Simple Mistakes Lead to Harmonic Distortion Problems in Water Treatment Plant

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Abstract – Specifications requiring compliance with IEEE Standard 519 [1] compelled the supplier of twin 400-kW ozone generation equipment to install multistage harmonic filters and isolation transformers at a water treatment plant in the midwest. The vendor, however, violated basic application guidelines associated with these devices, with undesirable results for operators of the facility. Damage to emergency lighting circuits, and high harmonic distortion readings in the facility were traced to operation of the ozone generators, despite the IEEE 519 specifications applied at the ozone power supplies, and vendors' attempts to head off potential harmonic problems with multistage shunt filters and isolation transformers. This paper identifies those errors, offers simple calculation methods to predict problems in advance, and outlines solution options to reduce operating problems in the facility.

I. INTRODUCTION

In recent years, the process of disinfecting fresh water has shifted from chlorination to ozone treatment. The ozone generator requires a dc source for producing the high frequency ac necessary to ionize oxygen and produce ozone. The water treatment plant that is the subject of this paper operated twin 400 kW ozone generators. Each was equipped with an electronic power supply consisting of a 6-pulse bridge rectifier utilizing silicon-controlled rectifiers (SCRs) to produce a controlled dc source.

Since the SCRs only conduct current during 120 degrees of each half cycle, the line current is rich in harmonics. In addition, SCR-controlled bridge rectifiers also produce line notching, due to the brief short-circuit that occurs when one pair of SCR's begins conducting an instant before the previous set has turned off. See figure 1.

In an unsuccessful attempt to comply with IEEE 519 terminology in the consulting engineer specifications, the ozone generator vendor installed a multistage harmonic filter, and an isolation transformer at each ozone power supply. The twin ozone generators were served from similar 480-V switchboards connected by a normally-open tie breaker, as shown in figure 2. Each was also equipped with a 500-kVA isolation transformer, and a three-stage harmonic filter. Lighting ballasts being affected by operation of the ozone generators were served from the same 480-V switchboard through a 277-V lighting panel.

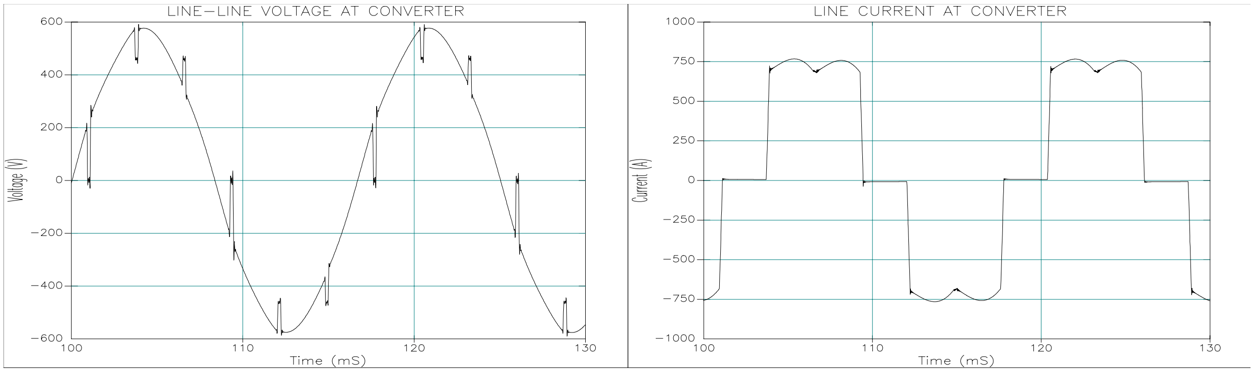

Figure 1 – Typical line-line voltage and phase current associated with operation of an SCR-controlled load similar to the ozone generators used in this water treatment plant.

