# 38

# Power Quality

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## 38.1 Introduction

Power electronics and power quality are irrevocably linked together as we strive to advance both broad areas. With the dramatic increases over the last 20 years in energy conversion systems utilizing power electronic devices, we have seen the emergence of "power quality" as a major field of power engineering. The power electronic technology has played a major role in creating "power quality," and simple control algorithm modifications *to this same technology* can often play an equally dominant role in enhancing overall quality of electrical energy available to end-users.

Power electronics has given us, as a industrial society, a plethora of new ways to manufacture products, provide services, and utilize energy. From a power quality impact viewpoint, applications such as

1. Switched-mode power supplies,
2. DC arc furnaces,
3. Electronic fluorescent lamp ballasts,
4. Adjustable speed drives, and
5. Flexible ac transmission components.

are often cause for concern. From the viewpoint of a utility supply system, these converter-based systems can lead to operational and life expectancy problems for other equipment, possibly not owned or operated by the same party. It was from this initial perspective that the field of power quality emerged.

In most cases, the same devices and systems that create power quality problems can also be used to solve power quality problems. "Problem solving" applications such as

1. Active harmonic filters,
2. Static and adaptive var compensators, and
3. Uninterruptable power supplies.

all utilize the same switching device technology as the "problem causing" applications.

As the number of potentially problematic power electronic-based loads has increased over time, so attention has given to enhanced converter control to maximize power quality. Perfect examples of these improvements include

1. Unity power factor converters,
2. Dip-proof inverters, and
3. Limited-distortion electronic lamp ballasts.

While these direct product enhancements are not mandatory in North America, today's global economy necessitates consideration of power quality standards and limits in order to conduct business in the European Union.

While many studies suggest increases in power electronic-based energy utilization as high as 70–80% (of all energy consumed), it is equally clear that we are beginning to realize the total benefit of such end-use technologies. Power quality problems associated with grounding, sags, harmonics, and transients will continue to increase because of the sheer number of sensitive electronic loads expected to be placed in service. At the same time, we are only now beginning to realize the total benefits that such loads can offer.

## 38.2 Power Quality

The term "power quality" means different things to different people. To utility suppliers, power quality initially referred to the quality of the service delivered as "measured" by the consumer's ability to use the energy delivered in the desired manner. This conceptual definition included such conventional utility planning topics as voltage and frequency regulation and reliability. The end-user's definition of power quality also centers around their ability to use the delivered energy in the desired manner, but the topics considered can be much more specific and include magnitude and duration of different events as well as waveshape concerns. Fortunately, a good working definition of power quality has not been a point of contention, and most parties involved consider "power quality" to be that, which allows the user to meet their end-use goals. The working definition is not complicated by particular issues; engineers are well aware that topics from many aspects of power engineering may be important.

Power quality can be roughly broken into categories as follows:

1. Steady-state voltage magnitude and frequency,
2. Voltage sags,
3. Grounding,
4. Harmonics,
5. Voltage fluctuations and flicker,
6. Transients, and
7. Monitoring and measurement.

The remainder of this section discusses each of the major categories in turn.

### 38.2.1 Steady-state Voltage Frequency and Magnitude

In most areas of North America, steady-state frequency regulation is not a significant issue due to the sufficient levels of generating capacity and the strong interconnections among generating companies and control areas. In other parts of the world, and North America under extreme conditions, frequency can deviate from 1/4 to 1/2 Hz during periods of insufficient generating capacity. Under transient conditions, frequency can deviate up to 1–2 Hz.

Frequency deviations can affect power electronic equipment that use controlled switching devices unless the control signals are derived from a signal that is phase-locked with the applied voltage. In most cases, phase locks are used, or the converters consist of uncontrolled rectifiers. In either case, frequency deviations are not a major cause of problems. In most cases, frequency deviations have more impacts on conventional equipment that does not use electronics or in very inexpensive electronic devices. Clocks can run fast (or slow), motor speeds can drop (or rise) by a few revolutions per minute, etc. In most cases, these effects have minimal economic impact and are not considered a real power quality problem.

**TABLE 38.1** ANSI C84.1 Voltage ranges

| | Service voltage (%) | Utilization voltage (%) |
|---|---|---|
| Range A | 114–125 | 108–125 |
| Range B | 110–127 | 104–127 |

Range A is for normal conditions and Range B is for emergency or short-time conditions.

Steady-state voltage regulation is a much more pronounced issue that can impact a wide range of end-use equipment. In most cases, utility supply companies do a very effective job of providing carefully regulated voltage within permissible ranges. In North America, ANSI Standard C84.1 suggests steady-state voltage ranges both at the utility service entrance and at the point of connection of end-use equipment. Furthermore, equipment manufacturers typically offer equipment that is tolerant of steady-state voltage deviations in the range of $\pm 10\%$. Table 38.1 shows the voltage ranges suggested by ANSI C84.1, with specific mention of normal (Range A) and contingency (Range B) allowable voltages, expressed in percent.

Virtually all equipment, especially sensitive electronic equipment, can be effected by deviating voltage outside the $\pm 10\%$ range. In most cases, overvoltages above $+10\%$ lead to loss of life, usually over time; excessive overvoltages can immediately fail equipment. Undervoltages below $-10\%$ usually lead to excessive current demands, especially for equipment that has a controlled output like an adjustable speed drive controlling a motor to a constant speed/torque point. The impacts of these prolonged excessive currents can be greater voltage drop, temperature rise in conductors, etc. In the extreme, undervoltages of greater than 15–20% can cause equipment to immediately trip. In most cases, such extreme undervoltages are associated with system faults and the associated protection system. These extreme undervoltages are so important that they are classified in a power quality category of their own called voltage sags.

### 38.2.2 Voltage Sags

Other than improper grounding, voltage sags are probably the most problematic of all power quality problems. At this time, a number of standards-making bodies, including IEEE, ANSI, and IEC, are working on standards related to sags. In most cases, sags are generally agreed to be more severe and outside of the scope of ANSI C84.1 and they are temporary in nature due to the operation of system protection elements. Because the electrical system is a continuous electrical circuit, faults in any location will have some impact on voltages throughout the network. Of course, areas closer to the faulted area will see a greater voltage sag due to the fault than other, more (electrically) remote areas. Sags can originate anywhere in a system, but are more pronounced in utility distribution systems because of the greater exposure of low-voltage systems to the causes of short circuits.

Most utility companies implement distribution system protection in what is known as a "fuse saving" methodology. Figure 38.1 shows a typical overhead distribution system with two feeders being supplied from the same substation transformer. Each primary circuit has its own automatic circuit recloser (ACR) and shows one fused tap.

With the protection system set up based on fuse-saving methodology, any fault downstream of a fault will be cleared first by the substation recloser followed by a reclosing operation (re-energization of the circuit) 1/2–2 later. If the fault is still present, the closest fuse should blow to permanently isolate the fault. (Note that in some cases, multiple reclosing attempts are made prior to the clearing of the fuse.)

