

Harmonic Design Considerations

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ABSTRACT

Power quality can be defined as the comparison of voltage and current waveforms to their fundamental “clean” sinusoidal waveforms. Pure sine waves that are free of distortion are sometimes referred to as clean power. Harmonic distortion is one of the main causes of power quality problems. Many papers have been written on this subject, so only a brief review of the subject will be presented here. It is the main intent of this paper to discuss some design ideas that should be considered when trying to decide whether harmonic mitigation is necessary, and if so, what type should be implemented.

INTRODUCTION

A harmonic is a wave whose frequency is an integer multiple of the fundamental frequency. The French mathematician Joseph Fourier coined the term ‘harmonics’ out of studies in relation to sound in the early 1800’s. From these studies, he developed methods to describe sets of complex repeating waveforms as sums of simple sinusoidal waveforms. When the higher frequencies are added to the fundamental, it will result in a distortion of the fundamental (see figure 1).

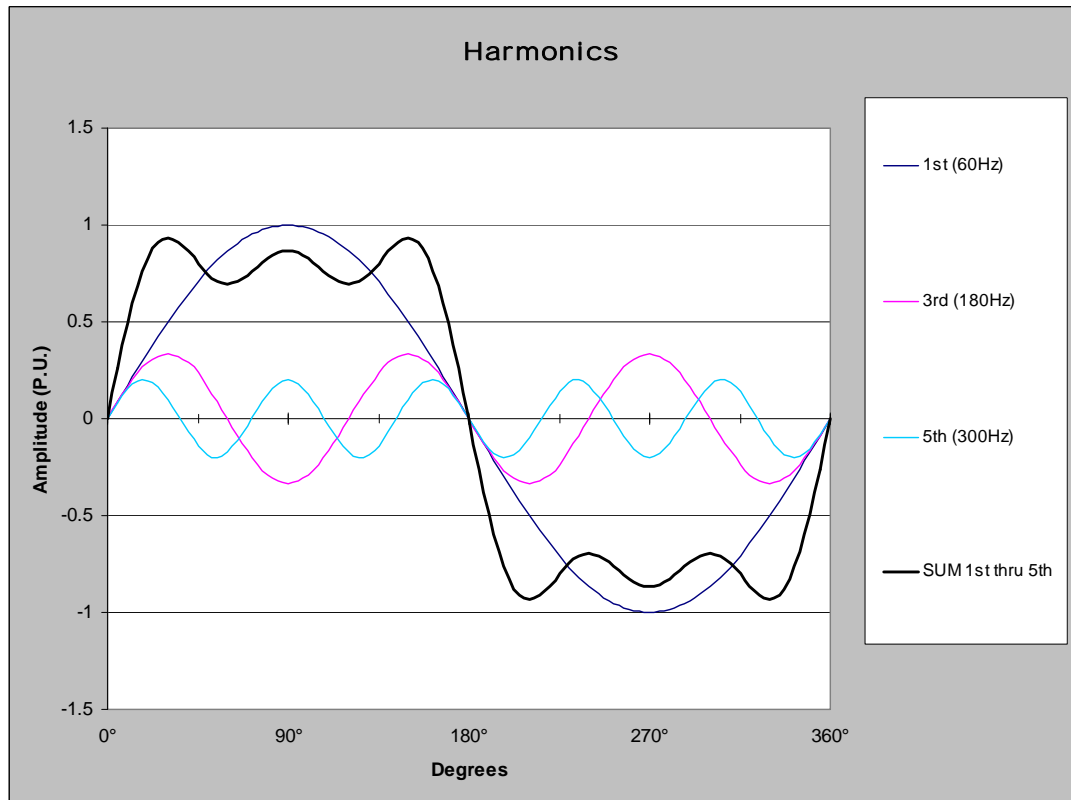
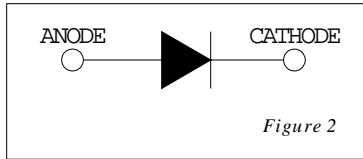


