

Lighting *Answers*

Power Quality

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NATIONAL
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Introduction

Concerns about the effects of lighting products on power distribution systems have focused attention on power quality. Poor power quality can waste energy and the capacity of an electrical system; it can harm both the electrical distribution system and devices operating on the system.

The National Lighting Product Information Program (NLPIP) prepared this issue of *Lighting Answers* to help lighting specifiers and consumers better understand power quality, so that they can more confidently select energy-efficient lighting products.

What is power quality?

For an electrical distribution system, power quality is the extent to which line voltage is a sine wave of constant *amplitude**. Figure 1 shows the waveform of a 120-volt (V), 60-hertz (Hz) line voltage of ideal power quality. In an alternating current circuit, electrons

flow towards the power source for one half of the cycle and away from the power source for the other half. At 60 Hz, the voltage wave completes a cycle every 1/60th of a second, or approximately every 17 milliseconds (ms).

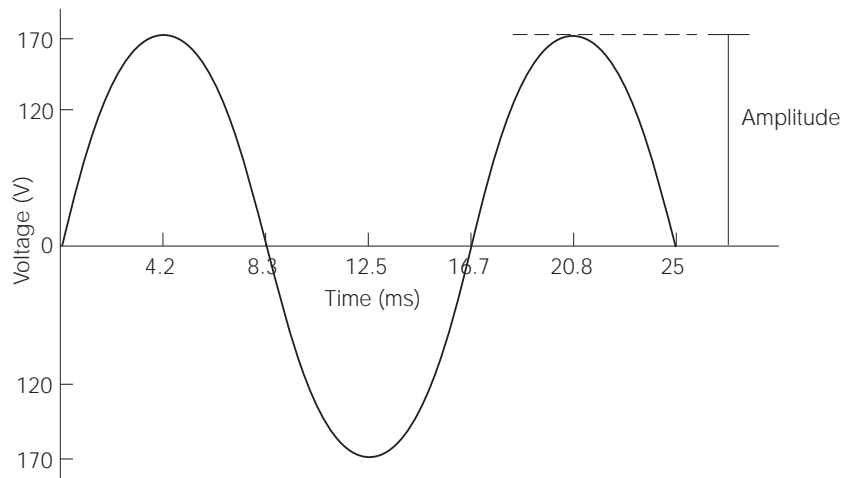
Problems with a utility's generators or distribution system can cause serious power quality problems such as voltage drops and *transients*, both of which can reduce the life of lighting systems and other electrical equipment. High levels of distortion (deviation from a sine wave) in the distribution system can also harm electrical equipment. Unlike voltage drops and transients, however, distortion often is caused by electric devices operating on the system.

For a specific electric device, the term power quality describes the extent to which the device both distorts the voltage waveform and changes the phase relationship between voltage and current. A device with ideal power quality characteristics neither distorts the supply voltage nor affects the voltage-current phase relationship.

* Terms in *italics* are defined in the glossary on p. 7.

Figure 1
Voltage waveform for a 120-V, 60-Hz power supply with ideal power quality

A smooth sine wave is characteristic of undistorted voltage. At the *frequency* of 60 Hz, the wave repeats every 16.7 ms. The amplitude is 170 V; the *root-mean-square* (rms) value of the wave is 120 V.



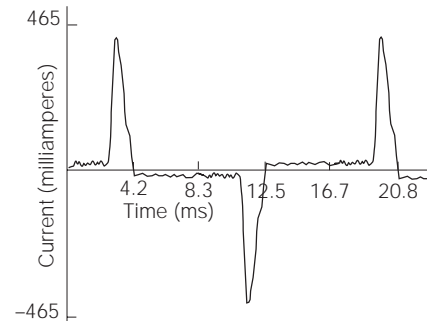
How do lighting systems affect power quality?

Most incandescent lighting systems do not reduce the power quality of a distribution system because they have sinusoidal current waveforms that are in phase with the voltage waveform (the current and voltage both increase and decrease at the same time).

