

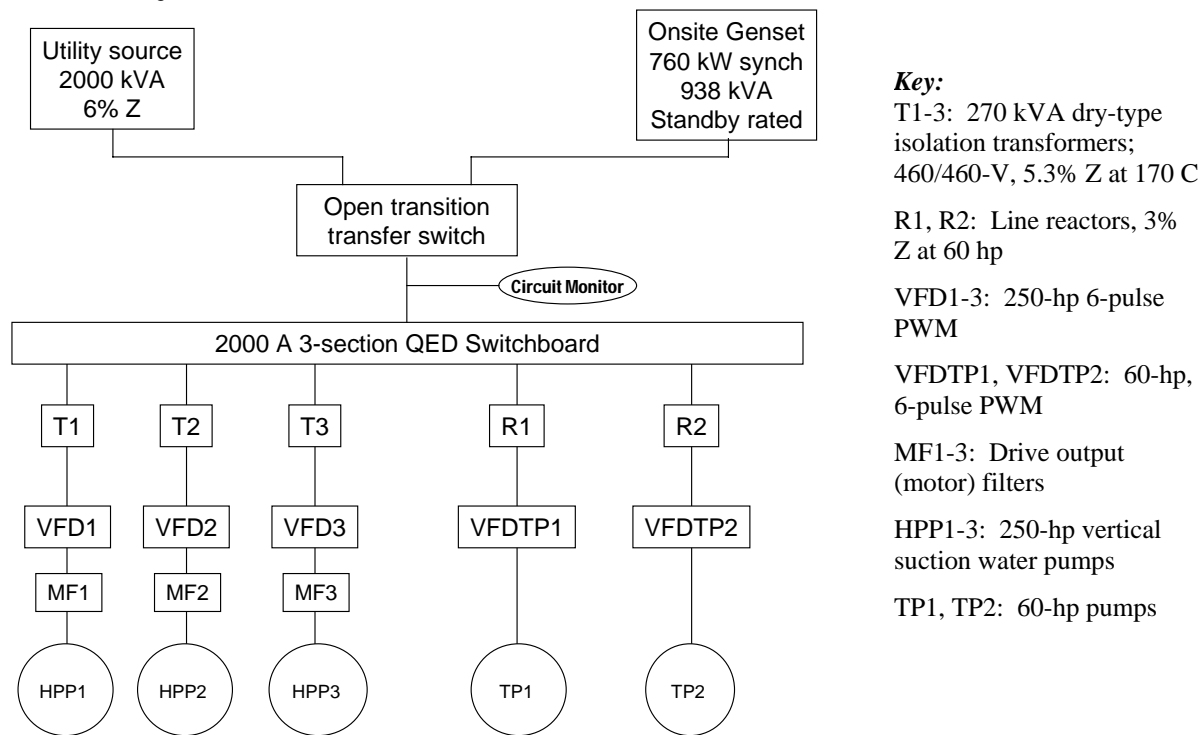
# Generator Loading, Harmonics Monitoring and Mitigating Analysis in a Water Treatment Plant

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## Abstract

Water treatment plants are often equipped with variable-frequency drives, ozone generators, and other loads that produce harmonic distortion. These facilities are also equipped, in many cases, with emergency standby generators required to operate critical electrical loads during extended electric utility outages. One such facility, a reverse-osmosis desalination plant located on the United States coast, was concerned about the ability of its 938-kVA standby generator to operate reliably in the presence of harmonic distortion injected by large VFD's serving pump motors. Subsequent harmonic measurements compared distortion levels on both utility and generator sources, and engineering analysis offered harmonic mitigating techniques indicated by the measured harmonic levels.

## Electric System



## Summary of Results

- ❖ Load measurements indicated that the onsite standby generator was loaded to about 53% of its rated capacity under the load conditions that existed at the time. Load levels peaked at 403 kW and 431 kVA during the test.
- ❖ Key power system parameters, including voltage regulation and unbalance, and current unbalance, were within acceptable limits during the test on both electric utility and generator sources.
- ❖ Harmonic distortion levels measured during the test did not cause noticeable operating problems for any of the plant equipment.
- ❖ Harmonic voltage distortion at the 480-V bus peaked at about 6.3% at highest load on the electric utility, and about 10.5% at highest load on the generator.

