A **Focal Press** Book

3RD EDITION

ELECTRICITY FOR THE ENTERTAINMENT ELECTRICIAN & TECHNICIAN

A PRACTICAL GUIDE FOR POWER DISTRIBUTION IN LIVE EVENT PRODUCTION

RICHARD CADENA

COMPANION @ WEBSITE

ROUTLEDGE

Electricity for the Entertainment Electrician & Technician

Now in its third edition, *Electricity for the Entertainment Electrician & Technician* is a comprehensive, practical study guide for aspiring and working professionals in live event production.

The book covers every aspect of power distribution from the fundamentals, like basic circuits, to 3-phase power, power calculations, grounding and bonding, electrical safety, portable power generators, and battery power. With ample photographs and illustrations, practice problems and solutions, and real-world examples from experience and first-hand accounts, it provides readers with the knowledge to safely design, set up, and monitor power distribution systems. The third edition expands on grounding and bonding, portable power generators, balanced and unbalanced 3-phase power calculations, battery power, and more. The last chapter walks readers through the process of prepping for a show, setting up a portable power distribution system, and monitoring every aspect of the system, including voltage, current, and heat using an infrared camera, explaining in detail best practices and the logic behind them.

Covering topics that are listed in the content outline for the ETCP Entertainment Electrician Certification exam as well as the ETCP Portable Power Distribution Technician Certification exam, this reference supports practicing technicians and provides new technicians the assistance they need for a successful career in the entertainment industry.

Additional resources, including conversion tables, voltage spreadsheets, articles from *Lighting & Sound International*, *Lighting & Sound America*, and *Protocol*, and animations and illustrations depicting electricity and electric power distribution developed for the author's workshops, can be found on the companion website www.electrics.tech.

Richard Cadena is a freelance lighting designer, lighting consultant, and the author of *Automated Lighting: The Art and Science of Moving Light*, *Lighting Design for Modern Houses of Worship*, and *Focus on Lighting Technology*. He has worked on concert tours, television, and theatre, and he has designed dozens of lighting systems for permanent installations. He is the technical editor for PLASA Media and a columnist for *Lighting & Sound America*, *Lighting & Sound International*, and *Protocol*, as well as a member in good standing of IATSE Local 205.

Electricity for the Entertainment Electrician & Technician

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Third Edition

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If you have ever loaded or unloaded a truck, set up power distribution, lighting, audio, or video gear, if you have toiled in the field of live event production, motion picture or television production, theatre, or corporate events, if you have crisscrossed the land in a tour bus or airplane, if you have missed birthdays, weddings, funerals, and holidays because you were on the road or in a theater, then you are amongst an elite group of people who are the hardest-working people I know, and this book is dedicated to you.

If you ever parented or taught, if you've ever mentored or encouraged someone, if you've ever helped someone better themselves, learn something, or helped them in their career, this book is dedicated to you. This book is also dedicated to my parents, Noe and Yolanda Cadena, without whose guidance and sacrifices I would be lost. Lastly, this book is dedicated to my wife, Lisa Cadena, and daughter, Joanna "Joey" Cadena.

Richard Cadena
Austin, TX and Lake George, NY, 2020

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Preface

Shortly after the Entertainment Electricians certification was launched in 2006, Jim Utterback from IATSE Local 22, who was on the Board of Directors of the ESTA Foundation at the time, called and invited me to teach an ETCP prep class in Washington D.C. Daniel Amadie of IATSE Local 8 traveled from Philadelphia for that class, along with about 40 or 50 people from Washington, Philadelphia, and New York City. He invited me to dinner one night and asked me to teach the same class for his local a couple of months later. That, in turn, led to more classes at Local 1 in New York (thanks to John Diaz, Paul Dean Jr., and Adam Braunstein), Local 2 in Chicago (thanks to Craig Carlson), Local 16 in San Francisco (thanks to Eddie Raymond and Danny Borelis), Local 58 in Toronto (thanks to Doug Hook and Morgan Myler), which then led to classes around the globe including Australia (thanks to Julius Grafton), the Philippines (thanks to Tony Esteban), and Bangalore, India (thanks to Santana Davis). And that has evolved into a career spanning 14 years and counting.

At most of those classes, attendees often asked if there was a book encapsulating the information. The answer was yes, there are lots and lots of books. The problem was that there are lots and lots of books, meaning the information was scattered and time-consuming to find. And that is how and why this book was written.

At the time, I didn't fully realize its purpose, other than to support and promote ETCP certification and to support those who wanted to learn more about the craft and advance their careers in entertainment electrics. It wasn't until 2013 that it became clear to me that there is a higher purpose.

In 2013, Chad Gilbert, the lead singer for the band *New Found Glory* was almost electrocuted on stage. He plays an electric guitar, and while he was performing, he grabbed the microphone and was shocked badly enough that he said his muscles froze, and he couldn't let go. I learned about it from his Twitter post:

> *"While recording the NFG live album at the chain reaction last night I was shocked by the microphone. In between songs I grabbed the mic to speak and when I did it felt like I couldn't let go. I was being shocked and it froze me in place and when I was able to release my hands off of the mic I collapsed. When I came to I had friends standing over me and it felt like I was asleep in one of those Sci Fi movies when they wake up after traveling for 3 years to fight an alien. My friends escorted me off the stage. I told the band to finish the set for the sake of the audio recording. At that point I still was in a daze. The ambulance came and picked me up and drove me to the nearest Emergency Room. After getting numerous tests off and on for about 12 hours from the friendly people at UC Irvine I was released. They checked my heart for most of that time to make sure the electrical current didn't make my heart beat irregularly. Everything came back positive.*
>
> *"I am gonna play the show tonight but this time with a wireless to settle my paranoia of this happening again because man it hurt and sucked."*

Luckily, he survived the shock. Others weren't so lucky. After Chad Gilbert's incident, I started research stage electrocution to better understand the causes, and, more importantly, how to prevent them in the future. What I learned is that there is a history of electrical accidents in live event production. Les Harvey, the lead guitar player for Stone the Crows, was electrocuted on stage in 1972, and Keith Relf, the lead singer for the Yardbirds, was electrocuted in his home studio when he touched a microphone in 1976. Countless other performers and stage technicians have received bad shocks and were very nearly electrocuted, as evidenced by numerous videos on YouTube and conversations in the online forums after the Chad Gilbert incident.

