CHAPTER 55

ELECTRICAL CONSIDERATIONS

PRODUCTION, delivery, and use of electricity involves countless decisions made along the way, by hundreds of people and companies. This chapter focuses on the decisions to be made about the building and equipment. Creating a building that works means including the best designs available, communicating needs and capabilities, and planning ahead.

For an owner-occupied building, the benefits of a properly designed building return to the owner throughout the building's life. For tenant-occupied spaces, such buildings have fewer problems with tenant and building system interference (e.g., lighting or appliances in one suite disrupting computers in a neighboring suite).

Because HVAC equipment can have a large impact on buildings, it is necessary to address electrical issues in buildings that specifically are caused by or have an effect on HVAC equipment.

SAFETY

The greatest danger from electricity is that it is taken for granted and not taken seriously as a hazardous energy source. Electricity can produce bodily harm and property damage, and shut down entire operations. The type of damage from electricity ranges from a mild shock to the body to a major electrical fire. Electrical safety is important in all occupational settings. See information on safety codes in the Electrical Codes section.

PERFORMANCE

In the United States, the National Electrical Code (NEC) is generally accepted as the minimum safety requirements for wiring and grounding in a structure. Other countries have similar requirements. The NEC ensures building design is safe, but may not provide the performance that a modern building requires. Rapid changes in electronic technologies have rendered many traditional electrical distribution practices obsolete and must be replaced with new designs. Electrical power distribution decisions made during design will impact occupants' productivity for the life of the building. Many improvements over the minimum requirements are relatively inexpensive to implement as a building is constructed.

Power quality, like quality in other goods and services, is difficult to define. There are standards for voltage and waveshape, but the final measure of power quality is determined by the performance and productivity of the equipment used by the building occupant. If the electric power is inadequate for those needs, then the quality is lacking.

Specifications for electric power are set down in recognized national standards. These are voltage levels and tolerances that should be met, on the average, over a long period of time. Electric utilities and building distribution systems generally meet such specifications. Voltage drop within a building is a fundamental reason for calculating the size of electrical conductors. Brief disturbances on the power line are not addressed in these time-averaged specifications; new standards are being developed to address these new concerns.

Interaction between tenants' electrical equipment is an ongoing problem. Often, a large load in one tenant's space can disrupt a small appliance or computer in another part of the building. Voltage drop along building wiring is usually the cause of the problem, and **dedicated circuits** usually solve the problem. By eliminating much of the wiring common to both pieces of equipment, the original performance of each is restored. With modern electronic loads, the interaction might easily involve a small load that interferes with large equipment. Disturbances might travel greater distances or through nondirect paths, so diagnostics are more difficult.

For tenants of a building with ordinary power distribution, lost productivity associated with power quality problems is an additional operating expense. The disturbance may last only milliseconds, but the disruption to business may require hours of recovery. This multiplication of lost time makes power quality a significant business problem.

Lost productivity may be the time it takes to restart a chiller, to repair a critical piece of equipment, or to retype a document. Another aspect of lost productivity is the stress on employees whose work is lost. The building owner may suffer loss, as well. Certainly the building equipment itself may suffer from the same damage or losses as tenant equipment. Sophisticated energy management systems, security systems, elevator controls, HVAC systems, and communications facilities are susceptible to disruption and vulnerable to damage.

PRINCIPLES OF ELECTRICITY

In a direct current (dc) electrical system, the electrons flow in only one direction. In an alternating current (ac) electrical system, the electrons continually alternate or change direction at a prescribed number of times per second. Voltage differential causes electron to flow. Electrons flow most efficiently over long distances at dangerously high voltages and must then be stepped down to a safer, lower, usable voltage. Alternating the current is the most efficient method to step down voltage.

Voltage Terms

An understanding of voltage nomenclature and the preferred voltage ratings of distribution and utilization equipment is essential to ensure that the dynamics of a power system are recognized and proper voltage control is applied so that satisfactory voltages are available to all equipment under all normal conditions of operation.

Alternating current electricity is a periodic time-varying current and voltage, the average values of which over the period are zero. The values vary over time in a sinusoidal manner. **Three-phase power** is supplied by three conductors, the currents (or voltages) of any two are 120° out of phase with each other.

Y (or **"wye"**) connection is a configuration of wiring so that each winding of a polyphase transformer (or three single-phase

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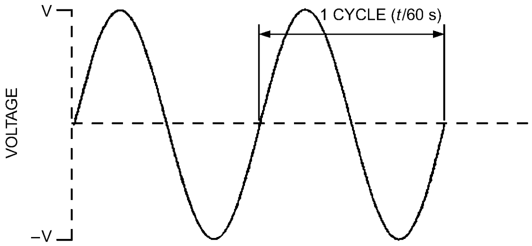

Fig. 1 Fundamental Voltage Wave

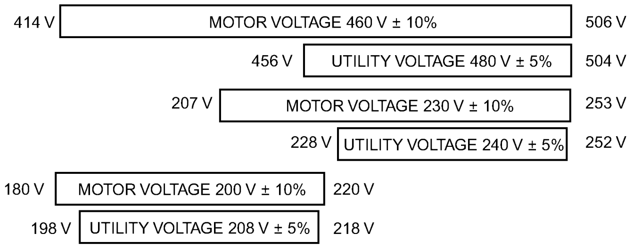

Fig. 2 Utilization Voltages Versus Nameplate Ratings

transformers) is connected to a common point, the “neutral.” A **delta**-connected circuit is a three-phase circuit that is mesh-connected, so the windings of each phase of a three-phase transformer are connected in a series for a closed circuit (i.e., in a triangle or “delta” configuration).

The **fundamental voltage** produced by an electric ac generator in the United States has a sinusoidal waveform with a frequency of 60 cycles per second, or 60 Hz. Other countries may have a similar waveform but at 50 cycles per second of 50 Hz.

A **cycle** is the part of the fundamental waveform where the electrical potential goes from zero to a maximum to zero to a minimum, and back to zero again (i.e., one complete wave; see Figure 1). At 60 Hz, there are 6 cycles in 0.1 s.

RMS (root-mean-squared) voltage is an effective way to compare ac to dc value. For a pure sinusoidal waveform, the mathematics are 0.707 times the peak value.

System voltage is the RMS phase-to-phase voltage of a portion of an ac electric utility system. Each system voltage pertains to a part of the system bounded by transformers or end-use equipment. **Service voltage** is the voltage at the point where the electric systems of the supplier and the user are connected. **Utilization voltage** is the voltage at the terminals of the utilization equipment.

The **nominal system voltage** is near the voltage level at which the electrical system normally operates. To allow for operating contingencies, utility systems generally operate at voltage levels about 5 to 10% below the maximum system voltage for which components are designed.

