  inverters present, we could obtain the contribution of the cable only, and seeing how this varies, identify whether or not the contribution given by the machine is being taken into account.

The variation of the Short circuit ratio is of the type:

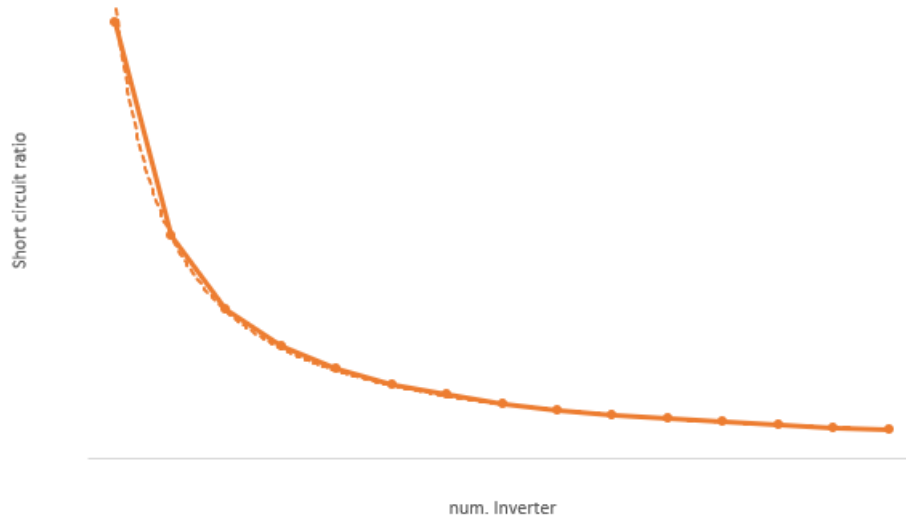


Figure 9.3: Variation of the Short circuit ratio parameter as the inverters increase in parallel

- if we consider that the inverter behaves like an ideal current generator then its contribution is zero and it is only  $Z_0$  to vary the short circuit ratio;
- if instead we consider that the cables, therefore the  $Z_0$ , we have an equal contribution for each inverter that is inserted, then starting from the case  $\approx 0$  inverter we will divide precisely by 2 for the contribution of the only  $Z_0$  and the remainder will be related to the inverter.

## 9.2 Network characterization

As mentioned in the introductory paragraph, we need to characterize the equivalent network upstream of the inverter device in a timely manner so that it can be transferred to the other software used for analysis and keep it constant during all simulations. The network scheme used in the Harmonic Calculation Software can be represented as in fig.9.4.



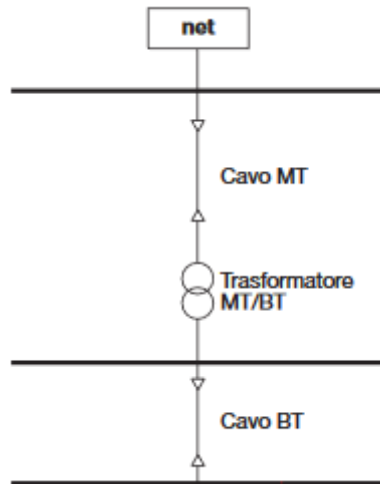


Figure 9.4: Example diagram of network under analysis

### 9.2.1 Equivalent impedance value in Spice

#### Transformer

$$Z = \frac{v_n \%}{100} \times \frac{V_{2n}^2}{S_n}$$

$$R_{transformer} = \frac{p_k \%}{100} \times \frac{V_{2n}^2}{S_n}$$

$$X_{transformer} = \sqrt{Z^2 - R_{transformer}^2}$$

$$\Rightarrow L_{transformer} = \frac{X_{transformer}}{2\pi \times 50}$$

#### Upstream power supply network

$$Z_{net} = \frac{V_{2n}^2}{S_{k''}}$$

$$\Rightarrow L_{net} \approx \frac{Z_{net}}{2\pi \times 50}$$

## Connecting cable

$$Z_{cable} = L \times (r_{cable} + x_{cable})$$

$$\Rightarrow L_{cable} \approx \frac{Z_{cable}}{2\pi \times 50}$$

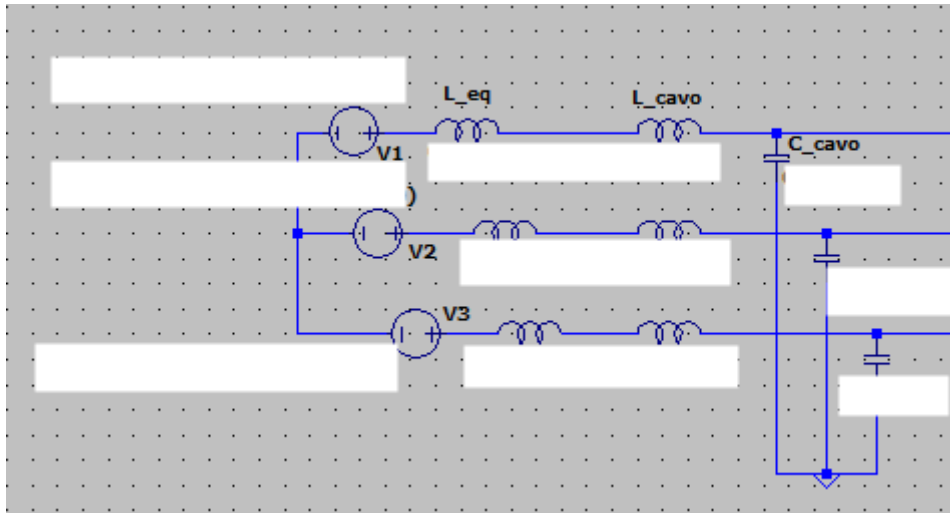


Figure 9.5: Equivalent network upstream the bridge rectifier

### 9.3 Spice simulations

In order to build the electrical diagram of the machine to simulate and compare the result with that of the Harmonic Calculation Software in Spice, we started from some considerations, such as:

- the power supply network common to all simulations is the one used in the Harmonic Calculation Software and presented in par. 9.2;
- takes into account having two inductances on the DC side, one in the upper part and one in the lower part of the model;
- both the case with a central  $C$  capacity and the case with double capacity  $C_1 = C/2$  and central socket with earth connection will be simulated;  $\rightarrow$  for simplicity, only the single capacity case will be used given the similar results.
- the value of the  $R_{load}$  will be obtained on the basis of the RMS value of the current flowing through the AC inductance, the value of which is provided by previous simulation in the Harmonic Calculation Software.

$\Rightarrow$  basically we have two unknowns, **the values of L, C.**

It will be an **iterative procedure**, starting from the initial hypothesis of two values for L and C;

To get the correct  $R_{load}$  value such that " $RMS_{HarmonicCalculationSoftware} = RMS_{I_{Linv}}$ " we extrapolate the data point by point from the current waveform  $I_{Linv}$  e we calculate the root means square value in excel as:

$$x_{RMS} = \sqrt{\frac{1}{N} \sum_1^N x_i^2} \quad (9.1)$$

From this we can obtain, through various simulations and corrections of the values of L and C, that the circuit components that allow me to obtain a circuit equivalent to the Harmonic Calculation Software, keeping the network upstream of the rectifier bridge constant

By inserting these quantities into the Spice circuit we obtain the following circuit diagram:

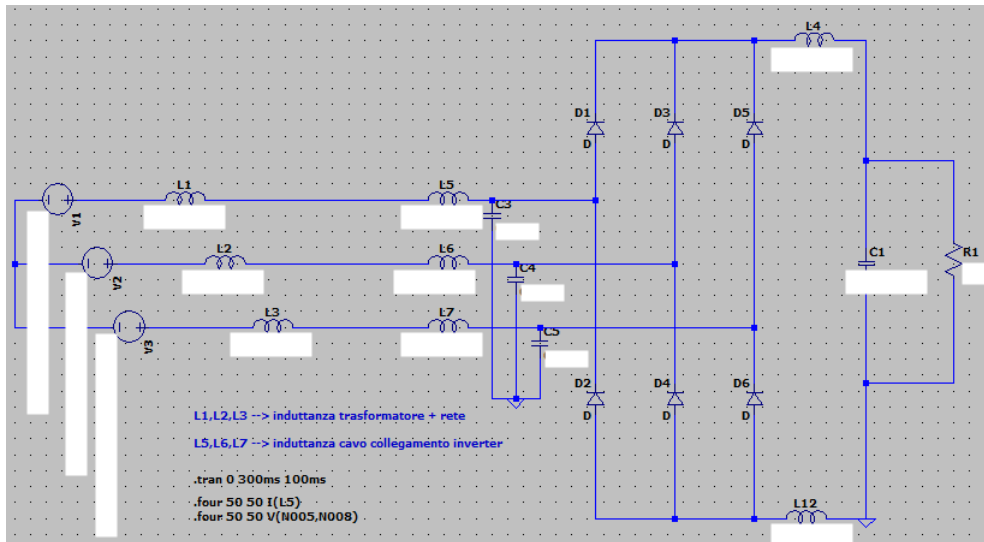


Figure 9.6: Inverter model used for Spice simulations

In Spice simulations, the insertion of several inverters in parallel takes place simply by copying and pasting the circuit diagram of the model, taking into account both its line of connection

to the equivalent network that of its inductances and capacities and filter; these elements cause **to change the network response!**

With this configuration it is possible to notice the decrease in the current distortion value, just as it was obtained from the Harmonic Calculation Software in par.9.1.1.

## 9.4 Neplan simulation

As already introduced, the purpose of the simulations made so far has been to reproduce the results obtained in the Harmonic Calculation Software and Spice also on Neplan, paying particular attention to the fact that, as the number of inverters connected in parallel to the same bus increases, has a **decrease of  $THD_i\%$** .

⇒ Our goal will be precisely to be able to reproduce this statistical variability which tends to compensate the harmonic currents as the number of inverters increases, reaching a saturation point where, it is expected, that the curve will not decrease further.

### 9.4.1 Inverter characterization in Neplan

To correctly characterize the Inverter unit in Neplan it is necessary to take into account that:

- each system that I insert in parallel must be characterized by its own L and C, by its distorting load and by its absorption;
- each system contributes by injecting a distorted current.