My greatest concern was that it would happen again and again unless we as the live event production community take steps to raise awareness and practice safer techniques. And that is the real purpose of this book. But we still have

much work to do because it did happen again, but with much worse results.

On November 23, 2014, Agustin Briolini, the lead singer/guitar player for the band The Krebs, was electrocuted during a sound check in a theater in Argentina. He was the lead singer/songwriter and electric guitar player. When he touched a microphone and the steel strings of his guitar simultaneously, he collapsed and died. After reading about it the next day, I reached out to the surviving band members and friended them on social media to learn what I could. About ten months later, two of the band's audio techs were charged with “wrongful death.” The prosecutor, Ricardo Mazzuchi, accused them of using a cable to power the guitar amplifier and PA that had the live and neutral conductors reversed with no grounding/earthing conductor. It was also stated that the thermal breaker was bypassed, and since the neutral and ground are bonded in the service panel, the result was that there was voltage on the chassis of the guitar amp, which eventually connects to the strings. When Briolini touched the strings, he was likely wearing rubber-soled shoes and was likely standing on a wooden or carpeted stage, so he was a “bird on a wire,” not completing the circuit. But when he touched the microphone, the circuit was completed from hand-to-hand through the shield of the microphone cable, through the chassis of the PA, and back to the electrical panel.

It was a very sad and touching story and it is one that we cannot afford to have repeated. Yet, in July 2017, it happened again. Barbara Weldens was a singer who liked to sing barefooted, and as a result, she was accidentally electrocuted on stage near Paris, France. Little information is available about the technicalities of the incident but touching a microphone should never cost anyone their life.

The vast majority of these accidents are preventable. Training and providing an understanding of the fundamentals of electrical circuits are the key to prevention. We can jump up and down and blink, and wave our arms, but these accidents will continue to happen until we are better trained in circuits and electrical safety. Still, as Douglas Adams wrote in *The Hitchhiker's Guide to the Galaxy*, “some people just won't see, or their brains won't let them see” the importance of training and certification because they think it's an SEP (somebody else's problem). That has to change if we are to prevent accidents in the future.

Safety training, education and certification may not be the answer to the ultimate question of life, the universe, and everything, but it's a great start. And coincidentally, or maybe not so coincidentally, “safety training, education and certification” has 42 characters.

Acknowledgements

When I was in third grade, there was a carnival at my elementary school, and I won a big, beautiful chocolate cake in the cakewalk. Each of the prize cakes was made by class mothers, and each had a small hand-typed slip noting which teacher's class had donated the cake. The one I won happened to be donated by someone in my own class, so it had my teacher's name on it. I was thrilled because, well, it was chocolate cake! And it was made possible by my favorite teacher, Mrs. Schweitzer. I was so excited when I was handed that beautiful chocolate cake that, as soon as it was in my hands, I ran across the room to show it Mrs. Schweitzer. She looked at the cake, read the tag that said "Mrs. Schweitzer," and thought I was giving it to her. She gasped in surprise, thanked me and walked off with the cake, just beaming. I too gasped in surprise and stood there, empty-handed, dreaming of just one taste of that luscious chocolate cake. She is still one of my favorite teachers because she literally takes the cake, and I thank her and all of my other teachers, especially my high school electronics teacher, Harry Hamilton.

I was also fortunate to have a great mentor and teacher named Richard Belliveau when I got my first job in the industry. He was the most demanding teacher/boss I've ever had, but he launched hundreds if not thousands of careers, including mine. I am also grateful to Lowell Fowler and Bob Schacherl, the other two owners of the Blackstone Audio Visual, which later changed its name to High End Systems.

If not for the ETCP program, this book would likely not exist; and for that, I am grateful to Lori Rubinstein—who had the vision to implement it and the stamina to see it through—along with the rest of the ESTA Foundation.

I also have to thank Alan Rowe, who for many years was the Safety and Training Director for IATSE Local 728 and is now the President of that Local. His focus on training is an inspiration for the rest of the industry. On the day that I learned that the industry was shutting down due to the COVID-19 pandemic I called him and said that we should put together some online training. "Funny you should say that," he said. "I'm sitting in (IATSE Training Trust Fund Executive Director) Liz Campos' office talking about the same thing." We were up and running in literally two days.

And for those many people who have been gracious enough to answer my steady barrage of questions and never complained, I'd like to thank you. At the top of that list goes NBA Production Electrician Rob Baxter (also my IATSE Local 205 brother); Rolf Lee of IATSE Local 16; Steve Terry of E.T.C; Ron Dahlquist of Dadco Power and Lights; George Long of Aggreko; E. H. B. "Chipmonck" Monck; M. Eric Rimes, Lighting Faculty at North Carolina School of the Arts; Karl Ruling of PLASA; Art Wanuch of KRE Electric; Keith Woods of IATSE Local 891; Mike Wood, Mike Wood Consulting; Guy Holt, who authors so many great articles in *Protocol* Magazine. There are some who answered my questions but did complain, and to you I am also grateful—but no cake for you.

If anyone deserves cake, it's all the great people at Focal Press, especially Stacey Walker and Lucia Accorsi for being really patient when I was past deadline. I am grateful for the invaluable feedback from Michelle Harvey. And I cannot forget Cara St. Hilaire (née Anderson), the acquisitions editor for the original version of this book.

And to the very special people who give meaning to my life and work, my wife Lisa and my daughter Joanna "Joey" Cadena, you take the cake *and* ice cream (gluten- and dairy-free of course).

As I write this, the live event production, motion picture and television industries have all but come to a complete standstill due to the COVID-19 pandemic. I'm currently in Orlando working as an electrician and court lighting director for the NBA Restart—thanks to a call from Rob Baxter—and I am extremely fortunate to be working right now. I'm also very fortunate that my contributions to *Lighting & Sound America*, *Lighting & Sound International*, and *Protocol* magazines have continued throughout the pandemic, and for that I owe a sincere debt of gratitude to Jackie Tien, Publisher of PLASA Media, who always has my back; David Barbour, Editor of L&SA; Claire Beeson, Editor of L&SI; and Teodora Lyubomirova, Assistant Editor of L&SI.

My most sincere hope is that this book will help everyone in the industry work more safely and efficiently, as well as help raise awareness about safety issues to prevent accidents. May we all work towards world peace, inner harmony, and lasting prosperity.