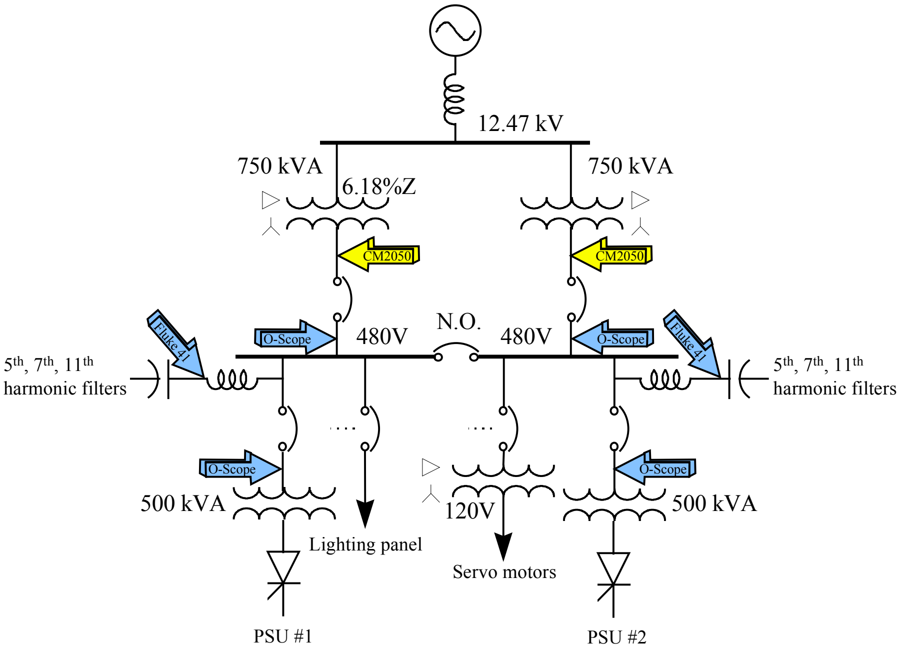

Figure 2 – Simplified single-line diagram of water treatment plant power system. Block arrows indicate points at which power monitoring readings were performed. Ozone generator power supplies, PSU #1 and PSU #2, are depicted by SCR symbols.

II. EMERGENCY LIGHTING BALLAST PROBLEMS

Despite the harmonic filters and isolation transformers, harmonic voltage distortion at the 480-V switchboards during ozone generator operation often exceeded 10% THD. In addition, plant operators correlated numerous failures of emergency lighting ballasts with ozone generation. The attempts to reduce harmonic distortion and notching failed because basic application considerations for the filters and isolation transformers were violated.

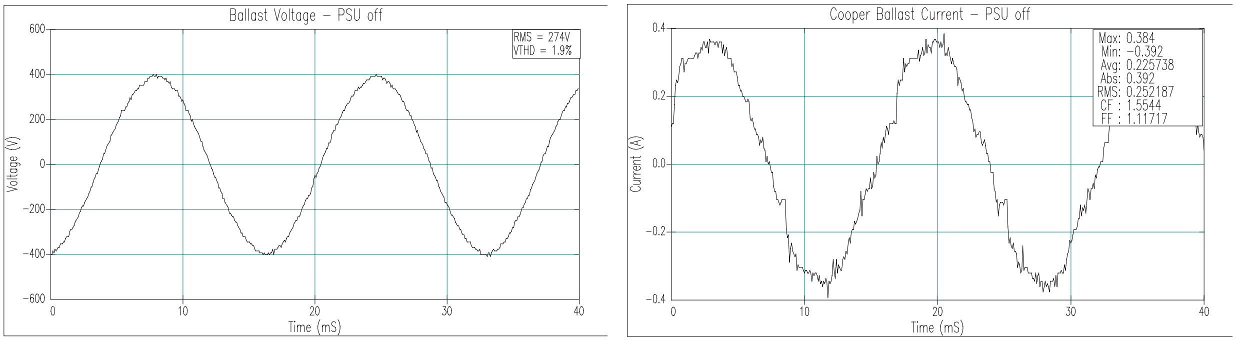

Figure 3 – Voltage (left) and current (right) at emergency lighting ballast with ozone generators off. Note that peak current is about 0.4 A, and effective current is about 0.25 Arms

