

## CHAPTER 56

## ELECTRICAL CONSIDERATIONS

|                                                        |       |
|--------------------------------------------------------|-------|
| <i>Terminology</i> .....                               | 56.1  |
| <i>Safety</i> .....                                    | 56.1  |
| <i>Performance</i> .....                               | 56.2  |
| <i>Electrical System Components and Concepts</i> ..... | 56.2  |
| <i>Power Quality Variations</i> .....                  | 56.7  |
| <i>Billing Rates</i> .....                             | 56.13 |
| <i>Codes and Standards</i> .....                       | 56.15 |

**P**RODUCTION, delivery, and use of electricity involve 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, good design means fewer problems with tenant and building system interference (e.g., lighting or appliances in one suite disrupting computers in a neighboring suite).

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

## 1. TERMINOLOGY

**Electricity:** fundamental form of energy found in positive and negative forms and expressed in terms of the movement and interaction of electrons.

**Volt (V):** practical unit of electric pressure; the pressure that will produce a current of 1 A against a resistance of 1  $\Omega$ ; equal to 1 J/s. Also called the **electromotive force (emf)**.

**Current (I):** movement of electrons through a conductor; measured in amperes.

**Ampere (A):** practical unit of electric current flow. If a 1  $\Omega$  resistance is connected to a 1 V source, 1 A will flow.

**Alternating current (ac):** a current that reverses at regular, recurring intervals of time and that has alternately positive and negative values. The values vary over time in a sinusoidal manner.

**Direct current (dc):** a current where electrons move steadily in one direction.

**Watt (W):** unit of real electrical power, equal to the power developed in a circuit by a current of 1 A flowing through a potential difference of 1 V.

**Volt-ampere (VA):** amount of apparent power in an alternating current circuit equal to a current of 1 A at an emf of 1 V. It is dimensionally equivalent to watts. Volt-ampere is equal to watts when voltage and current are in phase.

**Volt-ampere-reactive (VAR):** unit for reactive power. The symbols  $Q$  and sometimes  $N$  are used for the quantity measured in VARs. VARs represent the power consumed by a reactive load (i.e., when there is a phase difference between applied voltage and current).

**Power factor:** for an ac electric power system, the ratio of the real power to the apparent power, or W/VA.

**Three-phase power:** supplied by three conductors, with the currents (or voltages) of any two 120° out of phase with each other.

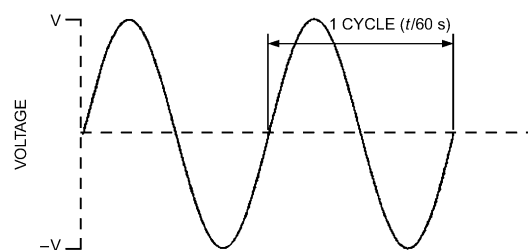


Fig. 1 Fundamental Voltage Wave

**Y (or “wye”) connection:** a configuration of wiring so that each winding of a polyphase transformer (or three single-phase transformers) is connected to a common point, the “neutral.”

**Delta-connected circuit:** 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).

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

**Cycle:** 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 60 cycles in 1 second.

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

**System voltage:** 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:** the voltage at the point where the electric systems of the supplier and the user are connected.

**Utilization voltage:** the voltage at the terminals of the utilization equipment.

**Nominal system voltage:** the rated system voltage level (i.e., 480 volts) at which the electrical system normally operates. To allow for operating contingencies, utility systems generally operate at voltage levels within –5% to +5% of nominal system voltage.

## 2. 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.

The preparation of this chapter is assigned to TC 1.9, Electrical Systems.

### 3. PERFORMANCE

In the United States, the *National Electrical Code*® (NEC; NFPA *Standard 70*) 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 affect occupants' productivity for the life of the building. Many improvements over the minimum requirements are relatively inexpensive to implement during building construction.

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 building occupant's equipment. 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 in 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 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 and harmonic distortion are often the causes of the problem. **Dedicated circuits** usually solve the voltage drop problem, but harmonic distortion must be solved at the contributing loads. 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 large load that interferes with smaller, more sensitive 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&R systems, and communications facilities are susceptible to disruption and vulnerable to damage.

### 4. ELECTRICAL SYSTEM COMPONENTS AND CONCEPTS

Voltage differential causes electrons to flow. In a direct current (dc) electrical system, electrons flow in only one direction. In an alternating current (ac) electrical system, electrons continually alternate or change direction at a prescribed number of times per second. The main disadvantage of dc voltage is its inability to be boosted or attenuated easily and efficiently. The alternating magnetic fields of ac make boosting or decreasing voltage with transformers feasible, which is why ac has been widely adopted. Electrons flow more efficiently at lower currents because  $I^2R$  losses are minimized. For the

same load, raising the voltage level reduces the current while delivering the same power. When long distances are involved, electric utility companies step up voltages to very high levels for transmission. However, these voltages are extremely dangerous, so they must be stepped down to a safer, lower, usable voltage before use. Transformers offer an efficient way to change voltage levels (step-up or step-down) for an alternating current power source.

#### Electrical Wiring (Conductors for General Wiring)

Just because a conductor is insulated does not mean it is suited for a specific application. NFPA *Standard 70* list designations of wires and cables that meet minimum fire, electrical, and physical requirements of relevant standards. Unless otherwise specified by codes, conductors must be aluminum, copper-clad aluminum, or copper.

To find allowable ampacities for insulated conductors at various temperatures, consult Tables 310.15(B)(16) to 310.15(B)(20) of NFPA *Standard 70*-2014. Tables 310.15(B)(2)(a) and 310.15(B)(2)(b) of that standard have correction factors for ambient temperatures other than 86 or 104°F. If more than one ampacity could apply for a given circuit, use the lowest value.

#### Transformers

Transformers are used to change one voltage to another voltage, typically to step up voltage levels from generators. Power can then be transmitted at a low current (with less loss). At the end of the transmission line, a step-down transformer reduces the voltage to a usable level.

