1 Introduction to Power Quality

1.1 DEFINITION OF POWER QUALITY

Power quality is a term that means different things to different people. Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 defines power quality as "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment." As appropriate as this description might seem, the limitation of power quality to "sensitive electronic equipment" might be subject to disagreement. Electrical equipment susceptible to power quality or more appropriately to lack of power quality would fall within a seemingly boundless domain. All electrical devices are prone to failure or malfunction when exposed to one or more power quality problems. The electrical device might be an electric motor, a transformer, a generator, a computer, a printer, communication equipment, or a household appliance. All of these devices and others react adversely to power quality issues, depending on the severity of problems.

A simpler and perhaps more concise definition might state: "Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy." This definition embraces two things that we demand from an electrical device: performance and life expectancy. Any power-related problem that compromises either attribute is a power quality concern. In light of this definition of power quality, this chapter provides an introduction to the more common power quality terms. Along with definitions of the terms, explanations are included in parentheses where necessary. This chapter also attempts to explain how power quality factors interact in an electrical system.

1.2 POWER QUALITY PROGRESSION

Why is power quality a concern, and when did the concern begin? Since the discovery of electricity 400 years ago, the generation, distribution, and use of electricity have steadily evolved. New and innovative means to generate and use electricity fueled the industrial revolution, and since then scientists, engineers, and hobbyists have contributed to its continuing evolution. In the beginning, electrical machines and devices were crude at best but nonetheless very utilitarian. They consumed large amounts of electricity and performed quite well. The machines were conservatively designed with cost concerns only secondary to performance considerations. They were probably susceptible to whatever power quality anomalies existed at the time, but the effects were not readily discernible, due partly to the robustness of the machines and partly to the lack of effective ways to measure power quality parameters. However, in the last 50 years or so, the industrial age led to the need for products to be economically competitive, which meant that electrical machines were becoming smaller and more efficient and were designed without performance margins. At the same time, other factors were coming into play. Increased demands for electricity created extensive power generation and distribution grids. Industries demanded larger and larger shares of the generated power, which, along with the growing use of electricity in the residential sector, stretched electricity generation to the limit. Today, electrical utilities are no longer independently operated entities; they are part of a large network of utilities tied together in a complex grid. The combination of these factors has created electrical systems requiring power quality.

The difficulty in quantifying power quality concerns is explained by the nature of the interaction between power quality and susceptible equipment. What is "good" power for one piece of equipment could be "bad" power for another one. Two identical devices or pieces of equipment might react differently to the same power quality parameters due to differences in their manufacturing or component tolerance. Electrical devices are becoming smaller and more sensitive to power quality aberrations due to the proliferation of electronics. For example, an electronic controller about the size of a shoebox can efficiently control the performance of a 1000-hp motor; while the motor might be somewhat immune to power quality problems, the controller is not. The net effect is that we have a motor system that is very sensitive to power quality. Another factor that makes power quality issues difficult to grasp is that in some instances electrical equipment causes its own power quality problems. Such a problem might not be apparent at the manufacturing plant; however, once the equipment is installed in an unfriendly electrical environment the problem could surface and performance suffers. Given the nature of the electrical operating boundaries and the need for electrical equipment to perform satisfactorily in such an environment, it is increasingly necessary for engineers, technicians, and facility operators to become familiar with power quality issues. It is hoped that this book will help in this direction.

1.3 POWER QUALITY TERMINOLOGY

Webster's New World Dictionary defines *terminology* as the "the terms used in a specific science, art, etc." Understanding the terms used in any branch of science or humanities is basic to developing a sense of familiarity with the subject matter. The science of power quality is no exception. More commonly used power quality terms are defined and explained below:

Bonding — Intentional electrical-interconnecting of conductive parts to ensure common electrical potential between the bonded parts. Bonding is done primarily for two reasons. Conductive parts, when bonded using low impedance connections, would tend to be at the same electrical potential, meaning that the voltage difference between the bonded parts would be minimal or negligible. Bonding also ensures that any fault current likely imposed on a metal part will be safely conducted to ground or other grid systems serving as ground.

Capacitance — Property of a circuit element characterized by an insulating medium contained between two conductive parts. The unit of capacitance is a farad (F), named for the English scientist Michael Faraday. Capacitance values are more commonly expressed in microfarad (μF), which is 10^{-6} of a farad. Capacitance is one means by which energy or electrical noise can couple from one electrical circuit to another. Capacitance between two conductive parts can be made infinitesimally small but may not be completely eliminated.

Coupling — Process by which energy or electrical noise in one circuit can be transferred to another circuit that may or may not be electrically connected to it.

Crest factor — Ratio between the peak value and the root mean square (RMS) value of a periodic waveform. Figure 1.1 indicates the crest factor of two periodic waveforms. Crest factor is one indication of the distortion of a periodic waveform from its ideal characteristics.

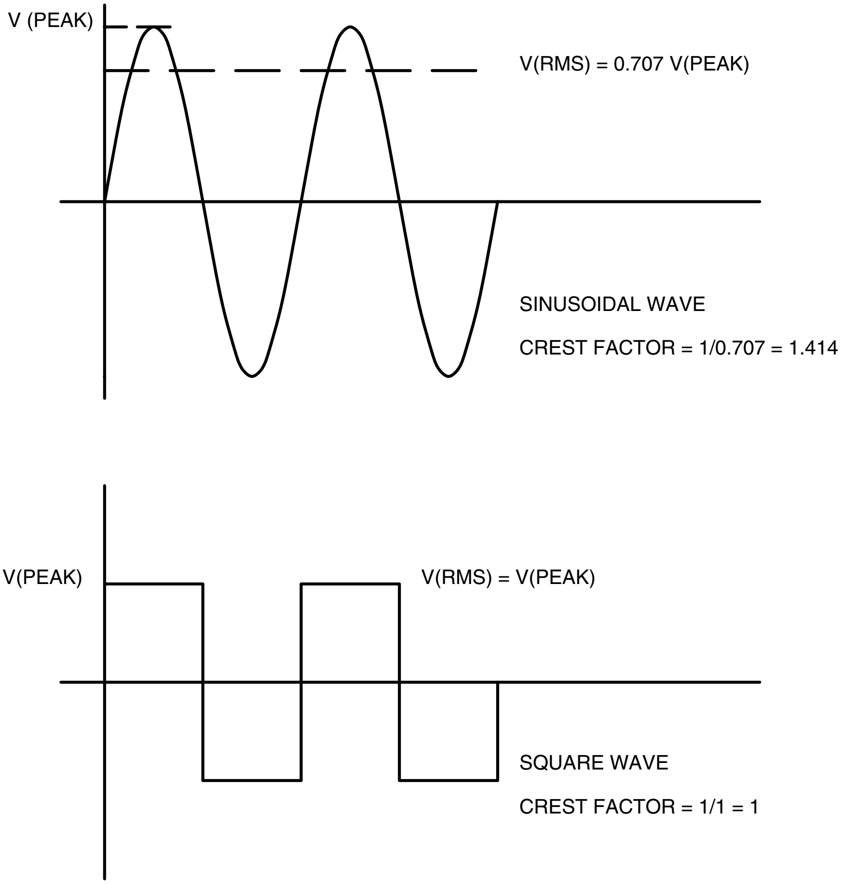


FIGURE 1.1 Crest factor for sinusoidal and square waveforms.