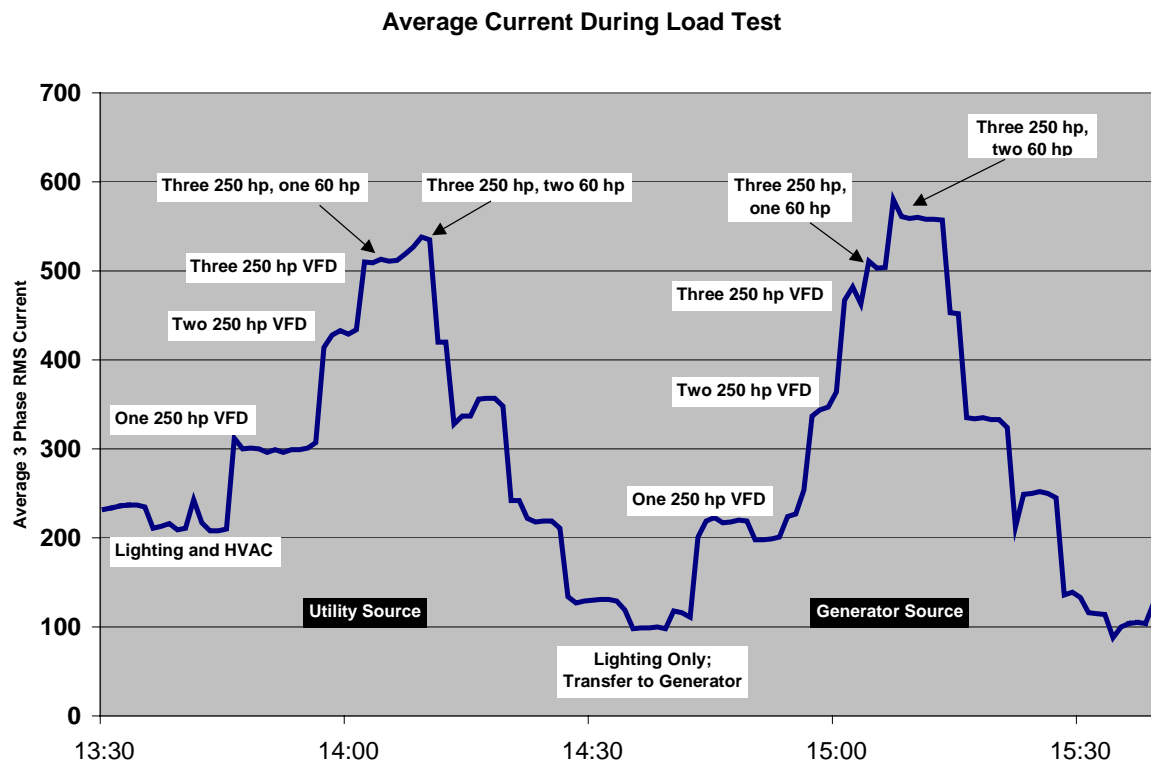
## Recommendations

- ❖ While harmonic distortion levels did not cause noticeable operating problems for the facility loads, harmonic reduction techniques should be considered in order to maximize equipment life and system reliability. IEEE Standard 519-1992 harmonic limits are being exceeded when operating on the standby generator.
- ❖ Bypassing one of the existing isolation transformers serving a 250-hp drive may achieve some beneficial effects due to increased harmonic cancellation of 5<sup>th</sup> and 7<sup>th</sup> current components, but this measure should be considered temporary.
- ❖ The better solution is to replace one delta/wye isolation transformer with a delta/zig-zag transformer to improve cancellation while maintaining attenuation effects.
- ❖ The best solution is to install an active harmonic filter at the service entrance.
- ❖ Onsite power monitoring should be installed to track performance of desalination facility in harmonic distortion, voltage quality, disturbances, and costs.

## Monitoring Results

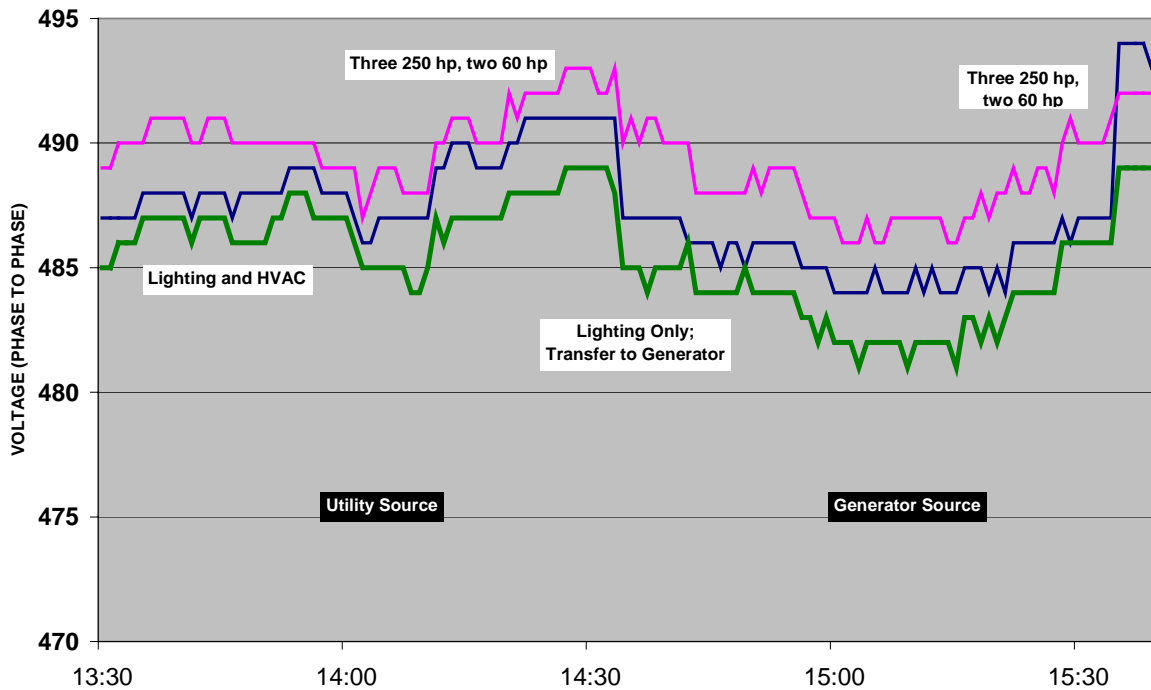
### Summary

Testing was performed at the line (source) side of the Square D QED switchboard serving the desalination facility. Testing was performed with a PowerLogic CM4000T Portable Circuit Monitor, capable of measuring over 200 power system parameters. Harmonic distortion measurements were taken at a sampling rate of 512 points per cycle, to provide accuracy to the 250<sup>th</sup> harmonic.