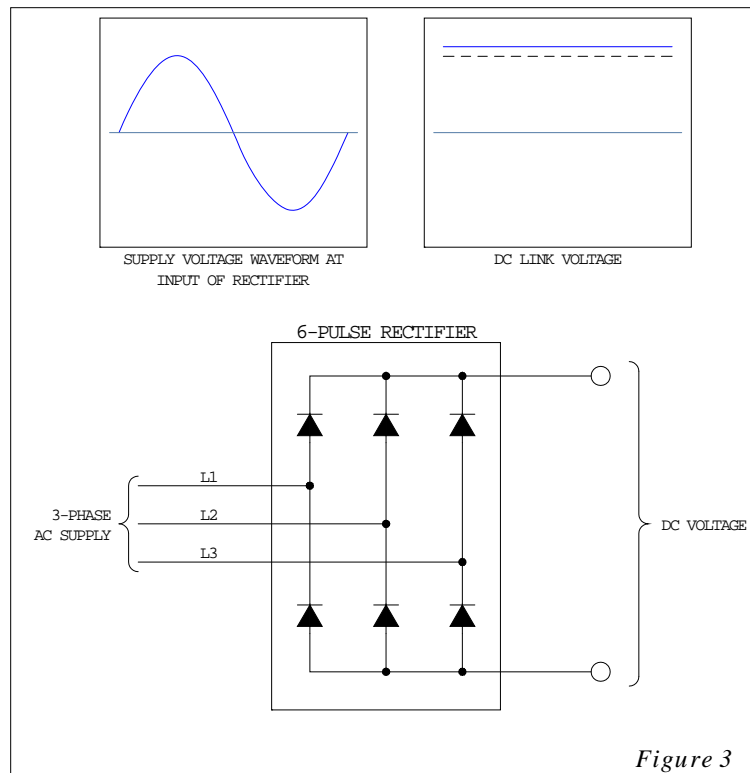
Figure 1

Harmonics can be caused by magnetic saturation in the cores of transformers. They are also caused by the switching action of electronic components such as diodes and thyristors, which are found in rectifiers and Switch-Mode Power Supplies (SMPS). The primary component of a rectifier is a diode (see figure 2).

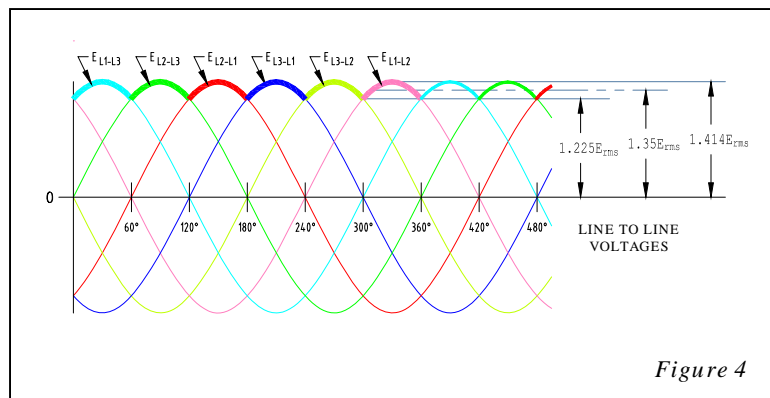
A diode is a device that allows current to pass through it in one direction when its terminal voltage (anode with respect to cathode) is positive. It will continue to behave like a closed switch and pass current until the current stops flowing. At this point it will behave like an open switch and block the flow of current. It will only resume conduction when the anode again becomes positive with respect to the cathode.



