BY DAVID LOHBECK • NATIONAL INSTRUMENTS

Hazardous-voltage primer

UNDERSTANDING THE HAZARDS ASSOCIATED WITH VOLTAGE AND KNOWING THE PRINCIPLES OF SAFETY AND THE IMPORTANCE OF CERTIFICATION ARE THE KEYS TO SAFE DESIGN AND PRODUCT USE. EVEN LOW VOLTAGE IS HAZARDOUS AND CAN DAMAGE PRODUCTS AND HARM USERS.

It is common knowledge that wall-outlet voltages of 120V in the United States and 230V in Europe can cause severe shock or death, but did you know that many people consider 120 and 230V to be low-voltage? Believe it or not, according to most standards, voltages less than or equal to 1000V are low. Voltages greater than 1000V are high and are not commonplace in the typical home or workplace. More specifically, peak voltage greater than 42.4V is hazardous; voltage less than or equal to 42.4V, or SELV (safety extra-low voltage), is nonhazardous. It is difficult to know when electricity can cause serious injury or be fatal. Contact for only 1 to 3 sec with currents of only 6 to 200 mA can cause electrocution by disrupting the normal rhythm of heart muscles, resulting in fibrillation and leading to death. An example of how little voltage or current it takes to electrocute a person is the 120V/15W nightlight. Drawing 125 mA, this seemingly innocuous everyday object has enough voltage and current to put it well within the danger zone. **Table 1** lists the standard ranges for low and high voltages.

Figure 1 A switch failure at the Eldorado substation in Boulder City, NV, sent this 100-foot long, 500-kV arc into the air (courtesy Stoneridge Engineering, www.teslamania.com).

TABLE 1 VOLTAGE TERMS AND VALUES

Range	Voltage term[1]	Value[1]	Description
Low	Safety extra-low voltage[2]	≤42.4V peak or ≤60V dc	"Safe," user-touchable secondary circuit designed and protected to remain under safe voltage levels in normal operation and under single fault; double insulation
Low	Extra-low voltage[2]	≤42.4V peak or ≤60V dc	Secondary, nontouchable circuit separated from hazardous voltage by basic insulation; not safety extra-low voltage or limited-current circuit and not fault-tolerant
Low	Low voltage[3]	≤1 kV ac	"Hazardous-voltage" circuit, such as primary circuit connected to low-voltage-mains supply, such as 120/230V ac[6]
High	Medium voltage[4]	>1 kV ac to 100 kV ac	"Distribution grid" from substations distributed to residences and commercial buildings
High	High voltage[4]	≥100 kV ac to ≤230 kV ac	"Transmission-grid" long-distance transmission-line voltage with typical maximum distances of approximately 300 miles (483 km)
High	Extra-high voltage[5]	>230 kV ac to ≤800 kV ac	"Transmission-grid" long-distance transmission-line voltage with typical maximum distances of approximately 300 miles (483 km)
High	Ultrahigh voltage[5]	>800 kV ac to 2 MV ac	"Transmission-grid" long-distance transmission-line voltage with typical maximum distances of approximately 300 miles (483 km)

[1] Terms and values are for illustration and may vary between standards.
[2] IEC 60950-1 and other standards.
[3] NEC-NFPA 70 low voltage=600V; ANSI/IEEE low voltage=1 kV ac; European Union's Low-voltage Directive: low voltage 50V to 1 kV ac, 75 to 1500V dc.
[4] ANSI C84.1 and IEEE 100.
[5] IEEE 1312 and IEEE 100.
[6] Hazardous voltage is greater than 30V rms and 42.4V peak or 60V dc. Test-and-measurement products are greater than 33V rms and 48.7V peak or 70V dc. National deviations may exist.