WHAT'S NEW IN THIS EDITION

For this edition of the book, I completely tore it down and reorganized it based on what I have learned from teaching entertainment electrics classes over the last 14 years. I tried to use more illustrations and less math, and include more real-world examples from practical experience. I am a bit of a math nerd but I recognize that not everybody is interested in the higher math behind the craft. For those who are, I didn't leave out the trigonometry, but I moved some of it to the appendices in the back of the book. I added more practical information based on my experience in the field, as well as more impractical content, a.k.a., my heart and soul. On the more practical side, I added information in Chapter 7 about how to calculate unbalanced 3-phase loads (with the trigonometry behind it provided in Appendix 6). I also updated many of the end-of-chapter questions and answers based on real world issues. I placed the information about portable power generators and battery power in their own chapters and I tried to sum it all up with a final chapter in which I walk the reader through an imaginary show, again based on my real-world experiences.

It has taken much longer to turn in my final manuscript than I originally thought it would, primarily because I turned the last edition of the book inside out to rewrite it in a form that I think will be much more accessible, more easily understandable, and more in line with the real world.

CHAPTER 1

Foundations of Electrical Systems

PULLING BACK THE VEIL OF MYSTERY

Electricity is a fascinating phenomenon. It is energy that can be manifest as light, sound, heat, or movement, and that's why it is so important to those of us in the entertainment industry. We use it to create fantastic lighting, beautiful sound, awesome video images, and spectacular special effects. But to a novice, the behavior of electricity can be elusive and challenging to understand because we can't see it; its nature is obscured by a veil of mystery.

Imagine how our perception of water might change if we could not see it. People would appear to magically fly through the air when they were swimming, and ocean waves would appear to be unexplainable forces that could knock you over at seemingly random times as you walked along the beach.

That's how I felt about electricity from a very early age. I was about 10 years old when I became fascinated with electronics and mystified by how radios and televisions work. I struggled to understand how a person's voice could come out of a radio or how a moving image could appear on a television. I decided I was going to find out.

One day my parents left me alone at the house, which was usually an invitation to trouble. It was then that I decided I was going to discover the secrets of electronics, so I took one of my father's old radios out to the garage. I was sure that if I could just have a peek inside, I could figure out how it worked. So, I took a screwdriver and removed the four screws that secured the cover of the radio to the chassis.

I know what you're thinking, but I didn't get shocked nor did I cause a short circuit and a shower of sparks. By that time, I knew enough to unplug the radio before I took it apart. But instead of uncovering the mysteries of electronics, what I found was a circuit board with transistors, resistors, capacitors, a transformer, and a speaker. That did nothing to help pull back the veil of mystery.

But I wasn't going to let that stop me. I just knew that if I could look inside of one of those components that I could figure it out. After all, I was a smart 10-year-old kid. So, I took a pair of pliers and randomly selected a component on the circuit board. It turned out to be a resistor. I wiggled it back and forth until it broke free from the circuit board, and then I took what I soon learned was one of my favorite tools for analyzing electronic devices—it's called a hammer—and I smashed the resistor in order to get a good look inside. All I found was a pile of black carbon powder. Again, that did nothing to help me figure it out. My desire to learn how it worked only intensified.

Years later when I went to high school and I found out they were offering an electronics class, I jumped at the opportunity. I would finally learn how these devices worked.

This was a two-year class, and in my first year there was a mix of first-year and second-year students. From day one, the teacher started talking about voltages and currents, and for the first couple of weeks, I was completely and hopelessly lost—until he explained it in terms I could understand. He told us how electricity behaves like water.

ELECTRICITY BEHAVES LIKE WATER

A hydraulic system, he said, has some similarities to an electrical system. Think of a big municipal water tower. The tank holds water high in the air, and the force of gravity pushes down on the surface of the water, which produces water pressure around the walls of the tank. If there is an open pipe attached to the water tower, water will flow through it, and the amount of water that flows depends on the amount of water pressure; the greater the water pressure, the more water will flow through the pipes. The only other limiting factor is the size of the pipes; the bigger the cross-sectional diameter of the pipe, the more water that can flow through it.

Water pressure in a hydraulic system is much like the "electrical pressure" or voltage in an electrical system. The pipe that carries the water to your neighborhood is like a conductor that carries electrical current from an electrical supply to a lamp or other load. The resistance to the flow of water due to the size of the pipe is like the resistance to the flow of electricity in an electrical circuit. The bigger the pipe, the easier the water flows; the smaller the pipe, the less the amount of water that can get through the pipe. A small pipe, then, is like a conductor with a smaller cross-sectional diameter, and a large pipe is like a large conductor. Along the way there might be valves that turn the water on or off, much like the electrical switches that turn electrical current on or off; when the tap is on, the water flows, and when the light switch is on, the current flows. (See Figures 1.1a and 1.1b.)

FIGURE 1.1A
Gravity pushes down on the surface of the water in the tank, which produces the water pressure that forces water through the pipe. The water pump (bottom right) increases the water pressure so that it can rise higher than the level in the tank. The smaller pipe resists the flow of water that runs through the pipe and reduces the flow of water.

FIGURE 1.1B
The electrical parallel to a hydraulic system is a DC circuit; the electrical pressure (voltage), supplied by a battery drives electrical current through the conductors (wires) in much the same way that the water pressure forces the water through the pipes. The resistor in the circuit limits the flow of electricity through the lamp so that the lamp will not blow or burn up.

VOLTAGE, CURRENT, AND RESISTANCE

A production electrician friend of mine once told me that I speak “engineer.” “What do you mean by that?” I asked.

“Well,” he said, “most production electricians and technicians say ‘volts,’ ‘amps,’ and ‘ohms,’ but you say ‘voltage,’ ‘current,’ and ‘resistance.’”

“True,” I said. “But we're referring to the same thing!”

“Yeah,” he said, “but not everyone knows that.”

He is right. Production electricians and technicians often carry meters that they use to measure voltage, current, and resistance, but that's not how the labels read. The labels read “volts,” “amps,” and “ohms.” Many of us learn on the job and never have the opportunity to have formal training in electricity or electronics, so are never taught the difference between voltage and volts, current and amps, resistance and ohms. And sometimes when we encounter these terms, it can be confusing.

The difference is that volts, amps, and ohms are the *units of measure* of voltage, current, and resistance, respectively. It is no different than referring to kilometers, kilograms, and Kelvins instead of distance, weight, and temperature.

