providing insights for today's hvac system designer

Engineers Newsletter

volume 47–1

*A primer for non-electrical engineers*

# Harmonic Distortion in Electrical Systems

The quest to lower electrical energy consumption of HVAC and other electrically-driven equipment has led to the introduction of 'non-linear' electrical loads to the electrical grid. Harmonic distortion caused by increasing non-linear loads can result in issues in a building's electrical system.

This newsletter provides a simplified explanation of the causes of harmonic distortion by taking the reader through some electrical system basics and moving on to what harmonic distortion means and why it matters. It's intended for those with little or no experience with electrical systems.

The term harmonics is used to describe a distortion in the fundamental voltage and/ or current waveform supplied from a utility or generator. In technical terms it's a mathematical way to describe the distortion. In a practical sense it gives us terminology to talk about the problems, both potential and real, due to the proliferation of energy saving devices.

## Start with the basics

Before we talk about the distortion let's back up and look at what is being distorted. Distortion can happen in any electrical system regardless of how the power is supplied to the system. For this discussion we assume electrical power is being supplied to the building from the common electrical grid. Harmonics on systems supplied by onsite generators have some unique problems as discussed in an earlier *Engineers Newsletter*, "How VFDs Affect Genset Sizing", volume 35-1.

Power is supplied to most buildings from an electrical utility. The utility provides power via an electrical distribution grid with wires going to each building. The key components of the supplied power are the *voltage*, *current*, and *frequency*.

**Voltage** is determined at the transformer serving the building. Many voltage choices are possible but once fixed by the transformer the voltage downstream of that transformer remains relatively constant. There are factors which will alter the average voltage but these tend to be short term.

**Current,** or amperage, depends on the supplied voltage and the electrical loads in the building. For a given building, as the electrical load increases so does the current flow. A combination of current, voltage, and power factor are used to determine the power used by the building.

**Frequency** is determined on a country-by-country basis. The United States, for example, uses 60 Hz, other countries may use 50 Hz, but within a distribution grid the utility supplying the power will stay with one frequency. This frequency is called the **fundamental frequency**. It is stable and consistent even when voltage or current change.

Figure 1 shows one cycle of a fundamental 60 Hz waveform. It's called a **periodic waveform** because of the repeating nature. The horizontal axis is time. As time passes the wave repeats over and over in the same shape. The shape can be mathematically described as a *sine wave*.

As shown in Figure 2 each complete cycle of the wave represents 360 degrees of rotation. Counting the number of complete wave cycles per second yields the **frequency** of the wave. The Y axis is used to define magnitude.

Alternating power, or AC power, means that the voltage supplied varies between positive and negative values as shown in Figure 3. This defines the fundamental voltage waveform supplied to the building.

The final piece for a basic understanding of power supply is the **current signal**. The utility defines the fundamental frequency and voltage but the current signal is dependent on the load. The *relationship between the voltage waveform and the current waveform is dependent on the type of electrical load*. This relationship is key to understanding how harmonic currents are created.

## Types of electrical loads

**Linear loads** draw current evenly and in proportion to voltage throughout the duty cycle; the sinusoidal waveform of the incoming power remains intact.

There are three types of linear loads. We'll start with **resistive** loads. Electric resistance heaters are a common example of a resistive load. For these loads the waveforms for voltage and current are different only in magnitude as shown in Figure 4.

**Inductive** loads, e.g., common electrical motors, result in a current signal that is shifted slightly (Figure 5) from the voltage signal. This shift is called *lagging* because for a given point on the time scale, the current waveform passes through that point after the voltage waveform passes the same point.

