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MASTER

# The application of an Active Harmonic Filter in a 10 kV Industrial Network

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**Electrical Engineering Department [5SE46]**
**Research group: Electrical Energy Systems**

# The application of an Active Harmonic Filter in a 10 kV Industrial Network

***Master Thesis Report***

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# Preface

During these last two years, people have been helping and supporting me to complete my master and this work. To these people I would like to share my acknowledgments and appreciations. First, I cannot thank enough professor Sjef Cobben for giving me an opportunity to work on this project. Also, professor Vladimir Cuk and my HyTEPS supervisor Christan Van Dorst, I would like to say thank you for your guidance, knowledge and patience. Sjef thanks for believing in me, it has been a pleasure to listen to you and to get knowledge and experience from you. I cannot wait to keep working together in the future.

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Special thanks to my girlfriend Emmelie and her family, with all of you by my side everything in the Netherlands is easier. I have to finish with Mexico, where the source of my life energy resides: my family. Their support have been unconditional all these years, they have been motivating me in every good and bad moment. I would like to thank them in Spanish... !Gracias familia! En especial, gracias a mi papá, mi mamá y mi hermana. Gracias por su amor inmenso y por estar siempre al pendiente de mi vida. Esta tesis es para ustedes, la cual representa de cada uno los conocimientos, oportunidades y experiencias que me han brindado.

# Contents

# List of Figures

# List of Tables

# List of abbreviations

| **Abbreviation** | **Definition** |
|---|---|
| AC | Alternating current |
| AHF | Active harmonic filter |
| DC | Direct current |
| DPL | DIgSILENT Programming Language |
| EHV | Extra-high voltage |
| EPRI | Electric Power Research Institute |
| GA | Genetic Algorithm |
| IEEE | Institute of Electrical and Electronics Engineers |
| IEC | International Electrotechnical Commission |
| IGBT | Insulated-gate bipolar transistor |
| LV | Low voltage |
| MV | Medium voltage |
| HV | High voltage |
| PQ | Power quality |
| PSO | Particle Swarm Optimization |
| PWM | Pulse-width modulation |
| SLD | Single line diagram |
| SA | Simulated Annealing |
| TDD | Total demand distortion |
| TIF | Telephone influence factor |
| THD | Total Harmonic Distortion |
| THC | Total Harmonic Current |
| VFDs | Variable Frequency Drives |
| PCC | Point of Common Coupling |
| MOSFET | Metal-oxide semiconductor field-effect transistor |

# Abstract

Harmonic distortion in the voltage of an existing industrial network is analyzed. Parties involved are concerned about the increase in harmonic distortion at the MV level which is expected to exceed the limits within a short-time frame with a possible future expansion. Possible solutions to reduce harmonic distortion are discussed, where it was concluded that the implementation of an active harmonic filter at the MV level will be the best mitigation technique. This involves a filter with a compensation current capacity of 560 [A] and a 1000 [kVA] dedicated transformer (10/0.69 [kV]). This would mitigate the $5^{th}$ and $7^{th}$ harmonic orders, which are causing failures in the electrical equipment within the plant. For this, the industrial meshed network is developed in cooperation with a company from the semiconductor industry to guarantee a realistic construction of the network. The network is modelled, simulated and deeply analysed with a power system analysis software (DIgSILENT Power Factory 2020). To automate simulations, scripts have been developed utilizing the DIgSILENT Programming Language (DPL) and used to scan the network through a wide range of situations and to reveal possible trends.

A harmonic analysis methodology for existing industrial power systems is implemented together with two methods for harmonic generation. These methods are investigated, where the first is based on an ideal current source and the second on the modelling of VFDs. These methods have major constructional differences. How these affect the harmonic currents and their manifestation in harmonic voltages, are researched. The harmonic distortion generated by an ideal current source is calculated based on harmonic current spectra, while the VFDs approach is based on the main harmonic generation component of these drives (6-pulse diode bridge rectifier). Once the harmonic generation is reproduced within the network, the active mitigation technique is implemented within the model to reduce selected harmonic orders ($5^{th}$ and $7^{th}$). A heuristic algorithm is developed to calculate the harmonic currents needed by the mitigation device. The results and effectiveness of the mitigation method are discussed.

From the simulation results, network characteristics and limitations are revealed for the network topology. The potential problems of the harmonic sources are identified. The results are focused on the Total Harmonic Distortion (THD), harmonic currents and impedances of the network with and without mitigation solution. With analysis, it is aimed to explain the connection between these results and also provide a comparison of the harmonic distortion levels at the MV level of the network against a standard concerning harmonics (EN 50160).

The analysis of the thesis will present valuable results and observations. In simulation, the mitigation of the $5^{th}$ and $7^{th}$ harmonic orders is possible even when the harmonic injection needed by the device is higher than its capacity. As consequence, the compensation current capacity of the active harmonic filter needs to be increased to effectively mitigate the desired harmonic orders in real practice. To do this, high quality and reliable data is needed from the recommended locations (PQ monitor devices) to improve the simulation model and therefore, a better design and specification of the mitigation technique. Regarding harmonic standards, THD and all individual harmonic voltages are below their limits, but the $5^{th}$ is close to surpass its individual limit. A future expansion and the trend in increasing distortion levels within the plant, could lead to have unacceptable levels of harmonic distortion. Also, there are several future directions that can be done to develop further this project, such as, economic/benefit analysis, different topologies, network expansion and harmonic cancellation effect.

# 1 Introduction

## 1.1 Background, problem definition and research questions

IEEE defines "Power quality" as powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and other connected equipment [1]. Nowadays, the economic losses and negative effects of power quality problems such as voltage interruptions, voltage dips, over-voltages, voltage fluctuations, voltage unbalance, transients and harmonics are becoming increasingly prominent [2]. As consequence of the integration of large number of non-linear loads into the power grid, harmonic distortion has become one of the great concerns for power customers and the utilities [3]. Firstly, harmonics are defined as sinusoidal voltages or currents that have frequencies that are integer multiples of the frequency at which the supply system is designed to operated (fundamental frequency in Europe is 50 Hz). Harmonics distortion is caused by non-linear devices in the power system.

In an industrial production system (e.g. semiconductor industry), the power supply quality is a crucial aspect regarding a continuously high quality process. The quality is affected by different situations such as distortions from the grid (e.g. external faults or fluctuating renewable sources) or rising share of non-linear loads [4]. Especially the last one, can raise the level of system perturbation in a greater way. As consequence, low power quality in industrial power systems can have negative effects on the electric equipment and also on the entire industrial processes [5].

In production systems, there are two main problems due to low power supply quality: (1) dysfunction or outage of equipment (outage of entire production) and (2) decline in the overall process quality due to effects on electric components. The first problem could stop the production process which translates into a loss of product output (economic losses). The second problem would decrease the efficiency of equipment which leads to higher degradation and a shortening of its lifespan. Several studies regarding the impact of low power quality on industrial systems can be found in literature [6][7][8].

In this thesis, the harmonic distortion in the voltage in an industrial grid is analyzed and evaluated. At the LV level of this network, several active harmonic filters have been installed, but according to power quality monitor device installed on-site the harmonic distortion on the MV level is still rising over time. The dominating voltage harmonics within the industrial campus are the $5^{th}$ and $7^{th}$. However, the spectrum differs from case to case depending from the equipment used in the LV network [9]. Network operator and end-user are concerned about the increase of harmonic pollution which is expected to exceed the limits within a short-time frame with future network expansion.

To minimize the harmonic distortion in the voltage, harmonic currents in the MV network has to be decreased. Several alternatives to reduce harmonics caused by non-linear loads has been shown in [10]. The thesis will only consider an active filter build for 10 kV voltage level as a mitigation device, together with a dedicated LV/MV transformer to inject harmonic currents into the MV network. This could eliminate the additional necessity of installing more cabinets and active filters at LV level. Access to information regarding the network (e.g. SLD, commissioning reports and measurement data) was given as well as data from a monitoring system installed on-site (distribution bus 1M-A) to get information about the power quality in the MV network. The design of such a system will take into account the following aspects:

1. The nominal current of the active filter: the current will be calculated after analyzing the data available.
2. Transformer design: it will take into account the distorted current which will flow in the transformer.

The objective of the project is to investigate and design an 10kV MV active filter. Such a system will consider pertinent features to assess its performance. Considering the context and objective of the project, it is important to address the following research questions:

1. What are the effects of the implementation of a MV active filter in a meshed network?
2. How the dedicated transformer characteristics would affect the performance of the mitigation device (AHF)?

3. How and where does the active filter should be connected to the MV network?
4. What are the positive/negative implications of adequate/inadequate power quality in terms of sustainable development?

## 1.2 Contribution

This project will provide the following contributions:

1. Methodology and harmonic study procedure for new or existing industrial environments.
2. Comparison and selection of harmonic mitigation solution for an existing industrial network. This includes the effectiveness of harmonic mitigation in a meshed topology as well as the impact of the components of the mitigation solution (e.g. dedicated transformer).
3. Heuristic method to achieve a THD reduction and elimination of selective order harmonics.
4. Datasets: All data collected as part of the project is stored and presented to the stakeholders. This provides a record of information which can be further used for more localized research.

## 1.3 Boundaries

Assessing and designing a system model (active filter and transformer) is an extensive task. Given the time constraints of the project, realistic choices must be made that will give the most efficient and most accurate result possible. Therefore, certain boundaries are set:

- **Boundaries for voltage levels**
  Active filter and transformer will be designed at LV/MV levels, therefore, HV level is out of the scope of the project.
- **Network topologies**
  At LV/MV levels there are several topologies such as loop/ring, radial and multi-loop. The application of the active filter will take place in a meshed LV/MV installation. Hence, the previously mentioned topologies are out of the scope of the project.
- **Active compensation**: active harmonic filters are used for active compensation of harmonic content, reactive power and load balancing. The last two active compensations are out of the scope.

## 1.4 Methodology

The applications of non-linear loads in the industrial installations is growing exponentially. There are different forecasts and estimates of the percentage of non-linear loads present in electrical installations. In [11] from 2013, the range of non-linear loads was established between 30% and 50% while in [12] from 2014 the estimation was around 60%. In a more recent paper [13], the ”Electric Power Research Institute” (EPRI) expected a share of non-linear loads of 50% to 70% in 2020. Therefore, the effects of harmonics within the electrical installation and its impact on the electric utility and neighboring installations must be examined to avoid equipment damage and shutdowns. It is recommend to perform a harmonic study in the following cases:

- At the design stage of a project, if the amount of non-linear loads exceeds 25% of the total loads on the installation.
- When there are harmonic-related problems such as failure/malfunction of electrical equipment.
- If an existing installation is going to be expanded and a significant amount of non-linear loads is going to be added.

According to the problem definition of the industrial installation to be analyzed and the cases where a harmonic study needs to be performed, it is concluded that the installation requires a harmonic analysis to check the compliance with contractual/international harmonic limits. To answer the research questions, the harmonic study procedure from Figure 1 has been used which provides an explanation of the steps that shall be followed for an existing industrial power system environment [11][14].

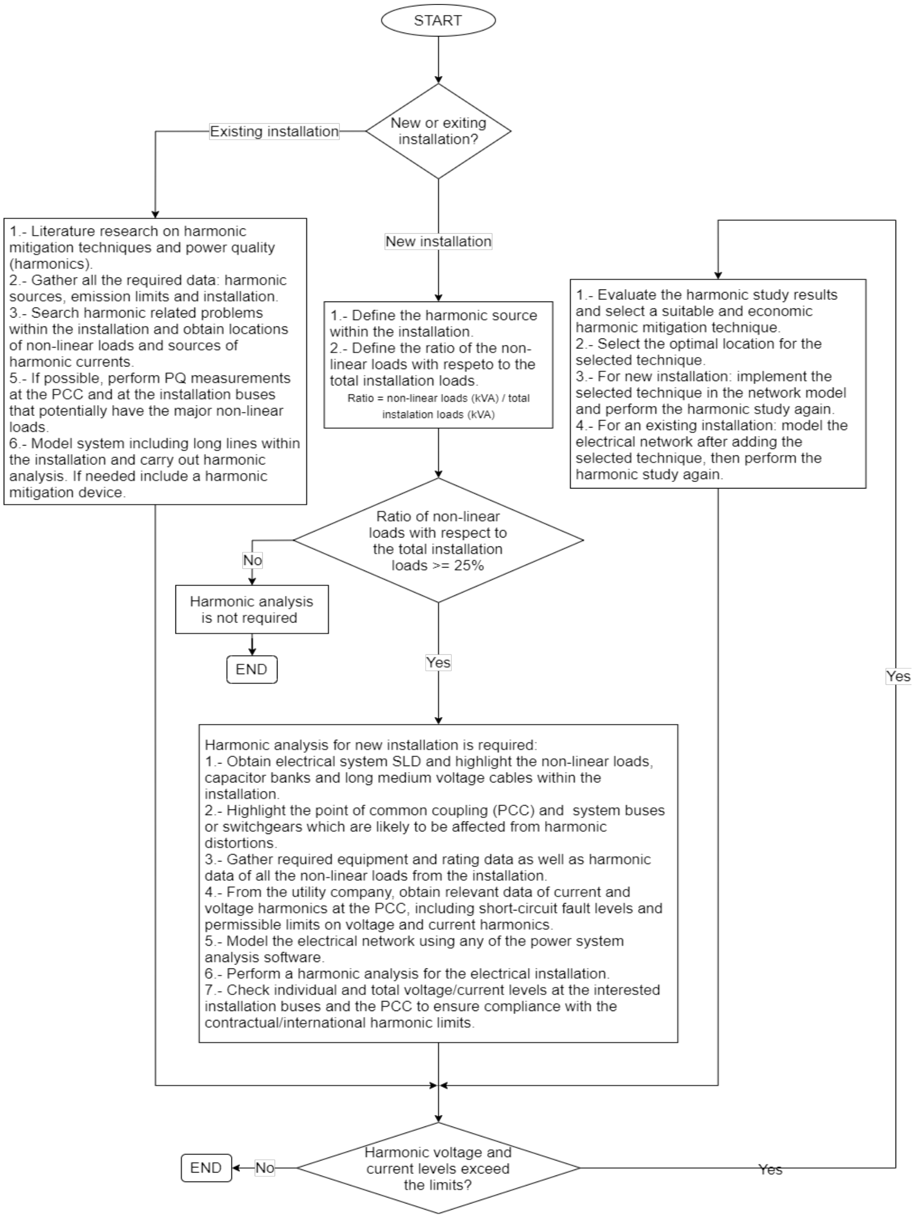

Figure 1: Harmonic analysis procedure for new or existing industrial power systems

## 1.5 Structure

The project report is structured as follows:

- **Chapter 1** ”Background, problem definition and research questions”: introduces the problem and current situation of an industrial power system. Also formulated the research questions, contributions and methodology of this project.

- **Chapter 2** ”Standards and guidelines”: establishes the applicable standards to industrial systems at MV level (planning levels).
- **Chapter 3** ”Theoretical framework”: discusses the concepts concerning harmonic current generation, harmonic indicators, resonance phenomena, network impedances and how these determine the harmonic content in the electrical network. Also, it explains the methods to reproduce the harmonic content within the installation based on available data from non-linear loads.
- **Chapter 4** ”Network description and Modeling”: provides an overview of the modeling of the industrial power system in PowerFactory.
- **Chapter 5** ”Mitigation Device”: discusses solutions for harmonic mitigation and a strategy for the allocation of any mitigation device.
- **Chapter 6** ”Simulation results”: analyzes and explains the simulation results.
- **Chapter 7** ”Benefits of harmonic management”: provides an insight on the benefits of managing harmonic content in installations and how this can improve the power system reliability.
- **Chapter 8** ”Conclusions and Future search”: provides the main conclusions of the project and identifies possible routes for further research.

# 2 Standards and guidelines

## 2.1 Harmonics historical background

Power system harmonics are defined as sinusoidal voltages and currents at frequency that are integer multiples of the fundamental frequency. These became a fact of life the very moment when the first AC power system was energized, where the first alternating voltages were severely distorted. Until designers succeed at building units that delivered nearly sinusoidal voltages, the early electrical engineers in the late 1890´s were kept on trying to understand and overcome the unstable form of energy delivered by alternating voltage and current [15].

A negative effect caused by AC power systems was the mysterious development of voltages larger than the voltage measured at the AC generator´s terminals. Resonances at higher harmonic orders or a significant Ferrantis´ effect at fundamental frequencies of 125 Hz or more were possible within a relative short length of line (∼10 km) [15][16]. As consequence, engineers worked hard to achieve new machine designs and already in 1895 a new generator design using distributed armature windings was developed. This design substantially improved the waveform (sinusoidal shape) as well as transmission distances. In addition, electric utilities were concerned about harmonic effects in their systems and the possible impact of a harmonic generating load upon other customers. Other harmonic problems mentioned in literature [16], were related to generators operating in parallel that involved excessive neutral current and overheating (zero-sequence harmonic voltages in wye connected machines), and telecommunication companies suffering interference (TIF), through the coupling of harmonics into telephone and telegraph wires parallel to the power lines.

The comprehension of AC phenomena, especially the current and voltage distortion related ones, was a slow process due to two main factors [16]: (1) unavailability of a accurate and inexpensive method of determining wave shapes and (2) limited practical experience. Oscilloscopes were not yet developed, electricians used oscillographs and primitive mechanical sample and hold contractors to measure instantaneous currents and voltages. Electricians were not trained to recognize harmonic phenomena and such devices were tedious and required hand plotting.

