Eliminating harmonics from the facility power system

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Adjustable-frequency drives and other devices can produce harmonics on a facility's power system. These harmonics can corrupt data, damage equipment (usually by excess heat), and cause erratic equipment performance. But these effects can be controlled by monitoring and analyzing the whole system, determining safe harmonic levels, and choosing the right attentuation solution.

Power system anomalies that periodically occur in a facility's electrical system can cause equipment malfunction, data distortion, transformer and motor insulation failure, overheating of neutral buses, nusiance tripping of circuit breakers, and solid-state component breakdown. The cost of power quality problems can be enormous. Equipment replacement can cost tens of thousands of dollars. Downtime, however, can run in the millions of dollars.

Power quality problems take many forms. Voltage sags, transients, and spikes are probably the most understood of these forms. Harmonic distortion, though, can occur from adjustable-frequency drives and other non-sinusoidal loads typically where ac/dc conversion is present.

In any facility, the voltage supplied by a power system is generally not a pure sine wave. Rather, it usually possesses some amount of distortion, which has a fundamental frequency and harmonics at that frequency, (see box, "Harmonic basics").

Distortion comes from various sources, particularly equipment with power-circuitry devices that draw current in a non-linear fashion. Non-linear devices are those that switch the current *on* and *off*, such as transistors, diode bridges, and SCRs. Two major classes of equipment that contain these devices and produce current harmonics are:

- Internal power supplies, such as computers, copiers, and electronic ballasts.
- Any type of static power converter, such as an uninterruptible power supply, dc drives, or adjustable-frequency controllers (AFC).

An AFC has a converter section, which converts ac line power to dc, and an inverter section, which converts dc to adjustable frequency ac. Both contain non-linear devices in their power circuitry, and therefore produce harmonics on the input and output lines.

Input line harmonics are caused solely by the converter section and are usually referred to as line-side harmonics. Output line harmonics are caused solely by the inverter section and are called load-side harmonics. They are completely isolated from each other. Thus, load-side harmonics only affect the equipment driven by the AFC, while line-side harmonics affect the whole power system.

Standard three-phase PWM drives typically use a six-diode rectifier bridge in the converter section, Figure 1. These diodes draw current non-linearly, in a 6-step converter waveform, Figure 2. The high levels (amplitude) of 5th and 7th harmonics

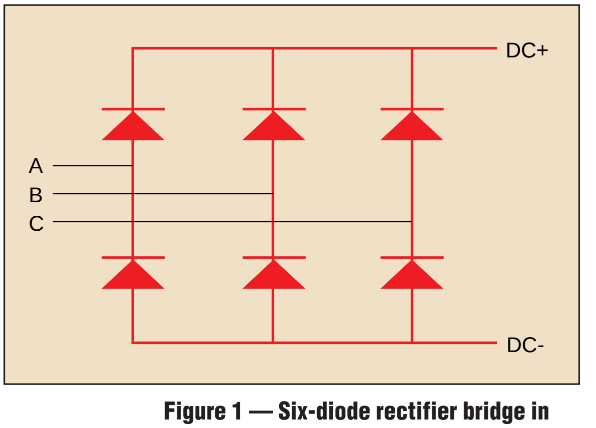

Figure 1 — Six-diode rectifier bridge in the converter section of a standard three-phase PWM drive.

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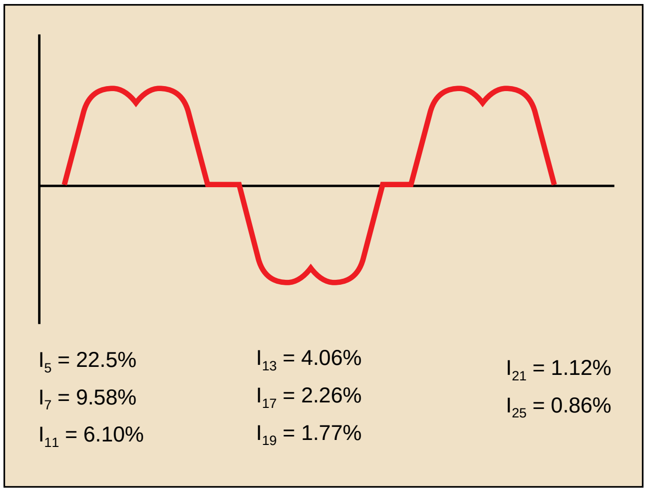


Figure 2 — A 6-step converter waveform.

and the magnitude of each decreases as harmonic number increases. Harmonics above the 25th generally have little effect and are usually considered insignificant.

