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Facultad de Ingeniería

Evaluation of active and passive harmonic filters for an Oil Field Production Company

TESIS

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20 de julio de 2023

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P R E S E N T E

En atención a su solicitud de Temario, presentada por los **Dres. Ciro Alberto Núñez Gutiérrez y Juan Segundo Ramírez,** Asesor y Coasesor de la Tesis que desarrollará Usted, con el objeto de obtener el Grado de **Maestro en Sistemas Eléctricos de Potencia**, me es grato comunicarle que en la sesión del H. Consejo Técnico Consultivo celebrada el día 20 de julio del presente año, fue aprobado el Temario propuesto:

TEMARIO:

"Evaluación de Filtros de Armónicos Pasivos y Activos para una Compañía de Campo Petrolero"

1. Introducción.
2. Caso: Lado Secundario de un Transformador de Subestación.
3. Caso: Bomba para Inyección de Disposición de Agua Salada.
4. Caso: Perforadora.
5. Conclusiones.

Referencias

"MODOS ET CUNCTARUM RERUM MENSURAS AUDEBO"

A T E N T A M E N T E

UNIVERSIDAD AUTONOMA DE SAN LUIS POTOSI
FACULTAD DE INGENIERIA
DIRECCION

DR. EMILIO JORGE GONZÁLEZ GALVÁN
DIRECTOR

Copia. Archivo
*etn.

I dedicate this work to my beloved wife, Alma.
And our precious blessings: Camila, Ivan, Timoteo, and Elizabeth.

Acknowledgment

To my Lord and Savior, Jesus Christ.

> Romans 11: 33-36 (LSB)
> Oh, the depth of the riches and wisdom and knowledge of God! How unsearchable are His judgments and unfathomable His ways! For who has known the mind of the Lord, or who became His counselor? Or who has first given to Him that it might be repaid to him? For from Him and through Him and to Him are all things. To Him be the glory forever. Amen.

Sola Scriptura
Sola Fide
Sola Gratia
Solus Christus
Soli Deo Gloria

Thank you to the institution and the professors that helped me in the way to reach this master degree. In special to the project FORDECYT-PRONACES/1311344/2020.

Declaración de autenticidad

Por la presente declaro que, salvo cuando se haga referencia específica al trabajo de otras personas, el contenido de esta tesis es original y no se ha presentado total o parcialmente para su consideración para cualquier otro título o grado en esta o cualquier otra Universidad. Esta tesis es resultado de mi propio trabajo y no incluye nada que sea el resultado de algún trabajo realizado en colaboración, salvo que se indique específicamente en el texto.

Ing. Francisco Iván Martínez Ezrré. San Luis Potosí, S.L.P., Julio de 2023

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Abstract

Since the beginning of the usage of electric non-linear devices to control the operation of motors, the adverse effects have been detected as disturbances feedback to the electrical grid. These devices are more commonly known in the Oil Field as Variable Frequency Drives (VFD) or Variable Speed Drives (VSD) and the feedback as harmonics, which are a response to the fundamental frequency but in a different frequency that is a multiplier of it. The scope of this work is to analyze the harmonic spectrum in one of these Oil Fields and utilize different methods to mitigate these harmonics. By analyzing this spectrum, not only the most problematic frequencies can be detected, but the Total Harmonic Distortions for voltage and current (vTHD and iTHD) can be measured. Specialized tools such as power quality meters will be mostly used to detect the before and aftereffects at the point of common coupling (PCC), selected on each individual case.

Chapter 1

Introduction

1.1 Background

With the technological advancement in the Oil Field, in the late 1980's the first hydraulic fracked well was developed and with it the need for better ways to pump the liquids out of the ground. The first steps were evolving the typical beam pump with the addition of a VFD to control the number of strokes per minute that the pump would perform, to the introduction of Electrical Submersible Pumps (ESP), which would go down a horizontal well that may be in the 1 to 2 miles depth. This new technology dramatically increased the production that a single oil well would produce and, consequently, the popularity of these pumps to the point that almost all new wells in the US would be driven by them. At the same time, having more liquids pumped out of the ground, the equipment in the surface had to get bigger to being able to handle them, thus also the adoption of VFDs for bigger pumps, and more facilities to separate and handle the sub-products of the oil wells (crude oil, produced water, and gas). Another piece of equipment that evolved in the oil field is the drilling rigs, in order to get to deeper layers of the sub-surface, bigger AC motors are used as well as hydraulic pumps to move the drilling bits. By nature, drilling rigs are designed to be mobile instead of a permanent installation, for this reason, portable generators are commonly used to power up all the equipment. Typically, these generators feed choppers to create a common DC bus, and this to different sizes of VFDs. The oil from deeper layers could be reach and pumped out, facilities have more capacity to supply the public demand of the oil and its subproducts; but now the problem is in the electrical system that powers up all these non-linear equipment, causing premature failure in essential equipment in the grid such as transformers, power cables, insulators, etc.

1.2 Theorical Reference

The main reference for this work is the IEEE Standard 519-2022: "IEEE Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems" [1]. In adjacent with this standard, it is necessary to use other standards in regards the design and measurement of this phenomenon [2, 3, 4]. Similar cases have been present in other oil fields, in particular one that had about 50,000HP installed in VFD driven ESPs. Not only poor power factor was detected by the utility company but also resonance when tried to use Power Factor Correction (PFC) Capacitors. After power system modeling it was found that passive harmonic filters would provide a solution to all the issues. The proposed solution was implemented bringing positive results, reducing the vTHD from 14%-19% below 5% and, as a secondary effect, having a power factor corrected near unity [5]. It also occurred on a nearly new oil field development near an industrial complex. After installing 10% of the planned 300 oil wells, continues failures on the ESPs were presented, this represented additional cost for repairs and replacement of equipment, but more importantly, the decrease of expected production. Further investigation reveled that the issue was the lack of filtered wave forms on the input and output side of the VFDs [6]. New methods keep being developed to represent more accurately the electrical power system model to include more parameters on the calculations, more specifically to contemplate the equivalent voltage models of harmonic sources. One method to estimate these parameters is called the Recursive Least Square (RLS) algorithm which has been found to be very accurate [7]. Not only the permanent equipment in the oil field is the cause of harmonic distortion but also the temporary equipment (i.e. drilling rigs) that are a very complex machine that uses hoists, pumps, drilling bits, etc. Due to the need of high torques, it is mostly common the usage of high horsepower DC motors instead of AC. Rectifiers are used to convert AC to DC in the form of DC VFDs, these technology not only produces very high harmonic distortion but also voltage notches. For these type of machinery, it is been found that multiple stages harmonic filters must be used to protect the power sources and the electrical equipment directly connected to them [8]. Two are the most common methods used to calculate the total harmonic impedance in a power system: the IEC61000-3-6 (or the IEC method) and the superposition index. Depending on the familiarity of the person performing the study, it can choose one or the other. However, after further investigation, it has been found that there needs to be a criteria of selection for each method depending on the effectiveness and reliability of the proposed framework, this is commonly verified thru simulations and field measurements [9]. Because the connections from power and harmonic sources to the rest of the equipment is done via cable, this represents the major impedance in the real world. Not having an accurate cable impedance may result on improper harmonic distortion calculations. It is noted that the actual impedance of the cable is not only dependent on its construction but also on the manner it is installed. Historically, to determine the harmonic impedance of the cable, it was done by using actual harmonic injection to get real data; the method discussed in this paper is algorithm based using online measurement equipment that does not inject harmonic distortions [10].

1.3 Problem statement

Several reports have been received from the operation personnel in multiple locations of an Oil Field patch about problems with the installation affecting the reliability of the facilities and causing shutdowns and replacement of electrical equipment, among the issues reported, some of them contained descriptions such as:

- Transformer's oil leakage from bushings or pressure relief valves,
- Transformer's excessive noise,
- Variable Frequency Drives (VFD) overtemperature trips,
- Inability of running VFD at full speed (60Hz).

During the visit of one of the electrical substations feeding an Oil Field, which consist in two power transformers feeding two different circuits, when reading the power quality and revenue meters connected to each transformer's secondary voltage (Case 1), the vTHD and iTHD were noticed to be high compared to the recommended limits in the IEEE 519 Standard [1]. At the same time, power quality meters installed in secondary bushings of transformers feeding large VSD were received and noticed high values of the same type of distortions (Case 2). The Tables below are the recommended values for THD and TDD from the standard referenced above.

Table 1.1: Recommended Voltage Distortion Limits, per IEEE 519-2022 Table 1.

Bus voltage V at PCC	**Individual harmonic (%)**	**Total harmonic distortion THD (%)**
$V \leq 1.0kV$	5.0	8.0
$1kV < V \leq 69kV$	3.0	5.0
$69kV < V \leq 161kV$	1.5	2.5
$1kV < V \leq 69kV$	1.0	1.5[a]

[a] High-voltage system can have up to 2.0(%) THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Table 1.2: Recommended Current Distortion Limits, per IEEE 519-2022 Table 2.

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)^{a,b}						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h < 50$	**TDD**
<20^c	4	2	1.5	0.6	0.3	5
20 <50	7	3.5	2.5	1	0.5	8
50 <100	10	4.5	4	1.5	0.7	12
100 <1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

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

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

[c] All power generation equipment is limited to those 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 the PCC under normal operating conditions.

The equations to calculate the THD and TDD factors are:

$$vTHD = \frac{\sqrt{\sum_{h=2}^{h_{\max}} (V_h)^2}}{V_1} * 100\% \tag{1.1}$$

$$iTHD = \frac{\sqrt{\sum_{h=2}^{h_{\max}} (I_h)^2}}{I_1} * 100\% \tag{1.2}$$

$$iTDD = \frac{\sqrt{\sum_{h=2}^{h_{\max}} (I_h)^2}}{I_L} * 100\% \tag{1.3}$$

Where:
V_1 = Fundamental voltage (at 60 Hz).
V_h = Harmonic voltage (at h*60 Hz).
I_1 = Fundamental current (at 60 Hz).
I_h = Harmonic current (at h*60 Hz).
I_L = Load current.