This can be achieved with the configuration shown in fig. 9.7

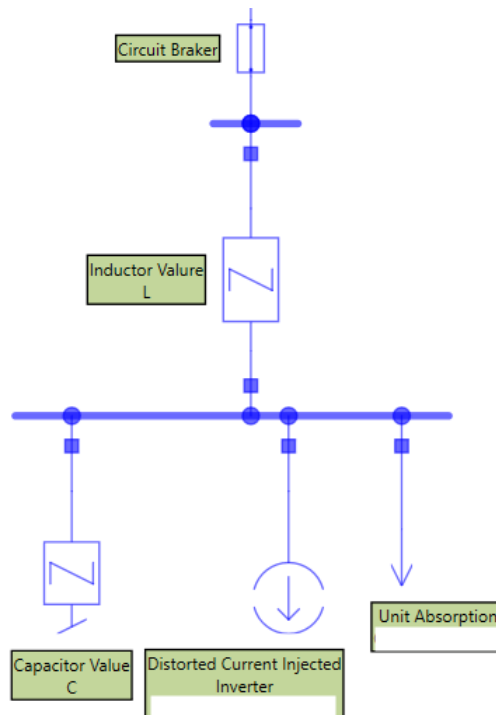


Figure 9.7: Inverter model used for Neplan simulations

The characterization of the distorting load is obtained starting from the data relating to the harmonic spectrum of the single inverter provided to us by the Harmonic Calculation Software, namely:

Harmonic order	Harmonic current [%]	Harmonic current [A]
1	100	319
5	31	101
7	13.5	43
11	8.1	25
13	5.2	16.5
17	4.3	13.7
19	3.1	9.8
23	2.7	8.5
25	2.1	6.6
29	1.7	5.6
31	1.4	4.6
35	1.2	3.7
37	1.0	3.3
41	0.8	2.6
43	0.7	2.3
47	0.6	1.8
49	0.5	1.7

Table 9.3: *Harmonic current spectrum of the inverter*

## 9.5 Analysis Results and Comments

To highlight the variability of the value of  $THD_i\%$  to the circuit breaker, the Harmonic Calculation Software initially considered the presence of a single inverter up to the case of 10 devices connected in parallel to the same busbar; With the same logic these simulations are made on LTSpice and Neplan and the results obtained, in terms of  $THD_i\%$  and  $THD_v\%$ , are presented in fig.9.8 and in fig.9.9.

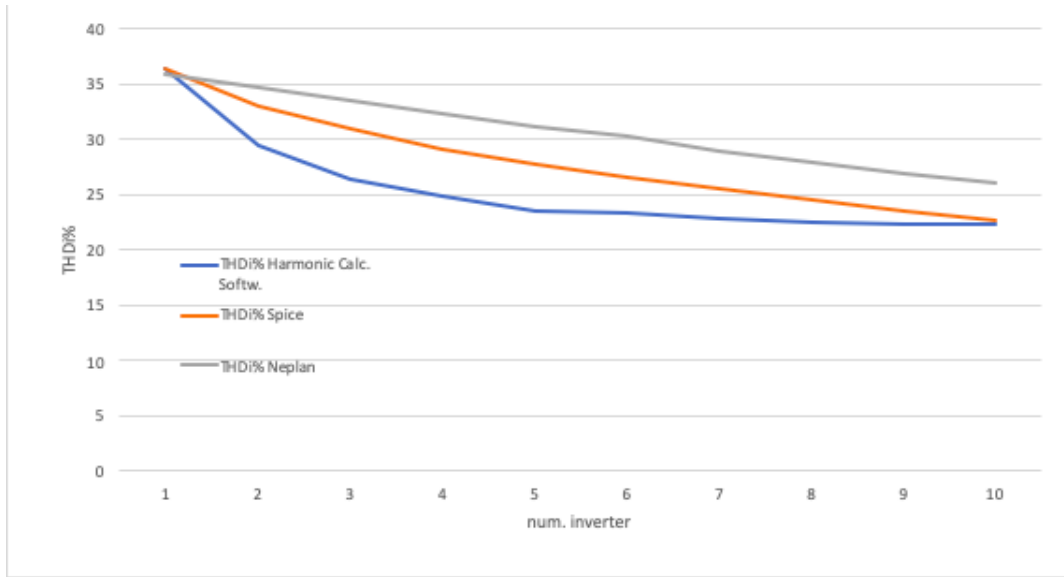


Figure 9.8: Variation of the value  $THD_i\%$  as the number of inverters in parallel increases

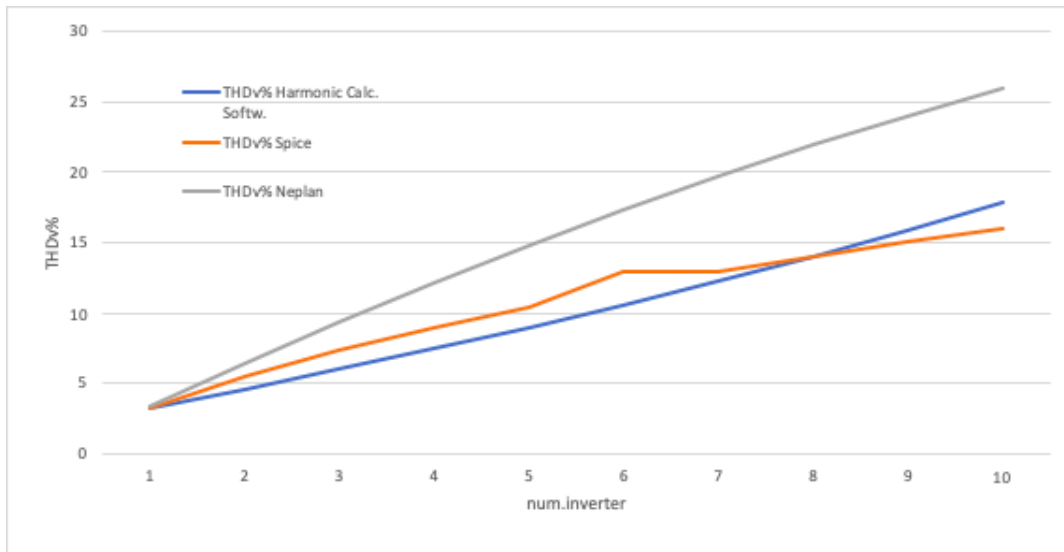


Figure 9.9: Variation of the value  $THD_v\%$  as the number of inverters in parallel increases

### 9.5.1 Considerations

As can be seen from the graphs proposed, Neplan gives me the precautionary case, that is the worst one, since in the analysis it considers all the current harmonics in phase between them and the sum. Statistically, however, the currents injected into the network by the devices are not in phase with each other and therefore there is a reduction effect, which both the Harmonic Calculation Software and LTSpice take into account. To obtain a result closer to the real one it would be advisable to modify the phases of the injected harmonic currents a little to obtain this compensation effect. Since the Spice simulation returns the values of the angles of the various current harmonics, it is possible to use this data on Neplan. The results show that:

- the angles of the current harmonic components are not generated in a random manner by the software;
- by varying the number of inverters connected in parallel to the same busbar, the phase shifts vary.

The most important harmonic components present a variation of the angles, as the number of inverters changes, which can be represented as:

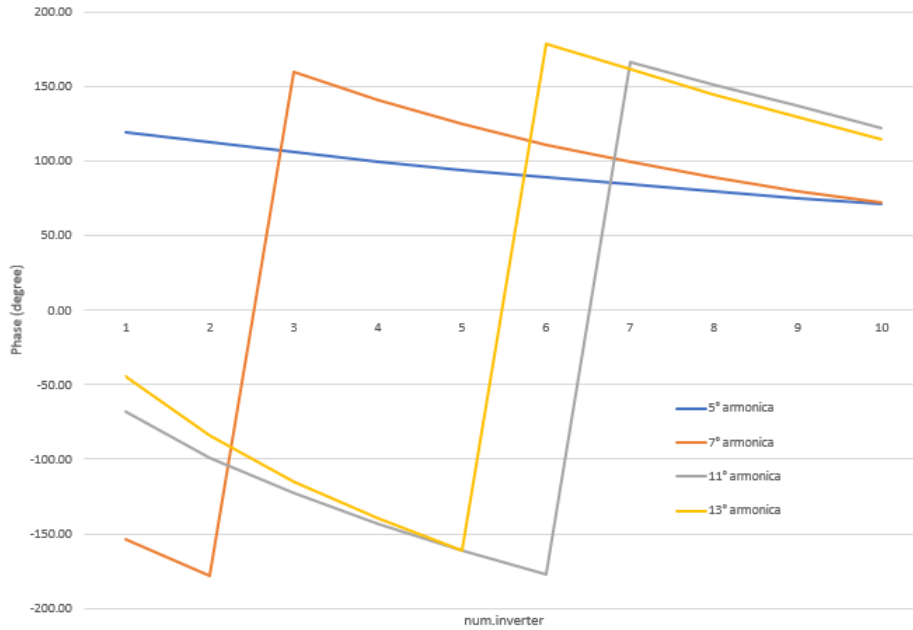


Figure 9.10: Variation of the phase value as the number of inverters in parallel increases

With further simulations, however, we realize that the phase angle  $\phi$  of which we tried to obtain the trend actually remains constant at the same harmonic current, as the number of inverters changes.  $\Rightarrow$  you need to watch the fundamental current!

In fact, we see how as the load increases, the voltage drops on the line impedance increase and the effect obtained is that of obtaining a reduction of the harmonic currents, therefore of the distortion. The fundamental of current undergoes a reduction. While in Pspice I have the exact circuit model with which it is possible to take into account the variation of the voltage at the terminals, thus proposing a result more similar to reality, on Neplan the load is represented by an ideal current generator that injects a certain current value regardless of the voltage at the terminals. Neplan's simplified model does not take into account the change in voltage due to increased falls.