For these reasons, the development of standards was needed to allow engineers to correct and prevent harmonic problems. IEEE Standard 519 ”Guide for Harmonic Control and Reactive Compensation of Static Power Converters” from 1891 was the first harmonic standard which set guidelines for harmonic voltage distortion [17]. Since 1891, the requirements of electricity users have changed enormously. Equipment is getting more sensitive to power quality variations and some of these can be the source of power quality problems. Therefore, standards must provide guidelines, recommendations and limits to help assure ”compatibility” between end use equipment and the overall system. Bad power quality impacts the end user. However, there are several other parties involved in creating, propagating and solving power quality problems. The following concepts are basic needs for the development of power quality standards [18]:

- **Indicators**: indices to characterize performance and to provide definitions for important power quality characteristics.
- **Measurement and monitoring procedures**: methods to characterize performance and valuation of equipment characteristics.
- **Benchmarking**: to understand power quality characteristics for different types of systems to establish guidelines and limits.
- **Guidelines and limits**: to provide ”compatibility levels” that define the expected power quality levels.
- **Application guidelines**: to provide guidance in controlling power quality and solving problems, including methods to understand the economic aspect of solving these issues at different levels.

## 2.2 Limits for harmonic voltages

The LV/MV networks in the Netherlands have a nominal voltage of 0.4 kV and 10 kV, respectively. These networks are composed mainly by underground cables mostly with a radial or mesh topology, and transformers with rated powers between 160 and 630 kVA. If a customer's load demand is 200 kVA or more, then the customer should have his own cables and transformers. The active filter will be installed at the MV level, therefore, in terms of limits only the MV level (planning levels) are taken into account.

Planning levels are systems-wide design targets at MV, HV and EHV for voltage harmonics based on the compatibility requirements for end-use equipment. Based on the planning levels, individual end-users contributions to the overall permissible voltage distortion are allocated based on the end-user size relative to the capacity of the system and other factors.

IEC 61000-3-6 and IEEE Std 519-2014 are two of the most applied international standards concerning harmonic content in large industry power systems. There are other several documents establishing the voltage and current distortion limits for each country. In case of voltage harmonics, in the Netherlands, every customer supply point has to meet the limits given in EN 50160. For the industrial grid under consideration in this thesis, the IEEE 519, IEC 61000 and EN 50160, would set up the voltage THD limit to 5% (up to 69kV), 3.5% (up to 35kV) and 8% (up to 35kV), respectively.

The IEC 61000 considers voltage distortion from a higher-voltage (supplying) portion of the system and a lower-voltage (serving) portion of the system when deriving the voltage distortion contributions to be distributed among distortion installations [19]. It is based on assigning current limits that are more rigorously derived from voltage quality targets and is designed to insure that if all customers are within their individual limits, then the system-wide voltage quality problems will not exist.

The IEEE 519 approaches a relationship between utilities and end-users to limit the impact of non-linear loads [19]. Voltage/Current waveforms are described as well as distortion goals for the system designer. Interface between the sources and loads are described to minimize interference between electrical equipment. This standard aims to limit the harmonic injection from individual end-users to avoid unacceptable voltage distortion levels for normal system characteristics as well as to limit the overall harmonic distortion of the system supplied by the utility.

The EN 50160 characterizes voltage parameters of electrical energy in public distribution systems and for the main voltage parameters and their permissible deviation ranges at the customer's point of common coupling (PCC) in LV/MV/HV electricity distribution systems, under normal operating conditions for European network operators [20]. These characteristics are defined in terms of frequency, magnitude, waveform and symmetry.

A comparison of these standards is given in Table 1 for planning levels (MV) together with the individual voltage harmonic levels. The standards provide voltage harmonic limits, but it is noticeable that IEEE voltage harmonic limits are constant across all frequencies whereas the permissible voltage harmonic magnitudes decrease with frequency in the IEC and EN standards. Limits in EN and IEC are nearly identical for harmonic voltages for its corresponding MV systems, except for the absence of higher-order harmonic limits in EN.

| **Standard** | **IEC 61000-3-6** | **IEEE 519-2014** | **EN 50160** |
|---|---|---|---|
| **THDu** | 3.5% | 5% | 8% |
| **Order** | **Harmonic voltage as a % of the fundamental** | | |
| $3^{rd}$ | 4 | 3 | 5 |
| $5^{th}$ | 5 | 3 | 6 |
| $7^{th}$ | 4 | 3 | 5 |
| $9^{th}$ | 1.2 | 3 | 1.5 |
| $11^{th}$ | 3 | 3 | 3.5 |
| $13^{th}$ | 2.5 | 3 | 3 |
| $15^{th}$ | 0.3 | 3 | 0.5 |
| $17^{th}$ | 1.7 | 3 | 2 |
| $19^{th}$ | 1.5 | 3 | 1.5 |
| $21^{th}$ | 0.2 | 3 | 0.5 |
| $23^{th}$ | 1.2 | 3 | 1.5 |
| $25^{th}$ | 1.09 | 3 | 1.5 |
| $25^{th}$ ¡ h $\leq 40^{th}$ | 1.9*(17/h)-0.2 | 3 | - |

Table 1: Standards comparison for harmonic voltages of odd order harmonics in MV power systems

The thesis will only consider distortion of the voltage waveform, $\text{THD}_u$ of the distribution buses will be used as an indication of the system harmonic performance. Table 1 and a maximum $\text{THD}_u$ of 8% will be used as a basis when assessing the results. Even and zero sequence harmonics are out of interest in this thesis due to their harmonic content.

## 2.3 Limits for harmonic currents

There is an interaction between current and supplied voltage, therefore, it is not possible to put limits to the voltage without limiting the distortion of the current. For this, there are methodologies for setting limits for harmonic current emission. These depend on the size of equipment or installation. For large equipment, the size of equipment is considered. Several sets of limits are defined and used dependent on the short-circuit power of the connection point and rated power of the equipment. These standards prevent the use of high power devices with high harmonic current emissions. For installations, harmonic current limits are not defined explicitly. But recommendations are provided as an assessment procedure, used by system operator during negotiations with customers. The limits depend on the short circuit ratio at the connection point of the customer. It aims to have relaxed limits for small end-users which cannot seriously affect the grid, like residential users, but more strict limit for high demanding users such as an industrial campus.

IEEE recommends several set of harmonic current limits for different voltage levels dependent of the short-circuit ratio (SCR):

$$SCR = \frac{S_{SC}}{S_i} \tag{1}$$

$S_{SC}$ = short-circuit power of the point of connection.
$S_i$ = installed power of the installation to be connected.

| **SCR** | **h<11** | **11≤h<17** | **17≤h<23** | **23≤h<35** | **h≥35** | **TDD** |
|---|---|---|---|---|---|---|
| <20 | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20<SCR<50 | 7.0 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50<SCR<100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| 100<SCR<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 |

Table 2: IEEE 519 Current Harmonic Limits (<69 kV)

The limits above are defined as relative to the maximal load current (fundamental component) and they are defined for Total Demand Distortion (TDD). The TDD is calculated by the division of the square sum of harmonics with the peak load current.

The IEC does not have a recommendation for harmonic current limits that can be used directly by the system operators. IEC 610003-6 provide guidelines with a methodology which operators can apply to make their own rules for connecting new potentially disturbing customers [21]. The objective is to limit the harmonic injection from the total of all distorting installations to level that will not result in distortion levels that exceed the planning levels [22]. There are three stages of evaluation, which may be used in sequence or independently:

1. **Evaluation of harmonic emissions**: conservative criteria for acceptance of small size distorting installations is define on MV and HV systems. If the total distorting load or the end-user's agreed power, is small relative to the short circuit capacity at the point of evaluation, it should not be necessary to carry on detailed evaluation of the harmonic emission levels. If this criteria is not meet, the total distorting load must be evaluated along with the available absorption capacity of the system.
2. **Harmonic emissions relative to the installation characteristics**: in this step, the characteristics of the end-user harmonic generation should be evaluated against the absorption capacity of the system (derived from the planning levels). The absorption is apportioned to individual end-users based on their demand with respect to the total system capacity. Distortion transferred from the supply system should be also considered. If the system is fully loaded and all customer are injecting up to their individual limits, it can be concluded that the voltage distortion from the end-users should be within the planning levels.
3. **Acceptance of high emission levels based on exceptional basis**: sometimes, under circumstances, a end-user may require exceptions to emit disturbances beyond the basic limits in stage II. In such a situation the utility operator and end-user agree to facilitate such a connection (special agreement). Study of the actual and future system characteristics is advised to determined these special conditions.

It is noticeable that the IEEE harmonic current limits can be considered as the simplest implementation of the IEC standards. The allowable current injection levels are pre-calculated in the IEEE 519 based on simple assumptions and that these currents will not cause the violation of harmonic voltage limits. The IEC avoids giving current harmonic limits in a general sense, the standard prefer these limits to be more derived based on voltage limits and system impedance characteristics. Nevertheless, such an standard relies on many assumptions which could affect the good purpose of the IEC standard.

# 3 Theoretical background

## 3.1 Harmonic Sources

All non-linear loads are defined as harmonic sources, because they draw non-sinusoidal currents when a sinusoidal voltage is applied. These loads act as a source of harmonic currents in power system causing voltage distortions at the various system buses due to the harmonic voltage drops across the system impedances. As already discussed, the negative effects of harmonics are present in both voltage and current. Harmonic currents cause distortion of the voltage because of the voltage drop on the impedances of the distribution system. High impedance results in high level of voltage distortion. In other words, the current distortion relates to the individual load (device performance), while voltage distortion relates to system performance. To calculate the system frequency response for this type of load the following elements are used in the model: system short circuit equivalent impedance, capacitor banks (if available) and characteristics of lines, cables and loads.

These are the main sources of harmonics in industrial applications [23]:

- **Saturable Magnetic equipment**: include power generators, transformers, motors and other iron core devices.
- **Power Electronic Devices**: include electronic power supplies, variable frequency drives (VFDs), rectifiers and static var generators.

## 3.2 Harmonic indicators

### 3.2.1 Individual Harmonic percentage

The amplitude value of any particular harmonic order can be expressed as a percentage of the fundamental or a percentage of the RMS value of the total voltage/current.

$$i_h(\%) = \frac{X_n}{X_1} * 100 \tag{2}$$

$X_n$ = amplitude of the voltage/current harmonic order.
$X_1$ = amplitude of the fundamental voltage/current or the RMS value of the total voltage/current.

### 3.2.2 Harmonic spectrum

This is a graphical representation of the previous concept, where the distorted signal can be analysed via its decomposition (Figure 2). The amplitudes of the individual harmonics are expressed in % related to the amplitude of the fundamental.

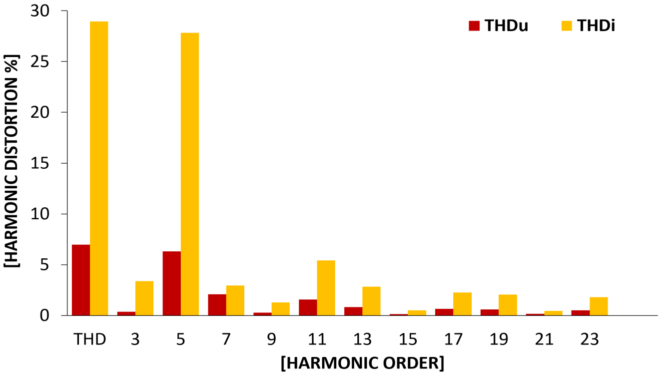

Figure 2: Harmonic voltage/current spectrums

### 3.2.3 Total Harmonic Distortion (THD)

The most common way to described the amount of harmonics in the voltage and/or current is not done by the individual harmonic percentages but with describing the Total Harmonic Distortion (for voltage $\text{THD}_u$ and for current $\text{THD}_i$). THD is defined as the ratio between the $RMS$ value of all individual harmonics and the RMS value of the fundamental frequency. This indicator is widely used to describe the power quality issues in transmission and distribution systems [24].

$$THD_x(\%) = \sqrt{\sum_{n=2}^{N} (\frac{X_n}{X_1})^2} * 100 \tag{3}$$

### 3.2.4 Total Harmonic Current (THC)

This indicator is the accumulated currents of the orders 2 to 40 that contribute to the distortion of the current waveform. This value is important in determining the required characteristics for the installation of active harmonic filters. When THC is known it can be compared with the fundamental current to provide a good visualization of the absolute harmonic currents in an specific load. The formula to compute this value can be seen below:

$$THC = THD_i * x_1 \tag{4}$$

$x_1$ = amplitude of the fundamental frequency.
$THD_i$ = total harmonic distortion current as a percentage of the fundamental.

## 3.3 Classification of Harmonics

Harmonics in which a signal is decomposed are entire multiples of the fundamental. They can be classified as Odd (symmetrical) and Even (asymmetrical) as well as according to its phase rotation with the fundamental:

- Positive sequence harmonics: same phase rotation than the fundamental, and circulate between phases ($4^{th}$, $7^{th}$, $10^{th}$,...).
- Negative sequence harmonics: opposite phase rotation than the fundamental, and circulate between phases ($2^{th}$, $5^{th}$, $8^{th}$,...).
- Zero sequence harmonics: also known as Triplen harmonics, they are phase with the fundamental and circulate between phases and neutral ($3^{th}$, $6^{th}$, $9^{th}$,...).

| **Sequence** | **Rotation** | **Effect** |
|---|---|---|
| + (Positive) | Forward | Excessive Heating Effect |
| - (Negative) | Reverse | Torque problems |
| 0 (Zero) | None | Adds voltage/current in neutral wire |

Table 3: Harmonic effects

## 3.4 Methods to reproduce harmonic content

To perform a harmonic study, the design engineer must identify the available harmonic sources and the harmonic currents generated by these. In order to determine the harmonic content (harmonic currents) within the installation the following two approaches are implemented at the LV level: (1) ideal current source and (2) VFDs. By modelling the system as function of frequency and harmonic sources to inject harmonic current or forced voltages, a harmonic analysis can be done to calculate the level and negative effects of the harmonic distortions in the power system.

### 3.4.1 Ideal Current Source

Harmonic sources can be modelled as ideal current sources for analysis purposes [25]. In other words, the non-linear loads can be replace with a current source (Figure 4). In harmonic simulations, there are two basic models to model the operation of non-linear loads [26]: (1) harmonic current source and (2) Norton equivalent circuit (Figure 3). The first one is the simplest where the characteristic load harmonic is modelled, but does not describe the interaction with the system and other loads (infinite harmonic impedance). The second, incorporates such system interactions through an admittance component.

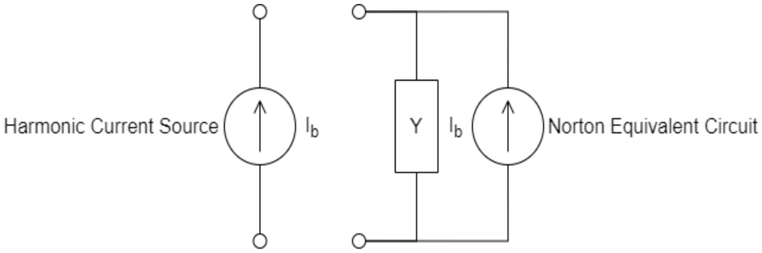

Figure 3: Basic Harmonic Load Models

As already defined in Section 1.1, harmonic problems are in the MV level. It is common to represent the harmonic model as Norton equivalent circuit, but the system interactions that this model can provide are already obtained from commissioning reports at the LV level. Therefore, the harmonic generation at the LV level will be reproduced with a harmonic current source model where the harmonic current profiles extracted from the reports are used as input. It is important to mention that the harmonic injection at the LV level has the only objective of reproducing the "same" levels of distortion at the MV level of the meshed network seen by the PQ monitor device installed in the distribution bus 1M-A.

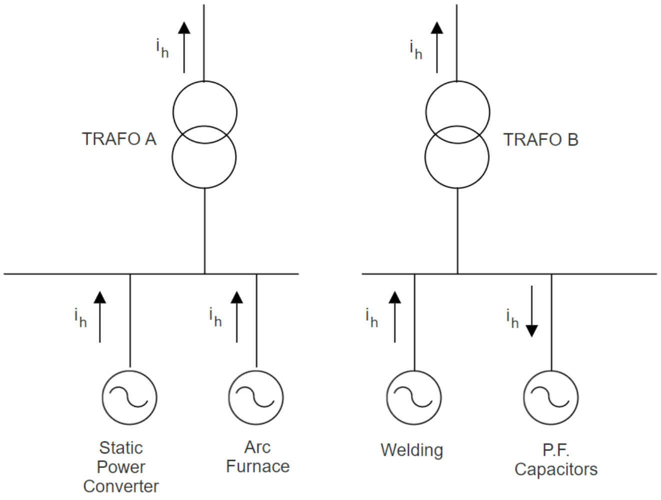

Figure 4: Non-linar loads modelled as current sources

### 3.4.2 Variable Frequency Drivers (VFD)

The harmonic currents present in the industrial electrical network considered in this thesis, are mainly caused by VFDs. A VFD consist of three components: (1) rectifier, (2) DC-Link (capacitor) and (3) inverter. The first stage of a VFD (rectifier) creates distortion of the AC-line as it chargers a capacitor bank (DC-link). The current is only drawn from the AC-line when the rectified voltage exceeds the voltage level to which the capacitor is charged. The modelling on PowerFactory is discussed in Section 6.1.2, while this section explains the mechanisms behind the harmonic current generation of the rectifier.

Figure 5 depicts the typical configuration of a 6-pulse bridge rectifier (diode based) where A, B and C are the three-phase input system. In this project, only diode rectifier is implemented as thyristors require gate-driving circuits, which can increase the complexity of their modelling. Let us assume an ideal case where the AC side of the rectifier has zero inductance. When phase A has the highest potential, diode D1 will be forward biased while diode D2 and D3 will be reversed biased. The same applies when phase B and phase C have the highest potential. As consequence, the potential of the positive DC-terminal is equal to the AC-phase with the highest potential while the potential of the negative DC-terminal will be equal to the AC-phase with the lowest potential. Therefore, the DC-voltage can be expressed with the following equation:

$$v_{DC} = v_P - v_N \tag{5}$$

$v_P$ = potential at positive DC-terminal.
$v_N$ = potential at negative DC-terminal.

