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Fundamentals of harmonic compensation and solution in Industrial Systems: a case study

Fundamentals of harmonic compensation and solution in Industrial System: a practical case.

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Abstract

This paper proposes to simplify the diagnosis of a case study of harmonic compensation, applied to the electrical installation of a Seed Processing Plant, which is in the central region of the State of Sinaloa, Mexico, through a spreadsheet that facilitates defining the magnitude of the problem, and informed decision making through the validation of devices with the potential to reduce this problem. Seeking to reach students and engineers interested in the subject to apply it in the redesign and provide solutions in the educational and / or business field.

Methodology

The topic integrates theory from the mentioned regulations and references, recording the data, calculating the components, specifying the filter and its losses, attaching an appendix with a comprehensive exercise elaborated in Microsoft Excel.

Results

An application of reactive compensation was presented, the recording of the data reaffirms the existence of harmonics characteristic of the frequency inverters, obtaining as an additional benefit the diagnosis for the aforementioned plant.

Implications

The impact caused by the charge translates into harmonic currents flowing into capacitors that come into resonance with them, and their equivalent reactance tends to rise, converting the current into heat that destroys the insulation of capacitors and transformers.

Originality

Since in the current literature the subject has been approached from primarily technical approaches, without presenting specific examples and / or presenting them only with partial information. We fill the empty spacesand we propose a case in a comprehensive and didactic way for a greater understanding and clarity of the subject.

Keywords

Power quality, capacitive compensation, harmonic content, passive filtering, non-linear circuit.

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I. Introduction

This document aims to present an application about power factor compensation in a Seed Treatment Plant in Central Sinaloa. In circuits with nonlinear loads, where motor control devices include power electronics (frequency inverters, soft starters) there are disturbances and electromagnetic phenomena that require different solutions. In our context, when assessing this test subject, appropriate solutions must be given that correspond to the needs to be met in industrial electrical systems. In this case, the category of the power quality problem is defined as harmonic distortion that causes resonance in the existing capacitor bank.

Sotelo Rosas, (Sotelo-Rosas & Ramírez-Carrera, 2005), believes that, in the diagnosis, measurement and collection of data allows defining the causes and characteristics of the problem. In this particular case, distortions, essentially, is the generation of harmonics from each frequency inverter device located in the drying area of the corn seed. A method developed for this purpose is proposed, detailing its stages, which involves identifying the category of the problem, characterizing it, identifying the range of solutions, technical evaluation of the solutions and economic evaluation of the optimal (Sotelo-Rosas & Ramírez-Carrera, 2005)technical solution.

This suggested method for troubleshooting starts by identifying the problem category. The transient phenomena or perturbations to be described in this document are harmonics.

Harmonics are integer frequencies multiples of the fundamental frequency (50 or 60 Hz) present in the electrical signal, either in the form of voltage or current waves. The harmonic waveform fundamental voltage waveform is illustrated in Figure 1. The interharmonic is generated between the frequency of both voltage and current, and its frequency is a non-integer multiple of the fundamental frequency. Non-integer multiples of the fundamental frequency are called Interharmonics, and these can appear as discrete frequencies. Both the harmonics and interharmonics summed together in the fundamental waveform are shown in Figure 1.

Power losses and distortion in the main supply voltage are generated by unwanted current flows in the network. Improper use of defective devices such as fluorescent lamps, household appliances or other equipment and also malfunction of ripple control, protective relays and network signaling. Additional losses in passive elements and rotating machines will affect the efficiency of the motors and create harmonics in the voltage or current of the line.

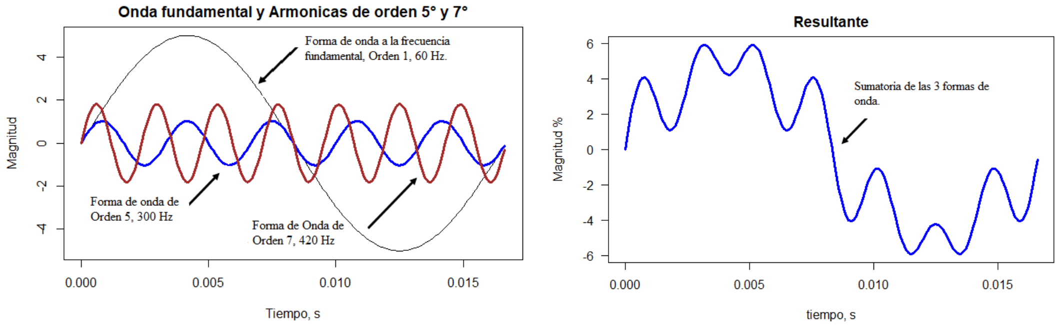


Figure 1. Upper: Fundamental wave and s wave of 5° and 7° order, Lower: Harmonic of 5° and 7° order added s with the fundamental waveform.

The impact of harmonic and interharmonic wave distortions on electrical systems is described below.

Current harmonic impact (THDi): neutral overload, transformer overheating, anonymous circuit breaker tripping, skin effect and capacitors used in power factor correction.

Voltage harmonic impact (THDv): voltage waveform distortions, induction motors and increasing current harmonics.

Impact of voltage interharmonics (THDv): Overheating of devices or equipment, the effects of Interharmonics are impact on light, flickering, overloading of filters tuned in series and saturation of the current transformer.

Remediation.: There are several techniques used to control harmonics that are: active filter in derivation, phase multiplication, harmonic injection, modulation technique and passive filters.

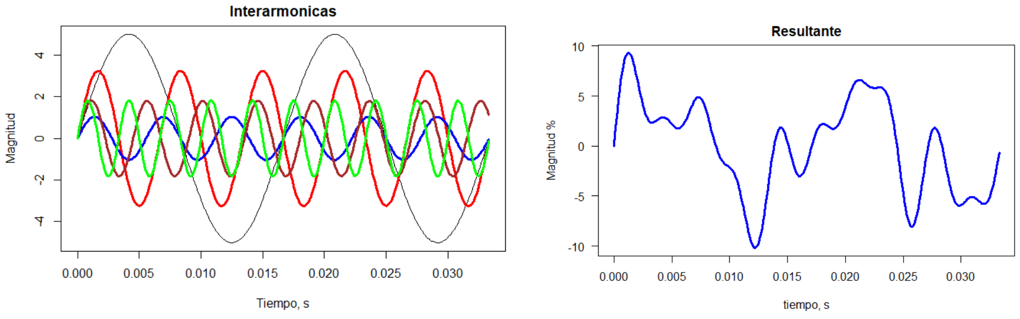


Figure 2. Top: Fundamental waveform with harmonics and interharmonics. Bottom: Sum of harmonics and interharmonics.