We consider and represent the grid sizes in Spice if 1 inverter and 2 inverters are connected to the network;

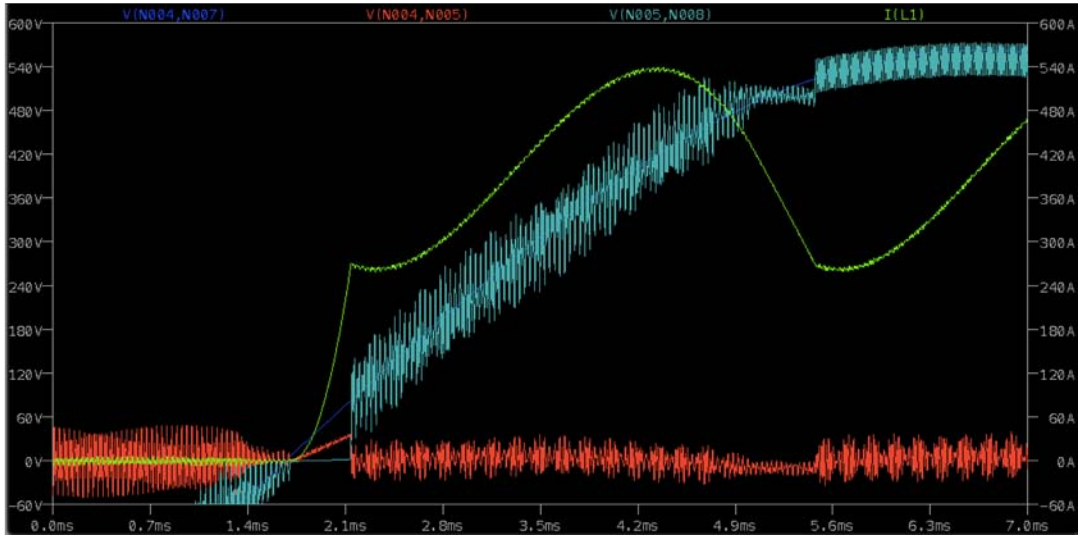


Figure 9.11: Voltages and current with the connection of 1 inverter

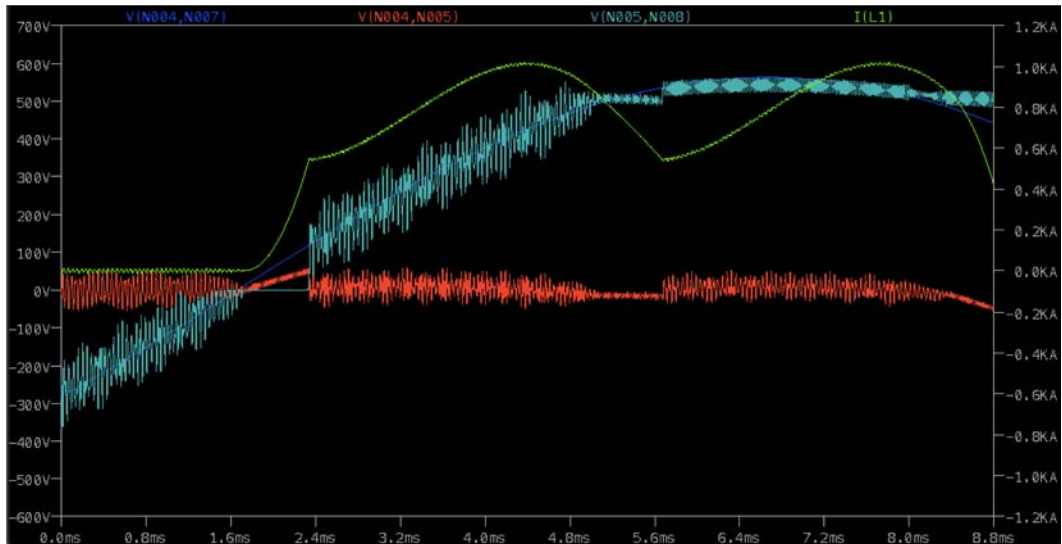


Figure 9.12: Voltages and current with the connection of 2 inverters

The quantities we are observing are:

- the inverter current in Yellow;
- in Blue the voltage downstream of the ideal voltage generator, which remains sinusoidal;
- in Red the voltage across the mains chokes;
- in Light Blue the voltage downstream of the mains choke

Once again cases from 1 to 10 inverters connected in parallel have been simulated, see C.1 and it can be seen that as the number of inverters increases, the load increases and therefore the voltage drop on the inductance of network (in red) therefore there is a drop in the fundamental current.

By reporting the data obtained from the simulations on Excel, it was possible to graph these variations to better explain the phenomenon. In fig. 9.13 it can be seen how the voltage



downstream of the mains inductance drops in terms of the fundamental component, while the other harmonic components increase. This fact explains the increase in the  $THD_v\%$  as the number of inverters connected to the same bus increases.

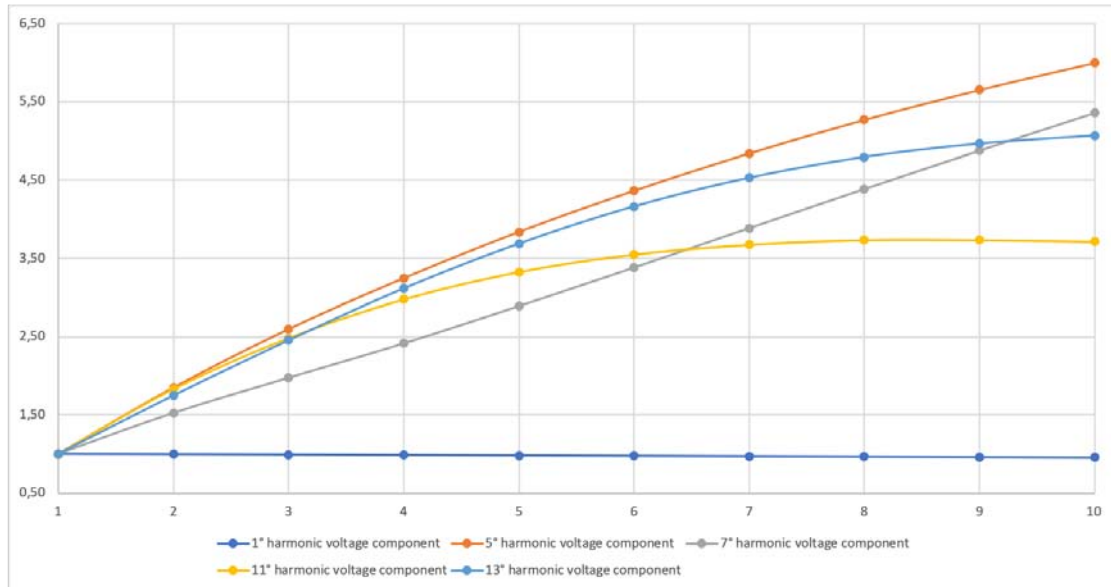


Figure 9.13: Voltage harmonic component variation downstream the main choke

Let us consider the only fundamental voltage component downstream of the mains choke, shown in fig. 9.14,

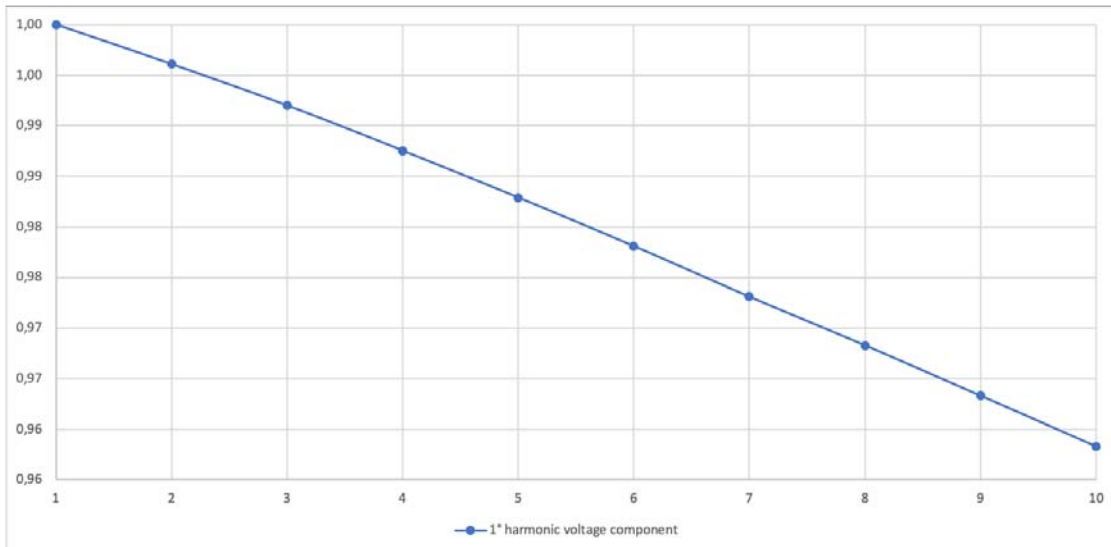


Figure 9.14: Variation of the 1° harmonic voltage component downstream the main choke

this decreases because the fundamental of the voltage drop across the mains inductance increases, as can be seen in fig. 9.15.

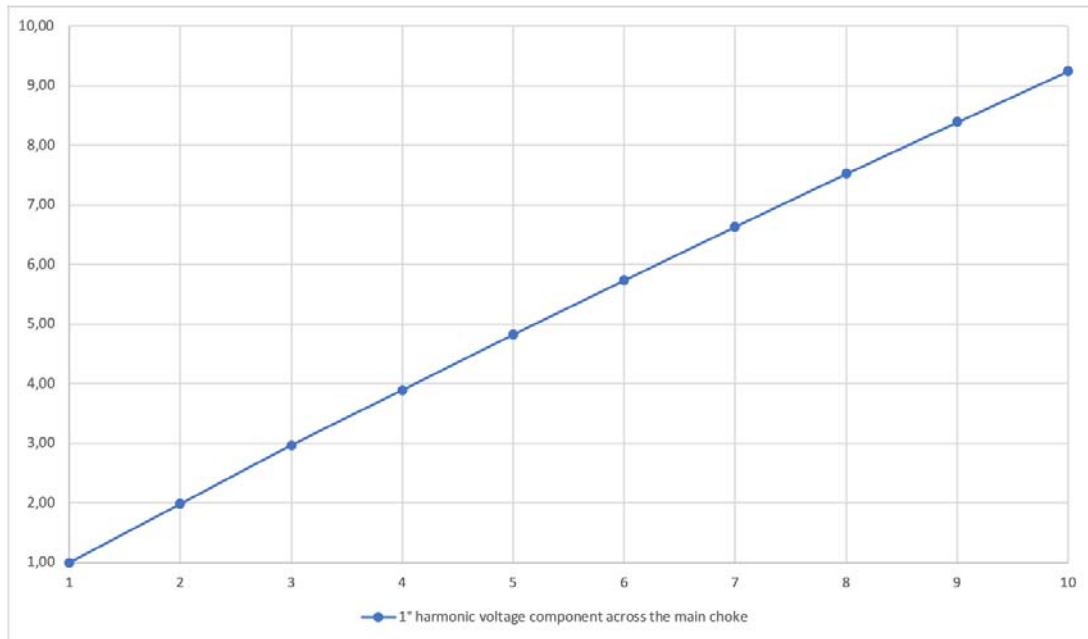


Figure 9.15: Variation of the 1° harmonic voltage component across the main choke

Now, since decreasing the fundamental voltage the network is more charged, the harmonic components of current will also decrease, as shown in fig. 9.16

