STUDY OVER THE HARMONIC EFFECTS IN ELECTRICAL DISTRIBUTION NETWORKS

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This paper analyses the implementation of modern remedial measures to current, and voltage distortion problems generated by power nonlinear industrial loads. For these types of heavily polluted consumers, traditional solutions such as passive or hybrid filters are not suited. Consequently, the active harmonic filters (AHF) are the only pieces of equipment to be considered. Their proper selection is attained only after performing an adequate power quality audit of the main electric parameters at the main low voltage switchboards. The paper presents an AHF-based solution for nonlinear industrial load which reduces the current and voltage harmonics. The solution is validated by harmonics measurements before and after AHF installation.

Keywords: active harmonic filters (AHF), nonlinear industrial load, power quality audit.

1. Introduction

Global trends and factors impacting the power quality (PQ) markets can be synthesized as follows [1]:

1. Technological
   - Active technologies (IGBT-based) are increasing and becoming more commercially accessible (est. 4-5% cost reduction year over year)
   - Electronic Var Compensation Systems are replacing conventional passive technologies.
2. Change in nature of loads:
   - Modernization push towards increased energy efficiency is leading to increased electronics, thereby causing fast changing load pattern and increases the harmonics in the network.
   - Traditional power factor correction systems are not fast enough to respond to new power quality challenges.

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3. End User awareness
   - Willing to embrace power quality ready strategies, instead of Measure - Analyze and Fix.
   - The need for reliable and connected power quality solutions has increased.
   - Demonstrate power quality asset performance.
   - Willing to pay more for active technologies given the benefits vs passive technologies.
4. Utility regulations
   - Apparent power-based tariffs are encouraging customers to embrace Unity power factor solution strategies.
   - Penalty for Leading / Capacitive Power Factor.
   - The IEEE 519-2014 edition was a recommended practice. The latest IEEE 519-2022 edition is a full standard calling for mandatory compliance.
5. Operating expenses (OPEX) costs reduction
   - Customers are expecting maintenance free / predictive maintenance strategies, which are hard to offer in passive technologies.

Sustainability
- CO_2 emission reduction
- Energy Efficiency

PQ-related problems can have societal costs related to them. For example, costs due to PQ events might be passed on to customers. Most likely, such costs would reflect the added material and labor costs to a manufacturing process that has been interrupted by a PQ event. Some industries might be more affected by PQ disturbances than others. In addition, some industries might be so affected that they choose to move out of one service area's territory for another due to the repeated losses resulting from the PQ events in that area. In this case, the employees living in the previous service territory might suddenly find themselves in need of employment — a real problem should local industries be few [2].

Electrical installations today face numerous power quality issues, like harmonics, sag/swell/interruptions disturbances, reactive energy, etc. with 80% of these disturbances typically originating from the equipment in use. The remaining 20% of disturbances come from the energy provider, like sag/swells/interruptions, voltage transients, voltage unbalance, voltage fluctuations. The interruption time equates to 52 minutes annually [3].

Harmonic Current Distortion is the most prevalent type of electrical pollution in modern industrial, institutional, and commercial facilities. Non-linear loads such as VSDs, electronic power supplies, arc furnaces, and any equipment with electronic components are responsible for generating current harmonics. Symptoms of current harmonics in a network include overheating of transformers and cables, nuisance tripping of circuit breakers, blown fuses, voltage distortion, and overheating of capacitors [4-10].

Harmonic voltage distortion is one of the challenging power quality problems in modern facilities. It is primarily caused by current distortion through standard transformers and, less commonly, by distorted voltage from the mains. Symptoms of voltage harmonics in a network include intermittent crashes of sensitive equipment (such as computers, PLCs, VSDs, medical devices, and communication systems), overheating motors, premature capacitor failures, and a high replacement rate for sensitive electronics. The solution to mitigate voltage harmonic distortion is to eliminate current distortion [10-12].

