Analysis and Mitigation of Harmonics for a Wastewater Treatment Plant Electrical System

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Abstract: – Power quality has become a pressing issue that demands solutions as power electronic equipment has been increasingly used in industrial sectors. One critical problem is how to mitigate harmful harmonics generated by the power electronic equipment. This study investigates harmonic distortion issues in a wastewater treatment plant to verify compliance with IEEE standard 519 using simulation software ETAP and realistic data from the plant. Harmonic quantification shows that the plant harmonic situation violates IEEE Standard 519 where harmonic levels exceed its voltage and current limits. Different methods were used to mitigate the harmonic situation where the core is using passive harmonic filters. It is found that the biggest contributor to the harmonic distortion is the system variable frequency drives. Using high-pulse variable frequency drives, such as 18-pulse, is proven to be beneficial for harmonic reduction. Further, installing passive harmonic filters in appropriate locations helps lower voltage and current harmonics to meet IEEE Std. 519 limits. However, adding a passive harmonic filter higher up the power distribution or adding passive filters to the feeder buses is not effective in lowering the Total Harmonic Distortion (THD) of the system. This would have the drawback of increasing the rating of the system bus voltages. Other findings include a lack of medium voltage passive filters on the market and high costs. The study contributes some insight understanding, experience, and methods for engineers when developing solutions for controlling harmonics in similar plants or industrial applications.

Key-Words: Distribution power system, filter, harmonics, power quality, Total Harmonic Distortion, variable frequency drive, wastewater treatment plant.

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1 Introduction

Increasing usage of nonlinear loads and power electronic equipment is a common problem when designing power systems for industrial applications. A load is said to be nonlinear when the current it draws does not have the same waveform as the supply voltage, [1]. The nonlinear loads and power electronic equipment generate harmonics, which are voltages and currents of various frequencies differing from the power system nominal frequency (60Hz or 50Hz). These harmonics interfere with the normal operation of the host power system and neighboring equipment. It is required that power being delivered by utility companies be almost perfectly sinusoidal. In the wastewater industry, the target sector of our study, harmonics can be created from large nonlinear loads such as variable frequency drives, motors, and backup DC systems, [2], [3], [4], [5]. In a typical water and wastewater plant, adjustable frequency drives are most often the main cause of harmonic distortion as they are typically used to control pumps, usually for high horsepower motors. The high horsepower motors usage implies that the adjustable speed drives represent a substantial part of the total electrical load on a given bus. A load is nonlinear if the impedance is composed of a reactive component that changes with the applied voltage. This change in impedance implies that the current drawn by these loads will not be sinusoidal even when connected to sinusoidal power sources. This results in a non-sinusoidal voltage drop across the non-linear load. These non-sinusoidal currents contain harmonic currents that interact with the different impedances found throughout the power distribution system that create a voltage distortion that affects the equipment found throughout the power distribution system and its connected loads. The voltage distortion caused by a load is a function of the system impedance and the amount of harmonic current injected into the system, [2]. If the system impedance is low, the voltage distortion is usually negligible in the absence of harmonic resonance. However, if harmonic resonance is not negligible, high harmonic voltage and currents are a result.

Harmonic currents cause line losses and stray losses in transformers. The problems caused by harmonics currents usually result in overloading of neutrals, overheating of transformers, nuisance tripping of circuit breakers, over-correction in power factor correction capacitors and skin effects in conductors, overheating of cables, transformers, standby generators, and electric motors. Harmonics can harm equipment in various ways depending on the equipment. In a transformer, for example, harmonics can cause additional power losses by increasing the eddy currents flowing throughout the transformers or by increasing the leakage current found in the insulation. Transformers being a victim of harmonics is important because most distribution transformers are delta primary and wye secondary. When the wye configuration's loads return significant amounts of 3^{rd} and 7^{th} harmonics, they typically go through the wye configuration's neutral conductor and are trapped in the primary delta winding where they circulate and cause extra heating. This will significantly reduce the lifespan of the transformer unless derated or designed to mitigate harmonics specifically, [3].

Problems caused by harmonics are power quality challenges. Hence, solutions must be sought to address the harmonics-related problems. Based on the above analysis, there is an urgent need to find effective methods to control harmonics, especially in industrial applications. Furthermore, harmonic control methods are increasingly needed to alleviate harmonic injection by today's popular power electronic systems such as VFD, solar inverters, and electric vehicle chargers.

This study first provides a short review of harmonic mitigation measures. Then, it presents an analysis of the harmonic situation in the electrical system of a wastewater treatment plant in California and measures to reduce the harmonic situation. It aims to contribute some insightful understanding, experience, and methods for controlling harmonics to assist engineers and industrial professionals when dealing with similar plants or industrial applications.

2 Harmonic Mitigation Techniques

According to IEEE standard 519, for voltage levels ranging from 1 kV to 69 kV, the total allowable level of Total Harmonic Distortion (THD) is 5% with no more than 3% of Individual Harmonic Distortion (IHD), [4]. To comply with IEEE 519, many harmonic mitigation techniques have been developed. These techniques can be divided into three different categories: passive techniques, active techniques, and hybrid techniques, [5], [6]. The hybrid techniques use a mixture of active technique and passive techniques.

