Proyecto Fin de Carrera
Ingeniería Industrial

Harmonic Analysis and Transient Overvoltages due to Capacitor Switching Analysis

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El tribunal nombrado para juzgar el Proyecto arriba indicado, compuesto por los siguientes miembros:

Presidente:

Vocales:

Secretario:

Acuerdan otorgarle la calificación de:

Sevilla, 2015

El Secretario del Tribunal

A mi familia

A mis maestros

Appreciation

Thanks to all those that have seen further, clearer and brighter but have not shined as expected.

Pedro Javier Rodríguez Delgado
Electrical Project Engineer
Sevilla, 2015

Resume

The objective of this document is to perform the harmonic analysis of the Barka Dissalination Plant as well as the Transient Overvoltages that may occur due to Capacitor switching. Also, solution proposals are included in this document in order to reach admissible limits as shown in reference standards.

Abstract

Power quality is becoming as important as electrical design nowadays due to the complex power electronic equipment that is being developed. The main reason of performing these analysis on Barka project is that overvoltages and harmonics caused several problems in some equipment that could lead to plants failure in long term.

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1 LOCATION

Esto es una cita al principio de un capítulo.

- El autor de la cita -

Barka (Arabic: بركاء) is a coastal city in the region Al Bāţinah, in northern Oman. The town is emerging as a tourist resort. Nearby is Bait Na'aman (Nu'man), a four-towered fort of the 17th-century iman Bil'arab bin Sultan, renovated in 1991.[1]

There are two major resorts in Barka, the Al-Sawadi resort and the Al-Nahda resort. In addition, a new quarter is now under construction in Barka, called "Blue City" (الزقاء المدينة), located in Sawadi. The development is 8 km from Sawadi beach, and many international companies are involved in Barka development projects. There is an estimated $15 billion in new construction currently taking place in Barka. (Source Wikipedia)

Figure 1 Barka Dissalination Plant Location

Figure 2 Barka Dissalination Plant Image

Figure 3 Barka Dissalination Plant Image

General description

The works involve the execution of a Desalination Plant with reverse osmosis technology in Barka, Oman.

The plant shall make it possible to supply the demand of over 225,000 inhabitants with a capacity to desalinate 45,000 m3 a day with reverse osmosis technology, from one of the heat exchangers of the refrigeration system of the existing energy and water integrated production installation.

Abengoa shall be responsible for undertaking the design, engineering, construction as well as the later support in operation and maintenance.

Location: Barka, Gulf of Oman (Oman)

Our participation

Technical assistance in foundations project, soil movement, drains, roads and civil works budget.

Client: ACWA Power International

EPC Contractor: Abeinsa EPC

Start date of works: August 2012

End date of works: December 2013

Figure 4 Barka Dissalination Plant 3D Model

Figure 5 Barka Dissalination Plant Image

(Source Teyma.com).

2 HARMONIC ANALYSIS

As power electronic devices are being used commonly nowadays in order to achieve better performance as well as high accuracy power quality analysis are a must.

Harmonic distortion is one of the most important power quality disturbances and requires strong in-depth analysis.

2.1. Scope

The Scope of this analysis is to check that the harmonic voltage of every electrical bus is within applicable standards, and if necessary, perform the filtering needed to achieve so.

This study has been performed in IFD (Issue for design) basis as no information from suppliers were available at that moment.

For this task ETAP software harmonic analysis´module will be used as it is common in engineering companies.

2.2. References

For further information collected here, consider the following documentation:

0331-ESP-ING-028-034-0006	LV and MV cable list
0331-MEM-ING-028-040-0001	Electrical power system philosophy
0331-MEM-ING-028-040-0002	Electrical design criteria.
0331-MEM-ING-028-040-0003	Electrical design criteria. Interlocking and protections
0331-LIS-ING-028-040-0001	Electrical HV & LV Consumer List
xxxx-ESP-ING-028-XXX-XXX	VFD Technical Specification

This information is confidencial and will be shown at the project defense

2.3. Design Standards

All National, Autonomous and Local Laws, Standards and Official Regulations (Technical, Health and Safety, Environmental, etc.) that are currently in force in addition to others that are expressly indicated shall be complied with.

When there are discrepancies between the different Standards or with this Document, the most demanding shall be applied. Otherwise, EPC shall be informed and decide which standard to apply.

The following codes and standards shall be applicable and for reference:

- IEEE 1531 IEEE Guide for Application and Specification of Harmonic Filters
- IEEE 519 1992 Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems
- UNE-EN_61000-2-4 2004 Compatibilidad Electromagnética – Niveles de compatibilidad para las perturbaciones conducidas de baja frecuencia en instalaciones industriales.

Any other Standard not mentioned above but applicable, is also mandatory.

It shall be the subcontractor responsibility to be, or to become, knowledgeable of the requirements of the codes and standards set out above. Any changes or alterations to the equipment required for compliance with these codes and standards shall be at Subcontractor cost.

2.4. Input Data

The input data for this analysis takes into account all the elements needed for a Load Flow analysis as well as the harmonic sources.

In order to model this elements project information regarding transformers, loads, cables, buses, ups and dc systems has been used.

All this information is shown at Annex I.

2.4.1. Single Line Diagram

- **Substation GSLD**.

  As shown, the input is at 15.75 kV and feeds the dissalination plant at 11 kV.

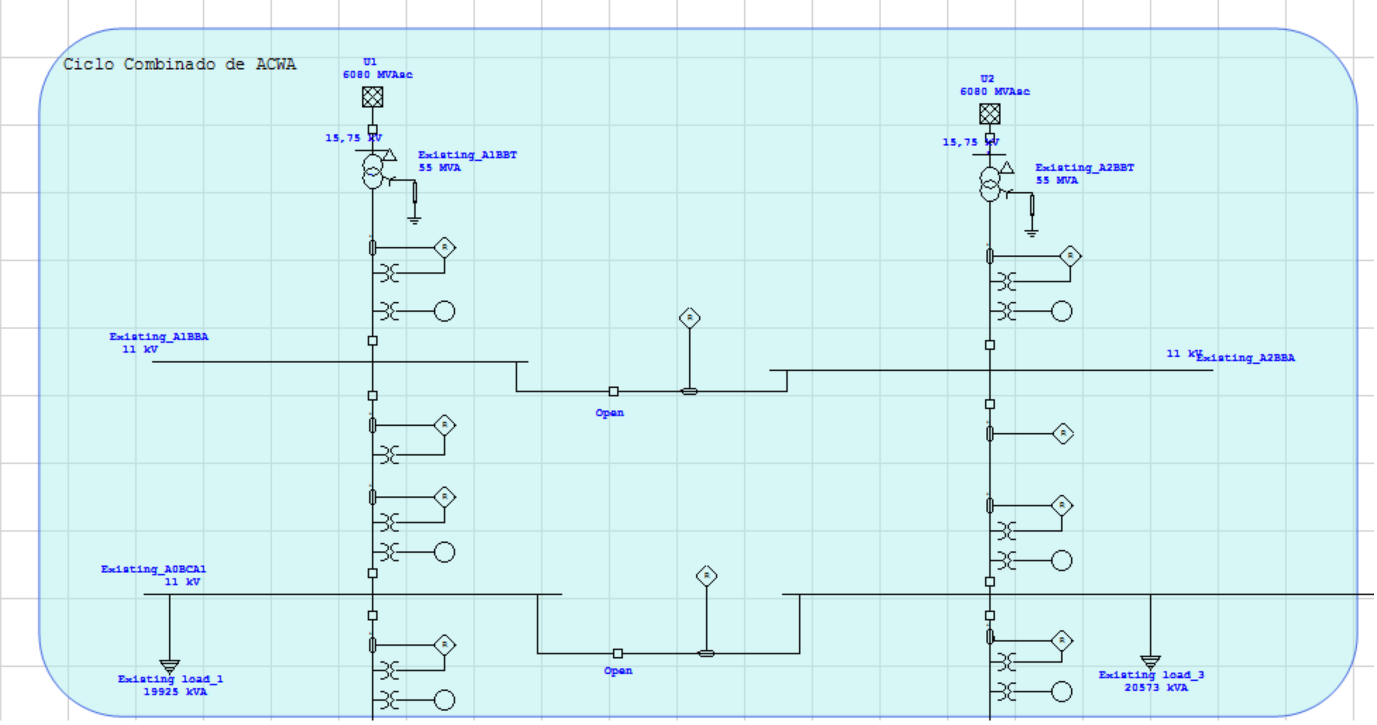


Figure 6 Barka Substation SLD

- Dissalination plant SLD.

As shown, main pumps are fed at 11 kV. And then two main MCC (690 V and 400 V) are used in order to feed secondary loads.

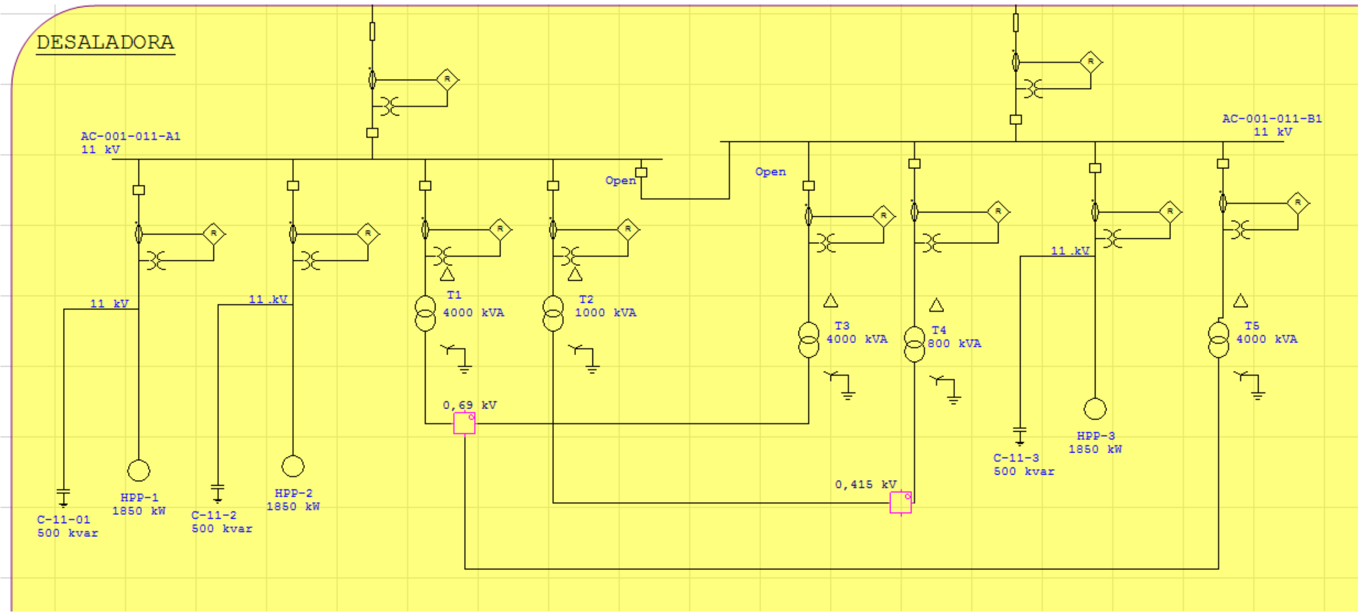


Figure 7 Barka Dissalination Plant Main SLD

- 690 V MCCs

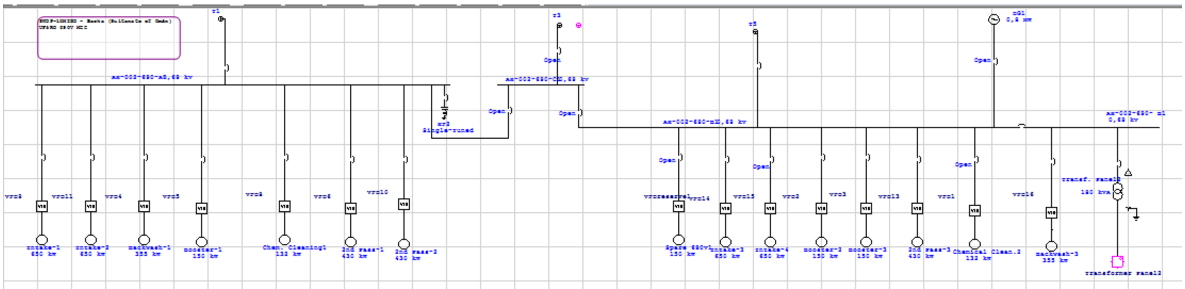


Figure 8 Barka Dissalination Plant 690 V SLD

- 400 V MCCs

The 400 V MCCs is used to feed low power and secondary loads, so it is difficult show the ETAP model for this busbar in this document.