A transformer consists of a ferromagnetic core wrapped with multiple coils, or windings, of wire. The input line is connected to the primary coil, and the output line is connected to the secondary coil. Alternating current  $I_1$  in the primary coil induces an alternating magnetic flux  $\phi$  that flows through the ferromagnetic core, changing direction during each electrical cycle. This flux in turn induces alternating current  $I_2$  in the secondary coil. The voltage  $V_2$  at the secondary coil is directly related to the primary voltage by the turns ratio (i.e., the number of turns  $N_1$  in the primary coil divided by the number turns  $N_2$  in the secondary coil).

An **ideal transformer** with two windings wrapped around a magnetized core is shown in Figure 2. The ideal model for a transformer assumes  $I^2R$  losses, core losses, leakage flux, and core reluctance are insignificant. A practical model includes these losses.

Transformer **losses** can be divided into core (or iron) losses, copper losses, and stray losses. Core losses include hysteresis losses and eddy current losses. All ferromagnetic materials tend to retain some degree of magnetization after exposure to an external magnetic field. This tendency to stay magnetized is called hysteresis, and it takes energy to overcome this opposition to change every time the magnetic field produced by the primary winding changes polarity. Eddy current losses result from induced currents circulating in the

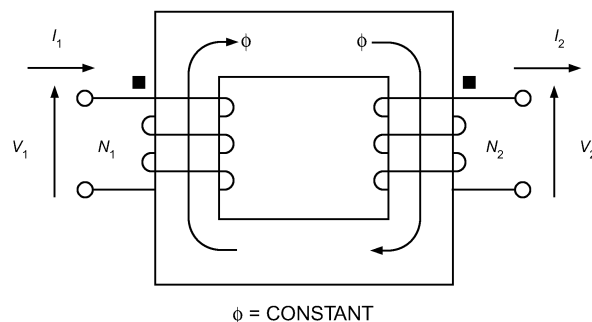


Fig. 2 Ideal Transformer

magnetic core perpendicular to the flux. Because iron conducts both electricity and magnetic flux, eddy currents are induced in the iron just as in the secondary windings from the alternating magnetic field.

Three identical single-phase, two-winding transformers may be connected to form a **three-phase bank**. The four possible connections are Y-Y, Y-Δ, Δ-Y, and Δ-Δ. The U.S. standard for marking three-phase transformers uses  $H_1$ ,  $H_2$ , and  $H_3$  on the high-voltage terminals and  $X_1$ ,  $X_2$ , and  $X_3$  on the low-voltage terminals;  $A$ ,  $B$ , and  $C$  identify phases on the high-voltage side of the transformer, and  $a$ ,  $b$ , and  $c$  identify phases on the low-voltage side. Typically, three-phase voltages present the higher voltage (phase-to-phase) first, followed by the lower voltage (phase-to-neutral). Single-phase voltages typically present the lower voltage (phase-to-neutral) first, followed by the higher voltage (phase-to-phase). For example, 208/120 V is three-phase and 120/240 V is single-phase.

Y-Y connections (Figure 3) are rarely used because of balancing and harmonics problems.

Y-Δ connections (Figure 4) are typically used for stepping down from high to medium voltage.

The Δ-Y transformer (Figure 5) is commonly used as a generator step-up transformer, where the Δ winding is connected to the generator terminals and the Y winding is connected to the transmission line. One advantage of the high-voltage Y winding is that a neutral point N is provided for grounding on the high-voltage side.

The Δ-Δ transformer (Figure 6) has the advantage that one phase can be removed for repair or maintenance while the remaining

phases continue to operate as a three-phase bank. The open Δ connection allows balanced three-phase operation with the kVA rating reduced to 58% of the original bank. These Δ-Δ connections are typically used in distribution networks.

An **autotransformer** has two windings connected in series (Figure 7). Whereas a typical transformer's windings are only coupled magnetically via the mutual core flux, an autotransformer's windings are both electrically and magnetically coupled.

An autotransformer has smaller per-unit leakage impedances than a two-winding transformer; this results in both smaller series