2.1 Passive Harmonic Filters

An example of a passive technique is a line reactor or a tuned harmonic filter. A passive harmonic filter filters harmonics by creating a low-impedance path at the tuned frequency, [7]. This technique essentially uses a tank circuit to provide a lower impedance path to harmonic frequencies than the power source, [8]. Passive filters can be designed to be low-pass, band-pass, or two-staged filters. The different versions of the passive harmonic filter deal with the harmonics present with varying levels of success, [9], [10], [11], [12], [13]. Passive filters have the following advantages, [14], [15]:

- They are cheap.
- They tend to have simple circuitry.
- They are typically easier to perform maintenance on.
- They can perform power factor correction to increase power factor.
- A single filter can compensate for multiple drives.

They can also have the following disadvantages:

- They require the use of computer-aided software like an electrical transient analyzer program (ETAP) to analyze and identify the present harmonics in the system to size the filter accordingly.
- Labor is necessary by consulting engineers to perform harmonic studies.
- May not reduce harmonic levels below IEEE 519 guidelines.
- During light load conditions, filters may lead to a leading power factor.
- They have a resonant issue due to simple circuitry.
- Single-tuned filters can eliminate a single harmonic order only.

2.2 Active Harmonic Filters

Active harmonic filters filter harmonics by injecting equal and opposite frequencies, similar to a noise cancellation system. The benefits of active harmonic filters include:

- Can be sized to meet specific levels of harmonic correction.
- Helps improve power factor to maximize efficiency.

- Less labor is needed by consultants as harmonic studies are not necessary.
- Remain unaffected by loading conditions.

The disadvantages of active harmonics filters include the following:

- Can cause energy losses and VFD (Variable Frequency Drive) tripping due to series impedance.
- Do not eliminate relay tripping, downstream failure, or harmonics downstream of the filters.
- Can only limit upstream grid harmonics.
- Are susceptible to voltage fluctuations.

A hybrid filter combines the techniques of the active filters and the passive ones. This implies that hybrid harmonic filters have a mix of the benefits of both filters but also the disadvantages of both types of filters. The main differences between the methods are the cost and complexity of the filters, with passive being the most inexpensive but also the most limited one, while active filters tend to be the most expensive but the most robust to control.

2.3 K-factor Transformers

Active Underwriters' Laboratories (UL) established a rating method called the K-factor, for dry-dry type transformers, to evaluate their performance in a harmonic polluted environment, [16]. The K-factor indicates the transformer's capability to supply various harmonic-producing loads without exceeding the temperature-rising limit of the transformer. Standard ratings include 4, 9, 13, 20, 30 and 50. The advantages of a K-factor transformer include:

- Reduction in voltage and current harmonics by adding line reactance to a load.
- Input protection from line transients to load.
- Can be used in combination to create special phase shifts for harmonic cancellation.
- Performance reliability and reduced damage due to excessive temperature rise caused by harmonics.

The disadvantages of K-factor transformers include:

- Not a true mitigation technique, just incorporates them into the system.
- Must be sized at full load current rating.
- More expensive than traditional transformers
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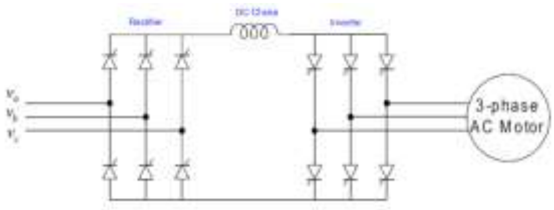

Fig. 1: A VFD configuration with DC Choke, [17]

2.4 Multi-pulse Variable Frequency Drive Configuration (6, 12, 18, 24 pulses)

Variable frequency drives (VFD) have an inherent harmonic mitigation within them as they hold transformers having a different connection topology (wye-delta or delta-wye) which creates a phase shift between their primary and secondary voltages, [18].

This phase shift is the key to minimizing the generated harmonic currents in the higher pulse drives. The typical relation is as follows:

$$h = p - 1$$

where h is the greatest harmonic order present in the drive, and p is the number of pulses in the VFD (typically a multiple of 6). The six-pulse drive, such as the one shown in Figure 1, is the simplest and least expensive drive manufactured. However, it is also the one that has the most harmonics present since the 5^{th} harmonic order is present. These drives typically hold an "AC Choke" which is another type of harmonic mitigation technique, but it typically depends on the manufacturer as to when the "AC Choke" and "DC Link" are introduced, [7].

The twelve-pulse drive is formed by connecting two six-pulse rectifiers in parallel with a three-winding transformer. This arrangement means that typically, the harmonics on the supply side will cancel each other since they would be in opposite phases. Theoretically, this would cancel up to the 11th-order harmonic. Increasing the number of pulses present in the drive also increases the cost of the equipment. VFDs are typically considered an economical solution to power motors but only if the load will not be required to run at 100% of capacity all the time.