**Figure 1. One cycle of a 60 Hz periodic waveform**

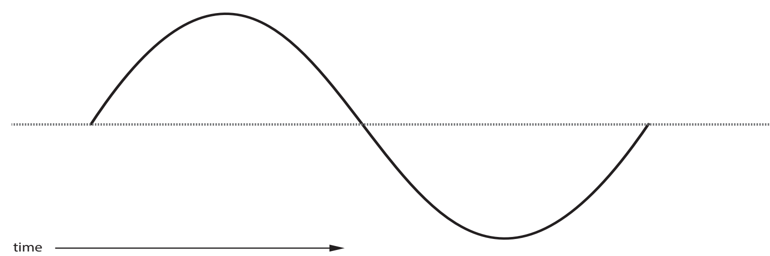



**Figure 2. The number of complete wave cycles per second yields the frequency of the wave**

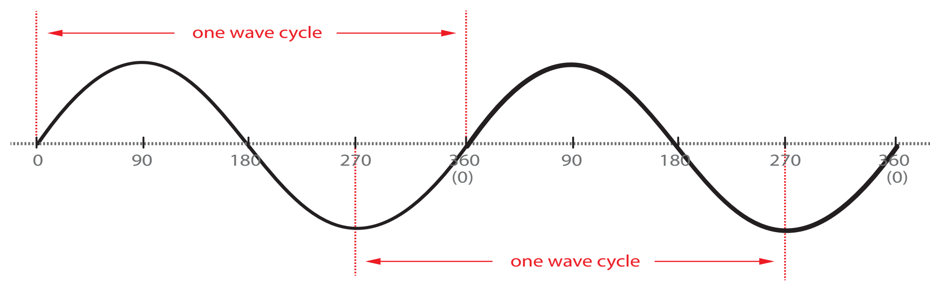



**Figure 3. Positive and negative voltage variation in alternating power**

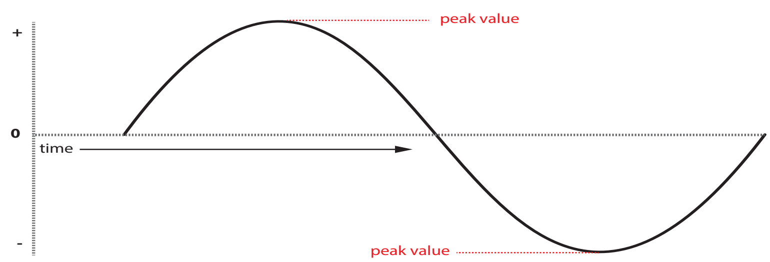



**Figure 4. Waveform difference between current and voltage magnitude (resistive load).**

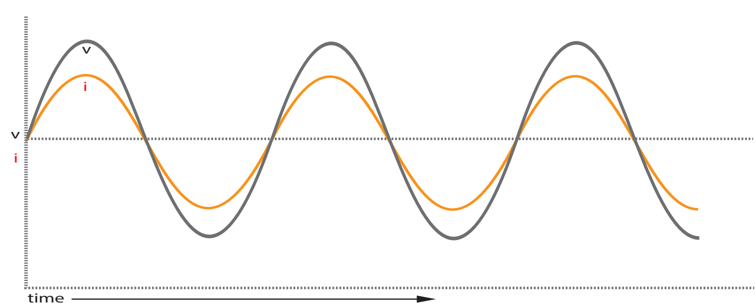
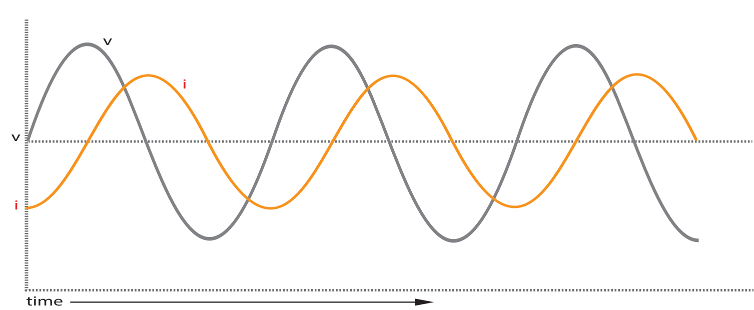



**Figure 5. Current signal that is shifted slightly from the voltage signal (inductive load).**



A third type of linear load is **capacitive** loads. A capacitive load shifts the current signal to lead the voltage signal. There aren't many work-producing loads that have a capacitive character but capacitors are sometimes added to electrical systems to balance the inductive loads.