Fluorescent, high-intensity discharge (HID), and low-voltage incandescent lighting systems, which use ballasts or transformers, may have distorted current waveforms. Figure 2 shows an example of a highly distorted current waveform typical of some electronic ballasts for compact fluorescent lamps. Devices with such distorted current waveforms draw current in short bursts (instead of drawing it smoothly), which creates distortion in the voltage. These devices' current waveforms also may be out of phase with the voltage waveform. Such a *phase displacement* can reduce the efficiency of the alternating current circuit. In Figure 3, the current wave lags behind the voltage wave. During part of the cycle the current is positive while the voltage is negative (or vice versa), as shown in the shaded areas; the current and voltage work against each other, creating *reactive power*. The device produces work only during the time represented by the non-shaded parts of the cycle, which represent the circuit's *active power*.

Reactive power does not distort the voltage. However, it is an important power quality concern because utilities' distribution systems must have the capacity to carry reactive power even though it accomplishes no useful work.

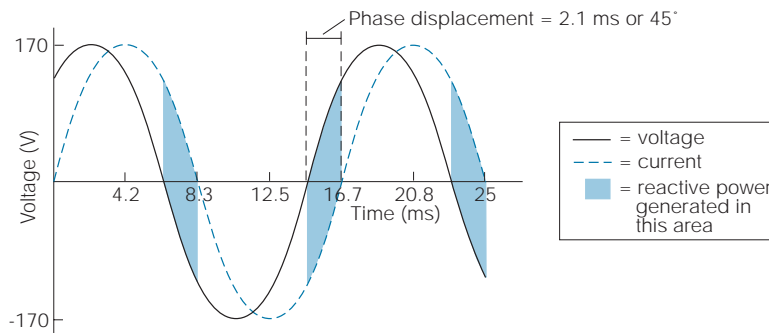
Figure 2
A highly distorted current waveform



Both lighting manufacturers and building owners can take steps to improve power quality. Most electronic ballasts for full-size fluorescent lamps have filters to reduce current distortion. Some electronic ballasts for compact fluorescent lamps have high current distortion, but contribute very little to voltage distortion because of their low power.

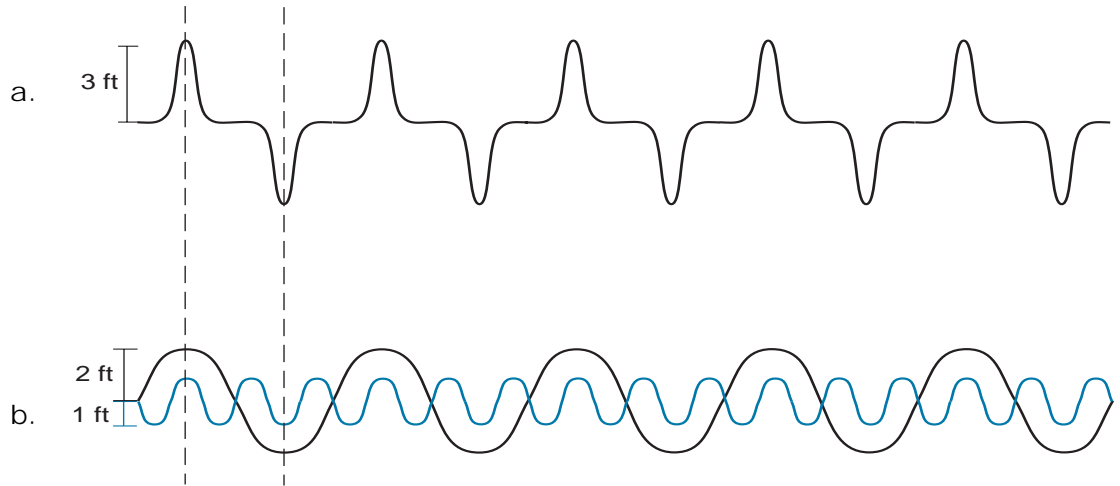
Magnetic ballasts for fluorescent and HID lamps typically have lagging current. Some magnetic ballasts contain capacitors that resynchronize the current and voltage, which eliminates reactive power. Building owners also can install capacitors in their building distribution systems to compensate for large loads with lagging current.