Utilization Equipment Voltage Ratings

Utilization equipment is electrical equipment that converts electric power into some other form of energy, such as light, heat, or mechanical motion. Every item of utilization equipment should have a nameplate listing, which includes, among other things, the rated voltage for which the equipment is designed. In some cases the nameplate will also indicate the maximum and minimum voltage for proper operation. With one major exception, most utilization equipment carries a nameplate rating that is the same as the voltage system on which it is to be used: that is, equipment to be used on 120 V systems is rated 120 V. The major exception is motors and equipment containing motors, where performance peaks in the middle of the tolerance range of the equipment: better performance can be obtained over the tolerance range specified in ANSI C84.1 by selecting a nameplate rating closer to the middle of this tolerance range. The difference between the nameplate rating of utilization equipment and the system nominal voltage is necessary because the performance guarantee for utilization equipment is based on the nameplate rating and not on the system nominal voltage.

The voltage tolerance limits in ANSI C84.1 are based on ANSI/NEMA MG 1, Motors and Generators edition, which establishes voltage tolerance limits of the standard low-voltage induction motor at ±10% of nameplate voltage ratings of 230 V and 460 V. Because motors represent the major component of utilization equipment, they were given primary consideration in the establishment of this voltage standard. Figure 2 compares utilization voltages to nameplate ratings.

Voltage Level Variation Effects

Whenever voltage at the terminals of utilization equipment varies from its nameplate rating, equipment performance and life expectancy change. The effect may be minor or serious, depending on the equipment characteristics and the amount of voltage deviation from the nameplate rating. NEMA standards provide tolerance limits within which performance will normally be acceptable. In precise operations, however, closer voltage control may be required. In general, a change in the applied voltage causes a proportional change in the current. Because the effect on the load equipment is proportional to the product of the voltage and the current, and because the current is proportional to the voltage, the total effect is approximately proportional to the square of the voltage.

However, the change is only approximately proportional and not exact: the change in the current affects the operation of the equipment, so the current continues to change until a new equilibrium position is established. For example, when the load is a resistance heater, the increase in current increases the heater temperature, which increases its resistance and, in turn, reduces the current. This effect will continue until a new equilibrium current and temperature are established. In the case of an induction motor, a voltage reduction reduces the current flowing to the motor, causing the motor to slow down. This reduces the impedance of the motor, increasing the current until a new equilibrium position is established between the current and motor speed.

Voltage Selection

Generally, the preferred utilization voltage for large commercial buildings is 480 Y/277 V. The three-phase power load is connected directly to the system at 480 V, and fluorescent ceiling lighting is connected phase-to-neutral at 277 V. Dry-type transformers rated 480 V/208 Y/120 V are used to provide 120 V single-phase for convenience outlets and 208 V three-phase for other building equipment. Single-phase transformers with secondary ratings of 120/240 V may also be used to supply lighting and small office equipment. However, single-phase transformers should be connected in sequence on the primary phases to maintain balanced load on the primary system.

Where the supplying utility furnishes the distribution transformers, the choice of voltages will be limited to those the utility will provide. For tall buildings, space will be required on upper floors for transformer installations and the primary distribution cables supplying the transformers. Apartment buildings generally have the option of using either 208 Y/120 V three-phase/four-wire systems, or 120/240 V single-phase systems, because the major load in residential occupancies consists of 120 V lighting fixtures and appliances. The 208 Y/120 V systems should be more economical for large apartment buildings, and 120/240 V systems should be satisfactory for small apartment buildings.

However, large single-phase appliances, such as electric ranges and water heaters rated for use on 120/240 V single-phase systems, will perform to the rated wattage on a 208 Y/120 V systems, because the line-to-line voltage is appreciably below the rated voltage of the appliance.

POWER QUALITY VARIATIONS

Power quality refers to varied parameters that characterize the voltage and current for a given time and at a given point on the electric system. A power quality problem is usually any variation in the voltage or current that actually results in failure or misoperation of equipment in the facility. Therefore, power quality evaluations are a function of both the power system characteristics and the sensitivity of equipment connected to the power system.

This section defines the different kinds of power quality variations that may affect equipment operation. Important reasons for categorizing power anomalies include the following:

- Identifying the cause of the power anomalies. Understanding the characteristics of a power quality variation can often help identify the cause.
- Identifying the possible impacts on equipment operation. A transient voltage can cause failure of equipment insulation; a sag in voltage may result in dropout of sensitive controls based on an undervoltage setting
- Determining the requirements for measurement. Some power quality variations can be characterized with simple voltmeters, ammeters, or strip chart recorders. Other conditions require special-purpose disturbance monitors or harmonic analyzers
- Identifying methods to improve the power quality. Solutions depend on the type of power quality variation. Transient disturbances can be controlled with surge arrestors, whereas momentary interruptions could require an uninterruptible power supply (UPS) system for equipment protection. Harmonic distortion may require special-purpose harmonic filters.

Power quality can be described in terms of *disturbances* and *steady-state variations*.

Disturbances. Disturbances are one-time, momentary events. Measurement equipment can characterize these events by using thresholds and triggering when disturbance characteristics exceed specified thresholds. Examples include transients, voltage sags, and interruptions.

Steady-State Variations. Changes in the long-term or steady-state conditions can also result in equipment misoperation. High harmonic distortion levels can cause equipment heating and failure, as can long-term overvoltages or unbalanced voltages. These are variations best characterized by monitoring over a longer period of time with periodic sampling of the voltages and currents. Steady-state variations are best analyzed by plotting trends of the important quantities (e.g., RMS voltages, currents, distortion levels).

These two types of power quality are further defined in seven major categories and numerous subcategories. There are three primary attributes used to differentiate among subcategories within a power quality category: frequency components, magnitude, and duration. These attributes are not equally applicable to all categories. For instance, it is difficult to assign a duration to a voltage flicker, and it is not useful to assign a spectral content to variations in the fundamental frequency magnitude (sags, swells, overvoltages, undervoltages, interruptions).

Each category is defined by its most important attributes for that particular power quality condition. These attributes are useful for evaluating measurement equipment requirements, system characteristics affecting power quality variations, and possible measures to correct problems. The terminology has been selected to agree as much as possible with existing terminology used in technical papers and standards.

The following descriptions focus on causes of the power quality variations, important parameters describing the variation, and effects on equipment.

Transients

Transients are probably the most common disturbance on the distribution systems in buildings and can be the most damaging. Transients can be classified as impulsive or oscillatory. These terms reflect the waveshape of a current or voltage transient.

Impulsive Transient. An impulsive transient (spikes or notches) is considered unidirectional; that is, the transient voltage or current wave is primarily of a single polarity (Figures 3 and 4). Impulsive transients are often characterized simply by a magnitude and duration. Another important component that strongly influences the effect on many types of electronic equipment is the **rate of rise**, or rise time of the impulse. This rate of rise can be quite steep, and can be as fast as several nanoseconds.

The high-frequency components and the high rate of rise are important considerations for monitoring impulses. Very fast sampling rates are required to characterize impulses with actual waveforms. In many power quality monitors, simple circuits are used to detect the peak magnitude and duration (or volt-seconds) of the transient. If impulse waveshapes are recorded, they usually do not include the fundamental frequency (60 Hz) component. When evaluating these disturbances, it is important to remember that the stress on equipment is based on the impulse magnitude plus the magnitude of the fundamental component at the instant of the impulse. The voltage, current available, and pulse width determine the amount of energy available in a transient.