All this information can be retrieved in annex I

2.5. Harmonic Sources

The harmonic sources that have been taken into account in this study are:

2.5.1. VFD

Regarding VFDs, the ABB ACS6000 6P has been taken into account as it is available in ETAP harmonics library.

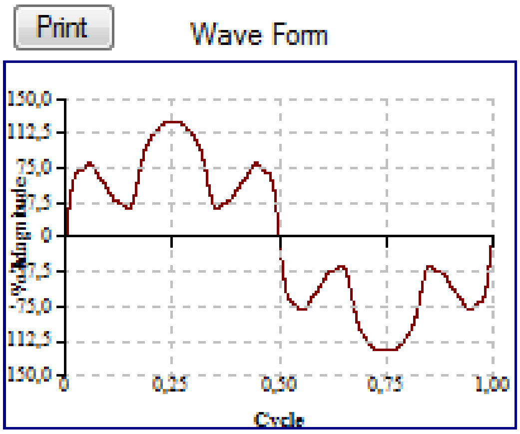


Figure 9 Harmonic Source Spectre for VFD

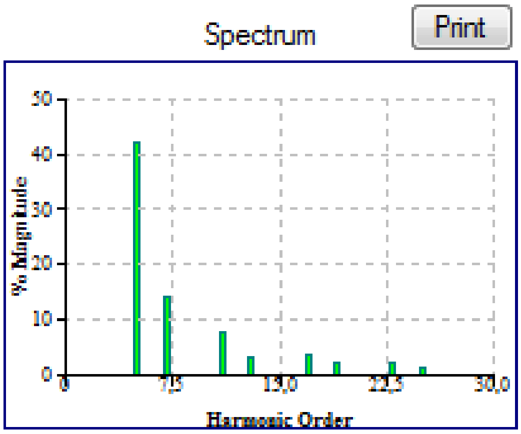


Figure 10 Harmonic Source Spectre for VFD

2.5.2. UPS

An IEEE standard spectrum as been considered for UPS devices due to the fact that no supplier information is available at project early stages.

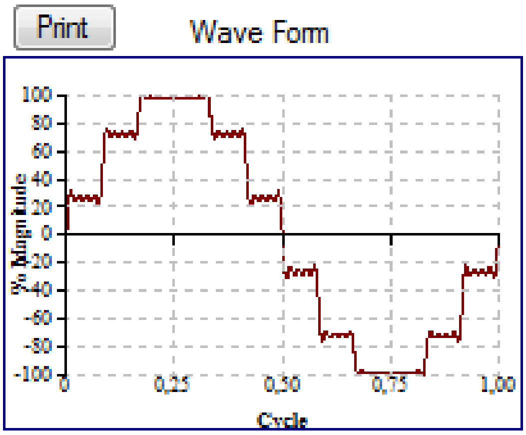


Figure 11 Harmonic Source Spectre for UPS

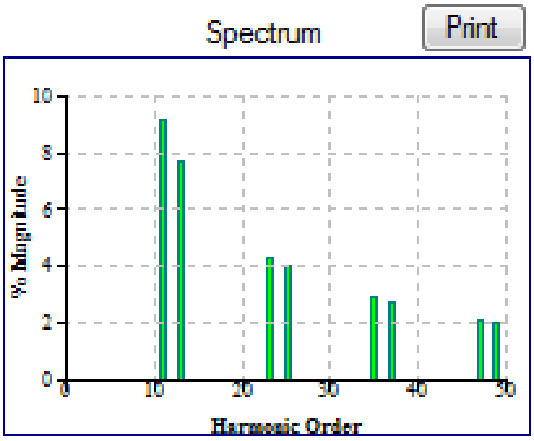


Figure 12 Harmonic Source Spectre for UPS

2.5.3. DC System

As the DC System power is very low compared to the VFDs and UPS systems, harmonic contribution have been not taken into account.

2.6. Harmonic Limits

Here is a comparison of the harmonic limits of both IEEE and IEC. As shown, IEC recommends VHD limits at buses that we may also consider.

2.6.1. IEEE Standard

The IEEE standard only shows current and voltage harmonic limits at the Point of common coupling (PCC). In our case, this point is the 15.75 kV connection.

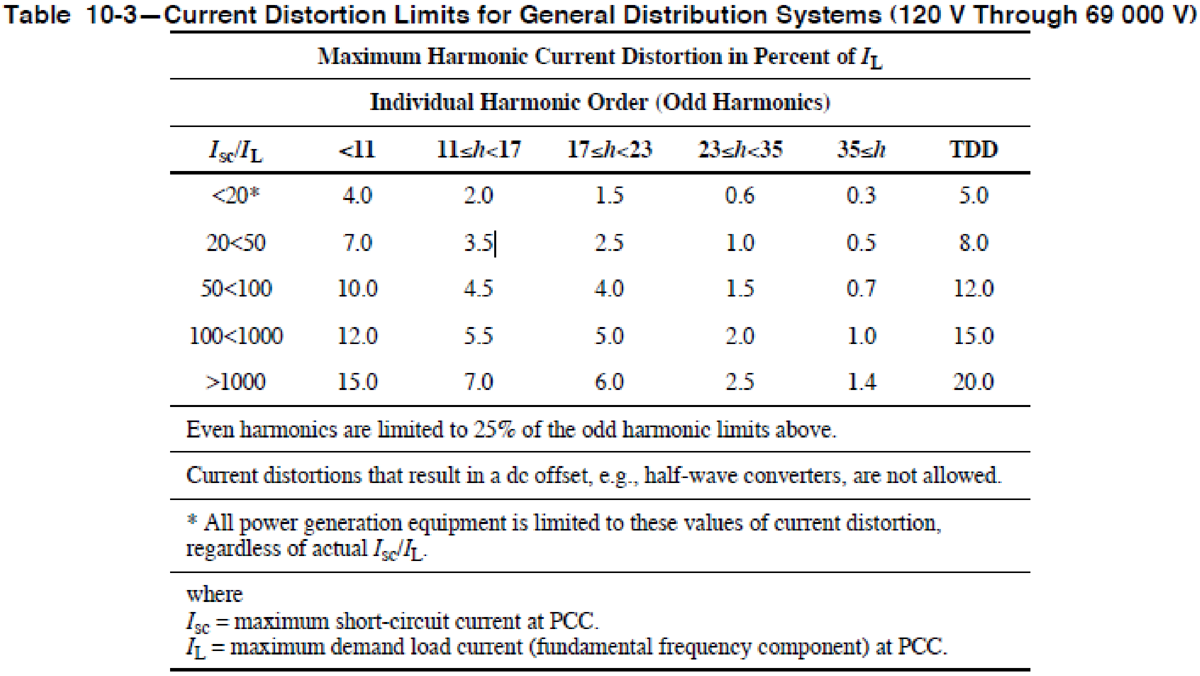


Table 10-3—Current Distortion Limits for General Distribution Systems (120 V Through 69 000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

* All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where
I_{sc} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

Table 1 Harmonic Limits for IEEE

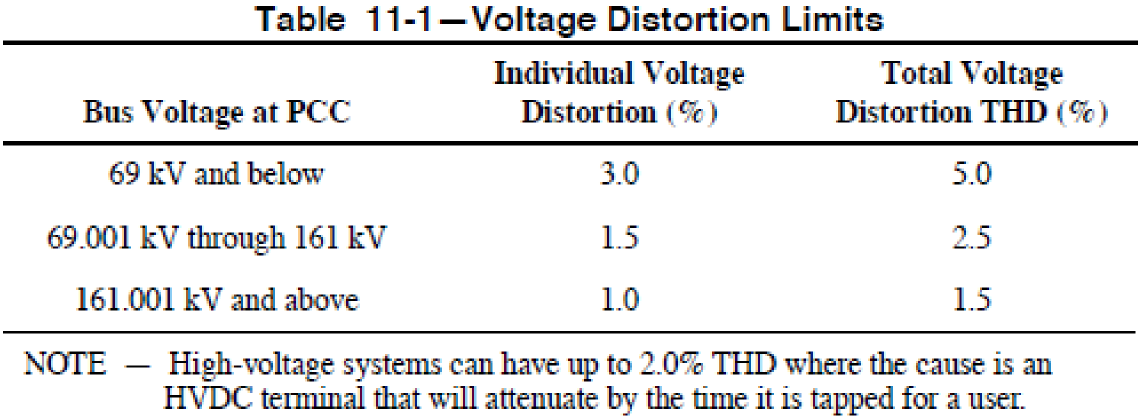


Table 11-1—Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE — High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Table 2 Harmonic Limits for IEEE

2.6.2. IEC

IEC standard shows limits depending on the Project class. Taking into account that our project is an industrial complex, we can assume that it belongs to class III (The most favourable). Also, IEC standard give harmonic limits for internal buses (MV and LV).

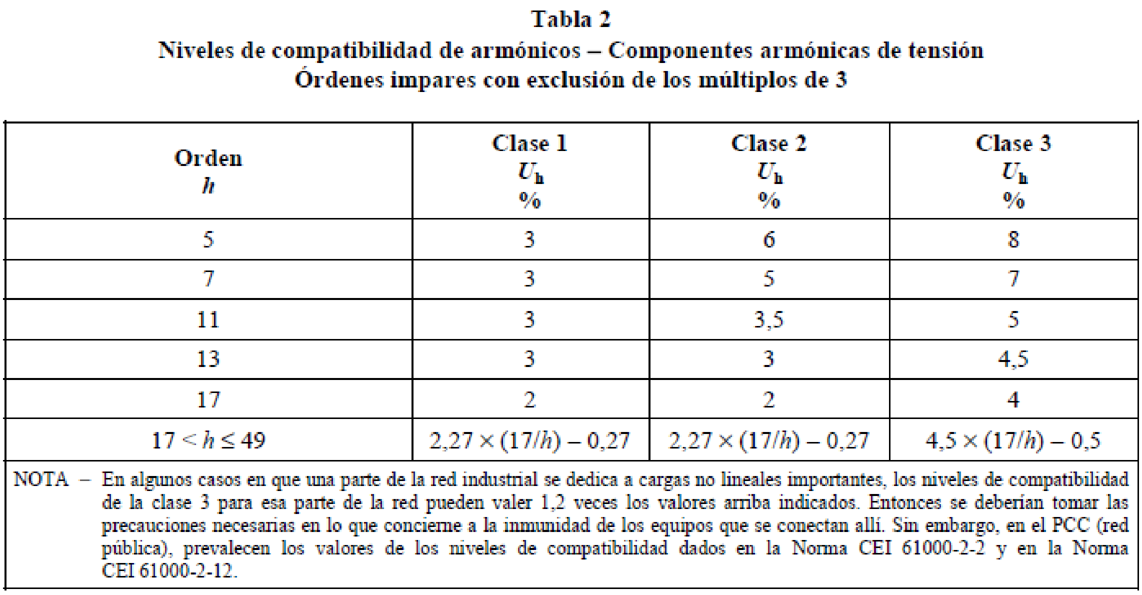


Tabla 2
Niveles de compatibilidad de armónicos – Componentes armónicas de tensión
Órdenes impares con exclusión de los múltiplos de 3

Orden h	**Clase 1** U_h %	**Clase 2** U_h %	**Clase 3** U_h %
5	3	6	8
7	3	5	7
11	3	3,5	5
13	3	3	4,5
17	2	2	4
$17 < h \leq 49$	$2{,}27 \times (17/h) - 0{,}27$	$2{,}27 \times (17/h) - 0{,}27$	$4{,}5 \times (17/h) - 0{,}5$

NOTA – En algunos casos en que una parte de la red industrial se dedica a cargas no lineales importantes, los niveles de compatibilidad de la clase 3 para esa parte de la red pueden valer 1,2 veces los valores arriba indicados. Entonces se deberían tomar las precauciones necesarias en lo que concierne a la inmunidad de los equipos que se conectan allí. Sin embargo, en el PCC (red pública), prevalecen los valores de los niveles de compatibilidad dados en la Norma CEI 61000-2-2 y en la Norma CEI 61000-2-12.