Terminology is important because confusion in communicating can lead to problems. Suppose, for example, a show has a 150-amp power distribution system (or “power distro”) and the head electrician says to a tech, “What's the current on the neutral?” What might happen if the tech misunderstands and interprets it as, “What is currently the voltage on the neutral?” If he takes a voltage reading instead of a current reading, and calls out “120,” then it would seem as if everything was okay. But if the current flowing through the 150-amp conductor was actually 175 amps, that's a problem! Miscommunication can cause problems or makes them worse.

Communicating clearly and effectively is very important, and that includes concepts and terminology. If we use different terminology, we might as well be speaking different languages. It is better, therefore, to learn the terminology of the craft we so love.

RESISTANCE

Resistance is the opposition to the free flow of electrical current. It is a physical phenomenon caused by free-flowing electrons, which are subatomic charged particles. Electricity is the flow of these particles, and as they make their way through a conductor, they collide with each other, producing friction and heat. If two different conductors with different resistances are carrying the same amount of current, the conductor with the highest resistance will also have a higher temperature. If two conductors with the same amount of resistance are carrying different amounts of current, the one with the highest current will have a higher temperature.

Every electrical circuit has to have at least some resistance; otherwise, too much current would flow, and the components would overheat and melt. Resistance is sometimes desirable and sometimes undesirable. It is desirable when we want to limit flow of current through a circuit to prevent it from overloading. It is undesirable when it comes to energy efficiency because the energy that is converted from electrical to heat energy is dissipated into the atmosphere and lost.

In some cases, we take advantage of the electrical-to-heat energy conversion process. Some circuit breakers have a mechanism that converts electrical current to heat. If too much current flows, it gets hot enough to trip the mechanism and interrupt the circuit, thereby preventing too much current from flowing. Incandescent lamps convert electrical current to heat, which causes the filament to produce light. Without this conversion process, neither thermal circuit breakers nor incandescent lamps would work. In other cases, we try to maximize energy efficiency by minimizing lost heat, such as in conductors and other circuit elements.

Electric circuits are designed to have the right amount of resistance to control the flow of current and limit it to the right intensity. An incandescent lamp, for example, has a tungsten filament with a very specific resistance to control the intensity of the current and thus, the wattage of the lamp. The resistance of the filament is determined by the thickness and length of the tungsten wire.

A perfect conductor is one that has no resistance. In the real world, under normal circumstances, no such thing exists. Even large feeder cable has a small amount of resistance. Some materials—like copper, aluminum, and gold—are very good conductors, and some—like rubber, glass, and air—are very poor conductors under normal circumstances. The resistance of any material depends on its atomic structure. If a material has high enough resistance, it can be used

as an insulator to protect against electric shock. For example, some cables have a jacket made of thermoset, which is a polymer or plastic, and that makes it safer to handle because the jacket provides shock protection.

The unit of measure of electrical resistance is called the ohm, after German physicist Georg Ohm (1789–1854). Resistance is abbreviated by the letter "R," but its unit measure is abbreviated by the Greek symbol omega (Ω). An ohm meter or a multimeter with a resistance function, for example, typically uses the omega symbol to indicate the resistance setting.

Resistance is an integral part of electric circuits, yet production electricians and technicians rarely, if ever, measure it. More often they measure the voltage applied to a system or component of a system and the current flowing through the system or a branch of the system. But they are all related, and in order to understand how circuits work, it is critical to understand the relationship between voltage, current, resistance, and power. The relationship between voltage, current, and resistance is established by a formula that we refer to as "Ohm's law," after the aforementioned George Ohm, a German physicist who explored the relationship. The relationship between voltage, current, and power is established by the power formulas. We'll discuss these in detail in later chapters.

Production electricians and technicians often use an ohm meter or a multimeter with an ohm meter function, but usually not to read the value of resistance. Instead, it is often used as a continuity tester. Very low resistance between two points in a circuit means there is continuity or there is a continuous conductive path between the two leads of the tester. (In theory, continuity is 0 Ω, although in the real world there is some resistance, typically less than 1 Ω.) If, for example, you want to know whether or not a fuse or lamp filament is blown (it is not always readily apparent by visual inspection), you can place the multimeter in continuity mode and touch the two leads to the two ends of the fuse or the two pins of the lamp. Most continuity testers will emit a tone or beep when there is continuity so that you get an audible verification when there is a complete circuit.

VOLTAGE

The unit of measure for voltage is the volt, and it is named after Alessandro Volta (1745–1827), an Italian physicist who invented the predecessor to the modern lead-acid battery called a "voltaic pile." Voltage is like electrical pressure. It provides the electromotive force (EMF) that causes electrons to flow through a conductor if there is a complete conductive path between the two terminals of the voltage supply. Voltage is potential energy; it has the potential to produce the flow of current if it is connected to a complete circuit. For that reason, it is sometimes referred to as electrical potential. When current flows, the potential energy is converted to electrical energy. It is similar to the potential energy represented by the pull of gravity. When you hold an object in your hand, the force of gravity wants to pull the object to the earth. If you let the object fall, then that potential energy is converted to kinetic energy while it is falling.

Electricity is a natural phenomenon, and physics is the study of nature; therefore, physics books usually cover electricity, and they usually refer to voltage as electromotive force or EMF, which is one in the same. So, we sometimes see the letter "E," meaning EMF or voltage, but most often voltage is abbreviated as *V*.

A battery is an energy storage device that supplies a constant voltage to a circuit (as long as it is sufficiently charged). When a battery is charging, it is storing energy: and when it is discharging, it is supplying energy. If it is charged but not connected to a circuit, then it has the potential to supply energy to anything connected to it. In other words, it has potential energy, which is to say that it stores energy that can be converted from one form, like chemicals, to another, like electricity. (See Figure 1.2.)

FIGURE 1.2
Left: The symbol for a battery showing the positive and negative terminals. Right: The symbol for alternating current or AC voltage. The polarity changes and the current reverses direction twice for each single cycle.

The electrical power grid is probably the most common source of power for live event production. It delivers energy from a generating plant (or several plants) to energy consumers at distant locations through a series of transformers that change the voltage for various purposes.

The voltage at the point of consumption (sometimes referred to as the “mains” voltage) varies according to geographic location. In Japan, it is 100 volts, while in North America and other places, it is 120 volts or 208 volts (depending how a load is connected). In many parts of Europe and various other locations the mains voltage is 230 volts, and in the UK, Australia, and many other parts of the world it is 240 volts. (See Appendix 5 for worldwide voltages in specific countries.)