For a fault on the load side of fused tap #2 in Fig. 38.1, customers on feeder #1 will see a voltage sag determined by the system and transformer impedance at the substation. Because this impedance is typically on the same order (or larger) as the feeder circuit impedance, a sag in substation bus voltage of 50% is common. This sag will persist until feeder #2 is cleared by the recloser opening. When the recloser re-energizes the circuit, a permanent fault will still be present and the substation bus will again experience a voltage sag. Of course, any sag in substation bus voltage will be delivered directly to all customers on feeder #1, even though there is no electrical problem on that feeder. Figure 38.2 shows a possible rms voltage profile that might be supplied to the customers on feeder #1 for a permanent fault on the load side of fused tap #2. Only one recloser operation is shown prior to fuse clearing.

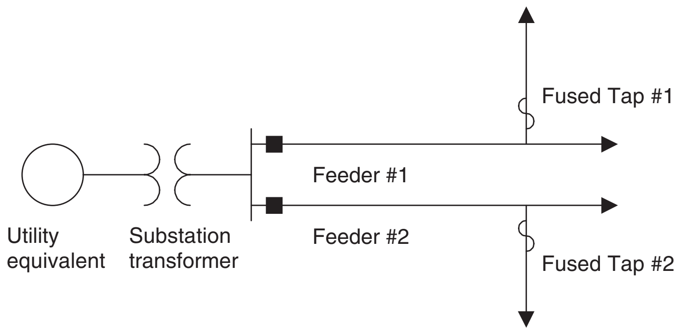


FIGURE 38.1 Overhead distribution system.

Just based on the voltage information shown in Fig. 38.2, it is impossible to tell if the end-use loads on feeder #1 will experience a problem. Equipment tolerance curves are required to assess the vulnerability of equipment to voltage deviations, including sags, and all equipment is different. Figure 38.3 shows the lower portions of two equipment tolerance curves, the (older) CBEMA and the (newer) ITIC curves for computer equipment. Most, but not all, power electronic-based equipment has a similar shape. Voltage sags with a duration that correspond to a point that is "below and to the right" of the tolerance curve will result in loss of equipment function, while sags of duration that plot "above and to the left" of the tolerance curve will not effect equipment performance. Note that only the lower portion of the curve has been shown; an upper tolerance curve also exists that is often used in transient (overvoltage) studies.

Voltage sags are probably the most common power quality problem that is "given" to the end-user by the supplying utility. However, improper equipment grounding is responsible for

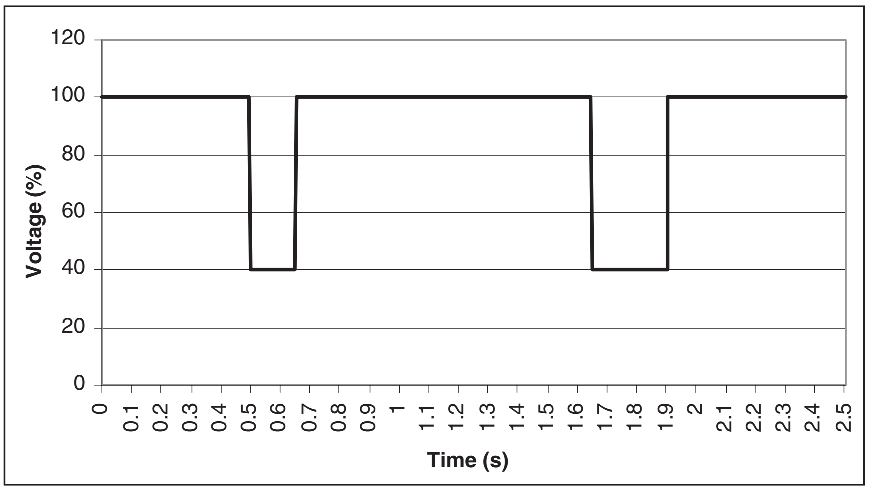


FIGURE 38.2 The rms voltage supplied to feeder #1 customers.

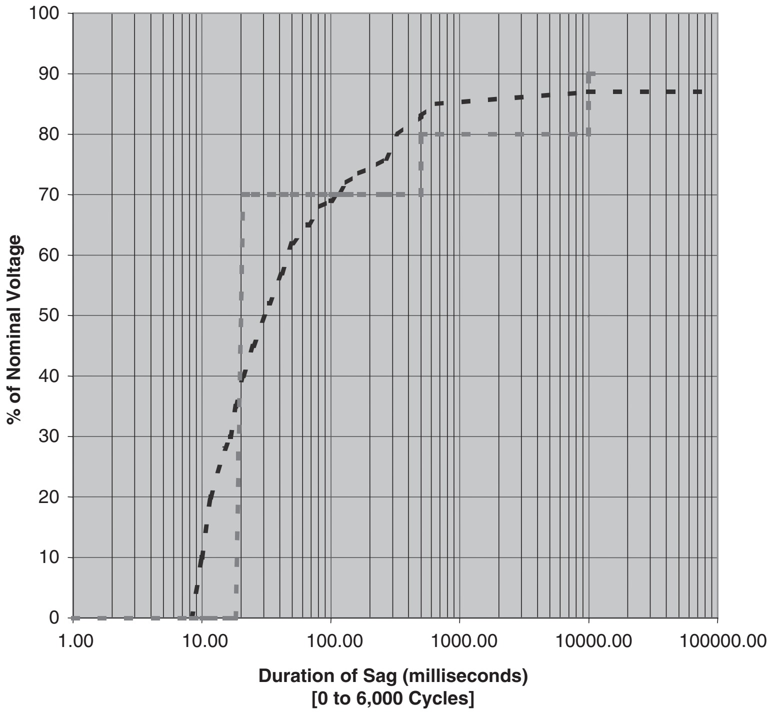


**FIGURE 38.3** CBEMA (curved line) and ITIC (square shape) tolerance curves.

the vast majority of power quality problems on the customer's side of the meter.

### 38.2.3 Grounding

Grounding of equipment was originally conceived as a personnel safety issue. However, the presence of an electrical conductor that is at zero potential has been widely used in many power electronic and microprocessor-controlled loads. In the United States, electrical systems in residential, commercial, and industrial facilities fall under the purview of the National Electric Code (NEC) which establishes specific criteria for grounding of equipment. While it was once thought that proper grounding according to the NEC was detrimental to power quality concerns, these opinions have gradually faded over time.

From a power quality perspective, improper grounding can be considered in three broad categories

1. Ground loops,
2. Improper neutral-to-ground connections, and
3. Excessive neutral-to-ground voltage.

The ground loop problem is a significant issue when power, communications, and control signals all originate in different locations, but come together at a common electrical point. Transients induced in one location can travel through the created ground loop, damaging equipment along the way.

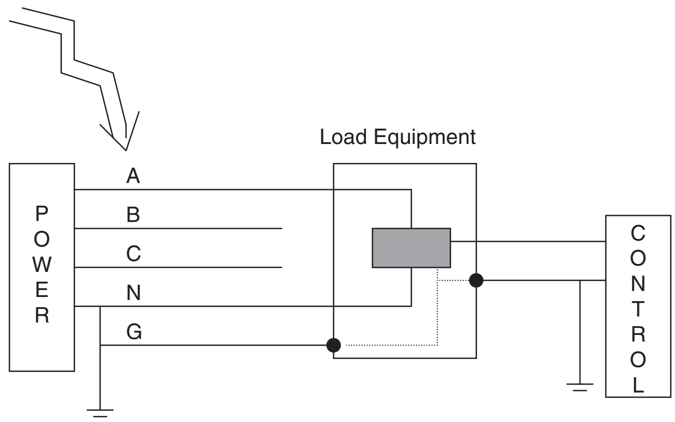


**FIGURE 38.4** Powering and control ground loop.

Improper neutral-to-ground connections will create a "noisy" ground reference that may interfere with low-voltage communications and control devices. Excessive neutral-to-ground voltage may damage equipment that is not properly insulated or that has an inexpensive power supply.