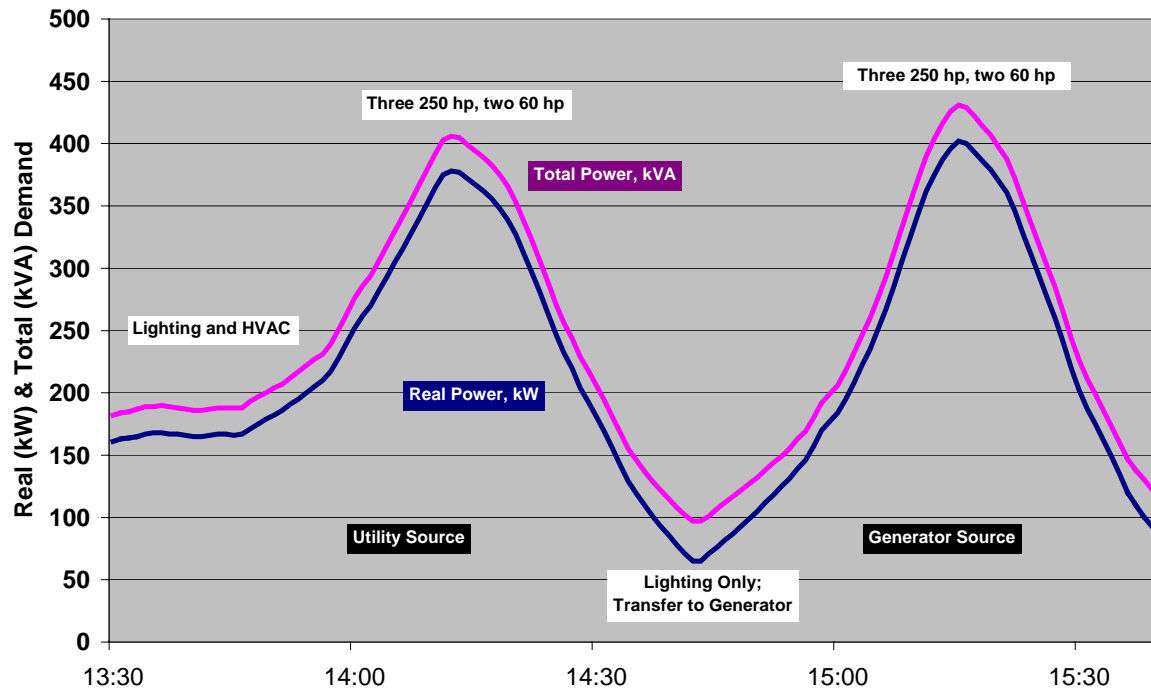
*Average RMS current during the test shows the effects of various machines operating. Current unbalance was acceptable during the test, about 20% without the drives operating (lighting and HVAC only), and less than 5% with drives operating.*

### RMS Voltage During Load Test



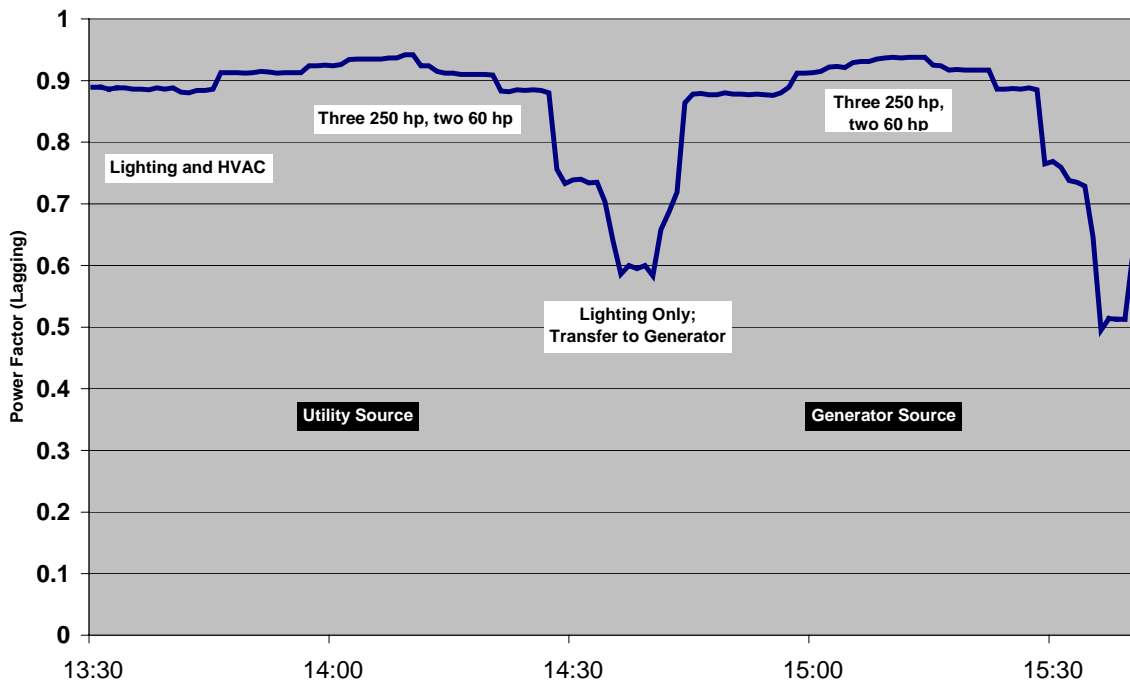
Voltage levels were slightly lower on the generator source, but both utility and generator sources were able to maintain acceptable steady state voltage (100% to 103% of 480 V) for the entire duration of the testing. Voltage unbalance was likewise within acceptable limits, less than 1%.