In this waveform, only certain harmonic orders are present: 5th, 7th, 11th, 13th, 17th, 19th, 21st, and 25th. To determine the number of harmonic orders in a wave for a six-diode bridge, solve for:

$h = 6k \pm 1$,

where k is an integer.

Almost any three-phase system will possess a degree of line unbalance, producing 3rd harmonics. In a balanced three-phase system, however, these harmonics are in phase with each other and their effect is typically small.

Load-side harmonic effects

As mentioned earlier, load-side harmonics are generated by the inverter section of an AFC and may effect the motor and connecting cables. AFCs can decrease motor life because of the additional heating caused by the harmonics (see PTD, "Solutions to motor insulation failures," 8/95, p. 43). High-efficiency motors with a service factor of 1.15 can help compensate for deleterious effects.

Line-side harmonic effects

Unlike load-side harmonics, line-side harmonics effect the whole power distribution system. Harmonic currents drawn from the source give rise to harmonic voltages that affect other equipment on the distribution system. How much these voltages effect the system depends on system load and impedance. Equipment considered sensitive to harmonics includes communication equipment, computers and computer systems, diagnostic equipment, switchgear and relays, transformers, and standby generators.

Communication equipment, computers, and diagnostic equipment are designed for operation on smooth sinusoidal input. Therefore, harmonics can corrupt data or result in false commands.

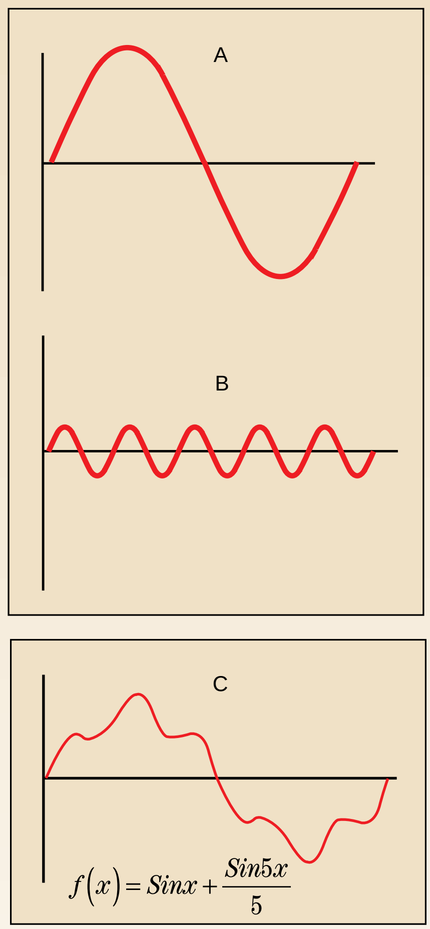
Transformers may experience extra heating in the core and windings. To combat potential problems, many transformer manufacturers rate their products with a K-factor. This factor indicates the transformer's ability to withstand degradation from harmonic effects. Some manufacturers simply derate their transformers to compensate for potential problems. Others incorporate special features to better handle harmonic cur-

Harmonic basics

Harmonic currents and voltages are usually multiple sinusoidal waveforms that combine to form distorted waveforms. Figure A and Figure B waveforms are both pure sine waves, free of distortion, and differing only in frequency and amplitude. Figure B has five times the frequency and one-fifth the amplitude of Figure A. The wave in Figure A is called the fundamental. The wave in Figure B is a harmonic of the wave in Figure A because its frequency is an integral multiple of it. Because the harmonic has a frequency five times that of the fundamental, it is called the 5th harmonic or 5th order harmonic.

If both waves are on the same power system simultaneously, they would add together, resulting in the waveform shown in Figure C. This resultant waveform is still periodic and has the same frequency of Figure A, but it now deviates from the sine-wave shape of its fundamental frequency.

Just as waveforms can be added to produce distorted waves, distorted waves may be decomposed into fundamental and harmonic components.



rents. These features include specially designed cores and windings to reduce eddy currents and heating, and an oversized neutral bus.