Chapter 2

CASE: SECONDARY SIDE OF A SUBSTATION TRANSFORMER.

2.1 Initial Conditions

For this case, the Point of Common Coupling (PCC) as defined per [1] is considered to be the secondary side of the substation transformer. This substation consists of two power transformers that reduce the voltage levels from transmission to distribution, in this case this is 138kV to 24.94kV. The substation have a four feeders that come out as overhead distributions lines, these vary in length up to a few tens of miles. Several types of facilities will connect to these overhead distribution lines along its route. The Figure 2.1 shows the one-line diagram, which represents one of these power distribution systems.

At the PCC, there are metering rated instrument transformers that connect to a power quality meter. The first step to corroborate that there are harmonic issues present in the distribution line was to capture the data from this meter. After taking a look at this data, it was found that the device only captures up to the 15th harmonic, but this was enough to determine that a high magnitude of harmonics was present.

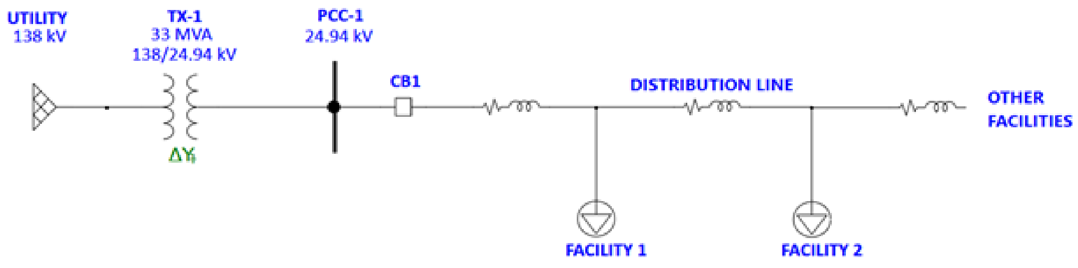
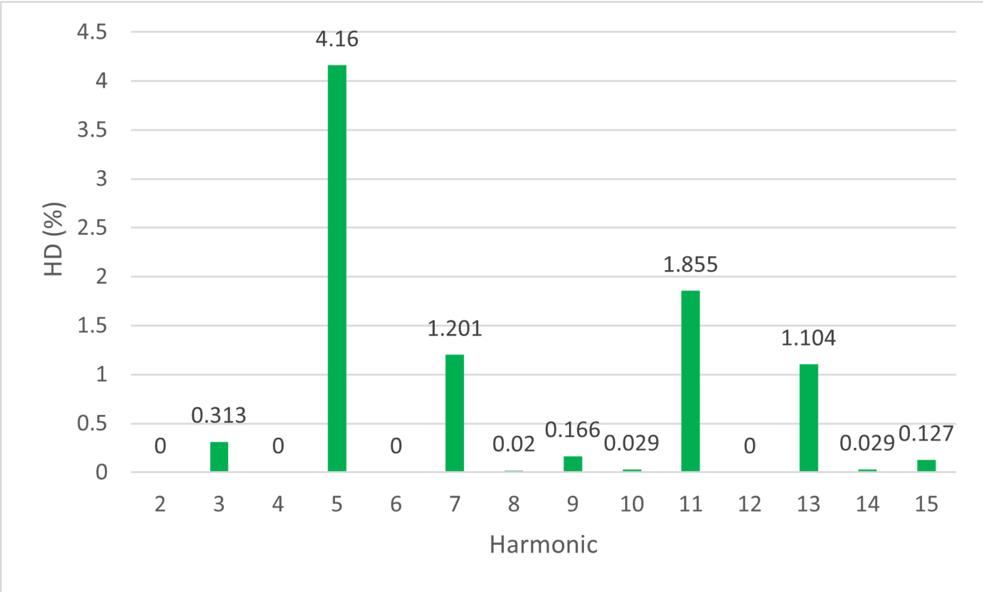
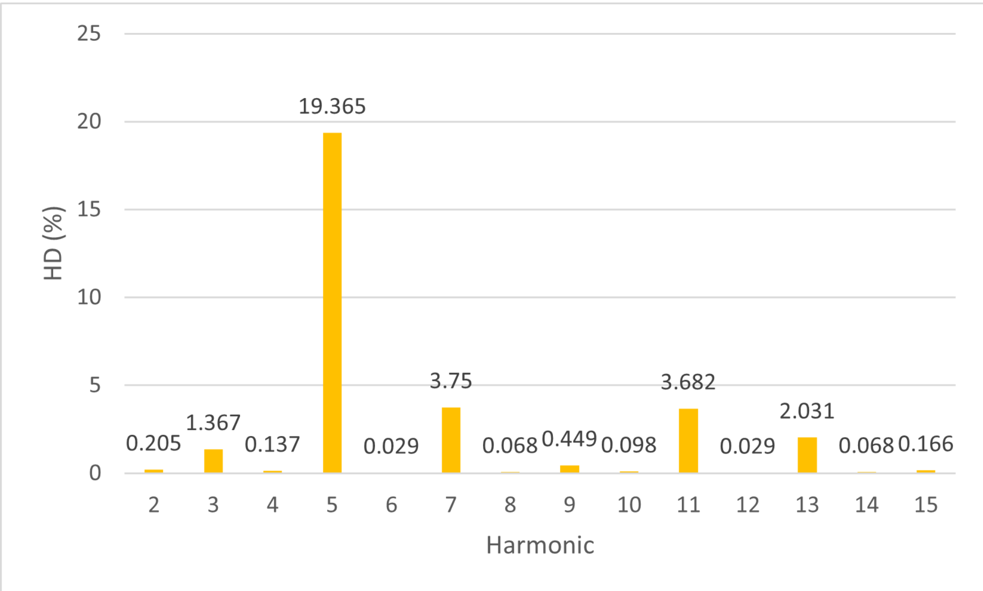


Figure 2.1: Substation simplified one-line diagram for one transformer and one feeder.

Figures 2.2 (a) and (b) represent the harmonic spectrums for this PCC.



(a)



(b)

Figure 2.2: (a) Voltage and (b) Current total harmonic distortions without LCL filter

2.2 Selection of the Solution

After conversation with three of the major harmonic filters manufacturer in North America, two of them respond that their filters by themselves cannot solve the issues due to the high level of existing harmonics in the line, because their products would be overloaded by these, and they would have to do especial design or de-rate their existing offerings resulting on a non-economical solution. However, the third manufacturer replied with an existing solution they have been using for similar application, which is using passive harmonic filters in a LCL configuration instead of shunt (a typical design for these filters is shown in Figure 2.3). The harmonic filters were installed at each service point for the ESP according to Figure 2.4 As a result of the conversations with this manufacturer, a pilot program was deployed installing the apparatuses in a location at the furthest end of one distribution line; this had existing wells operating without any harmonic filters in it (6 ESP) and the expansion consisted in six new wells with ESP to which harmonic filters were added.

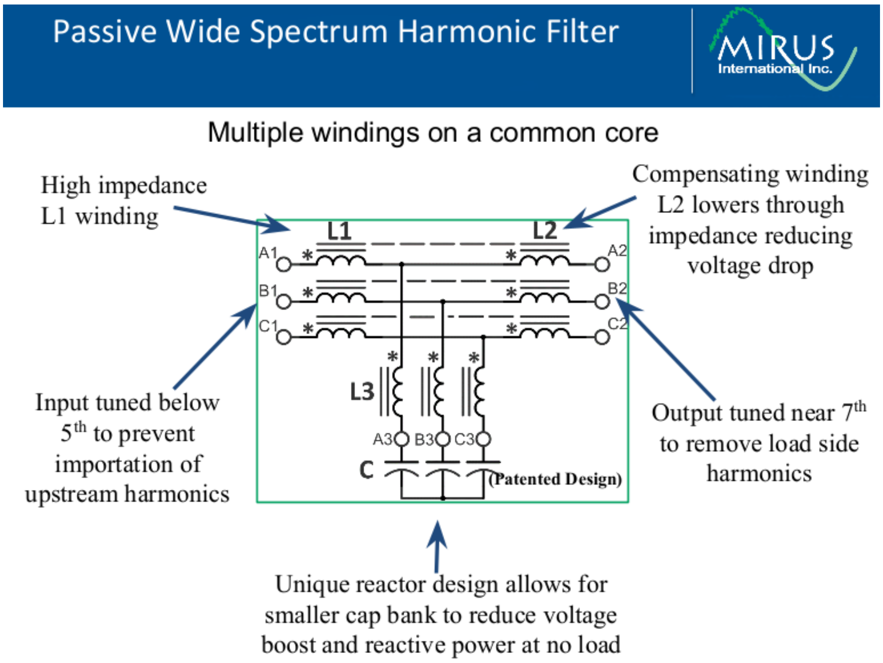


Figure 2.3: LCL harmonic filter design (Courtesy of Mirus International).