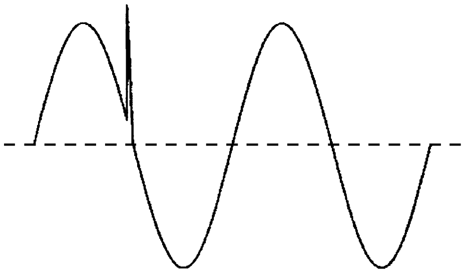

Fig. 3 Example of Spike

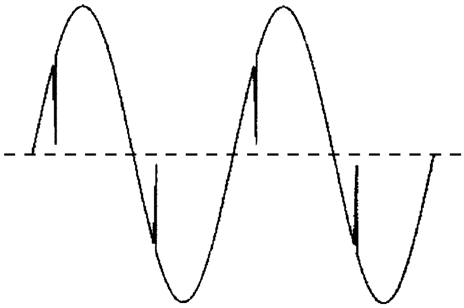

Fig. 4 Example of Notch

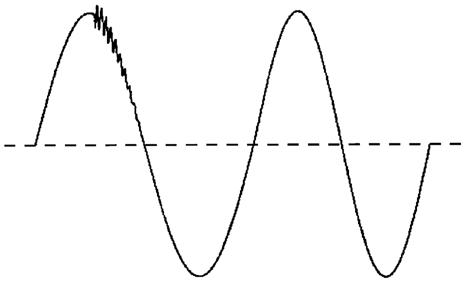

Fig. 5 Example of Oscillatory Transient

Oscillatory Transient. An oscillatory transient (Figure 5) is a voltage or current that changes polarity rapidly. Because the term "rapidly" is nebulous, the frequency content is used to divide oscillatory transients into three subcategories: high, medium, and low frequency. Frequency ranges from these classifications are chosen to coincide with common types of power system oscillatory transient phenomena.

As with impulsive transients, oscillatory transients can be measured with or without including the fundamental frequency. One way to trigger on transients is to continually test for a deviation in the waveform from one cycle to the next. This method will record any deviation exceeding the set threshold. When characterizing the transient, it is important to indicate the magnitude with and without the 60 Hz fundamental component.

Transients are generally caused by a switching event or by the response of the system to a lightning strike or fault. The oscillations result from interactions between system capacitances and inductances, and occur at the natural frequencies of the system excited by the switching event or fault.

High-frequency transients can occur at locations very close to the initiating switching event. Rise times created by closing a switch can be as fast as a few tens of nanoseconds. Short lengths of circuit have very high natural oscillation frequencies that can be excited by a step change in system conditions (e.g., operating a switch). Power electronic devices such as transistors and thyristors [i.e., silicon-controlled rectifiers (SCRs)] can cause high-frequency transients many times during each cycle of the fundamental frequency. The transients can be in the tens or hundreds of kilohertz, and occasionally higher.

Because of the high frequencies involved, circuit resistance typically damps transients out; thus, they only occur close (within hundreds of feet) to the site of the switching event that generates them. Characterizing these transients with measurements is often difficult because high sampling rates are required.

Medium-frequency transients are associated with switching events with somewhat longer circuit lengths (resulting in lower natural frequencies). Switching events on most 480 V distribution systems in a facility cause transient oscillations within this frequency range, which can propagate over a significant portion of the low-voltage system. Motor interruption (definite interruption) is a good example of a common switching event that can excite transients in this frequency range.

Transients coupled from the primary power system (e.g., coupled through the step down transformer) can also cause medium-frequency transients. The most common cause of transients on the primary power system is capacitor switching.

Capacitor energizing results in an initial step change in the voltage, which gets coupled through stepdown transformers by the transformer capacitance and then excites natural frequencies of the low-voltage system (typically 2 to 10 kHz). **Low-frequency transients** are usually caused by capacitor switching, either on the primary distribution system or within the customer facility. The lower-frequency transients result from capacitance of the switched capacitor bank oscillating with the inductance of the power system. The natural frequencies excited by these switching operations are much lower than those of the low-voltage system without the capacitor bank, because of the large capacitance of the capacitor bank itself.

Capacitor switching operations are common on most distribution systems and many transmission systems. Energizing a capacitor results in an oscillatory transient with a natural frequency in the range of 300 to 2000 Hz (depending on the capacitor size and the system inductance). The peak magnitude of the transient can approach twice the normal peak voltage (per unit), and lasts between 0.5 and 3 cycles, depending on system damping

Isolation transformers, voltage arresters, and/or filters can reduce transients.

Short-Duration Variations

Short-duration voltage variations are momentary changes in the fundamental voltage magnitude. Common causes are faults on the power system (short circuits between phases or from phase to ground). Depending on the fault location and system conditions, the fault can cause either momentary voltage rises (swells) or momentary voltage drops (sags). The fault condition can be close to or remote from the point of interest.

Sags. Sags are often associated with system faults but can also be caused by switching heavy loads or starting large motors (usually a longer-duration variation). Figure 6 shows a typical voltage sag that can be associated with a remote fault condition. For instance, a fault on a parallel feeder circuit (on the primary distribution system) will result in a voltage drop at the substation bus that affects all of the other feeders until the fault is cleared by opening a fuse or circuit breaker.

The percent drop in the RMS voltage magnitude and duration of the low-voltage condition are used to characterize sags. Voltage sags are influenced by system characteristics, system protection practices, fault location, and system grounding. The most common problem caused by voltage sags is tripping sensitive controls (e.g., adjustable-speed drives or process controllers), relays or contractors dropping out, and failure of power supplies to ride through the sag. Many types of voltage regulators are not fast enough to provide voltage support during sags, but ferroresonant transformers and some other line conditioners can provide some ride-through capability or can quickly compensate for deep sags.

In practice, sags are the type of power quality variation that most frequently causes problems. Fault conditions remote from a particular customer can still cause voltage sags that can cause equipment problems. Because there are no easy ways to eliminate faults on the power system, it will always be necessary for customers to consider the effects of sags.

Swells. Swells or **surges** can also be associated with faults on the primary distribution system (Figure 7). They can occur on nonfaulted phases when there is a single-line-to-ground fault.

Swells are characterized by their magnitude (RMS value) and duration. The severity of a voltage swell is a function of the fault location, system impedance, and grounding. On a three-phase ungrounded system (delta), the line-to-ground voltages on the sound phases will be 1.73 per unit (i.e., 1.73 times the normal line-to-ground voltage) during a single-line-to-ground fault condition. Close to the substation on a grounded system, there will be no voltage rise on the sound phases because the substation transformer is usually delta-wye, providing a low-impedance path for the fault current.