Case Study Features

The problem occurred in the Drying Substation whose highest load is four fans controlled by 12-pulse variable speed drives, 150 HP and 480 Vac. The distribution board of the Substation includes a power factor compensation equipment (capacitors). The source of the disturbance was identified in a practical way by measuring the amperage of the capacitors without a variator which was 65 A, and when one of the drying drives was energized, this amperage increased to 90 amperes, which rules out the supplier (CFE) as the source of the problem and implies that the source is internal. The problem has been latent and both the capacitor bank and the drying transformer had already been affected. The CFE supply company for its part carried out a first Energy Quality Analysis that confirmed the assumption, the problem comes from within the company.

The company requested a second study. For which we established the following field strategy. The field study will be a clear, reliable and simple method, which reduces the ambiguity and complexity present when looking for the diagnosis and solution to engineering problems.

II. Background

Sotelo Rosas, believes that, in the diagnosis, measurement and collection of data allows defining the causes and characteristics of the problem. In this particular case, distortions, essentially, is the generation of harmonics from each frequency inverter device located in the drying area of the corn seed. A method developed for this purpose is proposed, detailing its stages, which involves identifying the category of the problem, characterizing it, identifying the range of solutions, technical evaluation and solutions.(Sotelo-Rosas & Ramírez-Carrera, 2005)

IEEE Std 519 is a best practice that sets goals for the design of electrical systems that include both linear and nonlinear loads. The observance of the design objectives of this standard is to minimize interference between electrical equipment. This best practice addresses steady-state limitations. Transient conditions or interferences when quantities are exceeded may encounter limitations. This document establishes the quality of power to be provided at the common docking point. (IEEE, 1992)

IEEE Std 1159, this best practice covers monitoring the electrical power quality of AC power systems in single-phase and polyphase form. As such, it includes consistent descriptions of electromagnetic phenomena occurring in energy systems. The document also presents definitions of nominal conditions and deviations from these nominal conditions, which may originate within the supply source or loading equipment, or from source-load interactions.(IEEE, 1995)

IEEE Std 100,establishes a common authoritative language that defines quality and establishes technical criteria. By ensuring consistency and compliance through open consensus, IEEE standards add value to products, facilitate trade, drive markets, and ensure safety. In the last decade alone, hundreds of terms, describing the latest tools, techniques, and best practices have been added to the lexicon of IEEE standards.(IEEE, 2000)

IEEE Std 1531, addresses the selection of (1) components, (2) protection, and (3) control of harmonic filters. It does not address the engineering required to establish the proper size and configuration of harmonic filters, to achieve the desired performance. This document provides guidelines for passive shunt harmonic filters for use in 50 Hz and 60 Hz power systems to reduce harmonic distortion in the system(s). (There are no specific standards in place for harmonic filters, although there are standards for most components used in a filter. This guide refers to standards when they exist and provides typical criteria when appropriate standards do not exist.)(IEEE, 2003)

On the State of the Art

PérezAbril, establishes that harmonic filters fulfill the function of preventing the circulation of harmonic currents through the system and reducing voltage distortion. These can be passive (composed of impedance arrays) or active (based on power electronics). The characteristics of passive filters can be found in the specialized literature. However, the equations for their design are not shown in all cases, which makes it difficult to calculate their components and their stress under operating conditions. The main objective of this work is to develop the general procedure for the calculation of passive harmonic filters and determine the equations corresponding to the different types of filter. In addition, an application is described in Matlab that calculates the parameters R, L and C of the different types of filter and evaluates the stress to which the components of the filters are subjected.(Perez April, 2012)

Definitions

Electrical Power Quality (CE): It is a set of physical characteristics of voltage and current signals for a given time and a certain space to meet the needs of customers.

Monitoring: Method used to obtain information on events and variations that occur in the network.

Noise: Unwanted electrical signal with wideband spectral content less than 200 kHz superimposed on the voltage or current of phase conductors or neutral conductors, or signal conductors.

Harmonic(a): A sinusoidal component of a periodic wave or quantity that has a frequency that is an integral multiple of the fundamental frequency. Note: For example, a component, whose frequency is twice the fundamental frequency, is called a second-order harmonic. See also: non-characteristic harmonic; characteristic harmonic; relative harmonic content; harmonic components; Harmonic content. (IA/SPD/PE/T&D/SPC) 936-1987w, C62.48-1995, 599-1985w, 519-1992, 1250-1995.

Nonlinear loading. A charge that extracts a non-sinusoidal current wave when supplied by a sinusoidal voltage source. (IA/SPC/PES) 519-1992, 1100-1999.

Quality factor. Twice the ratio between the maximum energy stored and the energy dissipated per cycle at a given frequency. An approximate equivalent definition is that Q is the ratio of the resonant frequency to the bandwidth between those frequencies on opposite sides of the resonant frequency, where the response of the resonant structure differs by 3 dB from that of the resonance. If the resonant circuit comprises an inductance, L, and a capacitance, C, in series with an effective resistor, R.
Development – Dimensioning the problem

Methods and tests performed.

The measurement takes into account the drying area of the corn seed that is fed from substation 2. The T3 transformer has a capacity of 750 kVA, D-YT connection, Dyn 11, 34.5 kV, 440/254 V, (See Figure 3). The substation feeds the TDG3 Secado 100 general distribution board, which distributes the energy to the equipment shown in Figure 4. The ETAP (Electrical Transient Automation Program) is used to simulate the electrical system of the company in question.

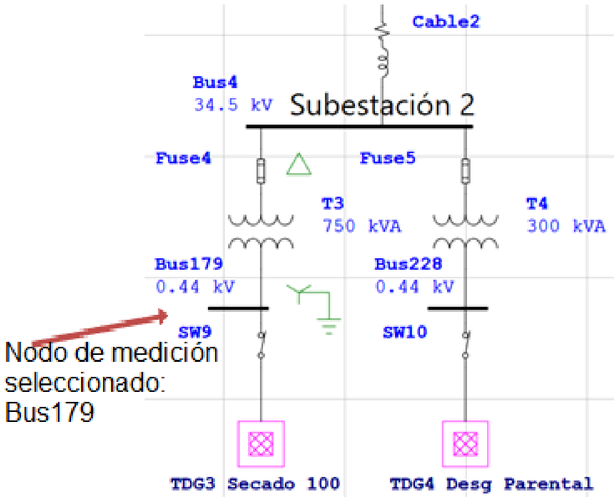


Figure 3. Electrical devices installed in substation 2.