### Real and Total Power Demand During Load Test



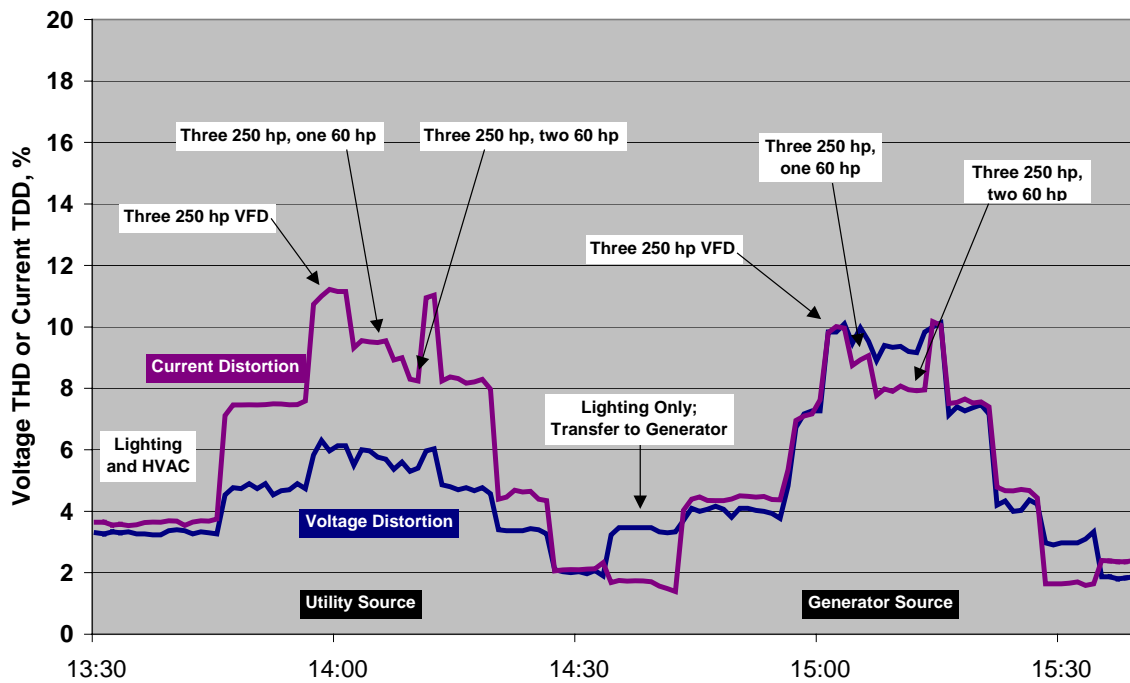
Real and total power demand trends on one-minute intervals during the test. Note that the 938-kVA-rated generator is about 50% loaded during peak operation.

### Power Factor During Load Test



Power factor during the load test. Note that power factor is lowest during times of lightest load and is high when all drives are operating. This makes it difficult to utilize conventional harmonic filters to reduce harmonics on this circuit due to their inherent power factor improvement characteristics.

### Harmonic Distortion During Load Test



Harmonic distortion levels during testing. Voltage distortion peaked at about 6.5% on the utility source and about 10% on the generator source. Note that current distortion drops when 60 hp drives are operated with 250 hp drives. This is due to the cancellation effects of the combination of delta-wye transformers and line reactors. Current Total Demand Distortion (TDD) is based on IL of 900 A, or 80% of the generator rating of 1129 A.