When the voltage and current waveforms line up, as they do with *resistive* loads, the voltage multiplied by current is always positive (Figure 6). However when the voltage and current waveforms are shifted, as with *inductive* loads, there are occasions when the product of voltage times current is negative (Figure 7). The negative portion (caused as stored energy is released) doesn't contribute to the positive work done by the load. The non-productive power is indicated by the **displacement power factor.**

Adding capacitors to systems with inductive loads improves the displacement power factor of the system by shifting the combined waveform toward unity.

Displacement power factor is defined as the ratio of positive work actually done (true power) to the positive work that would have been done if the waveforms aligned.

When voltage and current waveforms are not aligned some fraction of the current isn't doing positive work. The extra current must be generated by the utility and transmitted through the electrical distribution system even though the current isn't doing positive work. Anytime current travels though the electrical grid there are losses associated with the resistance of the system.

Although we're discussing linear electrical loads, the concept of current flow that doesn't do positive work is important to understand.

**Figure 6. Resistive loads always consume positive power**

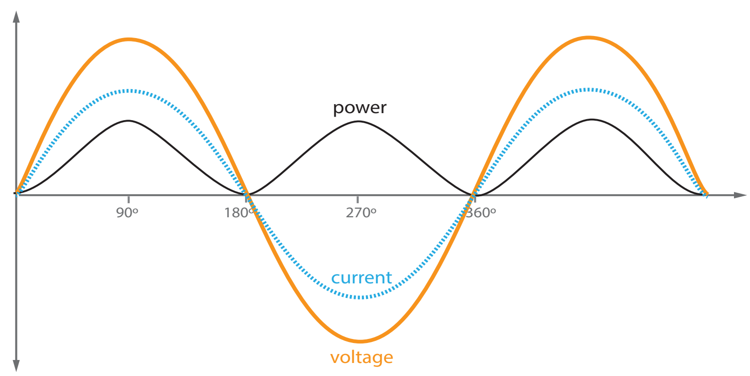
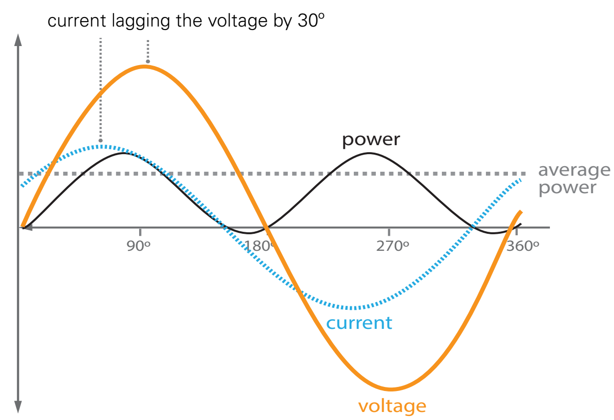



**Figure 7. Current and voltage waveforms shifted (inductive) consume positive and negative power.**




To a "non-electrical" engineer this concept may not make sense. To better understand, it's helpful to think of inductors and capacitors as energy storage devices. They affect the current by temporarily storing some of the energy internally. An inductive load, such as a motor, inherently stores energy as the voltage approaches the positive or negative maximum. As the voltage drops back toward zero, the stored energy is released back onto the grid delayed in time.

A capacitor works just the opposite. By shifting the current value in time relative to the voltage, these devices affect the current flow without doing any actual work. As stated earlier, even though the shifted current isn't doing any positive work, this current still needs to be generated and transmitted by the utility company.