With an ideal sinusoidal three-phase voltage waveform, it can be shown that the voltage $v_{DC}$ gets a pulsating waveform with amplitude $\sqrt{2} * V_{LL}$. Thus each pulse can be described as:

$$v_{DC} = \sqrt{2} * V_{LL} * cos(wt) \tag{6}$$

where $-\frac{1}{6}\pi < wt < \frac{1}{6}\pi$, during one period of line frequency, the DC voltage experiences six pulses (6-pulse rectifier). The average DC voltage, $V_{DC}$, can be calculated by integrating Equation 6 over the duration of one pulse and divide it by the duration.

$$V_{DC} = \frac{1}{\pi * 3} * \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} \sqrt{2} * V_{LL} * cos(wt) * dwt = \frac{3}{\pi} * \sqrt{2} * V_{LL} \approx 1.35 * V_{LL} \tag{7}$$

With a constant DC load current and non-inductance at the AC side of the circuit, it is possible to plot one of the AC phase's voltage and current waveform. It would be noticed that the current does not have a sinusoidal waveform. Through Fourier analysis on the AC current, the harmonic current amplitudes can be expressed as:

$$I_h = \frac{I_S}{h} \tag{8}$$

$I_S$ represents the amplitude of the fundamental frequency (50 Hz) and ”$h$” the harmonic order. In a balance and symmetrical three-phase system, the $3^{rd}$ harmonics and their multiples are canceled. Therefore, the 6-pulse bridge rectifier harmonic currents are given by $h_{6p} = 6h \pm 1$. The amplitude of these currents are theoretical ”$1/h$” times the amplitude of the fundamental current (e.g. $5^{th}$ has an amplitude of 20% of the fundamental current). Figure 6 depicts the harmonic current spectrum injected by a 6-pulse rectifier.

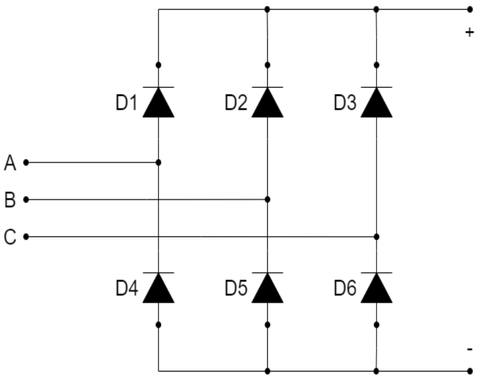

Figure 5: 6-Pulse diode bridge rectifier

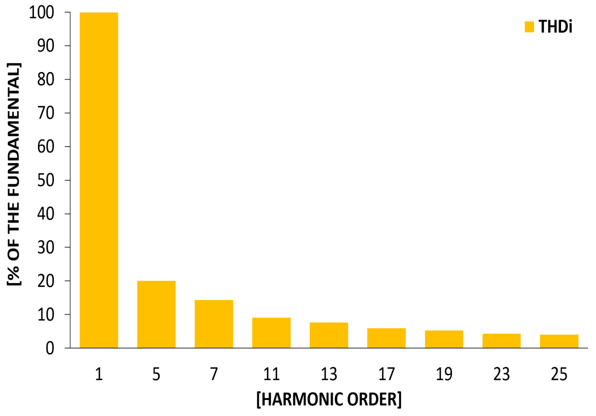

Figure 6: Harmonic current spectrum of 6-Pulse rectifier

## 3.5 Impedance and Resonance

To understand the harmonic currents behaviour and how they manifests themselves as harmonic voltages is crucial to have an understanding of the network impedances. At every busbar in the network, an equivalent network impedance can be calculated. For example, if a large harmonic current is fed into bus with a large network impedance, a large harmonic voltage will be generated. The reactances of an inductance and a capacitance are expressed as:

$$X_L = \omega * L = 2\pi f L \tag{9}$$

$$X_C = \frac{-1}{\omega * C} = \frac{-1}{2\pi f C} \tag{10}$$

From the last equations, it is possible to conclude that the magnitude of the reactances changes for different frequencies. In other words, the network impedance of a busbar changes substantially as the applied frequency is changed. At certain frequencies, resonance phenomena may occur. At these, the network impedances changes drastically within a short frequency range. This phenomena occurs in AC circuits due to the presence of energy storing components (e.g. inductors or capacitors). Both impedance and resonance can have an extreme impact on the harmonic's behaviour.

### 3.5.1 Series and Parallel Resonance

There are two types of resonances commonly observed in AC circuits, the series resonance and parallel resonance. Transmission system components create an RLC circuit which can result in resonance. The inductance and capacitance of the circuit can be represented as reactances (frequency domain). The total reactance of the circuit is expressed as:

$$X_T = X_L + X_C \tag{11}$$

At a specific frequency, the total reactance $X_T$ goes to 0 (resonance frequency). Therefore, the total impedance decreases dramatically as consequence of only consisting of the circuit's resistance. The resonance frequency can be expressed using Equations 9, 10 and 11 as:

$$f_{resonance} = \frac{1}{2\pi\sqrt{LC}} \tag{12}$$

This type of resonance is known as series resonance which is characterized by small impedance magnitude at the resonance frequency (sudden drop). However, for the type of network considered in this project, parallel resonance usually poses critical challenges than series resonance.

In a parallel RLC circuit, at the resonance frequency, the imaginary parts of the circuit's admittance's goes to 0. Then, the current $I_L$-$I_C$ goes to 0, causing the entire current to pass through the resistance. As consequence the impedance of the circuit increases dramatically (parallel connection in a sense disappears). This phenomenon is called parallel resonance where the resonance frequency can be expressed by Equation 12. If such a resonance is excited by a harmonic current this may lead to a significant distorted voltage.

### 3.5.2 Network Impedance Characteristics

To understand the harmonic behaviour in the system, the equivalent network impedances will be calculated. This is done by calculating a busbar's equivalent network impedance in a frequency range (0-2500 Hz). An interesting aspect of the network impedance is how it behaves if the electrical circuit parameters changes. What happens if the length of a cable is increased? What happens if the characteristics of a transformer is changed? The total capacitance (C) of a cable is needed to answer this type of question.

$$C = C^{'} * l \quad [F] \tag{13}$$

$C^{'}$ = capacitance per kilometer.
l = length of a cable [km].

Considering Equation 12, if the capacitance is increased, the resonance frequency decreases. If the inductance of a transformer is reduced, the resonance frequency increases. With this examples, it is noticeable that an electrical designer can manipulate the network impedance characteristics and its resonance frequencies. This is done by adjusting different network characteristics such as short-circuit impedance of a transformer and length or type of cable. This could reduced the harmonic content significantly. Nevertheless, resonance problem cannot always be avoided, as designers might not have the possibility to change the network parameters because the weight of other design criteria. A parallel resonance is shown in Figure 7 from the analyzed industrial power system.

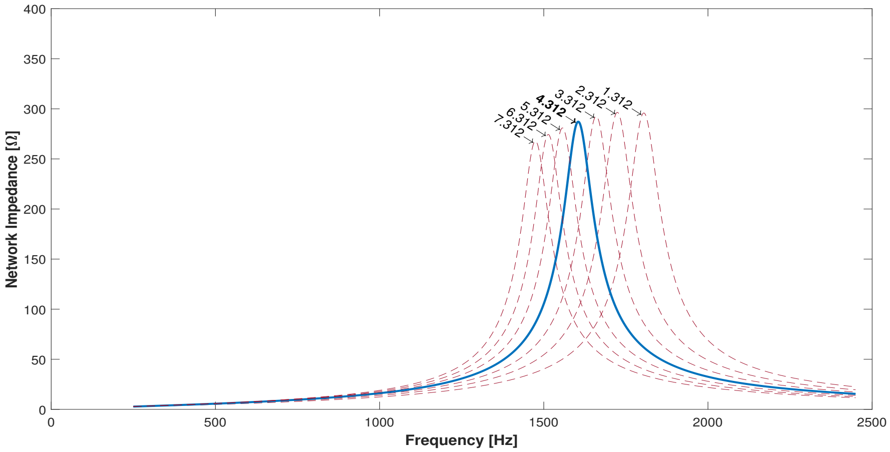

Figure 7: Network impedance characteristics of the industrial power system

Due to the inductance and capacitance characteristics of the network there will be a frequency where resonance will occur. In this case it is around the $32^{th}$ harmonic (1600 Hz) which according to PQ monitor device and commissioning reports is not present in the network. Therefore, a resonance problem in this case is not present. If the $32^{th}$ harmonic would be presented, this would translate into a increase in the voltage distortion at that frequency. Also, Figure 7 displays several plots of the network impedance development at 1M-B for different lengths of supply cable B734. The original length of the cable is displayed with blue color while the length variation with red. With a length of 1.312 [km], a parallel resonance is located close to the harmonic order 36 (shifted towards higher frequencies), while when the length of the supply cable further increases, the parallel resonance is shifted towards lower frequencies (harmonic order 28). If harmonic order 28 or 36 would be present in the analyzed network (depending on the resonance frequency of the network), current amplification of these orders would occur leading to increase $\text{THD}_u$ levels.

# 4 Network description and Modeling

## 4.1 Network description

The system to be studied can be viewed as an hierarchical power system with multiple levels and with a fundamental frequency of 50 Hz (Figure 8). Each of these levels are distinguished by a particular rate voltage range and electrically separated by a three-phase transformer. Power is generated at 157.5 kV in the utility network (Level A). The voltage is stepped down via a three-phase transformer to 11.6 kV on the double main busbars, these together form level B. Then, the voltage level is maintained for the third level (Level C) which consists of 5 interconnected distribution buses. The buses included in the next level (Level D) form the fourth and final level of the industrial power distribution system. This last level supply power to several large electric loads. The simulation model of the industrial power system in the power-system simulation software PowerFactory is shown in Appendix B.2.

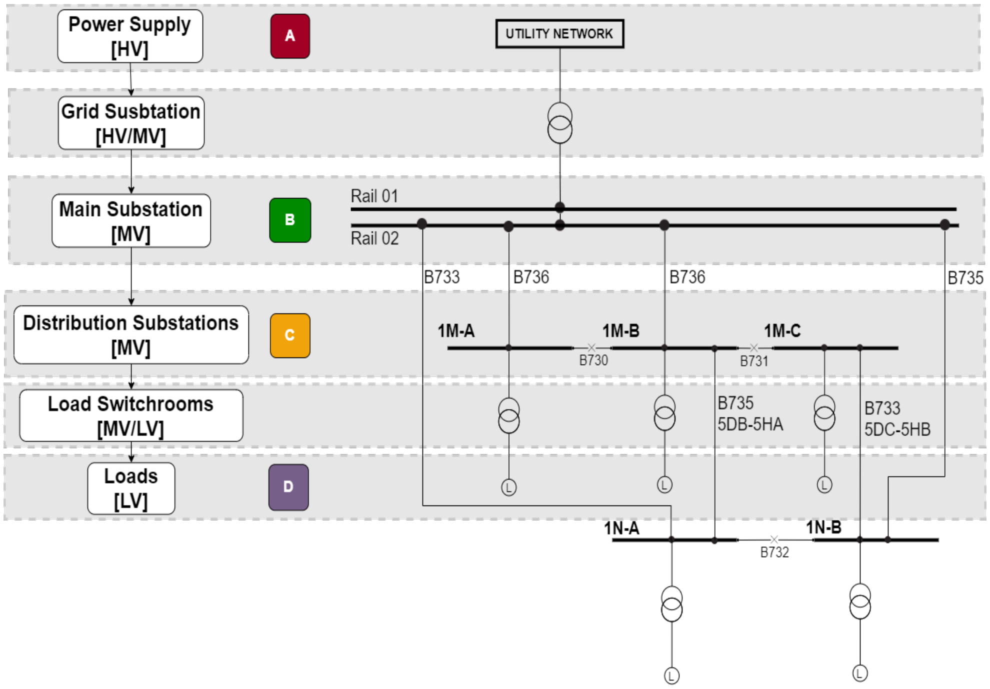

Figure 8: SLD - Industrial Power System

## 4.2 Model construction

### 4.2.1 Power Supply

The industrial site is supplied by the grid. In other words, the site is connected to the utility grid where the main power source is the HV transmission grid (150kV / 10kV). This connection is done via a HV/MV substation which includes a HV/MV switch-gear, HV/MV transformer and MV switchboard. The MV distribution topology connects the HV/MV transformer to the different MV substations (10kV). The MV distribution includes:

- Main substation: connected to the utility grid at HV transmission level. The main function is to distribute the electrical energy to the secondary substations.
- Distribution or Secondary substations: connected to the main one, they provide power to MV loads and to MV/LV transformers (10kV / 0.4kV).

Power transformers are used to transfer electrical energy in any part of the electrical circuit between the generator and the distribution primary circuits. These are used in distribution systems to step up and step down voltages. For this thesis, twenty seven MV/LV power transformers are used to supply power to loads within the 5 distribution busbars (10 kV), while one HV/MV transformer supply energy to the industrial meshed network. **??** shows the characteristics of the utility grid while Table 5 shows the specifications of such transformers.

| | **Main Substation** | **Distribution Substation** |
|---|---|---|
| **Parameter** | Value | Value |
| Short-Circuit Power "Sk" | 8000 [MVA] | 300 [MVA] |
| Short-Circuit Current "Ik" | 29 [kA] | 16 [kA] |
| Z2/Z1 | 1 | - |
| X0/X1 | 1 | - |
| R0/X0 | 0.16 | - |

Table 4: Power Transformers parameters

| | **MV/LV Power Transformer** | **HV/MV Power Transformer** |
|---|---|---|
| **Parameter** | Value | Value |
| Rated Voltage | 10/0.4 [kV] | 158/11.6 [kV] |
| Rated Power | 2.5 [MVA] | 77 [MVA] |
| Short-Circuit Voltage "Uk" | 6% | 24.51% |
| Vector group | Dyn5 | YNd1 |

Table 5: Power Transformers parameters

### 4.2.2 Cables

Harmonic analysis in power systems requires accurate cable modelling. PowerFactory offer two main methods: (1) geometrical and (2) electrical parameter input [27][28]. The geometrical approach used constructional data such as cross-section area, insulation thickness, sheaths, etc. With this PowerFactory calculate the electrical parameters based on both Maxwell´s equations (electromagnetism equations) and complex cable modeling methods to obtain frequency-dependent parameters. Nevertheless, this method is problematic due to the use of manufacturers' cables brochures as input which could not allow the parameter calculations converge in PowerFactory. Thus, the electrical approach will be used to avoid numerical problems as it uses the electrical sequence parameters per km as input which are found in the manufacturers' brochures [29]. When using the electrical approach the parameters are not calculated based on frequency-dependent. Table 6 shows the specifications of the aluminium cables for power transmission (XLPE conductor insulation).

| **Cable** | **Length** | **$U_o$/U** | **$I_{RATED}$** | **A** | **L** | **C** | **R** |
|---|---|---|---|---|---|---|---|
| B730 | 0.1 [km] | 12/20 [kV] | 0.695 [kA] | 800 [mm$^2$] | 0.29 [mH/km] | 0.45 [$\mu$F/km] | 0.0367 [$\Omega$/km] |
| B731 | 0.1 [km] | | | | | | |
| B732 | 0.1 [km] | | | | | | |
| B733 | 4.471 [km] | | | | | | |
| B734 | 4.312 [km] | | | | | | |
| B735 | 4.483 [km] | | | | | | |
| B736 | 4.312 [km] | | | | | | |
| B733 1MC-1NB | 0.220 [km] | | | | | | |
| B735 1MB-1NA | 0.226 [km] | | | | | | |

Table 6: Cable parameters

### 4.2.3 VFDs

Section 3.4.2 discussed the mechanisms behind the harmonic current generation by rectifiers. The harmonic study is focused at the supply-side of the VFD to get a realistic and accurate model. Therefore, only the rectifier and the DC-link will be modelled. The load (motor) will be modelled as a DC-load connected to the VFDs DC-link. Including an inverter would increase the model's complexity as well as the number of possible sources of error. An inverter requires a complete control and drive circuit system to assure correct switching operation. This approach provides advantages and focuses only on the harmonics caused by the rectifier which has the most relevance to the analysis. Nevertheless, such a simplification of the VFDs is fairly accurate for this project.

### 4.2.4 Rectifier

In PowerFactory, a 6-pulse bridge rectifier can be modelled either as a three-phase diode or a three-phase thyristor-controlled. Based on the arguments described in Section 6.1.2 and Section 3.4.2, only diode rectifier will be implemented.The rectifier is modelled as a load with constant active and reactive power (during steady-state operation). The transmitted DC power is given by [30]:

$$P_{DC} = U_{DC} * I_{DC} \tag{14}$$

In harmonic analysis, the rectifier is always modelled as a current source load. The fundamental AC current is determined by the power drawn by the load connected to the rectifier's DC-Link bus. The injected harmonic current spectrum is defined as the theoretical current spectrum of a 6-pulse rectifier as described in Section 3.4.2. All the VFDs are modelled as a 6-Pulse bridge rectifiers. A two-winding transformer model with a 5 electrical degree phase-shift will be used to supply the rectifiers.

### 4.2.5 Electric Loads

The sinusoidal PWM modulation of the inverter, the electrical motor and its mechanical load are simplified with the implementation of a DC-load connected to the VFD's DC-link bus. This load is modelled as a current source load to have a representation of the true behaviour of the electric motor. The load is characterized by its active power and reactive power flow in steady-state simulations. The main purpose of the load is to determine the fundamental current which regulates the amplitudes of the harmonic currents injected by the rectifier.