When diodes are connected as in figure 3, the output will be DC. This configuration is called a 6-pulse bridge rectifier. There will be a ripple unless filtering is applied. The bold portions of the sine waves in figure 4 represent the unfiltered DC ripple. A capacitor bank and some type of filtering are usually fitted and the theoretical DC output is equal to approximately 1.35x the RMS (Root-Mean-Square) supply voltage. This diode configuration is commonly found in AC Variable Frequency Drives (VFD's). But it is the switching action of the diodes, which allow current to be drawn from the supply in pulses that causes disturbances to the supply. The size and quantity of the loads connected to the diode bridges in relation to the size of the supply power generation equipment, will determine the degree of distortion. For example, a personal computer draws a relatively small amount of current through its SMPS.



So one computer will not cause a significant disturbance to the supply power. But a large office building that contains hundreds of computers will cause a significant disturbance to the supply power unless harmonic mitigating equipment is installed.



It is not always practical and sometimes not necessary to eliminate harmonics. IEEE Std 519-1992 (Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems) lists voltage and current distortion levels that they recommend should not be exceeded at the Point of Common Coupling (PCC). (See Table 1.). The

PCC is the point in the electrical system where ownership changes from the electric utility to the customer. Since the utility company is expected to supply clean power to all of its customers, this point is chosen in part so that each customer is responsible for minimizing their own harmonics to a level that will not adversely affect other users. It is also intended to prevent the utility company from having to purchase and install expensive harmonic mitigating equipment to correct any significant customer-generated harmonics.

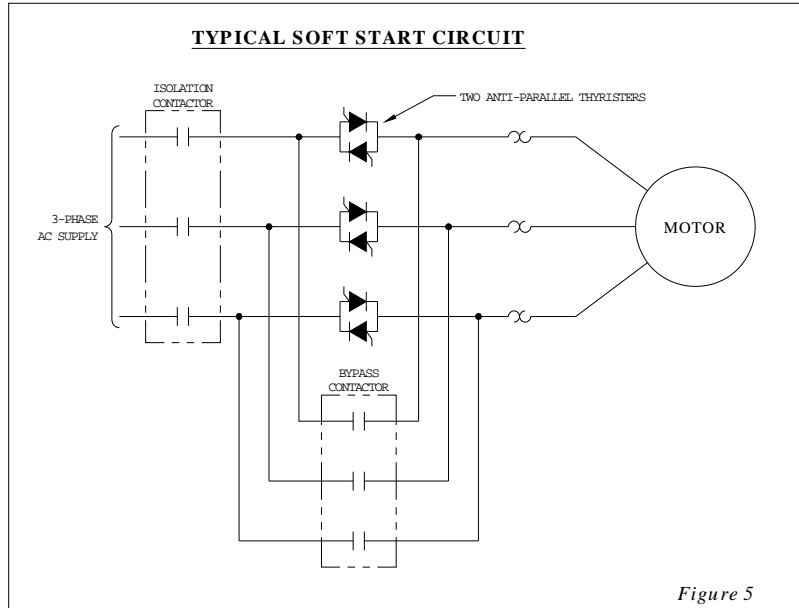
| Table 10.3 | | | | | | |
|---|------|---------|----------|----------|------|------|
| Current Distortion Limits for General Distribution Systems | | | | | | |
| 120 V Through 69,000 V | | | | | | |
| Maximum Harmonic Current Distortion | | | | | | |
| in Percent of I_L | | | | | | |
| Individual Harmonic Order (Odd Harmonics) | | | | | | |
| I_{sc}/I_L | <11 | 11≤h<17 | <17≤h<23 | <23≤h<35 | 35≤h | TDD |
| <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 |
| Even harmonics are limited to 25% of the odd harmonic limits above. | | | | | | |
| Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed. | | | | | | |
| *All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L . | | | | | | |
| where | | | | | | |
| I_{sc} = maximum short circuit current at PCC. | | | | | | |
| I_L = maximum demand load current (fundamental frequency component) at PCC. | | | | | | |

Table 1

Typically the utility's power generation equipment will be capable of delivering much more power than a facility's generator that is primarily used to supply emergency power. If the Total Harmonic Distortion (THD) is within acceptable limits while a facility is connected to the utility grid, then the facility need only to concern itself with the effects of harmonics on its own equipment while connected to the utility's grid. But a design engineer responsible for the power quality of that facility will also need to be aware of the affects that harmonics can produce when the facility is under generator power. For example, some phase detection relays can misinterpret poor power quality caused by harmonics as an undervoltage or phase failure condition.