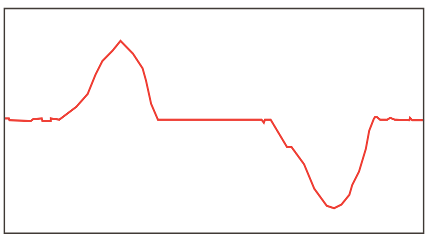
**Non-linear loads** distort the original current and voltage waveforms by drawing current in instantaneous pulses that are disproportionate to voltage.

Switch-mode power supplies (SMPS), found in computers, servers, monitors, printers, photocopiers, telecom systems, broadcasting equipment, and variable-speed motors and drives, are examples of non-linear loads. Single-phase, non-linear loads are prevalent in office equipment, while three-phase, non-linear loads are widespread in larger electrical systems.

Non-linear electric loads are characterized by a non-constant resistance during the applied voltage waveform. Because the resistance is not constant the resulting current waveform does not match the applied voltage waveform. Each of the various non-linear loads have a unique resistance characteristic, and thus, a unique current waveform shape.

The common SMPS load consists of a 2-pulse (full wave) rectifier bridge (to convert AC to DC) and a large filter capacitor on its DC bus. This load draws current in short, high-amplitude pulses that occur around the positive and negative peaks of voltage. The resulting current waveform is shown in Figure 8.

**Figure 8. Common SMPS current waveform**

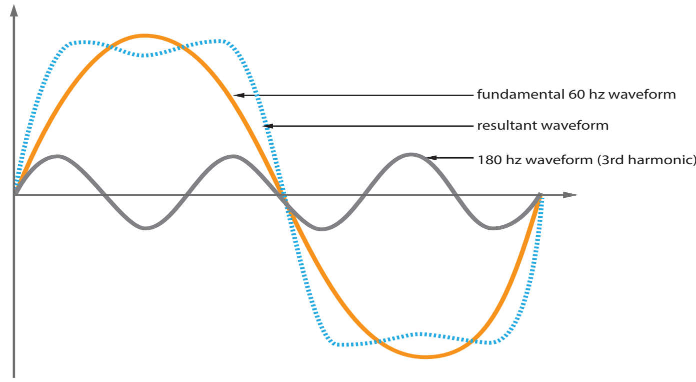


This power conversion creates harmonics. When the rectifier converts incoming AC power to DC power, its demand for current rapidly cycles on and off. This cyclic power draw distorts the original shape of the current waveform, "chopping up" the sinusoidal shape and imposing new waveforms that are multiples—*harmonics*—of the original signal. These harmonics are reflected back onto the electrical system.[1] The combination of the fundamental sine wave and its multiples cause "harmonic distortion," a new waveform of an entirely different shape.

Although the circuit is supplied by a 60 Hz sinusoidal voltage waveform, the resulting current waveform shown in Figure 8 isn't a simple 60 Hz sinusoidal waveform. This waveform can be described mathematically as being the combination of many sine waves of different frequencies.

To better understand this, it's necessary to understand how sine waves are added.

**Figure 9. Resultant waveform for the combination of fundamental and 3rd harmonic**




**Harmonics.** As mentioned earlier, the presence of harmonics in electrical systems means that current and voltage are distorted and deviate from sinusoidal waveforms.