Harmonic analysis of an existing industrial distribution power system is typically performed to quantify the harmonics created from the loads. It is important to note that there are two different kinds of harmonics, there is harmonic current and harmonic voltages, and they affect power systems differently. Harmonic currents influence system losses, system operation, and system performance while voltage harmonics degrade the insulation and shorten the lifespan of the equipment, [7].

The harmonic mitigation analysis of this study includes an analysis of currently being used techniques and the exploration of new technologies. Current techniques in harmonic mitigation are expensive and require lots of space which may conflict with the limited area present in electrical buildings dedicated for the electrical equipment. Studies may be performed using simulation software ETAP to obtain the magnitudes and phase angles of load bus voltages, reactive powers at generator buses, and real and reactive power flow throughout the system of interest, [19], [20], [21].

2.5 Wastewater Treatment Plant of Interest and Study Objective

The wastewater treatment plant chosen for this study is a highly critical plant located in Southern California. The wastewater treatment plant uses various 4160V, 18-pulse, VFDs to power and control the 800 HP pumps that move the water and other liquids throughout the treatment process.

The study was conducted to determine if it was worth using 6-pulse VFDs and adding harmonic filters considering budgetary limitations. It is important to note that budgetary limitations include space and cost. Due to the nature of this analysis, there must be a relationship between the cost of the electrical equipment, the size of the equipment, and the size of the filter introduced to deal with the corresponding harmonics in the system.

The size of the equipment is important because, in the wastewater industry, while a project is in the design phase, electrical engineers typically have the lowest priority in the design process. By the time electrical engineers have a say in the design, certain major sections of the design have already been done by other disciplines which limits the project space and cost. For example, the size of a room that houses equipment is designed by civil engineers Equipment data is provided in Table 4, Table 5 and Table 6 (Appendix) typically cannot be redesigned. In the wastewater industry, the order of disciplines is as follows: Civil (verify the topography, location of existing utilities, soil quality, etc.), which Structural (determines structural integrity of current and future buildings, etc.), Mechanical (places the equipment, heating, ventilation, air conditioning, "HVAC", etc.) and Electrical (power to equipment, deals with equipment communication, control of equipment, utility coordination, etc.). Space and money are the constraints that electrical engineers must design around and only an oversight from a preceding discipline will result in the change of the design.

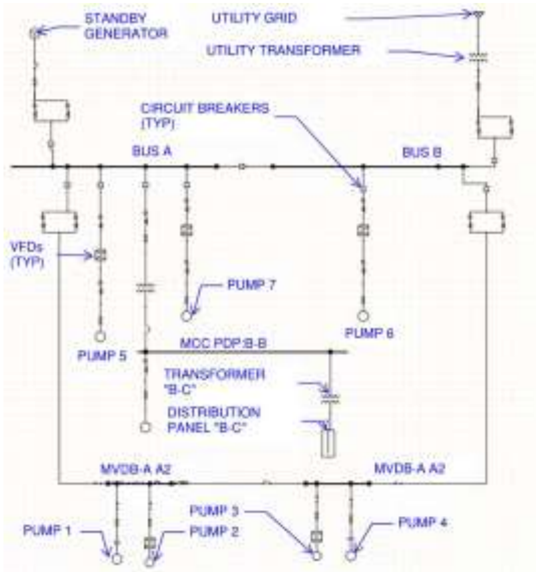

Fig. 2: The plant electrical system represented in ETAP

Space is important because there is limited space inside an electrical room that houses most of the electrical equipment.

The objective of this study is to consider the effect of nonlinear loads ranging from adjustable speed drives to industrial-size pumps and find the best way to mitigate them through computer models.

Commonly used loads in wastewater industrial applications are modelled in ETAP and a harmonic study will be performed to determine the best cost-effective solution that meets IEEE-519 standards.

3 ETAP Modeling, Analysis, and Mitigation of Harmonics for the Plant

A wastewater treatment plant that handles 90 million gallons of wastewater per day (MGD) was modeled in ETAP. Figure 2 shows a snippet of the model, labeled per the major busses. The system data are provided in Table 4, Table 5 and Table 6 (Appendix).

The system contains connections to utility and a backup to the generator, with four main switchgear (upper-left most are Bus A, upper-right most is Bus B, bottom-left most is MVDCB_A 1A, bottom-right most is Bus MVDB-A A2) and one motor control center (MCC), "PDP:B-B", that is fed from Bus A through a step-down transformer. The first bus contains a "tie-breaker" in the middle in case of a power failure of utility so that the generator can act as a backup for the entire system. The buses typically operate at 4160V and so do the VFDs and pumps. A transformer was added to feed a different bus system that operates a rolling gate and a panelboard that feeds several other 120-volt loads (controls, uninterruptible power supply "UPS", lights, etc.). Power factor, current, and number of poles used per load are actual values of the plant equipment which are entered into ETAP to model the electrical system realistically. The harmonics are examined about the utility transformer, as anything greater than 5% total harmonic distortion (THD) will result in the system failing the IEEE-519 standard. The resistors and inductors seen throughout the system are conduits that contain conductors that connect the system throughout the electrical room. Sometimes connections are made in parallel to limit the amperage traveling through each conductor to limit voltage drop and to supply enough current for the loads at the next switchgear. The main loads in the system are 800 horsepower-sized pumps.