CASE STUDY – SOFT STARTERS

Induction motors are the motors most widely used in industry. They are rugged, low-cost, and easy to maintain. If an induction motor is started across the line, it will draw a high in-rush current (locked-rotor current) that is typically 6 to 13 times its full load running amps. The load will also experience a high torque pulsation at the time that the motor is first started. Locked-rotor current is proportional to the voltage. Locked-rotor torque is proportional to the square of the voltage. Reduced Voltage Solid State (RVSS) starters (a.k.a. soft starters) contain thyristors connected in an anti-parallel configuration. An RVSS starter varies the firing angle of the thyristors to vary the voltage supplied to the motor. By reducing the voltage, they are able to reduce the locked-rotor current and torque. Soft starters can also ramp a motor down from full speed to zero speed. But they are not used to continually vary the speed of a motor.

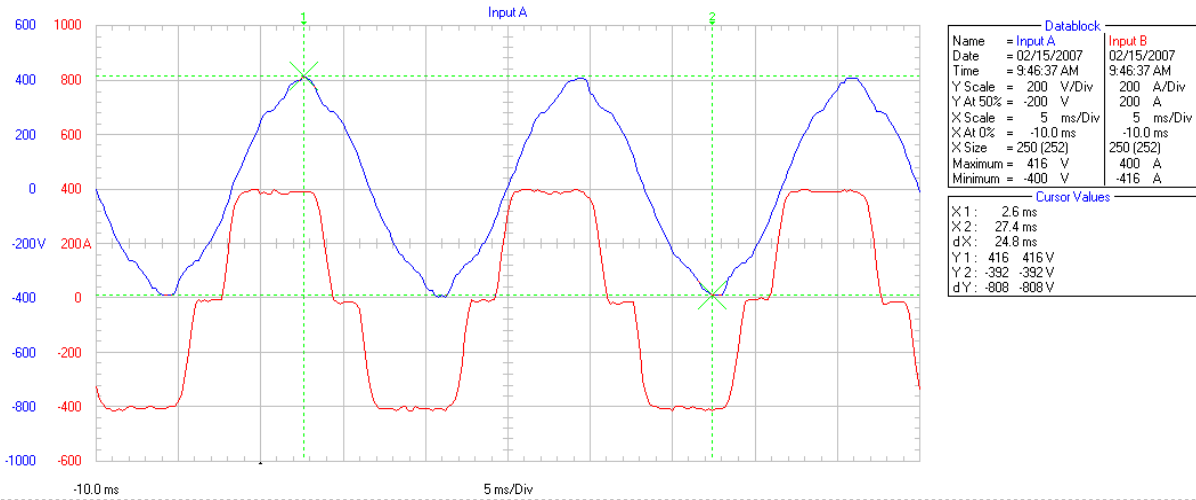


During the ramping up or down, significant harmonics can be generated. There are a few things that should be considered when soft starters are installed:

- How big is the soft starter/motor load in relation to the available supply?
- How often will the soft starter/motor load(s) be started?
- How long are the acceleration/deceleration ramps?