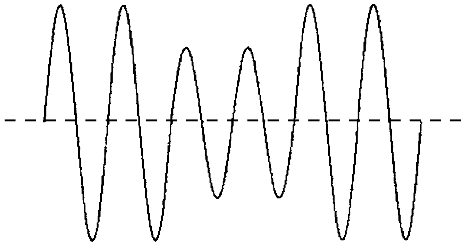

Fig. 6 Example of Sag

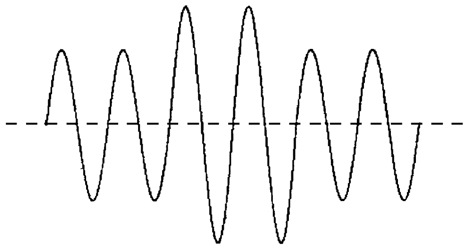

Fig. 7 Example of Swell (Surge)

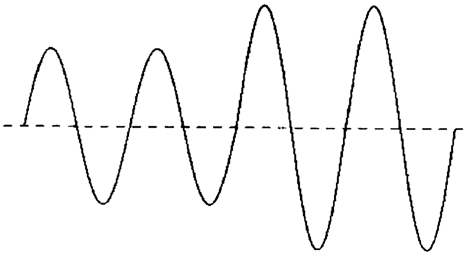

Fig. 8 Example of Overvoltage

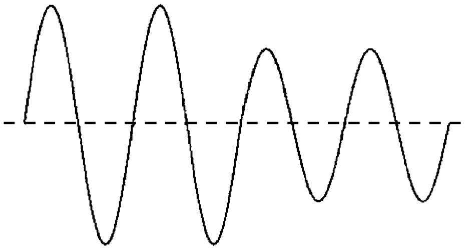

Fig. 9 Example of Undervoltage

Long-Duration Variations

Long-duration RMS voltage deviations generally do not result from system faults. They are caused by load changes on the system and system switching operations. The duration of these voltage variations depends on the operation of voltage regulators and other types of voltage control on the power system (e.g., capacitor controls, generator exciter controls). The time required for these voltage controllers to respond to system changes ranges from large fractions of a second to seconds. Long-duration variations can be overvoltages or undervoltages, depending on the cause of the variation. Voltage unbalance should be considered when evaluating steady-state or long-duration voltage variations. Unbalanced voltages can be one of the major causes of motor overheating and failure. With increasing emphasis on energy-efficient motors, requirements for voltage balance (i.e., limitations on negative sequence voltage magnitudes) may become even more important.

Overvoltages. Overvoltages (Figure 8) can result from load switching (e.g., switching off a large load), variations in system generation, or variations in reactive compensation on the system (e.g., switching a capacitor bank on). These voltages must be evaluated against the long-duration voltage capability of loads and equipment on the system. For instance, most equipment on the power system is only rated to withstand a voltage 10% above nominal for any length of time. Many sensitive loads can have even more stringent voltage requirements.

Long-duration overvoltages must also be evaluated with respect to the long-time overvoltage capability of surge arresters. Metal oxide variation (MOV) arresters in particular can overheat and fail due to high voltages for long durations (e.g., seconds).

Overvoltages can be controlled with voltage regulation equipment either on the power system or within a customer's facility. This can include various tap-changing regulators, ferroresonant regulators, line power conditioners, motor-generator sets, and uninterruptible power supplies.

Undervoltages. Undervoltages (Figure 9) have the opposite causes of overvoltages. Adding a load or removing a capacitor bank will cause an undervoltage until voltage regulation equipment on the system can bring the voltage back to within tolerances.

Motor starting is one of the most common causes of undervoltages. An induction motor will draw 6 to 10 times its full load current during starting. This lagging current causes voltage drops in the system impedance. If the started motor is large enough relative to the system strength, these voltage drops can result in a significant system undervoltage. The magnitude of this starting current decreases over a period ranging from 1 s to minutes, depending on the inertia of the motor and the load, until the motor reaches full speed. This type of undervoltage can be mitigated by using various starting techniques to limit the starting current and is largely self-corrected when the starting is completed. For more information, see the section on Motor-Starting Effects.

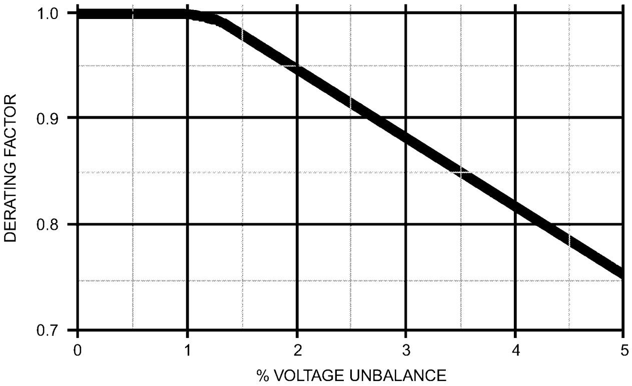

Fig. 10 Derating Factor Curve

Voltage Unbalance. Ideally, all phase-to-phase voltages to a three-phase motor should be equal or balanced. Unbalance between the individual phase voltages is caused by unbalanced loading on the system and by unbalances in the system impedances. Voltage unbalance is an important parameter for customers with motors because most three-phase motors have fairly stringent limitations on negative-sequence voltage (a measure of voltage unbalance), which is generated in the motor by unbalances in supplied voltages. Negative sequence currents heat the motor significantly. Voltage unbalance limitations (and steady-state voltage requirements in general) are discussed in ANSI *Standard* C84.1. The National Electrical Manufacturers Association (NEMA) has developed standards and methods for evaluating and calculating voltage unbalance. Unbalance, as defined by NEMA, is calculated by the following equation:

$$\text{\% Voltage Unbalance} = 100 \times \frac{\text{Maximum Deviation from Average Voltage}}{\text{Average Voltage}}$$

The motor derating factor caused by the unbalanced voltage curve from NEMA MG 1 shows the nonlinear relationship between the percent of voltage unbalance and the associated derating factor for motors (Figure 10). A balanced-voltage three-phase power supply to the motor is essential for efficient system operation. For example, a voltage unbalance of 3.5% can increase motor losses by approximately 15%.

Interruptions and Outages

Interruptions can result from power system faults, equipment failures, generation shortages, control malfunctions, or scheduled maintenance. They are measured by their duration (because the voltage magnitude is always zero), which is affected by utility protection system design and the particular event that is causing the interruption.

Interruptions of any significant duration can potentially cause problems with a wide variety of different loads. Computers, controllers, relays, motors, and many other loads are sensitive to interruptions. The only protection for these loads during an interruption is a back-up power supply, a back-up generator (requires time to get started) or a UPS system (can constantly be online).

Momentary Interruption. A typical momentary interruption lasts less than 3 s and occurs a during temporary fault, when a circuit breaker successfully recloses after the fault has been cleared (Figure 11). Lightning-induced faults will usually fall into this category unless they cause a piece of equipment (e.g., transformer) to fail.

Temporary Interruption. Temporary interruptions that last between 3 s and 1 min result from faults that require multiple recloser operations to clear, or require time for back-up switching to reenergize portions of the interrupted circuit (e.g., automatic throwover switches).

Power Failure/Blackout. Outages lasting at least 1 min are severe enough to be included in utility companies' reliability statistics. These failures are caused by fault conditions, maintenance operations that require repair crews, and emergency situations called blackouts (Figure 12).