An analysis of the harmonics present in the system was done to determine if the system meets IEEE Std. 519, as shown in Figure 3 and Figure 4.

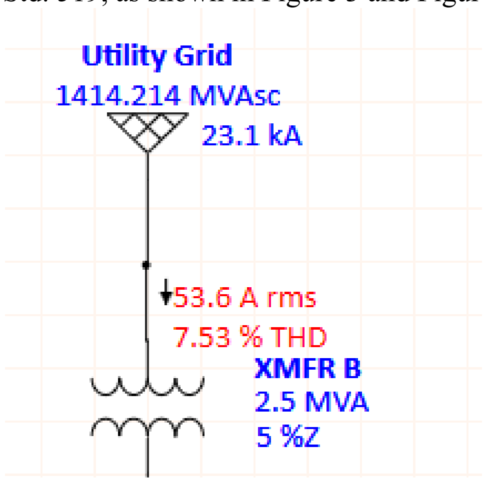

Fig. 3: Original THD of the system

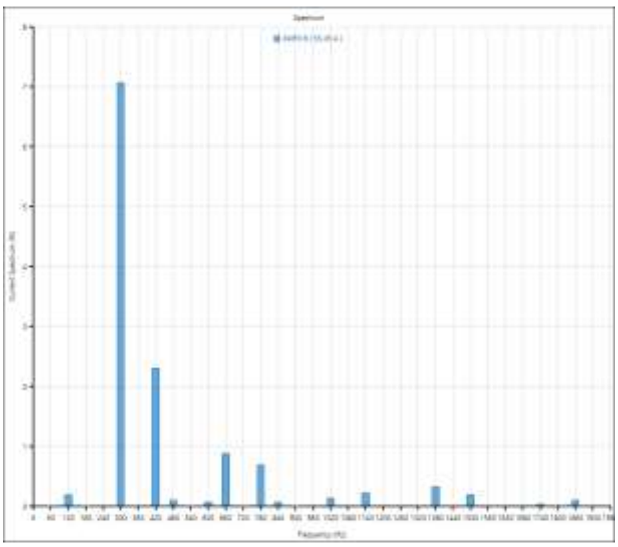

Fig. 4: Original current THD of the system

Table 1 and Table 2 show harmonic compliance criteria for voltage and current in IEEE Std. 519-2022. Table 1 shows the limits for application at the point of common coupling (PCC) between the system owner and the system user. For industrial applications such as a wastewater treatment plant through a unique service transformer, the PCC is on the transformer's high voltage side. This is why Figure 3 shows the THD from the point of the utility's transformer. For commercial customers, the PCC is on the low voltage side of the service transformer. Analysis of the system is done in multiple stages. The first stage aims to check if the system passes IEEE-519 standard as it was built. This stage includes the VFDs modelled as 18-pulse drives. For the second stage, the VFDs are modelled as 12-pulse drives, and the harmonics are measured. The third stage is done for 6-pulse VFDs.

Table 1. IEEE 519-2022 voltage compliance criteria

	Weekly 95th percentile short time		**Daily 99th percentile short time**	
Bus voltage (V) at PCC	**Individual Harmonic (%)**	**THD (%)**	**Individual Harmonic (%)**	**THD (%)**
$V \leq 1.0\ kV$	5.0	8.0	7.5	12
$1\ kV < V \leq 69\ kV$	3.0	5.0	4.5	7.5
$69\ kV < V \leq 161\ kV$	1.5	2.5	2.25	3.75

Table 2. IEEE 519-2022 current compliance criteria

I_{SC}/I_L	**Individual Harmonic Limits (Odd Harmonics) Values are in % of maximum demand load current**					**THD**
	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

For $h \leq 6$, even harmonics are limited to 50% of the harmonic limits shown in the table.
I_{SC} = Maximum short-circuit current at PCC.
I_L = Maximum demand load current at PCC under normal load operating conditions.

3.1 Performing Harmonic Analysis with ETAP

The single-line diagram in Figure 2 is used to perform a harmonic analysis on ETAP. ETAP has options in the equipment (cables, transformers, power grid, loads, circuit breakers) and the user must set the voltage and harmonic tabs if they exists for that piece of equipment. ETAP provides two options to model the harmonic of the equipment. One can choose the IEEE-519 equation or use pre-loaded library data where the user can choose the load type, model, and manufacturer. For this project, the Allen-Bradley (AB) VFD was chosen as it has an 18-pulse, 12-pulse, and 6-pulse version already in the harmonic library of ETAP.