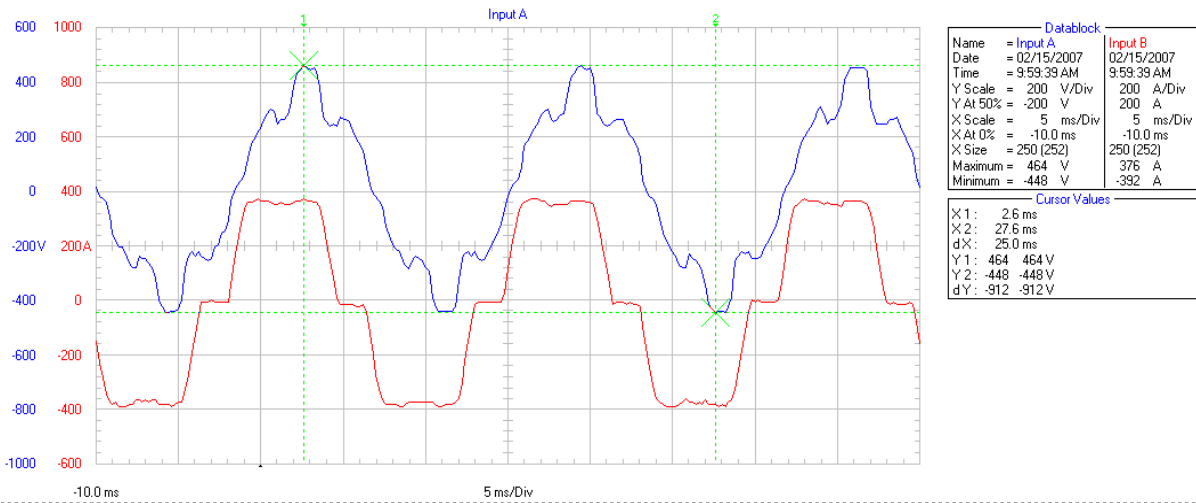
If the soft start/motor load is large and the motor will be started often with a long ramp time, then harmonic mitigation equipment should be considered. But if the opposite is the case, and the facility's remaining equipment is robust, then the design engineer may choose not to specify that harmonic mitigation equipment be installed.

A case in point was that of an airplane refueling facility. The facility had three 125hp refueling pump motors, which employed soft starters to smoothly ramp the motors up to speed. Each motor circuit contained a phase failure relay that was designed to prevent the motor from operating in the event of a phase failure or undervoltage condition. When the utility company was supplying the facility's power, the voltage distortion was at a tolerable level and the phase failure relays did not trip. Figure 6 contains a phase to ground voltage waveform captured during the soft start ramp while under utility power. When the refueling facility was being powered by their generator, the switching action of the soft starters distorted the voltage enough to cause the phase failure relays to trip during the ramping. Figure 7 depicts the voltage waveform when ramping under generator power. (Note: These measurements were taken at the input to the soft starter, not at the PCC.).



Pump #3 Ramping; Power source - Utility Power
 Channel A: Phase C - Gnd Voltage
 Channel B: Phase C mtr Current

Figure 6



Pump #3 Ramping; Power Source - Generator
 Channel A: Phase C - Gnd Voltage
 Channel B: Phase C mtr Current

Figure 7

An examination of the two figures reveals that for relatively the same amount of current distortion caused by the soft starter/motor (the red waveforms in both figures), the utility-supplied voltage (blue waveform) was much less affected as compared to when the generator was supplying the power to the facility. The facility determined that their equipment was robust enough to handle the occasional excessive harmonic distortion that occurs while the soft starter is ramping; so the solution was to bypass the phase failure relays only while the soft starter was in operation under generator power.

EQUIPMENT SOLUTIONS

Passive Filters

A passive harmonic filter is typically an inductor connected in series with capacitors. It is also known as a tuned filter because it will absorb whatever harmonic it is designed to filter out based on the values of the inductor and capacitor(s). A passive filter is a relatively low-cost filter. But a disadvantage of this filter is that it cannot absorb other harmonics that it is not designed to, and it cannot adapt to changes in the electrical system. Therefore, if other harmonic frequencies need to be filtered, additional passive filters tuned to absorb those frequencies will have to be added. Passive filters are a good, low-cost solution when tuning for specific harmonic frequencies usually produced by a specific piece of equipment. If a passive filter is determined to be the best solution for a facility, a harmonic study of the facility will need to be performed. GE has engineers that can perform the study and design a filter to suit your needs. A GE Auto GEMTrap Filter Bank is a passive harmonic filter that can also dynamically correct for power factor. This is a great product for facilities with a significant amount of motor loads (corrected by the power factor correcting capacitors) and fixed harmonic-generating loads (corrected by the filter).