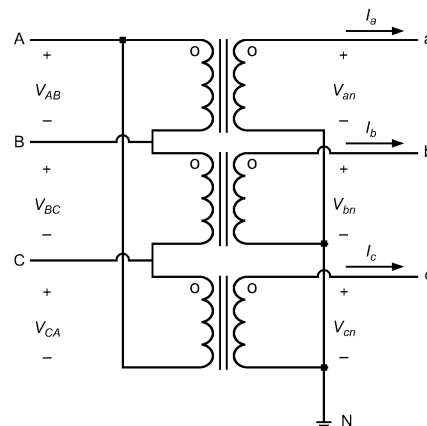


Fig. 5 Three-Phase Δ-Y Transformer

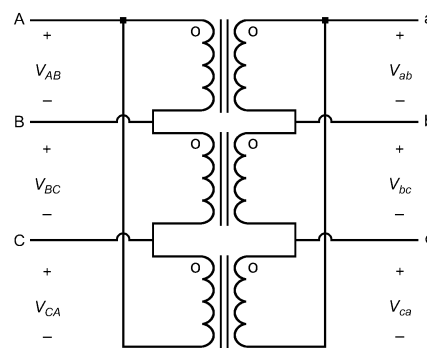


Fig. 6 Three-Phase Δ-Δ Transformer

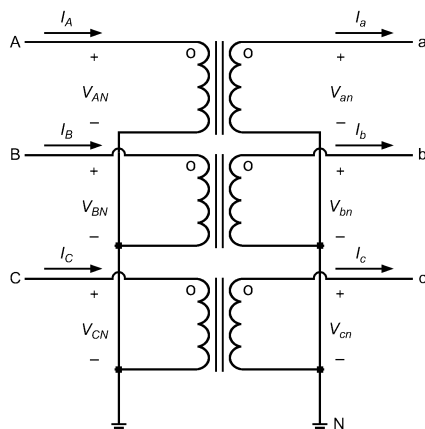


Fig. 3 Three-Phase Y-Y Transformer

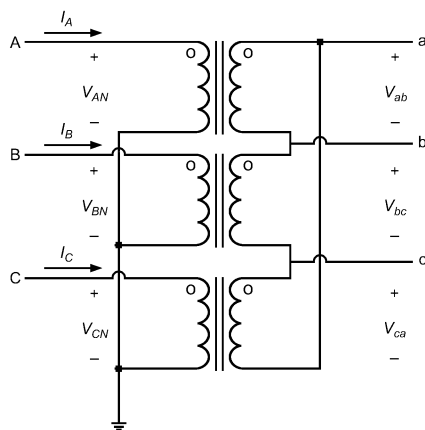


Fig. 4 Three-Phase Y-Δ Transformer

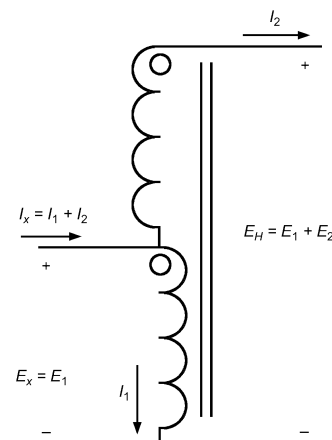


Fig. 7 Typical Autotransformer

voltage drops and higher short-circuit currents. It also has lower per-unit losses, lower excitation current, and lower cost, if the turns ratio is not large. An autotransformer is not isolated as well as a typical two-winding transformer; transient overvoltages pass through the autotransformer more easily because the windings are connected electrically.

**Transformer Coolants and Insulators.** Because heat is created by the flow of electrical current through the windings, a liquid (e.g., oil or silicone) is often used as a coolant inside the transformer. Such liquids are also good electrical insulators for the wire windings and iron core. **Dry transformers** do not require a liquid for cooling, instead using ambient air for cooling as well as insulation. Dust, dirt, moisture, and other contaminants in the air can reduce its insulating capabilities and deteriorate exposed parts, and may cause premature failure of the transformer.

## Emergency and Standby Power Systems

**Emergency Power Systems.** IEEE *Standard* 446-1995 defines these systems as independent reserves of electrical power that automatically take over if the usual supply experiences an outage or failure, and sustain mission-critical systems (i.e., those that, if inoperable, could present a danger to health and safety, or to property). Local or national codes may also mandate specific systems as required emergency power systems.

**Standby Power Systems.** Generally, these systems provide power back-up for loads that may be critical to production or product preservation, but do not present a danger to life or safety. They allow facilities to carry on with satisfactory operation during failure or outage of the usual supply source. NFPA *Standard* 70 distinguishes between those that are legally required and those that are optional.

**Emergency and Standby Power Supplies.** Diesel generators are still the dominant source of emergency power, particularly for emergency loads such as fire pumps or elevators that require large starting currents and must meet the outage's full capacity at start-up. Some natural gas engines meet the start-up requirements for emergency systems, and are popular for smaller standby applications such as homes, communication towers, and other operations where diesel fuel is undesirable and/or impractical. Some turbines are also used for standby service, but most turbines are dedicated to combined heat and power (CHP) applications (see Chapter 7 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*).

The use and constraints of emergency and standby power systems must be understood to ensure proper safety and operation of the electrical equipment they support. This is especially true with emergency systems and with standby systems that are expanded to carry the full facility load, including HVAC&R systems. Starting and load step capabilities also must be understood when replacing diesel engines with natural gas engines and turbines, which have very different acceptable load step characteristics.

Most codes require emergency generators used for life-safety loads to be online within 10 s. However, age, battery wear, and even improper exercising of the engine can cause delays and even failures to start. Even if the engine does start within 10 s, some type of ride-through device may be required to support electronic loads (including computers and energy management systems) until the generator starts and picks up the load.

National mandates on emissions, and state and local implementation of those mandates, also influence the generator type specified. In the United States, Environmental Protection Agency (EPA) tier ratings are required for off-road engine permits, including for generators. U.S. EPA (2012) addresses emissions of oxides of nitrogen (NO<sub>x</sub>), hydrocarbons (HC), particulate matter (PM), and carbon monoxide (CO). Earlier tier ratings limited diesel use to emergency applications in most cases, but the new tier 4 ratings allow their use for standby and CHP applications.

Another variable that must be considered with all generation equipment are the potential derates caused by elevation and weather. Combustion air has a direct effect, but of varying degrees, on the energy that can be generated during combustion. Ways to overcome these derates include precooling or humidifying the combustion air. It is important to find out from a manufacturer what the derating characteristics are and the cost in equipment and consumables for any correction system selected.

**Uninterruptible power supply (UPS) units** are most commonly used to keep computers and controls running during the transition from outage to generator operation. Batteries are sized to meet the load requirement for a specified period of time (frequently about 15 min). The UPS provides power through the interruption and, if generators fail to start, provides enough time for orderly system shutdown.

**Flywheel** technology is gaining ground where larger (e.g., whole-building) loads are supported. The flywheels are also sized for time and load, but may be cost prohibitive for orderly shutdown and even for engines that do not start until the second or third try (20 to 30 s). They are only rarely used to support a natural gas engine that may take between 1 to 3 min to start.

**Impedance** of emergency and standby power supplies is usually higher than that of utility electric service. Thus, power quality of a circuit typically deteriorates when it is switched from regular utility power to emergency power.

A key component of the emergency generator system is the automatic transfer switch (ATS) used to switch from the primary source (usually the utility) to the secondary source (usually the generator). The type of switch selected has important ramifications to the overall electrical system. The types of automatic transfer switches are as follows:

### Standard ATS (Figure 8)

- *Break-* (from one source) *before-make* (to another source) design.
- Mechanically interlocked electrical contactors move loads from one power source to another.
- Most can optionally be equipped for delayed transition (switch delays in the neutral position for a preset number of seconds). This allows larger (>50 hp) motors' residual voltage to decay before connection to the other source. Other timers are usually available to provide ride-through for one or two recloser operations (used by utilities to keep their system operational during momentary faults caused by falling limbs, high winds, etc.).
- An *in-phase monitor* can be preset and used in conjunction with or in place of the delayed transition to protect large motors during the transfer process.
- Can be two-, three- or four-pole, depending on phase and grounding scenario.
- Results in at least two momentary power outages: when utility service is lost and when the system switches back to the utility.

### Closed-Transition ATS (Figure 9)

- Provides momentary (less than six cycles) connection of load to both power sources within acceptable phase angle for seamless transfer when both sources are available.