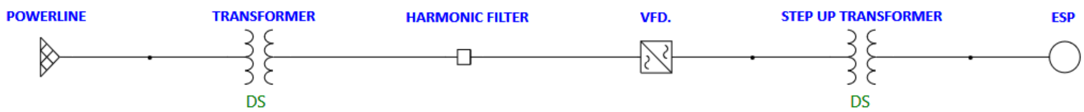
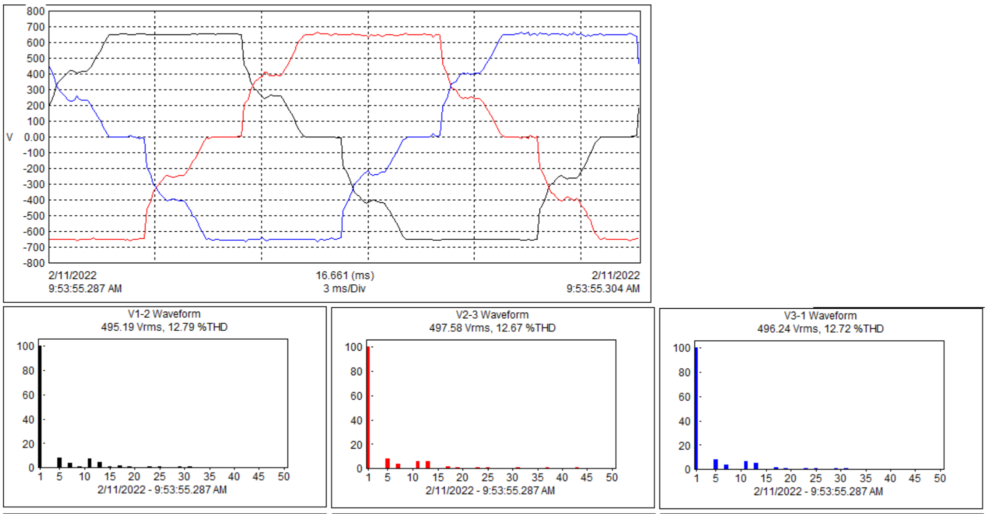


Figure 2.4: One Line Diagram For ESP installation with harmonic filter.

While everything was running, readings were taking on the existing and new service disconnect switches for the VFDs, in the case of the new installations at the line side of the LCL passive harmonic filter, the result was that the iTHD was 28% versus 7%, meanwhile the vTHD was 12.6% versus 9.5%. These results can be seeing in the following Figures:



V1-2 Waveform

	(%)		(%)		(%)
H01	100.0	H18	0.0	H35	0.7
H02	0.0	H19	1.0	H36	0.0
H03	0.4	H20	0.0	H37	0.6
H04	0.1	H21	0.2	H38	0.0
H05	7.9	H22	0.0	H39	0.1
H06	0.1	H23	1.4	H40	0.0
H07	3.8	H24	0.0	H41	0.7
H08	0.0	H25	0.9	H42	0.0
H09	0.9	H26	0.0	H43	0.4
H10	0.0	H27	0.1	H44	0.0
H11	7.2	H28	0.0	H45	0.1
H12	0.0	H29	0.8	H46	0.0
H13	5.0	H30	0.0	H47	0.4
H14	0.0	H31	0.8	H48	0.0
H15	0.8	H32	0.0	H49	0.5
H16	0.0	H33	0.2	H50	0.0
H17	1.7	H34	0.0		

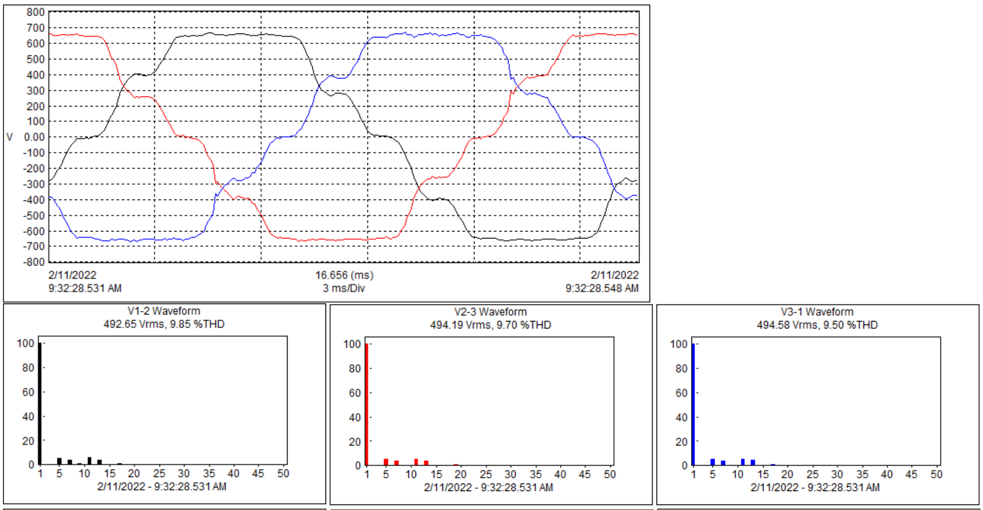
V2-3 Waveform

	(%)		(%)		(%)
H01	100.0	H18	0.1	H35	0.5
H02	0.1	H19	1.0	H36	0.1
H03	0.6	H20	0.1	H37	0.7
H04	0.1	H21	0.3	H38	0.0
H05	7.9	H22	0.1	H39	0.3
H06	0.1	H23	1.2	H40	0.0
H07	3.8	H24	0.2	H41	0.5
H08	0.1	H25	1.2	H42	0.0
H09	0.7	H26	0.0	H43	0.7
H10	0.1	H27	0.2	H44	0.1
H11	6.2	H28	0.1	H45	0.3
H12	0.1	H29	0.6	H46	0.0
H13	5.8	H30	0.0	H47	0.1
H14	0.1	H31	1.0	H48	0.1
H15	0.5	H32	0.1	H49	0.4
H16	0.0	H33	0.5	H50	0.1
H17	1.7	H34	0.1		

V3-1 Waveform

	(%)		(%)		(%)
H01	100.0	H18	0.1	H35	0.7
H02	0.1	H19	0.8	H36	0.1
H03	0.5	H20	0.1	H37	0.5
H04	0.1	H21	0.1	H38	0.0
H05	8.2	H22	0.1	H39	0.1
H06	0.1	H23	1.3	H40	0.0
H07	4.0	H24	0.2	H41	0.7
H08	0.1	H25	0.9	H42	0.0
H09	0.4	H26	0.0	H43	0.4
H10	0.1	H27	0.2	H44	0.1
H11	6.4	H28	0.1	H45	0.4
H12	0.1	H29	0.9	H46	0.0
H13	5.3	H30	0.1	H47	0.5
H14	0.0	H31	0.9	H48	0.1
H15	0.3	H32	0.1	H49	0.5
H16	0.0	H33	0.3	H50	0.1
H17	1.4	H34	0.1		

Figure 2.5: ESP vTHD without LCL filter.



V1-2 Waveform

	(%)		(%)		(%)
H01	100.0	H18	0.0	H35	0.2
H02	0.0	H19	0.4	H36	0.0
H03	0.3	H20	0.0	H37	0.1
H04	0.0	H21	0.3	H38	0.0
H05	5.4	H22	0.0	H39	0.0
H06	0.0	H23	0.2	H40	0.0
H07	3.7	H24	0.0	H41	0.1
H08	0.0	H25	0.1	H42	0.0
H09	0.8	H26	0.0	H43	0.2
H10	0.1	H27	0.1	H44	0.0
H11	6.0	H28	0.0	H45	0.2
H12	0.0	H29	0.1	H46	0.0
H13	3.9	H30	0.0	H47	0.3
H14	0.1	H31	0.1	H48	0.0
H15	0.7	H32	0.0	H49	0.1
H16	0.0	H33	0.1	H50	0.0
H17	1.1	H34	0.0		

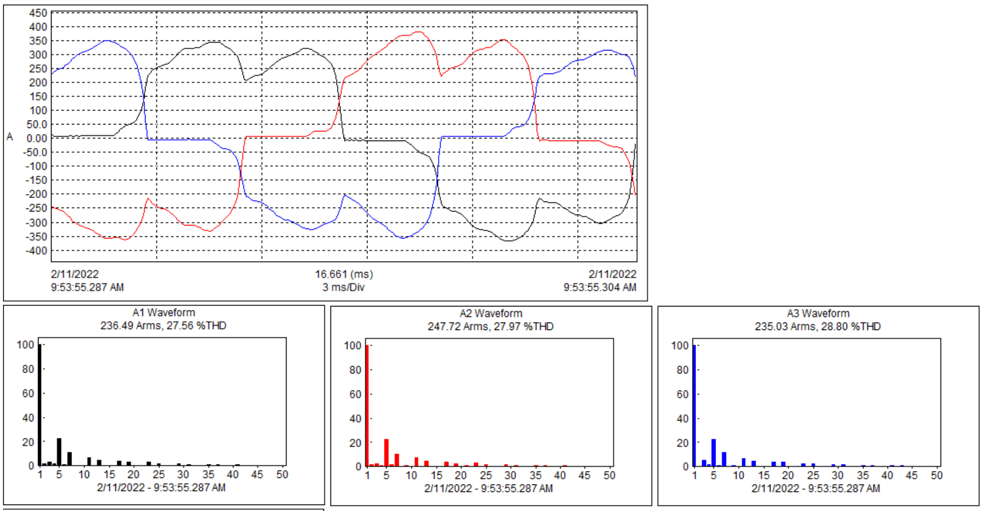
V2-3 Waveform

	(%)		(%)		(%)
H01	100.0	H18	0.1	H35	0.0
H02	0.1	H19	0.8	H36	0.0
H03	0.0	H20	0.0	H37	0.2
H04	0.1	H21	0.1	H38	0.1
H05	5.4	H22	0.1	H39	0.1
H06	0.0	H23	0.6	H40	0.0
H07	4.1	H24	0.1	H41	0.2
H08	0.0	H25	0.3	H42	0.1
H09	0.5	H26	0.0	H43	0.4
H10	0.0	H27	0.2	H44	0.2
H11	5.3	H28	0.1	H45	0.3
H12	0.1	H29	0.3	H46	0.0
H13	4.2	H30	0.0	H47	0.1
H14	0.0	H31	0.3	H48	0.1
H15	0.3	H32	0.1	H49	0.2
H16	0.0	H33	0.2	H50	0.0
H17	0.5	H34	0.1		

V3-1 Waveform

	(%)		(%)		(%)
H01	100.0	H18	0.1	H35	0.2
H02	0.1	H19	0.5	H36	0.1
H03	0.3	H20	0.0	H37	0.1
H04	0.1	H21	0.3	H38	0.1
H05	5.1	H22	0.1	H39	0.1
H06	0.1	H23	0.6	H40	0.0
H07	3.7	H24	0.1	H41	0.3
H08	0.0	H25	0.3	H42	0.1
H09	0.3	H26	0.1	H43	0.2
H10	0.1	H27	0.1	H44	0.2
H11	5.3	H28	0.1	H45	0.2
H12	0.1	H29	0.2	H46	0.0
H13	4.4	H30	0.0	H47	0.4
H14	0.0	H31	0.3	H48	0.1
H15	0.5	H32	0.1	H49	0.1
H16	0.1	H33	0.1	H50	0.0
H17	1.0	H34	0.2		

Figure 2.6: ESP vTHD with LCL filter.