Solutions involve using either UPS systems or back-up generators, depending on the critical nature of the load. UPS systems typically can provide uninterrupted supply for at least 15 min (based on battery capacity). This covers all momentary and temporary interruptions and provides sufficient time for an orderly shutdown. A UPS can be used in conjunction with a switching scheme involving multiple feeds from the utility to provide an even higher level of reliability. If back-up power is required beyond the capability of a UPS system, and multiple feeds are not realistic or adequate, then back-up generators are needed. Onsite generators are typically used in these applications.

Brownout. A brownout is a long-term voltage reduction, usually of 3 to 5%. This is an intentional reduction to reduce load under emergency system conditions.

Harmonic Distortion

Harmonic distortion of the voltage waveform occurs because of the nonlinear characteristics of devices and loads on the power system. These nonlinear devices fall into one of three categories:

- Power electronics
- Ferromagnetic devices (e.g., transformers)
- Arcing devices

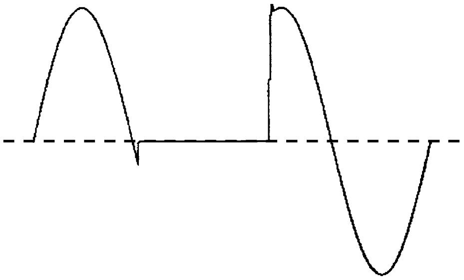

Fig. 11 Example of Momentary Interruption

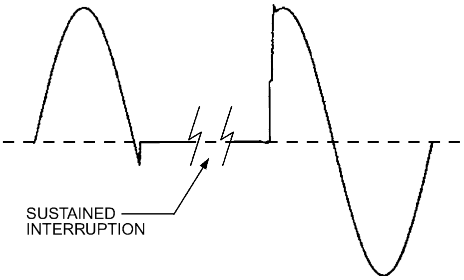

Fig. 12 Example of Blackout or Power Failure Waveform

These devices usually generate harmonic currents, and voltage distortion on the system results from these harmonics interacting with the system impedance characteristics. Harmonic distortion is a growing concern for many customers and for the overall power system because of the increasing applications of power electronic equipment. In many commercial buildings, electronic loads, such as computers and UPS systems, may be dominant in the facility. With more and more buildings switching to electronic ballasts for fluorescent lighting, an even higher percentage of the facility load falls into this category.

Harmonic distortion levels can be characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. However, it is more common to use a single quantity, the **total harmonic distortion (THD)**, as a single measure to characterize harmonic distortion of a particular waveform. It is important in general to distinguish between voltage distortion and current distortion because these quantities are handled differently in the standards and should be handled differently when performing measurements and interpreting data.

Voltage and current distortion is caused by the harmonic currents generated by nonlinear devices interacting with the impedance characteristics of the power system. A particular concern is when resonance conditions on the power system magnify harmonic currents and high-voltage distortion levels. Figure 13 illustrates the waveform with harmonic content.

Voltage Notches. A voltage waveform with notches (see Figure 4) caused by operating power electronics [e.g., adjustable-speed drives (ASD)] can be considered a special case that falls in between transients and harmonic distortion. Because the notching occurs continuously (steady state), it can be characterized through the harmonic spectrum of the affected voltage. However, frequency components associated with the notching can be quite high, and it may not be possible to characterize them with measurement equipment normally used for harmonic analysis. It is usually easier to measure with an oscilloscope or transient disturbance monitor.

Three-phase rectifiers (in dc drives, UPS systems, ASDs, etc.) with continuous dc current are the most common cause of voltage notching. The notches occur when the current commutates from one phase to another on the ac side of the rectifier. During this period, there is a momentary short circuit between two phases. The severity of the notch at any point in the system is determined by the source of inductance and the inductance between the rectifier and the point being monitored.

Often, an isolation transformer or ac choke (inductor) can be used in the circuit to reduce the effect of notching on the source side. The additional inductance will increase the severity of voltage notches at rectifier terminals (commutation time, or width of the notch, increases with increased commutation reactance); however, most of the notching voltage will appear across the ac inductor and notching will be less severe on the source side.

The steep voltage changes caused by notching can also result in ringing (oscillation) because of capacitances and inductances in the supply circuit. This oscillation can disturb sensitive controls connected to the affected circuit. The high frequencies involved can

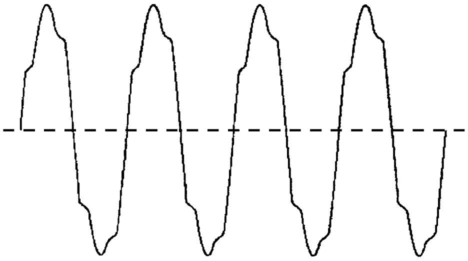

Fig. 13 Example of Harmonic Distortion

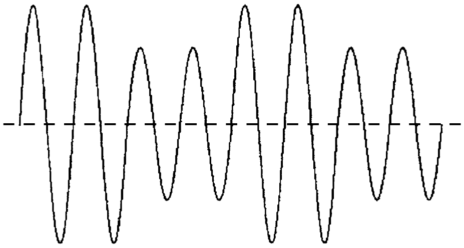

Fig. 14 Example of Flicker

also cause noise be capacitively coupled to adjacent electrical or communication circuits.

Voltage Flicker

Loads that vary with time, especially in the reactive component, can cause voltage flicker; the varying voltage magnitudes can affect lighting intensity. Arc furnaces are the most common cause of voltage flicker. The envelope of the 60 Hz variations is defined as the flicker signal *V*, and its RMS magnitude is expressed as a percent of the fundamental. Voltage flicker is measured with respect to sensitivity of the human eye. A typical plot of the 60 Hz voltage envelope characterizing voltage flicker is shown in Figure 14.

The characteristics of voltage flicker are mainly determined by load characteristics and the system short-circuit capacity. For a critical load, it may be necessary to provide a dedicated feed so that it is not on the same circuit with a major load that causes voltage flicker. Using fast switching compensation, such as a static voltampere-reactive (VAR) system, can mitigate the problem but is quite expensive. Another method is to effectively increase the short-circuit capacity at the point of common coupling with other loads by using a series capacitor. Protecting the series capacitor during fault conditions requires careful design.

Voltage flicker appears as a modulation of the fundamental frequency (similar to amplitude modulation of an AM radio signal). Therefore, it is easiest to define a magnitude for voltage flicker as the RMS magnitude of the modulation signal, which can be found by demodulating the waveform to remove the fundamental frequency and then measuring the magnitude of the modulation. Typically, magnitudes as low as 0.5% can result in perceptible light flicker if frequencies are in the range of 1 to 10 Hz. Flicker limitations are discussed in ANSI/IEEE *Standard* 146.

Light dimming, another type of light flicker, is caused by starting motors. Large single-phase motors and air conditioners have the undesirable effect of drawing several times their full load current while starting. This large current will, by flowing through system impedances, cause voltage sag that may dim lights.