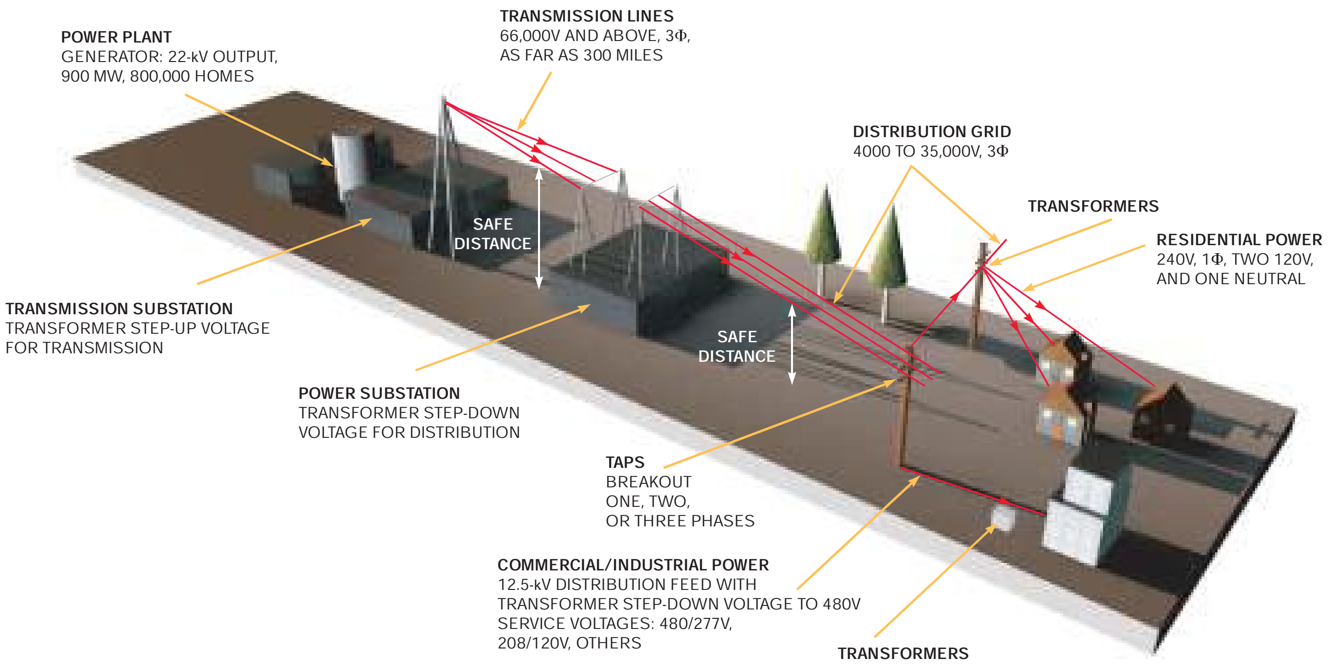

Figure 2 The typical power-distribution system includes multiple voltage levels and transmission standards.

Electricity kills or injures more than 1000 people a year in the United States. Voltages of 100 to 250V ac in wall outlets are the most common and can be lethal. This voltage range can cause significant current flow through the body. Outdoor electricity involves high voltages in which the duration of contact can be significant enough to cause deep burns and cardiac arrest. Electrical current travels at the speed of light, approximately 186,000 miles/sec, and follows the path of least resistance to ground. The human body is approximately 70% water and makes an excellent conductor. Human-body resistance varies depending on how well you are grounded, your age, your size, and your gender. The amount of perspiration on your body also affects your resistance; more perspiration increases your vulnerability. To illustrate how a 120V wall-outlet voltage can affect a person, you divide the 120V voltage by the resistance to yield the current. For a high body resistance, dividing 120V by 100 kΩ yields 1.2-mA current. For medium and low body resistance, divide the 120V by 10k and 1 kΩ, respectively, yielding 12 and 120 mA, respectively. At 1.2 mA, a human body would be on the threshold of feeling a tingling sensation; at 12 mA, the human body would feel the beginning of a freezing, or "can't-let-go," feeling. At 120 mA, the feeling would be extreme pain and possible ventricular fibrillation.

Current follows the path of least resistance to ground. Arteries, nerves, and muscles have low resistance, whereas bone, fat, and tendons have relatively high resistance. The human brain, heart, and nervous system are the most sensitive. These body parts feel a shock with a current as low as 0.5 mA. For hand-to-foot currents higher than 5 mA, a victim can't free himself from the source. Even if the jolt throws a victim free of the power source, he can go into respiratory arrest, cardiac arrest, or both. Currents greater than 20 mA may deliver a lethal shock (**Table 2**). Jolts higher than 1A throw the heart into a contraction; internal body heating is significant. Thermal burns may result in death or the loss of a limb long after the incident.