With standby generators and their voltage regulators, harmonics may cause them to put out a significantly high or low voltage. Or, because a generator has an impedance higher than typical distribution transformers, harmonic currents flowing in the generator can produce harmonic voltages three to four times the normal levels. Sensitive equipment, such as that used in hospitals and computer centers, may be severely affected. Thus, engineers should perform an extensive system study in any application of nonlinear devices on systems with standby generators.

Take care when applying harmonic-generating equipment on systems with large amounts of capacitance in parallel with inductance, such as systems with power-factor correction capacitors or capacitive welders. System resonance can occur at one of the harmonic frequencies. Resonance can amplify the harmonics, which would exacerbate the effects. Calculating the harmonic resonance-frequency will help determine if a problem may occur.

For example, with a 1,500 kVA transformer with a 5.75% impedance connected to a capacitor load of 600 kVA:

$$h_r = \sqrt{\frac{T_r}{Z\,C_r}}$$

$$h_r = \sqrt{\frac{1500}{(0.0575)\,600}} = 6.59$$

where:
h_r = harmonic resonance frequency
T_r = transformer rating, kVA
C_r = capacitor load, kVA
Z = impedance, %

The harmonic point of this example is the 6.59th harmonic, which can be problematic because the system resonance may be excited by the 5th and 7th harmonics. Attentuation of these two frequencies would likely avoid problems.

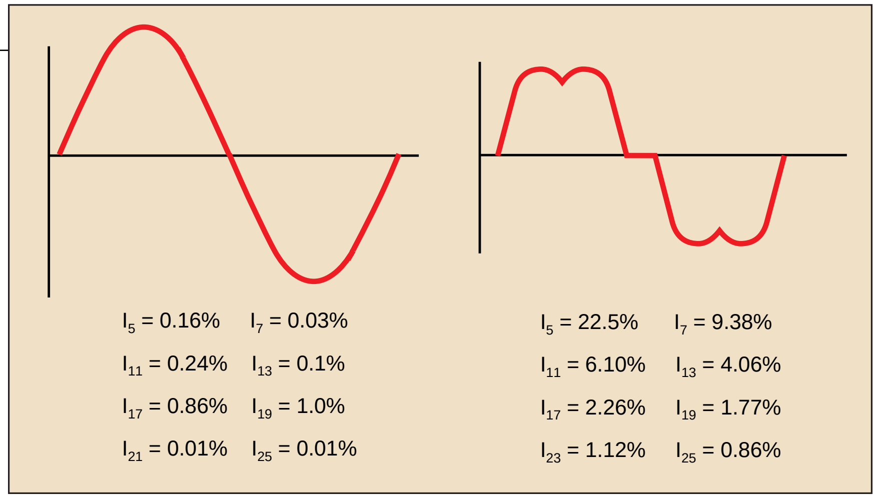
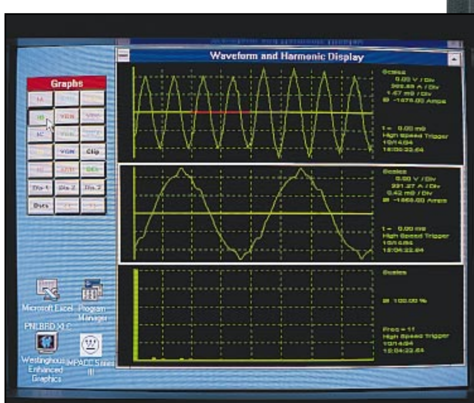


Figure 3— (Left side) Wave shape from a clean power rectifier for a 500-hp motor at 460 V. (Right side) Waveform and harmonic contents of a 6-pulse system. With this type of rectifier, no additional filters, inverters, or transformers are needed. It stops harmonics at their source.

Detecting harmonics

The first step in eliminating these power quality problems is identifying and isolating their source through power monitoring and data acquisition systems. Such systems provide real-time monitoring, sub-metering, electrical data trending, and specific information on magnitude, time, and direction of power quality related events.

A power monitoring system can include metering devices, protective relays, circuit breaker trip units, and motor starters. Data from these devices, passed to a control into available software packages, can then be graphically displayed on a personal computer or other operator interface device.



A harmonic analyzer is another device that can determine if a harmonics problem exists within a facility. Available from several sources, it is essentially a spectrum analyzer that decomposes a distorted wave into its component waveform and gives the relative amounts of each.