Noise

Noise, a continuous, unwanted signal on the power circuits (Figure 15), can have a wide variety of different causes (e.g., switching, arcing, electric fields, magnetic fields, radio waves) and can be coupled onto the power circuit in a number of different ways. The noise source and susceptible circuit can be coupled by electric or magnetic fields or by electromagnetic interference (EMI).

The frequency range and magnitude of noise depend on the source that produces the noise. A typical magnitude of noise measured in the voltage is less than 1% of the RMS voltage magnitude. Noise of a large enough amplitude will disturb electronic equipment such as microcomputers and programmable controllers. Some noise can be eliminated by using isolation transformers; other noise requires filtering or line conditioners. Wiring and grounding practices can also significantly affect the noise levels at particular loads. The appropriate method for controlling noise depends on the methods of coupling, frequency range of the noise, and susceptibility of the equipment being protected.

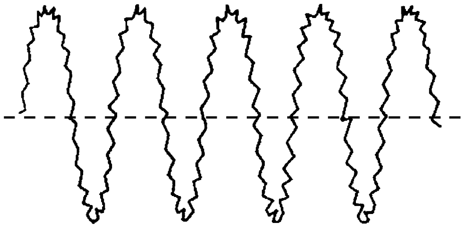

Fig. 15 Example of Electrical Noise

Inductive (Magnetic) Coupling. Magnetic fields induce currents in conductors. The magnetic fields are caused by current flowing in nearby power conductors, parts of circuits, data lines, or even building structure, and can be temporary or steady state. The actual coupled currents in power conductors and equipment conductors depend on the exposure (length of conductor in the field), angle between the conductor and the field, and magnetic field strength. Conductors carrying large currents and/or with large spacing between conductors can create strong 60 Hz magnetic fields that do not decay quickly with distance from the source. These fields can cause distortion on CRT or TV screens, and may interfere with sensitive electronic (especially analog) devices. During building design, steps should be taken to minimize the generation of strong magnetic fields, and to keep sensitive equipment well separated from these areas.

Current flow in the power system ground can be an important cause of magnetic fields because the loop area between the supply conductor and the return path through the ground can be very large. Therefore, grounding techniques to minimize noise levels can help reduce magnetic field problems. Magnetic shielding can also help.

Capacitive (Electrostatic) Coupling. Capacitive coupling between conductors results in coupling of transient voltage signals between circuits. Transient voltages with high-frequency components or high rates of rise are the most likely to be capacitively coupled between circuits (the coupling capability of a capacitor increases with frequency). Switch operations, arcing, lightning, or electrostatic discharge can cause these transients. Electric fields capacitively couple voltage between conductors. Strength is measured in volts per metre and may range from very slight to many kilovolts per metre.

High magnitudes of capacitively coupled voltages can affect normal operations of various types of electronic devices, or even cause discharges and damage. Possible solutions include applying shielding and coating, and improving design of power equipment to reduce the generation of high-transient-voltage conditions.

Electromagnetic Interference (EMI). EMI refers to interference caused by electromagnetic waves over a wide range of frequencies. Many interference sources start out as either strongly magnetic or strongly electric, but within about half a wavelength the fields convert to a balanced ratio of electric and magnetic fields (an electromagnetic field). Transients such as electrostatic discharge, arcing, contacts, power electronic switching, fluorescent lighting, and lightning cause electromagnetic waves. Steady-state EMI can occur in the form of radio frequency interference (RFI) from microwave and radar transmissions, radio and TV broadcasts, corona of high-voltage transmission line, arc welding, and other sources that generate radio-frequency electromagnetic waves. Although RFI is not destructive, it can cause a variety of malfunctions of susceptible electronic equipment and can disturb microcomputers and programmable controllers; the level of disturbance depends on the amount of RFI. Solutions include using appropriate shielding or filtering techniques.

MOTOR-STARTING EFFECTS

Light Dimming or Voltage Sags

Light dimming or voltage sag associated with motor starts can be more than a nuisance. Motors have the undesirable effect of drawing several times their full load current while starting. This large current, by flowing through system impedances, may cause voltage sag that can dim lights, cause contactors to drop out, and disrupt sensitive equipment. The situation is worsened by an extremely poor starting displacement factor, usually in the range of 15 to 30%. If the motor-starting-induced voltage sag deepens, the time required for the motor to accelerate to rated speed increases; excessive sag may prevent the motor from starting successfully. Motor-starting sags can persist for many seconds.

Motor-Starting Methods

The following motor-starting methods can reduce voltage sag from motor starts.

An **across-the-line start**, energizing the motor in a single step (full-voltage starting), provides low cost and allows the most rapid acceleration. It is the preferred method unless the resulting voltage sag or mechanical stress is excessive.

Autotransformer starters have two autotransformers connected to open delta (similar to a delta connection using three single-phase transformers, but with one transformer removed—carries 57.7% of a full delta load). Taps provide a motor voltage of 80, 65, or 50% of system voltage during startup. Starting torque varies with the square of the voltage applied to the motor, so the 50% tap will deliver only 25% of the full-voltage starting torque. The lowest tap that will supply the required starting torque is selected. Motor current varies as the voltage applied to the motor, but line current varies with the square of the tap used, plus transformer losses of ~3%.

Resistance and **reactance starts** initially insert an impedance in series with the motor. After a time delay, this impedance is shorted out. Starting resistors may be shorted out over several steps; starting reactors are shorted out in a single step. Line current and starting torque vary directly with the voltage applied to the motor, so for a given starting voltage, these starters draw more current than the line with autotransformer starts, but provide higher starting torque. Reactors are typically provided with 50, 45, and 37.5% taps.

Part-winding starters are attractive for use with dual-rated motors (220/440 V or 230/460 V). The stator of a dual-rated motor consists of two windings connected in parallel at the lower voltage rating, or in series at the higher voltage rating. When operated with a part-winding starter at the lower voltage rating, only one winding is energized initially, limiting starting current and torque to 50% of the values seen when both windings are energized simultaneously.

Delta-wye starters connect the stator in wye for starting, then after a time delay, reconnect the windings in delta. The wye connection reduces the starting voltage to 57% of the system line-line voltage, starting current and starting torque are reduced to 33% of their values for full voltage start.

BILLING RATES

Equipment specifications state how much electricity is used, but the cost of that electricity is usually the determining factor in HVAC system design and equipment selection. Electricity tariffs or rates set prices for

- How much electricity is used; energy (kWh)
- Rate at which electricity is used; demand (kW)
- Quality of electricity used; power factor (VAR)

Electric rates are contracts defining what the electricity user will pay for the amounts consumed. Rates may be cost-based, policy-based, or market-based. Designers should not assume that the types of rates will remain the same over the life of a building.