MEASURING VOLTAGE

A voltmeter (or a multimeter set to read voltage) is used to measure voltage. (See Chapter 10: Metering Safely and Categories of Meters.) It has two leads or probes that are connected to meter's terminals, and by placing them on two different points in the circuit, the voltage can be read across those two points. (See Figure 1.3.)

FIGURE 1.3
A voltmeter (or a multimeter set to read voltage) has two leads or probes, and the voltage it reads is the difference between any two points in the circuit.

Voltage is relative; it means nothing without a reference point. That's why a voltmeter has two probes instead of one. It reads the difference between the voltage at the two probes. You can measure voltage between two points but not at a single point. If you took one probe from your voltmeter and touched it to a 120-volt circuit, the read out would bounce around, never settling on any one value because it has no reference. But if you then touched the other probe to ground or earth, then it would read about 120 V. By the same token, if you put one probe on a 240-volt terminal and the other

on a 120-volt terminal, the meter would read about 120 volts because it reads the difference between the two voltages (240 volts − 120 volts = 120 volts). That's why a voltmeter has two probes, not just one.

This also explains why a bird on a high-voltage transmission line does not get a shock. The distance between the two legs of a bird is so small that the potential difference from one point on the transmission line to the other is so small that it does no harm to the bird. (See Figure 1.4.) In essence, the bird's body is at a very high potential but there is no reference to any other voltage, like the earth, which is by definition 0 volts.

FIGURE 1.4
A bird on a wire does not get shocked because there is essentially only one point of contact, and therefore there is no difference in potential.

CURRENT

When voltage is applied across a conductive material like copper, negatively charged electrons are pulled away from the atoms that make up that conductive material and they make their way through the conductor. That is electrical current and it is what we understand to be the flow of electricity. Electrical energy is transferred in the process, and it can be converted to heat, light, sound, or motion, or it can be temporarily stored in the form of a magnetic field or an electrostatic field.

A conductor has a limited capacity to carry current. Current is measured in “amps,” and the “ampacity” is the safe current-carrying capacity of a conductor. Ampacity is limited by the cross-sectional diameter of a conductor, the melting point of its jacket or insulation, and other factors. Ampacity is always a limiting factor in power distribution because the flow of current produces heat, and the higher the current, the more heat that it generates. A source of power can output only a limited amount of current before the conductors get too hot and start to degrade the insulation. A power distribution system can distribute a limited amount of current before the conductors start to get too hot and the connectors and insulation start to melt. The conductors in our power sources (transformers and/or generators) and power distribution systems are always insulated, and the insulation has a maximum temperature rating. If that temperature exceeds the rating, it will start to decompose. That's why we calculate the current draw based on the anticipated connected load before designing and building a power distribution system, and it is why we also monitor the current during operation to make sure we don't exceed the capacity of the system or any of its components.

Current is measured in amperes or amps (A), which is named after André-Marie Ampère (1775–1836), a French mathematician and physicist who explored the relationship between electricity and magnetism. We often see the letter “A” after a number, indicating a measure of amps, especially on amp meters. However, in formulas that are used to calculate current, the letter “I” is typically used, meaning the “intensity” of the current (I), which is measured in amps (A). The power formula, for example, looks like this: $P = V \times I \times PF$, where P is power, V is voltage, I is current, and PF is power factor (See Chapter 6, Power Factor.). If you're accustomed to seeing and using the letter A instead of I,

this can be confusing at first. The best remedy for that is repetition—practice using the formulas with the letter I until it becomes natural.

MEASURING CURRENT

When current flows, it creates a magnetic field around the conductor in proportion to the intensity of the current; the higher the current, the stronger the magnetic field. An amp meter, like the one shown in Figure 1.5, is also known as a clamp meter, amp clamp, or an ammeter. It works by measuring the strength of the magnetic field around a current-carrying conductor, which is proportional to the current.

FIGURE 1.5
Current can be measured using an amp meter, also known as a clamp meter, amp clamp, or an ammeter, or a multimeter in current mode. It works by measuring the magnetic field around a current-carrying conductor.

As long as you can clamp a single conductor in the circuit, it will display the current flowing through it. If you can clamp only multiple conductors, then you will read the net current from all of the conductors. A stinger or extension cord, for example, has two current-carrying conductors, one of which carries current to the electrical load and the other carries it back from the load. The current in these two conductors is equal in intensity and opposite in direction, so the meter will read 0 amps, or very close to it. To read the current drawn by a single load like a lamp, you have to have a way to clamp a single conductor supplying the load. An AC line splitter, like that shown in Figure 1.6 below, can be used for this purpose, or you can build a line splitter like the ones shown here.

FIGURE 1.6
A line splitter allows you to use a clamp meter to read the current drawn by a single load.

Once a power distribution system has been set up, the voltage should be checked before any loads are turned on to ensure they are not supplied with wrong voltage. After the loads are turned on, you should monitor the current at various points in the system to make sure that none of the conductors or components are too close to being overloaded and that the supply is not being taxed or run too hard. (It's a good idea to reserve 20% of the system capacity by loading it to a maximum of 80%. For example, a 20-amp circuit should be loaded to maximum of about 16 amps. A 100-amp system should be loaded to a maximum of about 80 amps. That allows some overhead to accommodate calculation errors, tolerance errors, errors due to environmental conditions, last-minute contingencies, etc. Sometimes the 20% overhead is a code requirement, but more often than not, in live event production the power distribution equipment we use is "fully-rated," so the overhead is just a rule of thumb.)

An electrical supply is typically either a feeder transformer or a portable power generator. The main parts of the circuit to monitor include the feeder cables and the branch circuits. If you have access to the feeder cables (i.e., they are not enclosed in conduit or in a multiconductor cable), then you can clamp individual conductors including the hot or live conductors, the neutral, and the grounding conductor. (Hint: there should never be any appreciable current in the grounding conductor but sometimes you will find an amp or three. I recently measured 13 amps in the grounding conductor of a large lighting system, which is an indication of a lot of leakage current!)

When you are monitoring the current in a power distribution system, it is important to know the ampacities of the conductors so you will know whether or not they are being overloaded. The ampacity a conductor depends primarily on its cross-sectional area or wire gauge, but also on the temperature rating of the jacket or insulation, the number of current-carrying conductors in contact with each other, the ambient air temperature, and whether or not the conductors are enclosed or are in free air. There are wire gauge charts that provide basic information about the ampacities of conductors based on cross-sectional area or wire gauge at a particular ambient air temperature, and the codes and regulations provide guidance on de-rating factors, like the ambient air temperature, the number of current-carrying conductors in contact, and so on.