Table 3 Harmonic Limits for IEC

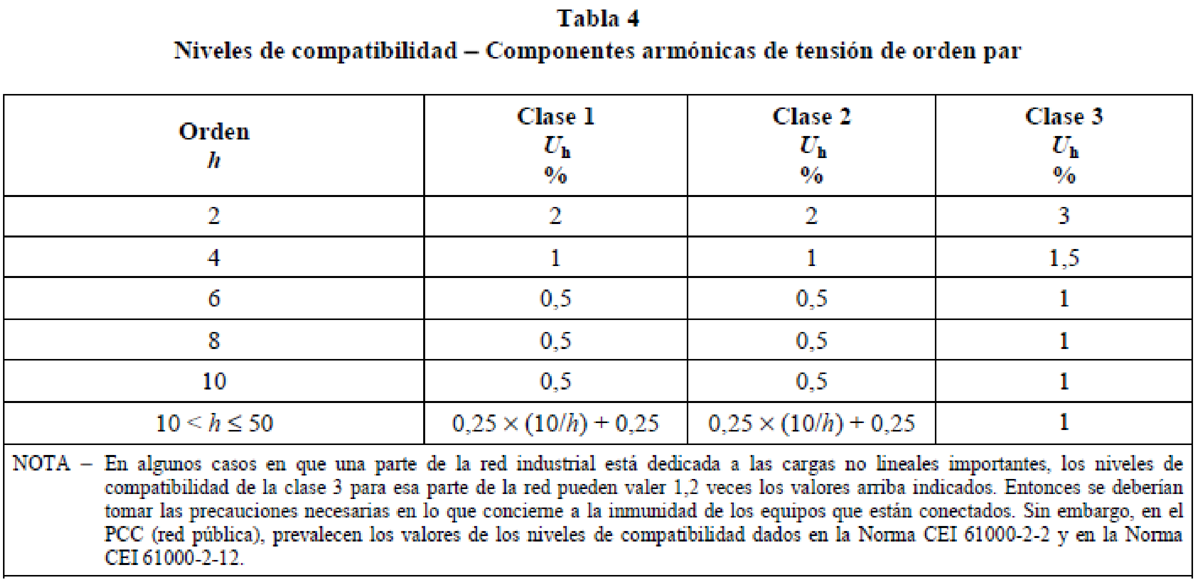


Tabla 4
Niveles de compatibilidad – Componentes armónicas de tensión de orden par

Orden h	**Clase 1** U_h %	**Clase 2** U_h %	**Clase 3** U_h %
2	2	2	3
4	1	1	1,5
6	0,5	0,5	1
8	0,5	0,5	1
10	0,5	0,5	1
$10 < h \leq 50$	$0{,}25 \times (10/h) + 0{,}25$	$0{,}25 \times (10/h) + 0{,}25$	1

NOTA – En algunos casos en que una parte de la red industrial está dedicada a las cargas no lineales importantes, los niveles de compatibilidad de la clase 3 para esa parte de la red pueden valer 1,2 veces los valores arriba indicados. Entonces se deberían tomar las precauciones necesarias en lo que concierne a la inmunidad de los equipos que están conectados. Sin embargo, en el PCC (red pública), prevalecen los valores de los niveles de compatibilidad dados en la Norma CEI 61000-2-2 y en la Norma CEI 61000-2-12.

Table 4 Harmonic Limits for IEC

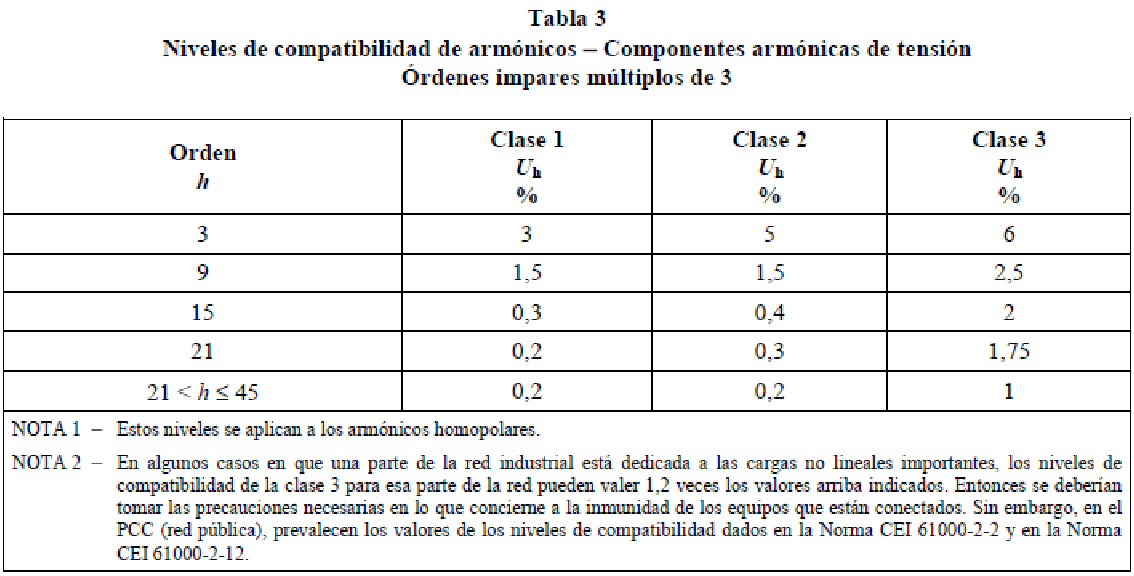


Tabla 3
Niveles de compatibilidad de armónicos – Componentes armónicas de tensión
Órdenes impares múltiplos de 3

Orden *h*	**Clase 1** U_h **%**	**Clase 2** U_h **%**	**Clase 3** U_h **%**
3	3	5	6
9	1,5	1,5	2,5
15	0,3	0,4	2
21	0,2	0,3	1,75
$21 < h \leq 45$	0,2	0,2	1

NOTA 1 – Estos niveles se aplican a los armónicos homopolares.

NOTA 2 – En algunos casos en que una parte de la red industrial está dedicada a las cargas no lineales importantes, los niveles de compatibilidad de la clase 3 para esa parte de la red pueden valer 1,2 veces los valores arriba indicados. Entonces se deberían tomar las precauciones necesarias en lo que concierne a la inmunidad de los equipos que están conectados. Sin embargo, en el PCC (red pública), prevalecen los valores de los niveles de compatibilidad dados en la Norma CEI 61000-2-2 y en la Norma CEI 61000-2-12.

Table 5 Harmonic Limits for IEC

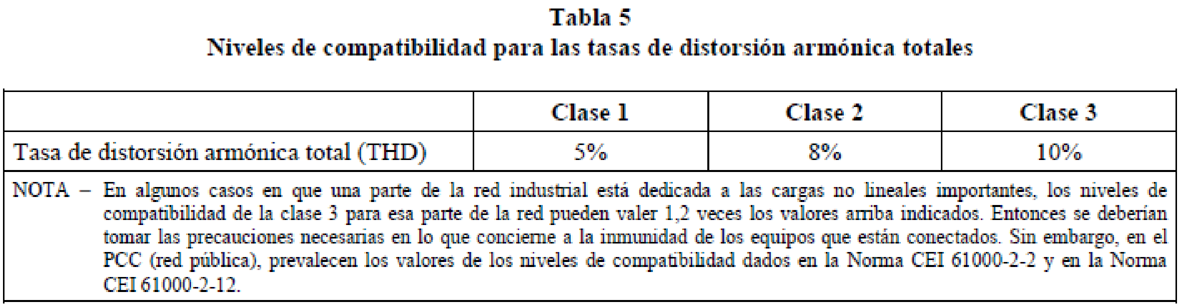


Tabla 5
Niveles de compatibilidad para las tasas de distorsión armónica totales

	Clase 1	**Clase 2**	**Clase 3**
Tasa de distorsión armónica total (THD)	5%	8%	10%

NOTA – En algunos casos en que una parte de la red industrial está dedicada a las cargas no lineales importantes, los niveles de compatibilidad de la clase 3 para esa parte de la red pueden valer 1,2 veces los valores arriba indicados. Entonces se deberían tomar las precauciones necesarias en lo que concierne a la inmunidad de los equipos que están conectados. Sin embargo, en el PCC (red pública), prevalecen los valores de los niveles de compatibilidad dados en la Norma CEI 61000-2-2 y en la Norma CEI 61000-2-12.

Table 6 Harmonic Limits for IEC

2.7. Harmonic Calculation Basis

The harmonic calculation, although being simple and not involving any transient nor “No lineal” model, needs a powerful software such as ETAP in order to perform the calculations.

The process should be the following:

1. The harmonic spectre is defined for all loads which could inject harmonic disturbances to our electrical installation. This data is retrieved from supplier datasheets along with the equipment data. However, at project early stage this information is not available so an IEEE or even other project´s equipment data should be used.
2. All loads, cables, transformers, CB and switches status data is defined. Due to the fact that a Thevenin equivalent is going to be made in order to perform the Analysis all system data should be correctly defined.
3. Thevenin Equivalent. At this point, the main calculation is performed. It involves two stages:
    a. For every Harmonic Frecuency (50, 100… Hz) the system data is updated taking into

    account that inductances and reactances suffer major changes with frecuency variations.

    b. A Thevenin Equivalent Impedance is calculated at every bus and for every frecuency considered at the harmonic calculation

4. Then, the harmonic current of every equipment is modeled as a current source adapted to the different harmonic frecuencies. This means that for example, when considering the 7th harmonic, only the equipment that has problems with 7th harmonic is modeled as a current source.

Finally, for every harmonic frecuency the system voltages and currents are studied and compared with the standards applicable in order to see if any correction measurement is needed.

2.8. Simulation Results without filters

For further information regarding simulation results see Annex I.

As secondary LV cables has not been modeled, the few buses that does not accomplish standards (AC-001-415-H.R.Bound 2; AC-001-415-H.R.Bound 4 and AC-001-415-TP1) can be grouped.