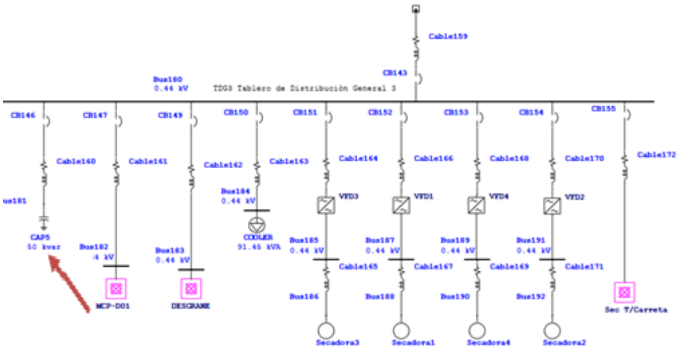


Figure 4. TDG3 Board Drying 100. The Capacitor is noted to be damaged due to electromagnetic disturbances. See the increased load represented by four 150 HP fans controlled by variable frequency drives.

Collect the data
With a Fluke 435 monitor-recorder, the following information was obtainedshown in Figures 5 to 12.
Capture of sinusoidal voltagesand non-sinusoidal currents.

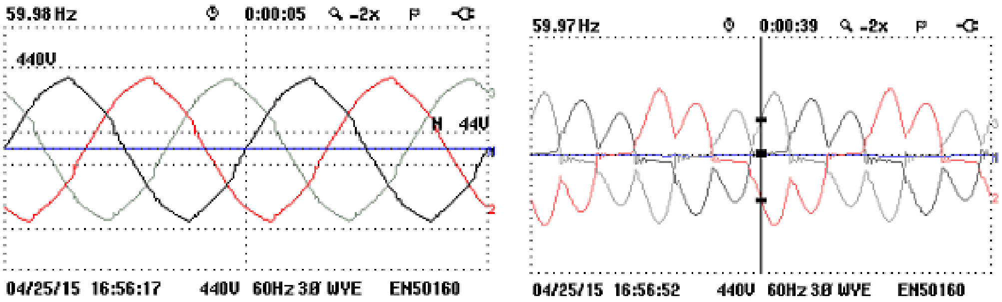


Figure 5. Waveforms of voltage and three-phase currentto s distorted.

Tensions on the node

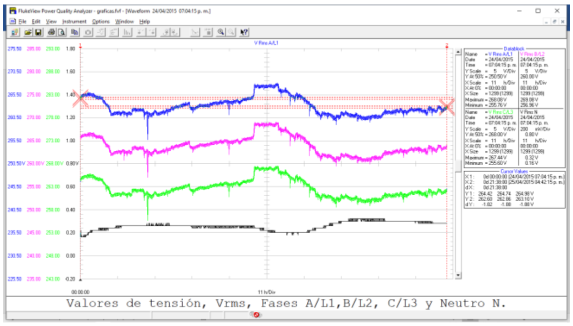

Valores de tensión, Vrms, Fases A/L1,B/L2, C/L3 y Neutro N.

Figure 6. 24-hour record of the operation of the Drying Area, Voltages values in the measuring node.

Currents in the node

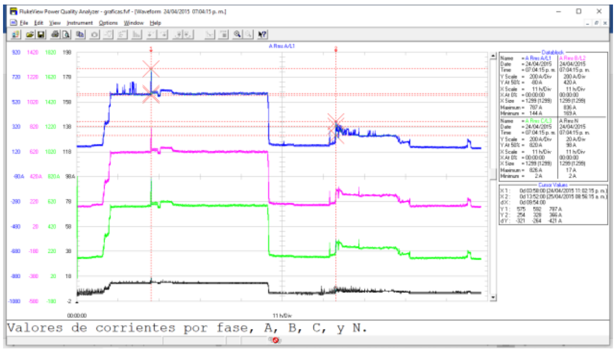
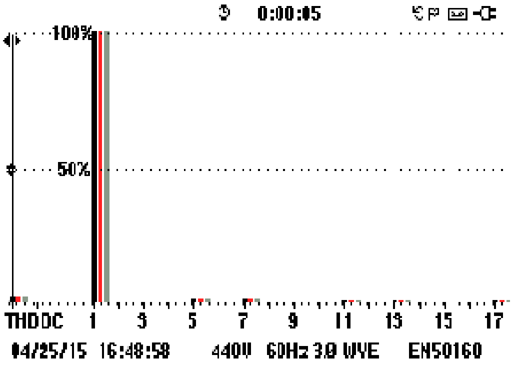

Valores de corrientes por fase, A, B, C, y N.

Figure 7. 24-hour record of the operation of the Drying Area, Current values in the measurement node

Capture of the harmonic spectrum.



(a)

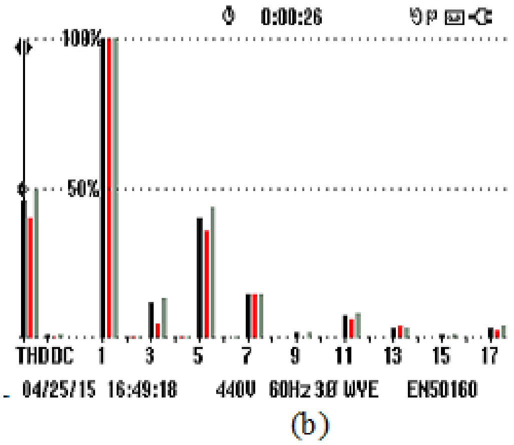


Figure 8. Capture of the harmonic frequency spectrum (histogram) a) in voltage and b) in current.

Figure 8b) shows that there is a high harmonic content offifth and seventhorder characteristic of 12-pulse variators. Figure 99.