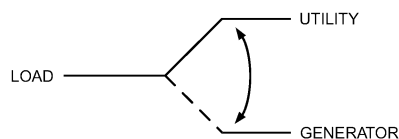


Fig. 8 Break-Before-Make Design for Standard ATS

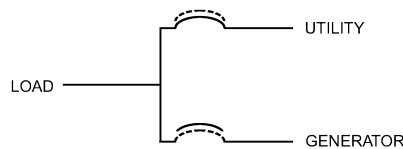


Fig. 9 Closed-Transition ATS

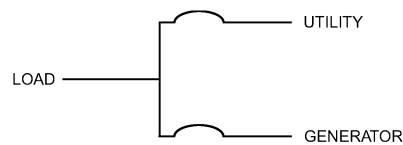


Fig. 10 Parallel-Transfer Switch

- Eliminates the second outage associated with a standard ATS and, in some cases, can be used to operate the generator as a peaking power source.

#### Bypass-Isolation ATS

- Same as a standard ATS except for its separate bypass mechanism to allow continuation of power to the load from either source while isolating the automatic switch device for maintenance or repair. Typically, the automatic portion of the switch can be mechanically isolated from the frame during this process.
- All other features of the standard ATS apply.
- Closed-transition and bypass-isolation can be combined to provide the capabilities of both.

#### Service-Entrance-Rated ATS

- Transfer switch includes a circuit breaker or fused device ahead of the transfer mechanism, allowing the device to act as the service-entrance point for building load.
- Fused protection can also be provided ahead of the secondary (generator) entrance point, but is normally omitted in lieu of locating the protection (circuit breaker) at the generator set.
- Can include any or all of the other ATS features listed in standard, closed-transition, or bypass-isolation types.

#### Parallel-Transfer (PT) Switch (Figure 10)

- Parallel switchgear in a simple one- or two-breaker design allows for parallel connection of the load to both power sources for an indefinite time period.
- Should include all protective relay devices as required by the local utility and generator supplier.
- Can include some of the features of a standard ATS, because most can also be operated as an open-transfer (break-before-make) switch.

Switch selection can profoundly affect the electrical system, especially if an existing back-up system is upgraded for an expanded role. For example, it may be necessary to completely replace the existing switchgear of a building if an original generator system with a small generator and a standard ATS is replaced with a larger generator and a closed-transition ATS.

If the emergency power system is being expanded to include large motor loads, such as chillers, then

- Set delay to account for chiller motor back current to dissipate.
- Size the generator set large enough to handle the motor loads' starting current requirements. The electrical engineer needs to know the starting requirements and maximum allowable voltage drop that the overall electrical system can handle, especially computer and control loads. Most major generator manufacturers can provide sizing software.

If a standard ATS is being replaced with a closed-transition or parallel-transfer switch,

- Verify that the existing switchgear can handle the added potential fault current of the generator set. For instance, if the available fault current from the utility is 65,000 A and the generator fault current is 30,000 A, then the system only has to be braced for 65,000 A with a standard ATS. It has to be braced for 95,000 A with either of the other two switches because fault current is additive with multiple sources connected at the same time.

If the emergency power system is being converted from diesel to natural gas, then

- Check the acceptable load steps of the new engine: the diesel likely accepted 100% load, but the natural gas engine may be limited to as low as 20% load. Chillers and other large loads frequently exceed the acceptable load increase.
- Determine whether large-motor-load starting systems can be changed to reduce starting requirements and meet acceptable load steps.

If the emergency system is being modified for peaking or curtailment uses, then

- Obtain the specific utilities' interconnection requirements; these tend to be utility-specific and may exceed normal NEC or local codes.
- Check the existing system for closed-transition or parallel-transfer switch issues and compatibility.
- Investigate emissions issues; standby emissions permit requirements are almost always less stringent than peaking requirements.

If the emergency system includes a UPS or flywheel system, then

- Size the UPS or flywheel for the maximum required load for a specific time; remember that capacity of these systems is  $x$  kW for  $y$  min.
- Avoid motor loads as much as possible.

## Motors

**Motor Control and Protection.** Chapter 45 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* addresses motor control and protection in detail, but is summarized and simplified here. Motor control must be effective without damaging the motor or its associated equipment. Control must be designed to prevent inadvertent motor starting caused by a fault in the control device. The control should be able to sense motor conditions to keep the motor windings from getting too warm.

Motor protection involves sensing motor current and line voltage, and can include bearing vibration, winding temperature, bearing temperature, etc. Motor temperature increase has two basic sources. Heating occurs when dirt or debris blocks airflow over or through the motor, or it comes from the motor current and is commonly referred to as  $I^2R$ , where  $I$  is motor current and  $R$  is motor winding resistance. Because the current is squared, its contribution is exponential.  $R$  is quite small and contributes a linear function to heating (and therefore temperature rise) in the motor. Motor windings can withstand temperature rise, depending on the motor winding temperature rating. The second source of motor temperature increase is lack of motor cooling. The primary source of cooling is moving air, usually from a shaft-driven fan. As a motor slows down, the fan runs more slowly; therefore, the less air movement, the less cooling. Because fan loads are also exponential, a small decrease in motor speed greatly reduces airflow on the motor, reducing cooling. To compound the issue, the slower the motor runs, the greater the slip, and the greater the motor current. This then becomes a vicious circle.

**Motor Starters and Thermal Overloads.** Motor starters energize (start), deenergize (stop), protect, and control the motor. They sense

motor current based on a time curve: the shorter the time, the more current they let through. They may also limit the number of motor starts in a given period of time so the motor does not exceed its ANSI rating. Another cause for concern is the starter's ambient temperature: if it is different from the ambient temperature around the motor controller, the thermal overloads need to be sized accordingly.

Several motor starter types are available, and they can function several different ways. The **across-the-line** starter is the simplest but may disturb electric service because of high motor-starting current requirements. Other starters reduce and may eliminate troublesome electrical disturbance; for instance, the **part-winding**, **reduced-voltage**, and **wye-delta** starters all act by reducing the starting voltage on the motor. Fan and pump loads can usually be started this way; this reduces starting current draw and demand, but sacrifices motor starting speed. **Soft-start** starters also reduce the voltage and limit demand during starting, thereby easing stress on the electric system during motor starting. **Variable-frequency drives (VFDs)** are also used to soft-start a motor, and are designed to control acceleration during starting as well as optimize motor speed to its load. See the section Motor-Starting Methods for more information.