## 4.3 Mitigation Approach

Several estimation algorithms have been developed to estimate certain parameter from a signal to enhance the power of measurements and to get the maximum information about the system. In power systems related issues several heuristic methods have been implemented. These methods are based on a computational procedure that determines an optimal solution by iterative trying to improve a candidate solution with regard to a give measure of quality. Even when these methods do not guarantee a finding of globally optimal solution, they are able to provide a solution which is satisfactory and within a reasonable time [31]. Nowadays, there are several heuristic algorithms used to optimization of solutions, a few examples are simulated annealing (SA), genetic algorithm (GA) and particle swarm optimization (PSO). It is not possible to unequivocally say that anyone of them is the best due to the fact that the success depends on settings of various parameters. A comparison have been made in [32] from these methods regarding the quality of their solutions, run-time, and repeatability. It was concluded that PSO has the best performance when its empirical parameters are selected suitably, SA performed the worst that could not guarantee an optimal solution within the same iterations. GA provided similar solutions as PSO with tuning less empirical parameters. Based on the previous arguments and good results showed in [33][34], it was determined to use GA for the mitigation approach.

Genetic Algorithm (GA) was introduced as an evolutionary computing based technique inspired by Darwin's theory of evolution to solve a problem by imitating an evolutionary process. It is an exploratory procedure that is often able to locate near-optimal solution to complex problems. In order to do this, it maintains a set of trial solution and forces them to evolve toward an acceptable solution. In a more extended way, the algorithm operates on the population of current approximations/individuals initially drawn at random, from which improvement is seek. These individuals are encoded as strings (chromosomes) over some particular character set, so that the chromosome values are exactly mapped into the decision variable domain. Once the decision variable of the current population is calculated, individual performance is assessed according objective function which characterizes the problem to be solved (basis of selection). At the reproduction stage, a fitness value is derived from the raw individual performance measure from the objective function and is used for the selection process (highly fit individuals have a higher probability to go to the next stage). Then, the selected individuals are modified using a genetic operator. After this, individuals chromosomes are decoded, evaluated and selected according to their fitness (process continues for different generations) [33] (Figure 9 shows the GA flowchart). The different steps of GA are summarized as follow:

- **Population**: the size depends only in the nature of the problem and must consider a balance between the time complexity and the search space measure (the narrower the range, the faster the GA converges).
- **Reproduction**: the reproduction operator determines how the parents are chose to create the offspring. In this step, chromosomes are copied according to their objective function values.
- **Crossover**: is the main operation in GAs because it creates a group of children from the parents by exchanging genes among them. This new offspring contain mixed genes from both parents. This allows to provide new points for further testing and also introduces representation of new chromosomes into the population for further evaluation (optimization process).
- **Mutation**: is an important step and works after the crossover operation. This process is repeated until the preferred optimum of the objective function is reached. In this step, there is a probability that each gene may become mutated when the genes are being copied from the parent to the offspring.
- **Evaluation**: the function of this step is to evaluate the fitness (cost function). In this case, the purpose is to minimize specified harmonics, therefore, the fitness function has to be associated to $\text{THD}_u$. In this thesis, the $5^{th}$ and $7^{th}$ harmonics at the MV level are to be minimized.

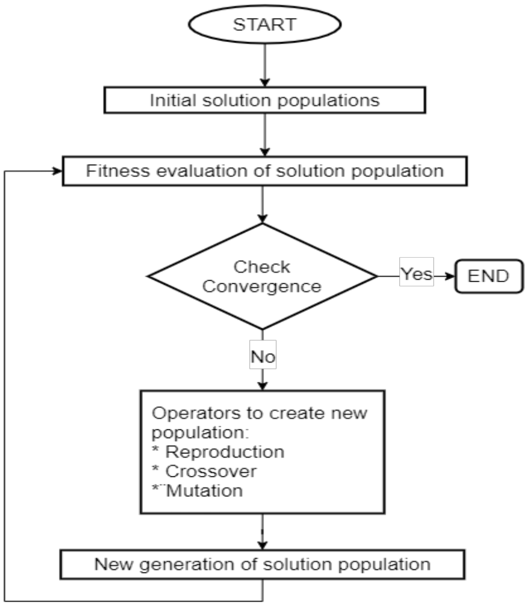

Figure 9: Flow chart - Genetic Algorithm

For the analyzed industrial system, the algorithm generates a random population (harmonic currents magnitudes and angles) and evaluates each randomly to generated currents and angles by allocating them into the mitigation device (active filter). Then a harmonic load flow is computed, the result of each pair of current and angle is stored, after that, the crossover of random row in the population is made to generate the offspring (new pair with random current and random angle is generated). Subsequently, mutation step is carried out, where some random current and angle from the already present currents and angles are picked and small values are added/subtracted/averaged. After that, all pairs are evaluated and the best solutions based on the fitness function are retained for next iteration. The fitness function in our case is used to find the lowest harmonic current for the harmonic order under study. These steps are run until total number of iterations are reached (all solutions converge into one optimum solution).

The algorithm implemented in PowerFactory allowed through programming mode the selection of the desired number for population size, number of iterations, harmonic orders to mitigate, balanced/unbalance analysis and rated current of the mitigation device (active filter). The goal of this algorithm is to reduce the $\text{THD}_u\%$ at the MV level of the network with the calculation of currents and angles needed by the active harmonic filter. DPL script for the GA implemented can be found in Appendix B.3.2. Simulation parameters are shown in the following table:

| **Parameter** | **Value** |
|---|---|
| Population size | 100 |
| Number of iterations | 5 |
| Last harmonic order to mitigate | $7^{th}$ ($5^{th}$ & $7^{th}$) |
| Rated current of mitigation device | 560 [A] |

Table 7: GA parameters

The mitigation system implemented in the model consists of an active harmonic filter and a dedicated transformer connected at the MV level (10 kV). The following tables provide the specifications from both components (based on the execution plan from the industrial plant):

| **Parameter** | **Value** |
|---|---|
| Rated current | 560 [A] |
| Rated voltage | 690 [V] |
| Type | 3P3W (+/- sequence harmonic compensation) |

Table 8: Active Harmonic Filter parameters

| **Parameter** | **Value** |
|---|---|
| Rated voltage | 10/0.69 [kV] |
| Rated power | 1000 [kVA] |
| Short-Circuit Voltage ”Uk” | 4% |
| Vector group | Dyn5 |

Table 9: Dedicated Transformer parameters

# 5 Mitigation Device

High levels of harmonic distortion can cause irregular operation of equipment to a shutdown of important plant equipment. Electrical utilities have different order of harmonics, therefore, it is necessary to eliminate those pre-specified order of harmonics. There are many solutions to mitigate harmonic distortion depending on the type of demand. A white paper about harmonic mitigation introduces the most relevant solutions [10]:

- **AC-Line Reactors or DC-Link Chokes**: they are used to plan the current peaks in a circuit and can be used on different positions within a drive to reduce harmonics. With chokes the current flow is expanded and the amplitude is reduced (harmonics will be reduced). This mitigation technique can increase the life time of the drives and enables the use of cost-effective mitigation solutions at installation level.
- **Multi-Pulse Converter Systems**: increasing the number of pulses of the converter system is the most common way to reduce the current distortion. Pre-condition is a dedicated transformer directly supplied from the MV network. This technique limits the harmonic pollution considerably (no further mitigation is needed), besides that, this solution is the most efficient in terms of power losses.
- **Passive Filters**: they consist of reactors and capacitors set up in a resonant circuit configuration which is tuned to the frequency of the harmonic order to be mitigated. They have a dual role (dimming harmonics and improving the system power factor). It must be noted that this can lead to capacitive work and increase the voltage during low load of the system.
- **Active Filter**: it is a sophisticated method which tracks the current that the load is taking from the network and generates and inverted waveform of an undesired current component. They cover a large extend of customer needs such as harmonics mitigation (up to the $50^{th}$ harmonic), reactive power compensation and load balancing.
- **Low Harmonic Drive**: due to replacement of the diode rectifier by an active IGBT converter is possible to consume energy like a normal inverter as well as to adjust the waveform of the mains current. As consequence, the negative effects on the mains due to harmonics can be avoided. This type of drive is the best performing solution for harmonic mitigation meeting all applicable standards and the easiest to implement (in new installations).

The paper [10] analyzed the described solutions based on the following criteria: (1) compactness (less space), (2) simplicity (easy to operate and design), (3) THD (mitigation percentage), (4) efficiency (energy efficiency level) and (5) value (in terms of costs). The rating system is based on points where each solution was awarded one to five points for each criteria (one point "more effort" up to five points "less effort"). The analysis was performed in an objective manner, therefore, due to the unique disadvantages of passive filters such as low power factor at partial loads and risk of causing resonances within the grid, they are not included in the comparison. Figure 10 shows the summary of ratings for all solutions.

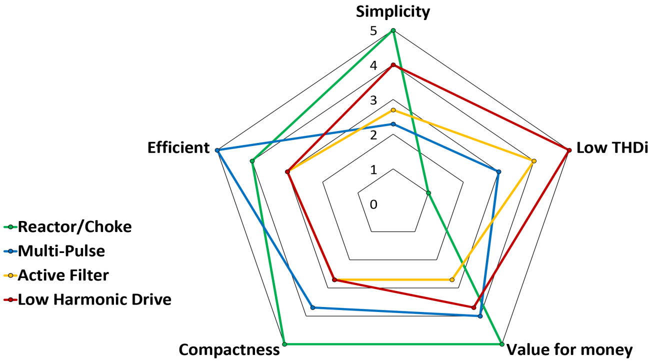

Figure 10: Net diagram for mitigation solutions

The selection of harmonic mitigation solutions can be done with all or a combination of the following steps:

1. **Establish priorities**: objectives must be defined depending on the process requirements and installation characteristics. In this case (industry process), priority on reliability have more weight than cost optimization. For example, in a commercial building, priority may be set on energy savings.

2. **Current situation on-site**: assessing the current situation focusing on different indicators such as power factor, harmonic distortion levels, line currents and power demand. This can be done by means power quality reports or by means of appropriate measurement devices installed at the head of the installation and on vital feeders. In this case, a power quality monitor device is installed at one of the five distribution buses within the installation at the MV level (bus 1M-A) and access to power quality reports was given.

3. **Efficiency and cost of different solutions**: includes the comparison of the different possible solutions, based on cost calculations, possible benefits and return on investment (future research path - Section 8).

Based on rating score of mitigation solutions (Figure 10), the first two steps from the list above, and knowing that the analyzed industrial installation is a existing one is possible to recommend a solution. The need to look for a mitigation solution was initiated because of high harmonic distortion in the MV level (it is expected to keep rising) and due to damage in electrical equipment (e.g. bearings of the electromotors from cooling machines). Therefore, the priority is set to improve the reliability and availability of the industrial plant. Regarding the current situation, harmonic distortion at the MV level was found to be the responsible for failures in the electrical equipment within the installation. Currently, the $\text{THD}_u$ level at MV is between 5 and 7 percent, based on data obtained from power quality monitor device installed at distribution bus 1M-A.

A multi-pulse solution is not recommended due to the fact that this is an existing installation. This technique is recommended for new installations where you can benefit from energy efficiency. The same happens with a low harmonic drive, it is not economically viable to replace each drive within the installation added to the fact that harmonic pollution coming from these devices is already solved with active harmonic filters installed at the LV level. A reactor/choke technique is the most economical option and compact but it does not mitigate $\text{THD}_i$ well. Therefore, the recommendation is to install an active harmonic filter.

## 5.1 Active Harmonic Filter (AHF)

The operating principles of active filters were firmly established in the 1970s. They had the attention of power electronics engineers and researches who have had concerns about harmonic pollution in power systems [35]. Added to this, a deeper interest in these devices has been growing due to the emergence of semiconductor switching devices (IGBTs, MOSFET, etc.) which are characterized by fast switching capability.

AHF are able to permanently monitor non-linear loads and dynamically provide precisely controlled current. This current has the same amplitude of the harmonic current but injected with an opposite phase-shift. As result the current supplied by the power source will remain sinusoidal. Another advantage is that AHF are not confined only to harmonic filtering, they can also provide reactive power control for power factor correction, voltage regulation, load balancing, voltage-flicker reduction, and/or their combinations. Nowadays, this is why AHF are competitive in cost and performance against traditional passive harmonic mitigation devices. Harmonic filters can be classified into 2 classes based on the type of topology network of the power systems:

- **3P3W (3Phase-3Wire)**: designed to cancel in 3 phases positive/negative sequence harmonics (e.g. $5^{th}$, $7^{th}$, $11^{th}$, $13^{th}$ up to $50^{th}$. They do not correct the $3^{th}$ and triple harmonics in the neutral. These type is commonly installed in industrial environments with VFDs and other such applications which have a large number of non-linear loads.

- **3P4W (3Phase-4Wire)**: designed to cancel in 3 phases and the neutral including $3^{th}$ and triplen harmonics (e.g. $3^{th}$, $5^{th}$, $7^{th}$, $11^{th}$, $13^{th}$ up to $50^{th}$). This filter is usually used where the neutral conductors are loaded with harmonics (e.g. hospitals, data centers, offices and commercial buildings).

## 5.2 Allocation of Mitigation Device

When a harmonic mitigation device is connected to an existing installation, it is important to check if the connection is possible or if there are conditions to consider. The allocation strategy for a mitigation device will be developed considering a generic power system. It will be applied to the industrial system described in Section 4.1. A hierarchical representation of a generic power system is shown in Figure 11. Level A, is the level at which power is generated for the system at the greatest voltage. A hierarchical level can be identified by either a power conversion module (e.g. transformer) or by a bus distributing power to loads or buses. The purpose of this strategy will indicate the most efficient location to decrease the level of power quality degradation system-wide.

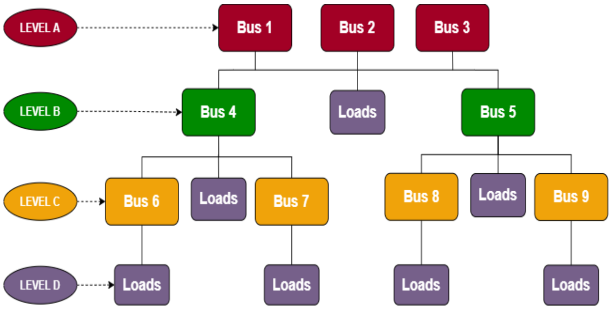

Figure 11: Hierarchical diagram of a generic power system

To validate whether the strategy correctly identified the proper location for the mitigation device, the following performance metrics have been proposed [36]:

- **Maximum THD$_u$ among sensitive loads**: extracted from active filter commissioning reports, this metric provide an insight of the possible effectiveness of the filter placement.
- **Average THD$_u$ among all power distribution buses**: to determine the system-wide efficiency of the mitigation device. This metric provides a measure of the range of effectiveness of a particular location.

This strategy only requires the voltage signals at each bus and their hierarchical affiliations to provide an indication. This approach is more practical and feasible for real applications because it does not require to assess the effect of placing a mitigation device at each potential location and does not require to know the system impedance or harmonic generation locations.

The SLD in Figure 8 will be analyzed to explore the effectiveness of the allocation strategy previously explained. Harmonic current is injected in 5 locations (busbars 1M-A, 1M-B, 1M-C, 1N-A and 1N-B) at the LV level (0.4 kV). The non-linear loads are modelled as sources of harmonic current which allows an injection of any harmonic current spectrum profile. The information related to the harmonic injection parameters are summarized in Appendix A. This approach will be successful even when considering a diverse array of non-linear loads.

To accomplish the purpose of this strategy, the most efficient location for a mitigation device is assumed to be at a bus. To clarify, a bus can be a single node or a set of nodes. Therefore, a bus is able to supply power to multiple loads and to lower level buses. Following this logic, the higher the hierarchical level of the bus on which a mitigation device is installed, the greater the number of nodes that will be affected. Nevertheless, it is possible that the power quality improvement is not successful when placing a mitigation device on the highest level. The higher the level, the lower the harmonic currents in impedances, which translates into lower harmonic distortion. To achieve the best filtering results, a mitigation device should take place as close to the source of pollution as possible. The aim of this strategy is to determine the highest level at which a mitigation device can be installed and be effective. To implement this strategy, the top level of the hierarchy (Level A) is the starting point. If Level A, has a higher level of distortion compare to the other levels the mitigation device should be placed on this level, otherwise the next level (Level B) should be considered. Again, distortion levels are compared downstream to determined whether or not to place it at this level. If neither of them have a higher distortion level, it is determined whether the next level (Level C) is the final hierarchical level. This process would continue in this way until a mitigation device is allocated or the final level of the installation is reached (Level D).

As stated before, there are several active filters installed in the LV level which according to Figure 11 is level D. The aim of the mitigation device is to decrease the THD$_u$ at the MV level, thus, Level A (HV) and Level D (LV) are not considered while MV Levels B and C are. Nevertheless, THD$_u$ LV data is considered in order to find the bus at Level D with the greatest disturbance (sensible loads) and to compute the THD$_u$ level at the MV distribution buses. An active filter is placed to absorb the $5^{th}$ and $7^{th}$ harmonics at each bus in the system individually for a fair comparison and to calculate the performance metrics.