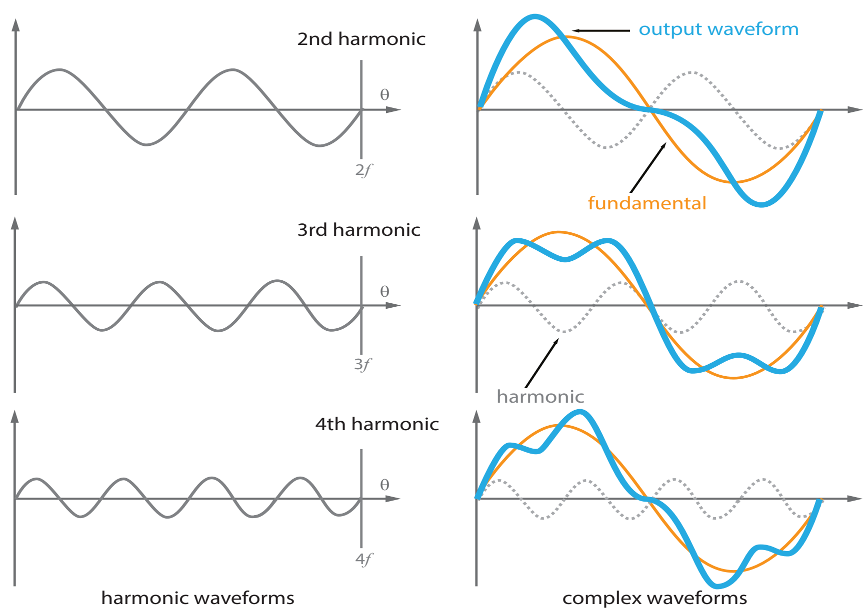
To demonstrate we'll start with a fundamental 60 Hz sine wave, similar to the one shown in Figure 1, and add a second sine wave with a frequency of 180 Hz (or 3rd harmonic). Figure 9 shows the 60 Hz wave in orange and the 180 Hz wave in gray. The waves are combined by adding the area under each curve.

Another way to look at this is that at any point along the x-axis, the value of the orange wave is added to the value of the gray wave. When both waves have the same sign, e.g., both are positive, the magnitudes add. When the waves have opposite signs the values subtract. The result is the dotted blue wave.

The harmonic frequencies are always integer multiples of the fundamental. Figure 10 shows the resulting waveform when second, third and fourth harmonics are added to the fundamental waveform.

Figures 9 and 10 show a single harmonic being added to the fundamental waveform to illustrate how the addition of harmonics changes the shape of the resulting waveform. The waveform addition used in Figure 10 can be used to add multiple harmonic waveforms at the same time.

**Figure 10. Resulting waveforms for 2nd, 3rd and 4th harmonics**



It's necessary to use many harmonic waves to produce the complicated waveforms created by non-linear loads. Figure 11 shows the addition of 3rd through 15th harmonics to create a "square" waveform.

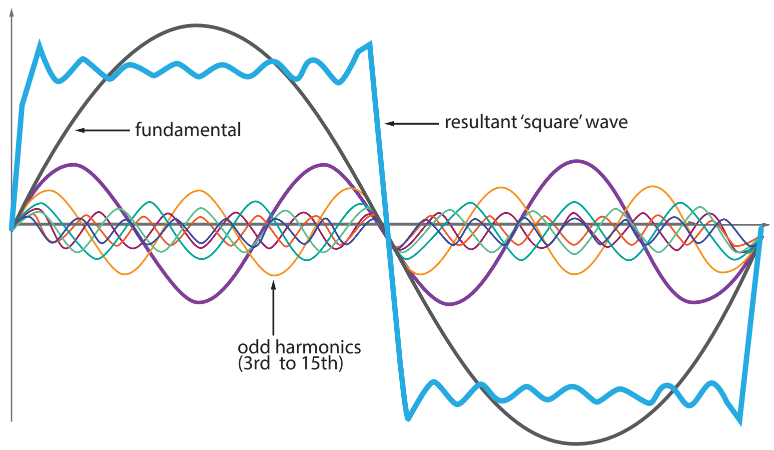
**More on power factor.** The previous section on linear electrical loads explained that the *displacement* power factor is used to indicate how much non-productive current is required by the *linear* load. Similarily, *non-linear* loads also result in non-productive currents. These currents are quantified by **distortion** power factor.

The total, or true, power factor for a system is the combination of *displacement* power factor and *distortion* power factor. These non-productive currents cost the utility. Although the utility can't charge for the extra current on a kW basis they may include a charge (penalty) for a low power factor. For example, in some markets a low power factor of 80 percent could be charged a 16% percent surcharge.[2]

If the power company includes a charge for low power factor there is a direct cost for harmonic distortion.