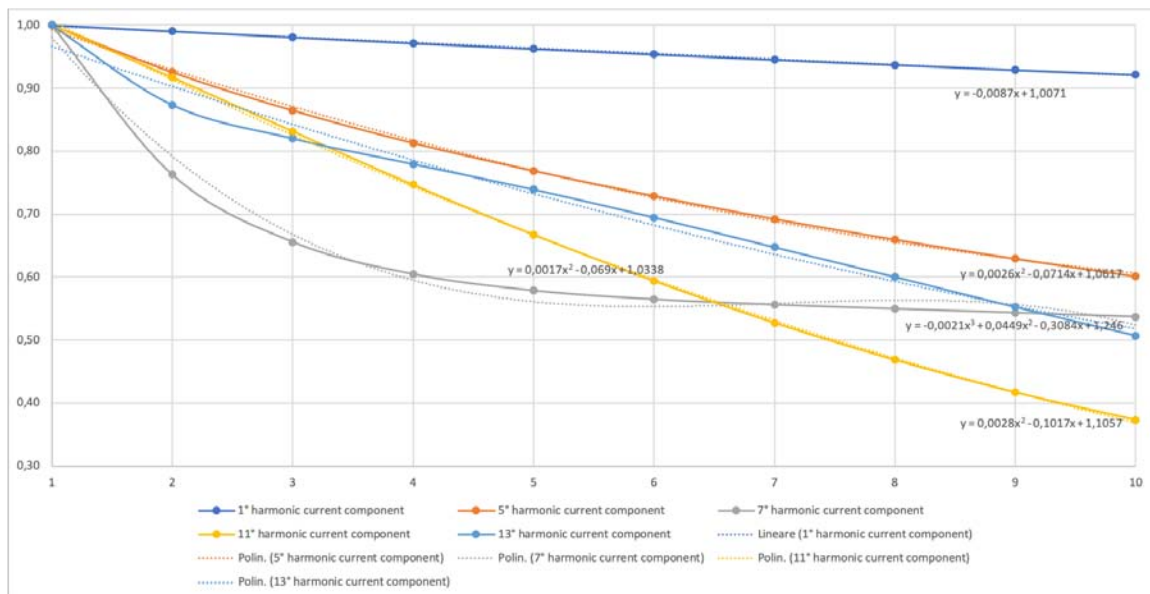


Figure 9.16: Current harmonic component variation

By averaging the harmonics trend lines, the polynomial describing the trend line of the decrease of the  $THD_i$  of the Spice presented in fig. 9.8

If you want to obtain different current harmonics as the number of inverters changes, the polynomial formulas referring to a certain harmonic order will be applied to obtain the variation.

## Chapter 10

# Conclusions

It can be said that the objectives of this work have been achieved. Neplan, in fact, using the reverse engineering strategies and the measures proposed in the last chapter has proven to be a functional tool for the analysis of harmonic distortion caused by the connection to the industrial network of air conditioning machines. In particular, we have seen how, based on the data made available, one path can be followed rather than another. The strong point of the analysis is the fact that it can be used in conjunction with Neplan free license software such as the Harmonic Calculation Software, to obtain the harmonic characterization of the inverter, and LTSpice to simulate the equivalent circuit and to obtain the phase shifts of the harmonic components. The trend of the results and the error obtained, as shown in par.9.5, demonstrates the goodness of the analysis and the fact that Neplan, compared to the other two software, is a precaution, therefore the worst case returns. The limits of the program emerge when you do not have a complete knowledge of the plant's working situation; this is demonstrated in par.8.8 where you have all the values needed to characterize the unit in Neplan but you are not aware of the machines operating in the other test cabins at the time of the measurements, this implies that the results Neplan simulations are in line with the real measurements on the machines (in fact the  $THD_i\%$  values do not differ much from those obtained through the network analyzer) but not knowing which other units are present in the network at the time of the measurements we are unable to verify the possible influences that these can have on the measurements themselves.

In light of the results obtained and the considerations made so far, we can think of the future development of this work as an application on a real case of the analysis carried out starting from the considerations made in the chapter.9. Knowing the capacitance values and the inductance of the DC bus, I can simulate the operation with Spice, varying the load R, reconstructing all the harmonic components, in this way the inverter will be organized for all its operating percentages. Therefore finding the law of variation of the harmonic components we can use it on Neplan for the simulation (with the same grid) in the case of  $n_{inverter}^{\circ} > 1$ .

If you do not know C, L it is not possible to perform the spice simulation or have an idea of the value of  $THD_i\%$ , but it will be possible to start from real measurements on single distinct loads constant of the equivalent network) and, applying the polynomial law of variation of the harmonic components on Neplan, it will be possible to take into account the variability of  $THD_i\%$  as  $n_{inverter}^{\circ}$  varies.

# Appendix A

## Harmonic analysis calculation method

### A.1 Introduction

Through this analysis we want to understand the diversity of the methodologies that NEPLAN offers for the calculation of harmonic distortion and to present a comparison of the various results obtained following the demonstrations.

### A.2 Harmonic sources

Sources with non-linear current-voltage characteristics are for example converters and arc furnaces. As a rule, these devices are represented by a current source of harmonics. Harmonic currents with their frequencies, amplitudes and phase angles depend on the construction and operation of these devices. In the ideal case, the harmonic currents of the converters can be calculated as follows:

$$I_k = \frac{1}{k} I_1 \quad (\text{A.1})$$

where  $k = n * p \pm 1$ ,  $n = 1, 2, 3, \dots$ ,  $I_k$  = k-th current harmonic,  $I_1$  = first current harmonic,  $p$  = number of converter pulses.

## A.3 Calculation algorithm

For a harmonic calculation, the following measures will be taken for each frequency you are interested in:

- Determination of the elements of the equivalent circuit  $R(f), L(f)$  (frequency dependent) and  $C$ ;
- Creation of the access matrix  $Y(f)$  for the network;
- Solution of the system of linear equations  $I(f) = Y(f)U(f)$ .

where,  $I(f)$ : vector of the node currents at the frequency  $f$ ;  $Y(f)$ : Y matrix at the frequency  $f$ ;  
 $U(f)$ : vector of the node voltages at the frequency  $f$ ;

For the impedance calculation, the program will take a fictitious current source (1.0 pu) for the node of interest. A constant amplitude, a constant phase angle and a frequency range will be related to the source. For all frequencies in this range, the program calculates the voltage in the nodes of interest. With the relationship between voltage and current for all frequencies, the program calculates the impedances (size and angle).

## A.4 Sum of harmonics from different sources

The addition of harmonics is usually done in vector mode. Consequently, the sum of two harmonic sources (voltage or current) with equal amplitude can vary considerably, between 0% and 200%. The problem is that in practice the harmonic angles in the sources are unknown. Therefore, there are four different ways to make adding harmonics, which come from different sources:

1. Vector;
2. Geometric;
3. in accordance with IEC 61000-2-6;
4. Arithmetic.

For each harmonic source and each harmonic, the network equation  $I(f) = Y(f)U(f)$  will be solved. The angle indicated in the harmonic sources is not considered for all calculations, *except for the calculation of the vector sum*. After calculating all the voltages for each source and harmonic, the sum can be constructed as follows:

1. Vector,  
The sum is constructed in a vector way:

$$U_h = U_{h1} + U_{h2} + U_{h3} + \dots$$

2. Geometric,  
The sum is constructed geometrically:

$$U_h = \sqrt{U_{h1}^2 + U_{h2}^2 + U_{h3}^2 + \dots}$$

3. IEC 61000-2-6,

The sum is constructed accordingly IEC 61000-2-6:

$$U_h = k_1|U_{h1}| + k_2|U_{h2}| + k_3|U_{h3}| + \dots$$

4. Arithmetic,

The sum is constructed arithmetically:

$$U_h = |U_{h1}| + |U_{h2}| + |U_{h3}| + \dots$$

The sizes proposed above mean:

- $U_h$ : node voltage for harmonic h;
- $U_{h1}$ : node voltage for the harmonic h caused by the harmonic source 1;
- $U_{h2}$ : node voltage for the harmonic h caused by the harmonic source 2;
- $U_{h3}$ : node voltage for the harmonic h caused by the harmonic source 3;
- $k_1$ : diversity factor for h harmonic and harmonic source 1;
- $k_2$ : diversity factor for h harmonic and harmonic source 2;
- $k_3$ : diversity factor for h harmonic and harmonic source 3.

The size of the  $k_i$  depends on the harmonic order h and the ratio between the voltage of the node  $U_{hi}$  caused by the single harmonic source  $i$  and the node voltage calculated arithmetically  $U_h$ .

The k factor can otherwise be calculated as:

$$k = \frac{\sum(I_h * h_h)^2}{\sum(I_h)^2}$$

*The vector sum is mathematically the correct one, but it can be very wrong in practice due to unknown angles of the harmonics. The geometric sum gives the smallest value and the arithmetic sum the highest value.*

→ If the node voltage for the h th harmonic is known, the harmonic currents for all branches can be calculated.

#### A.4.1 Analysis mode:: *Vector*

#### A.4.2 Analysis mode: *Geometric*

#### A.4.3 Analysis mode: *IEC 61000-2-6*



#### A.4.4 Analysis mode: *Arithmetic*

## A.5 Analysis mode results

The results obtained in the different simulations were compared to see how the calculation method affects the final result, in the fig.A.1 and in fig.A.2 the variations undergone by the  $THD_i$  and the  $THD_v$  are reported. In these cases, account is taken of what happens when two inverters of the same type are connected to the same busbar.