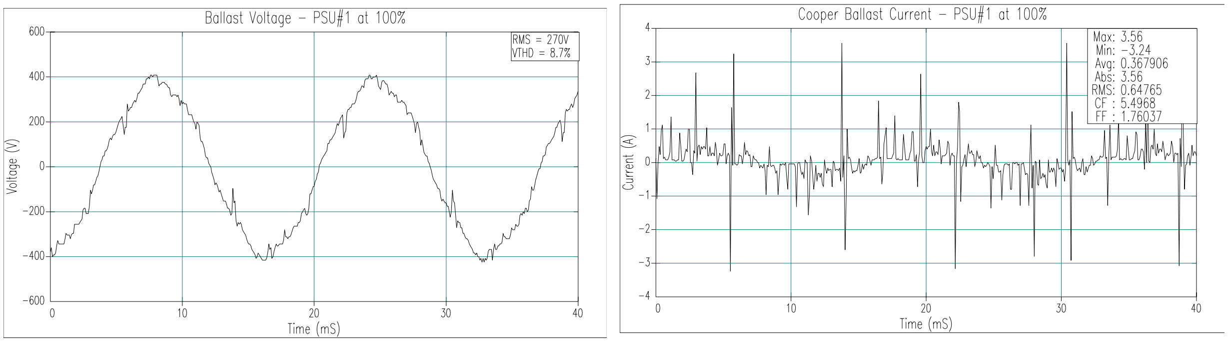

Figure 4 – Voltage (left) and current (right), again measured at emergency lighting ballast, during operation of one ozone generator at 100% power level. Ballast current has increased to 3.6 Apeak and 0.65 Arms. Large current spikes coincide with voltage notches.

III. IEEE 519 “COMPLIANCE”

Job specifications at the facility required that harmonic distortion be limited in accordance with IEEE Standard 519-1981 (even though the current version of the standard was updated in 1992). While the application of IEEE 519 at a 480-V bus inside a facility is somewhat outside 519’s original purpose, Table I below shows that harmonic limits for voltage distortion and notching were being exceeded at the switchboard. This finding was unexpected due to the existence of the harmonic filters and isolation transformers. Only closer inspection of the filters and power system design, as will be described later, exposed the design flaws that led to the excessive distortion.

Table I compares measured and calculated harmonic and notching data at the facility with the limits specified in IEEE 519. The limits apply to general systems serving both electronic loads and other building loads; different limits are provided for special (critical) applications and dedicated systems. Data was nearly identical for both 480-V switchboards.

	519 Limit	Measured	Calculated
Voltage THD (%)	5	8.7	
Max. Indv. Harm. (%)	3	6.1 (5th)	
Notch Depth (%)*	20	44.7	
Notch Area (V-μs)	22800	48960	
Imp. ratio min., ρ*	5		2.4

* The impedance ratio limit was replaced in 519-1992 with notch depth.

Table I – Harmonic voltage distortion and notching measurements exceeded limits proposed in IEEE 519. The impedance ratio is the ratio of the source impedance at the ozone power supply terminals compared to the source impedance at the line side of the isolation transformer serving the ozone power supply.

The last three categories in table I, notch depth, notch area, and minimum impedance ratio, pertain to notching measured in the line-line voltage. These limits are exceeded due to the high impedance of the main service transformers relative to the ozone generator isolation transformers, as will be shown.

IV. DESIGN FLAWS

A. INCORRECT HARMONIC FILTER TUNING

1. Filter Tuning Issues

Possibly one of the least considered but most important considerations in applying harmonic filters is the tuning frequency of the capacitor/inductor combination. Tuning has a dramatic effect on the component duties and the potential for future equipment problems. The purpose for installing tuned capacitors should be well defined. If the main objective is to correct power factor in the presence of harmonics, a lower tuning frequency should be chosen to lessen the impact of harmonic sources not accounted for in the initial design. However, if a significant percentage of internally generated harmonic currents must be removed – as was the case for the water treatment plant – then a tuning frequency closer to the predominant harmonic(s) must be chosen. Higher tuning usually requires a significant amount of system evaluation and simulation.

Typically, series-tuned filters are tuned 5-20% below the first predominant harmonic – normally the 5th (300 Hz) for industrial networks. Several reasons dictate this practice. First, tuning directly at a predominant harmonic will result in large amounts of harmonic current flow through the shunt elements, to the point that their ratings may be exceeded.