Harmonic currents travel through the electrical system along with the fundamental current. Electrical systems can tolerate some harmonic content but when the harmonics are excessive a host of issues can arise. Problems caused by harmonics can be widespread throughout the system, e.g., overheating of distribution equipment, or localized to the disruption of sensitive equipment, and interference with telecommunication circuits, etc. Voltage distortion resulting from the current distortion, can also result in equipment problems.

**Figure 11. Resulting square waveform with the addition of the 3rd to 15th harmonics**




**Displacement and Distortion Power Factor Comparison.**

**Linear Loads, Displacement Power Factor**

- Linear loads do not change the shape of the current waveform, but may change the phase angle between voltage and current.
- Power factor correction for linear loads can be achieved by adding capacitance to offset the inductive effect of the motors and re-align current with voltage.
- In linear circuits, the sinusoidal currents and voltages are of one frequency. The displacement power factor arises only from the difference in phase between the current and voltage.

**Non-Linear Loads, Distortion Power Factor**

- With a non-linear load, the current is drawn from the utility in pulses which may occur multiple times per electrical cycle.
- Non-linear loads create harmonic currents at higher frequencies in addition to the original current frequency.
- Power factor correction can be achieved using filters designed to pass only line frequency (50 or 60Hz), reducing harmonic current, and making the non-linear device now look like a linear load.
- Distortion power factor is a measure of how much the harmonic distortion of a load current decreases the efficiency of the power transferred to the load.

## Quantifying harmonic content

There are many different types of non-linear electrical loads in operation today. Each type has a unique waveform and distinct harmonic content. One way to describe the harmonic content of a particular source is to show the magnitude (as a percentage) and frequency of the harmonic waves that make up the resultant wave. For example Figure 12 illustrates the most notable harmonics for a switch mode power supply or 6-pulse, variable-frequency drive. The missing harmonics are not shown because they are zero and do not contribute to the distortion.

It's typical for the magnitude of the harmonics to decrease as the order of the harmonic increases. As a result, sometimes higher order harmonics are ignored because their contribution to the total is limited.

There are several metrics to help determine and measure the distortion caused by harmonics.

**Total harmonic distortion (THD)** is a measure of the effective value of the harmonic components of a distorted waveform.[3] It can be calculated for either current or voltage but is most often used to describe voltage harmonic distortion. It's mathematically calculated as the *root-sum-square of harmonic components to the fundamental component*. THD can be measured for an existing system or calculated for a proposed system using the following equation:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} M_h^2}}{M_1}$$

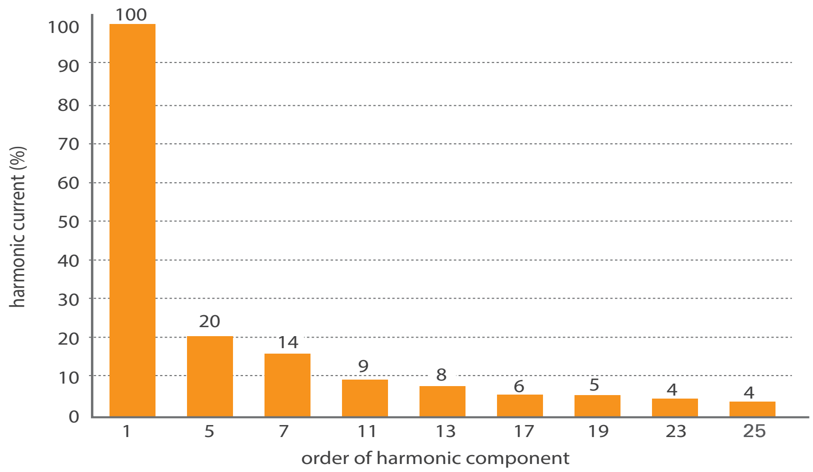
where:

$M_h$ = *individual harmonic component*

$M_1$ = *fundamental component*

$M$ can be either voltage or current

**Figure 12. Harmonic content of typical 6-pulse variable-frequency drive**




However, even a small current can have a high THD which can be misleading because it may not have significant impact if operating in light load conditions (such as variable-speed drive). As mentioned earlier, current distortion results in voltage distortion. There is a similar metric used for current called the **total demand distortion (TDD)**.