So we have two buses to analyse:

AC-001-415-TP1 and AH-002-690-A1

Below harmonic voltage distribution, voltage vs time and impedance vs frecuency graphs are shown

2.8.1. AC-001-415-TP1

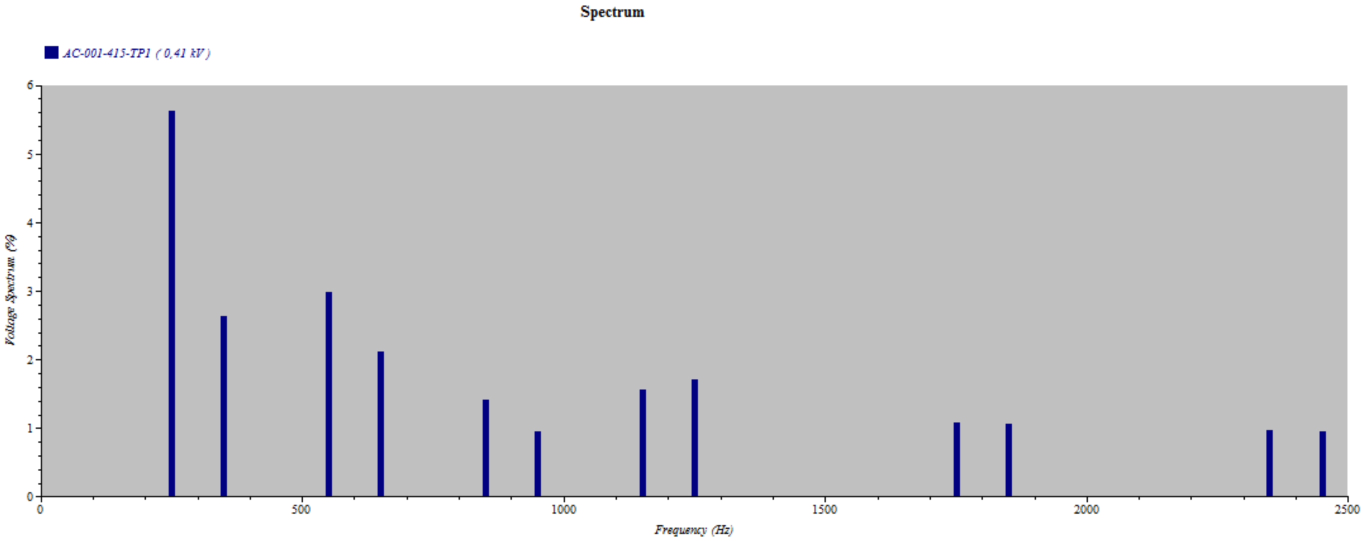


Figure 13 Simulation Results without filters

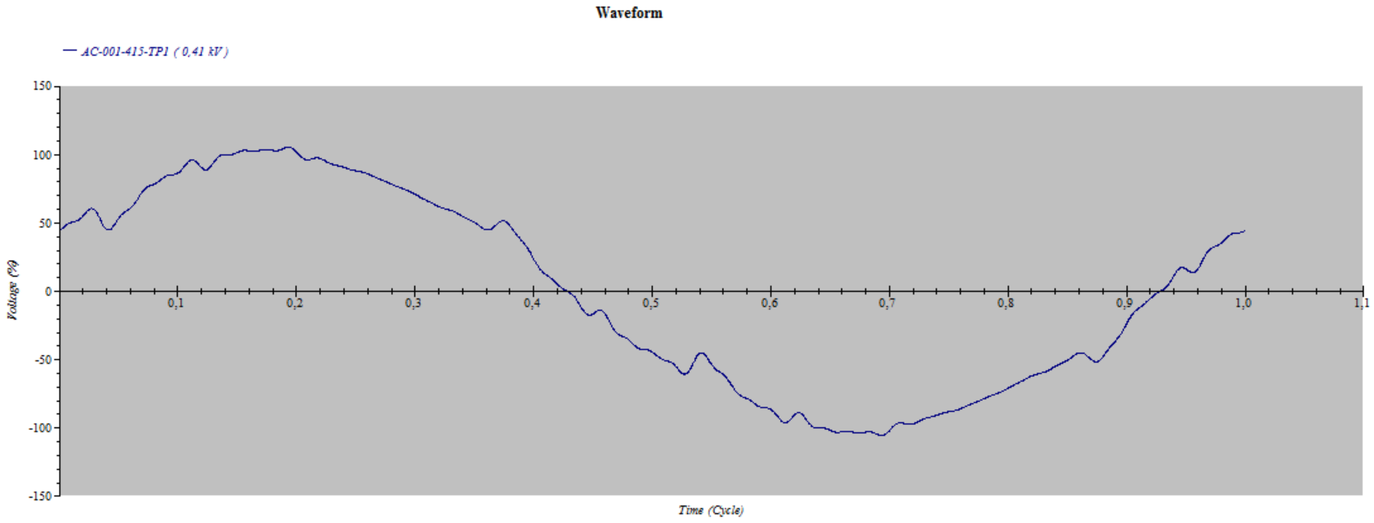


Figure 14 Simulation Results without filters

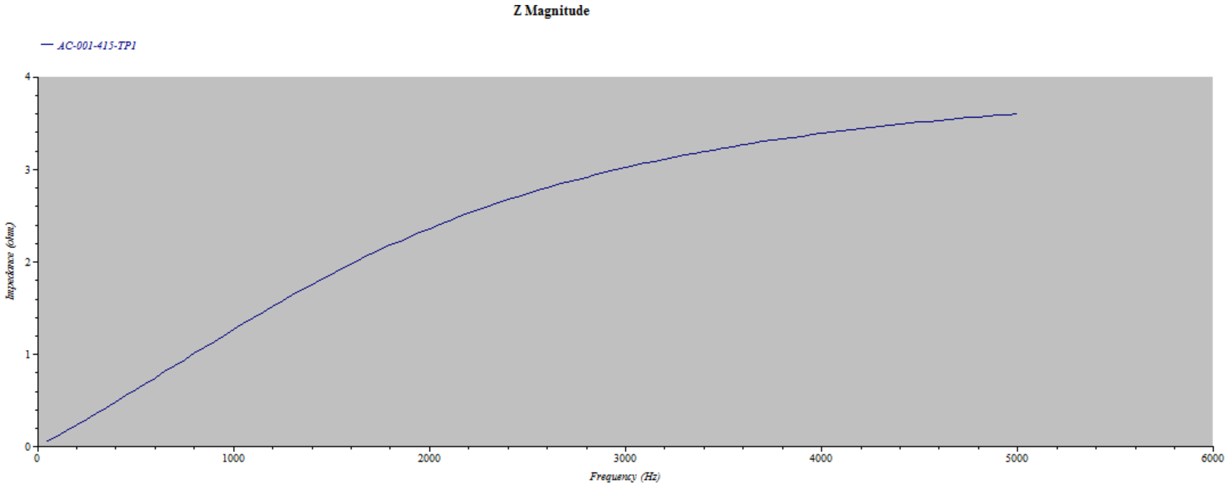


Figure 15 Simulation Results without filters

As we can see, both Z magnitude graphs show a typical behavior of a non power factor corrected system, as there is no resonant frecuency shown in them.

This should be very different in systems where capacitor banks are largely used, as they would set resonant peaks.

2.8.2. AH-002-690-A1

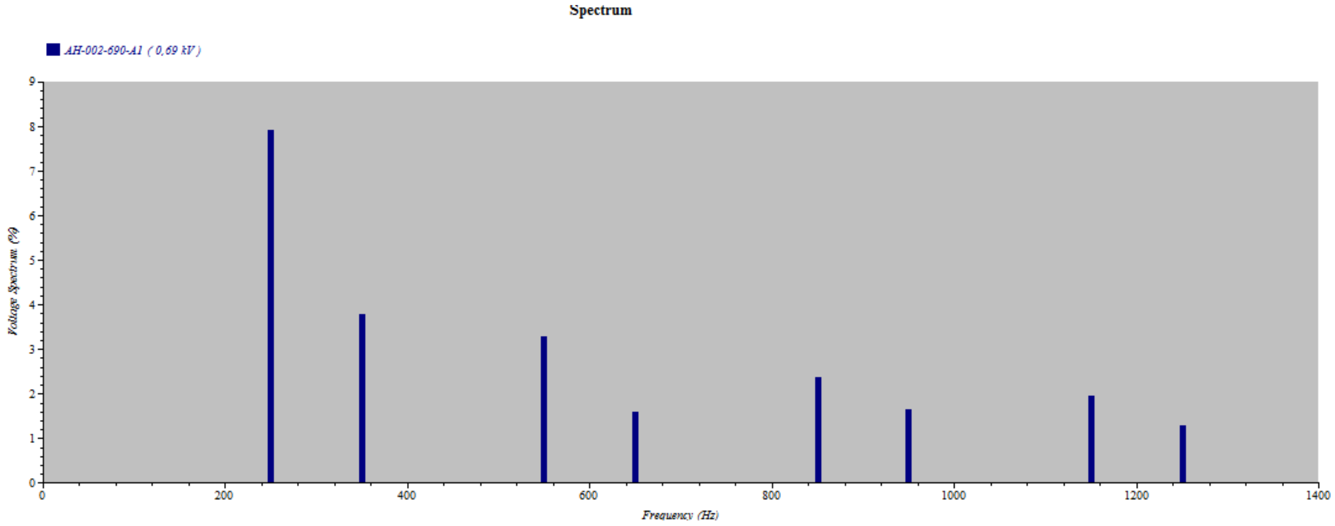


Figure 16 Simulation Results without filters

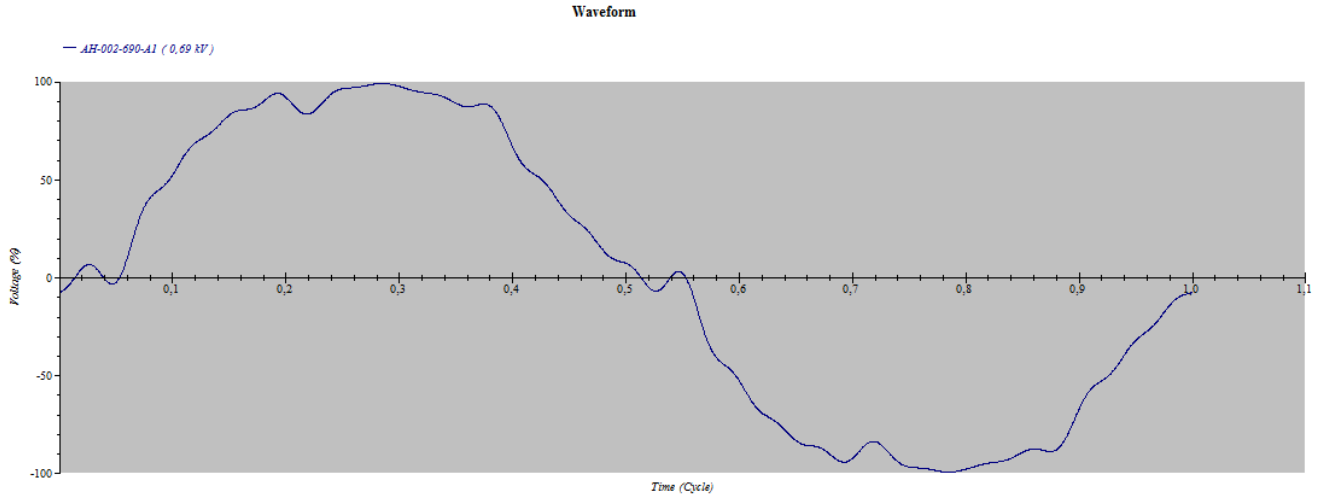


Figure 17 Simulation Results without filters

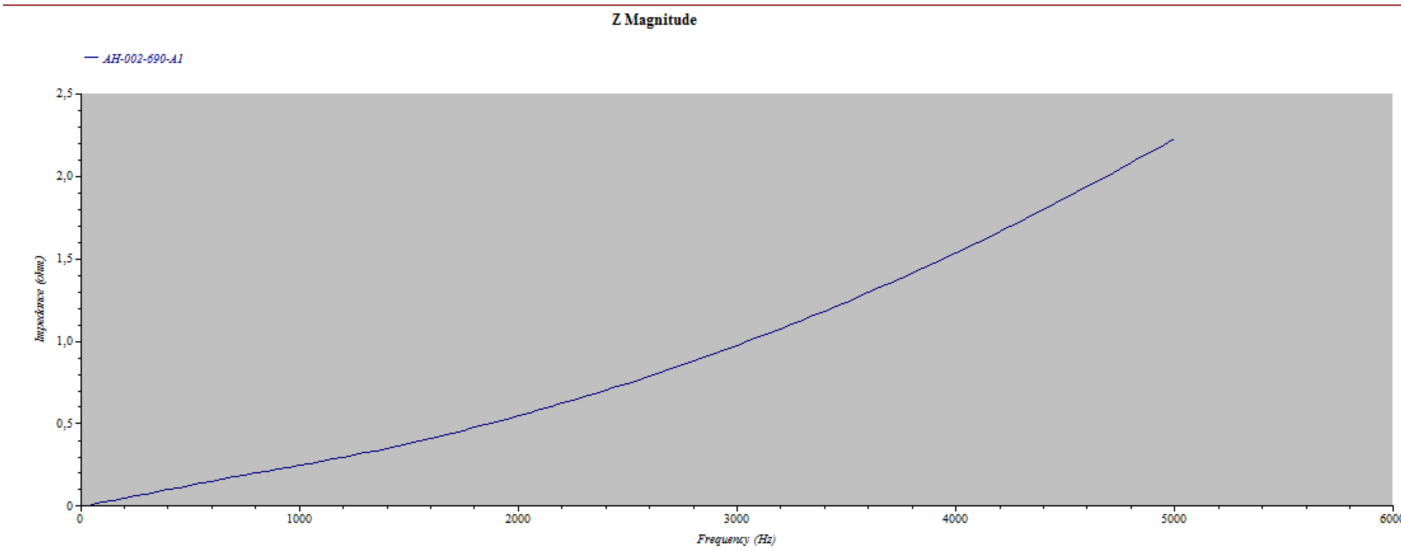


Figure 18 Simulation Results without filters

As we can see, both Z magnitude graphs show a typical behavior of a non power factor corrected system, as there is no resonant frecuency shown in them just like the previous case.