Apart from the technical reasons enumerated previously, another factor to reduce harmonic content is the regulation. According to IEEE Standard for Harmonic Control in Electric Power Systems (IEEE 519-2022), the harmonic voltage distortion limits are set to minimize potential negative impacts on end-user equipment. To keep the harmonic voltage below the imposed limits requires that [13]:

- all users must limit the harmonic current emissions.
- the system owner/operator must reduce voltage distortion levels.

In practice, harmonics (current and/or voltage) cause abnormal operation of all network components, which further will compromise the safety of the energy supply network. Therefore, a power quality study is essential to properly address harmonic issues.

Active Harmonic Filters (AHFs) are static power electronic devices that use digital logic and IGBT semiconductors to create a current waveform injected into the electrical network to cancel harmonic currents generated by nonlinear loads. AHFs utilize current transformers to measure load current and identify the harmonic current content. By injecting the synthesized current, they mitigate network harmonic currents, reducing the heating effects of these currents and minimizing voltage distortion, thereby allowing other equipment to operate correctly and extend their lifespan. Additionally, AHFs can correct displacement power factor (DPF) for both leading (capacitive) and lagging (inductive) loads and balance mains current. DPF correction addresses poor DPF caused by such loads, while mains current balancing is achieved by measuring the negative sequence current and injecting its inverse to balance the upstream network current [15-18].

In this paper there is presented an AHF solution implementation, for the case of an industrial network containing nonlinear loads.

The customer is an Automotive factory that supplies the production spaces through 6 electrical substations with one or two power transformers of 20/0.4 kV with S = 3200 kVA each (depending on the configuration of each electrical substation). Each power transformer supplies a main switchboard distribution panel on the low voltage side. In locations where there are two power transformers in the same electrical substation, each transformer feeds its own main electrical switchboard, connected by a longitudinal coupling (tie). In most cases, the longitudinal coupling between the two switchboards is open, so that the two transformers and the associated electrical distribution panels operate independently.

The site has been experiencing the following operating issues:

- The occurrence of operational anomalies within sensitive electronic control and command apparatus.

Excessive heat during the working cycle for several installation components even though the monitored values (electric currents) are below their nominal value.

- Heating of distribution power transformers and important noise.
- The capacitors keep burning out.
- The energy supplier has issued a notice requesting mitigation of voltage harmonic distortion at the common coupling point.

A comprehensive power quality assessment was conducted prior to harmonic mitigation equipment selection. This evaluation employed a power quality meter (Class A) [19], which was connected at the incoming point of each main low voltage switchboard to establish baseline characteristics.

Following the power quality (PQ) audit, it was determined that both harmonic levels (current and voltage) surpassed the thresholds outlined in relevant standards [20, 21]. Furthermore, these harmonic levels exhibited variability. To address this issue, the proper selection of an active harmonic filter (AHF) is the most suitable mitigation strategy. The power factor measurements obtained during the audit indicated satisfactory operation within established limits. Consequently, no additional power factor correction measures were implemented.

Due to a combination of installation owner requirements and budgetary constraints, the capacity of the AHF solution for each power transformer was limited to 600A, despite an identified potential need for up to 900A. It is important to note that while the AHF selection procedure presented here corresponds to a specific non-linear load scenario, the underlying design methodology can be adapted for application to a broader range of industrial consumers.

2. Study case - heavy industrial nonlinear load

For this case study we chose a location where we have two power transformers, TR1 and TR2, as shown in Fig. 1 and the measurements were performed independently at the secondary of each power transformer at the output of circuit breakers CB1.1 and CB2.1 but not at the same time. So, the power quality audits and sizing the harmonic compensation solutions were performed separately at each power transformer (main electrical distribution panel) independently, because most of the time the longitudinal coupling CB3 is open, but we have taken into consideration cases where one power transformer supplies both electrical distribution panels from the electrical substation (when tie breaker is closed due to maintenance tasks done at the second power transformer). Special installation and connection of the current transformers is performed on locations where two power transformers are installed together with its own main electrical switchboard to take into consideration the case where one power transformer feeds both main low voltage electrical switchboards, in case the second power transformer is disconnected.

Assume that the site had ran at peak load during the logging period. For simplification of the case study, the below data measurements were collected at the power transformer 1 (TR1), according to Fig. 1.