Figure 3
Phase displacement and reactive power



When a device's current waveform is out of phase with the voltage waveform, the difference between the two is the phase displacement. The shaded areas represent the reactive power that results.

Figure 4
Illustrating harmonics



The distorted waveform in Figure 4a can be described by the sum of one sine wave with frequency 1 Hz and amplitude 2 feet (ft), which is the fundamental, and a second sine wave with frequency 3 Hz and amplitude 1 ft, which is the third-order harmonic. The two component waves are shown in Figure 4b.

The “peaks” and “troughs” of the distorted wave result when a peak or trough of the fundamental coincides with a peak or trough of the harmonic. The flat

portions of the distorted wave result when the fundamental and harmonic cancel each other out.

The distorted wave in Figure 4a is similar to what a rope would look like if one person shook one end at the frequency and amplitude of the fundamental wave shown in Figure 4b, while another person shook the other end at the frequency and amplitude of the third-order harmonic shown in Figure 4b.

What are harmonics?

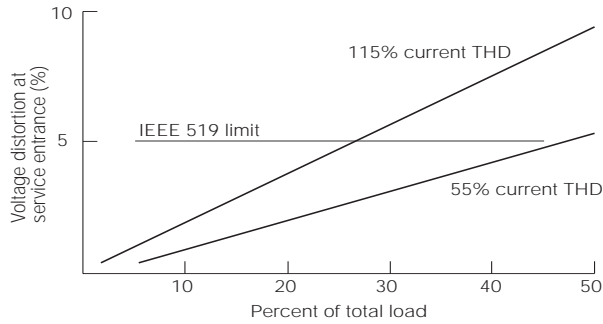
A *harmonic* is a wave with a frequency that is an integer multiple of the *fundamental*, or main wave. Any distorted waveform can be described by the fundamental wave plus one or more harmonics, as shown in Figure 4. A distorted 60-Hz current wave, for example, may contain harmonics at 120 Hz, 180 Hz, and other multiples of 60 Hz. The harmonic whose frequency is twice that of the fundamental is called the second-order harmonic; the third-order harmonic has a frequency three times that of the fundamental, and so forth.

Highly distorted current waveforms contain numerous harmonics. The even harmonic components (second-order, fourth-order, etc.) tend to cancel out each other’s effects, but the odd harmonics tend to add in a way that rapidly increases distortion because the peaks and troughs of their waveforms often coincide. The lighting industry calls its most common measure of distortion *total harmonic distortion (THD)*. The sidebar “Defining total harmonic distortion and harmonic factor” on p. 4 gives formulas for calculating THD.

Utilities typically supply voltage with less than 2% THD. However, current THD for electronic devices may be very high, often over 100%. Table 1 on p. 5 lists current THD from several types of lighting loads, as well as from common office equipment, as measured by NLPPI. Devices with high current THD contribute to voltage THD in proportion to their percentage of a building’s total load. Thus, higher-wattage devices can increase voltage THD more than lower-wattage devices. If harmonic distortion is a concern for a lighting system, NLPPI recommends that specifiers use electronic ballasts with filters to minimize THD.

The recommended maximum allowable voltage THD at the point where a building connects to the utility distribution system is 5% (IEEE 1992). Figure 5 on p. 4 shows that voltage THD reaches this limit when approximately half the building’s load has current THD of 55%, or when approximately one-quarter of the building’s load has current THD of 115%.

Figure 5
Voltage THD resulting from 55% and 115% current THD
(Adapted from Verderber et al. 1993, © 1993 IEEE)



The IEEE voltage THD limit is theoretically exceeded when approximately 47% of the total load in a building has 55% current THD or when approximately 26% of the load has 115% current THD.