Also note that the voltage graph presents high distorsion due to the 5th harmonic voltage levels.

2.8.3. Conclusion

As shown in Annex I and comparing these results with IEC standards we have the following limits exceded:

- AC-001-415-H.R.Board2
    - 47th 1.17%
    - 49th 1.14%
- AC-001-415-H.R.Board 4
    - 47th 1.17%
    - 49th 1.14%
- AC-001-415-TP1
    - 47th 1.17%
    - 49th 1.14%
- AH-002-690-A1
    - 5th 9.14%
    - Vthd 11.75%

As shown in standards, limits are:

- 47th 1.12%

- 49th 1.06%
- 5th 8%
- Vthd 10%

If we analyze these results, we see that 47 and 49 harmonics are very close to the limits. However, 5th armonic values as well as Vthd are far from limits and require some measures in order to reduce them.

In order to do so, notch filters has been taken into account.

2.9. Filter Calculation

In order to add a simple notch filter to a bus for reducing harmonic voltages the following criteria has been used.

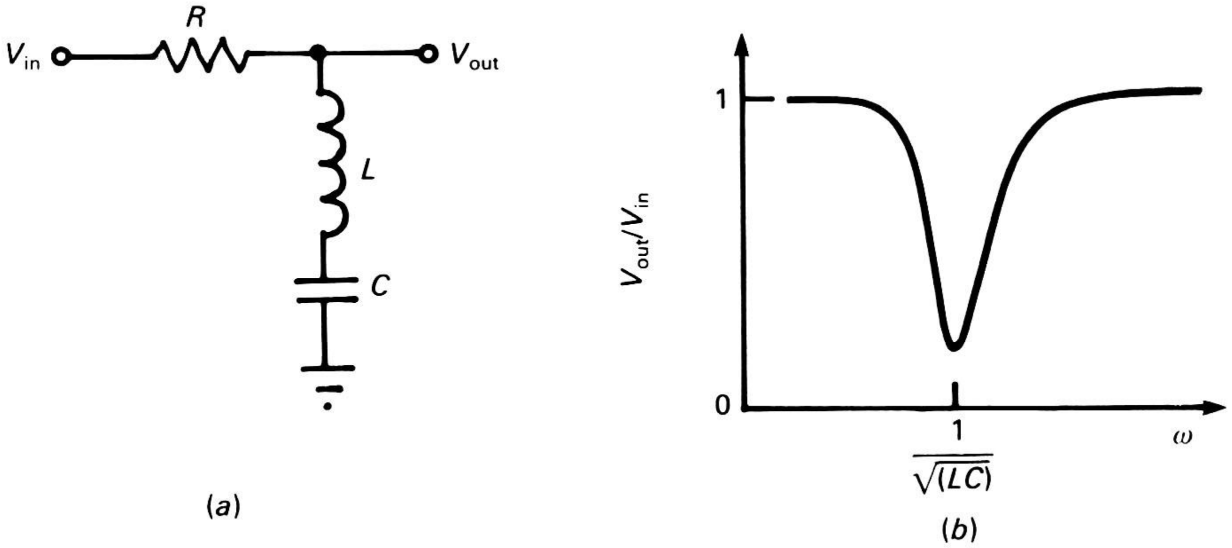


Figure 4.6. (*a*) A simple band reject (notch) filter; (*b*) its frequency response.

Figure 19 Harmonic notch filter config

1. As a capacitor element is needed for filtering, we will use already existing capacitors banks connected to the buses. If there are no capacitor at those buses, we will add a small capacitor bank which could be helpful for increasing the power factor at that bus.
2. Then we have to focus on the most unfavourable harmonic voltage level present at that bus. Considering a filter focusing in that frecuency will move the Impedance-Frecuency Graph at that specific frecuency to nearly 0. However, this has to be made wisely as the other frecuencies may be affected.

   Adding notch filters usually forces the resonant peak to be located on the left side of the notch frecuency, so these notch filtering should be started, in case that more than one frecuency is out-of-limits, from right to left (In a frecuency way, starting from higher frecuencies and ending with smaller frecuencies).

3. If it accomplishes the required standard levels the task is done. If not, we may have to readjust the filter. Another option is using series filtering in harmonic equipment in order to reduce harmonic sources. Also, more complex type of filtering is available as well as active filtering.

So, the calculations needed to size a simple notch filter are the following (As shown at IEEE 531-2003):

$$X_C = \left(\frac{h^2}{h^2 - 1}\right) X_{eff}$$

Where,

$$X_{eff} = \frac{kV_{LLSys}^2}{Q_{eff}(Mvar)}$$

And

$$Q_{eff} = S \times \sin(\cos^{-1} PF_0) - S \times \sin(\cos^{-1} PF_1)$$

A simple equation to calculate the inductive reactance at power frequency is,

$$\mathrm{X_L} = \frac{\mathrm{X_C}}{\mathrm{h}^2}$$

Where:

X_{eff} is the effective reactance of the harmonic filter,

Q_{eff} is the effective reactive power (Mvar) of the harmonic filter,

V_{LLsys} is the nominal system line-to-line voltage,

X_C is the capacitive reactance of the harmonic filter capacitor at the fundamental frequency,

X_L is the inductive reactance of the harmonic filter reactor at the fundamental frequency,

h is the harmonic number,

S is the total demanded VA at studied bus.

PF_0 is the original power factor

PF_1 is the desired power factor

Note that in the first ecuation, the capacitor reactance tuning is slightly different from the exact one. This is because if we select the exact tuning frecuency some problems can be found. The most important are:

- The low impedance at resonance can result in nearly all harmonic current at that frequency being absorbed by the harmonic filter. The harmonic filter is required to be larger and more expensive than is needed to achieve the required harmonic performance.

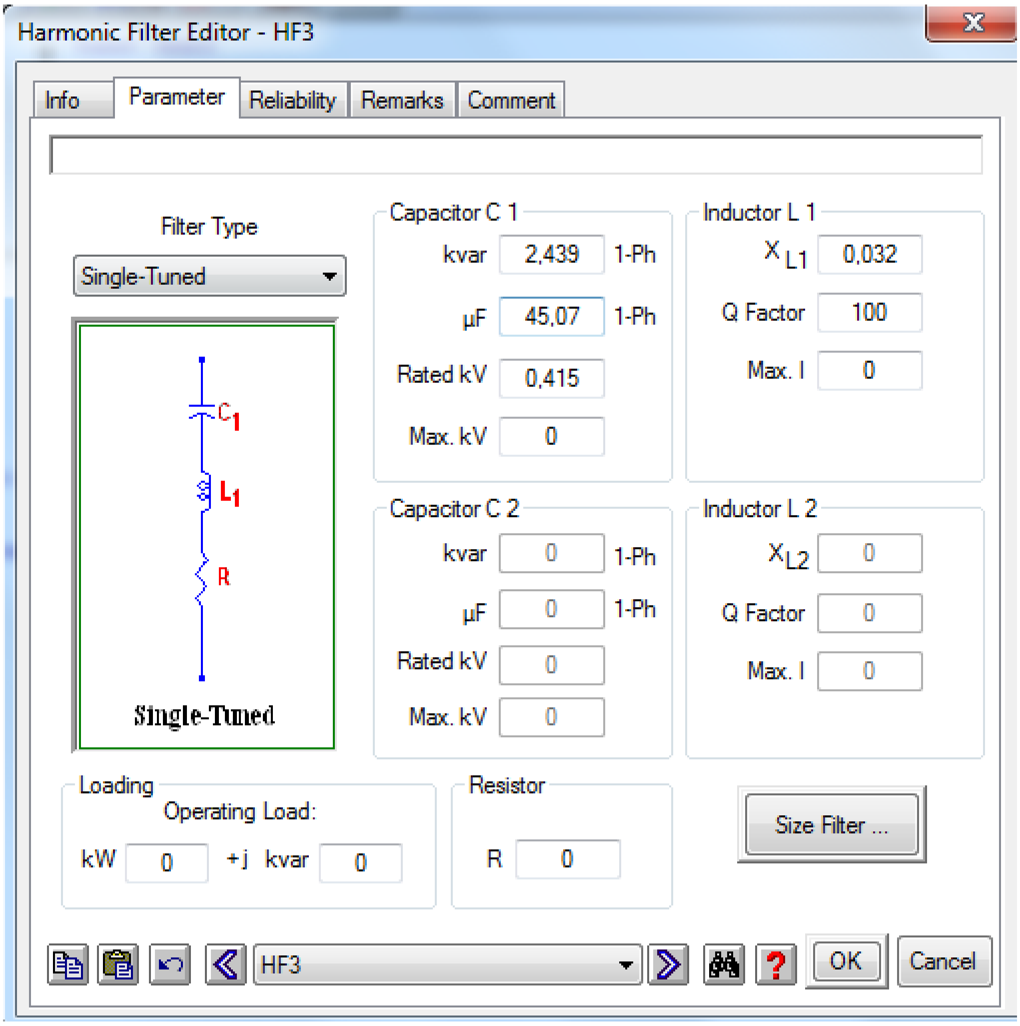
- The harmonic filter interaction with the system impedances results in a parallel resonance at a frequency just lower than the tuned frequency. If a harmonic filter is designed exactly at the harmonic frequency, a variation in the impedance values of the actual equipment from the design values could retune the harmonic filter and place the parallel resonant frequency very close to the harmonic. Instead of low impedance, the combined harmonic filter-system impedance becomes resonant at the harmonic frequency, distortion levels become unacceptable, and damaging voltage amplification may result in severe cases.

It is often advantageous to tune the harmonic filter to approximately 3% to 15% below the desired frequency. This tuning will provide for sufficient harmonic filtering, yet will also provide allowance for the detuning of the harmonic filter.