Figure 38.4 shows a common wye-connected service (assumed at the terminals of a transformer) that supplies power to equipment that is also remotely monitored and controlled from another location with a separate ground reference.

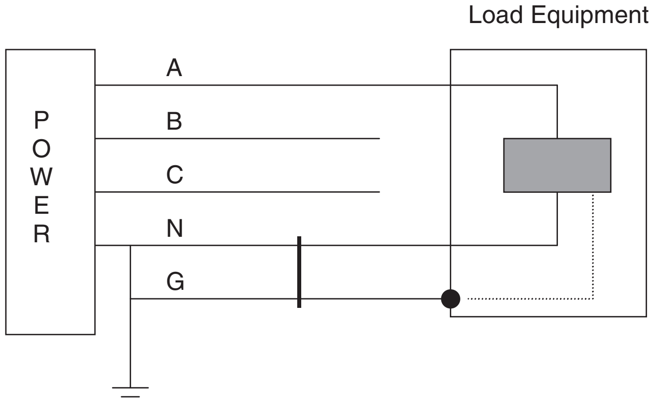


**FIGURE 38.5** Improper neutral-to-ground connections.

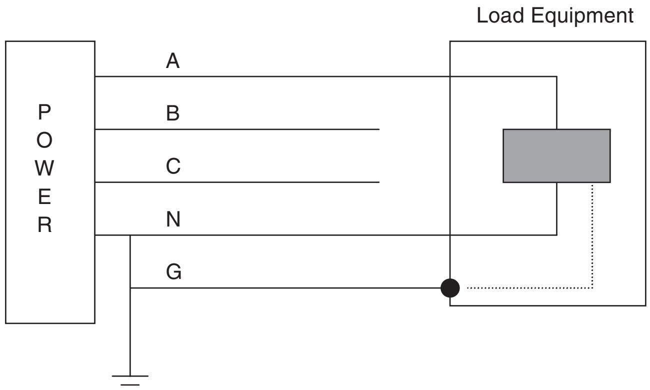


**FIGURE 38.6** Excessive neutral-to-ground voltage.

For any shift in ground potential for the power circuit, often caused by lightning as shown in Fig. 38.4, potentially large currents can flow through the grounding circuits and through the sensitive electronic equipment. Such currents can easily lead to equipment damage. Situations like these are common in

1. Residential areas, if power and CATV or telephone grounds are not the same and
2. Commercial and industrial complexes consisting of multiple buildings with linking communications, computer, or control circuits, when each building has its own power service (and therefore ground).

Figure 38.5 shows an example of an improper neutral-to-ground connection, and how this connection can create power quality problems.

Load current returning in the neutral conductor will, at the point of improper connection to ground, divide between neutral and ground. This current flow in the ground conductor will produce a voltage at the load equipment, which can easily disrupt equipment operation.

Figure 38.6 shows an example of the possibility for excessive neutral-to-ground voltage and how this can lead to power quality problems.

For load equipment that produces significant voltage drop in the neutral, such as laser printers and copying machines when the thermal heating elements are on, the voltage from the neutral-to-ground reference inside the equipment can exceed several volts. In many cases, this voltage is sufficient to damage printed circuit boards, disrupt control logic, and fail components.

### 38.2.4 Harmonics

In most cases, power electronic equipment is considered to be the "cause" of harmonics. While switching converters of all types produce harmonics because of the non-linear relationship between the voltage and current across the switching device, harmonics are also produced by a large variety of "conventional" equipment including

1. Power generation equipment (slot harmonics),
2. Induction motors (saturated magnetics),
3. Transformers (overexcitation leading to saturation),
4. Magnetic-ballast fluorescent lamps (arcing), and
5. AC electric arc furnaces (arcing).

All these devices will cause harmonic currents to flow and some devices, actually, directly produce voltage harmonics.

Any ac current flow through any circuit at any frequency will produce a voltage drop at that same frequency. Harmonic currents, which are produced by power electronic loads, will produce voltage drops in the power supply impedance at those same harmonic frequencies. Because of this inter-relationship between current flow and voltage drop, harmonic currents created at any location will distort the voltage in the entire supply circuit.

In most cases, equipment is not overly sensitive to the direct impacts of harmonic current flow. Note, however, that equipment heating is a function of the rms value of the current, which can significantly exceed the fundamental frequency value when large harmonic components are present. It is because harmonic currents produce harmonic voltages that there is a real power quality concern.

Most equipment can operate satisfactorily as long as the voltage distortion at the equipment terminals does not exceed around 5%. Exceptions to this general rule include ripple-control systems for converters (which are impacted by small even-order harmonics) and small harmonics at sufficiently high frequency to produce multiple zero crossing in a waveform. (Note that voltage notching due to simultaneous commutation of switching devices can also create multiple zero crossings.) Such a multiple crossing scenario is shown in Fig. 38.7 and represents a 60 Hz waveform plus a 1% voltage harmonic at 3000 Hz.

Converters that have a time-limited firing signal can directly suffer from excessive voltage distortion. For a six-pulse

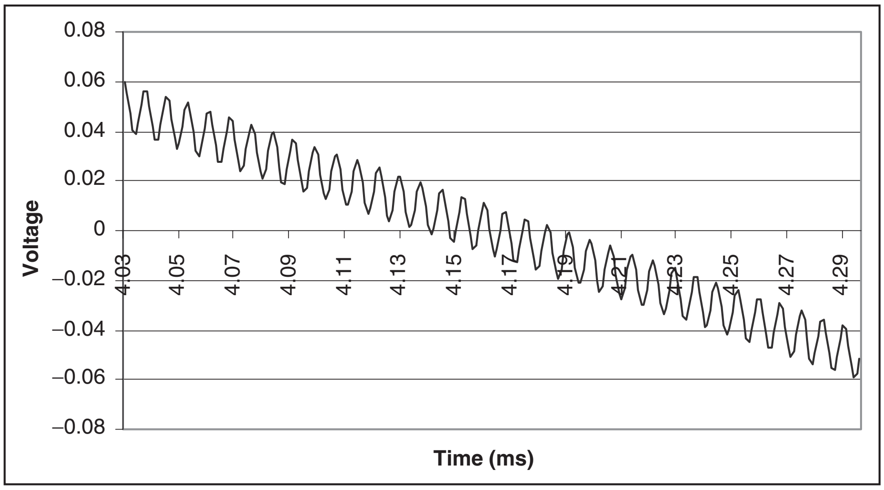


**FIGURE 38.7** Multiple zero crossings.

converter, a maximum time of 1/(6×60) seconds is available to turn on a switching device. Similarly, for a 12-pulse converter, a maximum of 1/(12×60) is available to turn on a switching device. Considering that all switching devices have a short (but non-zero) turn-on time, manufacturers tend to design drive circuits that bring up the firing pulse for a limited amount of time. If, for example, a firing pulse is maintained for 100 μs, the device must begin conduction in that time. In situations where voltage distortion is excessive, the device to be switched could be reverse biased during the first several milliseconds of the time available for device firing during which time conduction cannot begin. If the firing signal is removed before the certain classes of switching devices are correctly biased, conduction will not begin at all. This situation, commonly called a "misfire," can lead to equipment mis-operation and failure.