What is power factor?

Power factor is a measure of how effectively a device converts input current and voltage into useful electric power. It describes the combined effects of current THD and reactive power from phase displacement. A device with a power factor of unity (1.0) has 0% current THD and a current draw that is synchronized with the voltage. Resistive loads such as incandescent lamps have power factors of unity. A device is said to have high power factor (HPF) if the power factor is 0.9 or greater. Power factor between 0.5 and 0.9

is called normal power factor (NPF). Magnetic and electronic ballasts for fluorescent lamps may be either HPF or NPF. HPF ballasts usually have filters to reduce harmonics and capacitors to reduce phase displacement. On average these additional components add about 16% to the retail costs of ballasts (Dorr et al. 1994).

NLPIP measured power factor for several types of lighting loads, and for common office equipment; these data are shown in Table 1.

Defining total harmonic distortion (THD) and harmonic factor

Ballast manufacturers, electric utilities, and standards organizations define THD differently, which has caused some confusion in the lighting industry. In this report, NLPIP uses the Institute of Electrical and Electronics Engineers (IEEE) definition for THD given in IEEE 1035-1989, because that is how ballast manufacturers typically report THD.

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \dots}}{\sqrt{I_1^2}} \times 100 \text{ (to convert to percentage),}$$

where I_1 is the root-mean-square (rms) of the fundamental current waveform
 I_2 is the rms of the second-order harmonic current waveform
 I_3 is the rms of the third-order harmonic current waveform, etc.

The American National Standards Institute (ANSI), the Canadian Standards Association (CSA), and the International Electrotechnical Commission (IEC) use the above formula as the definition of "harmonic factor." CSA and IEC define THD as

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \dots}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \dots}} \times 100 \text{ (to convert to percentage),}$$

where I_1 is the rms of the fundamental current waveform,
 I_2 is the rms of the second-order harmonic current waveform
 I_3 is the rms of the third-order harmonic current waveform, etc.

According to the second definition, THD is always less than 100%. The table below gives some conversions between the two definitions.

Equivalent values of THD using the two definitions

THD (%) as commonly reported by manufacturers (IEEE 1035-1989)	THD (%) as defined by CSA and IEC
5	5
20	19.6
32	30.5
50	44.7
100	70.7
150	83.2

Table 1

Sample power quality characteristics for different electric loads*

	Active Power (W)	Power Factor	Current THD (%)
Compact fluorescent lighting systems			
13-W quad-tube compact fluorescent lamp w/ NPF magnetic ballast	16	0.54	13
13-W quad-tube compact fluorescent lamp w/ NPF electronic ballast	13	0.50	153
16-W quad-tube compact fluorescent lamp w/ HPF electronic ballast	16	0.91	20
Full-size fluorescent lighting systems (two lamps per ballast)			
T12 40-W lamps w/ energy-efficient magnetic ballast for T12 lamps	87	0.98	17
T12 34-W lamps w/ energy-efficient magnetic ballasts for T12 lamps	72	0.94	22
T10 40-W lamps w/ energy-efficient magnetic ballast for T12 lamps	93	0.98	22
T12 40-W lamps w/ electronic ballast for T12 lamps	72	0.99	5
T12 34-W lamps w/ electronic ballast for T12 lamps	62	0.99	5
T10 40-W lamps w/ electronic ballast for T12 lamps	75	0.99	5
T9 34-W lamps w/ electronic ballast for T12 lamps	79	0.99	5
T9 32-W lamps w/ electronic ballast for T8 lamps	61	0.98	6
T8 32-W lamps w/ electronic ballast for T8 lamps	63	0.98	6
High-intensity discharge lighting systems			
400-W high-pressure sodium lamp w/ magnetic transformer	425	0.99	14
400-W metal halide lamp w/ magnetic transformer	450	0.94	19
Incandescent lighting systems			
100-W incandescent A lamp	101	1.0	1
50-W MR16 low-voltage halogen lamp w/ magnetic transformer	62	0.97	6
50-W MR16 low-voltage halogen lamp w/ electronic transformer	51	0.99	10
Office equipment			
Desktop computer without monitor	33	0.56	139
13" high-resolution color monitor for desktop computer	49	0.56	138
Laser printer while in standby	29	0.40	224
Laser printer while printing	799	0.98	15
External fax/modem	5	0.73	47
Electric pencil sharpener	85	0.41	33