The following filters have been used in the electrical system:

2.9.1. AC-001-415-TP1

These bus harmonics that are out of limits are 47 and 49. Selecting the harmonic 47 as the one to filter and forcing the power factor to be corrected from 0.88 to 0.90 taking into account that the base demanded power at the bus is 50 kVA we have:



Harmonic Filter Editor - HF3

Filter Type: Single-Tuned

Capacitor C 1
kvar: 2,439 1-Ph
µF: 45,07 1-Ph
Rated kV: 0,415
Max. kV: 0

Inductor L 1
X_{L1}: 0,032
Q Factor: 100
Max. I: 0

Capacitor C 2
kvar: 0 1-Ph
µF: 0 1-Ph
Rated kV: 0
Max. kV: 0

Inductor L 2
X_{L2}: 0
Q Factor: 0
Max. I: 0

Loading
Operating Load:
kW 0 +j kvar 0

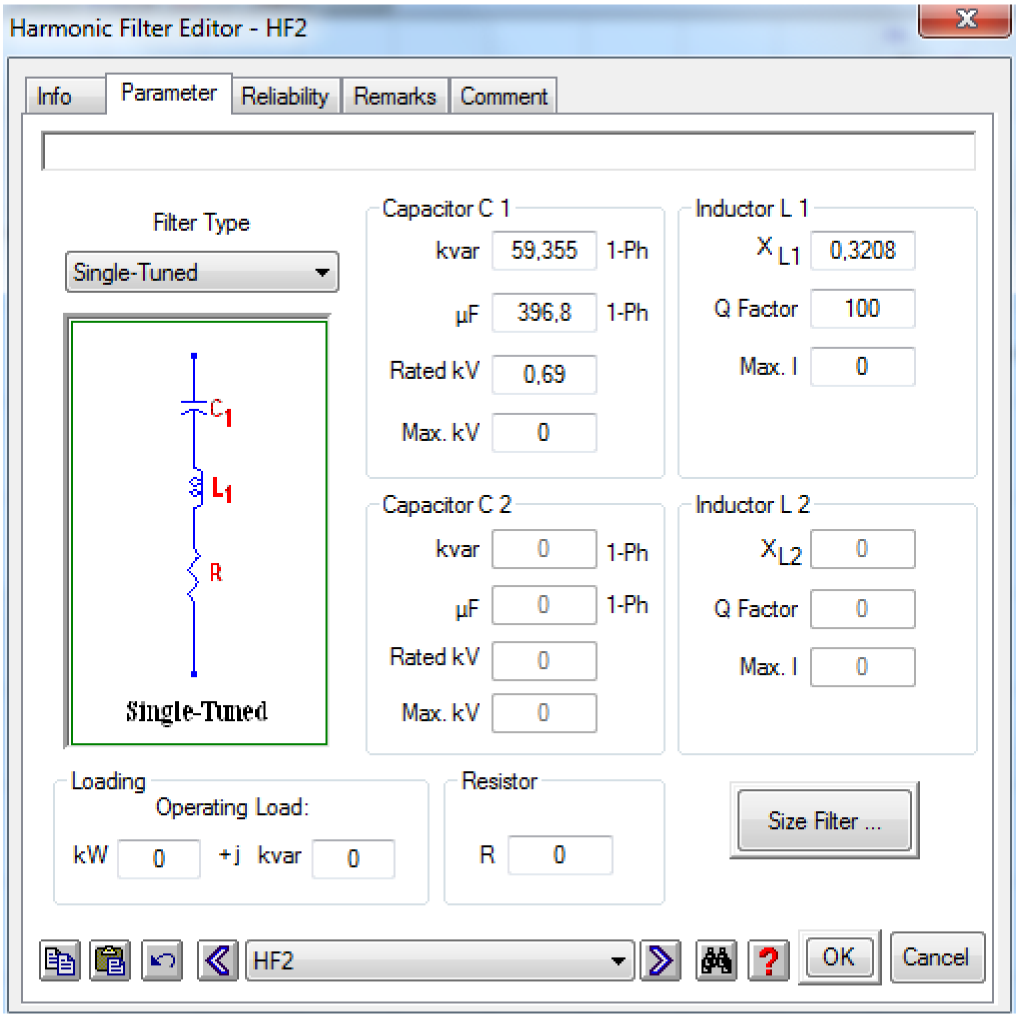
Resistor
R 0

HF3

Figure 20 Filter sizing

2.9.2. AH-002-690-A1

These bus harmonics that are out of limits are 5 and V_{THD}. Selecting the harmonic 5 as the one to filter and forcing the power factor to be corrected from 0.98 to 0.99 taking into account that the base demanded power at the bus is 1000 kVA we have:



Harmonic Filter Editor - HF2

Filter Type: Single-Tuned

Capacitor C 1
kvar 59,355 1-Ph
µF 396,8 1-Ph
Rated kV 0,69
Max. kV 0

Inductor L 1
X_{L1} 0,3208
Q Factor 100
Max. I 0

Capacitor C 2
kvar 0 1-Ph
µF 0 1-Ph
Rated kV 0
Max. kV 0

Inductor L 2
X_{L2} 0
Q Factor 0
Max. I 0

Loading
Operating Load:
kW 0 +j kvar 0

Resistor
R 0

HF2

Figure 21 Filter sizing

2.10. Simulation Results with filters

For full data see annex II

2.10.1.AC-001-415-TP1

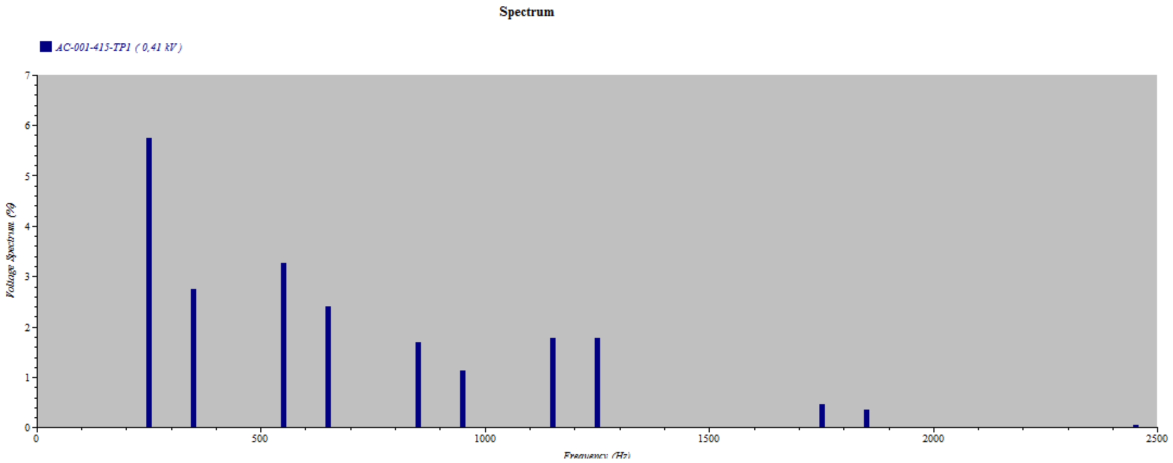


Figure 22 Simulation Results with filters

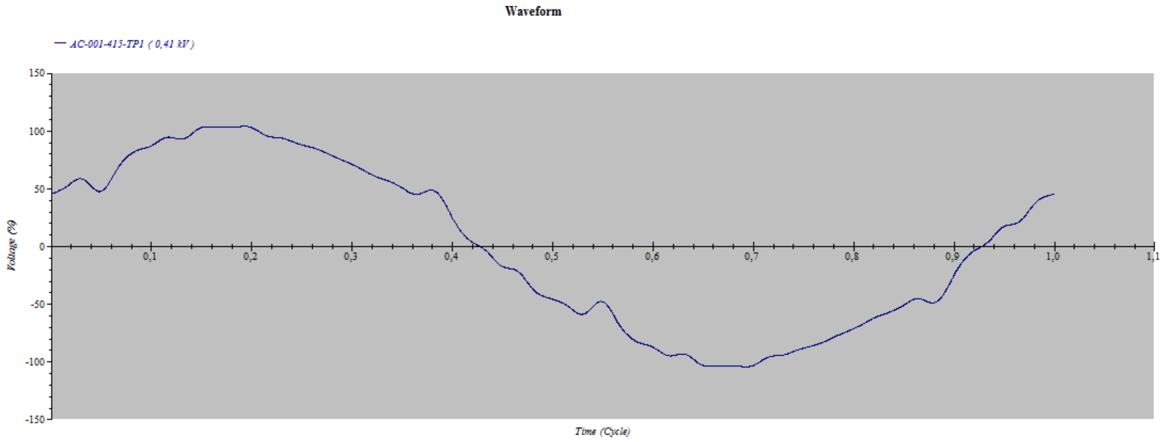


Figure 23 Simulation Results with filters

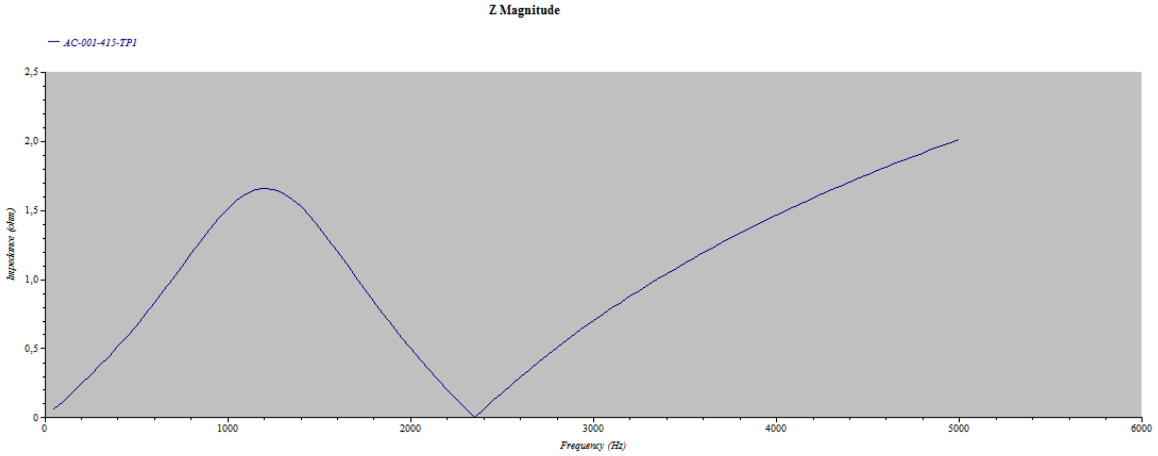


Figure 24 Simulation Results with filters

As shown, now we have a resonant peak on ~1200 Hz (24th Harmonic), so we will have to take care of lower harmonic values.