Because some switching devices can conduct in both directions when the firing signal is applied (but only one direction is intended to carry appreciable current), applying the firing pulse at a time when the voltage is of the wrong polarity can destroy the device. Excessive voltage distortion can certainly lead to such a situation, and manufacturers typically design products to function only under limited-distortion conditions.

Because of the numerous potential problems with harmonic currents, standards exist for their control. The IEC goes as far as to limit the harmonic currents produced by certain individual pieces of equipment, while the IEEE takes more "system-level" point of view and prescribes limits for harmonic currents for a facility as a whole, including one of more harmonic producing loads. Harmonic standards will be further discussed in Section 38.4.

### 38.2.5 Voltage Fluctuations and Flicker

Voltage flicker is not directly caused by electronic loads except in the largest of applications. Voltage fluctuations, and the corresponding light flicker due to them, are usually created by large power fluctuations at frequencies less than about 30 Hz. In most applications, only

1. Large dc arc furnaces and welders,
2. Reactive power compensators, and
3. Cycloconverters

are potentially problematic. Each of these types of end-use devices can create large, low-frequency (about 30 Hz or less) variations in the system voltage, and can therefore lead to voltage flicker complaints. At this time, the IEEE prescribes a "flicker curve" based originally on research conduction by General Electric. The IEC, however, has adopted a different methodology that can consider voltage fluctuations and flicker that are more complex than those considered by the IEEE flicker curve.

Most equipment is not sensitive to the voltage fluctuations that cause flicker complaints. The change in output of incandescent lamps as viewed by human observers becomes objectionable at levels of change around 0.3%, but electronic equipment will not be affected at all. Because most utility supply companies limit voltage fluctuations, regardless of the frequency of repetition, to less than a few percent, equipment malfunction or damage due to flicker is very rare. Figures 38.8 and 38.9 show plots of single-cycle rms voltage fluctuations due to large dc welders and arc furnaces, respectively; it is clear that the magnitude of the fluctuations are well above the level that could impact equipment. The waveform in Fig. 38.8 probably would generate numerous light-flicker complaints, whereas the waveform in Fig. 38.9 probably would not. Neither would disrupt equipment.

Due to the advances in power electronics that have offered devices with higher power ratings, reactive compensation systems have been developed to compensate for voltage fluctuations by adding or removing reactive power from

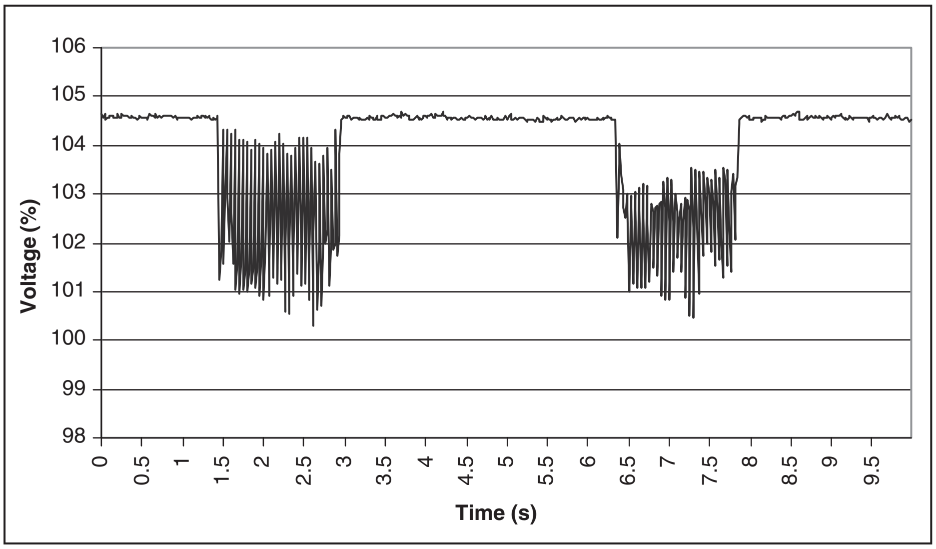


**FIGURE 38.8** Single-cycle rms voltage fluctuations due to a large dc welder.

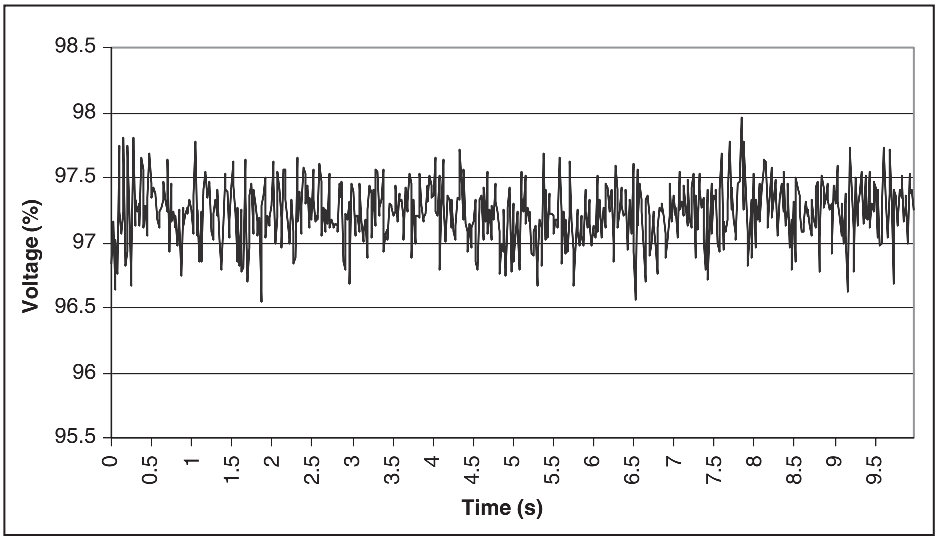


**FIGURE 38.9** Single-cycle rms voltage fluctuations due to a large dc arc furnace.

the supply circuit. These devices have allowed large flicker-producing loads like arc furnaces to be served from utility circuits that, without the compensator, could not serve the load. However, because the compensators can so directly impact system voltage, they can create flicker problems if they are not properly applied and controlled.