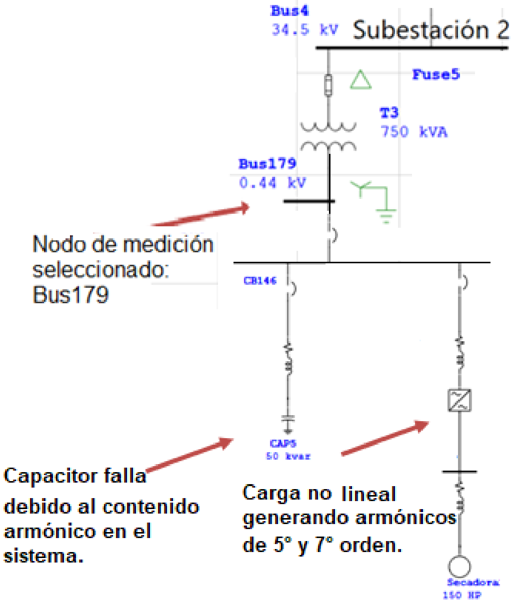
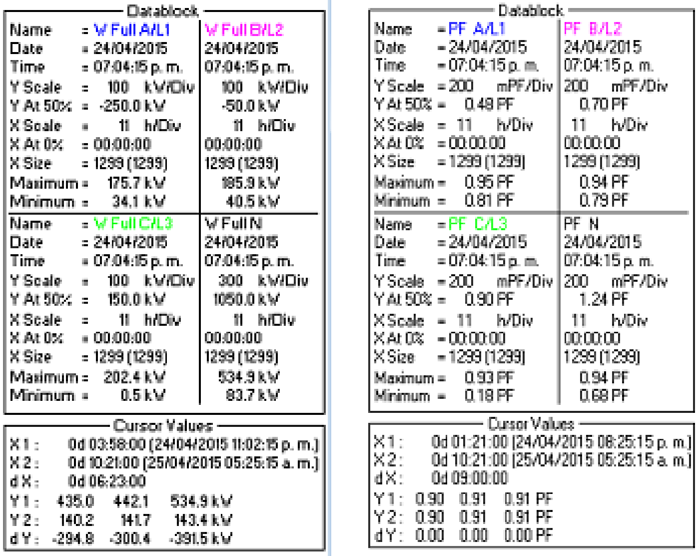


Figure 9. Causes and effects of the use of power electronics

The effects of installing a capacitor in a system with harmonic content.



```
Datablock
Name      = W Full A/L1        W Full B/L2
Date      = 24/04/2015         24/04/2015
Time      = 07:04:15 p. m.     07:04:15 p. m.
Y Scale   =   100   kW/Div      100   kW/Div
Y At 50%  = -250.0 kW          -50.0 kW
X Scale   =    11   h/Div        11   h/Div
X At 0%   = 00:00:00           00:00:00
X Size    = 1299 (1299)        1299 (1299)
Maximum   =   175.7 kW          185.9 kW
Minimum   =    34.1 kW           40.5 kW
Name      = W Full C/L3        W Full N
Date      = 24/04/2015         24/04/2015
Time      = 07:04:15 p. m.     07:04:15 p. m.
Y Scale   =   100   kW/Div      300   kW/Div
Y At 50%  =   150.0 kW         1050.0 kW
X Scale   =    11   h/Div        11   h/Div
X At 0%   = 00:00:00           00:00:00
X Size    = 1299 (1299)        1299 (1299)
Maximum   =   202.4 kW          534.9 kW
Minimum   =     0.5 kW           83.7 kW
Cursor Values
X 1 :    0d 03:58:00 (24/04/2015 11:02:15 p. m.)
X 2 :    0d 10:21:00 (25/04/2015 05:25:15 a. m.)
d X :    0d 06:23:00
Y 1 :   435.0    442.1    534.9 kW
Y 2 :   140.2    141.7    143.4 kW
d Y :  -294.8   -300.4   -391.5 kW
```

(a)

```
Datablock
Name      = PF  A/L1           PF  B/L2
Date      = 24/04/2015         24/04/2015
Time      = 07:04:15 p. m.     07:04:15 p. m.
Y Scale   = 200    mPF/Div     200    mPF/Div
Y At 50%  =    0.48 PF            0.70 PF
X Scale   =  11    h/Div        11    h/Div
X At 0%   = 00:00:00           00:00:00
X Size    = 1299 (1299)        1299 (1299)
Maximum   =    0.95 PF            0.94 PF
Minimum   =    0.81 PF            0.79 PF
Name      = PF  C/L3           PF  N
Date      = 24/04/2015         24/04/2015
Time      = 07:04:15 p. m.     07:04:15 p. m.
Y Scale   = 200    mPF/Div     200    mPF/Div
Y At 50%  =    0.90 PF            1.24 PF
X Scale   =  11    h/Div        11    h/Div
X At 0%   = 00:00:00           00:00:00
X Size    = 1299 (1299)        1299 (1299)
Maximum   =    0.93 PF            0.94 PF
Minimum   =    0.18 PF            0.68 PF
Cursor Values
X 1 :    0d 01:21:00 (24/04/2015 08:25:15 p. m.)
X 2 :    0d 10:21:00 (25/04/2015 05:25:15 a. m.)
d X :    0d 09:00:00
Y 1 :  0.90   0.91   0.91 PF
Y 2 :  0.90   0.91   0.91 PF
d Y :  0.00   0.00   0.00 PF
```

(b)

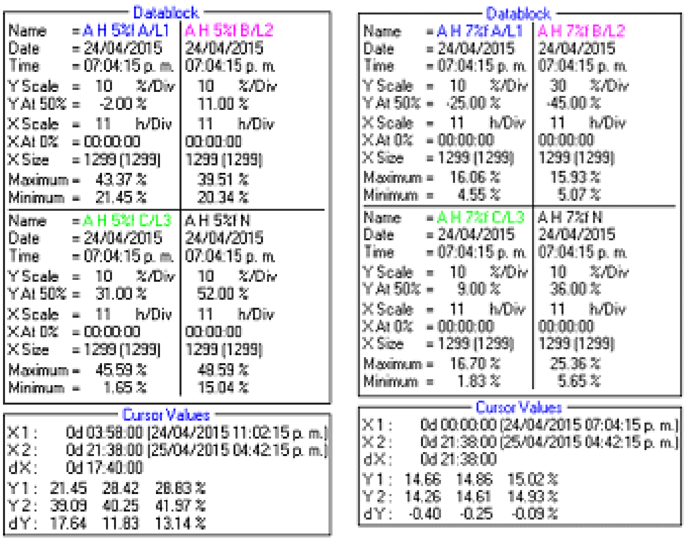
Figure 10. Recorded values of (actual power (a) and power factor (b), of the system under study.

Records show that the total system load is 534.9 kW, with a power factor of 94%, without the capacitor being kept de-energized, to identify the causes of the failure. The operating data of the load are: Real power: 534.9 kW, which at 94% power factor, results in an Apparent Power of569.04 kVA and a reactive power of 194.1 kVAr.

The capacitor bank is designed to improve the power factor, regardless of harmonic effects. The installed bench size: 50 kVAr, would decrease the reactive power of the load to 144.1 kVAr. This would reduce the apparent power of the load to 553.97 kVA. Actual power remains constant at 534.9 kW. And the new power factor would be 534.9×100/553.97 = 96.55%. The 750 kVA transformer would be loaded at 73.86% of the 553.97 kVA load. However, the capacitor was damaged, presenting insulation failure.

The harmonic content of the system.

The values in the monitor-recorder show a harmonic content of fifth and seventh order typical of frequency inverters, they are those shown in Figure 11.