A1 Waveform

	(%)		(%)		(%)
H01	100.0	H18	0.0	H35	1.2
H02	2.0	H19	3.1	H36	0.0
H03	3.5	H20	0.1	H37	1.0
H04	1.5	H21	0.2	H38	0.1
H05	22.4	H22	0.0	H39	0.1
H06	0.8	H23	3.2	H40	0.0
H07	11.2	H24	0.0	H41	0.9
H08	0.3	H25	1.9	H42	0.0
H09	0.5	H26	0.1	H43	0.7
H10	0.1	H27	0.1	H44	0.0
H11	6.7	H28	0.1	H45	0.1
H12	0.1	H29	1.6	H46	0.0
H13	4.4	H30	0.0	H47	0.7
H14	0.1	H31	1.4	H48	0.0
H15	0.3	H32	0.0	H49	0.5
H16	0.1	H33	0.1	H50	0.0
H17	3.9	H34	0.0		

A2 Waveform

	(%)		(%)		(%)
H01	100.0	H18	0.2	H35	1.1
H02	2.1	H19	2.8	H36	0.1
H03	2.5	H20	0.1	H37	0.9
H04	0.8	H21	0.8	H38	0.0
H05	23.3	H22	0.1	H39	0.2
H06	1.5	H23	3.2	H40	0.1
H07	10.6	H24	0.2	H41	0.9
H08	0.2	H25	2.0	H42	0.1
H09	0.9	H26	0.0	H43	0.7
H10	0.2	H27	0.2	H44	0.0
H11	7.1	H28	0.1	H45	0.1
H12	0.4	H29	1.5	H46	0.0
H13	4.4	H30	0.1	H47	0.6
H14	0.0	H31	1.3	H48	0.1
H15	0.6	H32	0.1	H49	0.5
H16	0.1	H33	0.3	H50	0.0
H17	3.7	H34	0.0		

A3 Waveform

	(%)		(%)		(%)
H01	100.0	H18	0.3	H35	1.1
H02	0.3	H19	3.8	H36	0.2
H03	5.2	H20	0.1	H37	1.0
H04	1.8	H21	0.6	H38	0.0
H05	23.2	H22	0.1	H39	0.1
H06	1.4	H23	2.5	H40	0.0
H07	11.9	H24	0.2	H41	0.8
H08	0.1	H25	2.1	H42	0.1
H09	0.9	H26	0.1	H43	0.8
H10	0.2	H27	0.1	H44	0.0
H11	6.5	H28	0.1	H45	0.1
H12	0.3	H29	1.5	H46	0.1
H13	4.8	H30	0.1	H47	0.6
H14	0.1	H31	1.6	H48	0.1
H15	0.4	H32	0.0	H49	0.7
H16	0.1	H33	0.1	H50	0.0
H17	3.6	H34	0.1		

Figure 2.7: ESP iTHD without LCL filter.

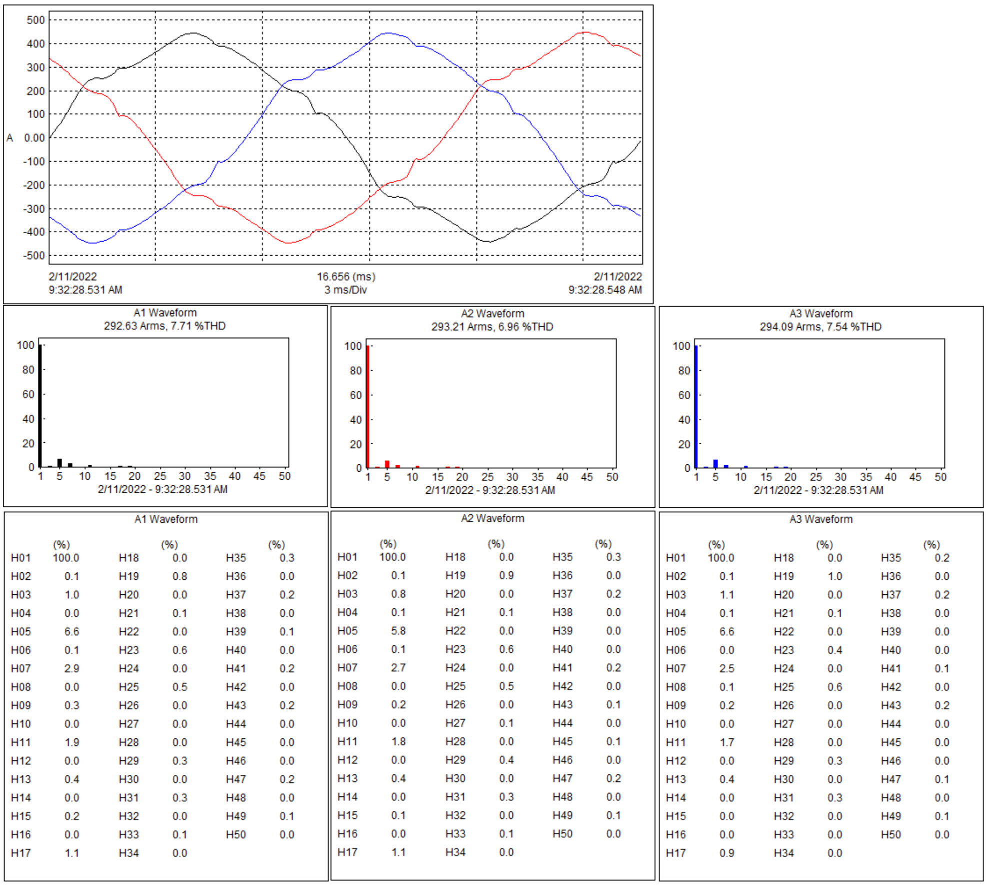


Figure 2.8: ESP vTHD with LCL filter.

It is clear from the figures that the current distortion of the particular loads were much less with the harmonic filter installed, however, it doesn't seems to be the same results for the voltage. The proposed hypothesis was that because the loads are at the end of a powerline that is heavy loaded with VFDs, the filters were not enough to compensate for the voltage distortion of the whole system but they were enough to make the new loads clean enough to avoid any issues at the service points, and when adding more filters to the same powerline, the vTHD will go down to recommended levels. With this in mind, more filters were added to different points in the line, particularly to any new ESPs.

2.3 Chapter's Conclusions

Months later after the initial pilot project was deployed, there were different changes in the electrical distribution system, in particular for the substation feeder that is being part of this case, the following was modified:

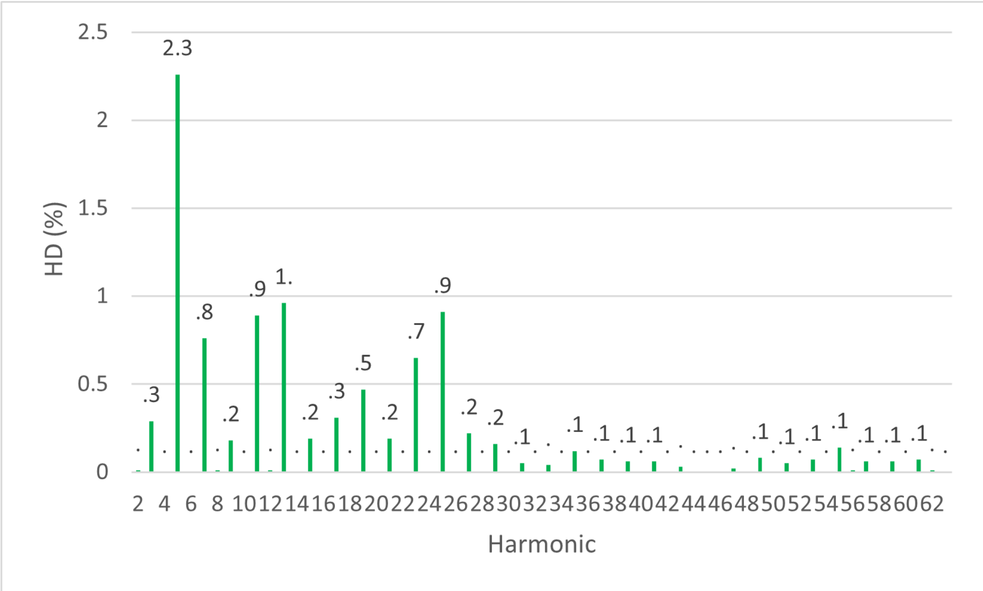
- The load demand was increased from 6MVA to 14MVA.
- Reconductor the powerline from 477ACSR to 795ACSR.
- Changing the powerline from a 15/20/25/28MVA transformer to 33/44/55/62MVA transformer.
- The power quality meter is now capable to take measurements up to the 63rd harmonic.
- Additional reclosers capable of harmonic measurements up to the 62th harmonic were added to the powerline.
- The total amount of LCL filters installed in the line are capable of filtering 38 individual loads up to 350HP and 2 of 450HP.