The user must click the "Harmonic Analysis" mode in the mode toolbar and on the right-hand side of the screen select "Run Harmonic Load Flow Study." ETAP has a built-in harmonic filter sizing. However, the current power factor, amperage, and MVA are needed. Luckily this information can be For commercial customers, the PCC is easily gathered with the "Load Flow" analysis module. Once the information is obtained for the location where the passive filter needs to be installed, the user needs to place a passive harmonic filter from the editor toolbox, open the settings, and go to the parameters page. Then, select the filter type, and click on the "Size Filter" button. The information needed will be harmonic order, harmonic current, existing pf, desired pf, and MVA values. Once this is filled in, click on "size filter" and then press on "substitute," finally, the option to add a resistor and a value of Q factor can be added as well.

The Q factor is the tuning response of the single resonant frequency filter. For a single-order passive harmonic filter, which typically comprises a capacitor, inductor, and resistor, the Q factor, or quality factor can be calculated from the following equation.

$$Q_f = \frac{n * X_L}{R} = \frac{X_C}{n * R} \quad (1)$$

where in formula (1) n is the harmonic order, R is the resistance, X_L is the inductor reactance and X_C is capacitor reactance. It is important to note that the inductor reactance and capacitor reactance are values that ETAP just calculated.

It is possible to calculate the single-tune filter parameters by hand based on [22]. An example for MCC PDP: B-B which is a 480-volt bus that operates at 91.8% power factor (PF). The desired for this calculation shall be 99%, and the 5th harmonic will be eliminated which ETAP shows that there exists 8 amps at the 5th harmonic. The real power in the bus is 18.943kW.

$$Q_{3PH_{filt}} = P_{real} * [tan(\cos^{-1}(\phi_{original})) - \tan(cos^{-1}(\phi_{desired}))$$

$$Q_{3PH_{filt}} = 18.943 * [\tan(cos^{-1}(0.918)) - \tan(cos^{-1}(0.99)) = 5.484 \text{ kVAR}$$

For a 480V system, the wye-equivalent filter (capacitive) reactance is as follows.

$$X_{filt} = \frac{kV_{ll}^2}{Q_{filt}} = \frac{1000 * .480v^2}{5.484\ kVAR} = 42.011\ \Omega$$

Tuning the filter for the 5th harmonic (as ETAP requires integer values).

$$X_{filt} = X_{Cap} - X_L$$

Solving for the X_{Cap} to determine the desired capacitive reactance:

$$X_{cap} = \frac{X_{Filt} * h^2}{h^2 - 1} = \frac{42.011 * 5^2}{5^2 - 1} = 43.76\ \Omega$$

$$X_L = \frac{X_{cap}}{h^2} = \frac{43.76}{5^2} = 1.75\ \Omega$$

In ETAP, the values entered at the capacitor and inductor kVAR and X_{L1} would be 5.484 kVAR and 1.75 Ω into the capacitor C1 and Inductor L1 respectively. A diagram of a single-tune filter is shown in Figure 7.

Only single-tuned passive filters are used in this study because this type of filter is the most common type in the wastewater industry. Further, the harmonic analysis (Figure 4) shows that the 5th harmonic is dominant. In addition, single-tuned passive filters were chosen over high-pass and low-pass filters. Low pass filters would let the lower order harmonics through the system, which is problematic as the lower order harmonics have a greater presence in the system. High-pass filters are more likely to be more helpful as they would block the lower harmonics but that would also affect the fundamental frequency, which is vital for the operation of the pumps present in the electrical system.

3.2 Outcomes of Harmonic Analysis and Mitigation

Outcomes of harmonic analysis

The preliminary analysis shows that a THD of 5.28% exists in the system. This is slightly above IEEE-519 standards as the PCC needs it to be less than 5% so corrective action must be taken. The system's current harmonics were calculated to verify if those met the standard set in Table 2. For the sake of simplicity, the utility grid is considered an infinite bus. The maximum short-circuit current at the PCC was calculated with the MVA method, the MVA method utilizes the following formulas (2) and (3):

$$S_{fault_{duty}} = \frac{XFMR_{MVA}}{Z\%} \quad (2)$$

$$I_{SC} = \frac{S_{fault_{duty}}}{\sqrt{3} * V_{pri}} \quad (3)$$

The calculation results are:

$$S_{fault_{duty}} = \frac{2.5MVA}{5\%} = 50MVA$$

$$I_{SC} = \frac{50MVA}{\sqrt{3} * 35.4KV} = 815.46\ A$$

Figure 3 shows the maximum demand load current at the PCC under load operating conditions. Calculating $\frac{I_{SC}}{I_L}$ comes out to a ratio of 15.2, suggesting that Row 1 of Table 2 applies to this project. Figure 4 shows that the 5th harmonic current is 7%, which fails to meet the limit in Table 2 (4%).

Outcomes of harmonic mitigation methods

There are multiple ways to make the system compliant. The authors first tried to determine why there was such a massive amount of harmonic noise occurring at the 5th harmonic order. Research done before the project suggests that most of the noise should be found at the distribution panel where the loads, such as lighting and UPS, are located. After turning off the breaker that feeds the distribution panel's transformer, it was found that while some of the harmonic noise did come from the distribution panel, it was not even 1% of the THD of the system. Another prior experience suggests that the harmonics could come from the VFDs. Isolating Bus B (Figure 2) showed that the total demand load at the PCC was only 9.4 A, but the THD was 51.01%. The authors tried different harmonic mitigation methods and obtained different results.