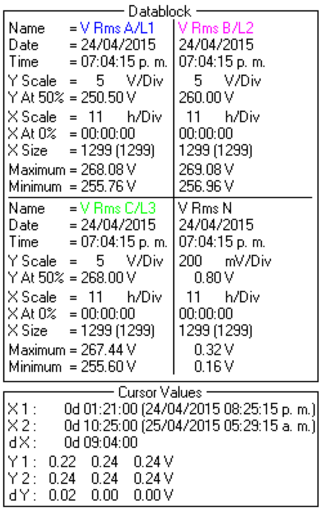


```
Datablock
Name      = A H 5%I A/L1       A H 5%I B/L2
Date      = 24/04/2015         24/04/2015
Time      = 07:04:15 p. m.     07:04:15 p. m.
Y Scale   =  10     %/Div       10     %/Div
Y At 50%  =  -2.00 %            11.00 %
X Scale   =  11     h/Div       11     h/Div
X At 0%   = 00:00:00           00:00:00
X Size    = 1299 (1299)        1299 (1299)
Maximum   =  43.37 %            39.51 %
Minimum   =  21.45 %            20.34 %
Name      = A H 5%I C/L3       A H 5%I N
Date      = 24/04/2015         24/04/2015
Time      = 07:04:15 p. m.     07:04:15 p. m.
Y Scale   =  10     %/Div       10     %/Div
Y At 50%  =  31.00 %            52.00 %
X Scale   =  11     h/Div       11     h/Div
X At 0%   = 00:00:00           00:00:00
X Size    = 1299 (1299)        1299 (1299)
Maximum   =  45.59 %            49.59 %
Minimum   =   1.65 %            15.04 %
Cursor Values
X1 :     0d 03:58:00 (24/04/2015 11:02:15 p. m.)
X2 :     0d 21:38:00 (25/04/2015 04:42:15 p. m.)
dX :     0d 17:40:00
Y1 :  21.45   28.42   28.83 %
Y2 :  39.09   40.25   41.97 %
dY :  17.64   11.83   13.14 %
```

```
Datablock
Name      = A H 7%f A/L1       A H 7%f B/L2
Date      = 24/04/2015         24/04/2015
Time      = 07:04:15 p. m.     07:04:15 p. m.
Y Scale   =  10     %/Div       30     %/Div
Y At 50%  = -25.00 %           -45.00 %
X Scale   =  11     h/Div       11     h/Div
X At 0%   = 00:00:00           00:00:00
X Size    = 1299 (1299)        1299 (1299)
Maximum   =  16.06 %            15.93 %
Minimum   =   4.55 %             5.07 %
Name      = A H 7%f C/L3       A H 7%f N
Date      = 24/04/2015         24/04/2015
Time      = 07:04:15 p. m.     07:04:15 p. m.
Y Scale   =  10     %/Div       10     %/Div
Y At 50%  =   9.00 %            36.00 %
X Scale   =  11     h/Div       11     h/Div
X At 0%   = 00:00:00           00:00:00
X Size    = 1299 (1299)        1299 (1299)
Maximum   =  16.70 %            25.36 %
Minimum   =   1.83 %             5.65 %
Cursor Values
X1 :     0d 00:00:00 (24/04/2015 07:04:15 p. m.)
X2 :     0d 21:38:00 (25/04/2015 04:42:15 p. m.)
dX :     0d 21:38:00
Y1 :  14.66   14.86   15.02 %
Y2 :  14.26   14.61   14.93 %
dY :  -0.40   -0.25   -0.09 %
```

Figure 11. Maximum and minimum values per phase of the 5° and 7° order harmonics that are presented in the system due to the electronic equipment installed.

The operation of electrical voltage with harmonic content.



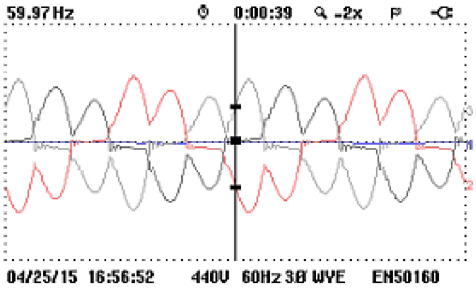
```
Datablock
Name      = V Rms A/L1     | V Rms B/L2
Date      = 24/04/2015     | 24/04/2015
Time      = 07:04:15 p. m. | 07:04:15 p. m.
Y Scale   =   5    V/Div   |   5    V/Div
Y At 50%  = 250.50 V       | 260.00 V
X Scale   =  11    h/Div   |  11    h/Div
X At 0%   = 00:00:00       | 00:00:00
X Size    = 1299 (1299)    | 1299 (1299)
Maximum   = 268.08 V       | 269.08 V
Minimum   = 255.76 V       | 256.96 V
Name      = V Rms C/L3     | V Rms N
Date      = 24/04/2015     | 24/04/2015
Time      = 07:04:15 p. m. | 07:04:15 p. m.
Y Scale   =   5    V/Div   | 200    mV/Div
Y At 50%  = 268.00 V       |    0.80 V
X Scale   =  11    h/Div   |  11    h/Div
X At 0%   = 00:00:00       | 00:00:00
X Size    = 1299 (1299)    | 1299 (1299)
Maximum   = 267.44 V       |    0.32 V
Minimum   = 255.60 V       |    0.16 V

Cursor Values
X 1 :     0d 01:21:00 (24/04/2015 08:25:15 p. m.)
X 2 :     0d 10:25:00 (25/04/2015 05:29:15 a. m.)
d X :     0d 09:04:00
Y 1 :  0.22   0.24   0.24 V
Y 2 :  0.24   0.24   0.24 V
d Y :  0.02   0.00   0.00 V
```

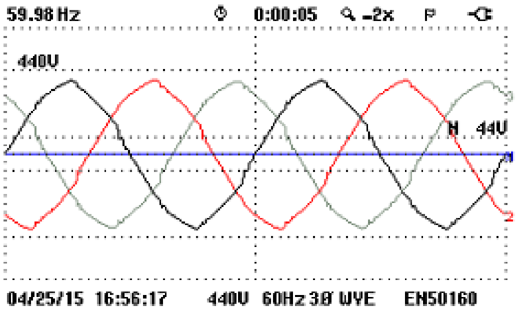
Figure 12. Maximum and minimum values of voltages per phase.

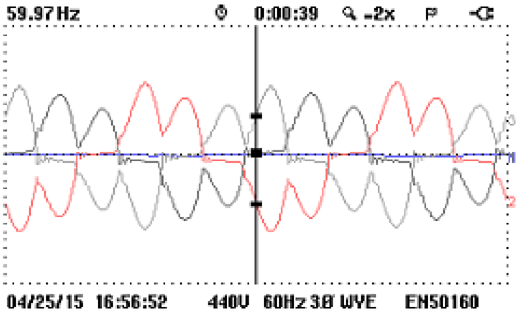
Measurement results.