In the United States, the National Electrical Code is commonly used by municipalities as a guide for codes and regulations, and Tables 400.5(A)(2) shows the ampacity of flexible cords and cables for certain cable types, including type S and type SJ, which are commonly used in live event production. (See Chapter 14 Figure 14.24 for a reproduction of the table.)

POWER

Power is the rate at which electrical energy is being converted to light, sound, heat, or motion. It is related to the magnitude of voltage and current; in fact, power is the product of the voltage and the current at any instant in time. Understanding how much power is consumed by a lighting, audio, video, or automation system is critical to the success of planning an event. Before the first rigging point is hung, and before the first road case is loaded off the truck, someone on the crew (usually the production electrician or head technician) should have already calculated the power requirements to make sure there is enough available power to handle the event and that the power distribution system is able to safely handle the load. It takes a skilled person to understand the power requirements well enough to make that determination.

Power is measured in watts, which is named after James Watt (1736–1819), a Scottish inventor whose improvements to the steam engine helped usher in the Industrial Revolution. We usually use the letter "P" to represent power, although the letter "W," short for "watts," is sometimes used. Power (P) is the entity, and watts (W) is the unit of measure of power.

MEASURING POWER

Although there are specialized meters that can measure power, they are very expensive and very rare in the live event production industry. Most production electricians and technicians rely on the manufacturer's specifications to find the wattage of any particular piece of gear. For example, the specifications for a Robe BMFL Spot list the power as 2000 watts at 230 volts and 50 Hz.

Alternatively, if you have a multimeter, you can measure the voltage and current for either the entire system or an individual component and then calculate the "apparent power" by multiplying the two values. The units measure of apparent power is not watts, but volt-amps (VA). For example, the specifications for a Clay Paky Mythos list the apparent power at 700 VA at 230 V and 50 Hz. Apparent power is not what we ordinarily think of as "power," but it is related to it by way of something called power factor. Power factor is a measure of how much of the current being drawn by the system or by a load is being converted to light, sound, heat, or motion compared to the apparent power. We'll discuss apparent power and power factor later on in Chapter 6.

Why would a manufacturer list the VA instead of the watts? Because the important bit of information for an electrician or technician to know is the current draw, and the apparent power is an indication of the current draw at a particular voltage. If, for example, the apparent power is 700 VA at 230 V and 50 Hz, then the fixture will draw about 3 amps at 230 V (700 ÷ 230 = 3).

UNDERSTANDING ELECTRICAL CONCEPTS

1.1 Electromotive force (EMF) is also known as _____.

1.2 If electricity behaves like water, what is the electrical equivalent of a water valve?

1.3 The unit of measure of current is _____.

1.4 Draw the symbol for an AC supply.

1.5 If you have a multimeter set to read voltage, and you touch one probe to a circuit part that is energized to 60 volts relative to earth, and you touch the other probe to a circuit part that is energized to 90 volts relative to earth, what will the meter read?

1.6 If you touched both probes from a voltmeter to the same point in a circuit, and that point is at 120 volts relative to earth, what would your meter read?

1.7 Resistance is the _____ to the free flow of current.

1.8 Why is it important to wear gloves when measuring voltage with a voltmeter?

1.9 Why is there less risk involved in metering power downstream from the supply?

1.10 Why is it important to measure the voltage before energizing equipment?

1.11 In the formula $P = V \times I \times PF$, which variable is measured in amps?

1.12 Why would you need a line splitter to measure current?

1.13 The ampacity of a cable or wire depends on five factors, including: _____, _____, _____, _____, and _____.

1.14 If you want to leave 20% overhead in a cable with an ampacity of 400 amps, what is the maximum intensity of current that you should allow?

1.15 The relationship between voltage, current, and resistance is known as _____.

1.16 One way that circuit designers control the intensity of current in a circuit is by using the right amount of _____.

1.17 The Greek letter Ω is shorthand for the unit of measure of _____.

1.18 In theory, continuity is _____ Ω.

1.19 According to the manufacturer's specifications for the Clay Paky Axcor Profile 900, what is the apparent power at 230 V and 50 Hz?

1.20 According to the user manual for the High End Systems SolaSpot 1000, what is the power consumption?

1.21 According to the manufacturer's technical specifications, what is the power factor (PF) for the Martin MAC Viper Performance fixture at 230 V and 50 Hz?

CHAPTER 2

Circuits and Circuit Laws

WHAT IS A CIRCUIT?

Any time you plug something in and turn it on, you're completing a circuit. The same is true if you accidentally come in contact with a live conductor and you get a shock. In either situation, current is flowing, and in order for current to flow, there must be a complete conductive path through which electrons can flow. If there is, it is a "complete circuit."

Only when a circuit is completed and voltage is applied does current flow. If there is a break in a circuit that prevents the flow of electricity, it is an "open circuit." Sometimes we open a circuit intentionally with a switch or by breaking a connection, and other times it happens accidentally, such as when a circuit breaker trips or a fuse blows.

If there is a malfunction, current can be diverted, and it can take an alternate path. For example, if the insulation around a conductor melts and the wire touches a metal chassis, the current will be diverted through the chassis and back to the supply. This is generally referred to as a "fault." If that path has very low resistance, it causes a lot of current to flow, and it is referred to as a "short circuit." If it is a path to a conductor that is connected to earth or ground, it is referred to as an "earth fault" or a "ground fault."

CONVENTIONAL CURRENT FLOW

The standard convention for the direction that current flows was established long ago. Convention says that current flows from the positive terminal of a supply, through the circuit, and back to the negative terminal, as shown in Figure 2.1. In this case, the supply is a battery, and it has a positive terminal and a negative terminal. In an alternating current (AC) supply, like the mains power we typically use in a show, the polarity of the two terminals is constantly changing between positive and negative at a rate that is double the operating frequency. For example, in North America the frequency is 60 cycles per second, or hertz (Hz), and the supply changes polarity 120 times per second; for the first half of the cycle, current flows in one direction, and for the second half of the cycle, the polarity changes and current flows in the opposite direction. It repeats this pattern over and over. In Europe, the frequency is 50 Hz, so the supply changes polarity 100 times per second. Historically, Nikola Tesla believed 60 Hz was the most efficient frequency for the transmission of electricity, and Westinghouse began using that frequency around the turn of the twentieth century. The frequency in Europe was changed to 50 Hz, probably because it is better suited to the metric system.