### 38.2.6 Transients

Transients, especially in the voltage supply, can create numerous power quality problems. The major sources of transients are

1. Lightning,
2. Utility circuit switching and fault clearing,
3. Capacitor switching, and
4. Load switching.

Lightning events can create the most severe overvoltages, but these transients decay rapidly. A typical lightning transient has decayed to zero in a few hundred microseconds, but it can reach a peak magnitude of several hundred percent if not controlled with surge suppression devices. Other categories of transients associated with power system switching are much smaller in magnitude (typically less than 200%), but last in the order of several hundred milliseconds. Considering the energy available in a transient, therefore, there is a considerable overlap in the range of severity of lightning and switching transients. It is the available energy that typically determines

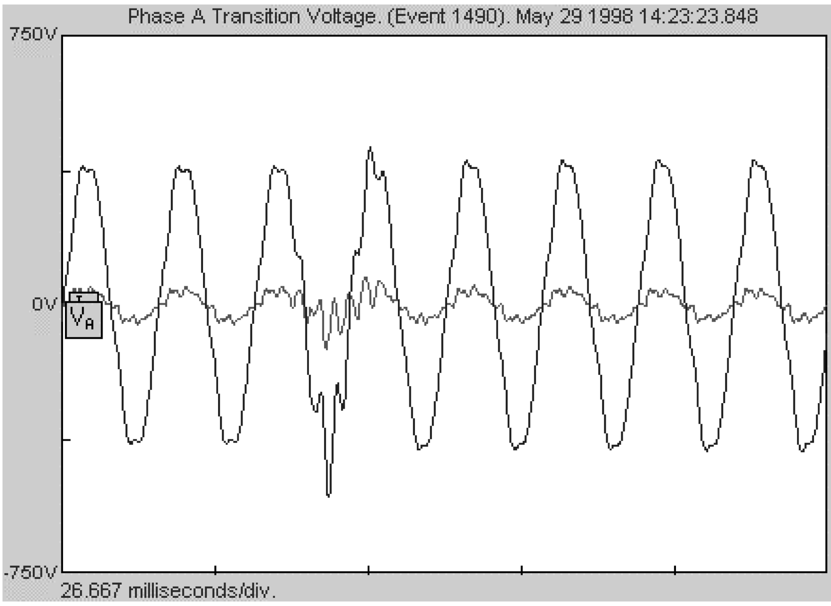


**FIGURE 38.10** Capacitor switching transient.

whether or not an equipment will be affected or damaged. Figure 38.10 shows a capacitor switching transient on a low-voltage (480 V) circuit. The magnitude and duration of the event are quite clear.

Transients such as those shown in Fig. 38.10 are generally sufficient to cause nuisance trips of electronic loads like adjustable speed drives. For these types of loads, the protection system settings are usually very tight due to the use of sensitive switching devices. Overcurrent and overvoltage settings of 120% are not uncommon. For a transient similar to that shown in Fig. 38.10, there is sufficient overvoltage for very large currents to flow through any conducting switching device to the drive's dc bus. The device's protection system see these overcurrents as a fault, and trip the drive. Similarly, the overvoltage at the terminals can be passed through to the dc bus and accumulate, where the drive may trip due to overvoltge on the dc bus.

## 38.2.7 Monitoring and Measurement

To consider or be able to diagnose power quality related problems, it is imperative to be able to measure various power quality parameters. Several different categories of monitoring and measurement equipment exist for these purposes, with costs ranging from a few hundred dollars to $10,000–20,000 for fully equipped disturbance analyzer.

The most basic category of power quality measurement tool is the handheld voltmeter. It is important that the voltmeter be a true-rms meter, or erroneous readings will be obtained that incorrectly suggest low or high voltage when harmonics are present in the signal. It is especially important to have true rms capability when measuring currents; voltage distortion is not typically severe enough to create large errors in the readings of non-true rms meters. Virtually all major measurement equipment vendors offer true rms meters, with the costs starting around $100.

The next step up from the basic voltmeter is a class of instruments that have come to be called "power quality analyzers." These instruments are handheld and battery powered. These instruments can measure and display various power quality indices, especially those that relate to harmonics like THD, etc. and can also display the input waveform. Newer models feature 20 MHz (and higher) bandwidth oscilloscopes, inrush measurements, time trending, and other useful features. Manufacturers such as Fluke, Dranetz, BMI, and Tektronix offer these types of instruments for around $2000.

In most power quality investigations, it is not possible to use handheld equipment to collect sufficient data to solve the problem. Most power quality problems are intermittent in nature, so some type of long-term monitoring is usually required. Various recorders are available that can measure and record voltage, current, and power over user-defined time period. Such recorders typically cost in the order of $3000–10,000. More advanced long-term monitors can record numerous power quality events and indices, including transients, harmonics, sags, flicker, etc. These devices, often called "line disturbance analyzers", typically cost between $10,000 and $20,000.

It is important to use the right instrument to measure the phenomenon that is suspected of causing the problem. Some meters record specific parameters, while others are more flexible. With this flexibility comes an increased learning curve for the user, so it is important to spend time on them before going out to monitor, to make sure all aspects and features of the equipment are understood.

It is equally important to measure in the correct location. The best place to measure power quality events is at the equipment terminals that is experiencing problems. With experience, an engineer can evaluate the waveforms recorded at the equipment terminals and correlate them to events and causes elsewhere in the power system. In general, the farther away from the equipment location the monitoring takes place, the more difficult is to diagnose a problem.

## 38.3 Reactive Power and Harmonic Compensation

The previous section specifically identified harmonics as a potential power quality problem. In that discussion, it was pointed out that non-linear loads such as adjustable speed drives create harmonic currents, and when these currents flow through the impedances of the power supply system, harmonic voltages are produced. While harmonic currents have secondary (in most cases) negative impacts, it is these harmonic voltages that can be supplied to other load equipment (and disrupt operation) that are of primary concern. Having parallel or series resonant conditions present in the electrical supply system can quickly exacerbate the problem.

### 38.3.1 Typical Harmonics Produced by Equipment

In theory, most harmonic currents follow the "$1/n$" rule where $n$ is the harmonic order ($180\,\text{Hz} = 3\times 60$; $n = 3$). Also in theory, most harmonic currents in three-phase systems are not integer multiples of three. Finally, in theory, harmonic currents are not usually even-order integer multiples of the fundamental. In practice, none of these statements are completely true and using any of them "exactly" could lead to either over- or under-conservatism depending on many factors. Consider the following examples:

1. Switched-mode power supplies, such as found in televisions, personal computers, etc. often produce a third-harmonic current that is nearly as large (80–90%) as the fundamental frequency component.
2. Unbalance in voltages supplied to a three-phase converter load will lead to the production of even-order harmonics and, in some extreme cases, establish a positive feedback situation leading to stability problems.
3. Arcing loads, particularly in the steel industry, generate significant harmonics of all orders, including harmonics that are not integer multiples of the power frequency.
4. Cycloconverters produce dominant harmonics that are integer multiples of the power frequency, but they also produce sideband components at frequencies that are not integer multiples of the power frequency. In some control schemes, the amplitudes of the sideband components can reach damaging levels.