The maximum phase voltage value in Figure 12 269.08 volts, then the phase-to-phase voltage is 466.06 volts. With a real power of 534.9 kW, the phase current is 750.17 A. This current is added to those of the harmonics, the 5th order requires a current of 363 A , and the 7th order a current of 197.52 A.

In the selected node we will measure the distortions caused by the equipment installed on the TDG3 board (see Figure 5), using a fluke 435 node meassuring equipment.







Calculations and mathematical models.

Analysis procedure

Measure and record. The measuring node is chosen by placing it in the Drying substation, on the secondary side of its 750 kVA, 440 Vac transformer.

The measurement resulted in a percentage of harmonics outside the limits established by the regulations. (IEEE, 1992)

The calculation of the filter required to mitigate according to the studies and the requirements of the regulations, is done for a passive filter, results that we use to specify it.

Calculating parameters of a passive filter

Theory

In general, all passive filters for parallel connection are composed of a capacitor C that provides most of the reactive power of the filter, in series to a circuit composed of inductances, capacitances and resistors whose impedance is a function of frequency n. Typically, the filter can be calculated: (1) from a known power capacitor () or (2) to obtain a desired reactive power () at the fundamental frequency (). In both cases the filter is designed to achieve a minimum impedance for the tuning frequency () and with a quality factor () necessary to achieve adequate filtering.$QcnQ_1fF = 60\ HzhQF$

The impedance Zf, of this simple tuning filter for agiven frequency calculates as:

$$\boldsymbol{Zf = R + j(h \cdot Xl - Xc/h)} \qquad \textbf{Eq. 1}$$

So the tuning frequency (h) at which the minimum impedance value occurs coincides with the resonant frequency of the filter.

$$h = \sqrt{Xc/Xl} \qquad \textbf{Eq. 2}$$

In this way, the selection of the capacitive reactance (Xc) and the inductive reactance (Xl) of the filter, knowing the nominal reactive power of the capacitor (Qcn) is very simple:

$$Xc = Vn^2/Qcn \qquad \textbf{Eq. 3}$$

$$Xl = Xc/h^2 \qquad \textbf{Eq. 4}$$

These single-tunefilters are used to eliminate low-order harmonics with a high quality factor ($QF = 20 - 150$) which is defined as:

$$QF = h \cdot Xl / R = Xc / (h \cdot R) \qquad \textbf{Eq. 5}$$

Therefore, known, the resistanceXl (R) is calculated by:

$$R = h \cdot Xl / Q \qquad \textbf{Eq. 6}$$

The impedance of this filter for the fundamental frequency is calculated as:

$$\boldsymbol{Z_1 = R + j(Xl - Xc)} \qquad \textbf{Eq. 7}$$

And the reactive power delivered by the filter to the fundamental one is:

$$\boldsymbol{Q_1 = imag\{Vn^2/Z_1^*\}} \qquad \textbf{Eq. 8}$$

But considering that the quality factor is high and therefore the resistance is very small, the approximation can be reached:

$$\boldsymbol{Q_1 = Vn^2/(Xc - Xl) = Vn^2/Xc(1 - 1/h^2) = Qcn(h^2/h^2 - 1)} \qquad \textbf{Eq. 9}$$

Therefore, it would be calculated approximately from as:XcQ_1

$$\boldsymbol{Xc = Vn^2/Qcn \approx (Vn^2/Q_1)(h^2/h^2 - 1)} \qquad \textbf{Eq. 10}$$

Numerical example

Initial data

- Fundamental frequency, *fF* = 60 Hz.
- Transformer T3 Data
- Apparent power: *Str* = 750 kVA
- Transformer Impedance: *Ztr* = 7.0%
- Current in transformer secondary: *Itr* = 984.12 A

Load data, without harmonics

- Actual load power, *P* = 534.9 kW
- Initial Power Factor ,FP_1 = 94%
- Load current : *Iload* = 704.92 A

Capacitor power required to compensate for power factor

- Reactive power: *Qc* = 50 kVAr

- Voltage between phases :*Vf* = 440 V
- Neutral voltage:*Vn* = 254 V

Transformer ballast

$$\boldsymbol{Xtrf = Ztr\ (Vf^2/Str)}$$ **Eq. 11**

Xtrf = 0.07*(440 V)^2/750 kVA) = 0.0180693Ω

Capacitor reactance

$$\boldsymbol{Xc = Vf^2/Qc}$$ **Eq. 12**

Xc = (440V)^2/50 kVAr =3,872 Ω

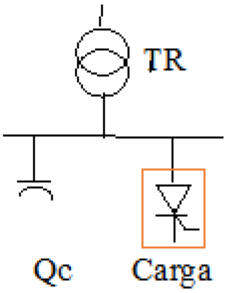


Figure 13. *Unifilar Case Diagram.*

Resonance frequency

It is called resonant frequency to that characteristic frequency of a body or a system that reaches the maximum degree of oscillation. Every body or system has one, or several, characteristic frequencies. When a system is excited to one of its characteristic frequencies, its vibration is the maximum possible.

$$n = \sqrt{Xc/Xl}$$ Eq. 13

The resonance frequency, n = = 14.64 order = 878.31 Hz.$\sqrt{3.872/0.01807}$

The resonance shown in Figure 15 is the cause of the recorded and calculated overvoltages, which eventually cause the capacitor insulation to fail.

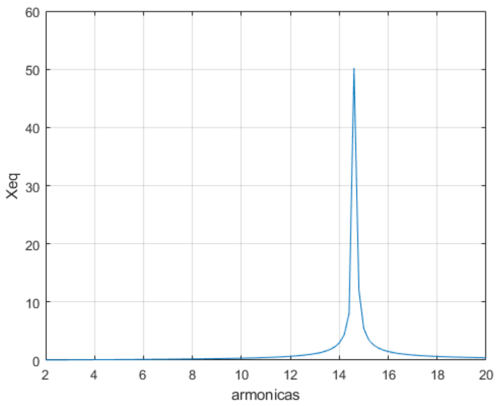


Figure 14. Resonance frequency of the unfiltered system.

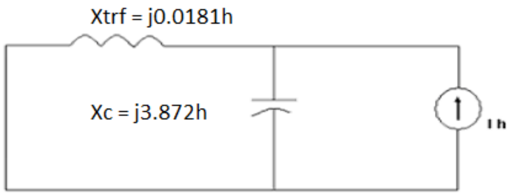


Figure 15. Circuit equivalent to the fundamental frequency.