Multipulse Transformers

Multipulse transformers (transformers providing more than six pulses of DC per cycle) are usually employed in installations involving equipment fed from multiple 6-pulse rectifier bridges. Common multipulse configurations are 12-pulse, 18-pulse, and 24-pulse. The greater number of pulses will result in a reduction of the input line current distortion, which in turn reduces the voltage distortion. A multipulse transformer is a phase-shifting transformer that has a 3-phase primary, and multiple secondaries. For example, a 12-pulse transformer will have a delta primary that allows for connection to a 3-phase supply, and a delta and wye secondary that allows for connection to two 6-pulse diode bridges that are connected in parallel (see figure 8) or series.

12-PULSE RECTIFICATION

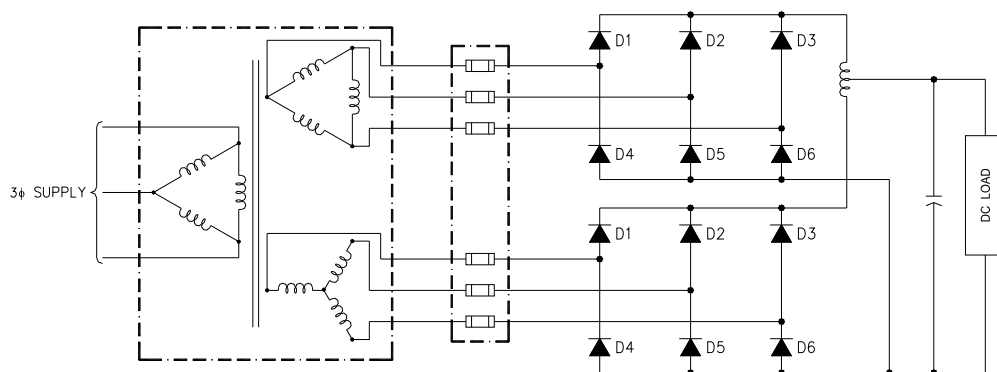


Figure 8

The designer of the transformer will determine the amount of phase-shift needed based on the number of 6-pulse converters.

A formula to determine which harmonics are significant (not cancelled by transformer/rectifier) is as follows:

$$\text{significant harmonic} = np \pm 1$$

where :

n = an integer number

p = number of pulses

Therefore, a 12-pulse system will still produce significant 11th, 13th, 23rd, 25th, etc. harmonics. But it will cancel the 5th, 7th, 17th, 19th, etc.