# Harmonic Analysis

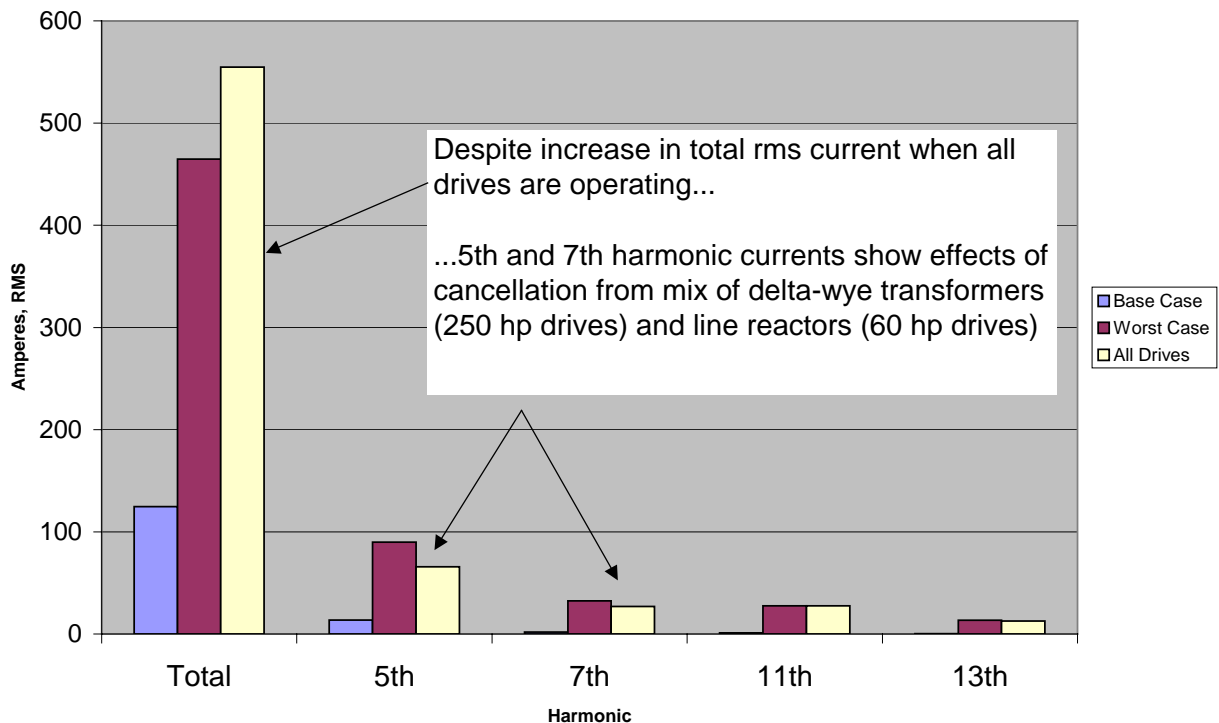
## Summary

Square D performed harmonic simulations to estimate the reduction in harmonic current that could be achieved by the following modifications. Note that the “Existing Harmonic Cancellation” section shows that some harmonic cancellation is already being achieved when 250-hp and 60-hp drives are operated at the same time. The other techniques that were considered include:

- ◆ Bypass one existing delta-wye isolation transformer serving a 250-hp drive to increase cancellation of 5<sup>th</sup> and 7<sup>th</sup> harmonics (short-term measure);
- ◆ Replace one existing delta-wye isolation transformer serving a 250-hp drive with a delta/zig-zag-wound transformer to increase cancellation of 5<sup>th</sup> and 7<sup>th</sup> currents, and to maintain the beneficial effects of harmonic attenuation;
- ◆ Install a passive harmonic filter at the 480-V main to remove harmonics injected by the drives.
- ◆ Install an active harmonic filter at the 480-V main.

## Existing Harmonic Cancellation

Harmonic Current Shows Effects of Cancellation



*Note that existing system of delta-wye transformers and line reactors serving the facility’s drives benefits from some cancellation of 5<sup>th</sup> and 7<sup>th</sup> harmonic currents. The system required about 27% and 16% less current at 5<sup>th</sup> and 7<sup>th</sup> harmonics, respectively, despite a 19% increase in total rms current. “Worst Case” occurs when only the 250-hp drives are operating.*

## Harmonic Reduction/Mitigation Analysis

### Replace One Isolation Transformer

Bypassing one of the existing three isolation transformers serving a 250-hp drive seems to have a beneficial effect on the amount of harmonic current distortion at the facility. As shown in the following summary, cancellation effects can be improved to further reduce 5<sup>th</sup> and 7<sup>th</sup> harmonic currents by bypassing one transformer and allowing its 5<sup>th</sup> and 7<sup>th</sup> harmonic currents to be unchanged. Once these currents are added to the other one or two 250-hp drive currents, additional cancellation occurs. This technique, however, should be considered only for temporary improvement until more effective means are installed.

Harmonic:	<11	11-17	17-23
<b>Measured</b>			
Worst Case	10.6%	3.4%	1.5%
All Drives	7.9%	3.4%	1.5%
<b>Simulated</b>			
w/o isol xfmr	6.5%	2.0%	1.1%

Current Total Demand Distortion,  $I_{TDD}$ , based on  $I_L=900$  A (80% of generator rating of 1129 A)

A better technique is to replace one isolation transformer – instead of bypassing it – with a harmonic mitigating transformer of similar impedance. This modification would provide both cancellation effects (harmonic currents are not phase-shifted through delta/zig-zag-wound transformers) and attenuation effects. At this point, however, the simple computer model breaks down, perhaps due to a resonance between the drive capacitance and the line reactor that may or may not be real. The model predicts a further reduction in 5<sup>th</sup> and 11<sup>th</sup> currents to about 5.8%, but shows an increase in 11<sup>th</sup> and 13<sup>th</sup> currents over the “w/o isol xfmr” case that cannot be fully explained.

### Other Techniques

Two other options were considered.

The first option that was considered but is not recommended is the addition of a 5<sup>th</sup> harmonic filter at the 480-V main. This option is not practical because passive harmonic filters of this type also increase fundamental power factor. Since power factor at the facility is already high (94%) at full load, the system cannot tolerate much parasitic capacitance without putting the facility into a leading power factor.

The best option that should be considered if further harmonic current reduction is desired is an active filter. Active filters measure the amount of harmonic current required by the load and inject current 180° out of phase with that current. This technique reduces the harmonic distortion levels considerably and is often used where stringent harmonic limits are applied.

### How Much Harmonic Distortion Is Too Much?

#### IEEE Guidelines

Drives and other facility loads operated without disruption during the May 7 testing, so why consider harmonic reduction? Since the adverse effects of harmonics may be manifested over an extended time period, it is difficult to determine the economic attractiveness of reducing harmonic distortion. The Institute of Electrical and Electronics Engineers developed the *Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*, IEEE Standard 519-1992, to offer guidelines on this question. While this standard was developed primarily as a recommended practice for electric utilities and their customers, not as an equipment or facility standard, it can be used to develop some guidelines.