Method 1 – Passive filter at MCC (Motor control center): Figure 5 shows the breakdown of the harmonic current for the single VFD configuration at Bus B. Figure 6 and Figure 7 show the values gathered to size a filter which is placed at the MCC (which is fed through a transformer connected to Bus A). After installing the filter at the MCC, the THD of that bus goes from 7.81% to 7.55%, meaning that placing a filter at the MCC is not effective.

Method 2 – Passive filters at Bus A and Bus B: Installing a passive filter at buses A and B (Figure 2) greatly improves the THD of the system. Figure 8 shows the results of installing the passive harmonic filters on both buses. Buses A and B were chosen because they were further upstream. Multiple smaller filters could be installed throughout each of the main buses. This was another experiment conducted on the system, but it was found to be not necessary.

Checking the current distortion on the system, the highest harmonic was found at the 5th and 7th harmonics which held a total of 2.4% and 1.6% respectively. These values are below the 4.0% THD limit for harmonic orders between 3rd and 11th.

Method 3 – Using 12-pulse VFD: With the 18-pulse VFDs now meeting IEEE Std. 519, the authors tried to step down VFD to 12. The motivation is that a 12-pulse VFD is cheaper than its 18-pulse counterpart. Background research and common sense suggest that, if one steps down the number of pulses in the VFD, the overall harmonic distortion will increase at the VFDs, typically starting from N-1 where N is the number of pulses in the VFD. This is due to the smaller phase shift between the rectifier portion of the VFDs, which results in an overall better harmonic cancellation.