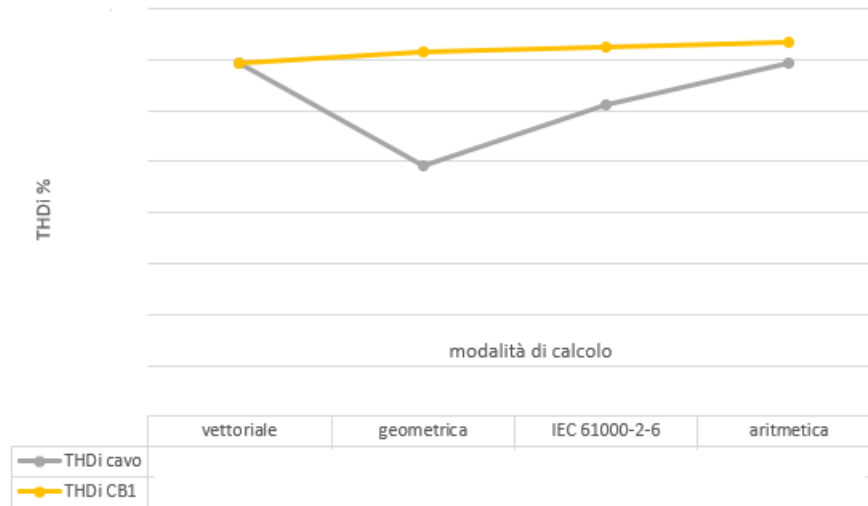


Figure A.1: Variation in the value of  $THD_i$  obtained by the different calculation methods

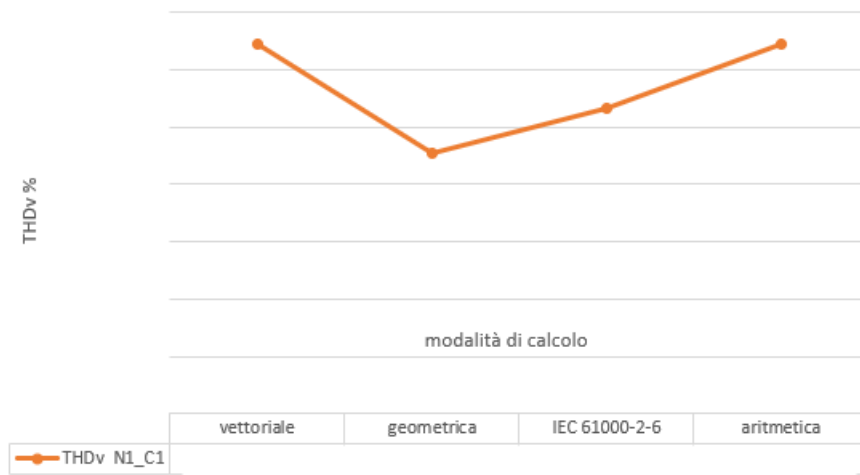


Figure A.2: Variation in the value of  $THD_v$  obtained by the different calculation methods

## Appendix B

### Inverter Mitsubishi

# Appendix C

## Network size variations

### C.1 Spice Curves

This paragraph shows the Spice curves obtained from the simulations starting from 1 inverter up to the case with 10 devices connected in parallel to the same busbar; in this way it is possible to notice the increase in the voltage drop across the inductors and the consequent decrease in the value of the current fundamental.

The quantities under observation are:

- the inverter current in Yellow;
- in Blue the voltage downstream of the ideal voltage generator, which remains sinusoidal;
- in Red the voltage across the mains chokes;
- in blue the voltage downstream of the mains choke.