2.10.2.AH-002-690-A1

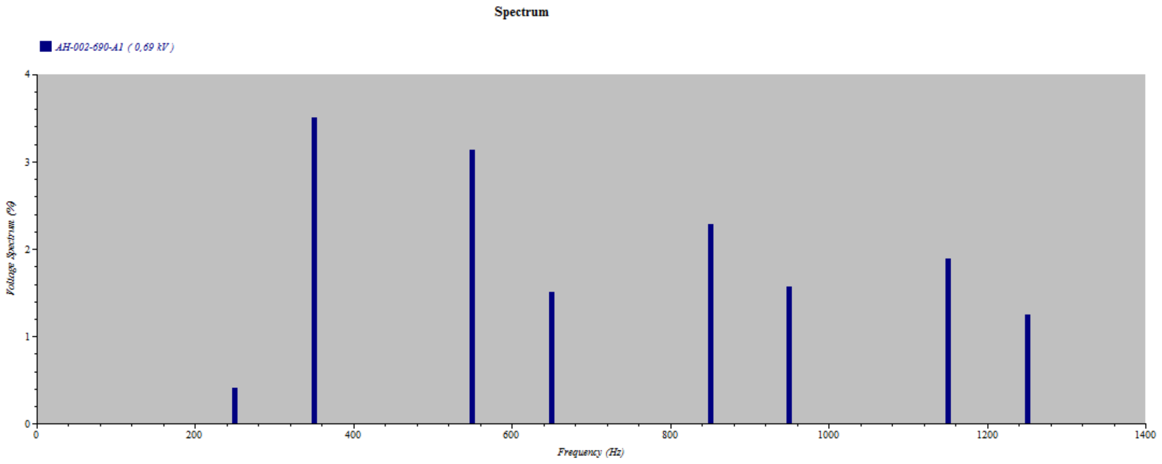


Figure 25 Simulation Results with filters

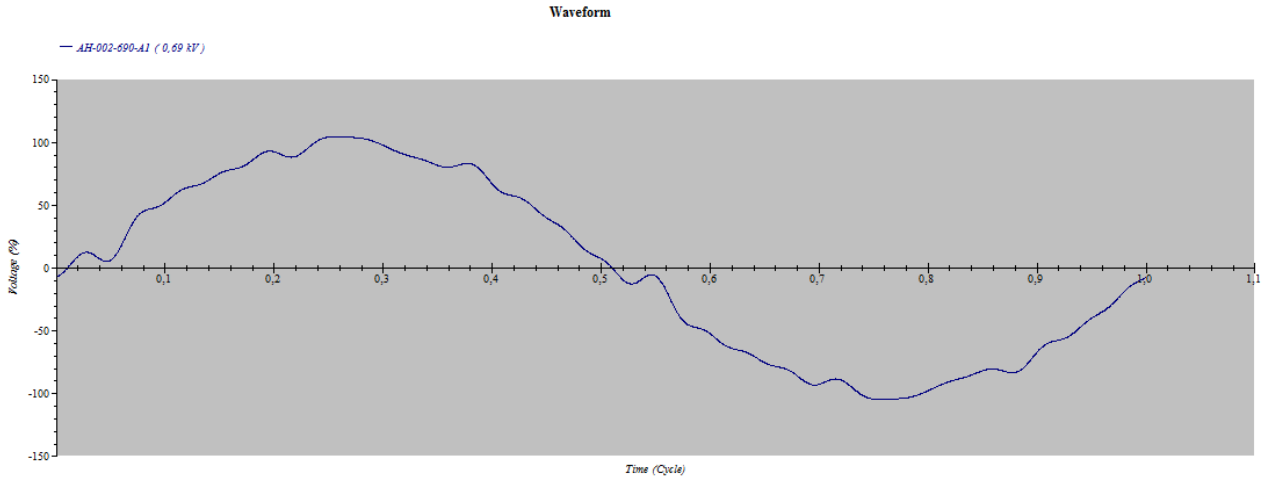


Figure 26 Simulation Results with filters

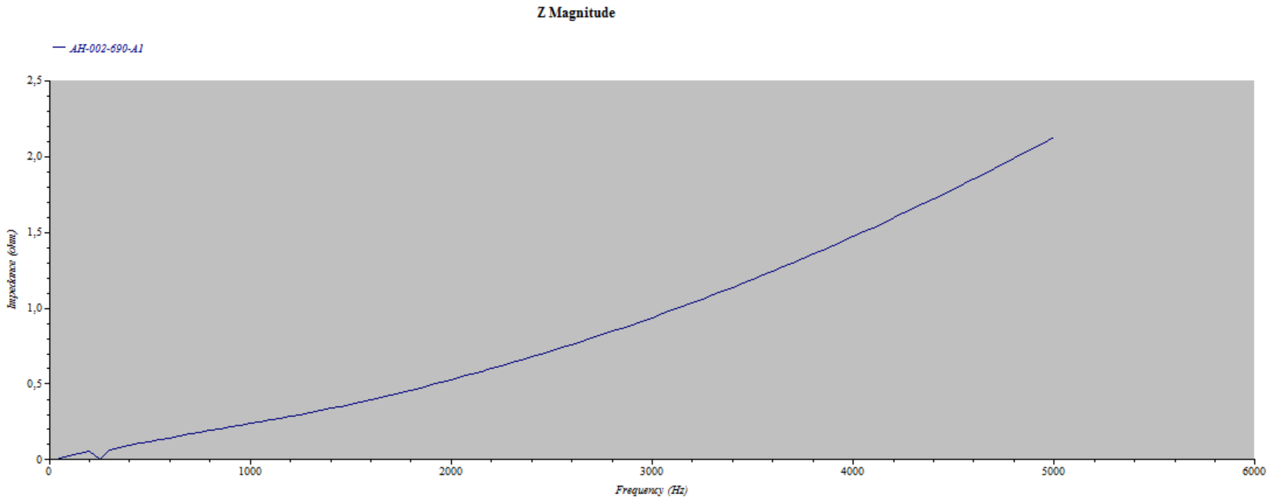


Figure 27 Simulation Results with filters

In this case, the notch frecuency is so small that the resonant reaction is very weak. However it has to be studied aswell.

2.10.3.Conclusion

As we can see in output reports, the harmonic voltages are now the following:

- AC-001-415-H.R.Board2
  - 47th 0.00%
  - 49th 0.04%
- AC-001-415-H.R.Board 4
  - 47th 0.00%
  - 49th 0.04%
- AC-001-415-TP1
  - 47th 0.00%
  - 49th 0.04%
- AH-002-690-A1
  - 5th 0.41%
  - Vthd 6.09%

As shown in standards, limits are:

- 47th 1.12%
- 49th 1.06%
- 5th 8%
- Vthd 10%

Also, it has been taken into account that some other harmonic voltages have been increased but after all they are also within limits.

This results shows that these simple notch filters are adecuate for harmonic filtering of simple systems.

3 TRANSIENT OVERVOLTAGES DUE TO CAPACITOR SWITCHING

3.1 Scope

This study provides an introduction to capacitor bank switching transients, illustrates the effects of the capacitor banks switching at the customer’s plant. Study covers different operational cases to find the suitable method or techniques can be used to limit the effect of capacitor switching transients.

This study has been performed in IFD (Issue for design) basis as no information from suppliers was available at that moment.

Transient disturbances in power systems may damage key equipment, potentially having a great impact on system reliability. These transients may be introduced during normal switching operations, lightning strikes, or because the equipment failure. Therefore, time-domain computer simulations are developed to study dangers cases due to transient occurrences.

The simulations are performed using the simulation software Electromagnetic Transient Program (EMTP). In this study, the Powerfactory Digsilent version 15.1 was applied on the Barka´s project electrical equivalent system.

3.2 Capacitor Energization

During the switching of shunt capacitor banks, high magnitude and high frequency transients can occur.The transient is characterized by a surge of current having a high magnitude and a frequency as high as several hundred Hertz.

There is also a transient overvoltage on the bus, caused by the surge of inrush current coming from the system source.

The system modeling can be simplified like the following:

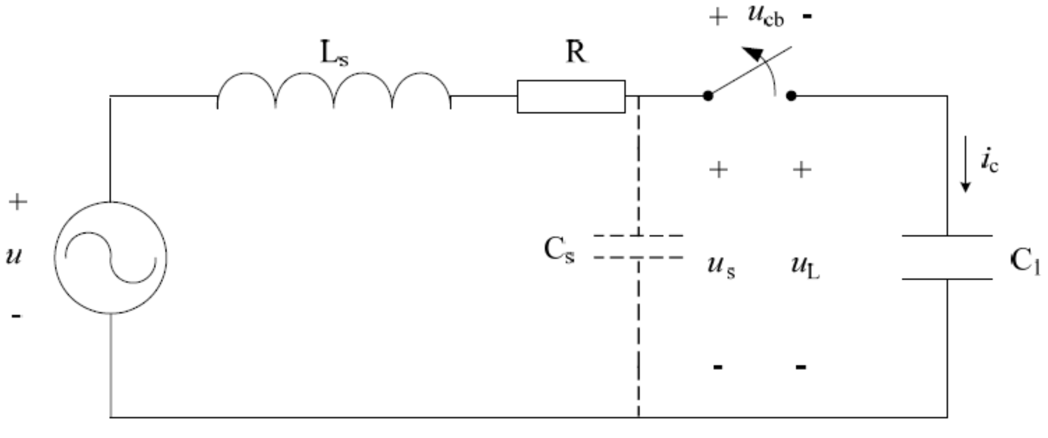


Figure 28 Capacitor Overvoltages model

KEY:

C_1	Capacitive load (capacitor bank)
C_S	Source side capacitance (stray capacitance)
u	Source voltage (rms value)
u_{cb}	Voltage across the circuit breaker (rms value)
L_1	Load side inductance
u_L	Load side voltage (rms value)
i_1	Capacitive current (rms value)
u_S	Voltage on source side of the circuit breaker (rms value)
L_S	Source inductance

$$\left(\frac{di_1}{dt}\right)_{max} = \omega_s I_{SC}\sqrt{2}$$

Where:

$\left(\frac{di_1}{dt}\right)_{max}$	Is the máximum rate of change of inrush current (A/s)
I_{SC}	Is the rated short circuit current
$\omega_s = 2\pi f_S$	Is the system frequency (rad/s) and fs is the power frequency (Hz)

Taking into account that we can model the capacitor energization as the switching of a RLC circuit, the following ecuation can be used:

$$u = Ri_1 + L\frac{di_1}{dt} + \frac{1}{C_1}\int i_1 dt$$

Where:

u is the applied voltage (V)

R is the resistance representing the losses in the circuit (Ω)

i_i is the inrush current (A)

$L = L_s + L_1$ is the inductance in the circuit (H)

C_1 is the capacitance of capacitor bank C_1 (F)

This ecuation is a second order linear homogenous differential equation with three possible solutions depending on the degree of damping in the circuit.

Taking $\boldsymbol{\alpha} = \mathbf{R/2L}$ and $\boldsymbol{\omega_i} \mathbf{=1/\ LC_1}$, the three solutions are given:

a) Critically damped $\alpha^2 = \omega_1^2$

$$i_1(t) = \frac{u}{L} te^{-\alpha t}$$

b) Underdamped $\omega_1^2 > \alpha^2$

$$i_1(t) = \frac{u}{L\sqrt{\omega_1^2 - \alpha^2}} e^{-\alpha t} \sin\left(\left(\sqrt{\omega_1^2 - \alpha^2}\right)t\right)$$

c) Overdamped $\alpha^2 > \omega_1^2$

$$i_1(t) = \frac{u}{L\sqrt{\alpha^2 - \omega_1^2}} e^{-\alpha t} \sinh\left(\left(\sqrt{\omega_1^2 - \alpha^2}\right)t\right)$$

As shown, depending on the values of L,C and R the system may behave one way or another.

If no resistors nor inductors are considered at capacitor energization, the system may behave as case b), which could lead to high overvoltages.

However, if connection resistances are taken into account, R series parameter could be as high as to consider the system overdamped which would result in smaller current peaks and then lower overvoltages.

3.3 System Input Data

As the information regarding the electrical system far from the coupling point of 15.75 kV is unknown assumptions has been performed in order to model a typical configuration.

As shown, a 132/15.75 kV Substation is located upstream Barka dissalination plant, which is fed from the general power grid at 132 kV from an overhead transmission line. Also, a load is modeled at 132 kV to represent secondary substations fed from this one.

Then, a 15.75 kV underground cable feeds the dissalination plant.

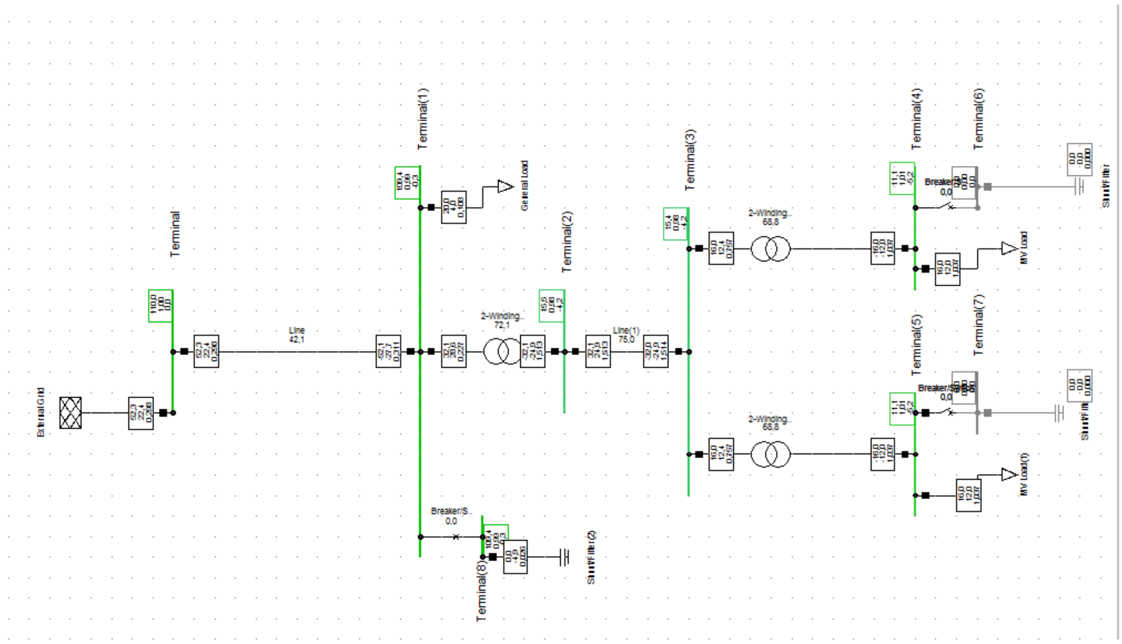


Figure 29 System Modelling

The different devices have the following characteristics:

3.3.1 Power Grid

In order to perform the initial load flow, the grid has been seleted as swing.