FIGURE 2.1
Current (indicated by the red dashed line above) flows from the positive terminal to the negative terminal through a complete circuit. The symbol on the left represents a DC supply, typically a battery, and the symbol on the right represents a resistive load, like an incandescent lamp, the heating element of a fog machine, and so on.

The amount of current flowing in a circuit is one of the main factors that determines how much power distribution we need and how much supply we need. The capacity of the supply and the size of the circuit breakers, cables and wires, fuses, connectors, and other components depends on how much current they need to carry or pass. If the supply or any of the components are undersized, then we run the risk of overloading the supply or circuit, which can cause a fuse to blow or a circuit breaker to trip, thereby opening the circuit. Every circuit has this protection built into it, and if it is not sized correctly, then the components can overheat and melt or burn up. Therefore, it is critically important that we understand how to calculate the current drawn by the gear, both for the entire system and for each individual circuit, based on the connected loads and the applied voltage. Then, and only then, will we know how much supply we need, how many circuits we need, and how to set up and operate a power distribution system safely.

CIRCUIT BASICS

A simple direct current (DC) circuit as shown in Figure 2.1, is an example of a circuit. The battery, indicated by the symbol on the left, supplies the voltage that makes the current flow (indicated by the red dashed line), provided there is a complete path of conductive material, like copper wire, from one terminal of the battery to the other. The wiring provides the conductive path, which completes the circuit. If the wire does not return to the other terminal, or if there are any breaks in the conductive path, then it is an open circuit.

On the right is the symbol for a resistor, which can be any “load” like a lamp or the heating element in a fog machine. Either way, the resistance of the load limits the amount of current flowing through the circuit by resisting the free flow of current. Every electrical circuit has to have at least some resistance; without resistance, there would be nothing to restrict the free flow of current except the size of the copper wire (which affects the resistance of the wire) and the voltage of the battery. If the resistance of the circuit is too low, the current will be very large and the battery, wire, and anything else in the path of the current would heat up, possibly to the point of destruction. The resistance prevents that from happening; and in real life, there would also be circuit protection (a fuse or circuit breaker) just in case there is a short circuit or an overload.

CIRCUIT LAWS

“What goes up, must come down.” This popular saying summarizes the universal law of gravity that Sir Isaac Newton wrote about in 1686. It's one of the laws of nature and there's just no getting around it. Electricity, like gravity, is a natural phenomenon, and as such, it follows the laws of nature. This means that there are underlying principles that all electrical circuits obey. When you understand these principles, you will have a much better understanding of how circuits work; and that, in turn, will allow you to use reason to solve problems and troubleshoot electrical systems.

Every time you make an electrical connection you are completing a circuit, and every circuit forms a loop from the supply, through the load or loads, and back to the supply. (A load is anything you plug in or anything that uses

electricity, like a light, video projector, or chain motor.) Every electrical circuit exhibits the following behaviors:

1. **Electricity Always Tries to Return to Its Source.** When current flows, it seeks a path back to its supply. The supply provides the energy, which flows through the circuit, and then back to the supply. The supply can be a battery, a transformer, a generator, or it could be a natural source like lightning. It may not be readily apparent, but when lightning flows from cloud to earth or from earth to cloud, it is returning to its source. If you think of the earth and its atmosphere as the source, then that makes sense.

   Electricity will not flow through any path that does not allow it to return to its source. For example, when a bird lands on a high-voltage transmission line, there is no path through the bird that takes the current back to the supply; therefore, the bird will not get shocked. The drawing in Figure 2.2 illustrates that. The symbol on the left indicates an alternating current (AC) supply, and a bird has landed on the conductor, but there is no path through the bird that can carry current back to the supply; therefore, the bird in this illustration will be safe.

FIGURE 2.2
If you trace a path from the supply on the left, through the load, and back to the supply, it does not pass through the body of the bird; therefore, the bird will not receive a shock in this situation.

By the same token, if a person standing on the earth were to touch the circuit, as shown with the illustration of the man in Figure 2.3, he would not receive a shock because there is no path through the person that carries current back to the supply. (I wouldn't try this in real life because there could be inductive coupling between the supply and the earth. This means that the strong magnetic field produced by a feeder transformer could transmit energy through the earth, which would complete the circuit and cause a shock!)

FIGURE 2.3
In this illustration, there is no path that can carry the current from the supply, through the person touching the conductor, and back to the supply; therefore, he would not receive a shock, provided there is no inductive coupling between the supply and the earth!

In real life, all of the sources of power that we commonly use in live event production are earthed, meaning that one side of the supply is physically connected to the earth (as indicated in Figure 2.4) by the symbol with three short lines forming a triangle in the lower left side of the illustration. This connection to the earth is for lightning protection as well as to create a good 0-volt reference because the voltage of the earth is always 0 under normal circumstances, and voltage is relative; i.e., the voltage at one point has meaning only relative to another point in the circuit. If you were to look around the outside of your venue or any performance space you are likely to find a copper rod driven into the earth with a bare copper wire connected to it, or some other form of connection to the earth. The copper wire is also connected to one side of the supply it so that, in the event of a lightning strike to the electrical system, it will carry the energy into the earth in order to safely dissipate it. (Lightning is a huge amount of energy, and, unless it is given a low-resistance path to a large mass like the earth, it concentrates the energy and becomes very destructive, likely resulting in an explosion and/or fire.)

FIGURE 2.4
Electrical systems are connected to the earth through a ground rod or grounding electrode (indicated by the symbol with the three short lines forming a triangle) in order to provide a path for lightning to the earth. In this illustration, there is a path through the body, through the earth, and through the ground rod that completes the circuit, thereby shocking the person.

If the person in the illustration above were to touch the same conductor but the supply was earthed, as shown in the illustration below, then there would be a conductive path for current that flows through the person's body, through the earth, and back to the supply through the earthing (or grounding) rod. Now the person would be shocked.

In the early days of electrical power distribution shortly after the turn of the twentieth century, electrical systems were commonly built without an earth connection. The logic was that, if a person accidentally came into contact with a single live conductor, they would not get shocked (as in the first illustration). They would have to accidentally contact two conductors, and the odds of that are much lower. Over time it became more apparent that it was safer to earth electrical systems and this became standard practice.

But the main point here is that current is always seeking to return to its source.