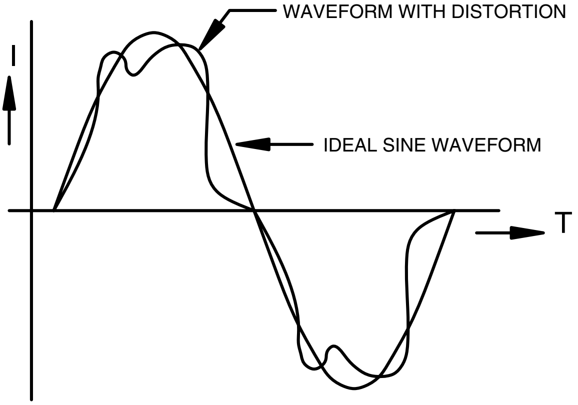


FIGURE 1.2 Waveform with distortion.

Distortion — Qualitative term indicating the deviation of a periodic wave from its ideal waveform characteristics. Figure 1.2 contains an ideal sinusoidal wave along with a distorted wave. The distortion introduced in a wave can create waveform deformity as well as phase shift.

Distortion factor — Ratio of the RMS of the harmonic content of a periodic wave to the RMS of the fundamental content of the wave, expressed as a percent. This is also known as the total harmonic distortion (THD); further explanation can be found in Chapter 4.

Flicker — Variation of input voltage sufficient in duration to allow visual observation of a change in electric light source intensity. Quantitatively, flicker may be expressed as the change in voltage over nominal expressed as a percent. For example, if the voltage at a 120-V circuit increases to 125 V and then drops to 117 V, the flicker, f, is calculated as $f = 100 \times (125 - 117)/120 = 6.66\%$.

Form factor — Ratio between the RMS value and the average value of a periodic waveform. Form factor is another indicator of the deviation of a periodic waveform from the ideal characteristics. For example, the average value of a pure sinusoidal wave averaged over a cycle is 0.637 times the peak value. The RMS value of the sinusoidal wave is 0.707 times the peak value. The form factor, FF, is calculated as $FF = 0.707/0.637 = 1.11$.

Frequency — Number of complete cycles of a periodic wave in a unit time, usually 1 sec. The frequency of electrical quantities such as voltage and current is expressed in hertz (Hz).

Ground electrode — Conductor or a body of conductors in intimate contact with earth for the purpose of providing a connection with the ground. Further explanation can be found in Chapter 5.

Ground grid — System of interconnected bare conductors arranged in a pattern over a specified area and buried below the surface of the earth.

Ground loop — Potentially detrimental loop formed when two or more points in an electrical system that are nominally at ground potential are connected by a conducting path such that either or both points are not at the same ground potential.

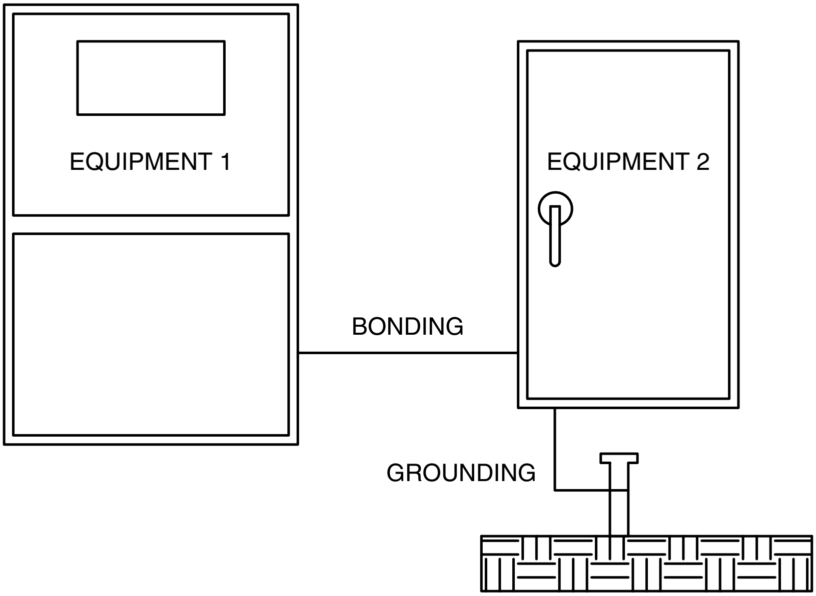


FIGURE 1.3 Bonding and grounding of equipment.

Ground ring — Ring encircling the building or structure in direct contact with the earth. This ring should be at a depth below the surface of the earth of not less than 2.5 ft and should consist of at least 20 ft of bare copper conductor not smaller than #2 AWG.

Grounding — Conducting connection by which an electrical circuit or equipment is connected to the earth or to some conducting body of relatively large extent that serves in place of the earth. In Figure 1.3, two conductive bodies are bonded and connected to ground. Grounding of metallic non-current-carrying parts of equipment is done primarily for safety reasons. Grounding the metal frame of equipment protects any person coming into contact with the equipment frame from electrical shock in case of a fault between an energized conductor and the frame. Grounding the equipment frame also ensures prompt passage of fault current to the ground electrode or ground plane; a protective device would operate to clear the fault and isolate the faulty equipment from the electrical power source.

Harmonic — Sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. If the fundamental frequency is 60 Hz, then the second harmonic is a sinusoidal wave of 120 Hz, the fifth harmonic is a sinusoidal wave of 300 Hz, and so on; see Chapter 4 for further discussion.

Harmonic distortion — Quantitative representation of the distortion from a pure sinusoidal waveform.

Impulse — Traditionally used to indicate a short duration overvoltage event with certain rise and fall characteristics. Standards have moved toward including the term *impulse* in the category of transients.

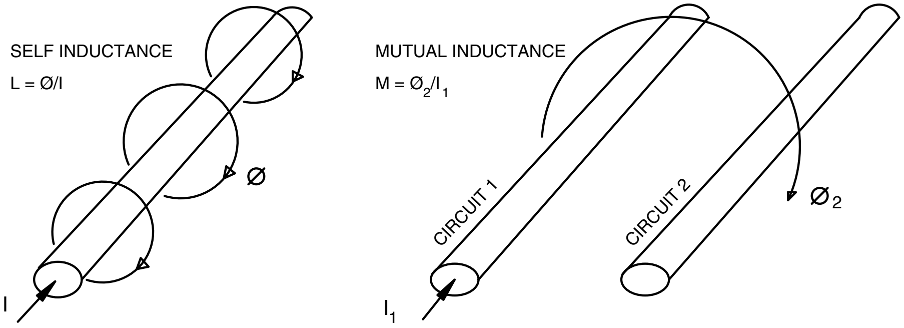


FIGURE 1.4 Self and mutual inductance.

Inductance — Inductance is the relationship between the magnetic lines of flux (Ø) linking a circuit due to the current (*I*) producing the flux. If *I* is the current in a wire that produces a magnetic flux of Ø lines, then the self inductance of the wire, *L*, is equal to Ø/*I*. Mutual inductance (*M*) is the relationship between the magnetic flux $Ø_2$ linking an adjacent circuit 2 due to current I_1 in circuit 1. This can be stated as $M = Ø_2/I_1$. Figure 1.4 points out the two inductances. The unit of inductance is the henry [H], named for the American scientist Joseph Henry. The practical unit of inductance is the millihenry [mH], which is equal to 10^{-3} H. Self inductance of a circuit is important for determining the characteristics of impulse voltage transients and waveform notches. In power quality studies, we also are concerned with the mutual inductance as it relates to how current in one circuit can induce noise and disturbance in an adjacent circuit.

Inrush — Large current that a load draws when initially turned on.