Second, virtually all low-voltage capacitors on the market today are constructed of metalized polypropylene film which exhibits a self-healing characteristic. This characteristic results in a gradual decrease in capacitance over the life of the capacitor. As can be seen in figure 3, a parallel or anti-resonance ("peak" on the impedance scan) always occurs just below the tuning frequency of each filter. This gradual loss of capacitance tends to shift the anti-resonant point over the harmonic intended to be filtered. This condition will result in the harmonic amplification that is the culprit behind most harmonic problems.

2. Calculating Filter Tuning Points

Three single-tuned filters were installed at the water treatment plant – one each tuned exactly to the 5.0th, 7.0th, and 11.0th harmonics. The impedance scan for the filter bus, obtained by simulation, is presented in figure 3.

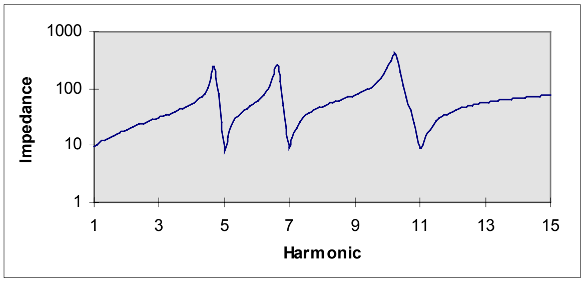

Figure 5 – The impedance of the multistage harmonic filter system at different harmonic frequencies was estimated using a computer simulation tool. Note that the scan identified tuning points at 5.0, 7.0, and 11.0. Harmonic tuning points are typically chosen 5-20% below the characteristic harmonic.

Prior to performing the harmonic simulation, field data and hand calculations were used to determine the approximate filter tuning points. Nameplate information, read directly from the inductors and capacitors comprising the multistage filters, showed the following values.

Nameplate Information			
Harmonic Filters	**5th Stage**	**7th Stage**	**11th Stage**
Inductance, millihenries	0.489	0.416	0.253
Capacitor Voltage, Vrms	480	480	480
Capacitance, kvar	50	30	20
Utility Transformers			
Capacity, kVA	750		
Impedance, %	6.2		
Isolation Transformers			
Capacity, kVA	500		
Impedance, %	5.5		

Table II – Nameplate information from the inductor and capacitor components comprising the multistage harmonic filters.

The tuning frequency of a single stage equals $h_0 \quad \sqrt{\frac{X_C}{X_L}}$. The tuning points were calculated using the nameplate information and the following formulas for X_C and X_L.

For the 5th stage of the filter,

$$X_C = 0.48^2\ kV / 0.05\ Mvar = 4.61\ ohms;$$

$$\text{and } X_L = 377 * 0.000489\ H = 0.184\ ohms.$$

Dividing X_C by X_L and taking the square root,

$$h_0 = sqrt\ (4.61 / 0.184) = 5.0.$$

Plugging in the nameplate information for the other filter stages yields similar results: 7.0 and 11.0 tuning points.

B. IMPROPER CAPACITOR SELECTION

As indicated earlier, harmonic trap filters consist of two common components, inductors and capacitors, selected and arranged to remove and cancel harmonic currents produced by electronic loads. In addition to the filter tuning points described in the preceding section, selection of the inductors and capacitors that make up the filter is another crucial consideration.

Capacitor selection, in particular, must consider the special duty placed on these components. Standard three-phase delta connected capacitors are used in filter applications, but capacitors with voltage ratings 10-25% higher than the system rating are required in filters. IEEE Std. 18 [3] requires capacitors to have the following overload capabilities:

- 110% of rated rms voltage
- 120% of rated peak voltage
- 135% of rated reactive power

Operating the capacitor within rated limits under normal conditions, thus leaving the overload margins for contingency situations, is desirable when designing traps.

Unfortunately, this practice was not followed in the design of the filters at the water treatment plant. The capacitors used in the filters were nameplate rated 480V, as shown before. All three filters were overloaded in one or more categories as shown in table III below. The 5th harmonic filter under normal conditions would be severely overloaded in all categories. Because the capacitor cell had lost a significant amount of capacitance, the numbers are skewed downward.

PSU filter*	Limit	5th	7th	11th
RMS volts (%)	110	105	106	104
peak volts (%)	120	127	136	116
kvar (%)	135	76	200	209
Inductor rating (%)	100	37	80	81

* Line voltage measured 487V.

Table III – Improper selection of the capacitors that were used in the multistage harmonic filters at the water treatment plant led to excessive peak voltage on these components.