* NLPPIP measured specific products and reported their characteristics. These characteristics may vary substantially for similar products; specifiers should check with product manufacturers for specific information.

What problems result from poor power quality?

Poor power quality can damage the distribution system and devices operating on the system. In rare instances, poor power quality can cause a dangerous overload of the neutral conductor in a three-phase circuit. In this type of circuit, three power supply wires share one grounded circuit conductor (the neutral conductor). In a system with no THD, the neutral wire carries no current. High-current-THD devices can send odd triple harmonics (third-order, ninth-order, fifteenth-order, etc.) onto the voltage supply, which do not cancel each other out. They add up on the neutral wire, and if the current exceeds the wire's rating, the neutral conductor can overheat and pose a fire hazard.

Voltage distortion can also shorten the life of utilities' transformers and cause capacitor banks to fail. Many utilities impose penalty charges on their customers if power factor, measured at the point where the utility service couples to the customer's site, falls below a certain value.

Reactive power uses capacity on the distribution system, which limits the amount of active power that a utility can deliver. This may be a problem during periods of peak demand.

When voltage THD is below the IEEE limit of 5%, most devices do not experience problems. Resistive loads such as incandescent lamps actually reduce voltage harmonics. Motor loads also reduce harmonics, but the motors are subject to overheating as voltage distortion increases. Fifth-order harmonics produce particularly negative effects: they rapidly degrade the motor's efficiency by producing torque in opposition to normal for part of the cycle.

Electric devices such as computers and fluorescent lighting systems are not affected by voltage distortion at this level because their power is filtered through the transformer or ballast.

High-frequency electronic ballasts operate at frequencies ranging from 20 to 60 kilohertz (kHz). The harmonics produced by these ballasts are at correspondingly high frequencies and can interfere with some communication equipment including radios, intercoms, and cordless phones. Devices that use power-line carrier signals, such as synchronized clocks and control modules for building energy management systems may also experience problems if harmonics exist at frequencies close to the carrier signal.

Lighting Answers: Electromagnetic Interference Involving Fluorescent Lighting Systems (1995) contains more information about this topic.

What limits for current THD and power factor are used in the lighting industry?

Standards organizations have not set power factor limits for lighting products, except for the requirement that power factor must meet or exceed 0.90 for manufacturers to claim that a product has high power factor. Lighting designers, architects, and other lighting specifiers often specify HPF ballasts for buildings with sensitive equipment, such as hospitals.

ANSI recently established a maximum current THD limit of 32% for electronic ballasts for full-size fluorescent lamps (ANSI 1993). The new standard also specifically limits the amplitude of the third-order harmonic to 30% of the fundamental amplitude, and limits the amplitude of all high-order harmonics (greater than eleventh-order) to 7% of the fundamental. CSA, IEC, and IEEE set a 20% current THD limit for electronic ballasts. Almost all electronic ballasts currently available for 4-foot T12 and T8 lamps are high power factor with current THD less than 20%.

Some compact fluorescent lamps (CFLs) have current THD greater than 100%, but they have low active power compared with other high-THD products such as personal computers, so standards organizations have not set power quality requirements for CFLs.

Some utilities set current THD requirements for products in their lighting incentive programs. For example, the Duke Power Co. in North Carolina and New England Electric Systems limit current THD for electronic ballasts for full-size fluorescent lamps to 20%. Additionally, New England Electric Systems limits current THD for CFLs to 25%.