With all these changes in account, Table 2.1 the new harmonic distortions at the PCC are vTHD=3%, and iTHD=6.5%, representing a reduction of 5.2% in the voltage and 26.5% for current. Now the PCC is complaint with the IEEE Standard requirements for a 24.94kV power system.

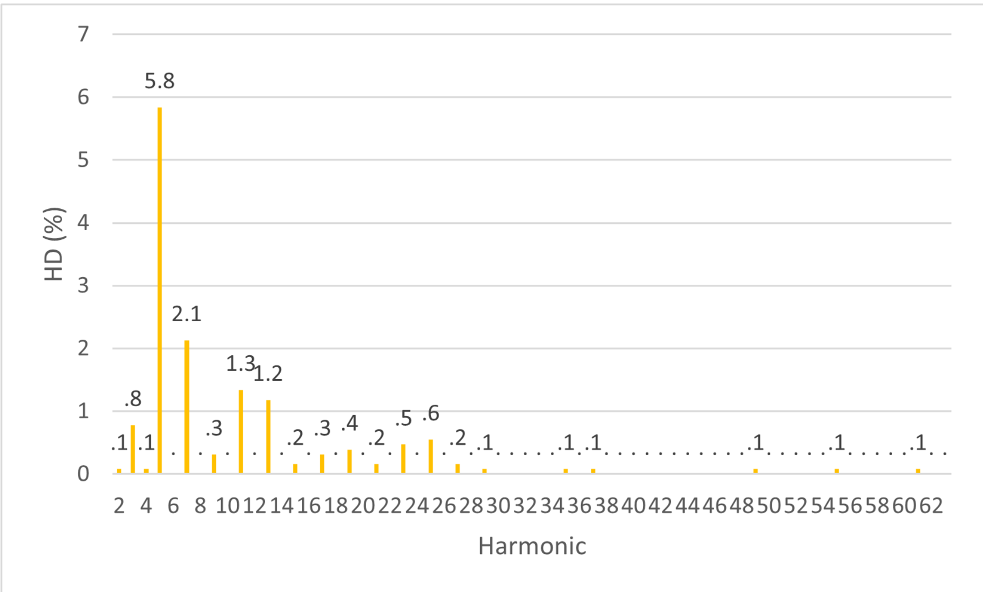
Table 2.1: Comparison of the harmonic distortion before and after the LCL filters.

Before LCL filters		**After LCL Filters**		**IEEE Std 519-2022**	
$vTHD$	$iTHD$	$vTHD$	$iTHD$	$vTHD$	$iTHD$
8.20%	33%	3%	6.50%	5%	8%

The new harmonic spectrums are represented in the following Figures 2.9



(a)



(b)

Figure 2.9: (a) Voltage and (b) Current total harmonic distortions with LCL filter

In conclusion, passive harmonic filters in a LCL configuration are a very good way to solve harmonic distortion issues in powerlines where the initial conditions are above the limits of shunt style passive harmonic filters (per manufacturers responses to the invitation to the project). The installation is similar between both styles of filters and the footprint is minimal. Although the capital cost of the LCL filter is more expensive, it pales when the shunt filter needs to be de-rated for the initial conditions discussed in this case.

Chapter 3

CASE: SALT WATER DISPOSAL INJECTION PUMP.

3.1 Initial Conditions

Among the facilities that are connected to the distribution power line, there are Salt Water Disposals (SWD), which are pumps that take the produced water resulting from the crude oil separation and injecting them back to the earth at depths similar to where the oil was taken. Figure 3.1 represents the typical one line diagram for one injection pump in this type of facility. The number of pumps can vary depending on the amount of water that needs to be handled:

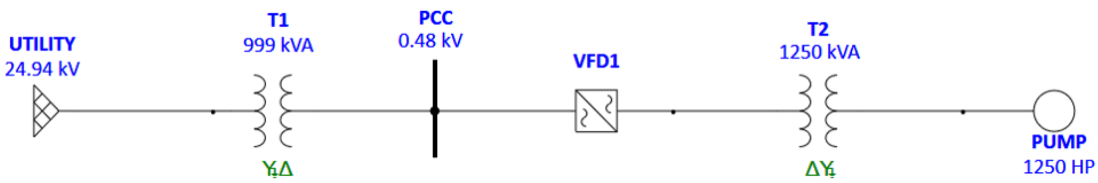


Figure 3.1: Typical one-line diagram for a SWD.

The first issue noticed with the typical installation was the size of the step-down transformer connected to the distribution line (T1), being smaller than the load. Additional to this, the VSD did not have a harmonic filter in its input side but only sine wave filters in the load side that were erroneously considered to be harmonic filters for the input side.

3.2 Selection of the Solution

Due to the size of the load to be filtered, it was considered the option of active harmonic filters to be the most effective because of the filter being sized to consider the harmonic current instead of the load current. Several iterations were made with the software of one of the manufacturers of these devices. Some of the cases were keeping the same installation, changing the size of the step-down transformer, selecting different sizes of active filters, among other changes. All these iterations are represented in the following Table 3.1:

Table 3.1: Results of iterations in manufacturer's software for selection of active harmonic filter and other changes.

Active Harmonic Filters Comparison			
Option	**Description**	$iTHD$	$vTHD$
1	No changes to the original installation	31.6	8.2
2	Add a 350A active filter	36.5	8.1
3	Add a 350A active filter and 5% line reactor	4	1.1
4	Add a 700A active filer	7.5	1.9
5	Change the step-down transformer for 1,500kVA	31.8	8.1
6	Change the step-down transformer for 1,500kVA, add a 350A active filter, and a 5% line reactor	4	1
7	Change the step-down transformer for 1,500kVA, add a 700A active filter	7.5	1.9

To solve the issues on this Point of Common Coupling (PCC), it was obvious that the selection of a bigger transformer was necessary, this limited the options to 5, 6, and 7. Then, after further investigation with the manufacturer of the VSD, it was indicated that some sort of line reactor was already added to it, thus it was decided that option 6 would had been the best solution, not only because of the better results on the simulations but also because the economic implications on buying an active filter with double the capacity of harmonic current injection. The new one line diagram for the installation is presented in Figure 3.2:

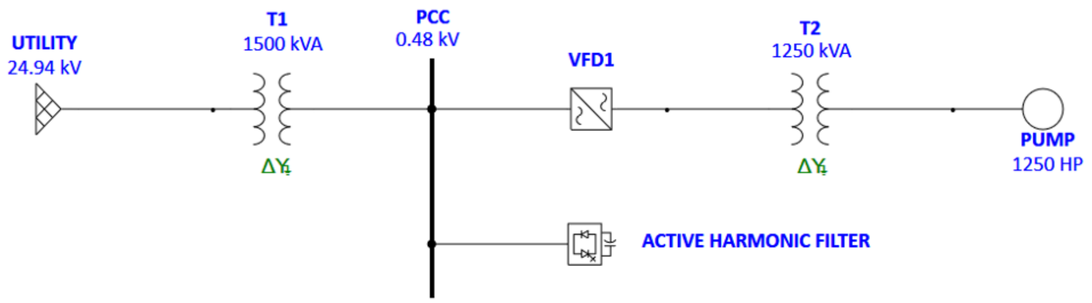
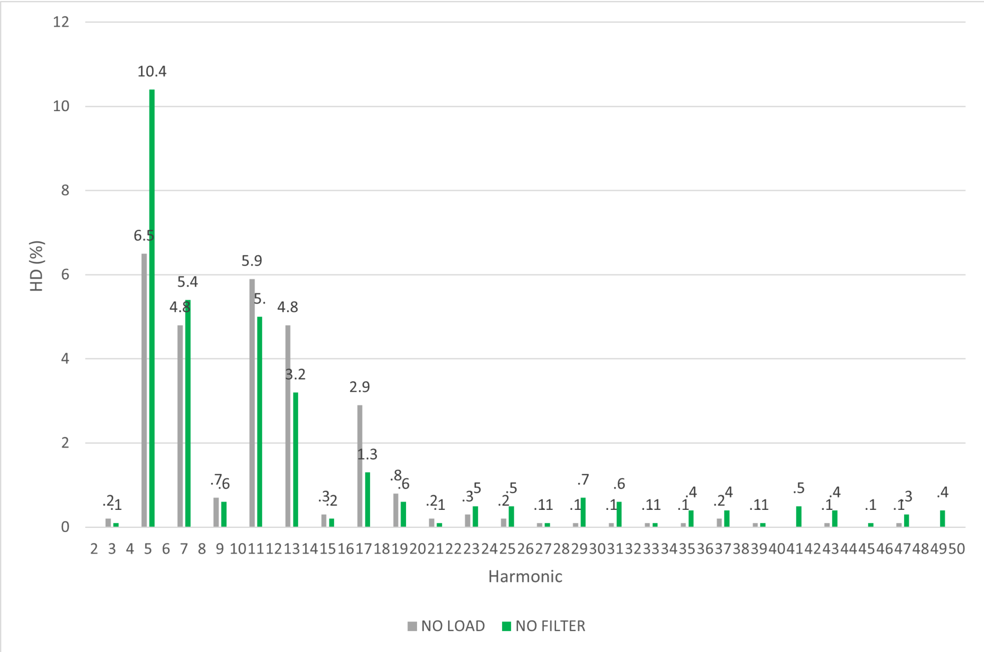


Figure 3.2: Typical one-line diagram for a SWD.