A VFD converts ac to dc and then back to variable-frequency, variable-voltage ac. Motor speed is varied by varying the frequency of the ac output voltage, typically using pulse-width modulation (PWM). This power conversion process results in distorted input current and may contribute to building power system voltage distortion. When motors and other loads are supplied from a distorted voltage source, their operating temperatures may rise.

**Phase Loss Protection.** Phase loss can be detected by sensing either voltage loss or current loss on one of the phases. Motor overloads often are set based on the nameplate data of the motor, but the real motor current draw is less because the motor may not be fully loaded. If one of three phases is lost, the current increases in the other two phases, but not by enough to trip the overloads. However, it will overheat and possibly damage the motor. Some phase loss detectors also check phase current to be sure that it is balanced within 10%. This protects the motor and makes the operator aware of potential motor or line problems.

**Motor-Starting Effects.** The following effects do not occur with all motors. For instance, brushless dc and inverter-driven motors, which are electronically controlled, do not have inrush currents that cause light dimming or sags.

**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.

The Illuminating Engineering Society of North America (IESNA) is precise in describing lighting reactions. *Dimming* is an intentional technique to enhance the ambiance of surroundings by varying the perceived lighting levels. It is also used to reduce the electrical power used by lamps when adequate natural lighting is available; the controller electronically follows the natural variations in a way that will not be optically perceived. Similarly, *flicker* is deliberately selected in some lamps to resemble a candle's flame. In contrast, this chapter discusses possible causes of *undesirable, perceptible* reductions of a lamp's lumen output.

Momentary undesirable lighting reductions from voltage sags, often caused by motor starting, were common with incandescent

lamps. More efficient lamps (especially fluorescent and electronic ballasts) are now the most common for most applications. For fluorescent lamps, electronic ballasts convert the 60 Hz electrical service to much higher frequencies, which eliminates perception of irritating flicker, and provides greater lumens per watt than the former magnetic ballasts. Similar improvements have occurred for mercury, metal halide, and sodium lamps, typically found in large stores, sports, and industrial applications. Including electronic circuitry in the lamps and lighting systems makes power quality even more important for building owners: electronic components are sensitive to both lower and upper threshold voltages, and the building's voltage may experience momentary voltage sag as large motors start. Specific product literature for lamps, lamp ballasts, and lighting controls should be reviewed to ensure client satisfaction with expected operations (starts, stops, and speed changes) of the HVAC system's motors and controls.

**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 start-up. Starting torque varies with the square of the voltage applied to the motor, so the 50% tap delivers 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%.

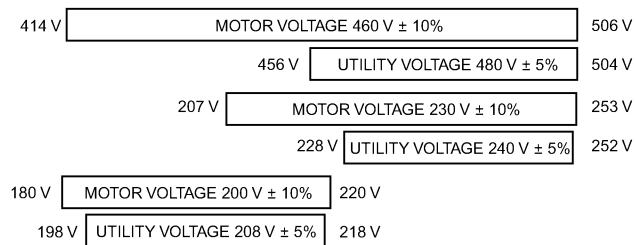
**Resistance and reactance starts** initially insert impedance in series with the motor. After a time delay, this impedance is shorted out. Starting resistors may be shorted out over several steps; starting reactors are shorted out in a single step. Line current and starting torque vary directly with 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.

## 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 also indicates 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



**Fig. 11 Utilization Voltages Versus Nameplate Ratings**

tolerance range of the equipment: better performance can be obtained over the tolerance range specified in ANSI *Standard* 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 *Standard* C84.1 are based on ANSI/NEMA *Standard* MG 1, Motors and Generators edition, which establishes voltage tolerance limits of the standard low-voltage induction motor at  $\pm 10\%$  of nameplate voltage ratings of 230 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 11 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 continues 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 480Y/277 V, three-phase. 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/208Y/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 all phases of the primary system.

Where the supplying utility furnishes the distribution transformers, the choice of voltages is limited to those the utility provides. 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 208Y/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 208Y/120 V systems are often more economical for large apartment buildings. Single-phase 120/240 V systems should be satisfactory for small apartment buildings and other small buildings.

However, large single-phase appliances, such as electric ranges and water heaters rated for use on 120/240 V single-phase systems, will not perform to the rated wattage on a 208Y/120 V systems, because the line-to-line voltage is appreciably below the rated voltage of the appliance.

## 5. 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 effects 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 swells, and interruptions.

**Steady-State Variations.** Changes in 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 time duration to a voltage flicker, and it is not useful to assign a spectral frequency 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 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 12 and 13). Impulsive transients are often characterized simply by 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. Repetitive subtractive transients (Figure 13), often caused by thyristors such as silicon controlled rectifiers (SCRs), are referred to as voltage notches.

The high-frequency components and 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 transient's peak magnitude and duration (or volt-seconds). 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 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.

**Oscillatory Transient.** An oscillatory transient (Figure 14) 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 deviation in the waveform from one cycle to the next. This method records 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 system response 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/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.

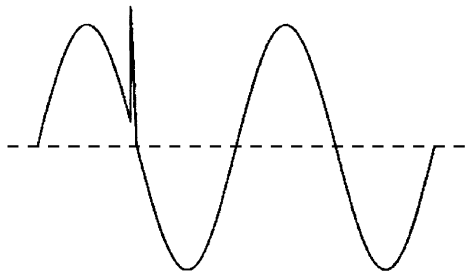


Fig. 12 Example of Spike

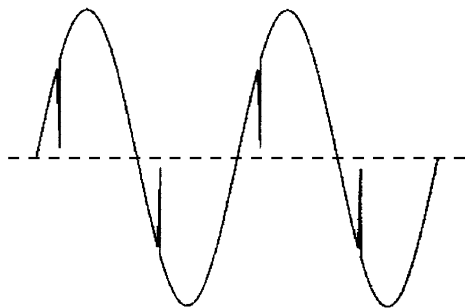


Fig. 13 Example of Notch

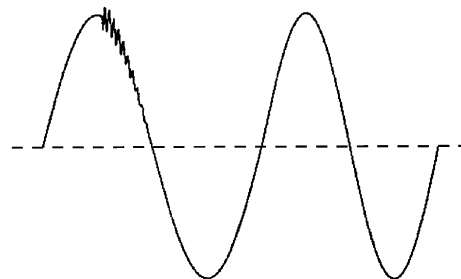


Fig. 14 Example of Oscillatory Transient

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. 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 (Figure 15) 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 15 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) results 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 contactors 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 is always necessary for customers to consider the effects of sags.