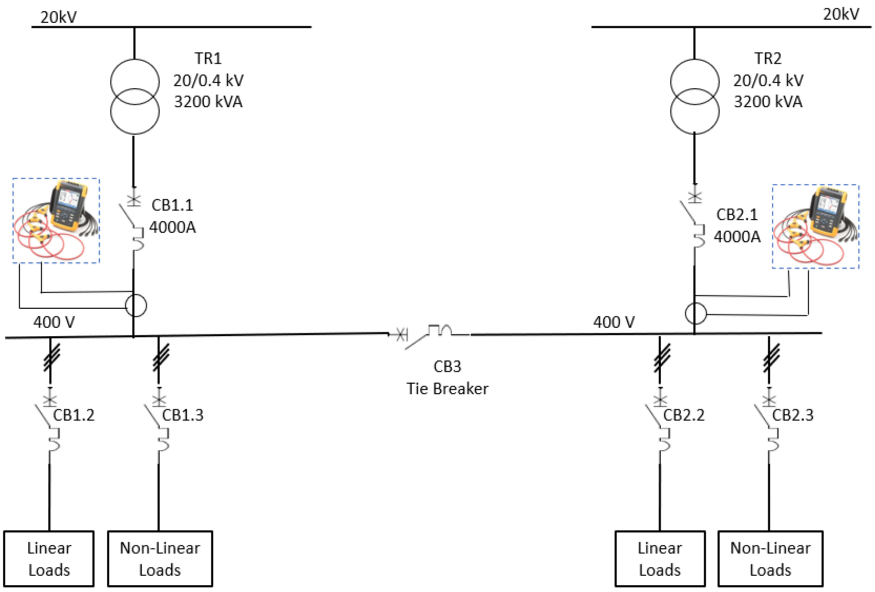

Fig. 1. Non-linear load connected to the PQ analyzer scheme.

Power Quality Investigation Methodology

In response to the operational concerns outlined by the client (described above), a comprehensive power quality investigation was undertaken to characterize the load profile. This involved the analysis of key electrical parameters using a portable power quality meter [19]. The meter was strategically connected at the main incomer for each load, located on the secondary side of the power transformer terminals (low voltage). Data registered was then downloaded to a PC for further analysis using the dedicated software provided by the power quality meter manufacturer. This software facilitated the comprehensive examination of all logged parameters.

Fig. 1 presents a schematic single-line diagram illustrating the power quality meter connection points within the system.

The investigation employed the Power-Log 430 II meter [22] to capture trends in critical electrical quantities. The recorded data, presented in Fig. 2, revealed a line-to-line voltage range of 405 V to 410 V. During the monitoring period, the average value of the current through the active phases of the loads is between 2500 A and 3120 A. Notably, the currents between the phases were balanced. The trend evolution of the real (*P*), apparent (*S*) and reactive power (*Q*) for each phase and total are given in Fig. 3 and Fig.4. The minimum active power captured was around 1,600 kW, and reached a maximum of 2,050 kW, due to various demand power requested by the manufacturing process. For the same monitored interval, the apparent power trend varies between 1,700 kVA and 2,170 KVA, while the reactive power varies between 425 kVAR and 558 kVAR.

The true power factor (PF) and the displacement power factor (DPF) trend evolutions are shown in Fig. 5. DPF is the power factor at fundamental frequency (50Hz) and does not count the harmonics content from the electrical network. The power factor at maximum kVA demand is 0.96 lagging, which meets the utility's requirement of > 0.9 lagging/leading.

The voltage and current waveforms distortions can be characterized, from the quantitative point of view, by the corresponding total harmonic distortions (THD_U, THD_I) - Fig. 6. The first three graphs from the top show the harmonic voltage line to line evolution, while the bottom 3 graphs highlight the current harmonics evolution. The graphs present the average values for THD_U (%) and *THD* (%) respectively and the harmonic spectrum for 5^{th}, 7^{th}, and 11^{th} harmonics orders.