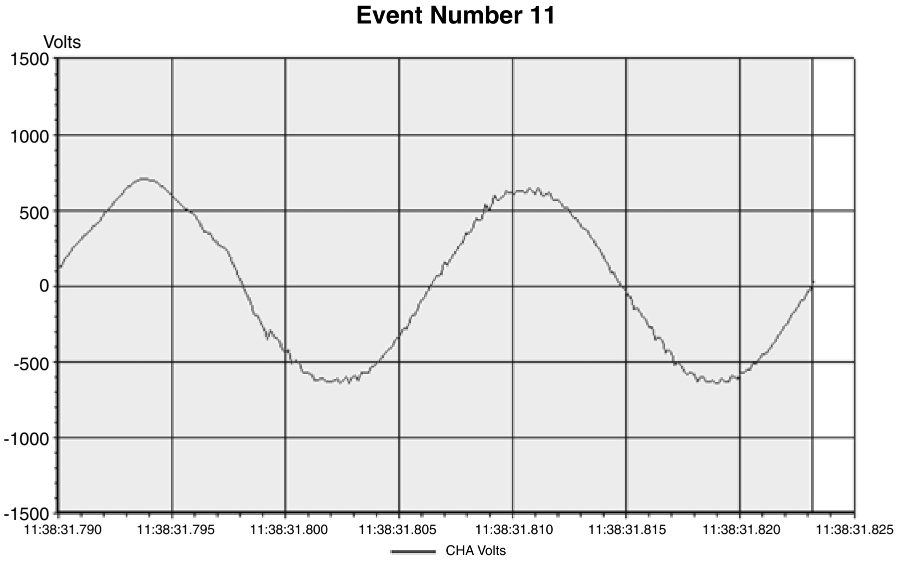
Interruption — Complete loss of voltage or current for a time period.

Isolation — Means by which energized electrical circuits are uncoupled from each other. Two-winding transformers with primary and secondary windings are one example of isolation between circuits. In actuality, some coupling still exists in a two-winding transformer due to capacitance between the primary and the secondary windings.

Linear loads — Electrical load which in steady-state operation presents essentially constant impedance to the power source throughout the cycle of applied voltage. A purely linear load has only the fundamental component of the current present.

Noise — Electrical noise is unwanted electrical signals that produce undesirable effects in the circuits of control systems in which they occur. Figure 1.5 shows an example of noise in a 480-V power wiring due to switching resonance.

Nonlinear load — Electrical load that draws currents discontinuously or whose impedance varies during each cycle of the input AC voltage waveform. Figure 1.6 shows the waveform of a nonlinear current drawn by fluorescent lighting loads.



Waveform event at 07/10/98 11:38:31.79

	PrevRMS	MiniRMS	MaxRMS	WorstIMP	Phase
AV Volts	476.2	448.9	464.4	0.0	0 deg.
BV Volts	475.3	446.3	458.7	0.0	0 deg.
CI Amps	0.072	0.063	0.065	0.000	0 deg.
DI Amps	0.165	0.148	0.157	0.000	0 deg.

FIGURE 1.5 Noise in 480-V circuit due to switching resonance.

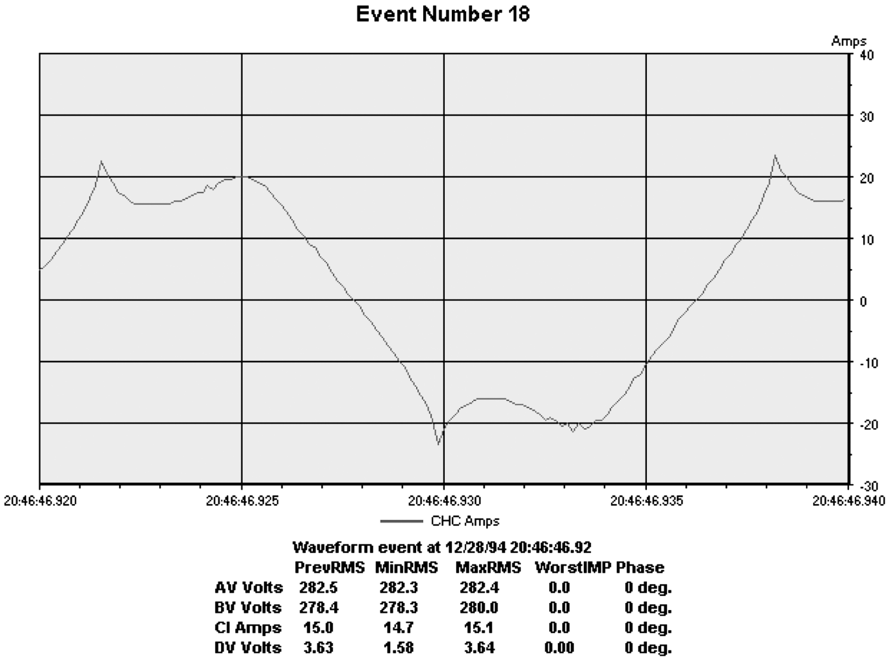
Notch — Disturbance of the normal power voltage waveform lasting less than a half cycle; the disturbance is initially of opposite polarity than the waveform and, thus, subtracts from the waveform. Figure 1.7 shows notch and noise produced by the operation of a converter in a variable speed drive.

Periodic — A voltage or current is periodic if the value of the function at time *t* is equal to the value at time $t + T$, where *T* is the period of the function. In this book, function refers to a periodic time-varying quantity such as AC voltage or current. Figure 1.8 is a periodic current waveform.

Power disturbance — Any deviation from the nominal value of the input AC characteristics.

Power factor (displacement) — Ratio between the active power (watts) of the fundamental wave to the apparent power (voltamperes) of the fundamental wave. For a pure sinusoidal waveform, only the fundamental component exists. The power factor, therefore, is the cosine of the displacement angle between the voltage and the current waveforms; see Figure 1.9.

Power factor (total) — Ratio of the total active power (watts) to the total apparent power (voltamperes) of the composite wave, including all harmonic frequency components. Due to harmonic frequency components, the total power factor is less than the displacement power factor, as the presence of harmonics tends to increase the displacement between the composite voltage and current waveforms.



Waveform event at 12/28/94 20:46:46.92

	PrevRMS	MinRMS	MaxRMS	WorstIMP	Phase
AV Volts	282.5	282.3	282.4	0.0	0 deg.
BV Volts	278.4	278.3	280.0	0.0	0 deg.
CI Amps	15.0	14.7	15.1	0.0	0 deg.
DV Volts	3.63	1.58	3.64	0.00	0 deg.

FIGURE 1.6 Nonlinear current drawn by fluorescent lighting loads.

Recovery time — Interval required for output voltage or current to return to a value within specifications after step load or line changes.

Ride through — Measure of the ability of control devices to sustain operation when subjected to partial or total loss of power of a specified duration.

Sag — RMS reduction in the AC voltage at power frequency from half of a cycle to a few seconds' duration. Figure 1.10 shows a sag lasting for 4 cycles.

Surge — Electrical transient characterized by a sharp increase in voltage or current.

Swell — RMS increase in AC voltage at power frequency from half of a cycle to a few seconds' duration. Figure 1.11 shows a swell of 2.5 cycles.

Transient — Subcycle disturbance in the AC waveform evidenced by a sharp, brief discontinuity of the waveform. This may be of either polarity and may be additive or subtractive from the nominal waveform. Transients occur when there is a sudden change in the voltage or the current in a power system. Transients are short-duration events, the characteristics of which are predominantly determined by the resistance, inductance, and capacitance of the power system network at the point of interest. The primary characteristics that define a transient are the peak amplitude, the rise time, the fall time, and the frequency of oscillation. Figure 1.12 shows a transient voltage waveform at the output of a power transformer as the result of switching-in of a motor containing power factor correction capacitors.