Third party companies also provide harmonic analysis for a fee. In some areas, electric utilities will provide such services as well.

A power analyzer, such as the IQ Analyzer, can provide data on harmonic distortion, current and power demands, trending, and events and alarms. Information is accessable in real time or can be recorded for later analysis.

IEEE 519 standard

The IEEE originally recommended safe levels of harmonics in the standard IEEE 519-1981. At that time, voltage distortion limits were set as shown in Table 1.

Application class	% distortion	Notch depth	Notch V-µsec
Special system	3%	10%	16,400
General system	5%	20%	22,800
Dedicated system	10%	50%	36,500

The latest revision of this standard sets more stringent limits on current distortion in addition to the voltage distortion limits. As can be seen in Table 2, the amount of current distortion allowed depends on the available short circuit current and the maximum load current at the point of common coupling (PCC).

As the system short circuit capacity becomes large compared to the load at the PCC, the distortion limits become more lenient. This is because the harmonic effects of small loads will be washed out on larger systems.

I_{sc}/I_L	TDD
< 20	5%
20 to 50	8%
50 to 100	12%
100 to 1,000	15%
> 1,000	20%

I_{sc} = Maximum short circuit current at the point of common coupling.
I_L = Maximum load current (fundamental frequency) at point of common coupling.
TDD = Total Demand Distortion: Harmonic content distortion as a percent of maximum demand load current.

Though harmonic analyzers provide an accurate and cost-effective means for determining the harmonic content on a system, they do not predict the effects of future system modifications. Some companies will perform a system study to determine if any harmonic attenuation is needed prior to installation of AFCs, and make recommendations.

Attentuation methods

To attentuate harmonics, users can use passive filters, inductive reactors, phase-shifting transformers, active filters, or multi-pulse converter sections.

Passive filters apply tuned series L-C circuits (circuits with inductance and capacitance) that attentuate specific harmonic frequencies. Circuit elements, similar to notch filters, tune to a given frequency. The filter offers a low-impedance path-to-ground for the chosen frequencies. Though conceptually simple, this solution has potential complications.

For one, it is system dependent, such that any future system changes may require re-tuning or resizing the filters. Also, the filter cannot discriminate between those harmonics created by an AFC and those created by other sources. Thus, a filter may be sized properly for one piece of equipment but undersized for the system.

Tuning filters is sometimes labor intensive, which may present high initial costs and future costs if re-tuning is required.

Inductive reactance, in the form of line reactors or isolation transformers, can help attentuate higher order harmonics and reduce overall harmonic content. This can be a simple, inexpensive method for attentuating harmonics, particularly if just a small reduction is needed.

An effective way of applying isolation transformers is to supply balanced loads from phase-shifting transformers. One load may be fed from a delta-delta transformer and a similar load fed from a delta-wye transformer (see PTD, the “1997 Handbook,” p. A50-51). A 30-degree phase shift between the harmonic sources will cancel the 5th and 7th harmonics. Users can expect about a 50% harmonic reduction from this method.

Loads that are phase-shifted from one another should be balanced for best effect. Lesser cancellation can occur for loads not precisely balanced.

Active filters, or adaptive compensators, constantly monitor the current on the line and inject equal and opposite harmonics as necessary. These devices are effective, but are still in the initial stages of development and implementation, and somewhat costly. There is also some concern about reliability, since most designs have transistors that are subject to the conditions on the line.

Multi-phase converters have separate rectifiers that are fed from phase shifted sources. These devices can be an integral component to some AFCs.

A 12-pulse multi-phase converter, for example, uses two separate 6-diode bridges fed from a special transformer. The transformer supplies the bridges with two three-phase sources phase-shifted by a given amount. In theory, the 12-pulse system generates harmonics according to the formula:

$h = 12k \pm 1$

It will eliminate harmonics to the 11th and reduces the 11th and 13th harmonics. Rectifiers come in stages of 6 pulses, thus, the next level rectifier is an 18-pulse system, which eliminates all harmonics to the 17th, and offers small reductions in the 17th and 19th harmonics, Figure 3. To accomplish these reductions, some rectifiers use a single 18-diode bridge with integral phase shifting. Thus, there are no additional bridges to balance with one another.

In general, any bridge rectifier generates harmonics according to $h = nk \pm 1$, where n is the number of pulses (or diodes) and k is an integer. ■