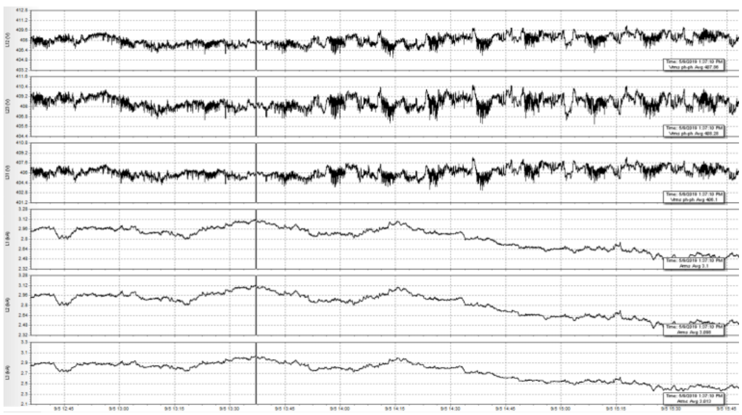

Fig. 2. Voltages (V) and currents (A) effective values – measured trends.

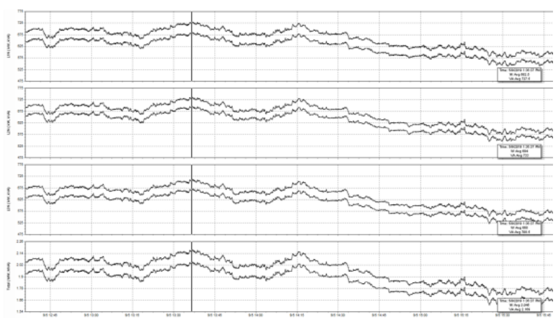

Fig. 3. Measured powers: *P* (kW) and *S* (kVA)

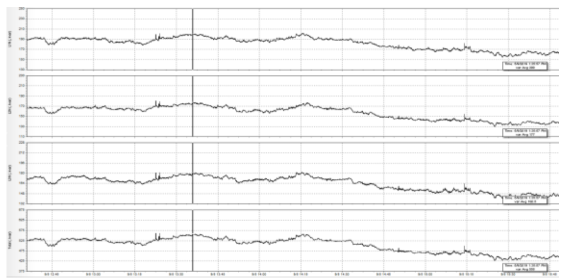

Fig. 4. Measured Q (kVAR).

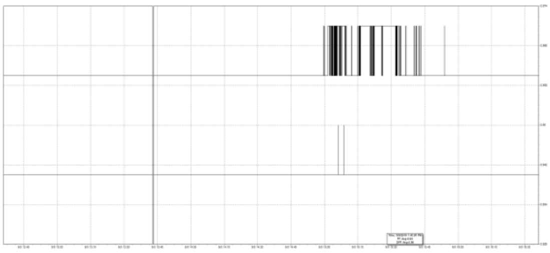

Fig. 5. Evolution of PF and DPF.

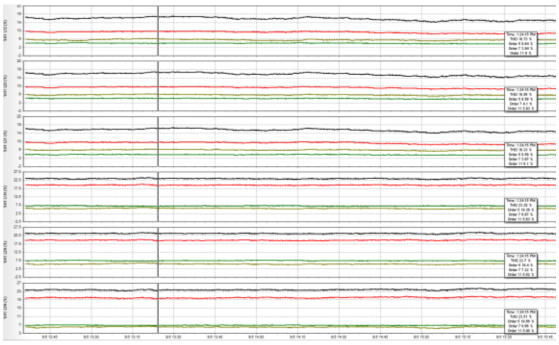

Fig. 6. Measured THD_U (%) and THD_I (%) trend evolution.

The investigation identified a significant level of harmonic distortion within the system.

Voltage distortion exhibited extreme values ranging from 15% to 18%, with an average Total Harmonic Distortion (THD_U) of 17%. Similarly, current distortion displayed extreme values between 23% and 25%, resulting in an average Total Harmonic Distortion Index (THD_I) of 24%.

The most prominent harmonic components were observed at the 5^{th}, 7^{th}, and 11^{th} orders. This harmonic signature is characteristic of installations containing a significant number of six-pulse nonlinear loads, such as variable speed drives (VSDs) and rectifiers.