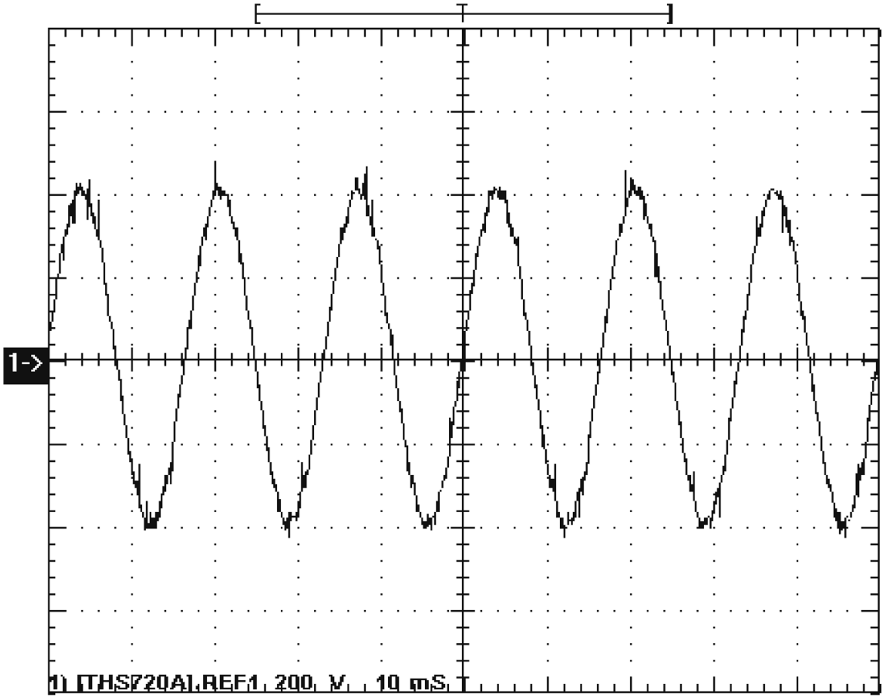


FIGURE 1.7 Notch and noise produced at the converter section of an adjustable speed drive.

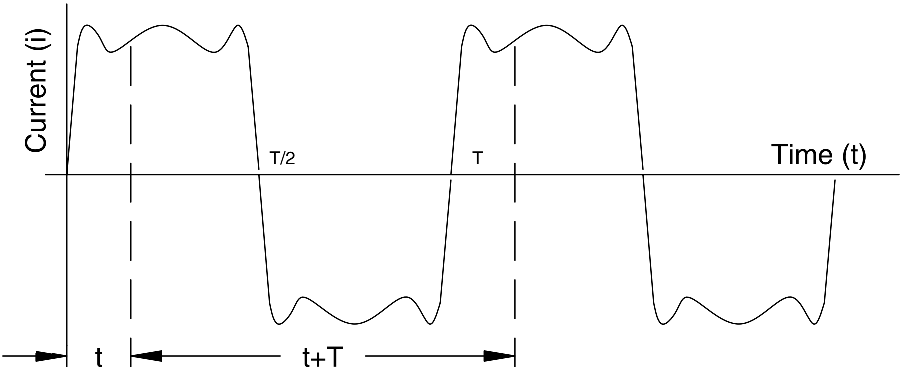


FIGURE 1.8 Periodic function of period *T*.

1.4 POWER QUALITY ISSUES

Power quality is a simple term, yet it describes a multitude of issues that are found in any electrical power system and is a subjective term. The concept of good and bad power depends on the end user. If a piece of equipment functions satisfactorily,

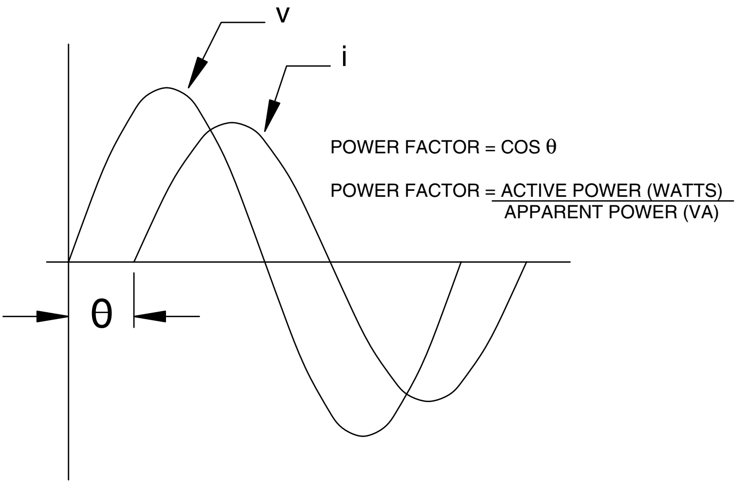


FIGURE 1.9 Displacement power factor.

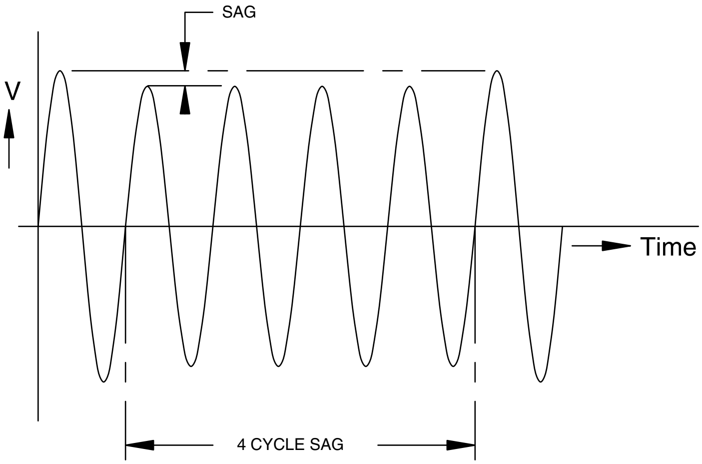


FIGURE 1.10 Voltage sag.

the user feels that the power is good. If the equipment does not function as intended or fails prematurely, there is a feeling that the power is bad. In between these limits, several grades or layers of power quality may exist, depending on the perspective of the power user. Understanding power quality issues is a good starting point for solving any power quality problem. Figure 1.13 provides an overview of the power quality issues that will be discussed in this book.

Power frequency disturbances are low-frequency phenomena that result in voltage sags or swells. These may be source or load generated due to faults or switching operations in a power system. The end results are the same as far as the susceptibility of electrical equipment is concerned. *Power system transients* are fast, short-duration