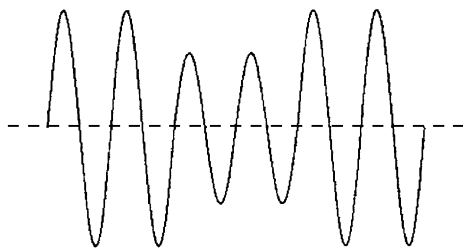


Fig. 15 Example of Sag

**Swells.** Swells or **surges** can also be associated with faults on the primary distribution system (Figure 16). They can occur on non-faulted 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 fault location, system impedance, and grounding. On a three-phase ungrounded system (delta), the line-to-ground voltages on the ground phases are 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 is no voltage rise on the ground phases because the substation transformer is usually delta-wye, providing a low-impedance path for the fault current.

### 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 17) 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).

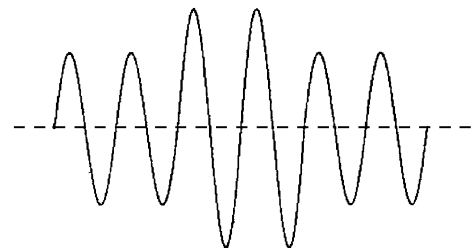


Fig. 16 Example of Swell (Surge)

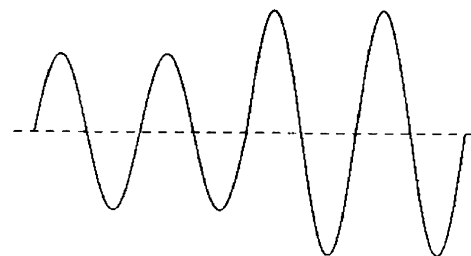


Fig. 17 Example of Overvoltage

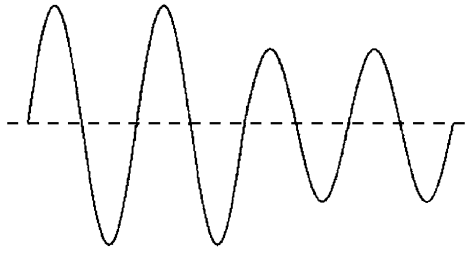


Fig. 18 Example of Undervoltage

Overvoltages can be controlled with voltage regulation equipment either on the power system or in 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 18) 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 draws 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 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.

**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) 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 *Standard* MG 1 shows the nonlinear relationship between the percent of voltage unbalance and the associated derating factor for motors (Figure 19). 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

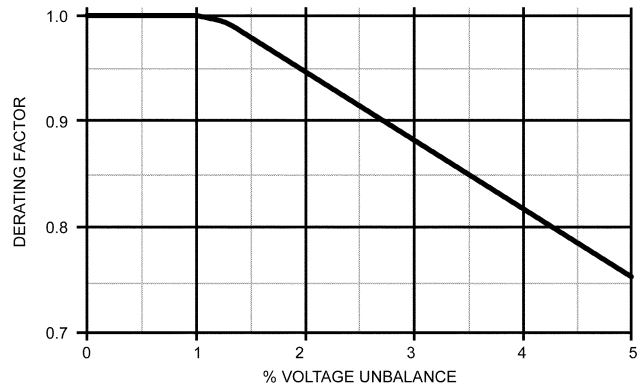


Fig. 19 Derating Factor Curve

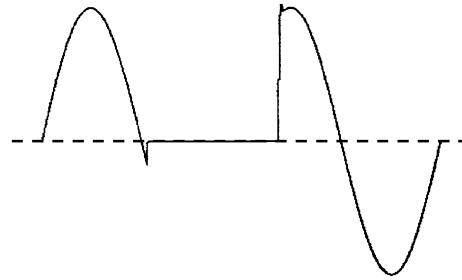


Fig. 20 Example of Momentary Interruption

protection system design and the particular event 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 (Figure 20) lasts less than 3 s and occurs during a temporary fault, when a circuit breaker successfully recloses after the fault has been cleared. Lightning-induced faults 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 (Figure 21) 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.

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. On-site 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

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 (nonlinear) loads, such as variable-frequency drives, computers, and UPS systems, may be dominant in the facility, especially as more buildings switch to electronic ballasts for fluorescent lighting.

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)**, 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 distortion is caused by the harmonic current emissions of nonlinear devices interacting with the impedance characteristics of the power system. Harmonic current distortion results in elevated true RMS current, which increases  $I^2R$  losses and elevated peak current. Because harmonics flow at frequencies higher than the fundamental frequency (e.g., 180 Hz, 300 Hz, 420 Hz), additional losses are experienced because of the reduction of conductor effective cross-sectional area, a phenomenon known as **skin effect**. These losses are attributed to  $I^2X_L$  at each harmonic frequency.

A particular concern is when resonance conditions on the power system magnify harmonic currents and high-voltage distortion levels. The natural resonance of the power system varies based on system inductance and capacitance and should be evaluated when adding nonlinear devices (equipment) or power factor capacitors to the system. Capacitors offer a low-impedance path to harmonic frequencies and can therefore attract harmonics, often resulting in reduced life, fuse blowing, or capacitor failure. Figure 22 illustrates the voltage waveform with harmonic content. Figures 23 and 24 illustrate distorted current waveforms.

Harmonic distortion can be reduced by adding an ac line reactor or harmonic filter at the input of individual nonlinear loads (Figure 25). A 5% impedance line reactor typically reduces

harmonic distortion for three-phase nonlinear loads to about 35% of the fundamental current.

Harmonic current distortion can be reduced to levels of 5 to 8% total harmonic current distortion, at the individual load, using a typical low-pass harmonic filter (Figure 26). The benefit of reducing harmonics right at the contributing load is that the entire upstream power system benefits from reduced levels of current and voltage distortion.