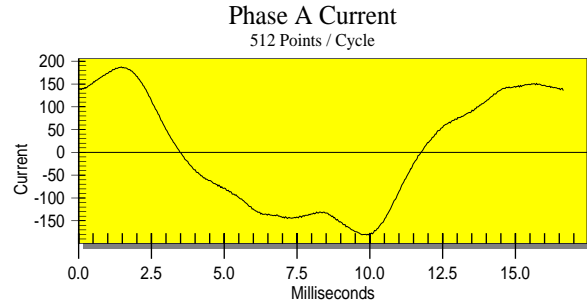
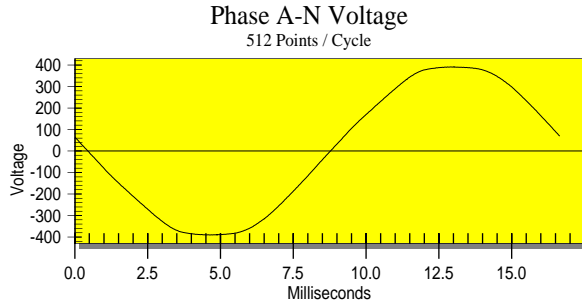
<b>Harmonic:</b>	<b>&lt;11</b>	<b>11-17</b>	<b>17-23</b>
IEEE "Limit"	4.0%	2.0%	1.5%
<b>Measured</b>			
Worst Case	11%	3.4%	1.5%
All Drives	7.9%	3.4%	1.5%
<b>Simulated</b>			
w/o isol xfmr	6.5%	2.0%	1.1%

*IEEE 519-1992 is often used as a guide for assessing existing harmonic current levels inside a facility even though that is not its primary purpose. This table shows the harmonic limits from Table 10-3 of the Standard typically imposed on power generation equipment. Note that these limits were exceeded during the onsite measurements. As before, "Measured" and "Simulated"  $I_{TDD}$  figures are based on 80% of the generator full-load amperage.*

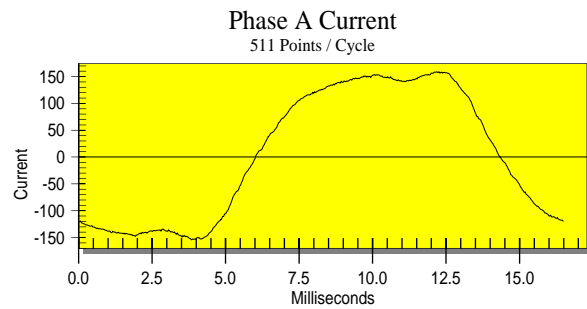
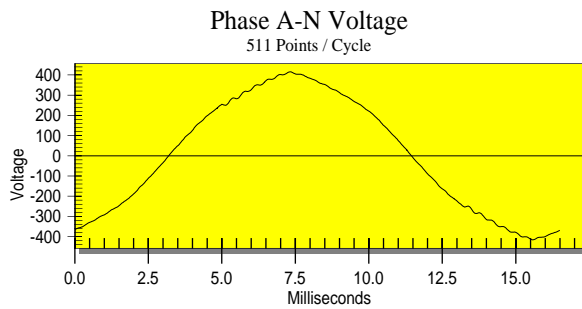
# Voltage and Current Waveforms

## Baseline – No Drives Operating

### Utility Source

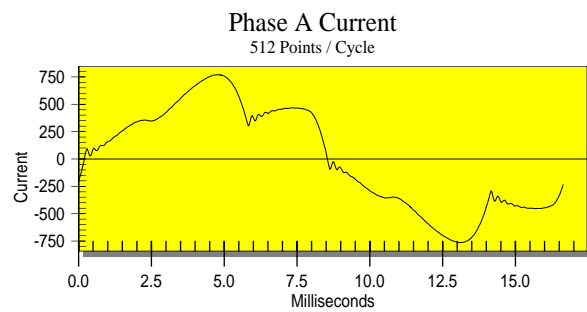
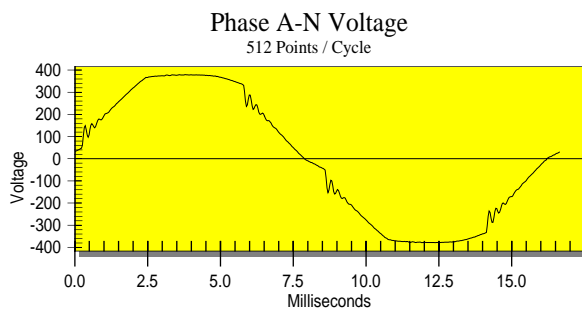


### Generator Source

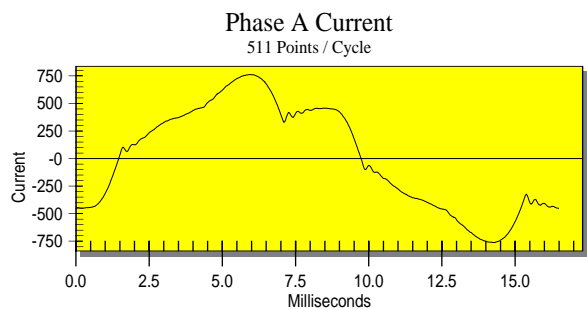
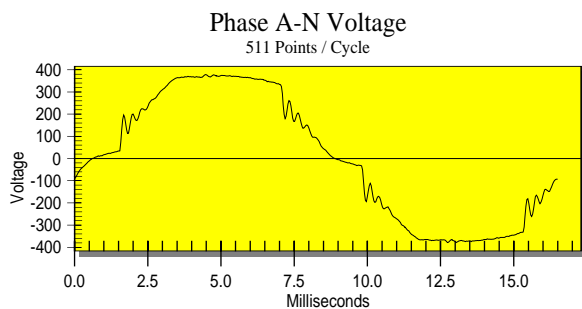