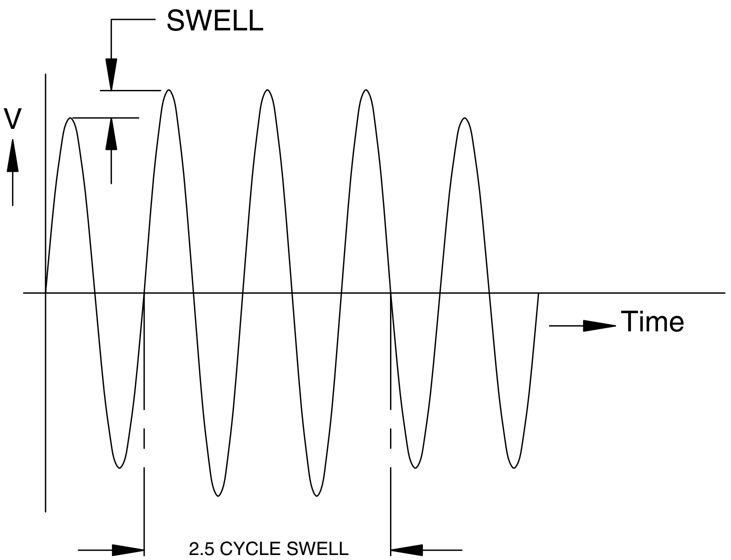
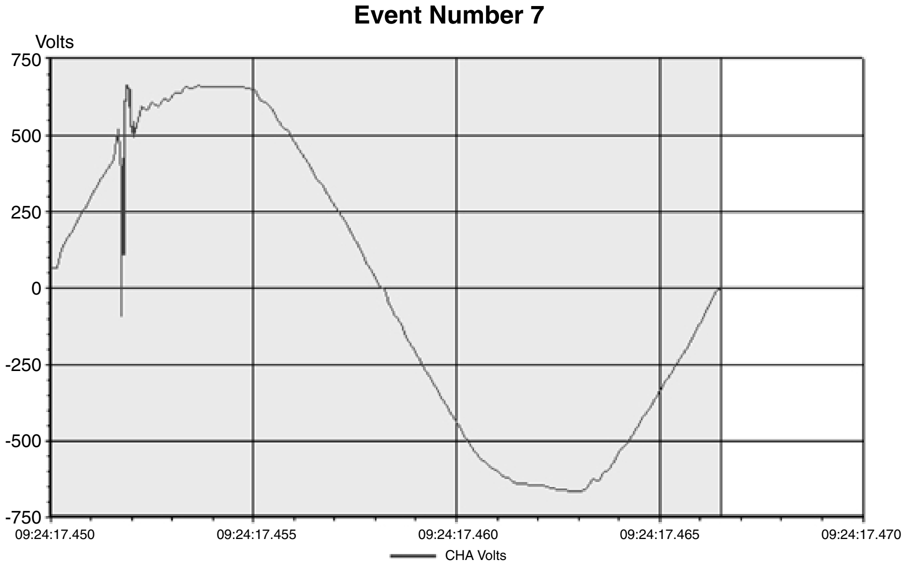


FIGURE 1.11 Voltage swell.



AV, BV, CV Impulse event at 08/22/95 09:24:17.45

	PrevRMS	MiniRMS	MaxRMS	WorstIMP	Phase	HF Hits
AV Volts	**481.9**	**476.0**	**476.0**	**-612.0**	**42 deg.**	**1**
BV Volts	**480.0**	**475.7**	**475.7**	**-486.0**	**184 deg.**	**2**
CI Amps	**481.1**	**477.4**	**477.4**	**671.0**	**282 deg.**	**2**
DI Amps	**1.534**	**1.395**	**1.395**	**0.000**	**0 deg.**	**0**

FIGURE 1.12 Motor starting transient voltage waveform.

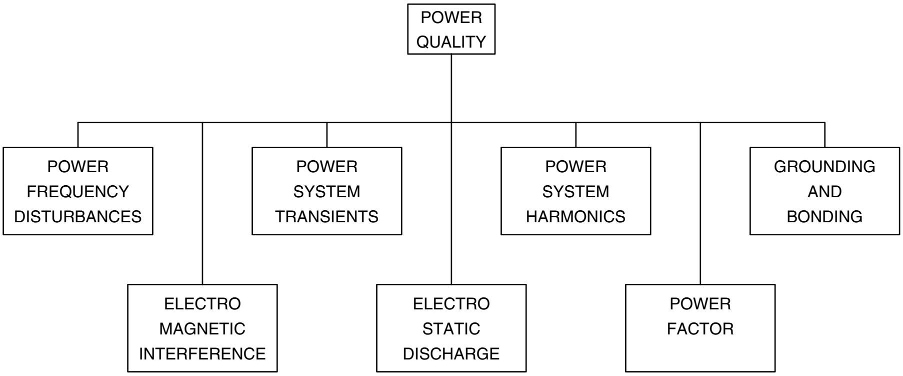


FIGURE 1.13 Power quality concerns.

events that produce distortions such as notching, ringing, and impulse. The mechanisms by which transient energy is propagated in power lines, transferred to other electrical circuits, and eventually dissipated are different from the factors that affect power frequency disturbances. *Power system harmonics* are low-frequency phenomena characterized by waveform distortion, which introduces harmonic frequency components. Voltage and current harmonics have undesirable effects on power system operation and power system components. In some instances, interaction between the harmonics and the power system parameters (R–L–C) can cause harmonics to multiply with severe consequences.

The subject of *grounding and bonding* is one of the more critical issues in power quality studies. Grounding is done for three reasons. The fundamental objective of grounding is safety, and nothing that is done in an electrical system should compromise the safety of people who work in the environment; in the U.S., safety grounding is mandated by the National Electrical Code (NEC®). The second objective of grounding and bonding is to provide a low-impedance path for the flow of fault current in case of a ground fault so that the protective device could isolate the faulted circuit from the power source. The third use of grounding is to create a ground reference plane for sensitive electrical equipment. This is known as the signal reference ground (SRG). The configuration of the SRG may vary from user to user and from facility to facility. The SRG cannot be an isolated entity. It must be bonded to the safety ground of the facility to create a total ground system.

Electromagnetic interference (EMI) refers to the interaction between electric and magnetic fields and sensitive electronic circuits and devices. EMI is predominantly a high-frequency phenomenon. The mechanism of coupling EMI to sensitive devices is different from that for power frequency disturbances and electrical transients. The mitigation of the effects of EMI requires special techniques, as will be seen later. *Radio frequency interference* (RFI) is the interaction between conducted or radiated radio frequency fields and sensitive data and communication equipment. It is convenient to include RFI in the category of EMI, but the two phenomena are distinct.

Electrostatic discharge (ESD) is a very familiar and unpleasant occurrence. In our day-to-day lives, ESD is an uncomfortable nuisance we are subjected to when we open the door of a car or the refrigerated case in the supermarket. But, at high levels, ESD is harmful to electronic equipment, causing malfunction and damage. *Power factor* is included for the sake of completing the power quality discussion. In some cases, low power factor is responsible for equipment damage due to component overload. For the most part, power factor is an economic issue in the operation of a power system. As utilities are increasingly faced with power demands that exceed generation capability, the penalty for low power factor is expected to increase. An understanding of the power factor and how to remedy low power factor conditions is not any less important than understanding other factors that determine the health of a power system.

1.5 SUSCEPTIBILITY CRITERIA

1.5.1 CAUSE AND EFFECT

The subject of power quality is one of cause and effect. Power quality is the cause, and the ability of the electrical equipment to function in the power quality environment is the effect. The ability of the equipment to perform in the installed environment is an indicator of its immunity. Figures 1.14 and 1.15 show power quality and equipment immunity in two forms. If the equipment immunity contour is within the power quality boundary, as shown in Figure 1.14, then problems can be expected. If the equipment immunity contour is outside the power quality boundary, then the equipment should function satisfactorily. The objective of any power quality study or solution is to ensure that the immunity contour is outside the boundaries of the power quality contour. Two methods for solving a power quality problem are to either make the power quality contour smaller so that it falls within the immunity contour or make the immunity contour larger than the power quality contour.

In many cases, the power quality and immunity contours are not two-dimensional and may be more accurately represented three-dimensionally. While the ultimate goal is to fit the power quality mass inside the immunity mass, the process is complicated because, in some instances, the various power quality factors making up the mass are interdependent. Changing the limits of one power quality factor can result in another factor falling outside the boundaries of the immunity mass. This concept is fundamental to solving power quality problems. In many cases, solving a problem involves applying multiple solutions, each of which by itself may not be the cure. Figure 1.16 is a two-dimensional immunity graph that applies to an electric motor. Figure 1.17 is a three-dimensional graph that applies to an adjustable speed drive module. As the sensitivity of the equipment increases, so does the complexity of the immunity contour.