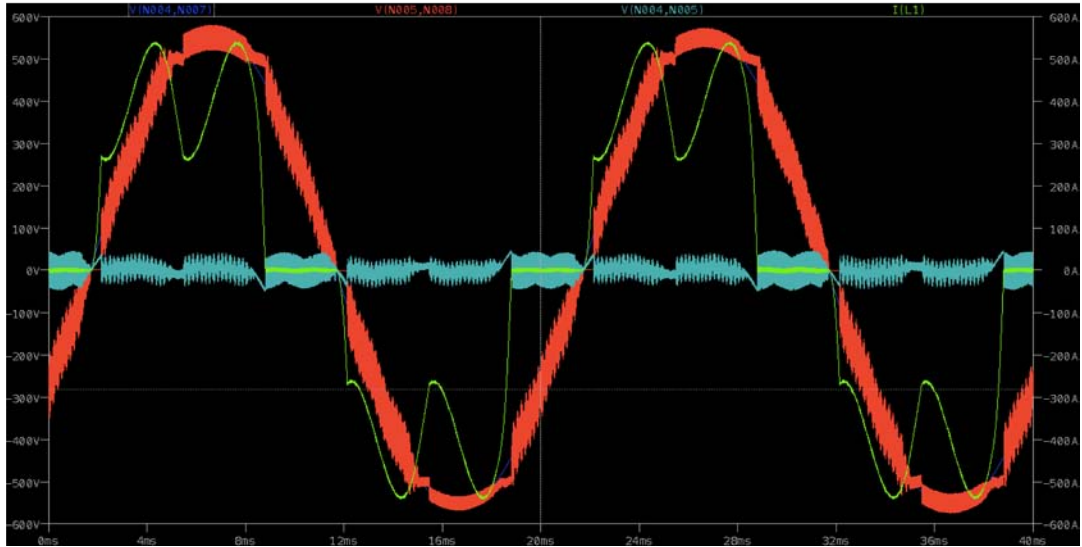


Figure C.1: Voltages and current with the connection of 1 inverter

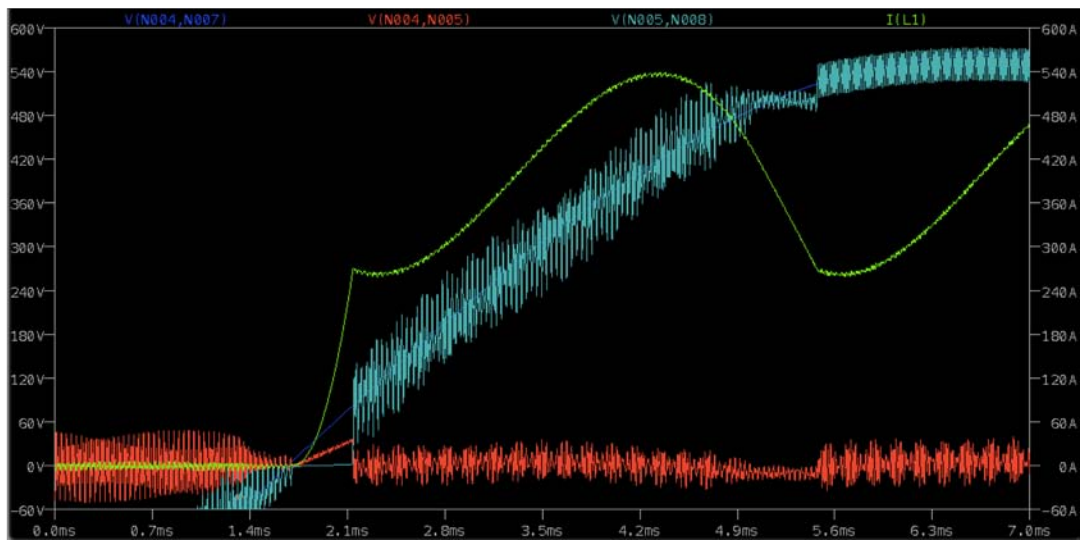


Figure C.2: Voltage and current enlargement, in case of connection of 1 inverter

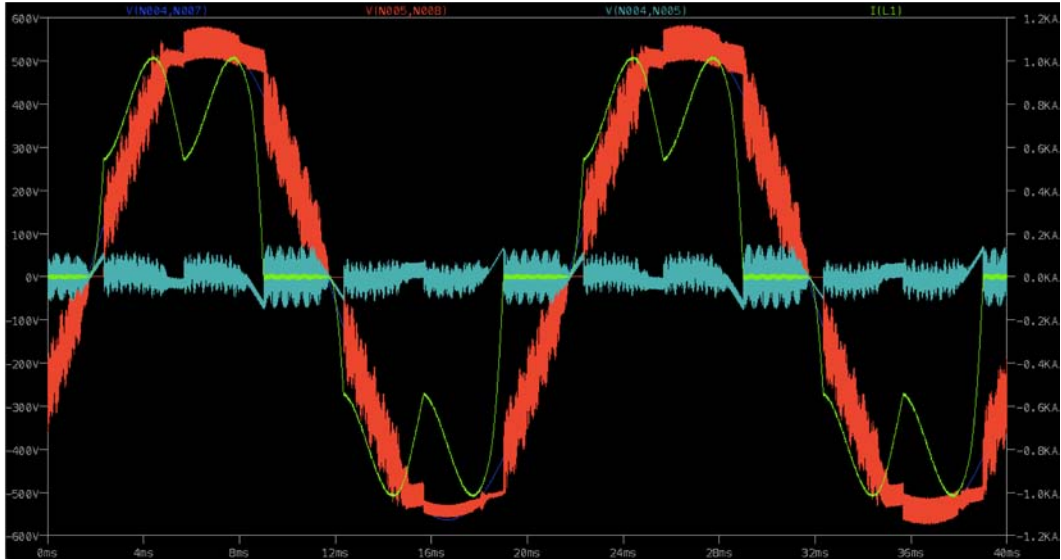


Figure C.3: Voltages and current with the connection of 2 inverter

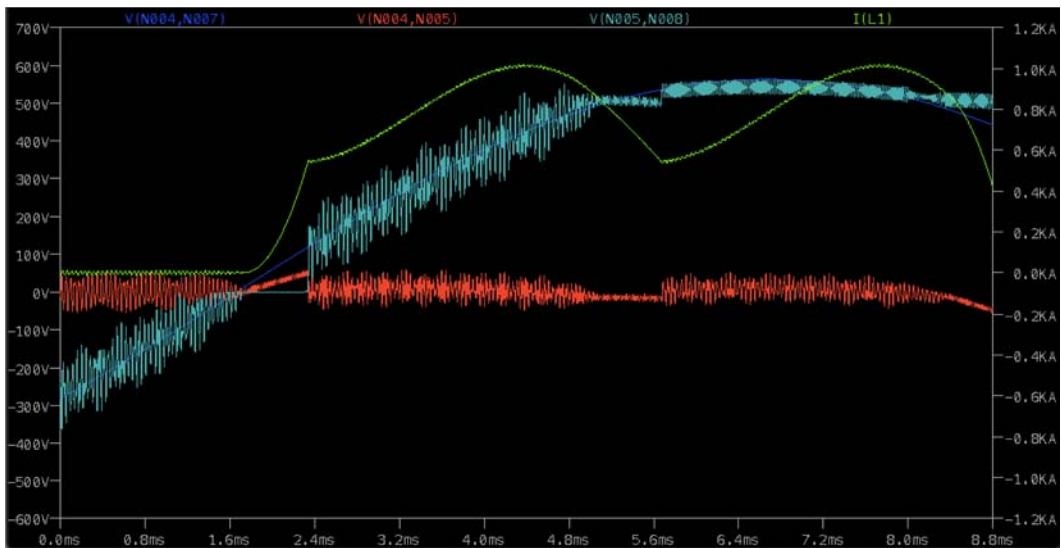


Figure C.4: Voltage and current enlargement, in case of connection of 2 inverter

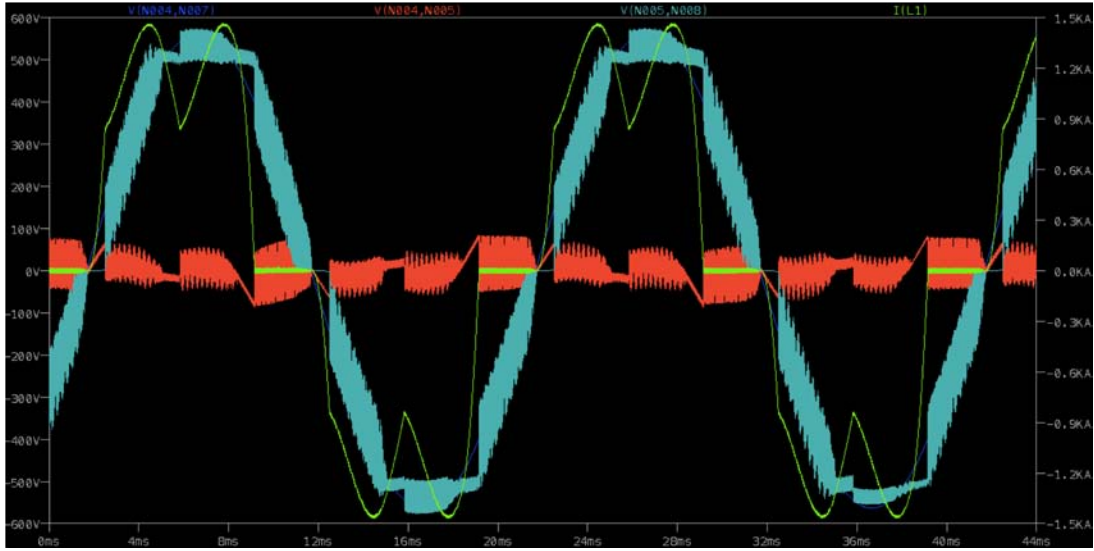


Figure C.5: Voltages and current with the connection of 3 inverter

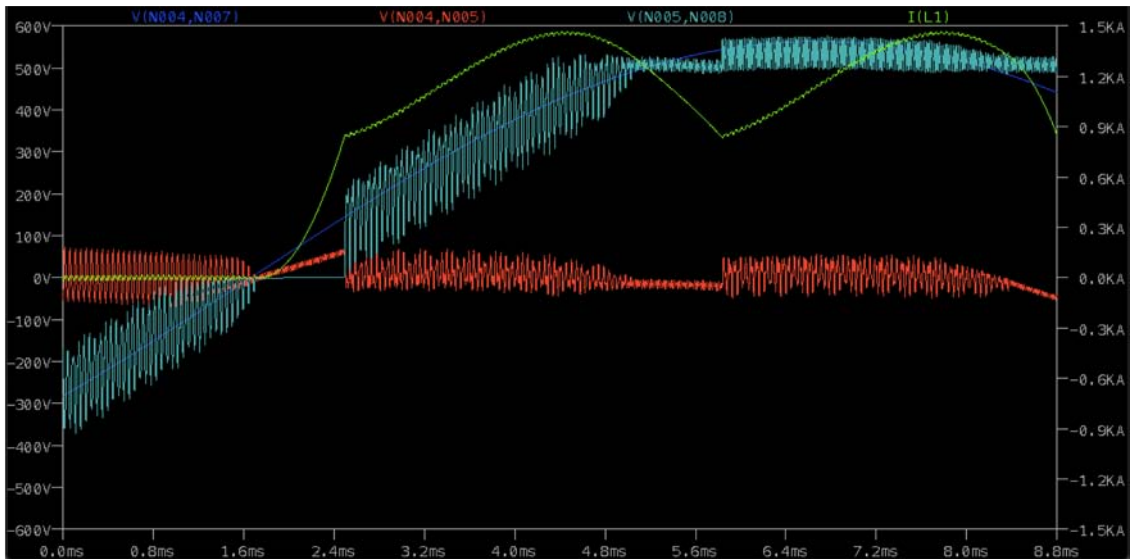


Figure C.6: Voltage and current enlargement, in case of connection of 3 inverter

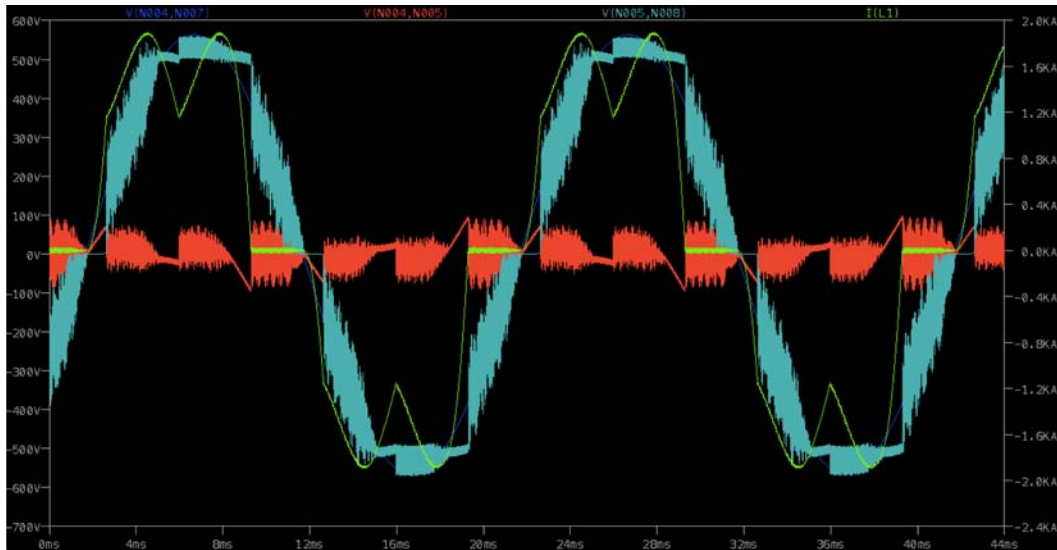


Figure C.7: Voltages and current with the connection of 4 inverter

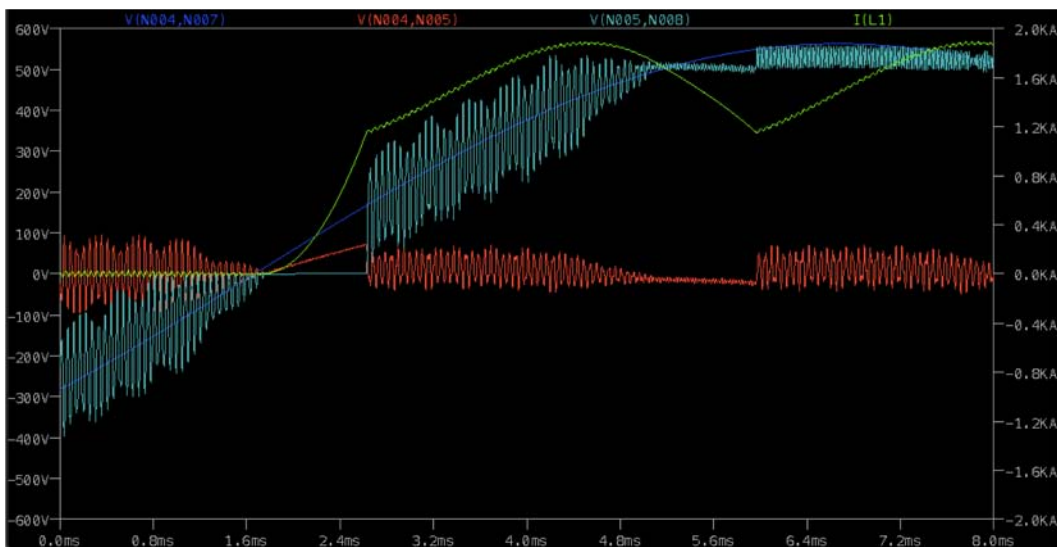


Figure C.8: Voltage and current enlargement, in case of connection of 4 inverter



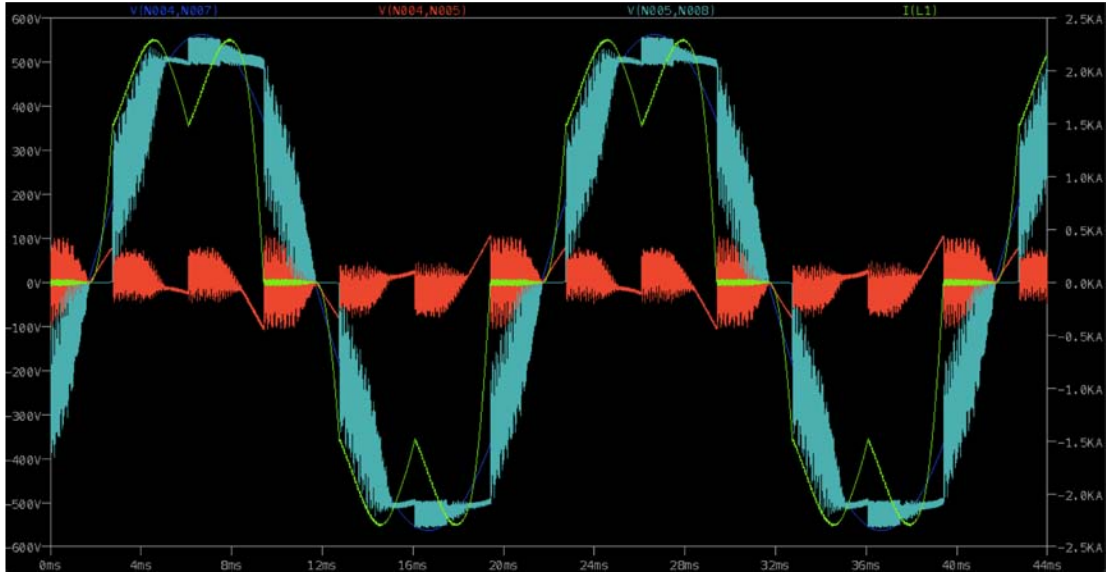


Figure C.9: Voltages and current with the connection of 5 inverter

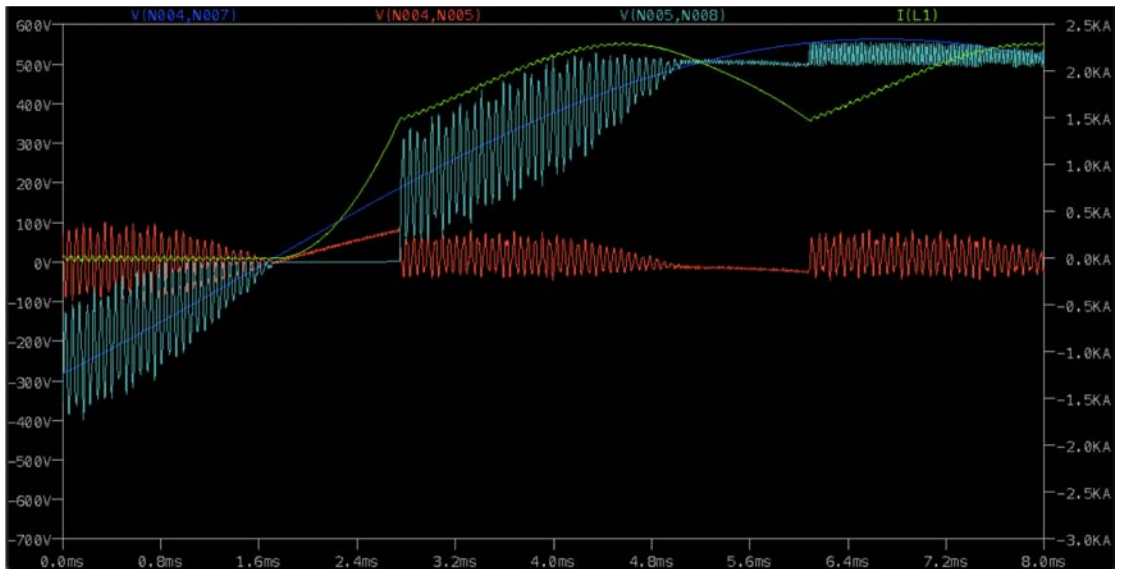


Figure C.10: Voltage and current enlargement, in case of connection of 5 inverter