TDD offers better insight by providing *"the total root-sum-square harmonic current distortion, in percent of the maximum* ***demand load*** *current."* [4]

Knowing these equations is not required in most cases but it is important to distinguish between *current* distortion and *voltage* distortion.

In practice the THD and harmonic content of the voltage and current in an electrical system are measured by a power quality analyzer. The analyzer measures the electrical system similar to a voltage meter and is able to display the detailed harmonics content as well as the calculated THD.

## How much is too much?

When it comes to harmonics knowing how much is too much can be difficult to determine. Calculating THD and TDD for a proposed system is a complicated process that requires a great deal of information about the system and the non-linear loads it will serve.

While the list of potential problems that could result from harmonic distortion is long, it should be noted that in many cases harmonics in the electrical system do not cause issues. The potential for problems is based on; the amount of harmonic distortion present, the size of the electrical system, and the sensitivity of equipment within the system to harmonics.

When non-linear loads are a small fraction (less than 20 percent) of the total load, the potential to cause problems is very low. However as more and more non-linear loads are added to the grid, the potential for harmonics-related issues increases.

Think of harmonics as the ripples caused by tossing pebbles in a pond. In a large pond, the ripples dissipate over distance and leave much of the water undisturbed. In a small pond, the ripples reach the nearby shores and reflect back, resulting in a chaos of interacting waves. Similarly, the size of the distribution system and the "stiffness" or "softness" of the electrical system influence the degree to which harmonics affect other equipment. A large system with stiff power not only reduces the voltage fluctuation that occurs when an electrical load is added to the system, but it also reduces disruptive harmonic effects.[5]

**Standard IEEE® 519** is the most commonly referred to standard when defining recommended limits for harmonic distortion. It's primarily intended to define limits for the amount of distortion that a building can place back on the electrical grid. Distortion placed back on the electrical grid by one customer can impact other customers on the same grid. The standard sets recommended limits for harmonics at the point of common coupling (PCC), i.e., the electrical connection between the building and the electrical grid (see sidebar).

**Standard IEEE 519 recommended limits.**

**Table 1. Current distortion limits for systems rated 120V through 69kV.**

| | short-circuit current / load current | Total demand distortion (TDD) limit | |
|---|---|---|---|
| large load on small system | <20 | 5% | more restrictive TDD limit |
| | 20-50 | 8% | |
| | 50-100 | 12% | |
| | 100-1000 | 15% | |
| small load on large system | >1000 | 20% | less restrictive TDD limit |

**Table 2. Voltage distortion limits.**

| Bus votage *V* at PCC | Individual harmonic (%) | Total harmonic distortion (THD) limit |
|---|---|---|
| $V \leq 1.0$ kV | 5.0 | 8% |
| 1kV < $V \leq 69$ kV | 3.0 | 5% |
| 69 kV < $V$ < 161 kV | 1.5 | 2.5% |
| 161 kV < $V$ | 1.0 | 1.5%* |

*High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

## What can be done to control harmonics?

From a building owner's perspective it can be difficult to predict the impact of harmonics on the electrical components and equipment in the building. All buildings contain non-linear electric loads that are generating harmonic distortion but few buildings suffer any ill effects. This doesn't mean harmonics can be ignored because there are buildings where they do create problems.

Caution is warranted when a large amount of non-linear load is added to an existing electrical system. This can happen when "energy saving" upgrades are made that convert linear loads to non-linear loads.