1.5.2 TREATMENT CRITERIA

Solving power quality problems requires knowledge of which pieces or subcomponents of the equipment are susceptible. If a machine reacts adversely to a

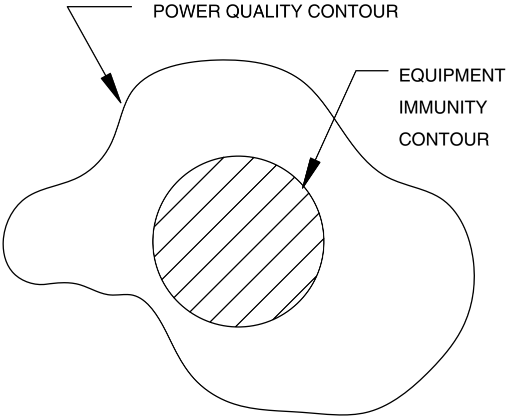


FIGURE 1.14 Criteria for equipment susceptibility.

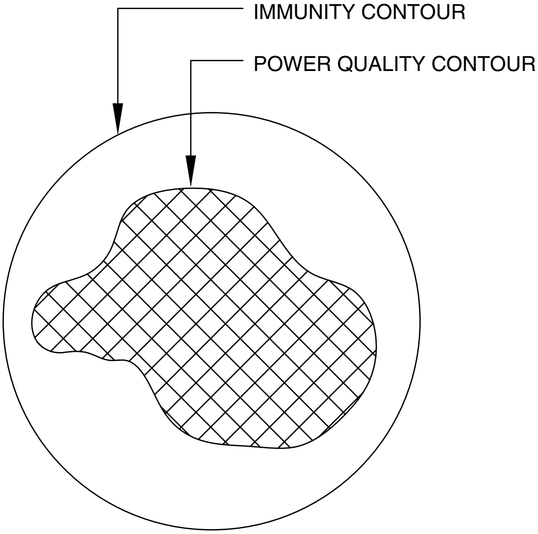


FIGURE 1.15 Criteria for equipment immunity.

particular power quality problem, do we try to treat the entire machine or treat the subcomponent that is susceptible? Sometimes it may be more practical to treat the subcomponent than the power quality for the complete machine, but, in other instances, this may not be the best approach. Figure 1.18 is an example of treatment of power quality at a component level. In this example, component A is susceptible to voltage notch exceeding 30 V. It makes more sense to treat the power to component A than to try to eliminate the notch in the voltage. In the same example, if the power quality problem was due to ground loop potential, then component treatment may not produce the required results. The treatment should then involve the whole system.

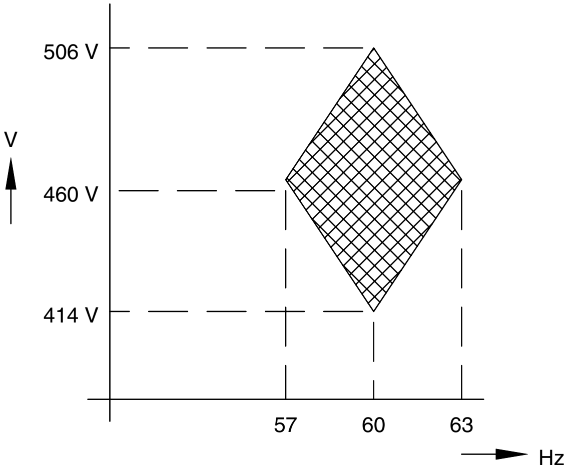


FIGURE 1.16 Volts–hertz immunity contour for 460-VAC motor.

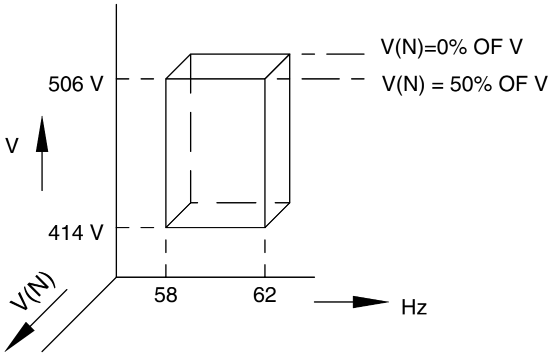


FIGURE 1.17 Volts–hertz–notch depth immunity contour for 460-V adjustable speed drive.

1.5.3 POWER QUALITY WEAK LINK

The reliability of a machine depends on the susceptibility of the component that has the smallest immunity mass. Even though the rest of the machine may be capable of enduring severe power quality problems, a single component can render the entire machine extremely susceptible. The following example should help to illustrate this.

A large adjustable speed drive in a paper mill was shutting down inexplicably and in random fashion. Each shutdown resulted in production loss, along with considerable time and expense to clean up the debris left by the interruption of production. Finally, after several hours of troubleshooting, the problem was traced to an electromechanical relay added to the drive unit during commissioning for a remote control function. This relay was an inexpensive, commercial-grade unit costing about $10. Once this relay was replaced, the drive operated satisfactorily

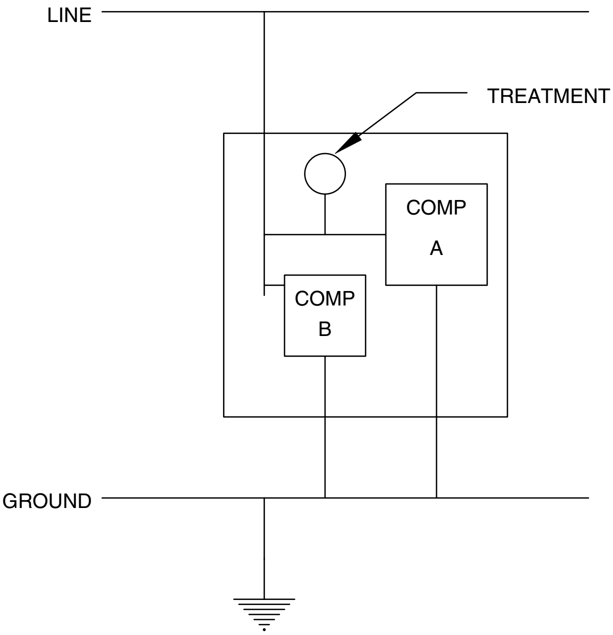


FIGURE 1.18 Localized power quality treatment.

without further interruptions. It is possible that a better grade relay would have prevented the shutdowns. Total cost of loss of production alone was estimated at $300,000. One does not need to look very far to see how important the weak link concept is when looking for power quality solutions.

1.5.4 INTERDEPENDENCE

Power quality interdependence means that two or more machines that could operate satisfactorily by themselves do not function properly when operating together in a power system. Several causes contribute to this occurrence. Some of the common causes are voltage fluctuations, waveform notching, ground loops, conducted or radiated electromagnetic interference, and transient impulses. In such a situation, each piece of equipment in question was likely tested at the factory for proper performance, but, when the pieces are installed together, power quality aberrations are produced that can render the total system inoperative. In some cases, the relative positions of the machines in the electrical system can make a difference. General guidelines for minimizing power quality interdependence include separating equipment that produces power quality problems from equipment that is susceptible. The offending machines should be located as close to the power source as possible. The power source may be viewed as a large pool of water. A disturbance in a large pool (like dropping a rock) sets out ripples, but these are small and quickly absorbed. As we move downstream from the power source, each location may be viewed as a smaller pool where any disturbance produces larger and longer-lasting ripples. At