**Voltage Notches.** A voltage waveform with notches (see Figure 13) caused by operating power electronics, especially where SCRs are involved [e.g., adjustable-speed drives (ASDs)], can be considered a special case that falls in between transients and harmonic distortion. Because notching occurs continuously (steady state), it can be characterized by 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 SCR rectifiers (those typically 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

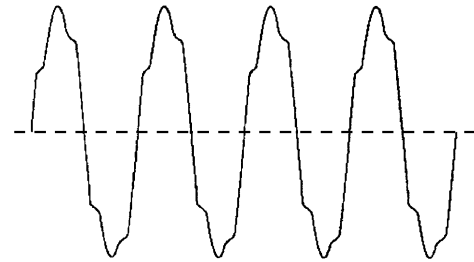


Fig. 22 Example of Harmonic Voltage Distortion

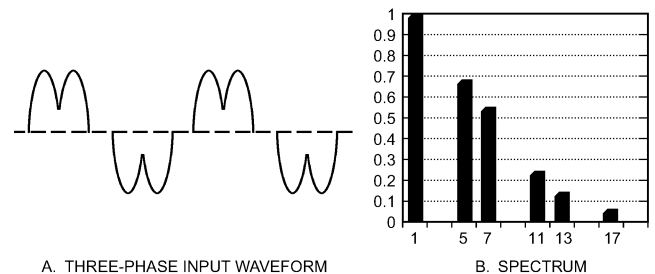


Fig. 23 Example of Harmonic Current Distortion for Six-Pulse Rectifier with 5% Impedance Reactor

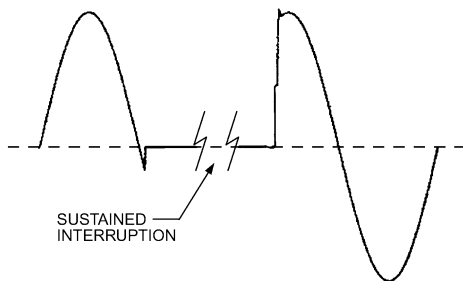


Fig. 21 Example of Blackout or Power Failure Waveform

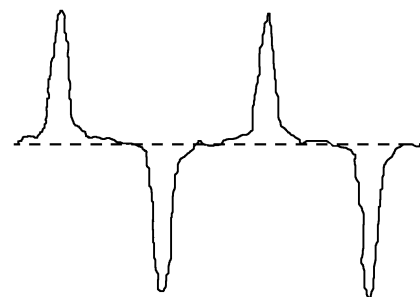


Fig. 24 Example of Harmonic Current Distortion for One-Phase Input Current for Single Personal Computer

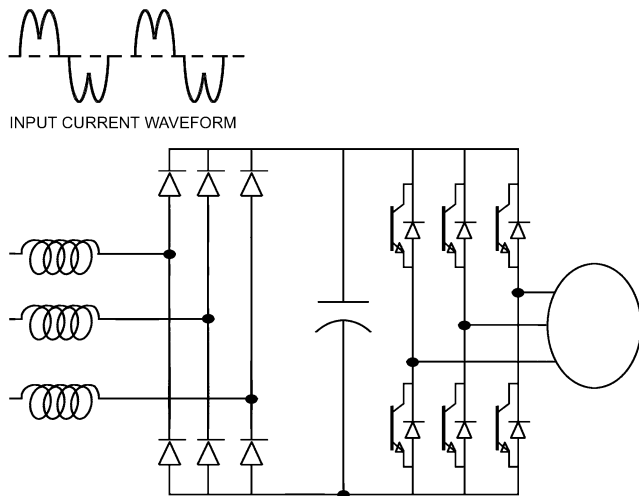


Fig. 25 Example of VFD with ac Line Reactor

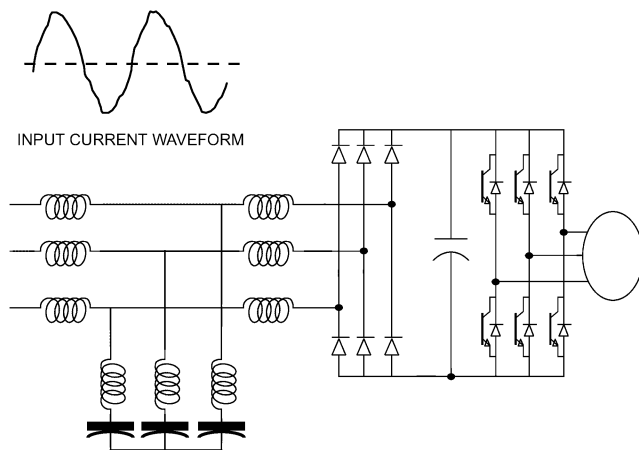


Fig. 26 Example of VFD with Low-Pass Harmonic Filter

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 3% impedance ac line reactor (inductor) can be used in the circuit to reduce the effect of notching on the source side. The additional inductance increases the severity of voltage notches at the rectifier terminals (commutation time, or width of the notch, increases with increased commutation reactance); however, most of the notching voltage appears across the ac inductor and notching is less severe on the source side, where other equipment shares a common voltage source.

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 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

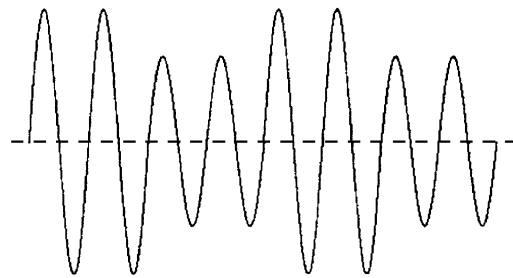


Fig. 27 Example of Flicker

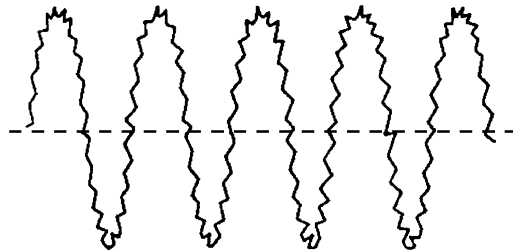


Fig. 28 Example of Electrical Noise

voltage flicker. The envelope of the 60 Hz variations is defined as the flicker signal  $V_f$  and its RMS magnitude is expressed as a percentage 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 27.