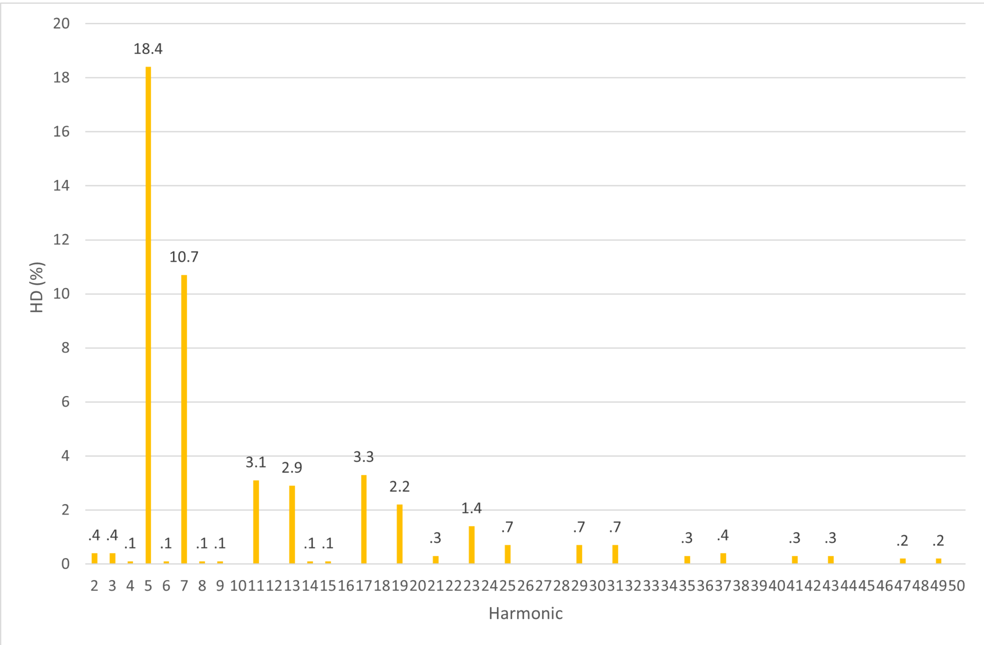
The first installation of an SWD with the new step-down transformer size and the 350A active harmonic filter was performed, a power quality meter was installed in the secondary side of the transformer to capture the data of three different scenarios:

1. Pre-existing conditions in the system resulting in voltage distortion without any load.
2. Harmonic distortion after turning the load on but having the active harmonic filter out of service.
3. Turning on the active harmonic filter.

Figures 3.3 represent the results of the measurements 1 and 2:



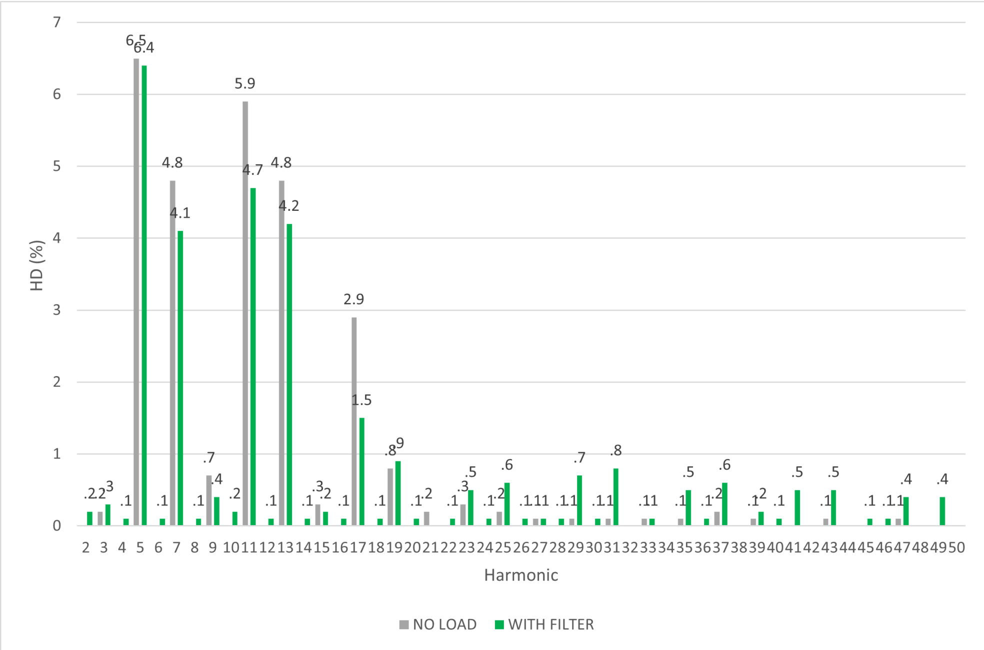
(a)



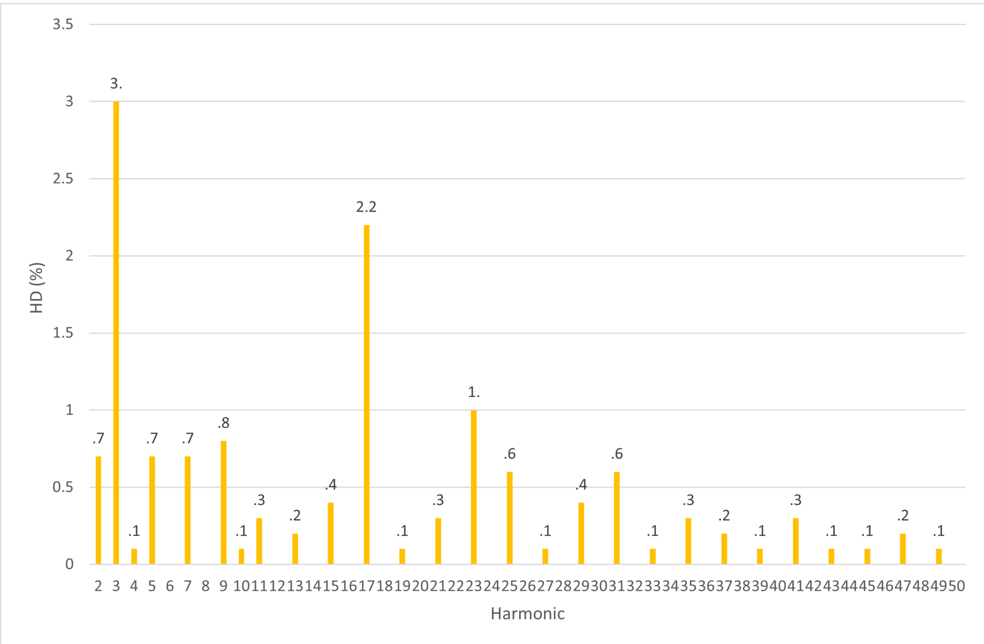
(b)

Figure 3.3: (a) $vTHD$ with no load and load but no active filter. (b) $iTHD$ with load but no active filter.

From the measurements above it is seen that the voltage distortion in the system even before turning on the load is 11%, then it increases when the pump is running to the magnitude of 13%, meanwhile the VSD produces a current distortion of 21%. According to the simulation, this is similar to the results on Option 1 from the Table 3.1; it is deduced that the vTHD is higher due to the pre-existing conditions and the iTHD is lower because the existence of a line reactor. Once the data was captured, the active harmonic filter was turned on, having as results the vTHD around 10% and the iTHD at 4%. A 1% reduction of the vTHD is noted, while the later result being the same as what was calculated in the simulation in Option 6. The following figures represent these values:



(a)



(b)

Figure 3.4: (a) $vTHD$ with no load and load with active filter. (b) $iTHD$ with load and active filter.

3.3 Chapter's Conclusions.

The active harmonic filters are a solution to the problem presented in the SWD, if the only purpose is to reduce the total harmonic distortions for voltage and current at the PCC; however, it is noted that, while reducing the most typical harmonic for an electrical system with 6-pulse drives, these filters increase the values of third and nineth harmonics on the secondary side of a wye-grounded transformer. Table 3.2 represents the results of the application of the active harmonic filters for this case:

Table 3.2: Comparison of the harmonic distortion before and after the active harmonic filters in SWD.

Before Active filters		**After Active Filters**		**IEEE Std 519-2022**	
$vTHD$	$iTHD$	$vTHD$	$iTHD$	$vTHD$	$iTHD$
13.8%	21.5%	10.5%	3.7%	5%	8%

A few issues that were presented along the way when using these active harmonic filters were the following:

- Commissioning of the units was slow, in some cases taking up to one day or more per filter.
- Constant trips from the filter's control system due to issues with the motherboard, it took the manufacturer months to detect what the issue was and solve it by replacing cards in the field. In the meantime, no harmonic filtering was in place for the pumps.
- A high sensitivity to high temperatures and problems replacing the air filters. It requires to de-rate the units that are installed outdoors, and the replacing of the air filters requires shutting down the units for dismantling several parts to get to them, making this a tedious and slow task.

Therefore, especial attention needs to be taken in place for the use of these filters, to consider maintenance of the units, perhaps installing them in a controlled environment is a better suit for these.

Chapter 4

CASE: DRILLING RIG.