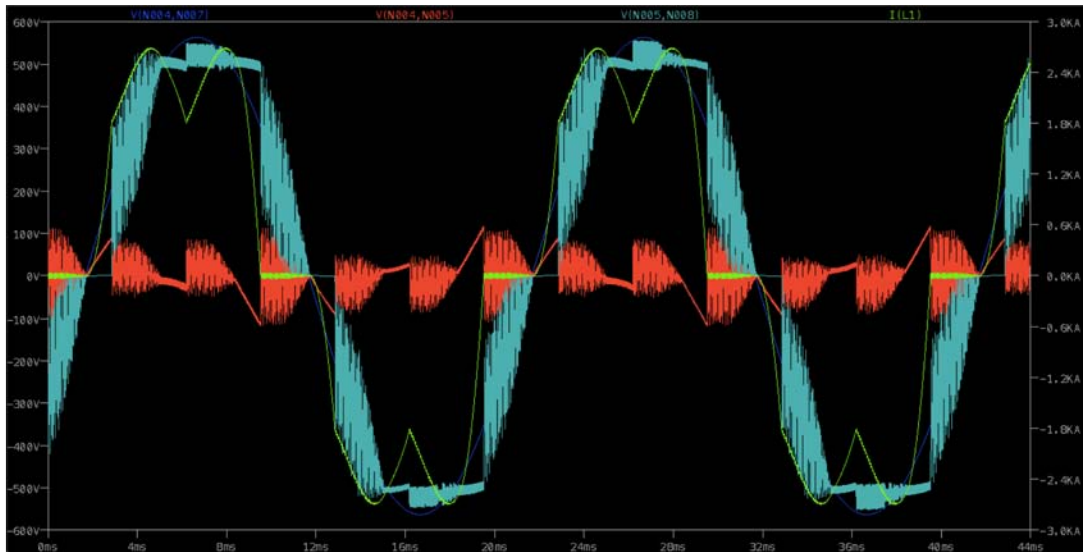


Figure C.11: Voltages and current with the connection of 6 inverter

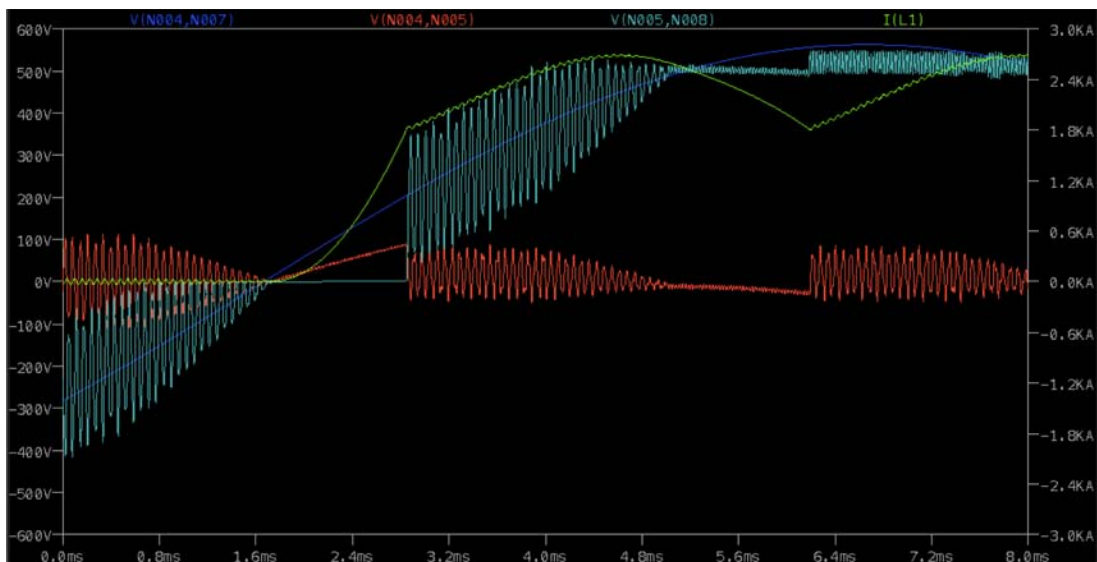


Figure C.12: Voltage and current enlargement, in case of connection of 6 inverter

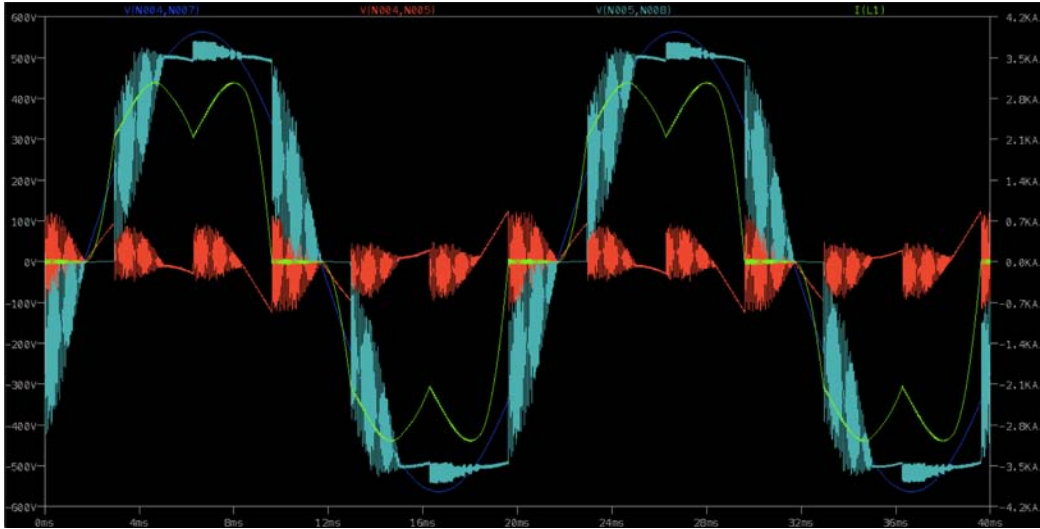


Figure C.13: Voltages and current with the connection of 7 inverter

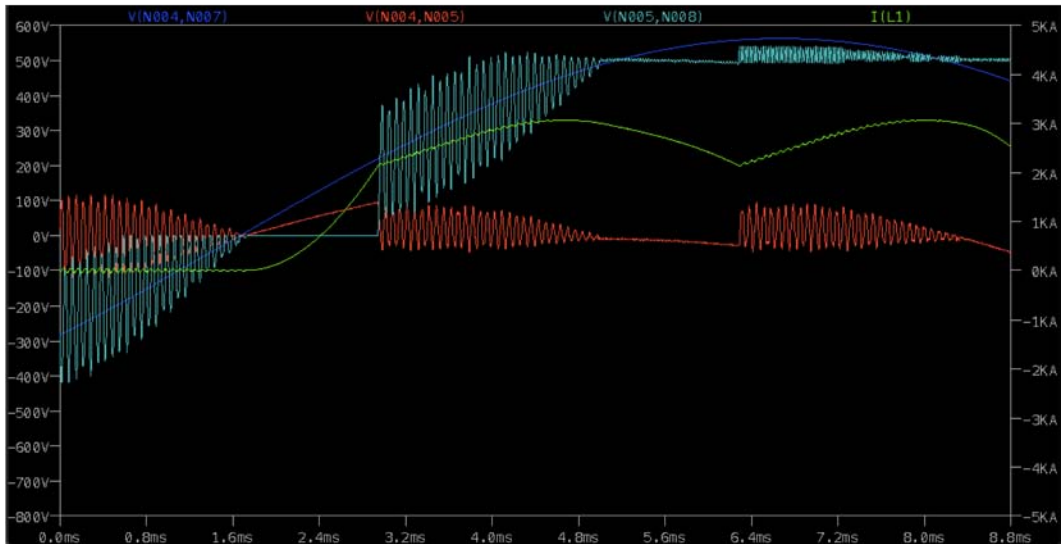


Figure C.14: Voltage and current enlargement, in case of connection of 7 inverter