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 volt-ampere-reactive (VAR) system or dynamic VAR compensation system, can mitigate the problem. 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- or three-phase motors, as used in air conditioners, have the undesirable effect of drawing 6 to 10 times their full load current while starting. This large current, by flowing through system impedances, causes voltage sag that may dim lights.

### Noise

Noise, a continuous, unwanted signal on the power circuits (Figure 28), 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 with enough amplitude disturbs electronic equipment such as microcomputers and programmable controllers. Some noise can be eliminated by using an isolation transformer with an electrostatic shield; other noise requires EMI filtering or line conditioners. Wiring and grounding practices 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.

**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 exposure (length of conductor in the field), angle between conductor and 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 such as radio-controlled equipment, energy and building automation systems, photoelectric sensors, test and measurement equipment, and data processing equipment. During building design, take steps to minimize 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. To minimize interference, power conductors should always be physically separated from control circuit conductors. 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. To minimize interference, power conductors should always be physically separated from control circuit conductors.

**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.

## 6. BILLING RATES

Equipment specifications state how much electricity is used, but the cost of that electricity is usually the determining factor in HVAC&R 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 or kVAR)

Electric rates are contracts defining what the electricity user will pay for the amounts consumed. Rates may be based on cost, policy, market, or a combination of cost/policy and market. Additionally, rates may be based on either kW or kVA demand. Designers should not assume that the types of rates will remain the same over the life of a building, and owner/operators should review with their utility about potential rate changes that might lower cost or improve reliability.

### Cost-Based Rates

Cost-based rates are designed to charge each class of consumer based on the utility's cost to serve that class. Costs depend on kilowatt-hours used, maximum demand, and time of day at which electricity is used. A customer class is a group of electricity consumers whose use characteristics are similar; each customer class has a different rate or tariff. Typical customer classes are residential, multifamily, 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 a customer's demand, 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 LF 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.  $[LF = \text{kWh used in the billing period} / (\text{peak demand} \times \text{hours in billing period})]$
- 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). These 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 consist of two 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, for example, the FAC results in lower prices to the consumer. Many utilities embed part of the fuel cost in the rate tariffs and include the remaining variable portion in the FAC.

**Demand Charge.** "Demand" is the maximum rate of use of electricity. It is expressed in kilowatts (kW) or kilovolt-amperes (kVA) and is

typically measured over 15, 30, or 60 min periods. For example, 1 kWh used in 15 min is equal to 4 kW demand (1 kWh/0.25 h). 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 wires and transformers serving the customer must be. From a system-wide perspective, the utility must also build enough generation and transmission capacity to serve the system load at its highest peak level. A **noncoincident demand (NCD) 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 charges are generally imposed to cover the cost to transform and deliver energy to the consumer. A **coincident demand (CD) charge** (also known as a **peak or on-peak demand 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 11:30 AM and 6:00 PM 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 current or previous 11 months preceding the electricity bill. 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 peaking 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 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 is 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 the same or 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 on-site generation who relies on the utility mainly when the on-site 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 (kVAR) 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, usually fixed charge that a consumer must pay, regardless of whether any electricity is used, for being a customer of a utility. This charge typically covers customer services such as the costs of billing, metering, and customer support services, such as call centers.

**Connection Fee.** When electric service is initiated, especially when construction (additional distribution lines, substations, distribution transformers, etc.) is required, 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 legislative 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 demand for that billing cycle.

**Lifeline Rate.** Lifeline rates are designed so lower-income consumers will still be able to afford necessary electricity (e.g., enough for refrigeration, lights, adequate heat in winter, etc.). For example, 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 on-site generation, still buy electricity from the grid, but sometimes can generate more electricity than is needed in their facility. Net metering is a contract in which the customer pays the utility for

the net electricity purchased (i.e., excess on-site 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 solar photovoltaic (PV) or wind turbines. Because electricity from such sources usually costs more than electricity produced by conventional generation, the green energy is sold at a premium.

**Surcharges.** Government agencies may add special surcharges to electric bills to provide funding for specific energy-related or general-purpose programs. For example, in the United States, many state governments collect public benefit funds through electric bills to provide money for energy efficiency, renewable energy, low-income weatherization, and research programs. Other surcharges may be for power plant upgrades or putting electric distribution lines underground. Surcharges can be fixed or charged on a per-kWh basis. Some surcharges may be capped at a specific dollar amount per type of customer.

**Taxes.** Government agencies may collect sales and other specific taxes through utility bills. The taxes may be calculated as a percentage total of the entire bill, or on a per-kWh basis (such as \$0.001 per kWh). For some customers, taxes and surcharges may comprise a significant portion of the total bill.

### 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, is more efficient, lower cost, and more congruent with consumer needs than regulated 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, because the hourly energy cost incorporates the demand charge. The RTP may only apply to the generation portion of the electric bill if transmission and distribution charges are still regulated.

**Fixed Pricing.** Some consumers in a deregulated market may opt for fixed prices for their electric supply. In these situations, the consumer may pay a price that is higher or lower than the RTP or spot prices. With this type of pricing, the burden of price risk goes to the supplier, who may charge a risk premium to the customer.

**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 (or go off-line) when requested to do so by the utility, in return for a lower price. The utility's requests may be 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. In other cases, there is no limit to the number or length of utility requests.

**Direct 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, heat pumps, resistance space heat, and controllable thermostats for HVAC&R systems. The tariff usually is in the form of a monthly rebate or fixed bill credit 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. In some cases, the rate, or type of rate charged, may not change, but customers receive bill credits or rebates based on a reduction in the electric company's rate of return.

**Performance Contracting.** In performance contracting, 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&R systems, lighting, building or process energy management, etc. The consumer's payments are indexed to successful equipment performance, which 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.

## 7. CODES AND STANDARDS

### NEC®

The *National Electrical Code*® (NEC; NFPA *Standard* 70) 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.

### IEEE

The Institute of Electrical and Electronic Engineers' *Standard* 519 suggests limits for both harmonic current and voltage distortion, based on electrical system conditions.

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