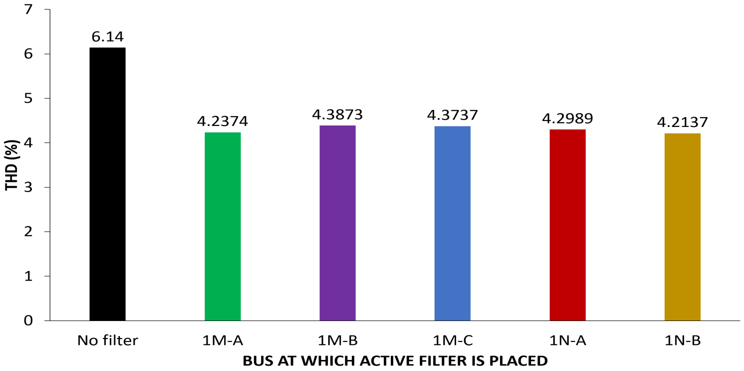

Figure 12: Maximum THD$_u$% - Level D (Sensitive Loads)

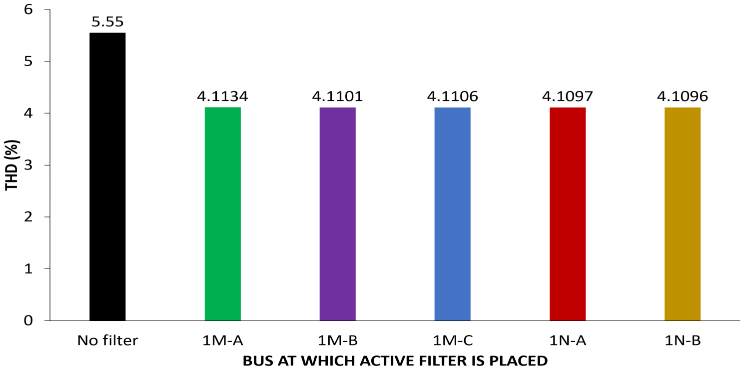

Figure 13: Average THD$_u$% - Level C (Power Distribution Buses)

According to simulation results, Level B has a THD$_u$ of 5.08% (8.30% less than Level C - 5.54%). Thus, it is determined to go to the next level (Level C). The average THD$_u$% from the power distribution buses (Level C) and maximum THD$_u$% among sensible loads (Level D) were calculated (Figure 13 and 12). The black bar in both figures is the representative value of the metric without any filter in the system. From Figure 13 can be concluded that the THD$_u$ on Level C at the distribution buses is very similar in each of them (difference of 0.0038% between the lowest and highest value). This is due to the fact that the network has a meshed topology, where the buses share an "average" THD$_u$ level. Figure 12 and 13 show that placing the active filter at bus 1N-B has the greatest effect on the THD$_u$ of the sensitive loads (reduction from 6.14% to 4.2137%) but also on the average THD$_u$ of all of the buses system-wide (reduction from 5.55% to 4.10%). Therefore, it is recommended to place the mitigation device at bus 1N-B to have the most effective and efficient location. Nevertheless, it is recommended to analyzed the installation considering three aspects: (1) topology where these MV distribution buses are not interconnected, (2) possible future expansion and (3) dimensions and physical requirements in the network (future research path).

# 6 Simulation Results

## 6.1 Mitigation

Based on the data extracted by the PQ monitor device on 1M-A (Appendix A.2), ∼60 [A] and ∼7 [A] need to be injected at the MV Level to compensate the $5^{th}$ and $7^{th}$ harmonic orders, respectively. Similar results were calculated with the simulation model, where harmonic currents of the $5^{th}$ and $7^{th}$ orders are around ∼66 [A] and ∼10 [A], respectively. It is important to stated that for the simulation a high harmonic voltage background was used (∼4%) to obtain a similar voltage distortion spectrum from the PQ monitor device (Appendix A.2) at the MV Level. Considering the specifications of the active harmonic filter (Table 8), how much current does the AHF need to inject to mitigate $5^{th}$ and $7^{th}$ harmonic orders generated within the industrial plant? Will be the AHF able to cope with the necessary harmonic injection? To calculate this, the GA was implemented where the harmonic current percentages per order were calculated (Table 10).

| | **Current Source** | | **VFD** | |
|---|---|---|---|---|
| **Harmonic Order** | **[%]** | **[A]** | **[%]** | **[A]** |
| $5^{th}$ | 166 | 929 | 189 | 1058 |
| $7^{th}$ | 53 | 296 | 57 | 319 |
| **Fund. Current** | 560 [A] | | | |
| **THC** | 975 [A] | | 1105 [A] | |

Table 10: Harmonic current calculation per approach

Based on the results from Table 10, it can be concluded that the compensation current capacity of the AHF needs to be increased to be suitable for the application requirements. Taking into account the current source approach, in order to mitigate the targeted orders the active filter needs to compensate 975 [A] (74% more than its rated current). In simulations there are not restrictions regarding the harmonic current injection of a filter (modeled as AC current source), but in real practice an AHF is limited by its compensation current capacity. Also, it is important to re-calculated the harmonic content of the electrical installation, once the PQ monitor devices at the MV level are installed at the suggested points established in Section 7. This would provide a better insight of the harmonic generation within the industrial plan as well as the harmonic background coming from the grid.

The large amount of harmonic current that the AHF needs to inject is due to the fact that the dedicated transformer is "step down" (10/0.69 kV), as consequence the mitigation device requires more harmonic current injection at the secondary side to achieve effective harmonic reduction at the primary side (MV level). Often the connection type of transformers is not a relevant issue for harmonic distortion. According to [37], several standard and non-standard connections were analyzed and discussed their impact on harmonic mitigation. It was shown that the connection type of a transformer does not improved the harmonic mitigation. In power transformers, the main consequence of harmonic currents is an increase in losses (mainly in windings). Higher losses are equal to more heat generation in the transformer (operating temperature increases). This will lead to deterioration of the insulation and a potential reduction of its lifespan. To avoid this problems, it is necessary to reduce the maximum power load on the transformer (de-rating). To estimate the de-rating, the load's "K" factor may be used. This factor is calculated according to the harmonic spectrum of the load current and is an addition of the additional eddy current load losses. In Europe, to estimate how much a standard transformer should be de-rated the following formula can be used [38]:

$$K = [1 + (\frac{e}{1+e})(\frac{I_1}{I})^2 \sum_{h=2}^{h_{max}} (h^q (\frac{I_h}{I_1})^2)]^{0.5} \tag{15}$$

e = ratio of fundamental frequency eddy current loss to ohmic loss, both at reference temperature
h = harmonic order
I = rms of the sinusoidal current including all harmonics
$I_h$ = magnitude of the $h^{th}$ harmonic
$I_1$ = magnitude of the fundamental current
q = a constant parameter, depending on type and construction of the windings

To calculate "K", it is necessary to establish the value of "e" (value is likely to lie in the range of 0.05 to 0.1). The exponent "q" depends critically on the construction of the transformer (value is likely to lie in the range 1.5 to 1.7). In principle the process calculation is as follows:

- Determine all the components of additional losses due to the presence of harmonics.
- Determine the harmonic spectrum (by measurement or estimation), considering all harmonic generating sources (e.g. power electronics).
- Calculate the contribution of each harmonic and determine the total additional loss.

The rated power and voltage of the dedicated transformer are 1000 [kVA] and 10/0.69 [kV], respectively. As result of the harmonic injection current coming from the AHF the transformer could be overloaded. If that is the case, the transformer cannot be used to its nominal power and should be de-rated. Based on the harmonic injection current and compensation current capacity of the AHF (Table 10), a rms value of total current can be calculated, after which the squares of the proportionate values of each harmonic current can be calculated as well, leading to the value of K. When e= 0.1 and q= 1.7, the transformer should be de-rated with a "K" factor of 1.3, which implies that the transformer could be used for only (or even less than) 80% of its nominal power (∼78% [1/1.3]). Therefore, the transformer size should be at least above 1300 [kVA] to have a loading of ∼50% (without de-rating ∼66%). Loading percentage in power transformers also affects their lifespan, the higher the load the shorter the lifespan. Nevertheless, this is a distribution transformer which is designed for maximum efficiency at 60% to 70% load as normally does not operate at full load all the time. Thus, a de-rating for the dedicated transformer is not needed.

### 6.1.1 Ideal current source

This approach provides a constant current irrespective of the system impedance seen by the source with or without including phase angle information. In most industrial application studies, non-linear loads (harmonic source) are considered an ideal current source. This approximation is most of the times reasonable and yields satisfactory results. The current harmonics injected into the distribution buses (1M and 1N) at the LV side, have a magnitude determined from a spectrum and fundamental current obtained from active filter commissioning reports. This method can be applied to balanced and unbalanced systems. In harmonic analysis, different types of harmonic sources determined whether or not the use of angle information is necessary. When only one type of harmonic source is involved, the phase angles can be ignored and only the magnitudes are used in the harmonic simulation. But when there are multiple types of harmonic sources within the installation, harmonic phase angles are needed to consider harmonic cancellation effect [39]. Figure 14 shows the harmonic simulation results based on this approach per harmonic order before and after the mitigation as well as a comparison against the individual limits proposed by the EN 50160 (planning levels). Figure 15 displays the THD at each MV distribution bus before and after the mitigation, and also the THD limit proposed by the EN 50160. Mitigation with an active harmonic filter and a dedicated transformer effectively canceled the targeted orders ($5^{th}$ and $7^{th}$). There was a reduction of $THD_u$ of 1.44% (system-wide) as well as 1.35% and 0.94% reduction on the harmonic orders $5^{th}$ and $7^{th}$, respectively. THD and all harmonic voltages are below the limits, only the $5^{th}$ is close to matching or exceeding its individual limit. A possible future expansion could potentially lead to surpass both the THD (system-wide) and individual limits (unacceptable harmonic distortion).

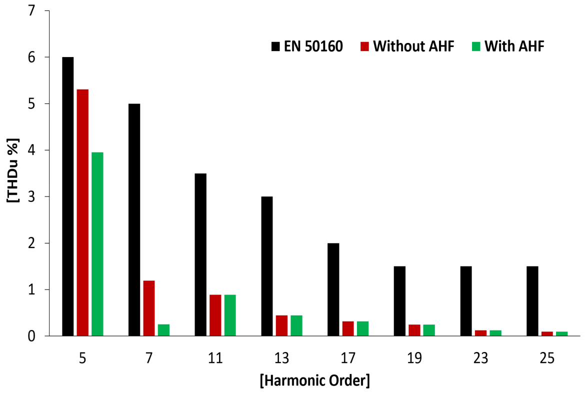

Figure 14: Harmonic voltage spectrum at bus 1M-A (MV Level)

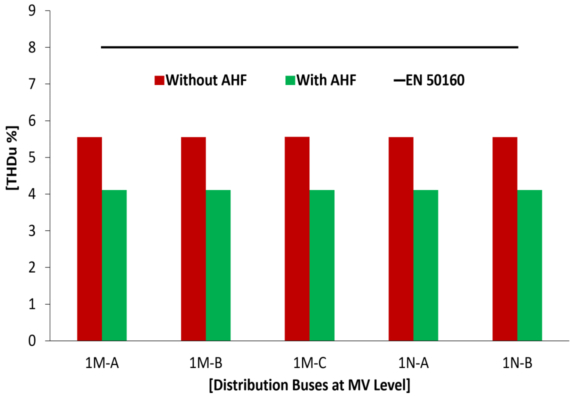

Figure 15: THDu% at each distribution bus (MV Level)

### 6.1.2 VFDs

As stated by DIgSILENT [30], the theoretical spectrum of rectifier is highly probable to result in higher harmonics than what would happen on real situations at any power system. Nevertheless, the theoretical spectra of the rectifier should provide a good basis for harmonic studies. This could explain why even when the spectra of both approaches are ”almost” the same, the VFD approach resulted in higher harmonic compensation by the mitigation device (Table 10). In this second approach, Figure 16 and 17, show the same parameters as in the previous results. The active harmonic filter and a dedicated transformer effectively canceled the targeted orders ($5^{th}$ and $7^{th}$). There was a reduction of THD$_u$ of 1.6% (system-wide) as well as 1.53% and 0.92% reduction on the harmonic orders $5^{th}$ and $7^{th}$, respectively. As expected, THD and all harmonic voltages are below the limits, only the $5^{th}$ is close to matching or exceeding its individual limit.

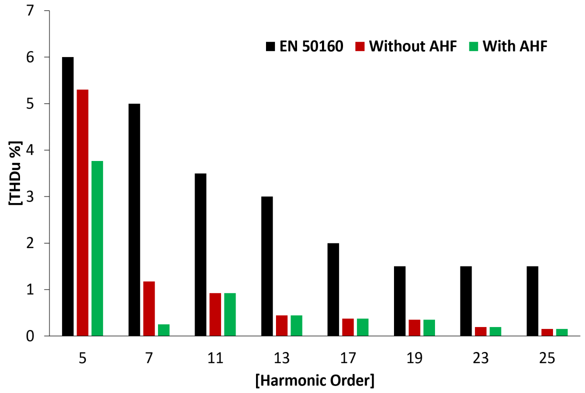

Figure 16: Harmonic voltage spectrum at bus 1M-A (MV Level)

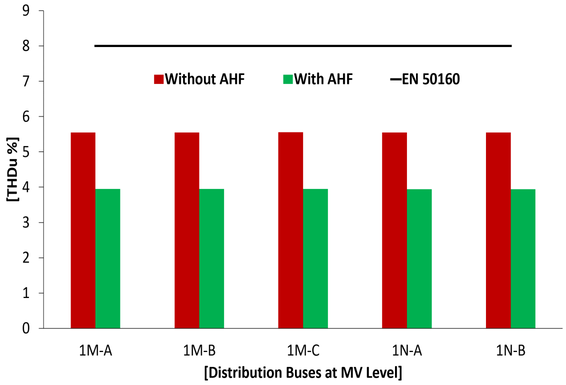

Figure 17: THDu% at each distribution bus (MV Level)

# 7 Benefits of Harmonic Management

Analysing both voltage and current in any installation will provide a good indication about possible overloading of components, unnecessary losses, energy used, reserve capacity, and many more important indicators. In this context, harmonics are often discussed where significant savings can be achieved along with the improvement of both power quality and electrical installation with the application of a harmonic mitigation technique. For this, it is important to understand the harmonics related losses. In any electrical network that contains no harmonic loads, the RMS current is equal to the fundamental current. But in a harmonics polluted network, the RMS current can be calculated with the following equation:

$$I_{RMS} = \sqrt{(I_1)^2 + (\sum_{h=2}^{n} I_1)^2} \tag{16}$$

From the equation above, it can be concluded that the RMS current in a harmonic polluted installation is higher than its value in a pure sinusoidal electrical network. This can lead to increased heat dissipation and deterioration of electrical equipment which may cause premature equipment failures and outages. The heat dissipation losses in electrical networks are calculated as the product of the square of the current by the system impedance. When the system has the presence of harmonic distortion, the total system losses are calculated by the summation of the individual losses at every harmonic frequency Equation 17 [40].

$$I^2 * Z = I_1^2 * Z_1 + I_2^2 * Z_2 + I_3^2 * Z_3 ... + I_n^2 * Z_n \tag{17}$$

Another problem that comes with harmonic losses is the additional temperature rise in the equipment which translates into a de-rate or limitation of an electrical equipment to work at the rated conditions for its specified lifetime. The effects of harmonics on electrical equipment cover a wide range of equipment such as generators, transformers, motors, capacitor banks, switch-gears, power cables, transmission lines, telecommunication systems and sensitive electronic devices [40][41].

To avoid the harmful effects of harmonic, managing harmonic content is vital to improve the energy efficiency in a new or existing installation. Improving this can lead to reduce energy consumption and energy cost paid to the utility operator, minimize the risk of outage and also sustain an efficient equipment operation (electronic waste reduction) (Table 11).

| **Aspects** | **Impacts** |
|---|---|
| Energy savings | Reduction of power losses in transformers, cables, switch-gear and motors |
| Energy cost optimization | Reduction on the demand power (MVA) (lower tariffs) |
| Availability & Reliability | Access to the total system capacity, without risk of overload or premature ageing of electrical equipment |

Table 11: Benefits of harmonic management

To define if harmonic management is required (PQ current status), it is needed to install devices that will measure the required parameters (e.g. quality monitor, voltage recorder, harmonic analyzer, portable quality analyzer, remote analyzer, etc.). Therefore, it is important to decide the installation site of such device, as it is not economically justified to cover the entire network with power quality monitors. The following flow chart simplified the justification of a power quality device installation in any electrical network [42].

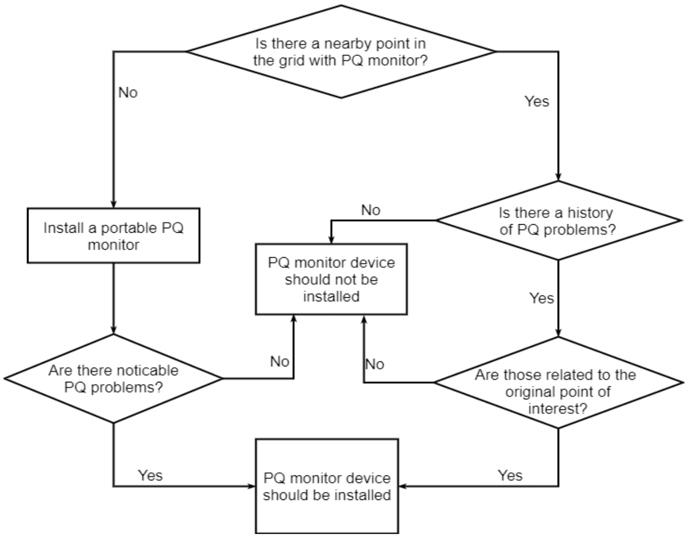

Figure 18: Flow chart - Decision making for PQ monitor installation

Based on the flow chart above, it is recommended to place a power quality monitor device at the distribution buses 1M-B, 1M-C, 1N-A and 1N-B (1M-A already has a PQ monitor device installed). This is based on the fact that the LV levels at these buses have a considerable amount of non-linear loads and active filters installed (power quality problems), but also due to the situation that the THDu levels at the MV level are increasing.

In Section 2, PQ standards were discussed. It is important to note that these only indicate emission limits and sometimes violating these does not lead to any penalties (e.g. economic fines). However, there is not yet a standard which establishes PQ limits and responsibilities at the customer's connection point. Nowadays, it is understandable that different customers demand different levels of power quality according to their needs. Therefore, network operators should be able to guarantee individual customer's needs. A solution for this could be power quality incentive schemes. Figure 19 shows the directions towards PQ regulations [43].