4.1 Initial Conditions

A drilling rig, by nature, is a variable non-linear load. The input of the rigs is usually by the means of electric generators, these feed rectifiers to create a common DC bus and some AC ancillary loads. From this DC bus, different DC VFDs are used for the main motors in the rig, these motors represent 90% of the load and its demand depends on the drilling operations. Figure 4.1 provides a typical drilling rig one line diagram:

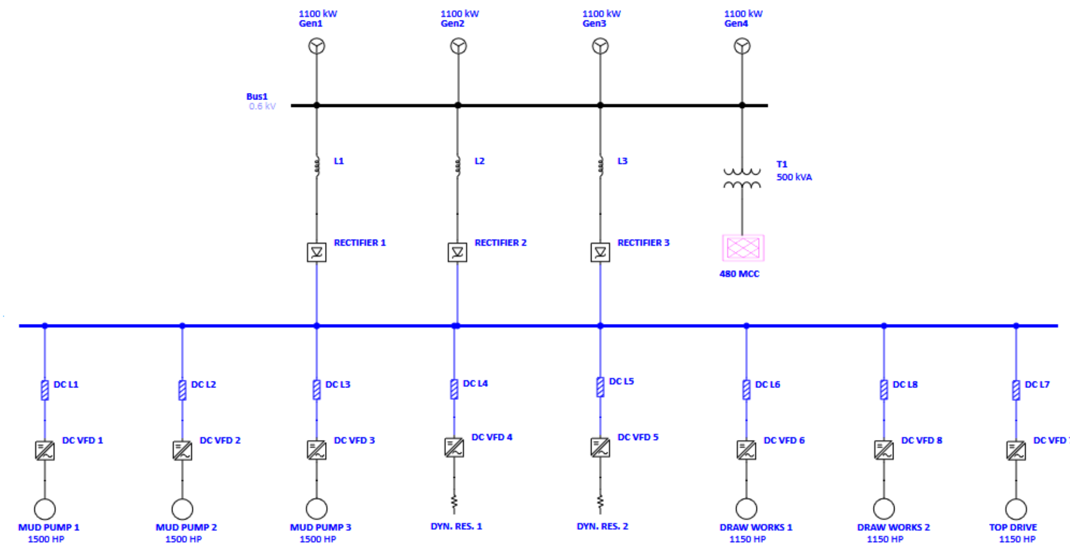


Figure 4.1: Typical one-line diagram for a four generator drilling rig.

A similar one line diagram can be found in the simulations performed in the Middle East by another operator [11].

To reduce drilling cost, many Oil and Gas Operators are looking into replacing the four generators with a portable substation that can connect directly to the grid and transform distribution voltage to 600V (See Figure 4.2). While this option is economically viable, it represents an issue for the utilities due to poor power factor and high harmonic content, causing different customers to present issues with the quality of the electricity provided to them. In some cases, the same operators have internal issues in their own producing fields because the VFDs for the ESPs will protect themselves and shutdown for poor power quality.

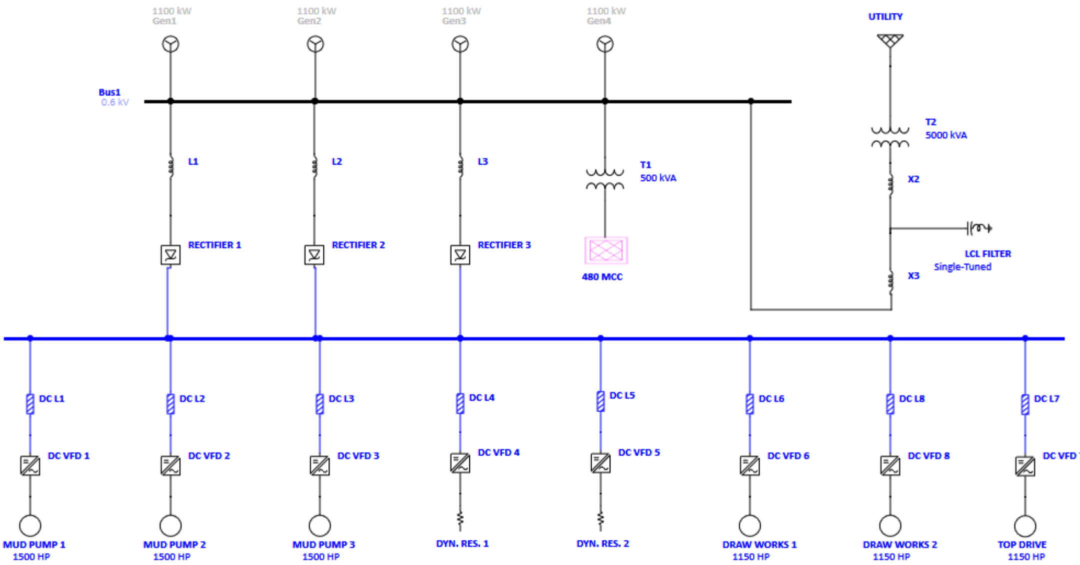


Figure 4.2: Typical one-line diagram for a drilling rig with portable substation.

Two similar drilling rigs were operating in the same region, drilling rig #1 did not any type of harmonic filter, and drilling rig #2 had a passive harmonic filter tunned for the 5th harmonic only. The trends for both rigs in a month period were captured and provided the following Figures 4.3 and 4.4:

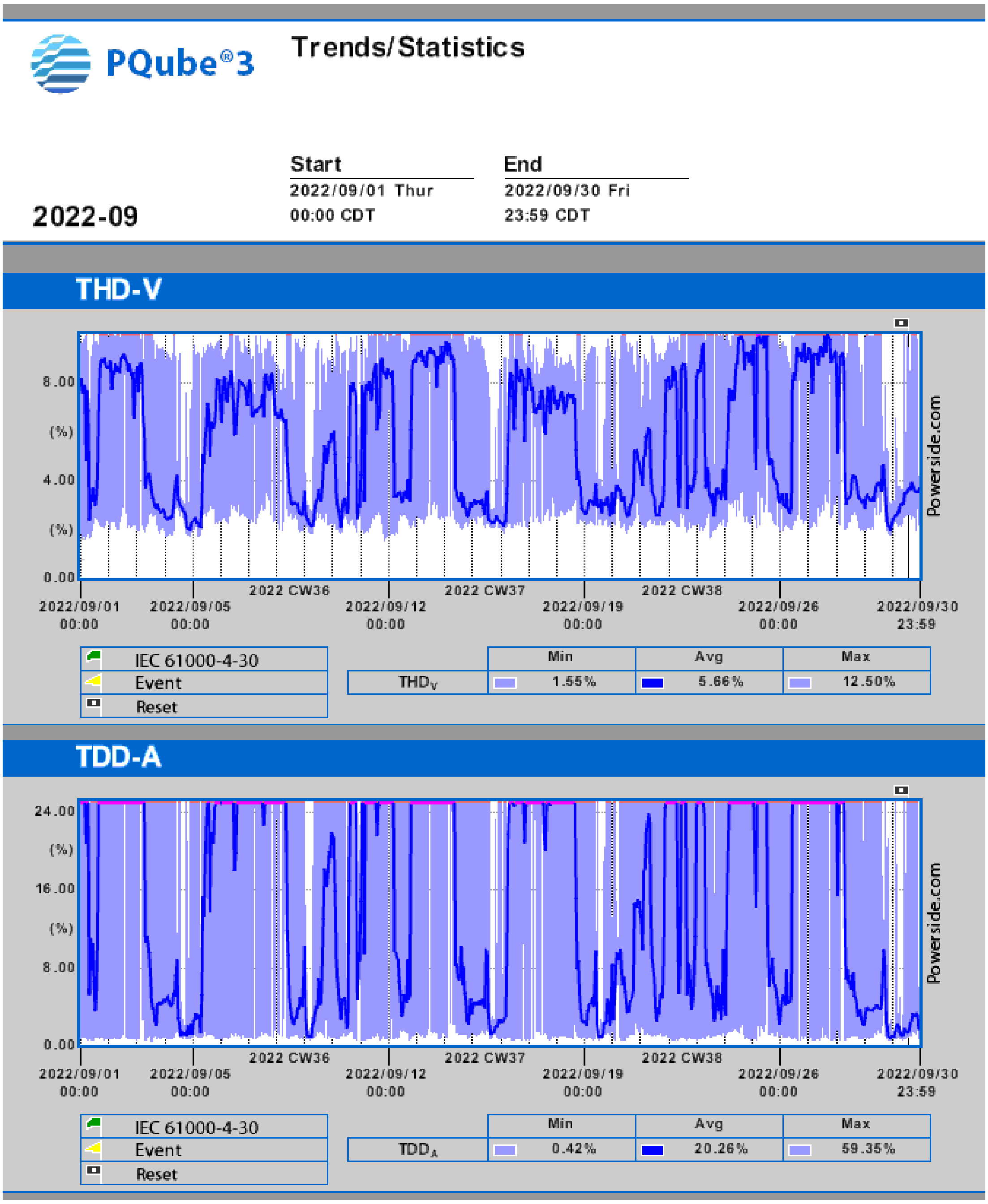


Figure 4.3: One month trending for drilling rig #1, no harmonic filter.

Figure 4.4: One month trending for drilling rig #2, with shunt harmonic filter tuned on the 5th harmonic.

Table 4.1 provides a simplified version of the values captured during the one month period for both drilling rigs:

Table 4.1: Comparison between drilling rigs #1 and #2.

	Parameter	Min	Avg	Max
Rig #1 - No Filter	vTHD	1.55 %	5.66 %	12.50%
	iTDD	0.42 %	20.26 %	59.35 %
Rig #2 - Shunt Filter	vTHD	3.21 %	7.92 %	16.07 %
	iTDD	0.00 %	6.25 %	22.07 %

As expected, the current values were much higher in the drilling rig without any type of filter, however, the values for voltage harmonic distortion are higher in the filtered one. The only possibility for this is that, although both are connected in the same substation, the location in the distribution system for rig #2 had more pre-existing voltage harmonics before it starts operating.

4.2 Selection of the Solution

In the experiment from reference [11], would be expected for drilling rig #1 to follow the results of "Only series inductor", in that case the expected vTHD is 13.8%, that would be between the average and maximum readings for the month. Meanwhile, drilling rig #2 would correspond to the "Only shunt filters only", the expected vTHD for this one is 6.07%, compared to the monthly readings of the average being 6.18% (please note that the experiment had filters of the 5th and 7th harmonic, and the rig only had for the 5th harmonic).

The conclusions [11] were shown that the use of line reactors with active filters, and line reactors with T-passive filters would provide very similar results in regards to the final voltage distortion; but the cost of the first option becomes very high and the reliability of the filter not very good. Based on the evidence and preliminary calculations of the drilling rig in figure 17, a T-passive filter is being pursued.