Cost-Based Rates

Cost-based rates are designed to charge each class of consumer based on the utility's cost to serve. Costs depend on the number of kilowatt-hours the customer uses, the maximum demand at which the customers uses electricity, and the times the customer uses electricity. A customer class is a group of electricity consumers whose usage characteristics are similar; each customer class has a different rate or tariff. Typical customer classes are residential, small commercial, large commercial, small industrial, large industrial, electric water heating, electric space heating, street lighting, etc. Cost-based rates are usually predicated on the following assumptions:

- The more electricity a customer uses the less it costs, per kilowatt-hour, to serve that customer.
- The higher the demand of a customer, the more it costs to serve that customer.
- It costs less per kilowatt-hour to serve a customer with a higher load factor. Load factor is defined as the customer's average demand divided by the peak demand, or the energy consumed in the billing period divided by the peak demand times the number of hours in the billing period. [LF = kWh/(peak demand × hours in billing period)]
- It costs less for a utility to deliver electricity at times of low system load than at times of high system load.

Energy Charge. The consumer pays the utility a fixed amount for every kilowatt-hour used. Small customers, especially residential, often simply pay for energy used. Certain loads may have usage profiles that allow the utility to provide electricity at times of low production costs (e.g., street lighting) or cost less per kilowatt-hour because the customer uses significantly more than a typical customer (e.g., electric space heating). Such loads are often metered separately and are charged a lower cost per kilowatt-hour than "general service" usage.

Fuel Adjustment Clause (FAC). A significant part of the cost of electricity is the fuel needed to generate it. In the 1970s, the price of primary energy sources (especially oil) became extremely volatile, and the fuel adjustment clause was designed to accommodate this without requiring frequent rate adjustments. Energy charges with FACs consists of 2 parts: a fixed charge per kilowatt-hour and a variable charge per kilowatt-hour that depends on the average price of fuel purchased by the power generator. During periods of low fossil fuel prices or high hydro runoff, the FAC will result in lower prices to the consumer.

Demand Charge. "Demand" is the maximum rate of use of electricity. It is expressed in kilowatt-hour and is typically measured over 15, 30, or 60 min periods. Demand charges are designed to cover the system capacity cost to deliver energy to a customer and/or the marginal generation cost to produce electricity at time of highest usage. To deliver electricity to a consumer, a utility must install wires, transformers, and meters; the higher the customer's projected demand, the larger the capacity of the wires and transformers serving the customer must be. From a systemwide perspective, the utility must also build enough generation and transmission capacity to serve the system load at its highest peak level. A non-coincident demand charge is a charge per kilowatt for the customer's maximum demand for electricity (in any 15, 30, or 60 min period) during the billing cycle. Noncoincident demand (NCD) charges are generally imposed to cover the cost to transform and deliver energy to the consumer. A coincident demand (CD) charge is a charge per kilowatt for the customer's maximum demand for electricity in any 15, 30, or 60 min period occurring during times of high system load. For example, in a summer-peaking utility, the demand charge may be applied only to the maximum demand occurring between 7:30 A.M. and 10:30 P.M. on weekdays from May to September. CD charges are designed to pay for additional generation and other system reinforcement costs needed to meet peak demands.

Ratcheted Demand Charge. Demand charges may be calculated based on the customer's maximum demand during each billing cycle, or the maximum demand during the 12 mo preceding the electricity bill. The latter is called a ratcheted demand charge because a high demand in one month "ratchets" the demand charge up for some or all of the following 11 months.

Seasonal Rate. Some utilities' generation costs vary significantly from one season to another. For example, spring runoff may yield more low-cost hydroelectric energy, or high summer air-conditioning loads may result in more power generation by less efficient plants. A seasonally adjusted rate reflects this by setting different kilowatt and/or kilowatt-hour charges for different seasons.

Time of Use (TOU) Rate. A utility's average production cost for electricity usually varies with the total system load. As demand increases, less efficient (i.e., more costly) generators are used. Increasing peak loads will also require that a utility invest in greater generation, transmission, and distribution capacity to meet the peak. A TOU rate is designed to recover the increased production or capacity costs during times of system peak. Electricity use is recorded by multiregister meters and priced at different levels, depending on whether the peak/off-peak or peak/shoulder/off-peak model was used. TOU rates are usually designed not only to "recover" time-differentiated production costs, but also to induce consumers to shift their electricity usage from peak periods to times of lower system load. In this way, TOU rates are both "cost-based" and "policy-based." Thermal energy storage (TES) systems are one method for consumers to reduce their on-peak demand or energy charges and to consume electricity during lower-cost, off-peak times. With TES, a consumer may use more total electricity but will pay less for it.

Declining Block Rate. In designing cost-based rates, the cost to serve is usually inversely proportional to the amount consumed. To reflect this, energy may be priced according to a declining block rate, where the cost per kilowatt-hour decreases as usage increases. For example, a residential customer may pay $0.12/kWh for the first 800 kWh used in a month, $0.10/kWh for the next 550 kWh, and $0.08/kWh for all electricity above 1350 kWh.

Demand-Dependent Block Rate. For larger customers, the size of the blocks of a block rate may depend on the measured demand. For example, a commercial consumer may pay $0.12/kWh for the first 75 kWh per kilowatt of billing demand, $0.10/kWh for the next 150 kWh per kilowatt of billing demand, and $0.08/kWh for every kWh above 225 kWh per kilowatt of billing demand.

Load Factor Penalty. Utilities recover their fixed costs (e.g., capital cost of a transformer) as well as production costs through energy (kWh) charges as well as demand charges. If a consumer's load factor is less than expected, then the utility's kilowatt-hour revenues may not be sufficient to recover its fixed costs. This may occur for a customer with self-owned onsite generation who relies on the utility mainly when the onsite generator is being maintained. In this case, the utility may impose a load factor penalty or surcharge.

Power Factor Penalty. A power system is more efficient and stable when all three phases are equally loaded (balanced) and serving pure resistive load (100% power factor). Some inductive loads, such as most lighting and motors, require reactive power, which may be more difficult and expensive for the utility to supply. Moreover, reactive power (VAR) is not always measured, and therefore not billed, by typical kilowatt-hour meters. Therefore, utilities often impose a power factor penalty or surcharge on customers with very reactive or inductive loads (power factor not close to 100%) to pay for the VARs that it must supply.

Customer Charge. This is a monthly charge that a consumer must pay, regardless of whether any electricity is used, for being a customer of a utility.

Connection Fee. When electric service is initiated, especially when construction is required (additional distribution line, a new substation, etc.), the utility may charge a connection fee. For example, a utility may charge a residential customer a fixed cost per foot of distribution line that must be constructed beyond an initial 500 ft of line. Some customers may require redundant facilities to ensure reliable service (e.g., a second feeder and load transfer switch for a hospital). The utility would probably include such costs in its connection fee.

Policy-Based Rates

Policy-based rates are designed to encourage consumers to modify their energy use to better conform with the objectives of the utility or regulatory body (e.g., using nonpolluting or renewable energy sources, deferring grid expansion or generator construction by shifting electricity demand from peak periods, better using waste heat from industrial processes, etc.). It can be argued that some policy-based rates are in fact cost-based, but they incorporate "externalities," or external costs that cannot be directly allocated to a consumer's electricity use. The time of use rate could fall under either category.