## Worst Case – Three 250-hp Drives Operating at 83% of Rated Load

### Utility Source

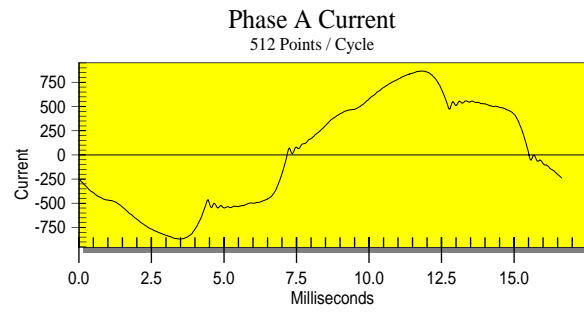
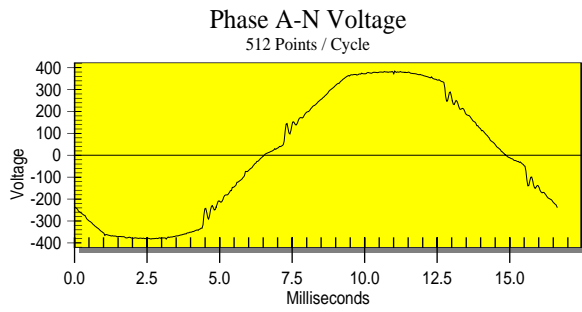


### Generator Source

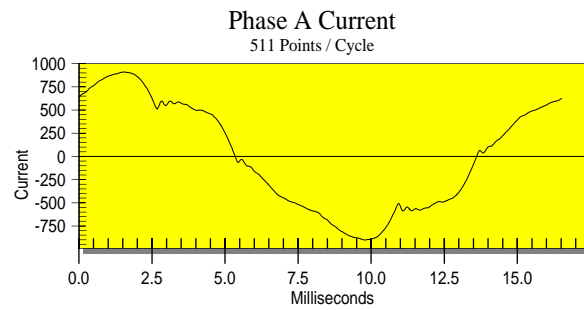
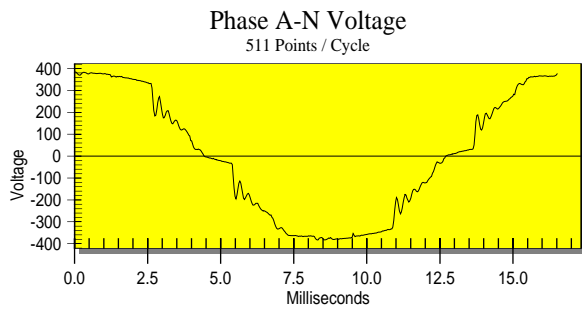


# All Drives Operating (Three 250 hp, Two 60 hp)

## Utility Source



## Generator Source



# Harmonic Distortion Fundamentals

## Introduction

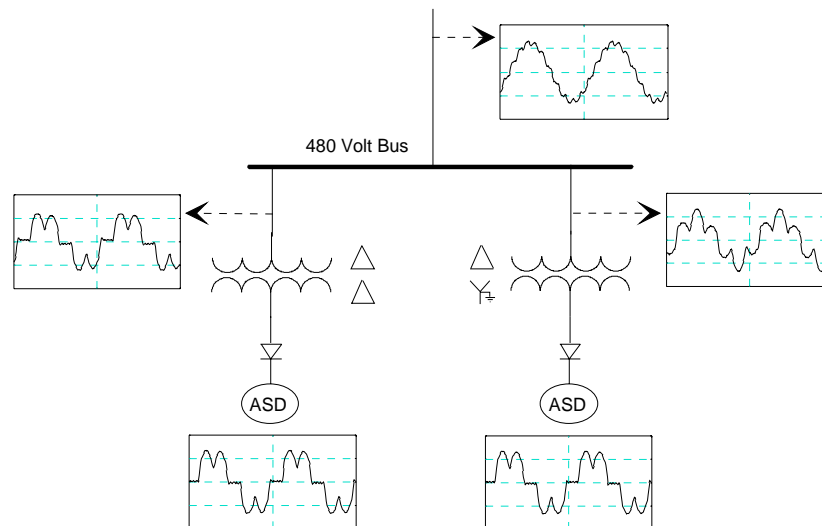
Electronic or “non-linear” loads, such as variable frequency and dc motor drives, computers, and automation equipment, draw current from the power system that is not sinusoidal. The resulting non-linear current may be expressed as a series of sinusoidal waves with frequencies equal to integer multiples of the 60 Hz system frequency. The individual high-frequency waves are referred to as harmonics—the 3<sup>rd</sup> harmonic is equal to 3 times the system frequency (i.e., 180 Hz), the 5<sup>th</sup> harmonic has a frequency of 5 x 60 Hz = 300 Hz, etc. Harmonic currents are undesirable because they are an additional source of thermal stress on various types of electric equipment, reducing the current-carrying capability of conductors and transformers. Harmonic currents also interact with line impedance, causing the system voltage to become distorted. When equipment such as capacitors or motors are served with a distorted system voltage, significant harmonic currents may flow, effectively reducing the lifetime of such equipment.