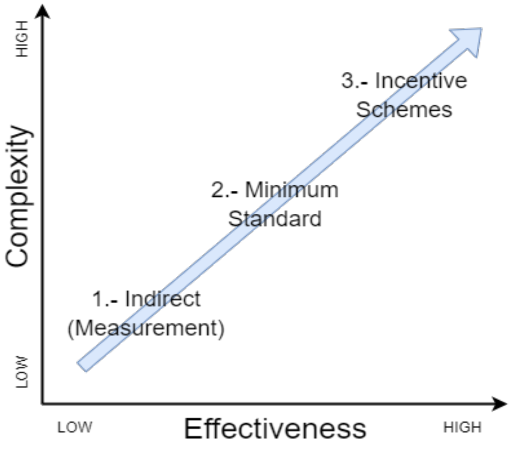

Figure 19: Towards PQ regulation

The first step is an indirect method where PQ monitor devices are continuously measuring the PQ aspects in the network. This will provide a comparison point to limit of the applicable PQ standards. Customer can be informed about the performance and power quality that they are getting from the network operator. The second step involves the developing of minimum standards for the networks power supply. This can be done by comparing several national and international standards to define the limiting values for each PQ parameter. Finally, the last step is used to introduce incentive schemes (penalty or reward) for the customers and network operators. This step is the most effective but also the most complicated one because it requires a customer which is educated more about the efficient usage of electricity and also because it requires a large number of PQ monitor devices within the network.

As already recommended in this section, PQ monitor devices should be installed within the network (important aspect for the third step towards PQ regulation). Incentive schemes have serious practical limitations [44]: (1) difficult to measure customer costs due to lack of quality and (2) collection of adequate and high-quality data. The first limitation involves a extensive research where these costs may differ from customer to customer. The second limitation is more serious as incentive schemes are based on the idea that the regulator has "good" information about the actual levels of power quality (input factor). This factor, determines the financial incentive based on the difference between the actual and the targeted performance. Therefore, without PQ monitor devices within the analyzed installation, the actual performance of the plant will not be known to a high degree of accuracy. As consequence, an incentive scheme may not be effective as the resulting financial incentive will be inaccurate. For this reason, good and reliable data is an important pre-condition for implementing an effective/accurate incentive scheme.

# 8 Conclusions and Future research

## 8.1 Conclusions from simulation results

**Simulation software**
DIgSILENT PowerFactory 2020 was used to construct a SLD interface, where all components and parameters could be accessed and specified. By means of DPL, results were defined and extracted with the use of coded scripts made for a specific simulation setup. Nevertheless, there are a few disadvantages when using this software due to its complexity. The user/designer must have experienced to get the true potential of the software. This based on the fact that PowerFactory has a wide-variety of tools as well as a very large number of parameters that can be included in a model. Depending on the application and type of model, it is vital to know what parameters are important for the simulation analysis. Also, there are several methods which might confused the user/designer. This potentially could lead to more difficult identification of possible sources of errors (extensive time-consuming debugging).

**Harmonic content methods**
The ideal current source method has several advantages. The harmonic content can be obtained directly (non-iterative), therefore, computationally efficient. In an ideal case, this method is able to handle several types of harmonic sources simultaneously. Nevertheless, one drawback is that typical harmonic spectra are often used to simulate the harmonic currents generated by power electronics by ignoring the interaction between the installation characteristics (network impedance) and the device. This could affect the assessment of cases which involve operating modes (e.g. partial load), excessive harmonic voltage distortion and unbalanced conditions. When the THDu of the harmonic source is equal or greater than 10%, the IEEE recommends to carefully apply this current injection method [25].

In the VFDs method, the DC loads were modeled as current source to obtain the real component behaviour of a motor. However, these loads could be modeled using an impedance model. The purpose of modeling these loads as harmonic current sources was to determine the correct current spectra. Their task was to guarantee a correct fundamental load current. The harmonic current spectra of this approach should be kept in mind when analyzing and discussing the results as is highly probable that on real situation harmonics are lower.

**Allocation of harmonic mitigation device**
The strategy can be done independently of the knowledge of the network impedance. Under the harmonic injection scenario in the analyzed network, a single bus was identified by the strategy as the most effective and efficient placement for an active harmonic filter. The location will protect sensitive loads and it will improve the quality of power at the MV distribution buses (system-wide). To verify its effectiveness, it could be analyzed implementing other mitigation techniques and different topologies.

**Mitigation approach - Genetic Algorithm**
To mitigate harmonics in the analyzed network, a method based on GA was applied to eliminate selected order of harmonics and to reduce the THD at the MV level. For this, the current and angles at the grid were considered as the basis for the mitigation. The GA was able to calculate the harmonics at the grid on each iteration and try to reduce them. Harmonic background could not be mitigated because it is at the other side of the grid, the code only worked for the mitigation within the industrial network. The results show that the method effectively minimized specific harmonics and reduced the harmonic distortion at the MV level. It is important to mention that such a reduction is possible in simulations but in real practice the AHF would not be able to mitigate the $5^{th}$ and $7^{th}$ according to the power system model, unless compensation capacity is increased or another solution such as possible parallel operation of active harmonic filters (search of available AHF in the market) is implemented.

**PQ monitoring**
Poor levels of power quality causes ”techno-economic” problems to transmission and distribution operators as well as end-users. Specially, harmonics can have a significant impact to end-users. The impacts go from

extra losses to efficiency/lifespan reduction. Depending of the situation, finding an optimal solution and defining PQ related responsibilities of the parties involved in the network is not an easy task. To solve this, power quality contracts (incentive schemes) can be implemented. Nevertheless, these suffer from the problem that measurement data is difficult to obtain and not always reliable. Therefore, to collect adequate and high quality data, it is advised to installed PQ monitor devices at representative locations within the network. This data also will allow to build a more accurate model of the installation, which can lead to a better design and specification of a mitigation technique.

**Real situation vs Simulation**

It is important to mentioned that there is a noticeable difference between the simulations and the PQ monitor device data. According to the simulations the harmonic spectrum is similar in both electric wiring (LV and MV), in other words, harmonic orders at secondary side of the transformers are getting reflected at the primary side. While in the data extracted from the PQ monitor device at bus 1M-A, harmonic orders $11^{th}$ and $13^{th}$ at the secondary side of the transformers are not getting reflected at the primary side. Simulations do not consider a harmonic cancellation effect, which could led to a harmonic reduction of those orders. There is not cancellation effect in the simulations due to the fact that only one type of harmonic source is considered. However when it would be considered different types of harmonic sources the $\text{THD}_i$ could be reduced since it would allow greater interaction of the different harmonics arriving at the MV level side of the installation (cancellation effect among themselves). This may lead to the same data extracted from the PQ meter installed on site.

## 8.2 Future research

Even when a method for conducting a harmonic analysis study in an industrial power system has been summarised and analyzed, future directions to improve and develop further this method can be identified:

- **Efficiency and cost of different harmonic mitigation techniques**: carry out an extensive economic/benefit analysis for suitable harmonic mitigation techniques to provide engineers, consultants and plant owners a tool to select the optimum economic mitigation technique. This must consider the complexity of the installation, maintenance and troubleshooting, mitigation device dimensions and physical space requirements, and market availability.
- **Mitigation device placement depending on the topology of the network**: investigate further the harmonic content of the installation depending on the type of topology. The topology has an influence on the resulting harmonic distortion as well as in the optimal location of the mitigation device. Currently, the analyzed industrial power system has a meshed topology which does not affect severely the best suitable location to improve the power quality system-wide. It is interesting to search the impact of the location of the mitigation device when the distribution buses are not interconnected.
- **Impact of possible future expansion**: to asses the impact of the meshed network topology, various loops should be added to the existing network. An expansion could increase or decrease the harmonic absorption capacity in the system as it might affect the average THDu in the entire installation.
- **Harmonic cancellation analysis**: to assess the cancellation effect that occurs due to phase angle dispersion between the same harmonic orders produced by different types of non-linear loads. This analysis is a complex problem, which is highly influenced by the composition of the aggregate loads and the network conditions/specifications (system impedance and voltage distortion).
- **Improvement of the simulation model**: based on data extraction from the new PQ monitor devices at the points of interest (MV level) suggested.

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# A Data

## A.1 Electrical variables

Data regarding the industrial loads was obtained from measurement and commissioning reports. These were carry out at each distribution board in which there is an active filter installed. This provided an insight into the power quality improvements by harmonic filters at LV levels. The summary of the commissioning results are displayed in Table 12, 13, 14, 15 and 16.

| **Distribution Board** | **Transformer** | **P [kW]** | **Q [kVAR]** | **PF** |
|---|---|---|---|---|
| 4-3-PZT01 | 01 | 24 | 3 | 0.95 |
| 4-3-PZT02 | 02 | 24 | 3 | 0.96 |
| 4-3-PZT03 | 03 | 24 | 3 | 0.96 |
| 4-3-PZT04 | 04 | 300 | 15 | 0.99 |
| 4-3-PZT05 | 05 | 444 | 27 | 0.99 |
| 4-3-PZT06 | 06 | 483 | 35.4 | 0.99 |

Table 12: PQ Measurement at Busbar 1M-A (LV side)

| **Distribution Board** | **Transformer** | **P [kW]** | **Q [kVAR]** | **PF** |
|---|---|---|---|---|
| 4-3-PZT07 | 07 | 124 | -3 | 0.99 |
| 4-3-PZT08 | 08 | 773 | 38.4 | 0.99 |
| 4-3-PZT09 | 09 | 848 | 40.4 | 1.0 |
| 4-3-PZT10 | 10 | 33.20 | 0 | 0.97 |

Table 13: PQ Measurement at Busbar 1M-B (LV side)

| **Distribution Board** | **Transformer** | **P [kW]** | **Q [kVAR]** | **PF** |
|---|---|---|---|---|
| 4-3-PZT11 | 11 | 29.1 | -2.6 | 0.98 |
| 4-3-PZT12 | 12 | 433 | 38.9 | 0.99 |
| 4-3-PZT13 | 13 | 368 | 49.87 | 0.99 |
| 4-3-PZT14 | 14 | 420 | 32.1 | 0.99 |
| 4-3-PZT15 | 15 | 845.6 | 46.9 | 0.99 |

Table 14: PQ Measurement at Busbar 1M-C (LV side)

| **Distribution Board** | **Transformer** | **P [kW]** | **Q [kVAR]** | **PF** |
|---|---|---|---|---|
| BTN-05I-211-HV-06 | 06 | 39 | 40 | 0.98 |
| BTN-05I-211-HV-07 | 07 | 28.80 | -0.3 | 0.99 |
| BTN-05I-211-HV-08 | 08 | 426.30 | 54 | 0.99 |
| BTN-05I-211-HV-09 | 09 | 36 | 4 | 0.97 |
| BTN-05I-211-HV-10 | 10 | 39 | 3 | 0.98 |
| BTN-05I-211-HV-22 | 22 | 360.80 | 29.80 | 0.99 |
| BTN-05I-211-HV-23 | 23 | 849 | 227.6 | 0.96 |

Table 15: PQ Measurement at Busbar 1N-A (LV side)

| **Distribution Board** | **Transformer** | **P [kW]** | **Q [kVAR]** | **PF** |
|---|---|---|---|---|
| BTN-05I-211-HV-01 | 01 | 136 | -9.0 | 0.99 |
| BTN-05I-211-HV-02 | 02 | 854.70 | 51.30 | 0.99 |
| BTN-05I-211-HV-03 | 03 | 28.80 | 0 | 0.94 |
| BTN-05I-211-HV-04 | 04 | 28.80 | 32 | 0.99 |
| BTN-05I-211-HV-05 | 05 | 28.80 | 3 | 0.95 |

Table 16: PQ Measurement at Busbar 1N-B (LV side)

## A.2 Harmonic Spectrum's

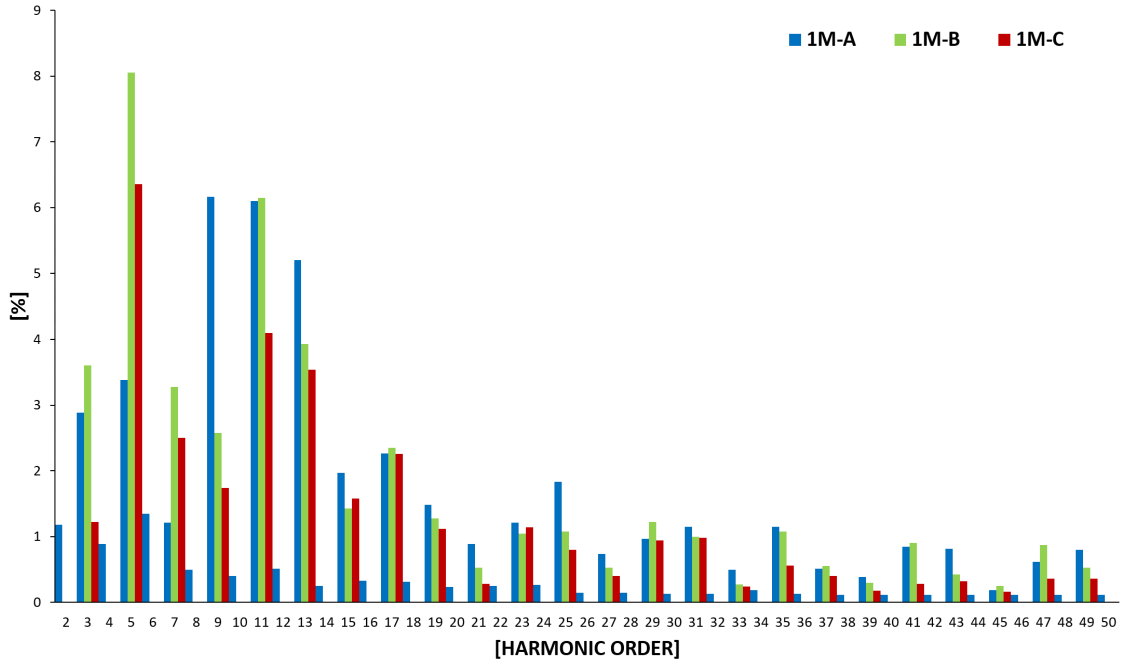

Figure 20: Harmonic current spectrum at LV side of a MV/LV transformer from distribution buses 1M-A, 1M-B and 1M-C

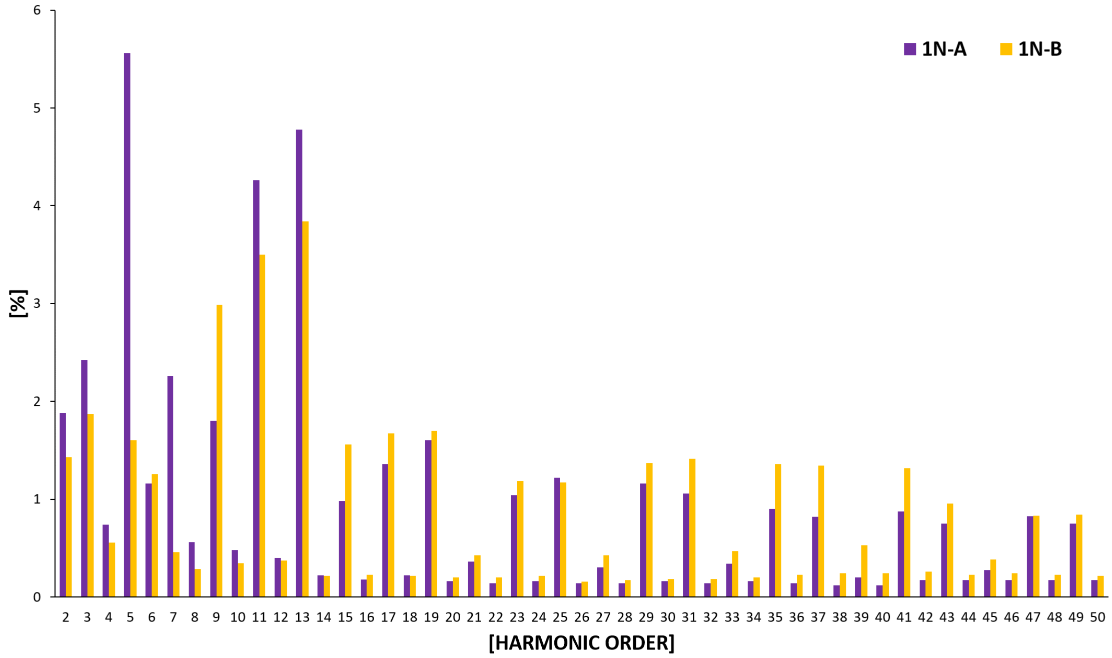

Figure 21: Harmonic current spectrum at LV side of a MV/LV transformer from distribution buses 1N-A and 1N-B

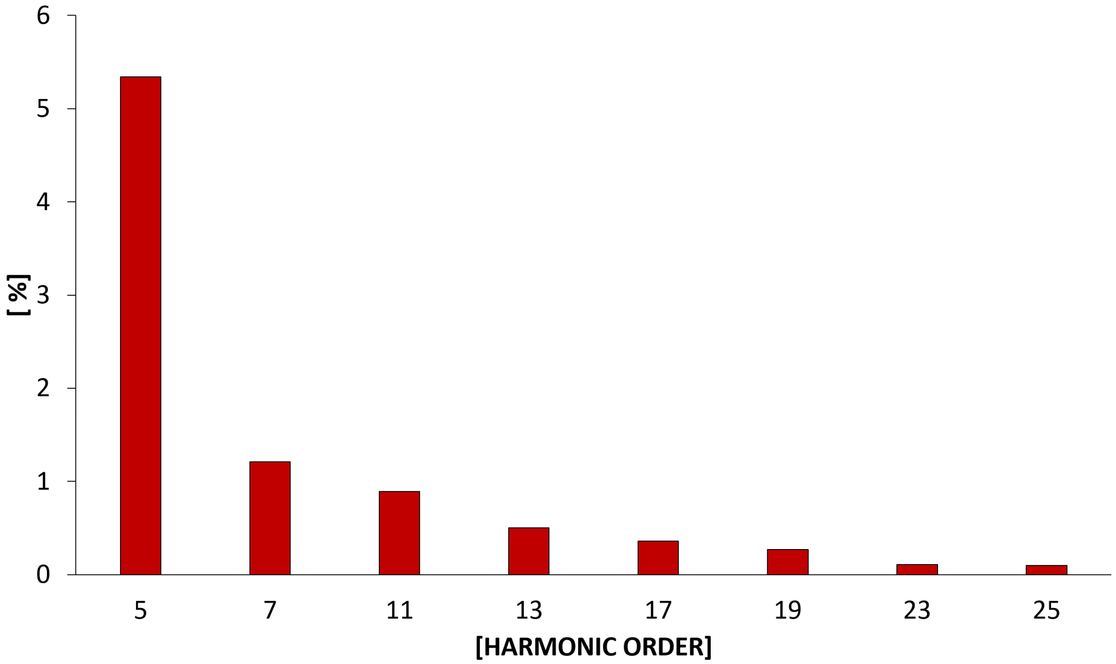

Figure 22: THD$_u$% spectrum extracted from PQ monitor device at distribution bus 1M-A [MV]