A common approach to avoiding problems caused by harmonics is to mitigate harmonics where they are created. It's not a practical option if the source of the harmonic distortion is a large quantity of small loads, e.g., personal computers, but if the building has large non-linear electric loads it may make sense.

There are many types of mitigation strategies that can be applied at the equipment level with varying levels of harmonic reduction and cost. The amount of reduction required is dependent on the other non-linear loads on the system and the sensitivity of other components and equipment to harmonic distortion. In short, it can be challenging to determine how much mitigation is needed.

The IEEE 519 limits for the PCC are sometimes applied at the equipment level. It's a stringent requirement to apply at the equipment level, and may add unnecessary cost, but it can be easy to specify and can reduce the impact a piece of equipment might have on the rest of the equipment within the system.

New electrical systems can be designed to manage some over-heating issues caused by harmonic currents; oversized neutrals and de-rated transformers for example. Systems can also be designed with transformers and other devices to reduce the transmission of harmonics to other equipment on the electrical system.

## Final thoughts

Harmonic distortion on electrical systems increases with the increased percentage of non-linear loads. The distortion doesn't always cause problems but it certainly can. As problems with harmonic distortion increase with the acceleration of energy-saving devices so do the solutions for reducing harmonic content. Understanding the source of harmonic distortion provides a basis for understanding potential issues and determining resolutions for harmonics in electrical systems.

By Dave Guckelberger, Bob Coleman and Chris Hsieh, Trane. To subscribe or view previous issues of the *Engineers Newsletter* visit trane.com/EN. Send comments to ENL@trane.com.

## References

[1] IEEE 519-2014 defines acceptable limits for harmonics in electrical power systems. For more information, visit http://standards.ieee.org.

[2] BC Hydro website. https://www.bchydro.com/accounts-billing/rates-energy-use/electricity-rates/power-factor.html

[3] "Electrical Power Systems Quality" by Dugan, McGranaghan, Santoso, and Beaty (ISBN 0-07-138622-X).

[4] IEEE Std 519-2014 - "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. "

[5] Nebuda, C. and B. Bradley. "How VFDs Affect Genset Sizing." Engineers Newsletter vol. 35-1. 2006.

*Join your local Trane office for the 2018 Engineers Newsletter LIVE!*

## *Mark your calendar!*

**Chilled-Water System Decisions.** Many chilled-water system decisions are made during the course of the design process. Those decisions lead to other application-specific system decisions – such as bypass line sizing and length, pump location, ice tank versus chiller location, use of pressure independent valves, buffer tank size, control of chillers in series etc. This ENL covers the reasons for many system design decisions.(March)

**Controls Communication Technologies**. Recent innovations in the industry have made open, standard communication protocols that deliver flexible, interoperable control systems more prevalent today. This ENL will review various communication protocols (using both wired and wireless technologies), discuss where each best applies, and describe ways to ensure the expectations of the owner are met. (May)

**Demand-Controlled Ventilation.** The mobility of a building's occupants poses a ventilation challenge: To bring enough outdoor air into the building to help ensure good indoor air quality without wasting energy by bringing in (and conditioning) too much. This ENL will discuss various methods used to vary outdoor airflow based on actual demand. It also reviews the related requirements for compliance with ASHRAE Standards 62.1 and 90.1. (November)

**Contact your local Trane office for dates and details.**

*Earn PDH credit - no charge and on-demand!*

## *NEW Online Courses Available!*

View all courses at **www.trane.com/ContinuingEducation**

**High-Performance Air Systems** examines the properties of high-performance air systems and provides guidance on their design. Topics include right-sizing and proper component selection, duct design guidelines, system control strategies, selection for part-load efficiency and much more.

**Demand Response in Commercial Buildings** discusses the relevant improvements that load shifting and demand response can provide, with examples of the types of utility and funding programs that are available.



*Trane,*
*A business of Ingersoll Rand*

*For more information, contact your local Trane office or e-mail us at comfort@trane.com*