Significant Harmonics from Bridge Rectifiers

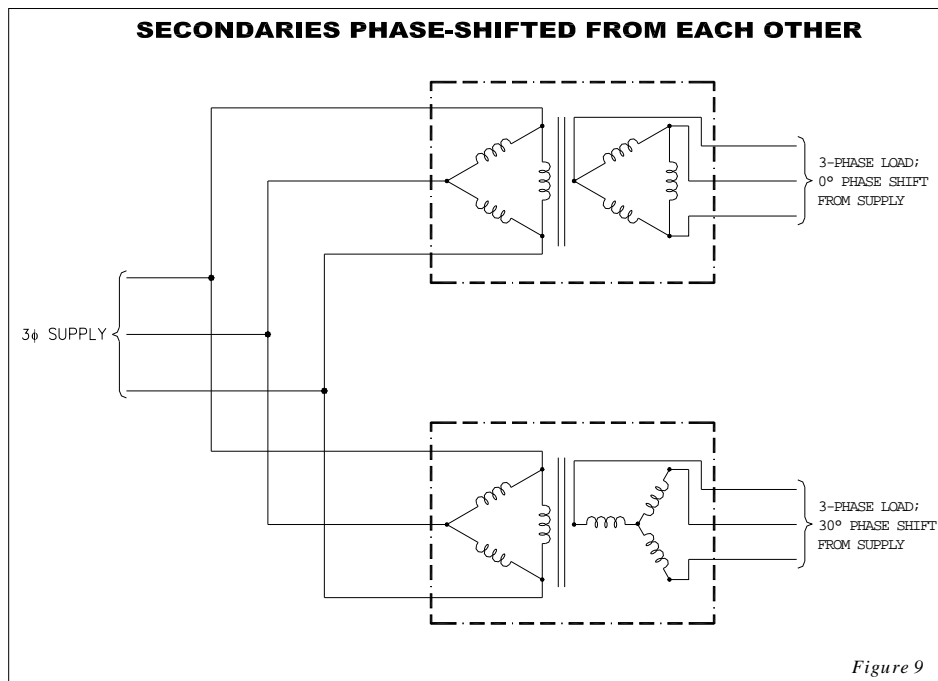
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | |
|-------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|---|
| Fundamental | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6-Pulse | X | | | | X | | X | | | | X | | X | | | | X | | X | | | | | X | | X |
| 12-Pulse | X | | | | | | | | | | X | | X | | | | | | | | | | | X | | X |
| 18-Pulse | X | | | | | | | | | | | | | | | | X | | X | | | | | | | |
| 24-Pulse | X | | | | | | | | | | | | | | | | | | | | | | | X | | X |

Table 2

Many multipulse configurations have been designed to be connected to VFD's. It is a good solution for mitigating harmonics on these known harmonic-producing products.

Harmonic Mitigation Transformers

Harmonic Mitigation Transformers (HMT) are transformers specifically designed to reduce system voltage distortion and reduce zero sequence harmonic currents also known as triplens. Triplens are third harmonics and all of their odd multiples (3rd, 9th, 15th, etc.). The mathematical phase properties of triplens are such that they add together in the neutral wire instead of cancelling each other out. The design nature of conventional, non-phase-shifting transformers and autotransformers (even phase-shifting autotransformers) does not address the mitigation of triplens. HMT's are designed to reduce triplens, and



when designed with other HMT's as part of a system, they can reduce other harmonics. A system of HMT's would consist of transformers of different phase shifts. Together their effect would be similar to that of a multipulse transformer—thus resulting in a large amount of harmonic cancellation. An example would be to fit a delta/delta transformer (0° phase shift) on the same supply as a delta/wye transformer (see figure 9). The result would be harmonic cancellation similar to that of a 12-pulse transformer, (assuming relatively balanced loads).

Active Filters

Active filters such as GE's GEMActive are a great solution for the reduction of harmonics, especially when the offending harmonic frequencies are changing throughout the day. The GEMActive cancels harmonics by dynamically injecting out-of-phase harmonic current. This reduces current distortion, which consequently reduces voltage distortion. Current transformers provide the GEMActive filter with the feedback required for closed loop control. It is able to constantly adjust for changing levels of harmonics. It cannot be overloaded. If the network's harmonics are greater than what the filter can correct for, the filter will supply its maximum harmonic-canceling current. If further reduction is necessary, multiple units can be connected in parallel to increase compensation.

CONCLUSION

Power quality has always been, and will continue to be a major concern, especially with the increased use of sensitive electronic equipment. Due to their energy savings nature, harmonic-producing devices will be installed more frequently. Since engineering and equipment costs will always be subjects that facility owners and planners will try to minimize, understanding and measuring harmonics are very important. Knowing what harmonic levels a system can safely tolerate can result in significant cost savings. And knowing when harmonic mitigation equipment needs to be installed, as well as what type of mitigation is necessary, can reduce equipment failures and expensive downtimes. GE can help owners and planners understand and measure a facility's harmonics, and can help design a cost-effective solution. Consult your local GE sales office for more information.

REFERENCES

IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems,
IEEE Std 519-1992

Power Electronic Converter Harmonics, Derek A. Paice