$S_k''{}_{max}$= 10000 MVA

c-Factor$_{max}$= 1.1

R/X (max)= 0.1

X_0/X_1 (max)= 1

R_0/R_1 (max)= 0.1

$S_k''{}_{min}$= 8000 MVA

c-Factor$_{min}$= 1.0

R/X (min)= 0.1

X_0/X_1 (min)= 1

R_0/R_1 (min)= 0.1

3.3.2 Overhead Transmission Line

A typical 132 kV transmission line has been selected.
N2XS(FL)2Y 1x300RM/25 64/110kV it

N=1
L= 10 km
R_1= 0.0613 ohm/km
X_1= 0.1445 ohm/km
R_0= 0.2451 ohm/km
X_0= 0.5781 ohm/km
S_1= 47.124 uS/km
S_0= 47.25 uS/km

3.3.3 132/15.75 kV Substation Transformer

132/15.75 kV Yn/Yn
S= 60 MVA
Taps at 132/16.5 kV (In order to adecuate MV Busbars voltages)
Z_1= 12%
Z_0= 12%
R_1/X_1= 0.022
R_0/X_0= 0.022

3.3.4 15.75 kV Underground Cable

A typical underground cable has been selected.

N2XSEYRGY 3x240rm 8.7/15kV
N=4
L= 0.5 km
R_1= 0.0786 ohm/km
X_1= 0.0942 ohm/km
R_0= 0.3142 ohm/km

X_0= 0.3769 ohm/km

S_1= 116.239 uS/km

S_0= 115.485 uS/km

3.3.5 15.75/11 kV Transformers

15.75/11 kV Yn/d

S= 30 MVA

Taps at 15.75/11.5 kV (In order to adecuate MV Busbars voltages)

Z_1= 3%

Z_0= 3%

R_1/X_1= 0.022

R_0/X_0= 0.022

3.3.6 Capacitors

3.3.6.1 At 110 kV

A 5 MVar capacitor has been set in order to improve the 110 kV substation power factor.

3.3.6.2 At 11 kV

A 2 MVar capacitor has been set at each 11 kV Busbar in order to improve the dissalination plant power factor. This is the capacitor switching that will be simulated.

3.3.7 Loads

3.3.7.1 At 110 kV

A 20 MW, 5 Mvar general load has been modeled in order to take into account secondary outgoings from the main substation

3.3.7.2 At 11 kV

A 20 MW 0.8 PF has been modelled in each of he two 11 kV busbars in order to model the dissalination plant. There is no need to model the 6.6 and 0.4 kV system as long as the worst conditions are given at 11 kV.

3.4 Results

Now, performing the transient simulation with the information above and taking a 3 secs time simulation we can see the following:

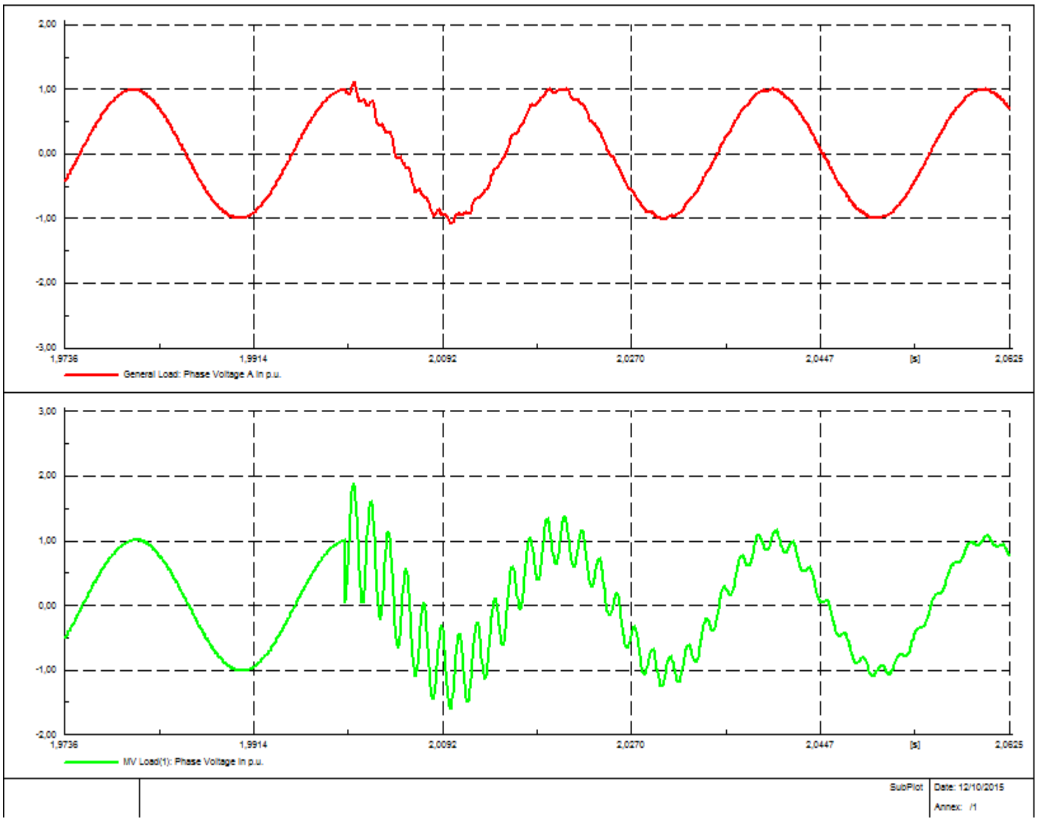


Figure 30 Overvoltages without measures

The first graph shows the voltage at the 110 kV substation when the dissalination plant capacitor is connected, and the green one shows the voltage graph at the 11 kV busbar.

The connection has been set on the worst possible condition that is when the senoidal curve is at its highest value.

As shown, the voltage peak can be as high as 2 pu, which means ~22 kV at the 11 kV busbar. This means that all the equipment at 11 kV should be sized with a transient voltage withdstand of >11 kV which results in high overcosts.

3.5 Solutions:

3.5.1 Synchronous connection

A solution could be adding a synchronous connection. This forces the capacitor connection to be performed on zero passing times. This would be the difference:

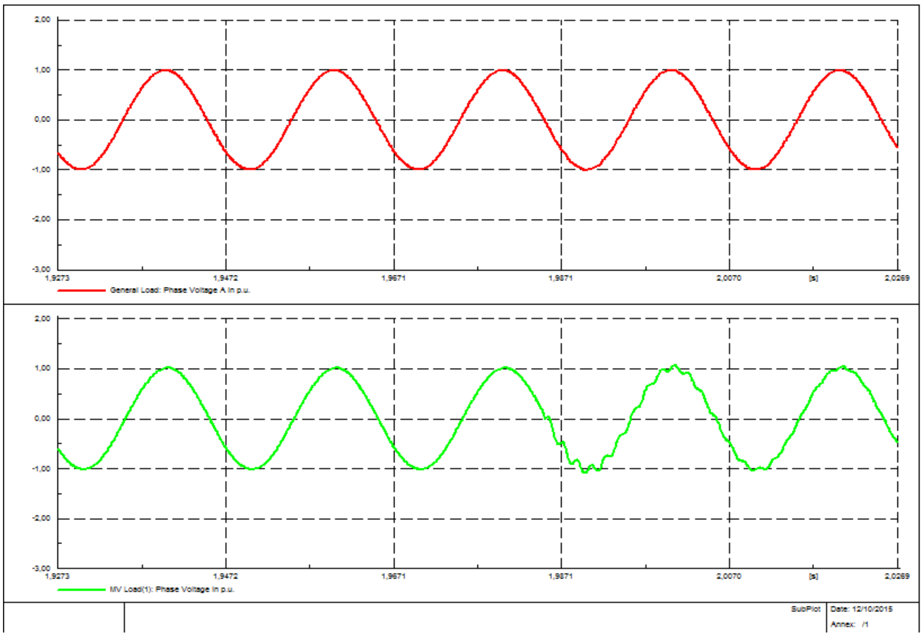


Figure 31 Overvoltages using Synchronous switching

As shown, the overvoltages are nearly unappreciable due to the switching is performed when the senoidal wave is at a 0 crossing.

3.5.2 Inductance-Resistance Addition

Another way to reduce the overvoltages caused by capacitor banks switchings is to add a series inductance and resistance that should reduce the voltage peak as shown in ecuations before.

This is the cheapest way to reduce system overvoltages, however losses may increase and have to be carefully checked.

If considering a Series resistance of 0.1 ohm and a Series inductance of 4.77 mH, the results are the following:

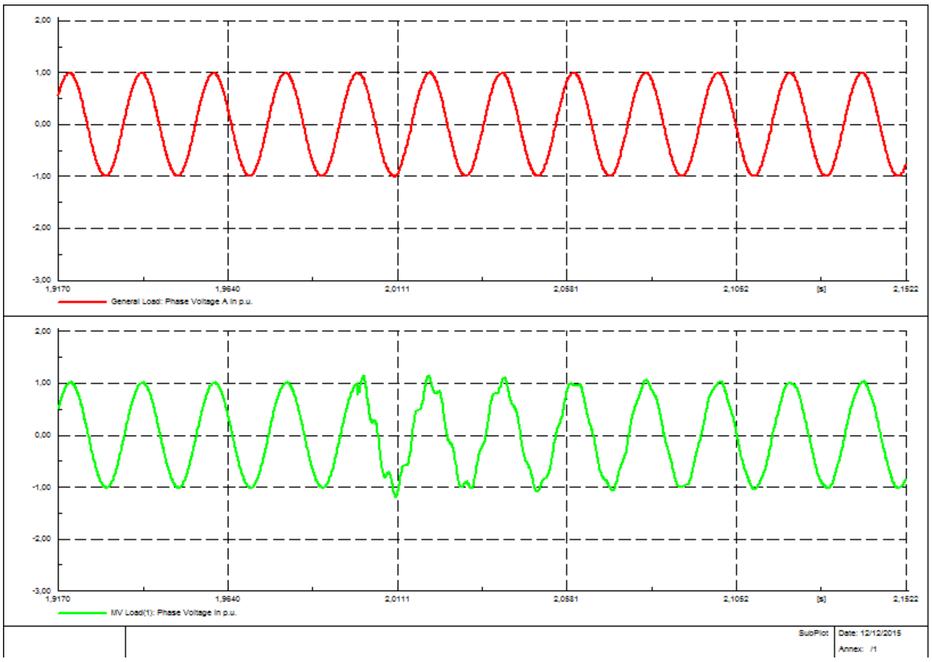


Figure 32 Overvoltages using series resistances and reactances

As shown, overvoltages are critically reduced even for the worst possible scenario.

3.6 Conclusion

Transient Overvoltages have to be carefully studied as the can lead to major problems in equipments.

As shown above, capacitor banks have to be selected taking into account system´s configuration and the worst situations applicable.

Making a balance between capacitor inductances and resistances, system configuration and capacitor placement can lead to a cheaper solution as well as a better protection against transients.

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