The analysis revealed that both THD_U, THD_I surpass the thresholds established by current standards and regulations [20, 21]. The threshold limit THD_U according to IEEE-519 and EN50160 for low voltage installations is 8%, while in the installation the level reached between 15% and 18%, with an average of 17%. Furthermore, harmonic voltage distortion exhibited particularly high values, which can represent a real threat to the entire electrical network.

In today's power systems, the integration of nonlinear loads has become increasingly common. However, these nonlinear loads introduce additional frequencies, known as harmonics, which coexist with the normal fundamental sine wave (50Hz/60Hz). Because the nonlinear currents are flowing through the electrical system, they interact with the impedance of the network, resulting in voltage distortions.

Consequently, many electrical devices, including AC motors, VSDs, and transformers, need to be derated to account for the presence of harmonics.

By understanding the impact of these harmonics on the power systems and implementing appropriate measures, we can ensure reliable and efficient operation while minimizing the risks associated with harmonics-induced problems. Fig. 7 shows the negative effects of harmonics.

Equipment	Effect of Harmonics
Motor	Over heating, production of non-uniform torque,increased vibration
Transformer	Over heating and insulation failure, noise
Switch gear and cables	Neutral link failure, increased losses due to skin effect and over heating of cables
Capacitors	Life reduces drastically due to harmonic overloading
Protective Relays	Malfunction and nuisance tripping
Power electronic equipment	Misfiring of Thyristors and failure of semiconductor devices
Control & instrumentation Electronic equipment	Erratic operation followed by nuisance tripping and breakdowns
Communication equipment / PC's	Interference
Neutral cable	Higher Neutral current with 3rd harmonic frequency, Neutral over heating and or open neutral condition
Telecommunication equipment	Telephonic interference, malfunction of sensitive electronics used, failure of telecom hardware

Fig. 7. Negative effects of harmonics.

3. Harmonics mitigation solution to decrease the harmonics in the network

To address the challenges presented in Fig. 7, a power quality audit is essential. In general, when it comes to Power Quality standards, we are referring to IEC and IEEE standards but also local standards, which in many cases are the international standards localized at country level. Between the power quality standards considered in the audit we can highlight: IEC 61000-4-30, IEC 62586-1/2, IEEE 519, IEC 61000-4-7, EN50160, IEEE 1159, etc,

. It assesses whether the voltage and current harmonics met the standards set by IEEE519 [20] and it helps to identify the sources of harmonics. Based on the audit findings, appropriate solutions can be designed and implemented. One solution is represented by AHF, which is a power electronic-based device capable of injecting both fundamental frequency current to correct the power factor and harmonic current to prevent load harmonics from being fed back into the grid. AHF offers rapid response times and, when engineered correctly, can effectively mitigate harmonic-related issues.

Based on the analysis of electrical load characteristics derived from the power quality measurements, the implementation of conventional harmonic mitigation solutions, such as passive filtering, is therefore unsuitable for this application. This is mainly because the level of voltage harmonics is too high and because multiple harmonics orders need to be mitigated. In light of the identified limitations of conventional solutions, the implementation of an AHF emerges as the most appropriate strategy to address the significant power quality issues generated by the studied nonlinear loads. When the network voltage distortion is up to 18%, the proposed active filtering solution can work in polluted networks up to a level of THD_U (%) =24%.

A. Sizing and Selection of the AHF System

AccuSine PCS+ AHF is a parallel connected power conditioning device that utilizes pulse width modulated (PWM) technology to inject reactive current in the electrical network. The PCS+ determines the current to be injected based on its sensing current transformers (CT) mounted at the incoming of the switchgear and on the voltage sensed internally from its alternative current (AC) bus.

The device uses the energy stored on its DC bus to inject the necessary current in the network by switching its IGBT at 20 kHz to inject a reactive current containing fundamental and harmonic components. The injection is managed by its Central Processing Unit (CPU) to improve the displacement power factor (DPF), mitigate harmonics, and rebalance the current on the electrical network. Any of the functions (DPF, Harmonic and Load balancing) can be activated or disabled at will be based on the project power quality objectives [22].