**TABLE 38.2** Typical harmonic spectra of load equipment

| Harmonic no. | Switched-mode power supply | Fluorescent lamp | Six-pulse dc drive | Six-pulse ac drive |
|---|---|---|---|---|
| 1 | 100.0 | 100.0 | 100.0 | 100.0 |
| 2 | 0.7 | 1.0 | 4.8 | 1.1 |
| 3 | 91.9 | 12.6 | 1.2 | 3.9 |
| 4 | 1.0 | 0.3 | 1.5 | 0.5 |
| 5 | 80.2 | 1.8 | 33.6 | 82.8 |
| 6 | 1.3 | 0.1 | 0.0 | 1.7 |
| 7 | 64.8 | 0.7 | 1.6 | 77.5 |
| 8 | 1.4 | 0.1 | 1.7 | 1.2 |
| 9 | 47.7 | 0.5 | 0.4 | 7.6 |
| 10 | 1.0 | 0.1 | 0.3 | 0.7 |
| 11 | 30.8 | 0.2 | 8.7 | 46.3 |
| 12 | 0.8 | 0.1 | 0.0 | 1.0 |
| 13 | 16.0 | 0.2 | 1.2 | 41.2 |
| 14 | 0.4 | 0.0 | 1.3 | 0.2 |
| 15 | 5.0 | 0.1 | 0.3 | 5.7 |
| 16 | 0.1 | 0.1 | 0.2 | 0.3 |
| 17 | 4.0 | 0.2 | 4.5 | 14.2 |
| 18 | 0.3 | 0.1 | 0.0 | 0.4 |
| 19 | 7.2 | 0.1 | 1.3 | 9.7 |
| 20 | 0.4 | 0.2 | 1.1 | 0.4 |
| 21 | 7.7 | 0.2 | 0.3 | 2.3 |
| 22 | 0.4 | 0.1 | 0.3 | 0.5 |
| 23 | 6.2 | 0.1 | 2.8 | 1.5 |
| 24 | 0.2 | 0.0 | 0.0 | 0.5 |
| 25 | 4.0 | 0.1 | 1.2 | 2.5 |

Table 38.2 gives the magnitudes, in percent of fundamental, of the first 25 (integer) harmonics for a single-phase switched-mode power supply, a single-phase fluorescent lamp, a three-phase (six-pulse) dc drive, and a three-phase (six-pulse, no input choke) ac drive. Together, these load types represent the range of harmonic sources in power systems. Note that seemingly minor changes in parameter values and control methods can have significant impacts on harmonic current generation; the values given here are on the conservative side of "typical."

### 38.3.2 Resonance

Considering only the harmonic current spectra given in Table 38.2, it would appear that a large number of harmonic-related power quality problems are on the verge of appearing. In reality, most current drawn by many residential, commercial, and industrial customers is of the fundamental frequency;

the amplitudes of the individual harmonic currents, in percent of the *total* fundamental current, are often much less than that shown in Table 38.2. For this reason, end-use locations employing non-linear loads often do not lead directly to significant voltage distortion problems. A parallel resonance in the power supply system, however, changes the picture entirely.

Series and parallel resonance exist in any ac power supply network that contains inductance(s) and capacitance(s). The following simple (but usable) definitions apply:

1. Series resonance occurs when the impedance to current flow at a certain frequency (or frequencies) is low.
2. Parallel resonance occurs when the impedance to current flow at a certain frequency (or frequencies) is high.

For a given harmonic-producing load that generates harmonics at frequencies that correspond to parallel resonance in the supply system, even small currents at the resonant frequencies can produce excessive voltages at these same frequencies. The principle of series resonance, however, is usually exploited to reduce harmonics in power systems by providing intentionally low impedance paths to ground.

In many cases, end-users will install power factor correction capacitors in order to minimize reactive power charges by the supply utility. In most cases, these capacitors are located on the customer's low-voltage supply buses and are therefore in parallel with the service transformer. In most cases where the power factor correction capacitors are sized to provide a net power factor (at the service entrance) to 0.85(lag)–1.0, the parallel resonance occurs somewhere between the fifth and nineth harmonic. Considering Table 38.2, it is apparent that a large number of loads produce harmonics at these frequencies, and the amplitudes can be significant. Even a small increase in impedance at these frequencies due to resonance can lead to unacceptable voltages being produced at these same frequencies. Figure 38.11 shows and example plot of impedance looking into a utility supply system when a typically-sized capacitor bank has been installed to improve overall plant power factor.

From Fig. 38.11, it is clear that 1.0 A at the 9th harmonic will produce at least 150 times more voltage drop than would be produced by the same 1.0 A if it were at the fundamental frequency. A look back at the Table 38.2 shows the clear potential for problems. Fortunately, the series resonance principle can be used to provide a low-impedance path to ground for the harmonic currents and thus reduce the potential for problematic voltage distortion.

Since capacitors are required to produce parallel resonance, it is often a "cheap fix" to slightly modify the capacitor to include a properly sized series reactor and create filter. This filter approach, designed based on the series resonance concept, is usually the most cost-effective means to control harmonic voltage distortion.

### 38.3.3 Harmonic Filters

Harmonic filters come in many "shapes and sizes." In general, harmonic filters are "shunt" filters because they are connected in parallel with the power system and provide low impedance paths to ground for currents at one or more harmonic frequencies. For power applications, shunt filters are almost always more economical than series filters (like those found in many communications applications) for the following reasons:

1. Series components must be rated for the full current, including the power frequency component. Such a requirement leads to larger component sizes and therefore costs.

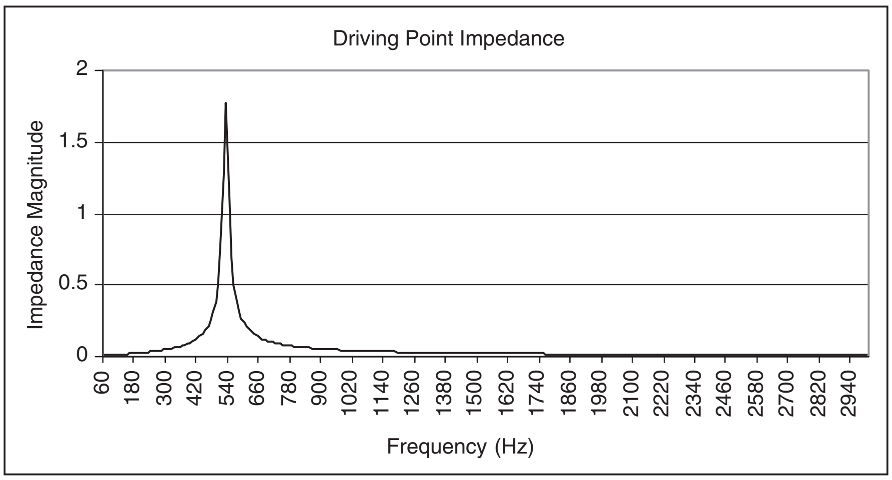


**FIGURE 38.11** Driving point impedance.

2. Shunt filter components generally must be rated for only part of the system voltage (usually with respect to ground). Such requirements lead to smaller component sizes and therefore costs.

Shunt filters are designed (or can be purchased) in three basic categories as follows:

1. Single-tuned filters,
2. Multiple- (usually limited to double) tuned filters, and
3. Damped filters (of first-, second-, or third- order, or newer "c-type").

The single- and double-tuned filters are usually used to filter specific frequencies, while the damped filters are used to filter a wide range of frequencies. In applications involving small harmonic producing loads, it is often possible to use one single-tuned filter (usually tuned near the fifth harmonic) to eliminate problematic harmonic currents. In large applications, like those associated with arc furnaces, multiple tuned filters and a damped filter are often used. Equivalent circuits for single- and double-tuned filters are shown in Fig. 38.12. Equivalent circuits for first, second, third, and "c-type" damped filters are shown in Fig. 38.13.