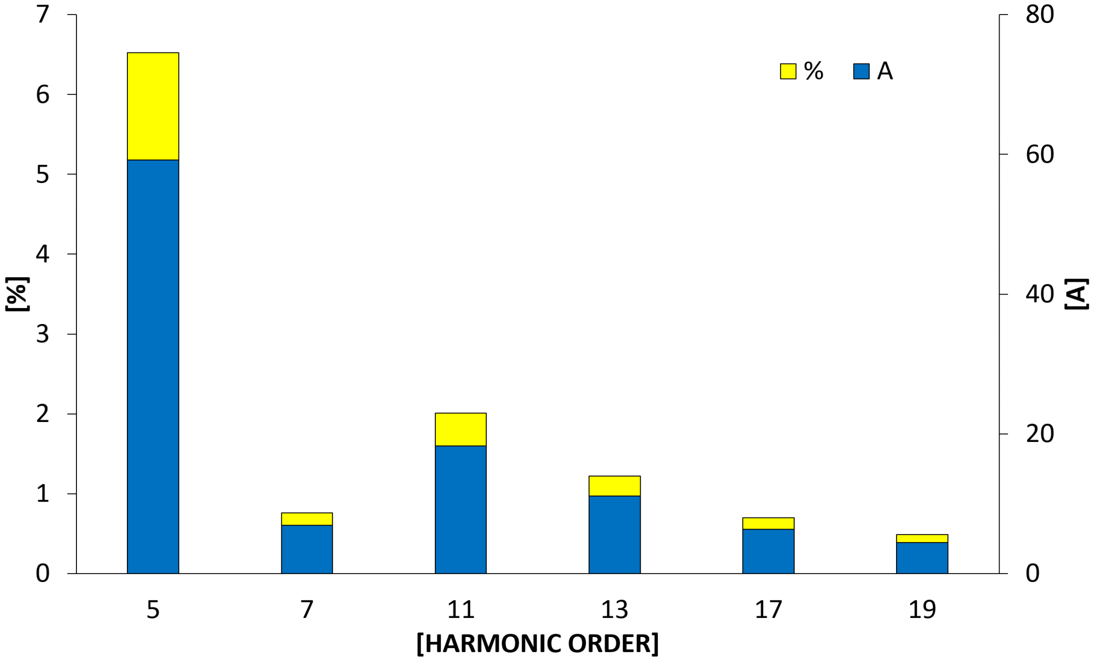

Figure 23: THD$_i$% spectrum extracted from PQ monitor device at distribution bus 1M-A [MV]

# B PowerFactory

## B.1 Calculation tools

### Load Flow

The "Load Flow" calculation tool is used in the designing process of the network. This allows to prevent overloading of cables and transformers, and to guarantee acceptable busbar voltages. For AC Load Flow calculations, PowerFactory uses the Newton-Raphson method to solve non-linear equations. As designer, two formulations choices were given: (1) current or (2) power equations. The selection of the method should be based on the type of network to be calculated. According to the topology, size and load classification of the system to be analyzed, the power equations are used which usually converge the best.

### Harmonic Load Flow

The "Harmonic Load Flow" tool is used to calculate harmonic voltages and currents. To use this tool, the designer has to defined in advance the harmonic sources within the system. Then based on these, PowerFactory is able to identify all harmonic orders present. On each harmonic order, a load flow calculation and impedance matrix is calculated due to the network impedance change. These calculations generated harmonic current and voltages spectra as well as THDu and THDi. This provides an overview of the harmonic conditions in the network.

### Frequency Sweep

With the previous tools (harmonic and load flow), PowerFactory only calculates the impedances for the relevant frequencies. To understand the network impedances of the whole system, a "Frequency Sweep" tool must be used. The designer defines the upper and lower limits (frequency) and the incremental step size for the calculation.

### DIgSILENT Programming Language (DPL)

DPL is an internal programming language that offers an interface for automating tasks in PowerFactory. The script language uses a syntax similar to the C++ programming language allowing designers to create tailored simulation tools. The project uses DPL to construct a simulations setup, for the harmonic and resonance analysis, which can be simulated through several network variations.

## B.2 Industrial Power System

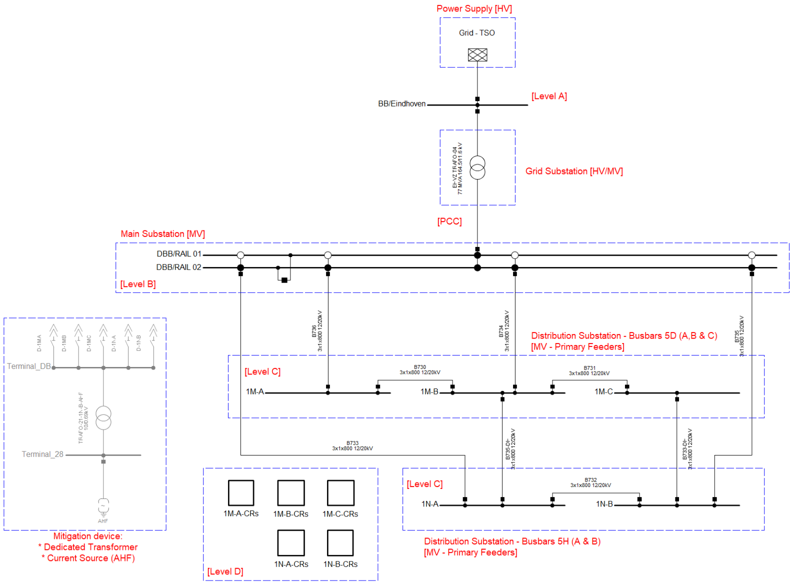

Figure 24: Industrial Power System - PowerFactory

## B.3 DIgSILENT Programming Language (DPL) - Scripts

Pseudo-codes (not suitable for compilation or execution) of the DPL scripts are presented as follow:

### B.3.1 Harmonic Load Flow and Frequency Sweep

```
!--------------------------------------------------------------------------------------------------!
!Harmonic Load Flow/Frequency Sweep - DPL Simualtion script

!J.L. Arellano Camacho
!Master thesis, Sustainable Energy Technology (SET)
!Research group: Electrical Energy System (EES)
!July, 2021
!--------------------------------------------------------------------------------------------------!

sRec = AllRelevant('*.ElmRecmono',0);     !Load all Recrifiers
nRec=sRec.Count();                        !Count number of rectifiers
sACC = AllRelevant('*.ElmIac',0);         !Load all Current Sources
nACC=sACC.Count();                        !Count number of current sources
sGrid = AllRelevant('*.ElmXnet');         !Load external grid in set sGrid
oGrid = sGrid.First();                    !Load object with external grid
Ldf=GetCaseObject('ComLdf');              !Access load flow object
SumGrid = SummaryGrid();                  !Load summary of grid!
sBus = AllRelevant('*.ElmTerm',0);        !Store all buses
sBus.SortToName(0);                       !Sort objects
sLine = AllRelevant('*.ElmLne');          !Stores all lines
sLine.SortToName(1);                      !Sort objects

!---------------------- Harmonic Analysis (Rectifiers) ----------------------!

if (nRec<>0) {            !If rectifiers are present
    ResetCalculation();
    ClearOutput();
    Lib = GetGlobalLib('TypHmccur');   !Stores harmonic types
    S = Lib.GetContents();             !Stores harmonic types
    hldf  = GetCaseObject('.ComHldf');   !Load hldf handle with harmonic load flow
    comres = GetCaseObject('.ComRes');   !Load comres handle with result file
    comres:iopt_exp = 6;
    comres:iopt_csel = 0;
    comres:from = 2;
    comres:to = 49;

    sheet=1;
    num=0;
    for (oRec=sRec.First(); oRec; oRec=sRec.Next()) {      !Access each rectifier
         err=xlStart();
         if(err){
            printf('Error: Unable to start MS Excel application');
            exit();
            }
         xlNewWorkbook();
         if(err){
            printf('Error: Unable to open Excel file');
            xlTerminate();
            exit();
            }
         num+=1;
         RecName = oRec:loc_name;      !Access rectifier name
         Rec = oRec:phmc:TypHmccur;
```

```
        if (oRec:i_int=1){
            oRec:i_int=0;
            }
        O = S.FirstFilt('6-Pulse Bridge (B6)'); !Obtain 6 pulse bridge
                !sheet+=1;
                oRec:phmc:TypHmccur =O;     !Sets 6 pulse bridge rectifier
                str1 = O:loc_name;          !Stores harmonic source name
                ResetCalculation();
                hldf.Execute();
                xlActivateWorksheet(sheet);            !Activates worksheet
                xlSetWorksheetName ( sheet, str1 );    !Sets worksheet name
                xlSetValue(1,1,'Bus ID');              !Sets excel cell with string
                xlSetValue(2,1,'THD %');
                xlSetValue(3,1,'HD %');
                xlSetValue(4,1,'RMS Voltage (pu)');
                row=2;
                for (oBus=sBus.First(); oBus; oBus=sBus.Next()) {     !Loop through each bus
                      busname = oBus:loc_name;     !Stores bus name in string busname
                      THD = oBus:m:THD;
                      HD  = oBus:m:HD;
                      Urms = oBus:m:urms;
                      xlSetValue(1,row,busname);    !Sets excel cell with busname
                      xlSetValue(2,row,THD);
                      xlSetValue(3,row,HD);
                      xlSetValue(4,row,Urms);
                      row+=1;
                      }    !End of loop for buses
                xlAddWorksheet ();
                comres:f_name = sprintf... !Sets result file name
                ('C:\\Results\\Harmonic Analysis\\HA Rectifier %d %s.csv',num,str1);
                comres.Execute();      !Runs results file
         !Sets back original harmonic source in rectifier under study
        oRec:phmc:TypHmccur =Rec;
        xlDeleteWorksheet(1);
        FileName = sprintf...
        ('C:\\Results\\Harmonic Analysis\\HA Rectifier %d.xlsx',num);    !Sets file name
        err = xlSaveWorkbookAs(FileName);
        if (err) {      !If error in saving the excel file
            Error('Workbook could not be saved');
            }
        xlTerminate();    !Terminates excel control
        }                 !End of Main For Loop for nRec
    }                     !End of nRec If Statement

!----------------------- Harmonic Analysis (Current Sources) -----------------------!

if (nACC<>0) {        !If current sources exists
    ResetCalculation();
    ClearOutput();
    Lib = GetGlobalLib('TypHmccur');       !Stores harmonic sources in Lib
    S = Lib.GetContents();                 !Stores harmonic sources in set S
    hldf  = GetCaseObject('.ComHldf');     !Load harmonic load flow handle
    comres = GetCaseObject('.ComRes');     !Load results handle
    comres:iopt_exp = 6;                   !Sets result file properties
    comres:iopt_csel = 0;
    comres:from = 2;
    comres:to = 49;

    sheet=1;
```

```
    num=0;
    for (oACC=sACC.First(); oACC; oACC=sACC.Next()) { !Loop through every source current
         err=xlStart();
         if(err){
            printf('Error: Unable to start MS Excel application');
            exit();
            }
         xlNewWorkbook();
         if(err){
            printf('Error: Unable to open Excel file');
            xlTerminate();
            exit();
            }
         num+=1;
         ACCName = oACC:loc_name;        !Stores current source
         ACC = oACC:phmc:TypHmccur;      !Stores harmonic current source
         O = S.FirstFilt('Userdefined');          !Current source
                !sheet+=1;
                oACC:phmc:TypHmccur =O;     !Sets harmonic current source type
                str1 = O:loc_name;          !Stores name of harmonic current source type
                ResetCalculation();
                hldf.Execute();
                xlActivateWorksheet(sheet);
                xlSetWorksheetName ( sheet, str1 );
                xlSetValue(1,1,'Bus ID');      !Sets bus ID in excel cell
                xlSetValue(2,1,'THD %');
                xlSetValue(3,1,'HD %');
                xlSetValue(4,1,'RMS Voltage (pu)');
                row=2;
                for (oBus=sBus.First(); oBus; oBus=sBus.Next()) {    !Loop through every bus
                      busname = oBus:loc_name;    !Stores bus name
                      THD = oBus:m:THD;
                      HD  = oBus:m:HD;
                      Urms = oBus:m:urms;
                      xlSetValue(1,row,busname);    !Sets busname in excel cell
                      xlSetValue(2,row,THD);
                      xlSetValue(3,row,HD);
                      xlSetValue(4,row,Urms);
                      row+=1;
                      }     !End of loop for buses
                xlAddWorksheet ();
                comres:f_name = sprintf...
                ('C:\\Results\\Harmonic Analysis\\HA Current Source %d %s.csv',num,str1);
                comres.Execute();      !Runs results file
         oACC:phmc:TypHmccur =ACC;      !Set back original harmonic current source type
         xlDeleteWorksheet(1);            !deletes extra worksheet from excel
         FileName = sprintf('C:\\Results\\Harmonic Analysis\\HA Current Source %d.xlsx',num);
         err = xlSaveWorkbookAs(FileName);     !saves workbook with filename
         if (err) {
             Error('Workbook could not be saved');
             }
         xlTerminate();
         }      !End of Main For Loop for nRec
    }           !End of nRec If Statement

!----------------------------- Resonance with line length variation -----------------------------!

FS=GetCaseObject('ComFsweep');
FS:iopt_net=0;
```

```
FS:fstart=0.1  ;
FS:fstop=2500   ;
FS:fstep=0.5   ;
FS:i_adapt  =0;
comres = GetCaseObject('.ComRes');
comres:iopt_exp = 6;
comres:iopt_csel = 0;
oLine = sLine.FirstFilt('E734*.ElmLne');
length=oLine:dline;
printf('Original Length Found = %.3f',length);
L.Init(7,1,0);
L.Set(1,1,length-3);
L.Set(2,1,length-2);
L.Set(3,1,length-1);
L.Set(4,1,length);
L.Set(5,1,length+1);
L.Set(6,1,length+2);
L.Set(7,1,length+3);
linename = oLine:loc_name;
for (i=1; i<=7; i=i+1){
      Mag=L.Get(i,1);
      printf('Now processing length %.3f....',Mag);
      oLine:dline=Mag;
      ResetCalculation();
      FS.Execute();
      comres:f_name = sprintf('C:\\Results\\Freq Sweep\\%s %.3f.csv',linename,Mag);
      comres.Execute();
      }
oLine:dline=length;

!------------------------ Frequency Sweep Analysis (Rectifiers) ------------------------!

if (nRec<>0) {          !If rectifiers exist
    ResetCalculation();
    ClearOutput();
    Lib = GetGlobalLib('TypHmccur');      !Load type of harmonic sources library
    S = Lib.GetContents();                !Loads set S with harmonic sources type
    FS=GetCaseObject('ComFsweep');       !Accessing frequency sweep analysis
    comres = GetCaseObject('.ComRes');   !Make comres handle for resutls
    comres:iopt_exp = 6;        !Sets result properties
    comres:iopt_csel = 0;
    num=0;
    for (oRec=sRec.First(); oRec; oRec=sRec.Next()) {  !Loop through every rectifer
         err=xlStart();
         if(err){
            printf('Error: Unable to start MS Excel application');
            exit();
            }
         xlNewWorkbook();
         if(err){
            printf('Error: Unable to open Excel file');
            xlTerminate();
            exit();
            }
         num+=1;
         RecName = oRec:loc_name;        !Store rectifer name
         Rec = oRec:phmc:TypHmccur;      !Sets harmonic source type
         if (oRec:i_int=1){         !If ideal
              oRec:i_int=0;         !Then set userdefined
```

```
            }
        O = S.FirstFilt('6-Pulse Bridge (B6)'); !Filters 6 pulse rectifier
                !Sets rectifier with Object for harmonic source type
                oRec:phmc:TypHmccur =O;
                str1 = O:loc_name;      !Stores type name
                FS.Execute();           !Executes frequency sweep analysis
                comres:f_name = sprintf...
                ('C:\\Results\\Frequency Sweep Analysis\\...
                Freq Sweep %d %s.csv',num,str1);
                comres.Execute();   !Stores results
        oRec:phmc:TypHmccur =Rec; !Sets harmonic source type
        }      !End of Main For Loop for nRec
    }          !End of nRec If Statement

!-------------------- Frequency Sweep Analysis (Current source) --------------------!

if (nACC<>0) {
    ResetCalculation();
    ClearOutput();
    Lib = GetGlobalLib('TypHmccur');      !Load type of harmonic sources library
    S = Lib.GetContents();                !Loads set S with harmonic sources type
    FS=GetCaseObject('ComFsweep');        !Accessing frequency sweep analysis
    comres = GetCaseObject('.ComRes');    !Make comres handle for resutls
    comres:iopt_exp = 6;
    comres:iopt_csel = 0;
    num=0;
    for (oACC=sACC.First(); oACC; oACC=sACC.Next()) {!Loop through every current source
         err=xlStart();
         if(err){
            printf('Error: Unable to start MS Excel application');
            exit();
            }
        xlNewWorkbook();
         if(err){
            printf('Error: Unable to open Excel file');
            xlTerminate();
            exit();
            }
        num+=1;
        ACCName = oACC:loc_name;         !Store current source name
        ACC = oACC:phmc:TypHmccur;       !Sets harmonic source type
        O = S.FirstFilt('Userdefined');
                oACC:phmc:TypHmccur =O;
                str1 = O:loc_name;
                FS.Execute();      !Executes frequency sweep analysis
                comres:f_name = sprintf...
                ('C:\\Results\\Frequency Sweep Analysis\\...
                %s Freq Sweep %d %s.csv',ACCName,num,str1);
                comres.Execute();
        oACC:phmc:TypHmccur =ACC;
        }      !End of Main For Loop for nRec
    }          !End of nRec If Statement

!End of DPL Script
!-----------------------------------------------------------------------------------!
```