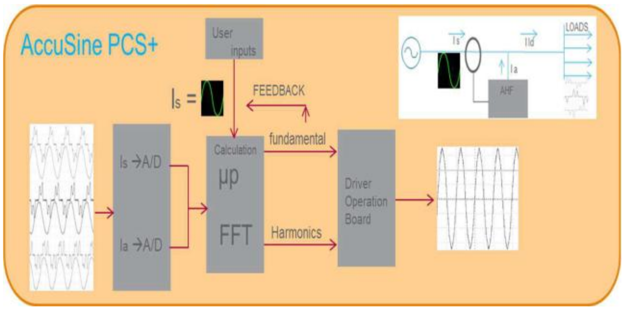

Fig. 8. Active Harmonic Filter control concept.

AHFs employ two primary control scheme options. The first method is based on Fast Fourier Transforms (FFT) to calculate the effective values and phase angles of individual harmonics within the voltage and current waveforms. Based on this analysis, the AHF injects compensating currents and voltages with the same magnitude but opposite phase for targeted harmonic orders. However, this technique suffers from limitations, such as:

- Restricted response: It can only address specific harmonic orders, typically even harmonics.
- Slow response time: it can be up to twice or more fundamental period cycles (> 40 ms), potentially impacting real-time mitigation.

Modern AHFs utilize a more advanced approach known as "full spectrum cancellation." This control strategy relies on analog algorithms instead of FFT. The AHF control unit receives the signals (current, voltage) from dedicated sensors. It then isolates the fundamental harmonic component and begins injecting the corrective component (time order of μs) [22, 23]. This allows the suppression of a wider range of harmonics, including both odd and even orders, from the electrical source's harmonic spectrum. Consequently, full spectrum cancellation AHFs are particularly well-suited for demanding industrial applications.

Because the power factor is above the 0.9 threshold, we will not consider in the sizing of the solution, power factor improvement. We will be focusing only on the harmonic’s mitigation. Since we have mainly harmonic current, which means 3-phases VSDs, so 3-Phases 3-Wires active harmonic filters will be proposed.

B. AHF Sizing and Design Considerations

The selection of an appropriately sized AHF necessitates precise electrical operating data for the targeted nonlinear load. Fortunately, the measurements presented in the preceding section provide the foundation for a well-informed choice of the AHF solution. Additionally, the design process should incorporate the manufacturer's specific selection guidelines for the chosen AHF.

To determine the current harmonic component requiring mitigation, we can employ the following approach:

- Target THD_I: Establish a desired (target) level of current Total Harmonic Distortion (THD_{I_new}) – in this case, 5%.

- Safety Factor: Introduce a computation safety factor (Ks) to account for potential variations or uncertainties. A commonly adopted value is Ks = 1.25 [13, 15, 23-25].

By considering these factors, we can calculate the specific current harmonic component that the AHF needs to mitigate.

$$I_{AHF\_harm} = K_s \cdot I_{harm\_RMS} - I_1 THD_{I\_new}, \text{ with:}$$
$$I_1 = \frac{I_{RMS}}{\sqrt{1+THD_I^2}}, \; I_{harm\_RMS} = \sqrt{\sum_{k=2}^{n} I_k^2} = I_1 THD_{I}. \tag{1}$$

where:

- I_{harm_RMS} = 723 A - current effective value of the superior harmonics.
- I_1 = 3015 A - the fundamental harmonic current.
- I_{RMS} = 3100 A - the load current effective value.
- I_k – the current harmonics components.
- THD_I = 24 % is the measured current total harmonic distortion (before AHF installation).

The filtering current harmonic solution corresponds to I_{AHF_harm} = 755 A.