The first step to size and corroborate that the proposed T-passive filter will actually provide the solution to meet power quality requirements, was to try to simulate the original one line diagram for the rig to try to get the same results and then proceed with the sizing of filter inserting it to the same calculations, this was done using SOLV (version 6.6), a program by Mirus International. The results were very similar to the readings of drilling rig #1:

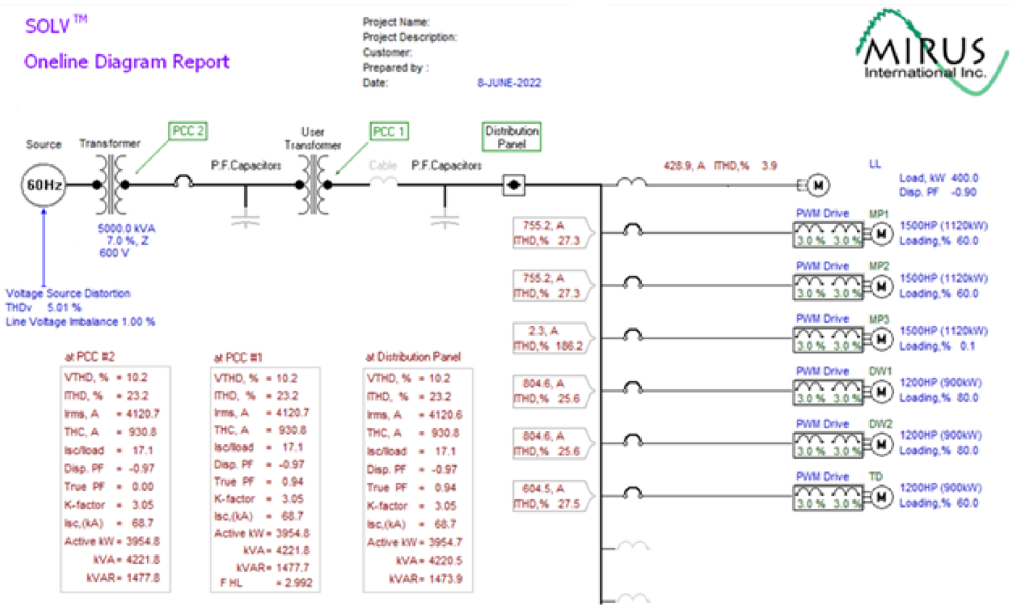


Figure 4.5: THD Calculations for drilling rig without harmonic filters.

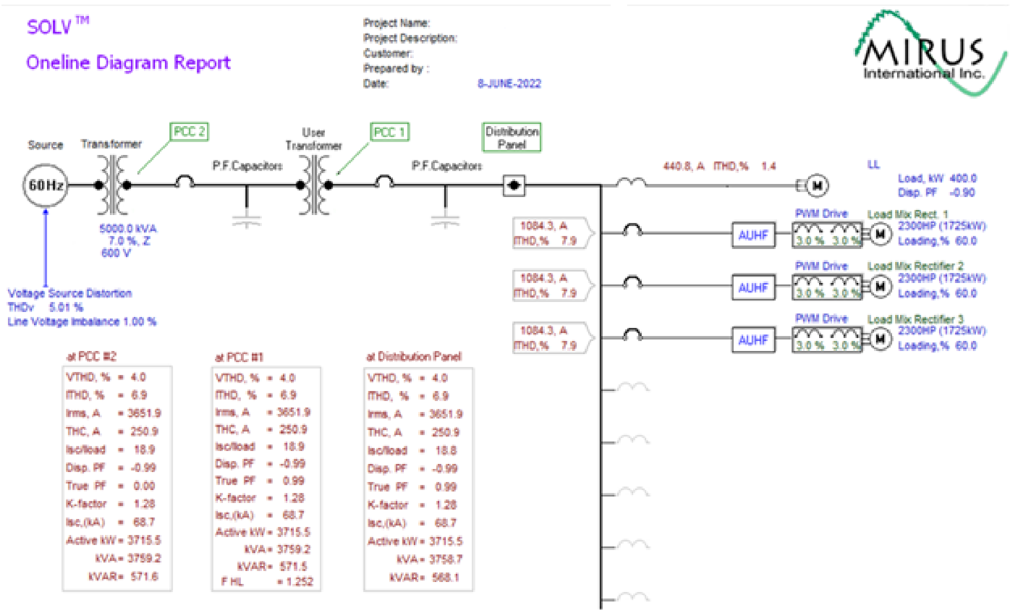


Figure 4.6: THD Calculations for drilling rig with harmonic filters.

4.3 Chapter's Conclusions.

By the time this Tesis was written, the harmonic filters selected for this case did not arrive to site, thus there is no true evaluation of the solution, but there is high level of confidence that the results are going to be similar to the computer simulations.

Chapter 5

CONCLUSIONS

After reviewing the use of passive and active harmonic filters it is concluded that both have their pros and cons, the most drastically of all is the performance of the units in an Oil Field environment where maintenance is not performed regularly, for this case, the active harmonic filters are the ones that suffer the most due to their nature. Being based on power electronics, they required a constant monitoring to make sure everything is between operating parameters. This is an issue that is not present on the passive harmonic filters because they are based and magnetic elements instead, if they are specified correctly, these units can withstand most of the harsh environments without limiting their performance and usage.

Another aspect to consider when selecting the correct technology for the application is the economics, while it is important to reduce the harmonic levels low to keep operations going on, these comes with a cost. As expected, the active harmonic filters are more expensive, not only for the cost of the unit itself but the installation cost is significantly higher due to the requirement of having current transformers from the PCC to the load to monitor the harmonic content and try to reject their effects back to the supplier. Meanwhile, the passive harmonic filters, being connected in series, are always energized and trapping the harmonics before going back to the utility.

In the other hand, and advantage for using active harmonic filters is that there is no overloading on them, their are design to inject a maximum current and, although the load would require more rejecting current, the filter would not provide more. In the other hand, the passive harmonic filter has the chance to be overloaded if not specified correctly, it is utterly important to make sure knowing how much current is going to pass through the filter to size the correct unit to avoid damaged caused by a constant overloading. Some of these filters will come with fuses for the capacitors to avoid damage on them, but the reactors are still in series with the load and they can still be damaged.

On both cases, it is imperative to consider not only what is mentioned above but also the current conditions of the PCC, in many cases, especially in the Oil Field, the harmonics are already present in the utility even before any load is started by the Companies. In the case of the active harmonic filters, not counting with the pre-existing harmonic levels can result on an undersized unit that will not be able to reduce enough of the harmonic content of the voltage signal; in the other case, the passive harmonic filters are designed with some limitations in their magnetic components that having too much vTHD in the input side may resonance or even overloading by a normal design output load.

The following table provides some more insight on the conclusions:

Table 5.1: Performance of active and passive harmonic filters in different conditions.

Condition	Active (Shunt)	Passive (Series)
Oil Field Environment	Poor	Best
Monitoring and Maintenance Requirements	High	Normal[1]
Equipment and Installation Cost	High	Normal[1]
High vTHD already present in the utility	May not reduce enough	May be overloaded and damaged

[1]Normal is comparing to any other similar electrical equipment in the Oil Field.

In conclusion, each person in charge of selecting the appropriate technology to meet their needs must exhaust all possibilities to make sure the harmonic filter selected will, in fact, not only be able to meet the Standard [1], but limiting the possibility of the solution causing another type of issues to the Company in regards to the usage (e.g. maintenance, cost, resonance, etc.).

References

[1] "IEEE standard for harmonic control in electric power systems," *IEEE Std 519-2022 (Revision of IEEE Std 519-2014)*, pp. 1–31, 2022. 2, 3, 5, 32

[2] "IEEE draft guide for applying harmonic limits on power systems," *IEEE P519.1/D12, July 2012*, pp. 1–124, 2015. 2

[3] "IEEE recommended practice for monitoring electric power quality," *IEEE Std 1159-2019 (Revision of IEEE Std 1159-2009)*, pp. 1–98, 2019. 2

[4] "IEEE recommended practice for the analysis of fluctuating installations on power systems," *IEEE Std 1453-2015 (Revision of IEEE Std 1453-2011)*, pp. 1–74, 2015. 2

[5] M. Farbis, A. H. Hoevenaars, and J. L. Greenwald, "Oil field retrofit of esps to meet harmonic compliance," *IEEE Transactions on Industry Applications*, vol. 52, no. 1, pp. 718–728, 2016. 2

[6] R. Pragale and D. D. Shipp, "Investigation of premature esp failures and oil field harmonic analysis," in *2012 Petroleum and Chemical Industry Conference (PCIC)*, pp. 1–8, 2012. 2

[7] J.-I. Park, H. Lee, M. Yoon, and C.-H. Park, "A novel method for assessing the contribution of harmonic sources to voltage distortion in power systems," *IEEE Access*, vol. 8, pp. 76568–76579, 2020. 2

[8] A. H. Hoevenaars, M. McGraw, and K. Rittammer, "Preventing centrifuge failures due to voltage distortion on a drilling rig," *IEEE Transactions on Industry Applications*, vol. 52, no. 1, pp. 633–640, 2016. 2

[9] F. Xu, W. Pu, J. Zhao, Z. Ma, and W. Lv, "Study on the verification of the calculated harmonic impedance," *IEEE Access*, vol. 8, pp. 75409–75418, 2020. 2

[10] S. Babaev, S. Cobben, V. Cuk, and H. van den Brom, "Online estimation of cable harmonic impedance in low-voltage distribution systems," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 6, pp. 2779–2789, 2020. 3

[11] A. R. Dekka, A. R. Beig, and M. S. AlRahis, "Retrofitting of harmonic power filters in onshore oil drilling rigs: Challenges and solutions," in *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 1424–1430, 2012. 23, 27