A plot of the impedance as a function of frequency for a single-tuned filter is shown in Fig. 38.14. The filter is based on a 480 V, 300 kvar (three-phase) capacitor bank and is tuned to the 4.7th harmonic with a quality factor, $Q$, of 150. Note that the quality factor is a measure of the "sharpness" of the tuning and is defined as $X/R$ where $X$ is the inductive reactance for the filter inductor at the (undamped) resonant frequency; typically $50<Q<150$ for tuned filters.

A plot of impedance as a function of frequency for a second-order damped filter is shown in Fig. 38.15. This filter is based on a 480 V, 300 kvar capacitor bank and is tuned to the 12th harmonic. The quality factor is chosen to be 1.5. Note that the quality factor for damped filters is the inverse of the definition for tuned filters; $Q=R/X$ where $X$ is the inductive reactance at the (undamped) resonant frequency. Typically, $0.5<Q<1.5$ for damped filters.

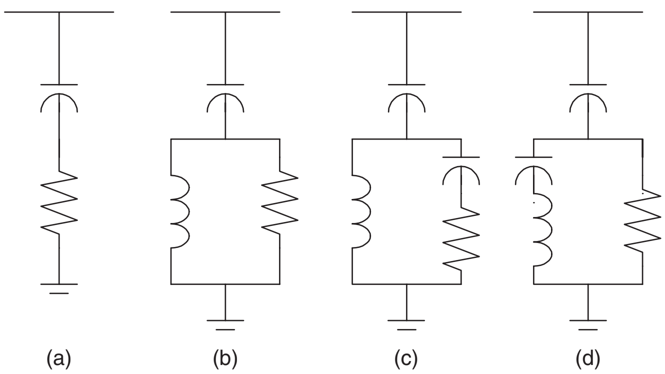


**FIGURE 38.13** Damped filters: (a) first-order; (b) second-order; (c) third-order; and (d) C-type.

In most cases, it is common to tune single-tuned filter banks to slightly below (typically around 5%) the frequency of the harmonic to be removed. The reasons for this practice are as follows:

1. For a low-resistance series resonance filter that is exactly tuned to a harmonic frequency, the filter bank will act as a sink to all harmonics (at the tuned frequency) in the power system, regardless of their source(s). This action can quickly overload the filter.
2. All electrical components have some non-zero temperature coefficient, and capacitors are the most temperature sensitive component in a tuned filter. Because most capacitors have a negative temperature coefficient (capacitance decreases and therefore tuned frequency increases with temperature), tuning slightly lower than the desired frequency is desirable.

Damped filters are typically used to control higher-order harmonics as a group. In general, damped filters are tuned in between the corresponding pairs of harmonics (11th and 13th, 17th and 19th, etc.) to provide the maximum harmonic reduction at those frequencies while continuing to serve as a (not quite as effective) filter bank for frequencies higher than the tuned frequency. Because damped filters have significantly higher resistance than single- or double-tuned filters, they are usually not used to filter harmonics near the power frequency so that filter losses can be maintained at low values.

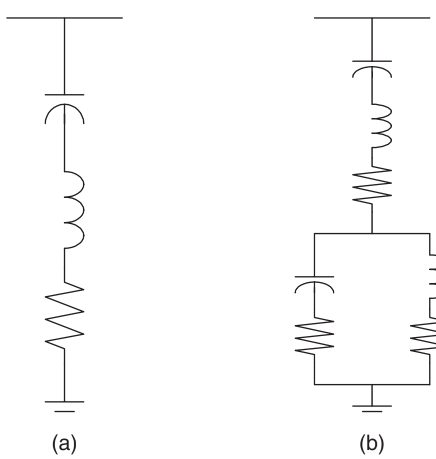


**FIGURE 38.12** Harmonic filters: (a) single-tuned and (b) double-tuned.

## 38.4 IEEE Standards

The IEEE has produced numerous standards relating to the various power quality phenomena discussed in Section 38.2. Of these many standards, the one most appropriate to power

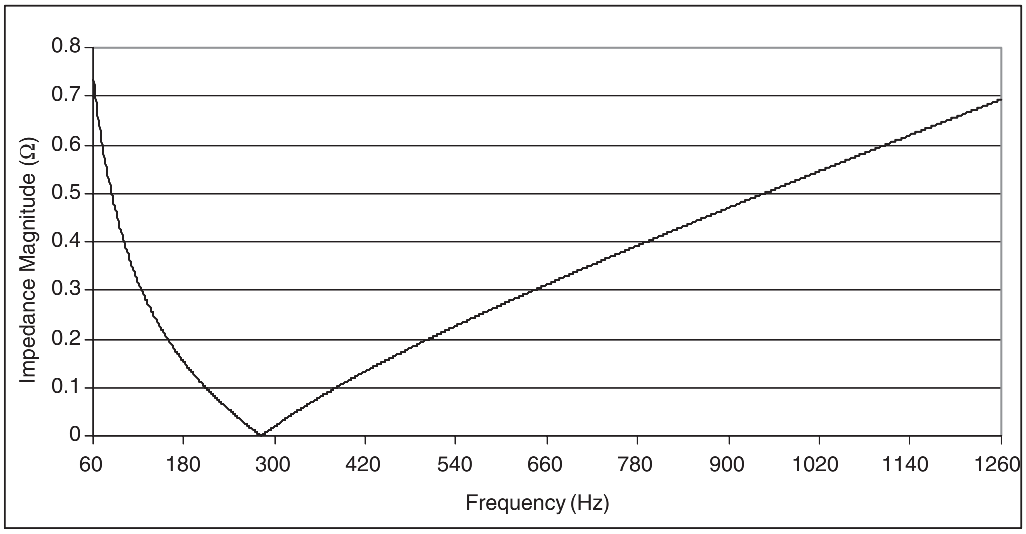


**FIGURE 38.14** Single-tuned filter frequency response.

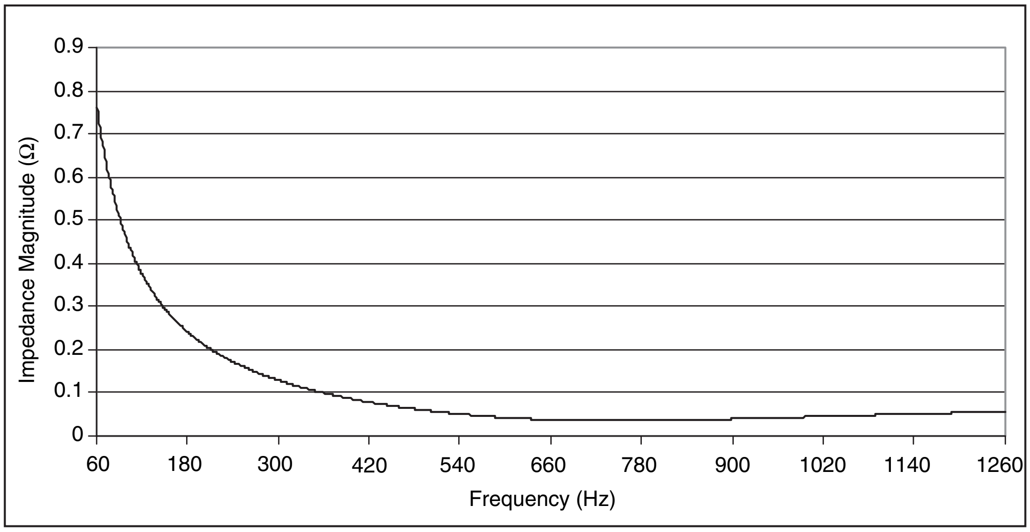


**FIGURE 38.15** Second-order damped filter frequency response.

electronic equipment is IEEE Standard 519-1992. This standard is actually a "recommended practice," which means that the information contained within represents a set of "recommendations," rather than a set of "requirements." In practice, this seemingly small difference in wording means that the harmonic limits prescribed are merely suggested values; they are not (nor were they ever intended) to be absolute limits that could not be exceeded.