Inverted Block Rate. The marginal cost to provide an existing customer with additional energy decreases as energy use per kilowatt of connected load increases. However, additional energy use often hastens the need to construct new generation facilities. An inverted block rate motivates the consumer to reduce energy use by charging less for the first kilowatt-hour used. For example, a residential consumer may pay $0.08 for the first 850 kWh per month, $0.10 for the next 500 kWh, and $0.12 for all usage above 1350 kWh. As with the declining block rate, the break points between "blocks" may be based on the demand for that billing cycle.

Lifeline Rate. Lifeline rates are designed so poor consumers will still be able to afford necessary electricity (e.g., enough for refrigeration, lights, adequate heat in winter, etc.). A consumer pays a subsidized price per kilowatt-hour for a minimal amount of electricity and the market rate for any usage above the minimum (e.g., $0.04/kWh for the first 675 kWh and $0.12/kWh for usage above 675 kWh/month).

Net Metering. This is applicable for consumers who own their own onsite generation, still buy electricity from the grid, but sometimes can generate more electricity than is needed in their facility. Net metering is a contract where the customer pays the utility for the net electricity purchased (i.e., excess onsite generation is "sold" to the grid and offsets what the customer owes the utility for "purchases" from the grid).

"Green" Power Rate. Customers may sign up for blocks of electricity produced by renewable sources, such as wind turbines. Because of electricity from such sources usually costs more than electricity produced by conventional generation, the green energy is sold at a premium.

Market-Based Rates

Electric utilities are restructuring to disaggregate electricity production, transmission, and distribution and open the market to competition. The theory is that a competitive electricity sector, governed by market rules, will be more efficient, lower-cost, and more congruent with consumer needs than regulated monopolistic electric utilities. Market-based rates are not new, but they are becoming more prevalent. Rates tend to be volatile, and are structured as a contract between the consumer and energy supplier, rather than as a traditional tariff. As a result, they tend to be more customer-specific than uniform over a customer class.

Real-Time Pricing (RTP). Under this scheme, the cost of electricity varies with each hour. The supplier sets a price for electricity based on its forecasted cost to produce or provide the electricity. Hour-by-hour prices are communicated to the customer from 1 to 24 h in advance, and the consumer decides what, if any, action to take in response to the forecasted prices. The most common RTP programs send prices to consumers each evening, to cover the next day. Some programs send prices 4 h in advance, and several also allow 1 h alerts for "surprise" prices during system emergencies or forced outages. Consumers who were on a demand (kilowatt) and energy (kilowatt-hour) rate often are billed only for energy use (kilowatt-hour) on RTP, as the hourly energy cost incorporates the demand charge.

Spot Pricing. Consumers in some regions may purchase some or all of their electricity on the spot market, based on the current marginal cost of electricity. This is done through a power exchange, with the consumer either contracting directly with the exchange or going through a third-party electricity broker. Consumers may also purchase electricity through a combination of long-term contracts and spot market purchases.

Interruptible Rates and Responsive Loads. At times of high marginal electricity costs, it may be more cost-effective for a utility to pay its customers to reduce electricity consumption than to contract for additional electricity supplies. With interruptible rates, a consumer agrees to reduce power consumption to or below an agreed-upon level when requested to do so by the utility, in return for a lower price. The utility's requests are limited in number of times per year (or month) the consumer can be asked to reduce load, maximum duration of the load reduction, and minimum notice required (typically 1 to 4 h) before electric load is reduced.

Load Control. This is similar to interruptible load, but instead of the consumer's complying with the utility's request, the utility can exercise direct control over the consumer's appliances. Appliances commonly contracted for load control programs are water heaters, swimming pool pumps, air conditioners, resistance space heat, and controllable thermostats for HVAC systems. The tariff usually is in the form of a monthly rebate for each controllable appliance.

Performance-Based Rates. These are designed to ensure that the consumer receives acceptable quality and reliability of electric supply. The utility and consumer agree on a minimum standard for service quality in terms of number and duration of outages, voltage sags and swells, harmonic levels, or other transient phenomena. If these minimum service quality levels are not met, the utility must rebate money to the consumer; the amount rapidly increases as performance or service quality declines.

Performance Contracting. Performance contracting is a means where a consumer contracts with a third party to pay for the end-use applications of electricity. This usually involves an agreement where the performance contractor [often called an energy service company (ESCO)] installs and sometimes operates and maintains improved equipment for HVAC systems, lighting, building or process energy management, etc. The consumer's payments are indexed to successful equipment performance. That performance is often evaluated in terms of the facility's utility bills and calculated cost savings comparing the actual energy costs with estimates of what the costs would have been without the ESCO's intervention. A more detailed explanation of performance contracting is presented in ASHRAE *Guideline* 14-2002, Measurement of Energy and Demand Savings.

ELECTRICAL CODES

NEC®

The National Electrical Code® (NEC) is devised and published by the National Fire Protection Association, a consensus standards writing industry group. It is revised every three years. The code exists in several versions: the full text, an abridged edition, and the NEC Handbook (which contains the authorized commentary on the code, as well as the full text). It sets minimum electrical safety standards, and is widely adopted.

UL Listing

Underwriters Laboratories (UL), formerly an insurance industry organization, is now independent and nonprofit. It tests electrical components and equipment for potential hazards. When a device is UL-listed, UL has tested the device, and it meets their requirements for safety (i.e., fire or shock hazard). It does not necessarily mean that the device actually does what it is supposed to do. The UL does not have power of law in the United States; non-UL-listed devices are legal to install. However, insurance policies may have clauses that limit their liability in a claim related to failure of a non-UL-listed device. The NEC requires that a wiring component used for a specific purpose is UL-listed for that purpose. Thus, certain components must be UL-listed before inspector approval and/or issuance of occupancy permits.

CSA Approved

The Canadian Standards Association (CSA) is made up of various government agencies, power utilities, insurance companies, electrical manufacturers, and other organizations. They update CSA *Standard* C22.1, the Canadian Electrical Code (CEC), every two or three years.

The Canadian Standards Association (or recognized equivalent) must certify every electrical device or component before it can be sold in Canada. Implicit in this is that all wiring must be done with CSA-approved materials. Testing is similar to UL testing (a bit more stringent), except that CSA approval is required by law. Like the UL, if a fire is caused by non-CSA-approved equipment, the insurance company may not pay the claim.

ULC

Underwriters Laboratory of Canada (ULC) is an independent organization that undertakes the quarterly inspection of manufacturers to ensure continued compliance of UL listed/recognized products to agency reports and safety standards. This work is done under contract to UL, Inc.; they are not a branch or subsidiary of UL.

NAFTA Wiring Standards

Since the North America Free Trade Agreement (NAFTA) came into effect on January 1, 1994, CSA approval of a device is legally considered equivalent to UL approval in the United States, and UL listing is accepted as equivalent to CSA approval in Canada. Devices marked only with UL approval are acceptable in the CEC, and CSA approval by itself of a device is accepted by the NEC. This allows much freer trade in electrical materials between the two countries. This does not affect the electrical codes themselves, so differences in practice between the NEC and CEC remain.