Considering the above findings, a modular solution was deemed most suitable. The chosen system is the Schneider Electric Accusine PCS+ active harmonic filter range. This device offers the advantage of parallel connection for up to 10 units, in a master-slave configuration. The master units are designed to read current sensor data. This capability allows for the anticipation of potential future changes in the load's characteristics. Considering the selected manufacturer's product range and available current ratings, three Accusine PCS+ 300A units are recommended for installation in a master-slave configuration. This configuration provides a total capacity of 900A, incorporating a buffer to accommodate potential increases in demand that may not have been captured during the limited on-site measurement period. According to the AHF producer recommendations, 3% of AC chokes should be installed for the non-linear loads (e.g. VSDs) if neither AC nor DC chokes are installed. The primary function of these devices is to safeguard both the load and the active harmonic filters (AHFs) from transient over-voltages originating from various disturbances within the supply network. Furthermore, they offer the additional benefit of attenuating harmonic currents flowing through the line. Furthermore, they decrease the line current harmonics. The AC chokes will decrease the supply voltage to the VSD by 3%. The effect of decreased supply voltage to the VSD should be checked by the VSD supplier and the site engineers.

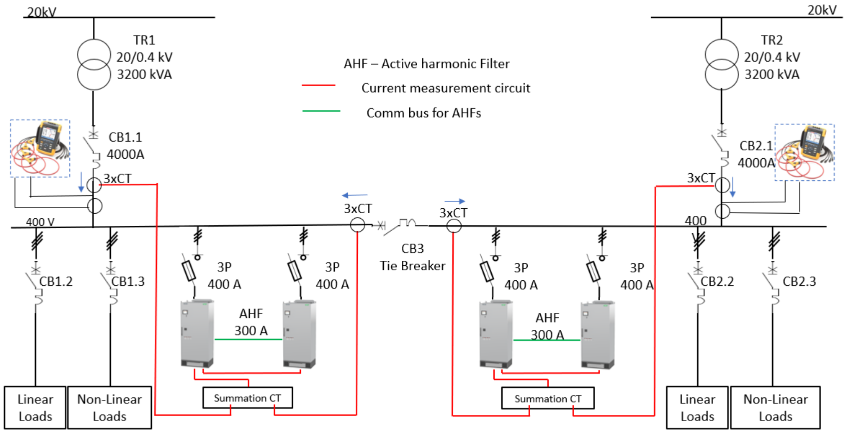

Fig. 10. The simplified single-line schematic of the AHF installation.

The diagram described in Fig. 10 above provides an example for applying an active filter to the main panelboard. Under normal operating conditions, the tie breaker CB3 is open, the left active filters are provided with the total current from the left side main breaker CB1.1. The right-side active filters provide the total current information from the right-side main breaker CB2.1. The two sets of CTs at the tie breaker have no current on the primary due to the tie breaker being open.

This configuration requires that each left active filter is sized for the loads connected to the left of the tie breaker, and that the right active filter is sized for the loads on the right side of the tie breaker. The opposite is true when the right-side main breaker is closed, and the left side main breaker is open with the tie breaker closed. The polarity of the CT installation is crucial in this application and are detailed by arrows in the diagram from Fig. 10. The CTs that are connected at the secondary wiring must be on the same phase with opposing polarity. To validate the CT installation, the system must be tested under every possible operating condition.

C. Solution Implementation

Due to economical constrains, the customer chooses to install only 2 AHF units of 300A, in total 600A rated harmonics current for each section, how it is exposed in Fig. 10, and at the later stage the 3rd unit of 300A to be installed for each switchboard. Following the installation of two parallel 300A Active Harmonic Filter (AHF) units connected to the nonlinear load, a significant improvement in key power quality parameters was observed. However, these improvements were not sufficient to achieve full compliance with all relevant standards. Fig. 11 provides the trend evolution for the voltage and current revealing a range of 400-408 V for line-to-line voltage. The current through the loads' active phases presents an average value between 2500 A and 3400 A for monitored period with relatively balanced values between phases.

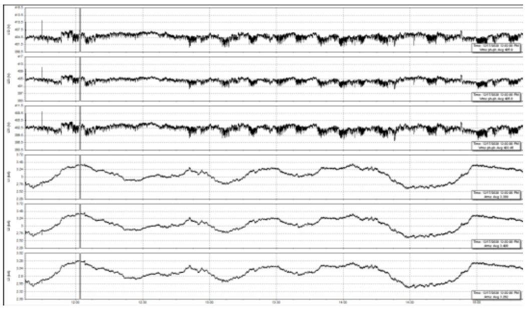

Fig. 11. Measured trends effective values - voltages and currents.