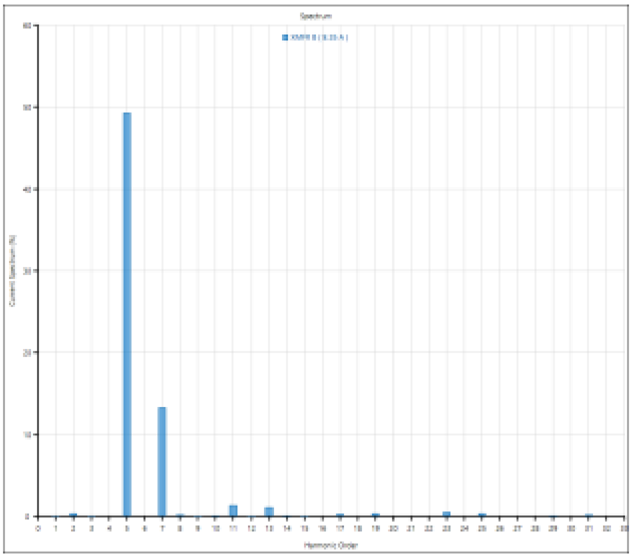

Fig. 5: Current THD for the single VFD configuration at Bus B

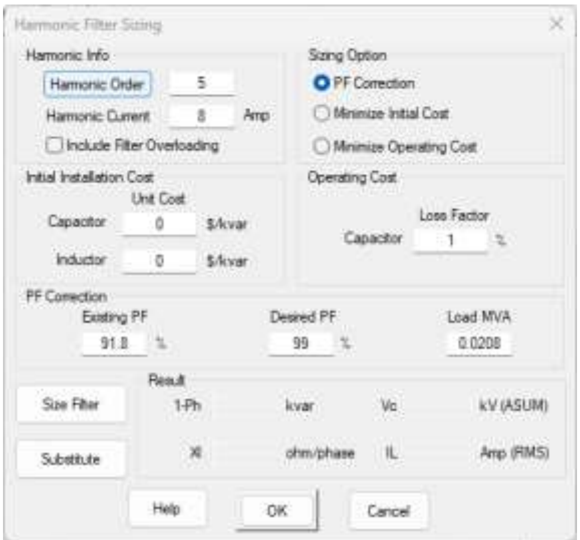

Fig. 6: Harmonic filter sizing done with ETAP for the MCC filter

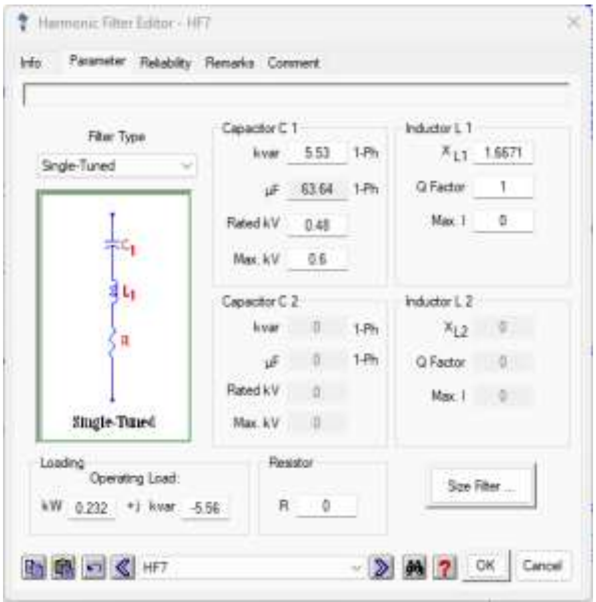

Fig. 7: Resulting values from the sizing shown in Figure 6

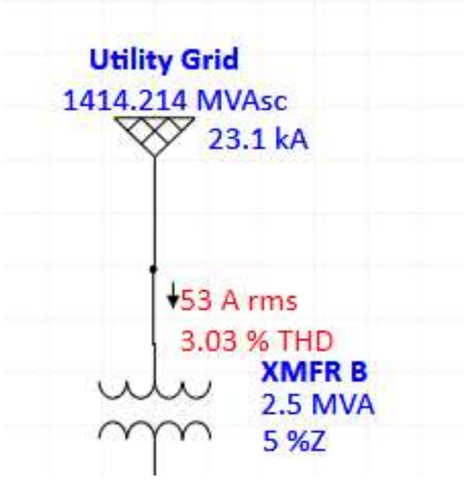

Fig. 8: THD after the first version of the passive harmonic filter was installed

Table 3. EATON's MCC – Low Voltage Design Guide, [23]

Harmonic Current (Amperes)	Input Voltage	Disconnect Type	Standard Unit Space ⓘ Inches (mm)	Standard Unit Space (X)
50 A active harmonic filter ⓘ	Up to 480 V	Molded case switch	72.00 H x 20.00W (1828.8 H x 508.0 W)	12X
100 A active harmonic filter ⓘ	Up to 480 V	Molded case switch	72.00 H x 20.00W (1828.8 H x 508.0 W)	12X

Turning off all the harmonic filters resulted in a THD of 8.8%. The authors use the same passive harmonic filters that were sized for the 18-pulse VFDs to verify if this would be enough to correct the harmonic distortion in the system. The voltage harmonics were brought down to meet IEEE Std. 519 but the current harmonic distortion failed since the 11^{th} and 13^{th} harmonics were measured at 3.34% and 2.6%. Out of curiosity, the authors also added passive filters in the other buses, but this method could never quite limit the overvoltage that would occur. Installing the filters at Bus A and Bus B would put all the main buses at 99.65% of the rated 4160-V voltage capacity, which is disadvantageous.

It should be noted that large equipment have a maximum voltage that they can accommodate which is higher than their operational voltage. For example, MCCs are typically operated at 480V but they are rated for 600V. Another example is that a 4.16kV switchgear can be operated at up to 4.76 kV. However, it is not desirable to operate equipment at or near the upper limit of equipment voltage because this increases the risk of having arc flashovers.

Method 4 – Using 6-pulse VFD: Moving forward to the analysis of the possible use of 6-pulse VFDs, the authors turned off all the harmonic filters and checked the THD of the system. The THD of the system was 15%, which is triple the allowed THD. Turning on the previous filters lowered the THD to 6.5%. In addition, the authors tried to space out the filters to see if that would make a difference. However, the THD of the system did not change enough to make a difference. It failed the current harmonic distortion at multiple harmonics ranging from the 5^{th} order to the 17^{th} order. The outcomes indicate that using 6-pulse VFD is not feasible for this system as IEEE Std. 519 limits are not met.

4 Real-world Challenges and Lessons Learned

To add equipment to the switchgear and MCCs, the authors must determine if there is enough space in the MCC to add the passive harmonic filters. It is known that EATON company manufactures the existing MCCs and Switchgears, but the serial code of the equipment is not known. EATON has MCC design guides that show how much space active harmonic filters would take in an MCC, as shown in Table 3.

Table 3 shows that the active harmonic filter takes up 72-inches in height and 20-inches in width. 72-inches is the maximum size of the usable space in an MCC. MCCs are typically 90 inches in height but the top and bottom 9-inches are used as wireway space. This means that an active harmonic filter takes up a whole MCC cabinet. The active harmonic filters are in the EATON design guide because passive harmonic filters are considered out of date. Because the system's as-built drawings are missing an elevation, it is impossible to determine if there is sufficient space for the filters. The other option would be to install another MCC and have some conductors go to that MCC.

For filter cost analysis, one of the authors contacted a well-known harmonic filter manufacturer, TRANSCOIL, also known as “TCI,” to obtain a quote estimate for the pricing of the harmonic filters. It turns out that medium voltage harmonic filters are either no longer made or incredibly scarce. This is confirmed by another manufacturer, Rockwell Automation.