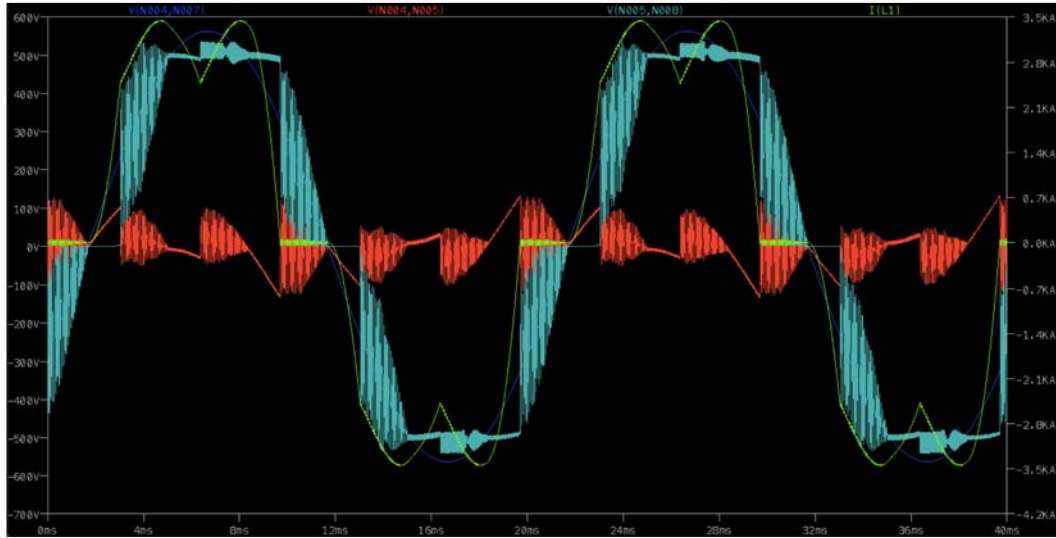


Figure C.15: Voltages and current with the connection of 8 inverter

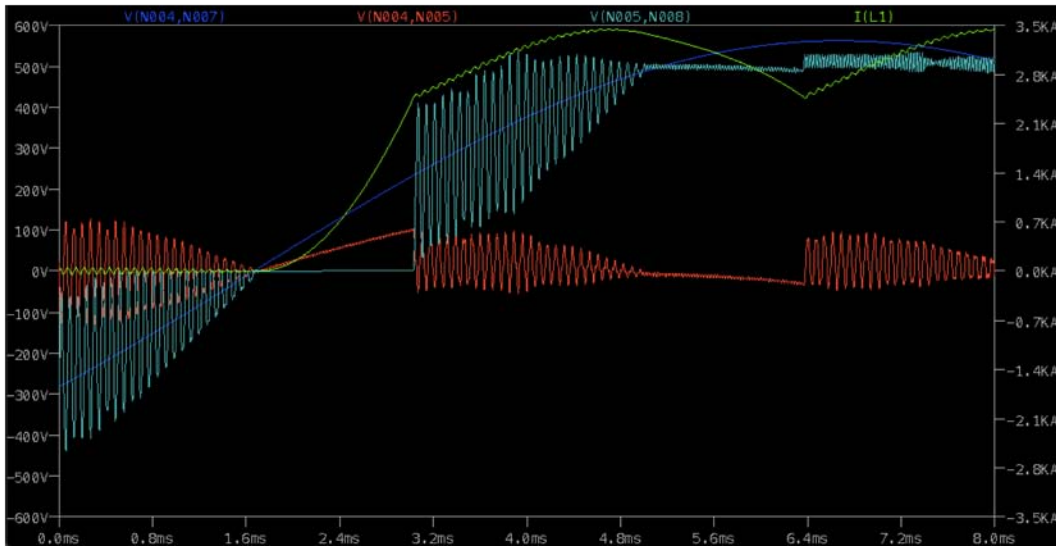


Figure C.16: Voltage and current enlargement, in case of connection of 8 inverter

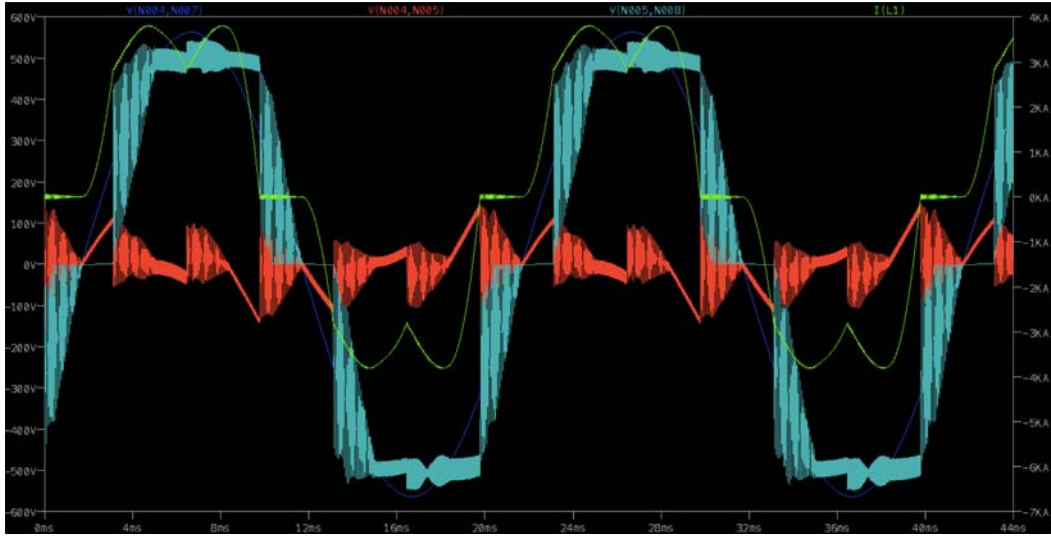


Figure C.17: Voltages and current with the connection of 9 inverters

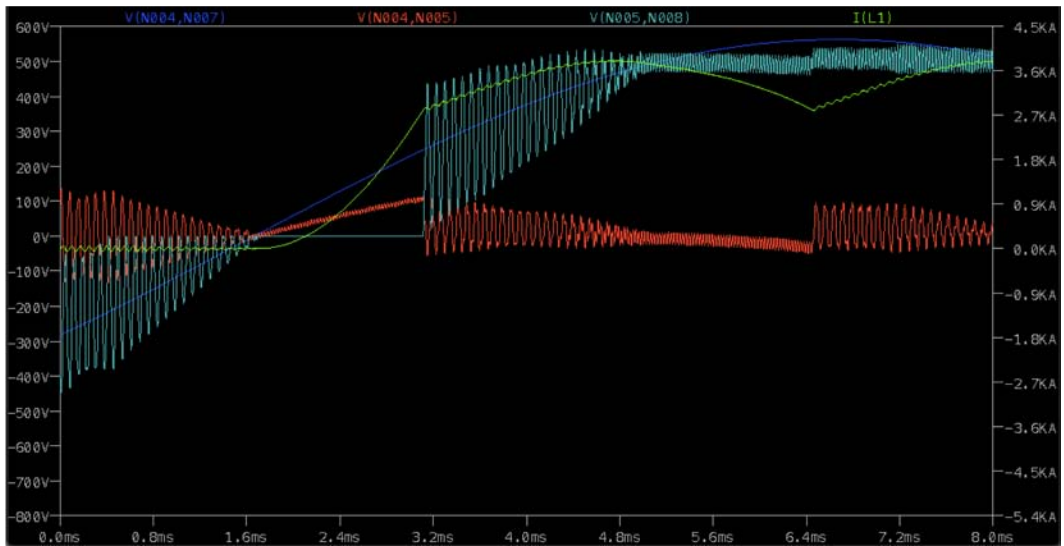


Figure C.18: Voltage and current enlargement, in case of connection of 9 inverters

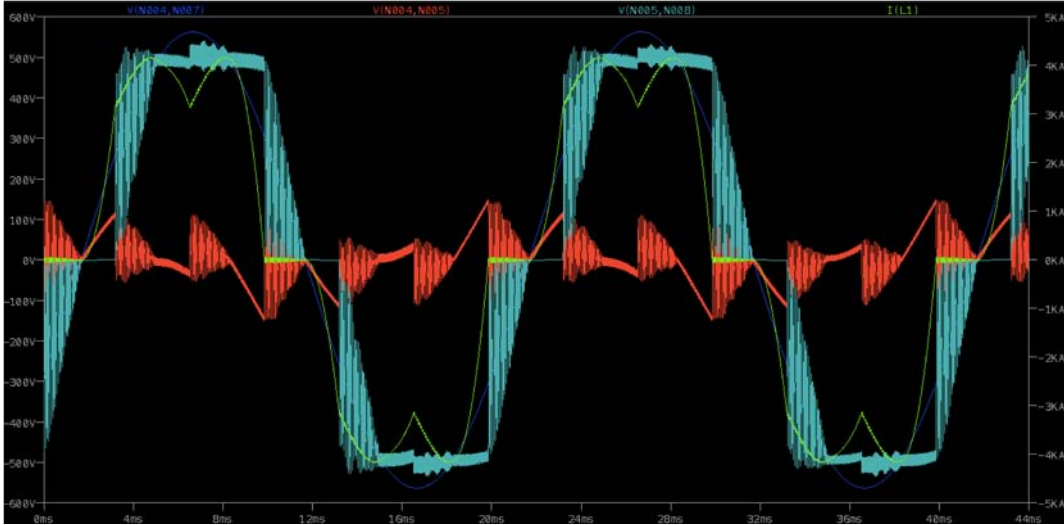


Figure C.19: Voltages and current with the connection of 10 inverter

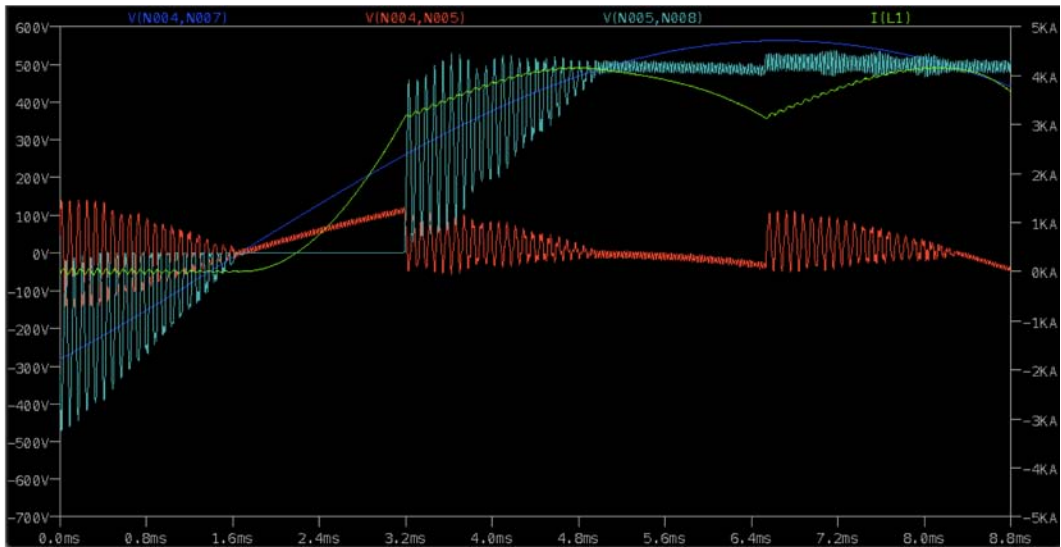


Figure C.20: Voltage and current enlargement, in case of connection of 10 inverter

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