When power factor correction capacitors are installed in a facility that contains harmonic-producing loads, the plant electrical system should be evaluated to ensure that no resonant conditions are created that could cause excessive harmonic voltage or current levels within the facility. *Parallel resonance* occurs when the installed capacitance interacts with the existing power system to create a high impedance at some resonant frequency greater than the 60 Hz system frequency. As a result, harmonic currents near the resonant frequency are amplified, in turn producing harmonic voltage levels higher than would normally be expected.

## Cancellation Effects

Harmonic cancellation is an effective means of reducing harmonic distortion, especially among three-phase drives. Cancellation works best when pairs of drives of similar size are operating at similar loading on the same bus. Cancellation is achieved by serving one of the drives from a delta-wye transformer, and the other by a delta-delta transformer or simple line reactor. Some cancellation can also be achieved by using a combination of delta-wye transformer and no inductive device, as has been modeled for Dare County.

Cancellation is achieved because 5<sup>th</sup> and 7<sup>th</sup> harmonic frequency current components are phase-shifted by 30° in a delta-wye transformer. When these phase-shifted currents are combined with the unchanged currents passing through line reactors or delta-delta transformers, significant cancellation can occur.

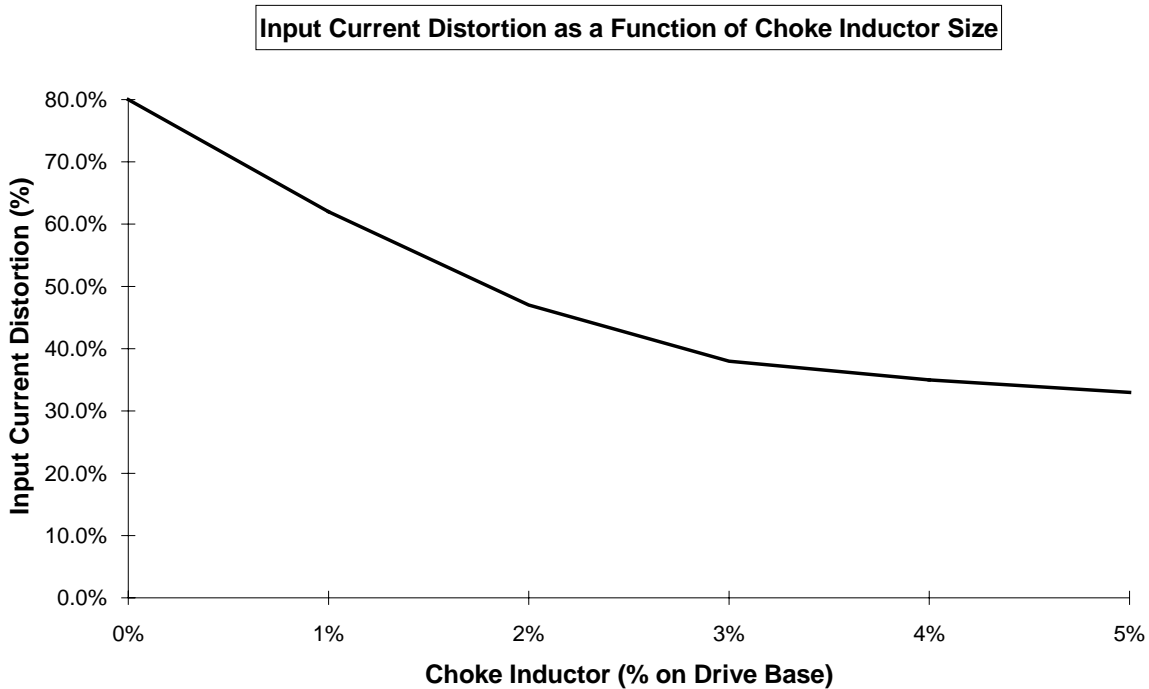


*Harmonic cancellation can be achieved on similar size adjustable-speed drives (ASD) operating at similar load levels. Source: IEEE Standard 519a, Draft Application Guide.*

## Attenuation Effects

Harmonic distortion can be reduced by adding impedance, usually in the form of an isolation transformer or line reactor, between the harmonic load and its source. Inductive impedance serves to limit the amount of higher

frequency currents that the harmonic load can inject into the system. Of course, there is a limit to the amount of impedance that can be inserted into the system without affecting performance and operation of the harmonic load.



*Reduction in harmonic currents can also be achieved by attenuation. This chart shows the typical drop in current distortion for line reactors (inductors) of various impedances.*

### **Harmonic Mitigating Transformers**

Harmonic Mitigating Transformers, or HMT's, use phase shifting, electromagnetic flux, and source impedance to help reduce the effects of harmonics in electrical distribution systems. These devices provide the beneficial effects of harmonic cancellation and harmonic attenuation, as described above, in order to improve reliability of power systems serving variable-frequency drives. These transformers can be supplied with either delta/wye windings that provide 30° phase shift for 5<sup>th</sup> and 7<sup>th</sup> harmonics, or delta/zig-zag windings that do not provide phase shifting.

### **System Modeling**

A computer simulation of the power system was performed using the SKM Hi\_Wave computer program. The model of the system, compiled from data collected by the Power Logic monitoring along with information gained from inspection of equipment at the site, depicts the major loads and sources. Information about the utility system was derived based on load measurements taken during the onsite visit.