TABLE 2 THRESHOLD AND UL LIMITS FOR CONTINUOUS 60-Hz CURRENT AND THEIR EFFECTS

Physiological effect	Reaction	Threshold for continuous 15- to 100-Hz current (mA)	UL-specified limit for continuous 60-Hz sinusoidal current (mA)
Involuntary muscular reaction	Perception level, tingling sensation	0.5	0.51
Inability to let go (tetanized muscle)	Painful shock, freezing current, inability to let go	10	5
Ventricular fibrillation	Heart rhythm affected, death may occur	35	20

Notes:

1. Ordinarily, a limit of 0.75 mA applies to stationary or fixed cord-connected products with equipment-grounding connectors.

2. IEC Publication 479 describes data in the third column.

The factors that determine the severity of an electrical hazard and its effect on the human body are voltage, current, resistance, frequency, duration, and pathway. Voltage forces current to flow, which can damage the heart or brain or cause involuntary muscle contractions. Current determines the extent of the damage and can cause heating of external and internal human-body tissues and organs. Human-body resistance varies depending on how dry or moist the body is and on the current's path through the body. Current passing though the arm generates more thermal damage than through the abdomen because the arm has a smaller cross-sectional area than the abdomen. Frequency also influences the danger; ac causes more ventricular fibrillation than dc, but both can lead to injuries. Duration affects the severity of heating human tissues and organs; the longer the contact, the greater the damage. A 60% chance of mortality exists for a hand-to-hand current pathway through the heart, and 20% mortality exists for a hand-to-foot path. An old adage says to place one hand in your pocket when working near hazardous electricity so that current does not pass through your chest. A better recommendation is not to touch hazardous voltages!

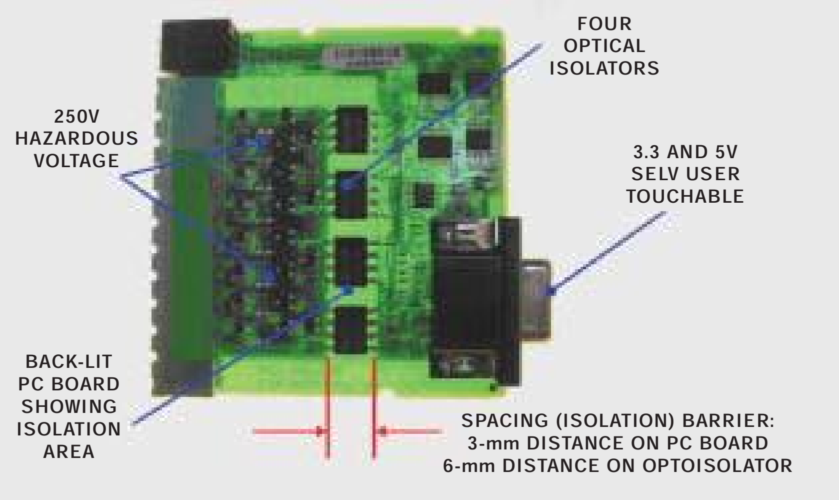

Figure 3 If a capacitor short-circuits in the 5V-dc circuit of a pc-board assembly, the voltage is safe, and the current is only 0.5 mA during normal operation.

Electrical injuries can result from direct contact with electrical energy; electricity arcs, or "flashover," through the air to a person or object; burns from hot surfaces or burning materials; and muscle contractions or startled reactions from falling, dropping a product, or similar scenarios. Direct contact with electricity is the most obvious and commonly encountered danger. Direct contact occurs when someone touches a hazardous, or "live," voltage: greater than 30V rms and 42.4V peak or 60V dc. Proper insulation and distance help protect people from direct contact.

Electricity arcs emanate from lightning strikes, motor startups, and line surges. Staff at the Eldorado substation (Boulder City, NV) captured one such extra-high-voltage electric arc. When one of two switches fails to open, an air break switch opens "hot," resulting in a 500-kV arc more than 100 feet long (**Figure 1**). Burns come from surfaces heated by excessive current flow. Touchable surface limits are typically 70°C (158°F) for metals and 80°C (178°F) for plastics. Excessive power consumption can also generate enough heat to cause a fire that expands beyond the product to its surroundings.