The TCI representative said that the most common harmonic filter was 150A as anything over that size became “incredibly expensive” and doubled in footprint. If a harmonic filter were required what could be done was to add a step-down 4160V/480V transformer and connect the passive harmonic filter as a load. The idea behind this is that the passive filter will correct harmonics upstream. However, there are problems with this solution. The first problem is that if the harmonics are large enough, the harmonics can cause overcurrent in the transformer. The second problem is that the equipment is now being doubled and the overall cost would be more expensive. Introducing a transformer also adds to the cost over time of the system as there will be copper and winding losses in the transformer. It is also important to keep in mind that the current harmonic distortion found when stepping down the VFDs occurs at 4160V, and when we step up voltage from 480V to 4160V we step down in current, so to influence the current present in the high side of the transformer, there would need to be a massive amount of current in the low voltage side. This results in having to use much bigger harmonic filters at the low voltage side.

Another challenge involves the equipment modeling capability of ETAP. Because of ETAP limitation in modeling capability, the obtained results are close, but may not be the same as real-world system responses. Though, it is believed that ETAP is useful to use as a frame of reference. Further, ETAP only supports the modeling of passive harmonic filters. When customizing the VFDs, there is an option to add equipment before its input terminals (line reactors), as well as after the output terminals (load reactors) or in the middle of the equipment (DC chokes), but ETAP does not allow users to do that.

These are real-world challenges that design engineers and professionals should be aware of when developing solutions for controlling harmonics.

5 Conclusion

This study diagnoses and analyses harmonic sources in the electrical system of a wastewater treatment plant and explores several methods to mitigate the harmonic situation using simulation software ETAP. The data input into the software was based on actual equipment used in the wastewater treatment plant. The major findings are as follows:

a) The biggest contributor to the harmonic distortion in this plant ended up being the various variable frequency drives used in the system.
b) Using high-pulse variable frequency drives, such as 18-pulse, is proved to be beneficial for harmonic reduction. ETAP is limited to an 18-pulse drive configuration, but variable frequency drive technology has advanced to the point that there is now an active front-end version, which claims to have a unity power factor.
c) Adding a passive harmonic filter higher up the power distribution or adding passive filters to the feeder busses, such as MVDB-A 1A and MVDB-A 2A, is not effective in lowering the THD of the system. Further, this would have the drawback of increasing the rating of the voltage that would exist on the buses.
d) Installing passive harmonic filters in appropriate locations, in this case, in parallel with the greatest contributor of harmonics – the VFDs, helps lower voltage and current harmonics to meet IEEE Std. 519 limits. In the case of this study placing the filters in Bus A and Bus B seemed to be the most effective locations to deal with the harmonics generated by the VFDs in the system.

Power quality has become a pressing issue as power electronic equipment has been increasingly used in industrial sectors. All the equipment generates harmonics which adversely impact the host power system that supplies the equipment. Per the U.S. National Renewable Energy Laboratory, [24], the U.S. annual economic loss due to power outages is $45.7 billion, and due to power quality issues is $6.7 billion. Problems caused by harmonics are power quality challenges. Therefore, solutions must be sought to solve the harmonics-related problems.

Mitigating harmonics in wastewater treatment plants is a special industrial issue that has not received sufficient attention, based on our observation. Our study, therefore, helps fill in this gap. Our study findings contribute some insight understanding, experience, and methods for engineers when developing solutions for controlling harmonics in similar plants or industrial applications. Effective mitigation of harmonics enables plants and manufacturing facilities to meet IEEE 519 standards, and potentially obtain significant savings, which results from more efficient operation of their equipment. It also ensures proper waveforms for the correct operation of power systems to avoid damaging outages.

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APPENDIX

Table 4. MVDB-A 1A and 2A load schedule

MVDB-A 1A and MVDB-A 2A Load & Demand Schedule					
Description	**Motor HP/ Device kVA**	**Connected Load kVA**	**Connected Load Amps**	**Demand Load kVA**	**Demand Load Amps**
Pump "P1"	500	471	65	0	0
Pump "P2"	800	775	108	775	108
Pump "P3"	800	775	108	775	108
Pump "P4"	500	471	65	0	0
Total:		**2492**	**346**	**1550**	**215**

Table 5. Bus A and Bus B load schedule

BUS A and BUS B Load & Demand Schedule					
Description	**Motor HP/ Device kVA**	**Connected Load kVA**	**Connected Load Amps**	**Demand Load kVA**	**Demand Load Amps**
MVDB-A 1A and 2A	2492	2492	346	1550	215
Pump "P5"	800	775	108	775	108
Pump "P6"	800	775	108	775	108
Pump "P7"	800	775	108	775	108
Transformer "B-A"	250	215	30	215	30
Subtotal:		**5032**	**700**	**4090**	**568**

Table 6. PDP: B-B load schedule

PDP B-B Load Schedule			
Description	**Motor HP/ Device kVA**	**Connected Load kVA**	**Connected Load Amps**
Switchgear Room Roll-Up Door	2	3.4	3.4
Transformer "B-C"	45	54	54
SUBTOTAL:	**47**	**57**	**57**

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- Axel Rivas Bonilla: Identification of research issues, system data acquisition, design and implementation, simulation, writing an original draft, and revising.
- Ha Thu Le: Refining research issues and scope, methodology, technical advising, refining simulation scenarios, review of results, formatting and editing the final draft, revising the reviewed paper to meet publisher requirements.

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