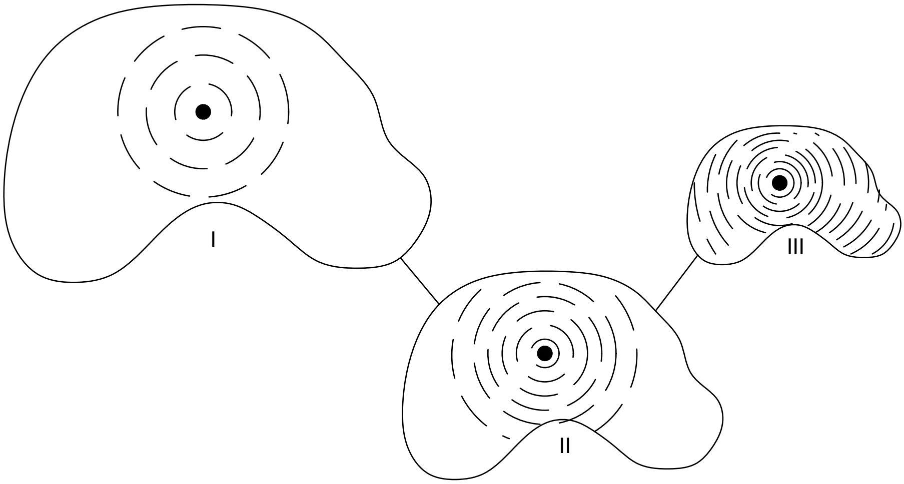


FIGURE 1.19 Power quality source dependence.

points farthest downstream from the source, even a small disturbance will have significant effects. Figure 1.19 illustrates this principle.

1.5.5 STRESS–STRAIN CRITERIA

In structural engineering, two frequently used terms are stress and strain. If load is applied to a beam, up to a point the resulting strain is proportional to the applied stress. The strain is within the elastic limit of the material of the beam. Loading beyond a certain point produces permanent deformity and weakens the member where the structural integrity is compromised. Electrical power systems are like structural beams. Loads that produce power quality anomalies can be added to a power system, to a point. The amount of such loads that may be tolerated depends on the rigidity of the power system. Rigid power systems can usually withstand a higher number of power quality offenders than weak systems. A point is finally reached, however, when further addition of such loads might make the power system unsound and unacceptable for sensitive loads. Figure 1.20 illustrates the stress–strain criteria in an electrical power system.

1.5.6 POWER QUALITY VS. EQUIPMENT IMMUNITY

All devices are susceptible to power quality; no devices are 100% immune. All electrical power system installations have power quality anomalies to some degree, and no power systems exist for which power quality problems are nonexistent. The challenge, therefore, is to create a balance. In Figure 1.21, the balanced beam represents the electrical power system. Power quality and equipment immunity are two forces working in opposition. The object is then to a create a balance between the two. We can assign power quality indices to the various locations in the power system and immunity indices to the loads. By matching the immunity index of a

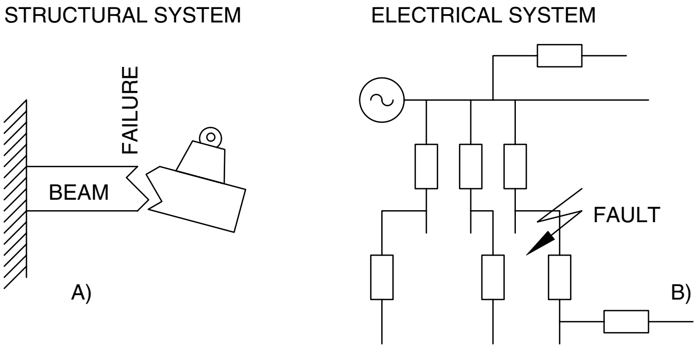


FIGURE 1.20 Structural and electrical system susceptibility.

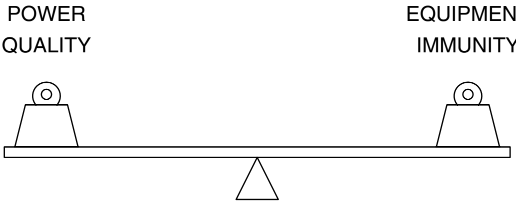


FIGURE 1.21 Power quality and equipment immunity.

piece of equipment with the power quality index, we can arrive at a balance where all equipment in the power system can coexist and function adequately. Experience indicates that three categories would sufficiently represent power quality and equipment immunity (see Table 1.1). During the design stages of a facility, many problems can be avoided if sufficient care is exercised to balance the immunity characteristics of equipment with the power quality environment.

1.6 RESPONSIBILITIES OF THE SUPPLIERS AND USERS OF ELECTRICAL POWER

The realization of quality electrical power is the responsibility of the suppliers and users of electricity. Suppliers are in the business of selling electricity to widely varying clientele. The needs of one user are usually not the same as the needs of other users. Most electrical equipment is designed to operate within a voltage of ±5% of nominal with marginal decrease in performance. For the most part, utilities are committed to adhering to these limits. At locations remote from substations supplying power from small generating stations, voltages outside of the ±5% limit are occasionally seen. Such a variance could have a negative impact on loads such as motors and fluorescent lighting. The overall effects of voltage excursions outside the nominal are not that significant unless the voltage approaches the limits of ±10% of nominal. Also, in urban areas, the utility frequencies are rarely outside ±0.1 Hz of the nominal frequency. This is well within the operating tolerance of most sensitive

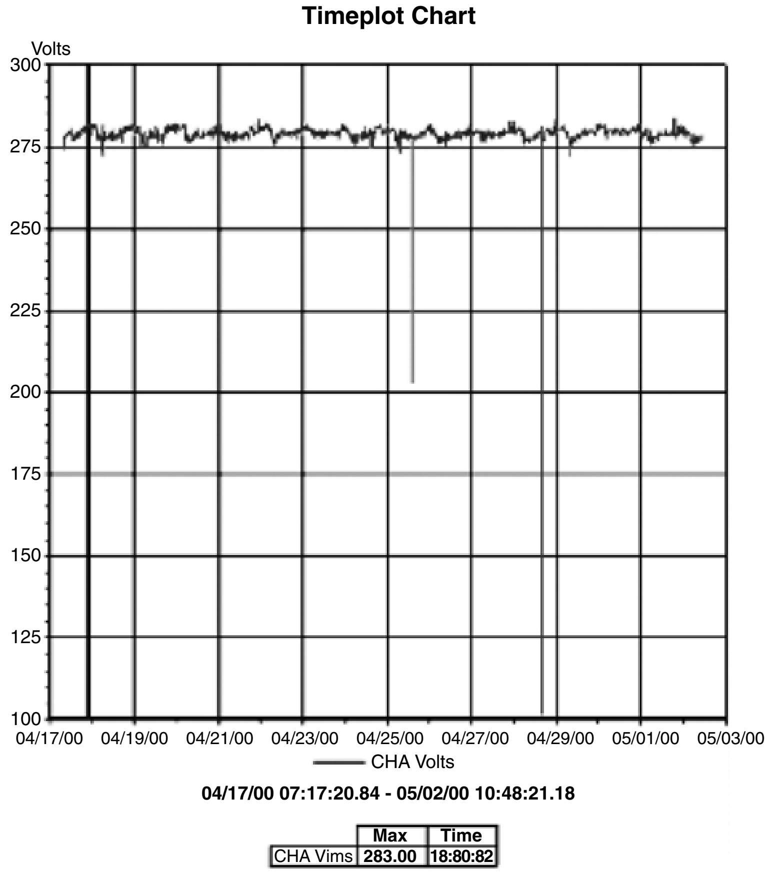
TABLE 1.1
Immunity and Power Quality Indices

Index	Description	Examples
	Equipment Immunity Indices	
I	High immunity	Motors, transformers, incandescent lighting, heating loads, electromechanical relays
II	Moderate immunity	Electronic ballasts, solid-state relays, programmable logic controllers, adjustable speed drives
III	Low immunity	Signal, communication, and data processing equipment; electronic medical equipment
	Power Quality Indices	
I	Low power quality problems	Service entrance switchboard, lighting power distribution panel
II	Moderate power quality problems	HVAC power panels
III	High power quality problems	Panels supplying adjustable speed drives, elevators, large motors

equipment. Utilities often perform switching operations in electrical substations to support the loads. These can generate transient disturbances at levels that will have an impact on electrical equipment. While such transients generally go unnoticed, equipment failures due to these practices have been documented. Such events should be dealt with on a case-by-case basis. Figure 1.22 shows a 2-week voltage history for a commercial building. The nominal voltage at the electrical panel was 277 V phase to neutral. Two incidents of voltage sag can be observed in the voltage summary and were attributed to utility faults due to weather conditions. Figure 1.23 provides the frequency information for the same time period.