POWER DISTRIBUTION AND SAFE DISTANCE

Electricity starts at a power plant with nuclear reactors or steam turbines burning coal, oil, or natural gas to drive the plant generators. These generators provide three-phase ac power that steps up to high voltage for long-distance transmission, and power substations step down the transmission voltages for the distribution grid. The grid distributes three-phase medium voltage, which typically ranges from 4 to 35 kV. Finally, transformers step down the distribution voltage to less than 1 kV for use in

Figure 4 Without proper current limiting, a shorted capacitor in the 5V-dc circuit of a pc-board assembly can start a fire within seconds (a). After 30 sec, the fire has caused considerable damage (b), destroying the pc board and connector (c).

Figure 5 Product-certification marks are independent, third-party evidence of compliance and are mandatory in some localities.

homes and commercial buildings. In some areas, the distribution lines are underground with transformers typically above ground (**Figure 2**).

The wires on the large steel towers are transmission lines. Extra ground wires sometimes run along the tops of these towers in an attempt to attract lightning, so that it does not travel to the grid and buildings' electrical installations. Distribution lines are at the top of the poles running along roads and are easy to spot because they hang between porcelain insulators. Taps on these poles break out one, two, or three lines to run in different directions. Ground wires running between poles connect to a bare grounding wire that runs down each pole, which is buried six to 10 feet into the earth. Additional wires lower on these poles provide connections for phone, cable TV, or other purposes. Power lines are noninsulated, and what appears to be insulation on some wires is only weatherproofing. Towers and poles separate people and structures from dangerous power lines. The minimum safe distance from persons and structures to power lines is 3m.

GENERAL PRINCIPLES OF SAFETY

Applying the general principles of safety and meeting safety standards are the minimum requirements for compliance with safety laws and meeting consumer expectations. Engineers should design products that meet safety principles, standards, and the latest state of safety technology. Sometimes, product designs must exceed safety standards, such as in cases in which standards do not cover technologies, materials, or construction methods or industry practice has identified a new safety principle. Product designers must consider normal operating conditions as well as likely fault conditions, consequential faults, foreseeable misuses, and external influences, such as temperature, altitude, pollution, moisture, and overvoltages.

The principles of safety are safe design, protective measures, and warnings. You should specify safe design and construction criteria that eliminate or reduce hazards as much as possible. If you cannot implement safe design and cannot eliminate the risks, take the necessary protective measures, such as employing guarding or protective devices. After you have exhausted all other means, inform users of any shortcomings using warnings about residual risks and the need for safeguards, such as training and personal-protection equipment.

When designing products for safety, designers must consider both users and service persons. Typically, users have no access to the hazards that exist in service-access areas, such as behind secured covers. Users are not trained to identify hazards and do not intentionally place themselves in a hazardous situation. Service persons are trained to avoid injury from obvious hazards but should still be protected against unexpected hazards. Manufacturers can achieve this goal by locating parts requiring service away from electrical and mechanical hazards, providing guards to limit accidental contact, and providing warnings or instructions to caution personnel about residual risks. They can place service warnings on the product or document them, depending on the likelihood and severity of injury.

User instructions should focus on avoiding misuse and situations likely to create hazards, such as connection to wrong power source and incorrect fuse replacement. User warnings indicate that a product has some residual risks. Some manufacturers misunderstand when they should apply warnings and use them in place of safe designs. User warnings may be unjustified and therefore violate safety standards and laws, such as when safe design is possible or when a standard does not permit a warning. Safe design is the highest priority and the best way to protect users and ensure that a product remains safe during normal operation, under fault conditions, and with foreseeable misuse.

Users must be safe during reasonably foreseeable misuse, which is use of a product in a way the manufacturer did not intend but could have predicted as a consequence of human behavior. For example, products must remain safe even if a user sets adjustments, knobs, or controls in a way that differs from the instructions. Manufacturers must consider or foresee how a user could misuse a product and design products that are safe in such cases, not relying on user warnings to limit the manufacturers' liability.