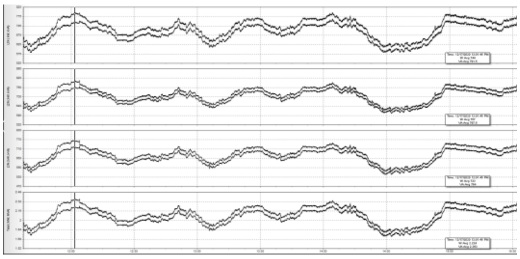

Fig. 12. P (kW) and S (kVA) evolution, after harmonic mitigation.

According to Fig. 12, the apparent power varies between 1,850 KVA and 2, and 2,350 kVA real power between 1750 kW and 2,225 kW.

The minimum active power captured was around 1,750 kW, and reached a maximum of 2,225 kW, due to various demand power requested by the manufacturing process and it was approximately 5% higher compared to the maximum values captured on the initial measurements. For the same monitored interval, the apparent power trend varies between 1,750 kVA and 2,225 KVA.

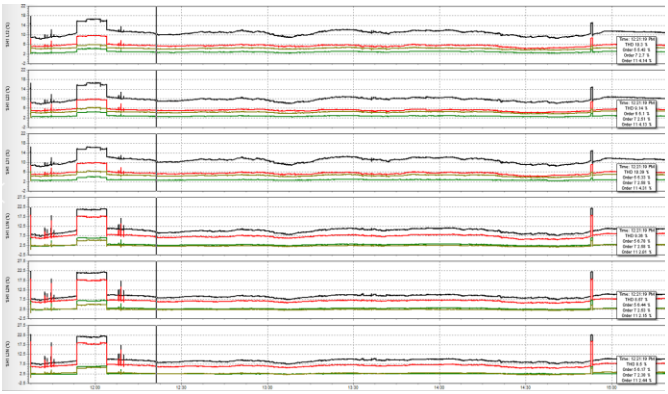

Fig. 13. THD_U and THD_I evolution - after AHFs installation.

As highlighted in Fig. 13, after installing the AHF filters the harmonics reduced considerably, the THD_U (%) decreased from approx.17% to approx. 10%, but not below the standard targets. For THD_I (%) the reduction was from 22% down to 9%.

4. Conclusions

Low-voltage and medium-voltage networks are experiencing a rising trend of harmonic pollution in voltage and current waveforms. This phenomenon is primarily driven by the increasing presence of non-linear loads in modern power systems. These non-linear loads, characterized by rapid and frequent parameter variations, inject harmonic currents into the network, leading to distorted voltage and current waveforms. The resulting power quality issues pose a significant threat, impacting the functionality and efficiency of various installation components. To handle these problems, specific to modern industrial equipment rich in electronic components, active harmonic filters represent the most suitable solution.

This paper investigates the application of active filtering techniques to address severe voltage and current waveform distortion within an industrial low-voltage power distribution system. The distortion is attributed to the presence of significant non-linear loads, such as rectifiers and variable speed drives (VSDs). Accordingly, after a proper power quality audit was carried out, an active harmonic filter solution sized at 900 A was recommended to be implemented, but due cost constraints the provisory solution was to install only 600A AHFs (2 units of 300A at 400V) in parallel connected at the main low voltage switchboard. Recommendations to decrease even more the THD_U (%) and THD_I (%) have been proposed and implemented accordingly. To validate the solution, measurements were taken before and after implementing the afore-mentioned solutions.

In conclusion, AHFs offer a comprehensive solution by mitigating harmonic distortion and by:

- reducing process-related voltage fluctuations: This enhances process stability and reduces the risk of equipment malfunctions.
- targeting load balancing: Improved load balancing can optimize system efficiency and capacity utilization.
- extending equipment operating life and system capacity: By mitigating harmonic distortion and voltage fluctuations, AHFs contribute to a more reliable and durable power system.

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