Harmonic control via IEEE 519-1992 is based on the concept that all parties use and pay for the public power supply network. Due to the nature of utility company rate structures, end-users that have a higher demand pay more of the total infrastructure cost through higher demand charges. In this light, IEEE 519-1992 allows these larger end-users to produce a greater percentage of the maximum level of harmonics that can be absorbed by the supply utility before voltage distortion problems are encountered. Because the ability for a harmonic source to produce voltage distortion is directly dependent on the supply system impedance upon the point where distortion is to be evaluated, it is necessary to consider both

1. The size of the end-user and
2. The strength (impedance) of the system

at the same time in order to establish meaningful limits for harmonic emissions. Furthermore, it is necessary to establish tighter limits in higher voltage supply systems than lower voltage because the potential for more widespread problems associated with high-voltage portions of the supply system.

Unlike limits set forth in various IEC Standards, IEEE 519-1992 established the "point of common coupling," or PCC as the point at which harmonic limits shall be evaluated. In most cases (recall that IEEE 519-1992 is a "recommended practice"), this point will be:

1. In the supply system owned by the utility company,
2. The closest electrical point to the end-user's premises, and
3. As in (2), but further restricted to points where other customers are (or could be in the future) provided with electric service.

In this context, IEEE 519-1992 harmonic limits are designed for an entire facility and should not be applied to individual pieces of equipment without great care.

Because the PCC is used to evaluate harmonic limit compliance, the system strength (impedance) is measured at this point and is described in terms of available (three-phase) short-circuit current. Also, the end-user's maximum average demand current is evaluated at this point. Maximum demand is evaluated based on one of the following:

1. The maximum value of the 15 or 30 minute average demand, usually considering the previous 12 month's billing history or
2. The connected kVA or horsepower, perhaps multiplied by a diversity factor.

The ratio of $I_{SC}$ to $I_L$, where $I_{SC}$ is the available fault current and $I_L$ is the maximum demand current, implements the founding concept of IEEE 519-1992: larger end-users can create more harmonic currents, but the specific level of current that any end-user may produce is dependent on the strength of the system at the PCC. Tables 38.3–38.5 show the harmonic current limits in IEEE 519-1992 for various voltage levels.

In general, it is the responsibility of the end-user to insure that their net harmonic currents at the PCC do not exceed the values given in the appropriate table. In some cases, usually associated with parallel resonance involving a utility-owned capacitor bank, it is possible that all customers will be within the prescribed limits, but voltage distortion problems exist. In these cases, it is generally the responsibility of the supply utility to insure that excessive voltage distortion levels are not present. The harmonic voltage limits that are recommended for utility companies are given in Table 38.6.

**TABLE 38.3** Current distortion limits for general distribution systems, 120 V–69 kV

| Maximum harmonic current distortion in percent of $I_L$ | | | | | | |
|---|---|---|---|---|---|---|
| $I_{SC}/I_L$ | <11 | $11 \leq h < 17$ | $17 \leq h < 23$ | $23 \leq h < 35$ | $h \geq 35$ | TDD |
| <20[1] | 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 |

Individual harmonic order $h$ (odd harmonics).
Even harmonics are limited to 25% of the odd harmonic limits above.
Current distortions that result in a dc offset are not allowed.
[1]All power generation equipment is limited to these values of current distortion regardless of the value of $I_{SC}/I_L$.

**TABLE 38.4** Current distortion limits for general subtransmission systems, 69.001–161 kV

| Maximum harmonic current distortion in percent of $I_L$ | | | | | | |
|---|---|---|---|---|---|---|
| $I_{SC}/I_L$ | <11 | $11 \leq h < 17$ | $17 \leq h < 23$ | $23 \leq h < 35$ | $h \geq 35$ | TDD |
| <20[1] | 2.0 | 1.0 | 0.75 | 0.3 | 0.15 | 2.5 |
| 20<50 | 3.5 | 1.75 | 1.25 | 0.5 | 0.25 | 4.0 |
| 50<100 | 5.0 | 2.25 | 2.0 | 0.75 | 0.35 | 6.0 |
| 100<1000 | 6.0 | 2.75 | 2.5 | 1.0 | 0.5 | 7.5 |
| ≥1000 | 7.5 | 3.5 | 3.0 | 1.25 | 0.7 | 10.0 |

Individual harmonic order $h$ (odd harmonics).
Even harmonics are limited to 25% of the odd harmonic limits above.
Current distortions that result in a dc offset are not allowed.
[1]All power generation equipment is limited to these values of current distortion regardless of the value of $I_{SC}/I_L$.

**TABLE 38.5** Current distortion limits for general transmission systems, >161 kV

| Maximum harmonic current distortion in percent of $I_L$ | | | | | | |
|---|---|---|---|---|---|---|
| $I_{SC}/I_L$ | <11 | $11 \leq h < 17$ | $17 \leq h < 23$ | $23 \leq h < 35$ | $h \geq 35$ | TDD |
| <50[1] | 2.0 | 1.0 | 0.75 | 0.3 | 0.15 | 2.5 |
| ≥50 | 3.0 | 1.5 | 1.15 | 0.45 | 0.22 | 3.75 |

Individual harmonic order $h$ (odd harmonics).
Even harmonics are limited to 25% of the odd harmonic limits above.
Current distortions that result in a dc offset are not allowed.
[1]All power generation equipment is limited to these values of current distortion regardless of the value of $I_{SC}/I_L$.

**TABLE 38.6** Voltage distortion limits

| Bus voltage at PCC | Individual harmonic magnitude (%) | Total voltage distortion (THD in %) |
|---|---|---|
| ≤69 kV | 3.0 | 5.0 |
| 69.001–161 kV | 1.5 | 2.5 |
| >161 kV | 1.0 | 1.5 |

## 38.5 Conclusions

In this chapter, various power quality phenomena have been described, with particular focus on the implications on power electronic converters and equipment. While one popular opinion "blames" power electronic equipment for "causing" most power quality problems, it is quite clear that power electronic converter systems can play an equally-important role in reducing the impact of power quality problems. While it is true that power electronic converters and systems are the major cause of harmonic-related problems, the application (in general terms) of IEEE 519-1992 limits for current and voltage harmonics has led to the reduction, elimination, and prevention of most harmonics problems. Other power quality phenomena, like grounding, sags, and voltage flicker, are most often completely unrelated to power electronic systems. In reality, advances in power electronic circuits and control algorithms are making it more possible to control these events and minimize the financial impacts of the majority of power quality problems.

## Further Reading


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