What are the responsibilities of the power consumer? Some issues that are relevant are energy conservation, harmonic current injection, power factor, and surge current demands. Given the condition that the utilities are becoming less able to keep up with the demand for electrical energy, it is incumbent on the power user to optimize use. Energy conservation is one means of ensuring an adequate supply of electrical power and at the same time realize an ecological balance. We are in an electronic age in which most equipment utilizing electricity generates harmonic-rich currents. The harmonics are injected into the power source, placing extra demands on the power generation and distribution equipment. As this trend continues to increase, more and more utilities are placing restrictions on the amount of harmonic current that the user may transmit into the power source.

The power user should also be concerned about power factor, which is the ratio of the real power (watts) consumed to the total apparent power (voltamperes) drawn from the source. In an ideal world, all apparent power drawn will be converted to useful work and supply any losses associated with performing the work. For several reasons, which will be discussed in a later chapter, this is not so in the real world. As the ratio between the real power needs of the system and the apparent power



	Max	Time
CHA Vims	283.00	18:80:82

FIGURE 1.22 Voltage history graph at an electrical panel.

drawn from the source grows smaller, the efficiency with which power is being utilized is lowered. Typically, power suppliers expect a power factor of 0.95 or higher from industrial and commercial users of power. A penalty is levied if the power factor is below 0.95. Utilizing any one of several means, users can improve the power factor so the penalty may be avoided or minimized. It is not difficult to appreciate that if power suppliers and users each do their part, power quality is improved and power consumption is optimized.

1.7 POWER QUALITY STANDARDS

With the onset of the computer age and the increasing trend toward miniaturization of electrical and electronic devices, power quality problems have taken on increasing importance. The designers of computers and microprocess controllers are not versed in power system power quality issues. By the same token, power system designers and operators have limited knowledge of the operation of sensitive electronics. This environment has led to a need for power quality standards and guidelines. Currently,

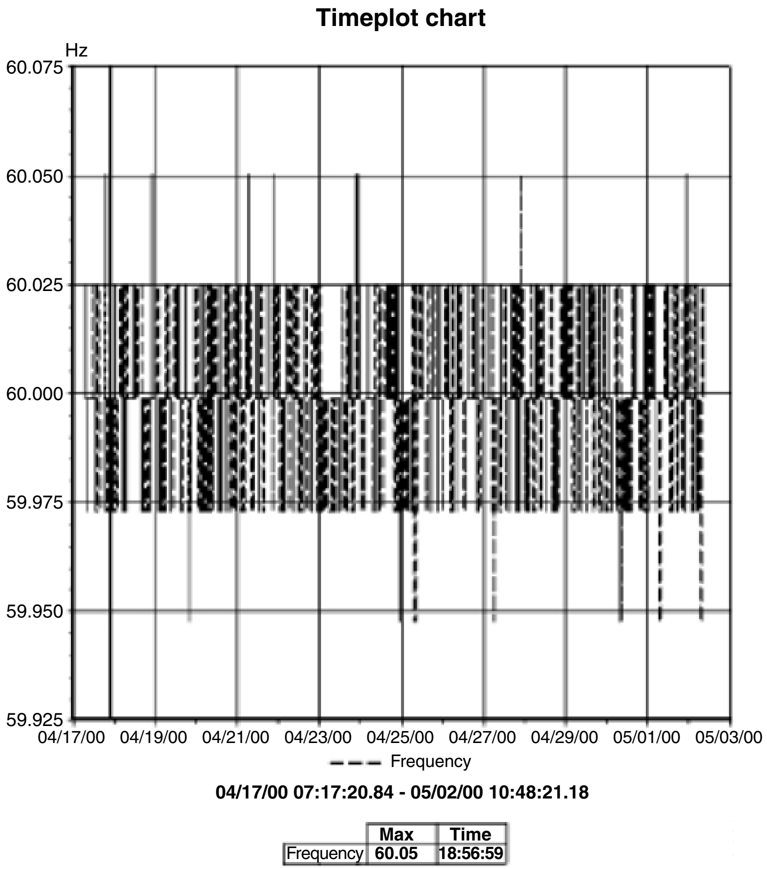


FIGURE 1.23 Frequency history at an electrical panel.

several engineering organizations and standard bearers in several parts of the world are spending a large amount of resources to generate power quality standards. Following is a list of power quality and related standards from two such organizations; some of the standards listed are in existence at this time, while others are still in process:

Institute of Electrical and Electronic Engineers (IEEE); Piscataway, NJ; http://www.ieee.org

IEEE 644	Standard Procedure for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines
IEEE C63.12	Recommended Practice for Electromagnetic Compatibility Limits
IEEE 518	Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources

IEEE 519	Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems
IEEE 1100	Recommended Practice for Powering and Grounding Sensitive Electronic Equipment
IEEE 1159	Recommended Practice for Monitoring Electric Power Quality
IEEE 141	Recommended Practice for Electric Power Distribution for Industrial Plants
IEEE 142	Recommended Practice for Grounding of Industrial and Commercial Power Systems
IEEE 241	Recommended Practice for Electric Power Systems in Commercial Buildings
IEEE 602	Recommended Practice for Electric Systems in Health Care Facilities
IEEE 902	Guide for Maintenance, Operation and Safety of Industrial and Commercial Power Systems
IEEE C57.110	Recommended Practice for Establishing Transformer Capability when Supplying Nonsinusoidal Load
IEEE P1433	Power Quality Definitions
IEEE P1453	Voltage Flicker
IEEE P1564	Voltage Sag Indices

International Electrotechnical Commission (IEC); Geneva, Switzerland; http://www.iec.ch

IEC/TR3 61000-2-1	Electromagnetic Compatibility — Environment
IEC/TR3 61000-3-6	Electromagnetic Compatibility — Limits
IEC 61000-4-7	Electromagnetic Compatibility — Testing and Measurement Techniques — General Guides on Harmonics and Interharmonics Measurements and Instrumentation
IEC 61642	Industrial a.c. Networks Affected by Harmonics — Application of Filters and Shunt Capacitors
IEC SC77A	Low Frequency EMC Phenomena
IEC TC77/WG1	Terminology
IEC SC77A/WG1	Harmonics and Other Low Frequency Disturbances
IEC SC77A/WG6	Low Frequency Immunity Tests
IEC SC77A/WG2	Voltage Fluctuations and Other Low Frequency Disturbances
IEC SC77A/WG8	Electromagnetic Interference Related to the Network Frequency
IEC SC77A/WG9	Power Quality Measurement Methods

1.8 CONCLUSIONS

The concept of power quality is a qualitative one for which mathematical expressions are not absolutely necessary to develop a basic understanding of the issues; however, mathematical expressions *are* necessary to solve power quality problems. If we cannot effectively represent a power quality problem with expressions based in mathematics, then solutions to the problem become exercises in trial and error. The expressions are what define power quality boundaries, as discussed earlier. So far, we have stayed away from much of quantitative analysis of power quality for the purpose of first developing an understanding. In later chapters, formulas and expressions will be introduced to complete the picture.