### B.3.2 Genetic Algorithm (GA)

```
!----------------------------------------------------------------------------------!
!Genetic Algorithm GA - DPL Simualtion script

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!Research group: Electrical Energy System (EES)
!July, 2021
!----------------------------------------------------------------------------------!


sACC = AllRelevant('*.ElmIac',1);         !Stores all AC current sources in sACC set
oACC = sACC.FirstFilt('AHF*.ElmIac');     !Stores the mitigation device in oACC object
nACC=sACC.Count();                        !Counts number of AC Current Sources
oACC:Ir = R_Curr;                         !Sets the rated current of mitigation device
oACC:icurref = 1;                         !Sets h. current reference of mitigation device
sGrid = AllRelevant('*.ElmXnet');         !Stores Grid in set sGrid
oGrid = sGrid.First();                    !Stores the only grid in oGrid object
oGrid:iHmcType=1;                         !Disable Harmonic Background
hldf  = GetCaseObject('.ComHldf');        !Access harmonic load flow object

!-------------------------- Balanced/Unbalance Type --------------------------!

if (Type=0) {              !If balanced --> balanced harmonics
    hldf:iopt_net = 0;     !Set harmonic load flow to balanced type
    Mit:i_usym = 0;        !Set mitigation device to balanced type
    Mit.GetSize('kbal',size);
    for (i=0; i<size; i+=1) {
         Mit.SetVal(0,'kbal',i);
         Mit.SetVal(0,'cbal_phase',i);
         }
    }
else{        !Unbalanced harmonics
    hldf:iopt_net = 1;
    Mit:i_usym = 1;
    Mit.GetSize('ifreqs',size); !Get size of mitigation device matrix
    for (i=1; i<=size; i+=1) {
         Mit.SetVal(i,'ifreqs',i-1);
         Mit.SetVal(0,'ka',i-1);
         Mit.SetVal(0,'kb',i-1);
         Mit.SetVal(0,'kc',i-1);
         Mit.SetVal(0,'ca_phase',i-1);
         Mit.SetVal(0,'cb_phase',i-1);
         Mit.SetVal(0,'cc_phase',i-1);
         }
    }
comres = GetCaseObject('.ComRes');    !Access results object
comres:iopt_exp  = 6;                 !Export All variables in result file
oACC:phmc:TypHmccur = Mit;
oRec = sRec.First();

ResetCalculation();
hldf.Execute();
case = GetActiveStudyCase(); ! Get active study case
if (case) {
    aFiles = case.GetContents('*.ElmRes'); !Get all ElmRes inside active case
    Nfiles = aFiles.Count();
    if (Nfiles>0) {
```

```
check=1;
for (res=aFiles.First(); res; res=aFiles.Next()) {
      str = res:loc_name;
      check = strcmp(str,'Harmonics');
      if (check=0){
           break;
           }
      }
 for (H=3; H<=LHO; H+=1)  {
      rem = modulo(H,2);
      H_index=H-1;             !Set H_index variable to access result from result file
      if (rem =0)              !Skip even harmonic orders
           continue;
      if (Type=0){             !If balanced harmonics
           check=0;
           for (i=1; i<=16; i+=1){   !Finds the index of balanced harmonic order
                 HO=Hrm_Index.Get(i,2);
                  if (H==HO){
                      check=1;
                      !Store the index of harmonic order stored in Hrm_Index Matrix
                      index = Hrm_Index.Get(i,1);
                      H_index=index+1;
                      break;
                      }
                  }
           if (check=0)    !If harmonic order is not balanced then skip that order
                continue;
           }
      printf('Harmonic Order= %d',H);

      !Mitigation device OFF state (for calculating the base harmonic current)
      oACC:outserv=1;
      ResetCalculation();
      hldf.Execute();
      LoadResData(res);     !Load result file data
      c = ResIndex(res, oGrid, 0);  !Search index of the result related to grid
      err = GetResData(HC,res,H_index,c);  !Picks h. current magnitude @H_index
      printf('HC = %.3f',HC);
      if (HC <=0.09) continue;    !If HC is less than 0.09 magnitude then skip

      !----------------------------------------------------------------------!
      !---------------------- Population Generation -------------------------!
      !----------------------------------------------------------------------!

      if (Type=0){                !If balanced type
            LL = 0.1;               !set lower limit
            UL = (HC*2/0.4)*10000/R_Curr;     !set upper limit
           }
      else{                 !If unbalanced type
            LL = 0.1;
            UL = (HC*1.75/0.4)*10000/R_Curr;       !Set upper limit
            }
      !Population Generation for percentage of harmonic injection current
      for (i=1; i<=Population_Size; i+=1) {
            Ran_Mag = Random(LL,UL);
            A.Set(i,1,Ran_Mag);
            }
      for (i=1; i<=Population_Size/4; i+=1) {
            Ran_Ang = Random(0.1,359.9);
```

```
     A.Set(i,2,Ran_Ang);
     }
!Population Generation for angles
for (i=(Population_Size/4)+1; i<=Population_Size/2; i+=1) {
     Ran_Ang = Random(-0.1,-359.9);
     A.Set(i,2,Ran_Ang);
     }
for (i=(Population_Size/2)+1; i<=Population_Size; i+=1) {
     Ran_Ang = Random(-0.1,-110);
     A.Set(i,2,Ran_Ang);
     }
oACC:outserv=0;  !Switch On Mitigation Device
p2=0; P=0; p=0;

for (i=1; i<=Population_Size; i+=1) {  !Loop - Evaluation of each pair
     Mag1=A.Get(i,1);   !Get % of harmonic injection current (Matrix A)
     Ang1=A.Get(i,2);   !Get angle from Matrix A
     if (Type=0){
         Mit.SetVal(Mag1,'kbal',index); !Set magnitude of m. device
         Mit.SetVal(Ang1,'cbal_phase',index); !Set angle of m. device
         }
     else {
         Mit.SetVal(Mag1,'ka',H-1);  !Set magnitude of m. device
         Mit.SetVal(Mag1,'kb',H-1);
         Mit.SetVal(Mag1,'kc',H-1);
         Mit.SetVal(Ang1,'ca_phase',H-1);  !Set angle of m. device
         Mit.SetVal(Ang1,'cb_phase',H-1);
         Mit.SetVal(Ang1,'cc_phase',H-1);
         }
       hldf.Execute();    !Execute harmonic Load flow
       LoadResData(res); !Load result file data
       err = GetResData(Mag,res,H_index,c);  !Get magnitude of h. current
       A.Set(i,3,Mag);  !Store magnitude of h. current in matrix A
       p1=A.Get(i,3);   !Get latest h. current magnitude from A & store in p1
       if (i>1)      !If i>1 store magnitude in p2
           p2= A.Get(i-1,3);
       if (p1-p2<=0.0001)  !If difference between adjacent 2 magnitudes
           P+=1;    !Increase P by 1
       else
           P=0;     !Re-Initialize P with 0
       if (P>=6){ !If no change in resultant h. current mag. terminate code
           printf('This order couldnt be mitigated. Moving to Next Order');
           p=1;
           break;  !Breaks the loop if P>=6
           }
       }          !End of for loop for evaluation of each pair

 err = A.SortToColumn(3);  !Sort Popul. Matrix A with Column 3 low to high
 N=1;
 for (iter=1; iter<=Num_iter; iter+=1) {     !For loop for iterations
      if (p=1)   !if there is no change in adjacent six magnitudes
          break; !terminates the order loop
      printf('Iteration No: %d',iter); !Prints iteration number

!-----------------------------------------------------------------------!
!----------- Offspring Generation (Cross Over) -------------------------!
!-----------------------------------------------------------------------!

     !Cross over of some population
```

```
      for (i=1; i<=Population_Size/4; i+=1) {
            !Generates random number from population indices
            Ran = Random(1,Population_Size/4);
            !Get random % of h. injection current
            Mag1=A.Get(Ran,1);
            !Generates random number from population indices
            Ran = Random(1,Population_Size/4);
            Ang1=A.Get(Ran,2);                         !Get random angle
            !Set random % of h. injection current at random index in matrix A
            A.Set(i+Population_Size/4,1,Mag1);
            !Set random     at random index in matrix A
            A.Set(i+Population_Size/4,2,Ang1);
            }
      !Cross over of some population with small variation
      for (i=1; i<=Population_Size/2-2; i+=2) {
            Mag1=A.Get(i,1);
            Ang1=A.Get(i,2);
            A.Set(i+Population_Size/2,1,Mag1+8);
            A.Set(i+Population_Size/2,2,Ang1+0.1);
            A.Set(i+1+Population_Size/2,1,Mag1+5);
            A.Set(i+1+Population_Size/2,2,Ang1+0.2);
            }
!-------------------------------------------------------------------------!
!------------------------------ Mutation ---------------------------------!
!-------------------------------------------------------------------------!
  !Random mutation which changes some % h. injection current
  !... &    with small amounts
      for (i=1; i<=Population_Size/4; i+=1) {
            !Generates random index of population entry
            Ran = Random(Population_Size/6,Population_Size);
            !Get random % of h. injection current
            Mag1=A.Get(Ran,1);
            !Mutate randomly accessed % h. injection current with subtracting
            A.Set(Ran,1,Mag1-15);
            Ran = Random(Population_Size/4,Population_Size);
            !Mutate randomly accessed angle with subtracting
            Ang1=A.Get(Ran,1);
            A.Set(Ran,1,Ang1+1);
            }
      for (i=1; i<=Population_Size/20; i+=1) {
            Mag1=A.Get(i,1);     !Get random % h. current
            Ang1=A.Get(i,2);     !Get random angle
            !Subtract from random % h. current
            A.Set(i+Population_Size/2,1,Mag1-0.5);
            !Add in random angle
            A.Set(i+Population_Size/2,2,Ang1+7);
            }
            Mag1=A.Get(i,1);
      for (i=1; i<=10; i+=1) {
            Ang1=A.Get(i,2);
            Ran = Random(Population_Size/2,Population_Size);
            !Add in random percent harmonic current
            !Subtract from random angle
            A.Set(Ran,1,Mag1+0.2);
            A.Set(Ran,2,Ang1-0.1);
            Ran = Random(Population_Size/2,Population_Size);
            A.Set(Ran,1,Mag1-0.1);
            A.Set(Ran,2,Ang1+0.1);
            Ran = Random(Population_Size/2,Population_Size);
```

```
           A.Set(Ran,1,Mag1+0.8);
           A.Set(Ran,2,Ang1-0.01);
           Ran = Random(Population_Size/2,Population_Size);
           A.Set(Ran,1,Mag1-0.4);
           A.Set(Ran,2,Ang1+0.01);
           }
!----------------------------------------------------------------------!
!------------------------------ Evaluation ----------------------------!
!----------------------------------------------------------------------!
!It evaluates all population entries with simulating harmonic load flow
      for (i=1; i<=Population_Size; i+=1) {
           Mag1=A.Get(i,1);      !Get magnitude from matrix A's ith index'
           if (Mag1<0){       !If % of harmonic injection current
           !Re-Initalize that % with random number between lower and upper limit
               Ran_Mag = Random(LL,UL);
               A.Set(i,1,Ran_Mag);
               }
           Ang1=A.Get(i,2);
           if (Type=0){
               Mit.SetVal(Mag1,'kbal',index);
               Mit.SetVal(Ang1,'cbal_phase',index);
               }
           else {
                 Mit.SetVal(Mag1,'ka',H-1);
                 Mit.SetVal(Mag1,'kb',H-1);
                 Mit.SetVal(Mag1,'kc',H-1);
                 Mit.SetVal(Ang1,'ca_phase',H-1);
                 Mit.SetVal(Ang1,'cb_phase',H-1);
                 Mit.SetVal(Ang1,'cc_phase',H-1);
                 }
           ResetCalculation();
           hldf.Execute();
           LoadResData(res);
           !Stores resultant magnitude of H. current
           err = GetResData(Mag,res,H_index,c);
           A.Set(i,3,Mag);
           }
      err = A.SortToColumn(3);     !Sort the matrix A with column 3
      N_Value=A.Get(1,3);    !Stores smallest value of resultant magnitude
      printf('Current Stage Best Value = %.3f',N_Value);
      if (iter=Num_iter) {    !If current iteration = to total number iterations
          Mag=A.Get(1,3);   !Get lowest resultant h. current
      !If lowest resultant h. current is greater than the mag. in base case...
      !(without mitigation device)
          if (Mag>HC) {
              if (N<=1){       !If there is no rolling back executed before
                 N+=1;         !Increase rolling back variable by 1
                 iter=0;       !Set back the iteration to zero
                 printf('Rolling back') ;
       !Re-Initialization of population matrix while retaining 1st 10 results
                 for (i=10; i<=Population_Size; i+=1) {
                      Ran_Mag = Random(LL-10,UL+10);
                      A.Set(i,1,Ran_Mag);
                      }
                 for (i=10; i<=Population_Size/4; i+=1) {
                      Ran_Ang = Random(0.1,359.9);
                      A.Set(i,2,Ran_Ang);
                      }
                 for (i=(Population_Size/4)+1; i<=Population_Size/2; i+=1) {
```

```
                                  Ran_Ang = Random(-0.1,-359.9);
                                  A.Set(i,2,Ran_Ang);
                                  }
                              for (i=(Population_Size/2)+1; i<=Population_Size; i+=1) {
                                  Ran_Ang = Random(-0.1,-110);
                                  A.Set(i,2,Ran_Ang);
                                  }
                              }
                          }
                      }
              }  ! End of Iteration loop

             err = A.SortToColumn(3);    !Sorting population matrix A with 3rd column
             Mag1=A.Get(1,1);     !Taking 1st entry % h. current (which is the best result)
             Ang1=A.Get(1,2);     !Taking 1st entry angle (which is the best result)
             N_Value=A.Get(1,3);   !Stores 1st resultant magnitude
             if (Type=0){    !If balanced harmonic load flow
             !If % h. current is greater than zero and lowest resultant...
             !magnitude is less than base magnitude
                 if ({Mag1>0}.and.{N_Value<HC}.and.p=0){
                 printf('Following Current and Angle has been set for Mitigation of
                 ...%d Harmonic Order',H);
                 printf('Current Set at %.3f',Mag1);
                 printf('Angle Set at %.3f',Ang1);
                      }
                 else
                   {  Mag1=0; Ang1=0;     }
                 Mit.SetVal(Mag1,'kbal',index);
                 Mit.SetVal(Ang1,'cbal_phase',index);
                 }
             else {    !If unbalanced harmonic load flow
                   if ({Mag1>0}.and.{N_Value<HC}.and.p=0){
                 printf('Following Current and Angle has been set for Mitigation of
                 ...%d Harmonic Order',H);
                 printf('Current Set at %.3f',Mag1);
                 printf('Angle Set at %.3f',Ang1);
                       }
                   else
                     {  Mag1=0; Ang1=0;  }
                   Mit.SetVal(Mag1,'ka',H-1);
                   Mit.SetVal(Mag1,'kb',H-1);
                   Mit.SetVal(Mag1,'kc',H-1);
                   Mit.SetVal(Ang1,'ca_phase',H-1);
                   Mit.SetVal(Ang1,'cb_phase',H-1);
                   Mit.SetVal(Ang1,'cc_phase',H-1);
                   }
             printf('\n');
             }  !End of Harmonic Order Loop
        }
        else {Warn('There are no result files stored in the active study case');}
    }
    else {Warn('There is no active study case');}
oACC:outserv=0;     !After setting the best results in mitigation device turn it ON
EchoOn();
hldf.Execute();     !Executes load flow
oGrid:iHmcType=0;

!End of DPL Script
!-------------------------------------------------------------------------------------!
```

# C Definitions

For the purpose of this thesis (harmonic analysis), the following terms and definitions apply. The definitions are extracted from the IEEE std.519 [45].

- **Harmonic**: a sinusoidal component of a periodic wave or quantity having a frequency that is an integral of multiple of the fundamental frequency.
- **Fundamental (component)**: component of an order 1 (e.g. 50 Hz, 60 Hz) of the Fourier series of a periodic quantity.
- **Harmonic (component)**: component of order greater than one of the Fourier series of a periodic quantity. For example, in a 50 Hz system, the harmonic order 3, also known as the third harmonic, is 150 Hz.
- **Point of Common Coupling (PCC)**: point on a public power system, electrically nearest to a particular load, at which other loads are, or could be, connected. It is a point located upstream of the considered installation.
- **Short circuit ratio**: at a particular location, the ratio of the available short circuit current to the load current.
- **Power Quality**: the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment.
- **Voltage distortion**: any deviation from the nominal sine wave form of the AC line voltage.
- **Cable**: a conductor with insulation, or a stranded conductor with or without insulation and other coverings (single conductor cable) or a combination of conductors insulated from one another (multiple conductor cable).
- **Substation**: an enclosed assemblage of equipment (e.g. switches, circuit breakers, buses, and transformers) under the control of qualified persons, through which electric energy is passed for the purpose of switching or modifying its characteristics to increase or decrease voltage or control frequency or other characteristics.
- **Utility**: an organization responsible for the engineering and supervision (design, construction, operation, and maintenance) of a public or private electric supply.
- **Transmission system**: an interconnected group of electric transmission lines and associated equipment for the movement or transfer of electric energy between points of supply and points for delivery.