Significant frequencies present

Table 1. Behavior of harmonic content. The most significant frequencies are selected.

Order	1	5	7
f(Hz)	60	300	420
% In	100%	49%	25%
Load (A)	704.9	342.5	178.8
(Load)^2	496912	117320	31958
Harmonic irms (A)	803.86		

Selecting the initial filter tuning

The filter will normally be set to the lowest frequency of the most significant harmonics. Harmonic filters are often tuned to a tuning factor approximately 3% to 15% below the selected harmonic frequency.

Tuning frequency

The action of tuning, on the other hand, refers to the adjustment of a frequency or the harmonization or coincidence of one idea with another. So the tuning frequency at which the minimum impedance value occurs coincides with the resonant frequency of the filter.

Quality Factor, $QF = 100$

Order of the selected harmonic frequency,$Ofs = 5$

Tuning factor: $Fn = 7.00$ %

Tuning frequency:$h = Ofs \times (1 - Fn) = 5 \times (1 - 0.07) = 4.65$

Tuning frequency reactance

$Xc = 3.8720$ohms

$Xl = Xc / h^2 = 3.872 / (4.65)^2 = 0.1791\ \Omega$

Tuning frequency resistance

$$\boldsymbol{R = h \cdot XL/QF} \qquad \textbf{Eq. 14}$$

$R = 4.65 \times 0.1791 / 100 = 0.00833\Omega$

Filter impedance at tuning frequency

The impedance of this filter for the tuning frequency is calculated as:

$$\boldsymbol{Zf = R + j(Xl - \mathrm{Xc}/h)} \qquad \textbf{Eq. 15}$$

$Zf = 0.0083\text{-}3.6929i\ \Omega$

Treatment of the system as a single-phase circuit

In this way, the selection of *Xc* and *Xl* knowing the nominal reactive power of the capacitor is very simple:

$Vn = 254$ V

$Qcn = 16.67$ kVAr

$h = 4.65$

Xc Y: Capacitor reactance at fundamental frequency (Y connection)

$$XcY = \mathrm{Vn}^2/Qcn \qquad \textbf{Eq. 16}$$

$XcY = 3{,}872\ \Omega$

Xc D: Capacitor reactance at fundamental frequency (connection D)

$Xc\ D = 3 * \mathrm{Xc} = 11.6160\ \Omega$

Inductor reactance.

$$\boldsymbol{Xl = \mathrm{Xc}/h^2} \qquad \textbf{Eq. 17}$$

*Xl Y (*Inductive reactor reactance at tuning frequency, (Connection Y)

$xl\ y$=0.1791 Ω

*Xl D (*Inductive reactor reactance at tuning frequency, (Delta Connection)

$Xl\ D = 3 \times 0.1791 = 0.5373\ \Omega$

$Xl\ D = 0.5373\ \Omega$

Calculation of the minimum filter value

In both cases the filter is designed to achieve a minimum impedance for the tuning frequency (h) and with a quality factor (Q) necessary toachieve adequate filtering.

Connection selection
The filter is designed by selecting a Delta Conexión.
Quality Factor, QF.
These filters are used to remove low-order harmonics with a high quality factor (QF = 20-150) which is defined as:

$$QF = h \cdot (\mathrm{Xl}/R) = Xc/(h \cdot R) \qquad \textbf{Eq. 18}$$

A value is selected for the Quality factor of:
Q = 100.00 pu
Filter resistance
Therefore, known Xl, the resistance is calculated by:

$$R = h \cdot Xl/Q \qquad \textbf{Eq. 19}$$

R = 0.025 Ω
Minimum impedance of the filter
The minimum impedance of this filter for the fundamental frequency is calculated as:

$$Z_1 = R + j(Xl - Xc) \qquad \textbf{Eq. 20}$$

Z_1 = 0.025-11.0787i= 11.0787 -89.77 ° ∠Ω
Reactive filter power
The reactive power delivered by the filter at the fundamental frequency is:

$$Q_1 = imag\{Vn^2/Z_1^*\} \qquad \text{Eq. 21}$$

Vn = 254 0.00 ° V∠
*Z_1** = 0.025+11.0787i = 11.0787 89.77 ° ∠Ω
Q_1 = 5824.96i VAr
The absolute value of its imaginary part is 5.82 kVAr.
But considering that the quality factor is high and therefore the resistance is very small, the approximation can be reached:

$$\boldsymbol{Q_1 = Vn^2/(Xc - Xl) = Vn^2/Xc(1 - 1/h^2) = Qcn(h^2/h^2 - 1)} \qquad \textbf{Eq. 22}$$

Q_1 = 6.11 kVAr
Filter Capacitor C1 Reactance
Therefore, Xc would be calculated approximatelyfrom Q_1 as:

$$\boldsymbol{Xc = Vn^2/Qcn \approx (Vn^2/Q_1)(h^2/h^2 - 1)} \qquad \textbf{Eq. 23}$$

Xc = 11,074 Ω
Inductive Reactance of the Filter Reactor

$$Xl = Xc/h^2 \qquad \text{Eq. 24}$$

Xl = 0.1550 Ω
The resulting minimum circuit is

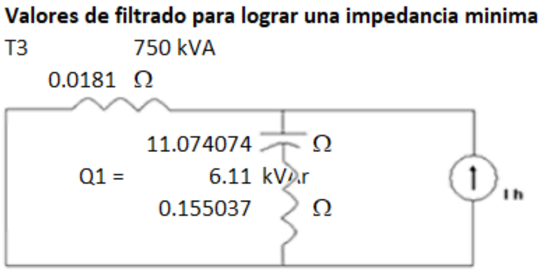
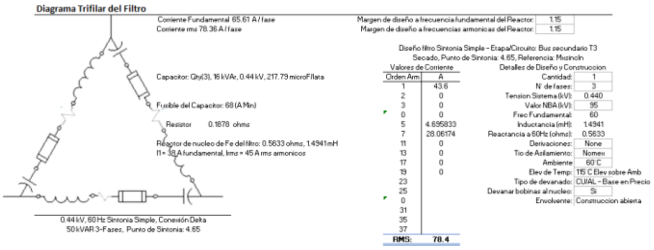


Figure 16. Resulting single-phase circuit.

The tuned circuit we will adopt is:

Specification of the simple tuner filter, connected in Delta.