Assessing the impact of electric devices on power quality

Electronic devices affect power quality in proportion to their percentage of the total electric load. For example, an electronic ballast with 32% current THD may produce less voltage distortion than a magnetic ballast with 20% current THD, because the electronic ballast uses less power. Similarly, although a 16-W CFL with a low-power-factor ballast may produce nearly 30 W of reactive power, the amount of power that a distribution system must carry actually decreases if the CFL replaces a 60-W incandescent lamp.

Specifiers can use the equations in this publication to estimate the distortion current produced by electronic devices. For example, consider two devices from Table 1 on p. 5: the 13-W quad-tube CFL with NPF electronic ballast and the laser printer while printing. Both devices have rms voltage of 120 V; their rms current can be determined using the power factor equation given in the glossary on p. 7. This gives an rms current of 0.22 amperes (A) for the CFL and 6.79 A for the printer. These values are the rms of each device's fundamental current waveform and can be used in the THD equation in the sidebar on p. 4 to estimate the total harmonic current of each device. The resultant values of 0.33 A for the CFL and 1.02 A for the printer show that although the printer has relatively low current THD (15%), the actual distortion current produced by the printer is more than three times that of the CFL because the printer uses more power.

Glossary

active power Also called input power, it is the power (in watts) used by a device to produce useful work.

amplitude The maximum absolute value attained by a periodic wave.

frequency The number of cycles completed by a periodic wave in a given unit of time. Frequency commonly is reported in hertz (Hz), which is cycles per second.

fundamental The component of a periodic wave that has the lowest frequency. It is also called the first-order harmonic.

harmonic For a distorted waveform, a component of the wave with a frequency that is an integer multiple of the fundamental.

phase displacement The extent to which voltage and current waveforms are out of synchronous phase with one another. Current “lags” or “leads” voltage, depending on whether the current waveform crosses a reference point after or before the voltage waveform, respectively. Phase displacement can be expressed as a unit of time, as a fraction of the period, or as an angle in degrees with one period corresponding to 360°. When voltage and current are synchronized, phase displacement is zero.

power factor A measure of how effectively an electric load converts power into useful work. Power factor (PF) is calculated using the equation:

$$\text{PF} = \frac{\text{active power}}{\text{rms voltage} \times \text{rms current}}$$

Phase displacement and current distortion both reduce power factor.

reactive power Power that creates no useful work; it results when current is not in phase with voltage. Calculated using the equation:

$$\text{reactive power} = V \times A \times \sin\theta$$

where θ is the phase displacement angle.

root-mean-square (rms) The effective average value of a periodic quantity such as an alternating current or voltage wave, calculated by averaging the squared values of the amplitude over one period, and taking the square root of that average.

total harmonic distortion (THD) For current or voltage, the ratio of a wave's harmonic content to its fundamental component, expressed as a percentage. Also called “harmonic factor,” it is a measure of the extent to which a waveform is distorted by harmonic content.

transients For an alternating current circuit, a momentary voltage surge, often at amplitudes 10 to 20 times the normal voltage.

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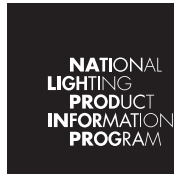
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Author: Robert Wolsey
Program Director: Robert Davis
Editors: Amy Fowler and Kevin Heslin
Production: Jason Teague and Nancy Bayer
Graphics: Jason Teague

Reviewers: Warren Anderson (OSRAM SYLVANIA INC.), Dennis Gibbs (PSI Energy), Brien Krieger (PSI Energy), Dave Pileggi (New England Power Service Company), Chris Prince (PSI Energy), Mark Rea (Lighting Research Center), Dave Torrey (Rensselaer Polytechnic Institute), and Dave Toso (Madison Gas and Electric Company). Reviewers are listed to acknowledge their contributions to the final publication. Their approval or endorsement of this report is not necessarily implied.

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