There are several causes for these overload conditions. First, the fundamental voltage rises across a capacitor in a series tuned configuration. The voltage division analysis can be simplified to yield the following formula for fundamental voltage rise on the capacitor.

$$\%V_{rise} \quad \frac{h_o^2}{h_o^2 \quad 1},$$ where h_0 is the harmonic tuning point.

For example, the 5th harmonic filter component is subjected to an effective voltage rise of $5^2 / (5^2 – 1) = 25 / 24 =$ 104%.

Second, the capacitor will draw a large amount of current near the tuning frequency, causing the peak voltage to rise even further. The voltage increase occurs because the fundamental and harmonic components tend to peak at the same time. This increase in peak voltage can puncture the dielectric film in the capacitor elements resulting in a loss of capacitance.

Inductors have their own application considerations when applied in filters. Low voltage filter inductors are typically three-phase iron-core devices. The inductance is selected based on the series capacitance and the desired tuning frequency. Additional rating requirements are based on thermal concerns. The total rms current that will flow through the reactor must be known. Assuming all available harmonic current will flow through the filter and adding a 25% safety margin for unknown harmonic sources and background utility system distortion is generally adequate. The harmonic spectrum of the current must also be specified since reactor heating and noise is frequency dependent.

Since typical overcurrent devices will not adequately protect the reactor in an overload condition, the installation of a thermal protective device in the reactor, such as a thermistor and relay, is highly recommended. Thus, if the filter does become overloaded due to a shift in tuning frequency or unknown harmonic sources, the overloaded unit can be de-energized before irreversible damage occurs.

C. INADEQUATE CONSIDERATIONS FOR VOLTAGE NOTCHING

1. Isolation Transformer Selection

As pointed out earlier, the ozone power supplies were equipped with SCR-controlled rectifiers that tend to produce voltage notching during normal operation. These notches are not reduced by conventional harmonic trap filters, but require other design considerations to reduce their effect on other loads.

The usual method of limiting adverse effects associated with notching is to apply isolation transformers between the SCR-controlled load and other loads. A quick review of figure 1 confirms that the ozone power supplies were "isolated" from the rest of the 480-V system with isolation transformers. Yet the voltage notches are clearly evident at the emergency lighting ballast, as shown in figure 3. Why were the isolation transformers ineffective in reducing these notches?

Note in figure 1 that the isolation transformers are rated at 500-kVA, and the 12-kV to 480-V utility transformers are rated at 750-kVA. When the SCR load and its isolation transformer are large in comparison to the upstream transformer serving them, the isolation transformer effectiveness in notch reduction is considerably compromised. In fact, as the last row in Table I suggests, the impedance ratio between the isolation transformer and its immediate source transformer should exceed 5:1. Simply put, the source transformer should be several times larger than the isolation transformer for the same nameplate percent-impedance in order to be effective.

2. Source Impedance Estimating Method

As with harmonic filter tuning points, simple hand calculations can aid in determining if the transformers' impedance ratio is at least 5:1. As shown in figure 5, the impedance at the ozone generator (denoted by the current injection symbol on the right side of the diagram) is comprised of the isolation transformer and the service entrance transformer in series. The source impedance at the line side of the isolation transformer is simply the service entrance transformer impedance.

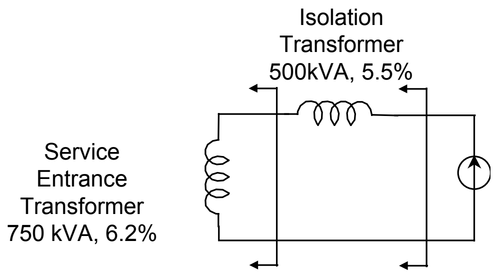

Figure 6 – The impedance ratio can be estimated using hand calculations that assume that the isolation transformer, and its immediate source transformer, are the major impedance components.

In ohms, the impedance of a transformer is

$Z\ (\Omega) = kV^2 * Z\% / 100 / MVA$.

For the isolation transformer,

$Zi = 0.48^2 * 5.5 / 100 / 0.5 = \mathbf{0.0253\ \Omega}$.

Likewise, for the service entrance transformer, Zs = 0.482 * 6.2 / 100 / 0.75 = **0.0190 Ω**.