Margen de diseño a frecuencia fundamental del Reactor:	1.15
Margen de diseño a frecuencias armonicas del Reactor:	1.15

Diseño filtro Sintonia Simple - Etapa/Circuito: Bus secundario T3
Secado, Punto de Sintonia: 4.65, Referencia: Misinoln

Valores de Corriente

Orden Arm	A
1	43.6
2	0
3	0
0	0
5	4.695833
7	28.06174
11	0
13	0
17	0
19	0
23	
25	
0	
31	
35	
37	
RMS:	**78.4**

Detalles de Diseño y Construccion

Cantidad:	1
N' de fases:	3
Tension Sistema (kV):	0.440
Valor NBA (kV):	95
Frec Fundamental:	60
Inductancia (mH):	1.4941
Reactancia a 60Hz (ohms):	0.5633
Derivaciones:	None
Tio de Aislamiento:	Nomex
Ambiente:	60 C
Elev de Temp:	115 C Elev sobre Amb
Tipo de devanado:	CU/AL - Base en Precio
Devanar bobinas al nucleo:	Si
Envolvente:	Construccion abierta

Figure 17. Design and construction specifications of the selected filter.

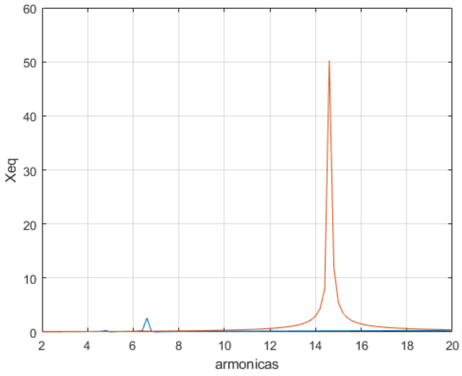
To obtain the characterization of the effect caused by the analyzed disturbances we will use the MATLAB platform, we show below the generated code where we include the values results of the study, to obtain Figure Figure 14Figure Figure 18

Resonance and attenuation of harmonics

Code in MATLAB for graphing harmonics from 2 to 20 in 0.2 steps

```
Harmonic Range
h=2:0.2:10;
Straight lines of Tr and Cap a frec. fundamental
xtr = 0.0180693; Xc = 3,872;
Filter ballasts at frec. 300 Hz attenuating at 7%, h=4.65.
Xc(5) = 3.334775343; XL(5)=0.046686855;
Reduction of Xc(5) filter ballasts || XL(5).
x=((-Xc(5)*i./h)*XL(5)*i.*h);
y=(Xc(5)*i./h)+XL(5)*i*h;
Equivalent filter ballast
Xeq1=x./y;
Xtr || ballast reduction Xeq1
a=(Xtr*h).*Xeq1;
b=Xtr*i*h+Xeq1;
Equivalent reactance of Tr and Xeq1 to frec. resonant
Xeq35=a./b;
x=((Xtr*i*h)).*(-3.818368166*i./h);
y=(Xtr*i.*h)+(-3.818368166*i./h);
Xeqcap=x./y;
Resulting graphs
plot(h,abs(Xeq35),h,abs(Xeqcap));
Grid;
xlabel ('harmonic');
ylabel('Xeq');
```

Obtaining the graphical representation of the problem before and after filtering. The resonance shown in Fig. 15 is the cause of the recorded and calculated overvoltages, which eventually cause the capacitor insulation to fail.



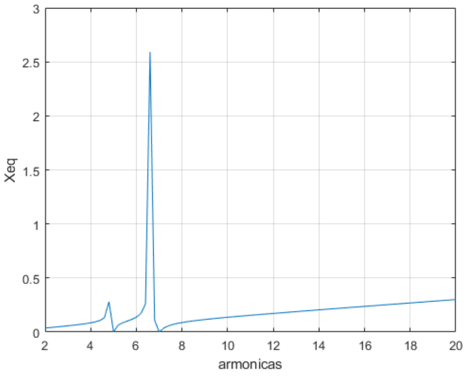


Figure 18. Characteristic response of filtering. Left: The resonance is shown in the interharmonic 14.4; Right: Attenuation is shown in 5th and 7th harmonica.

Analysis of results
The resonant circuit is damped for the 5th harmonic, adding to the capacitor an inductive reactance in series that eliminates overvoltage and resonance. (Figure 16 and 18).
The shows that as the system is weaker it has that the resonance frequencies are closer and closer to frequencies that can coexist in the system, this case the 15th harmonic thus causes resonance problems causing the destruction of the capacitor bank, and eventually the isolation of the transformer. The filtering ensures that the surges cease to exist avoiding the Figure 14 Figure Figure 18).

III. Conclusions And Recommendations

In this practical case, the measurement and collection of data allowed to define the causes and characteristics of distortions in the quality of the energy, harmonics were generated from each controller (frequency inverters) in the drying area of the corn seed. Causing this harmonic currents flowing into the capacitors that resonate with them, raising the voltage, converting the current into heat that destroyed the capacitor insulations, if the cause had persisted, it would damage the transformer insulation as well. An application of reactive compensation has been presented, through the registration of the data the existence of harmonics in the company's electrical system was reaffirmed, evaluating the harmonic distortion of fifth and seventh order, characteristic of the frequency inverters of 12 pulses.

Finally, we present the calculation of the passive resonant filter size that would attenuate distortion and prevent further damage to electrical equipment due to thermal effects. This failure results in momentary or lasting interruptions that impact the operating costs (Capex) and productivity costs of the company in question (Opex).

With these benefits we will seek to reach students and engineers who are interested in the subject apply it in the redesign and provide solutions in the educational and / or business field.

References

[1]. IEEE. (1992). Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems. IEEE Std 519-1992. NU. Retrieved November 2, 2020, from https://edisciplinas.usp.br/pluginfile.php/1589255/mod_resource/content/1/IEEE-519-1992.pdf
[2]. IEEE. (1995). Recommended Practice for Monitoring Electric Power Quality. IEEE Std 1159-1995. NY: The Institute of Electrical and Electronics Engineers, Inc.
[3]. IEEE. (2000). The Authoritative Dictionary of IEEE Standards Terms, IEEE Std 100. New York: IEEE Press publications.
[4]. IEEE. (2003). Guide for Application and Specification of Harmonic Filters. IEEE Std 1531-2003. (I. P. Society, Ed.) NY: The Institute of Electrical and Electronics Engineers, Inc.
[5]. Perez Abril, I. (2012). Calculation of parameters of passive harmonic filters. Energy Engineering, XXXIII(2), 134-143.
[6]. Sotelo-Rosas, O. E., & Ramírez-Carrera, L. C. (2005). From the scientific method to the diagnosis of engineering problems in Mexico. Engineering, Research and Technology, VI(2), 139-146. Retrieved November 2, 2020, from shorturl.at/chGH3

Alcantar-Bazúa Luis Pedro, et. al. “Fundamentals of harmonic compensation and solution in Industrial Systems: a case study.” *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, 17(5), 2022, pp. 33-46.