Products must provide protection against electric shock and fire risk during normal operation and during a fault. Some products use power supplies with high-power outputs, which, when a fault occurs, can cause current to increase dramatically. For example, if a capacitor short-circuits in the 5V-dc circuit of a pc-board assembly, the voltage is safe, and the current is only 0.5 mA during normal operation (**Figure 3**). However, current rises to more than 20A after the capacitor fault occurs, starting a fire within seconds on the pc board (**Figure 4**). The fire extinguishes itself in a couple of minutes. You can imagine what damage could occur in only a couple of minutes if the fire spread outside the product. It is important to evaluate all electrical circuits and to design products with fusing or circuit breakers to limit shock and fire hazards (**references 1** and **2**).

PRODUCT CERTIFICATION

Standards developers write most specifications out of concerns for the safety of life, property, and the environment.

Product-safety standards and laws require manufacturers to protect users from hazards, including dangers from hazardous voltage. Products must comply with safety standards during normal use, under fault condition, and during foreseeable misuse. The ultimate responsibility for providing safe products lies with the manufacturer. However, if an incident occurs, damages may be sought from everyone in the supply chain. With the increased awareness of safety, the number of incidents has dropped over the past 20 years, but cost per incident has dramatically risen.

The technical and legal aspects of product safety can be rigorous and confusing. It is difficult for anyone but a full-time trained professional to keep up with standards, laws, interpretations, and national differences. Safety engineers evaluate and test products according to recognized standards and industry norms, and, on request, they provide proof of compliance for product suppliers, users, and enforcement authorities.

Europe's CE (Conformité Européenne) marking is a manufacturer's self-declaration symbol and not a third-party certification or approval (**Reference 3**). Product-certification marks, on the other hand, are independent, third-party evidence of compliance (**Figure 5**). Certification marks are mandatory in some locations, such as New York, Los Angeles, and Washington. If a product bears a certification mark, then, with few exceptions, it is generally safe to use when you operate it within its specifications. Certification marks are manufacturers' best proof of due diligence should a product's safety compliance come into question (**references 4** and **5**).

MORE AT EDN.COM ▷

+ Go to www.edn.com/ms4190 and click on Feedback Loop to post a comment on this article.

With an increasing awareness of the potential dangers that hazardous voltage poses, it is incumbent on manufacturers to consider the general principles of safety. Designers must also understand the relevant safety standards and laws to equip themselves with the necessary tools to design safe products. Product-certification marks provide visible proof of a product's compliance and offer consumers peace of mind (**references 6** through **8**). **EDN**

REFERENCES

1 Lohbeck, David, "Safety isolation protects users and electronic instruments," *EDN*, Sept 30, 2004, pg 59, www.edn.com/article/CA454635.

2 Lohbeck, David, "Safety Design and Certification For Test and Measurement Products, Part 2," *Evaluation Engineering*, November 2003, www.evaluationengineering.com/archive/articles/1203prodsafe.htm.

3 Lohbeck, David, *CE Marking Handbook: A Practical Approach to Global Safety Certification*, August 1998, Newnes, www.books.elsevier.com.

4 Lohbeck, David, "Safety Certification for the T&M World," *Test & Measurement World*, August 2004, www.reed-electronics.com/tmworld/article/CA439351.

5 Lohbeck, David, "The CE marking: separating fact from fiction," *EDN*, Jan 2, 1997, pg 133, www.edn.com/archives/1997/010297/01df_06.htm.

6 Lohbeck, David, "Safety Design and Certification For Test and Measurement Products, Part 1," *Evaluation Engineering*, November 2003, www.evaluationengineering.com/archive/articles/1103prodsafe.htm.

7 Lohbeck, David, "A review of CE Marking," *Design News*, Sept 23, 1996, pg 212, www.designnews.com/article/CA151162.

8 Lohbeck, David, "Walk the Path to the European CE Marking," *Test & Measurement World*, November 1995, pg 23.

AUTHOR'S BIOGRAPHY

David Lohbeck is a product-safety engineer at National Instruments (Austin, TX). Previously, he worked for Motorola, Dell, and TUV in international product safety, machine safety, and electromagnetic compatibility. Lohbeck has published numerous articles on safety and EMC and was an EDN *Innovation finalist for "Best Contributed Article" in 2004 (***Reference 1***). Lohbeck is also the author of* CE Marking Handbook: A Practical Approach to Global Safety Certification. *You can reach him at dave.lohbeck@ni.com.*