So the impedance ratio as designed is (0.0253 + 0.0190) / 0.0190 = **2.3**!

This impedance ratio is considerably below the recommended minimum of 5.0. The service entrance transformer, for the same 6.2% impedance, would have to have a capacity in excess of 2250 kVA in order to meet the ratio requirement necessary to limit voltage notching on the 480-V system.

V. FILTER DAMAGE EXPOSED BY MEASUREMENTS

Measurements were collected at several key locations near the ozone generator power supply in an attempt to explain 8-9% voltage THD appearing at the 480-V switchboards. The figures below expose the problem, the 5th harmonic filter was damaged and rendered ineffective. The current waveform and harmonic spectrum recorded at the primary of the drive isolation transformer. The waveform is characteristic of a current source inverter variable frequency drive (VFD). Figure 4 shows the current waveform and spectrum recorded ahead (source-side) of the harmonic filters. The 5th harmonic current ahead of the filter, which is expected to be *less* than the load current component, was actually 1.5 times the 5th harmonic load current!

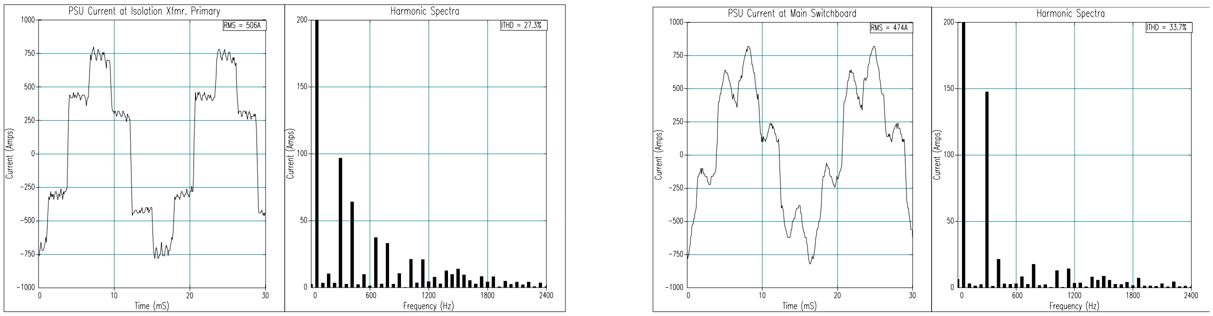

Figure 7 – Current waveform and harmonic spectrum measured on the line side of the harmonic filter (two figures on the left) showed about 150 A of 5th harmonic current. The same measurements on the load side of the filter (right) showed only 100 A injected by the ozone generator. This harmonic current amplification indicated that the 5th harmonic filter was damaged.

VI. SOLUTION OPTIONS

A. SUMMARY OF OPTIONS

Recommendation	Cost	Effectiveness	
		Notch	*Distortion*
Re-tune multistage harmonic filter	Low	Low	Medium
Replace multistage with 5th only	Medium	Low	Medium
Replace multistage with active filter	Medium	Low	High
Serve lighting from separate transformer	High	High	Medium
Install RC filters	Medium	Medium	Low
Replace emergency lighting ballasts	Low	Medium	--

Table IV – Possible solution options for the water treatment plant harmonics and notching problems, ranked according to cost and effectiveness in reducing notching and harmonic distortion.

B. HARMONIC DISTORTION REDUCTION OPTIONS

1. Re-Tune Existing Multistage Filter

The filters at the water treatment plant were redesigned by selecting 600V-rated capacitors that would tune appropriately with the existing inductors without exceeding rated conditions under normal operation. This solution resulted in a reliable filtering system that limits voltage distortion contribution from the ozone generator power supply to about 1.5% THD.

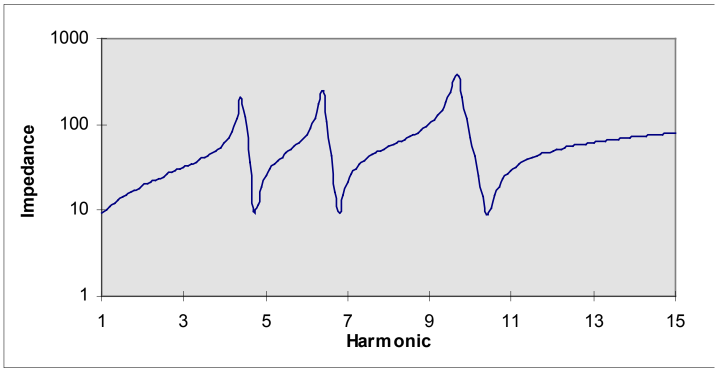

Figure 8 – The capacitors in the existing multistage filter can be replaced with 600-V capacitors, selected to achieve tuning points well below each characteristic harmonic, as shown above.

2. Replace Multistage Filter With Single-Stage Filter

In most cases, multistage harmonic filters are not required. A 5th harmonic trap can remove approximately 80% of the 5th harmonic and 30% of the 7th harmonic depending on the source impedance. Properly designed, such a system will generally bring an industrial facility within IEEE 519 limits without additional stages. In fact, only a marginal improvement is gained using the multiple-tuned system at the water treatment plant compared to a 5th harmonic trap of the same total kvar. Current THD decreases from 20% to 16% for the multiple-tuned system when compared to the re-designed 5th-only system. Installing the single trap simplifies the design and greatly reduces the capacitor duties resulting in a more reliable system.

3. Active Filters

In some cases, a single-stage filter is insufficient to meet IEEE 519 guidelines, and a multistage filter, as previously pointed out, can be difficult to apply. In these cases, an active harmonic filter in conjunction with a single-stage filter, provides the best results. These hybrid filter units offer dramatic reductions in harmonic distortion, without the tricky application issues associated with multistage filters.

C. VOLTAGE NOTCH REDUCTION OPTIONS

1. Retrofit Options for Notch Reduction Are Costly

As the options outlined below will demonstrate, solving the voltage notch problem after the power system is installed and operating is costly and difficult. The superior alternative is to recognize the voltage notch concern at the design phase of the project, and configure the distribution system to isolate the individual SCR loads from each other and from other loads in the facility. Simple guidelines, like the impedance ratio calculation, can be used to evaluate the potential for notching problems in a proposed facility so that mitigating techniques can be employed at the outset.

2. Replace Emergency Lighting Fixtures

The water treatment facility could address the notching issue at the load being affected, rather than by reducing the notch depth and width at its source. It was demonstrated that the emergency ballast circuit drew 2.5 times as much effective current at almost 10 times the peak current during ozone operation compared to normal conditions. The ballast circuit was inadvertently and unfortunately “tuned” to be sensitive to the sudden change in voltage associated with the notch. Other ballast configurations should be considered to determine their sensitivity to this notch.

3. Change Service Entrance Transformers

As mentioned in earlier, the required impedance ratio can be obtained by changing the twin service entrance transformers and installing larger (lower impedance) transformers. This change would provide the same reliability benefits as the previous design (both ozone generators can still operate if one service entrance transformer fails). The cost of the new transformers, plus all the other considerations associated with new conductors, overcurrent protection, greatly increased available fault current, make this option prohibitively expensive.

4. Serve Lighting Loads From Different Source

Rather than replace both service entrance transformers, a lower-cost option would be to set a new 12-kV to 480-V transformer dedicated to lighting and miscellaneous building loads. This would effectively isolate the ozone generators to the two 750-kVA transformers. Note that a new 480-V to 480-V transformer dedicated to lighting and building loads would not be sufficient since the 480-V system from which the new transformer would be fed is subjected to notching.

5. Install Resistor-Capacitor Notch Filters

Finally, the facility could consider installing a different kind of filter, termed an RC filter, based on its two major components, resistor and capacitor. A series-connected capacitor can be very effective in reducing notch problems, but an RC filter brings along its own set of application considerations. The necessary resistor component, for example, wastes energy and dissipates a considerable amount of heat that must be accommodated by building equipment and systems.

VII. REFERENCES

[1] IEEE Std 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.* New York: IEEE Press, 1993.

[2] IEEE Std 18-1992, *IEEE Standard for Shunt Power Capacitors.* New York: IEEE Press, 1993.

[3] IEEE Std P519A/D5, *IEEE Guide for Applying Harmonic Limits on Power Systems.* May 4, 1996, draft.