2. **In Order for any Current to Flow, There Must be a Complete Path from the Supply, through the Circuit and Back to the Supply.** A switch allows you to intentionally interrupt a circuit, thereby created an open circuit, or to close and complete the circuit. Fuses and circuit breakers are also a means of interrupting a circuit in the event of an overload or a short circuit. When you connect a load and turn it on, you are creating a complete circuit, causing current to flow. By the same token, if you accidentally touch a live conductor while you are earthed or grounded, you are completing a circuit through the earth and back to the supply: this is why it is important to wear leather gloves and rubber-soled shoes when you are working with live power distribution equipment. As long as they are dry, thick leather gloves offer some shock protection, as do rubber-soled shoes. (See Chapter 10: Electrical Safety.)
3. **Current Will Take as Many Paths as Are Available.** You may have heard that current takes the path of least resistance. That is not exactly true. Current actually takes every available path, although it is true that the current

will divide in proportion to the resistance in each path. That phrase is a simplification that has gained a life of its own because it is easy to remember but not completely accurate.

The illustration in Figure 2.5 shows how this works. The AC supply provides power through a circuit breaker to a load with a metal chassis. (The metal chassis is indicated by the dashed lines in the illustration.) The green line represents the grounding or conductor (sometimes called the "equipment grounding conductor" or EGC), which should always be present and should always be connected to the metal chassis of any device powered by electricity. The purpose of the grounding conductor is to provide a low-resistance path for current in the event of a ground fault, meaning that the hot or live conductor (black line) has accidentally come in contact with the metal chassis. A ground fault like this can create a dangerous situation because the supply voltage is applied to the metal chassis, and unless it causes the circuit breaker to trip and open the circuit, if someone touches it, they will get shocked. But if the grounding conductor is doing its job correctly, it will carry the fault current back to the supply and cause the circuit breaker to open and interrupt the circuit.

If you happen to be touching the chassis at the exact moment that the fault occurs, then there are two parallel paths for the fault current: One is through you, through the earth, to the ground rod, and back to the supply. The other is through the chassis and through the grounding conductor and back to the supply. Current will flow through both paths even though the grounding conductor undoubtedly has far less resistance than the path through the human body and the earth. The resistance of the human body varies a lot, depending on the circumstances, but it can range from a few hundred ohms to many thousand ohms. The resistance of the grounding or earthing conductor, on the other hand, is very low, probably on the order of a few ohms or a fraction of an ohm. Clearly the path of least resistance is the grounding conductor, yet some of the current will take the alternate path through you.

4. **Current Divides According to the Resistance of Each Path.** In the illustration above, most of the current will flow through the green grounding conductor because the resistance in that path is much lower than the resistance through the path that returns to the supply through the human body, the earth, and the ground rod. The higher the resistance of the path, the less current that will flow through it; and if there are two or more conductive paths, the current will divide in proportion to the amount of resistance along each path. If, for example, there are two conductive paths, one with 1 Ω of resistance and the other with 100 Ω of resistance, then 100 times more current will flow through the path with 1 Ω of resistance compared to the other path. (See Figure 2.6) Electrical systems are designed so that, if there is a short circuit to the metal chassis of the equipment, most of the fault current will flow through the green grounding conductor, even if someone is touching the chassis. This is an important safety feature.
5. **If You Trace the Path of a Circuit and Add Up the Voltage Around the Loop, They will Add to 0V.** Every circuit forms a loop that includes the supply, the conductors, and the load(s). The supply elevates the voltage, and every component in the circuit drops the voltage. Think of it as an elevator ride. The supply takes the elevator to the top floor (120 floors in North America or 230 floors in Europe and Australia), and each component in the circuit—including the wiring—brings it down some number of floors until it is back to the ground floor. In addition to the wiring, which has some resistance and contributes to the voltage drop or line loss, other components include lamps, motors, amplifiers, video projectors, computers, and so forth. If the cross-sectional diameter of the conductors is too small for the amount of current that it is carrying, or if the cable is run a long distance, then the resistance will be high, causing the voltage drop across it to be significant. Otherwise, the voltage drop might be sufficiently small that it wouldn't have an appreciable affect. The result of excessive voltage drop is that the conductors will overheat and the voltage applied to the load will be less than the supply voltage so may not work properly, depending on the type of load. We'll discuss excessive voltage drop in greater detail later on.

FIGURE 2.5
A current takes every available path and then divides in proportion to the amount of resistance in each path. In this illustration, there is a parallel path for the fault current through the grounding conductor and through the person's body. Most of the current flows through the grounding conductor because it has much lower resistance; however, some current also flows through the person.

FIGURE 2.6
A current takes every available path and divides in proportion to the amount of resistance in each path.

Notice that one side of the power supply in Figure 2.7 is at the "ground floor" or 0V. That's because the grounding/earthing electrode (symbolized in the illustration by the three short lines forming a triangle) makes a solid mechanical and electrical connection to the earth. That forces one side of the supply to take the same voltage as that of the earth, which is 0V. This connection is typically a copper rod that is driven into the earth (although there other types of grounding/earthing electrodes), and it is connected to one side of the supply with a grounding/earthing electrode conductor—typically a bare copper wire or a conductor marked with either green tape or green with a yellow stripe, depending on the region of the world. The grounding/earthing electrode is an important part of the power distribution system.

FIGURE 2.7
The sum of the voltages around a circuit is 0V. The supply (V_T) raises the voltage, and the circuit elements (V_1, V_2, and V_3) drop the voltage. In addition to providing lightning protection, the grounding or earthing electrode (indicated by the symbol with the three short lines forming a triangle in the lower left) is there to make sure that that point in the circuit stays at 0V, thereby ensuring the stability of the voltage.

OHM'S LAW

Ohm's law is another natural law of electricity and it is one of the most important and useful fundamental relationships. It relates to just about everything we do as an electrician or technician. For example, when we run a long cable, there will be some voltage drop across it. Whether or not the voltage drop is significant enough to necessitate consideration depends on the current and resistance, and this is related by Ohm's law. Also, if we get shocked, how badly we will be injured depends on the current flowing through our body, which is related by Ohm's law. If we have a good understanding of what Ohm's law is and how to use it, then we will have taken a large step toward demystifying electricity and electronics. Much of what we need to know about electricity and electrical safety is related to Ohm's law.

Ohm's law describes how voltage, current, and resistance are related to each other. It simply says that voltage is the current times the resistance.

$$\text{Ohm's law:} V_{volts} = I_{amps} \times R_{ohms}$$

This is a simple algebra equation, and it is easy to solve for the voltage *V* if we know the values of the current and the resistance. If you know how to use a calculator, then you can solve this problem. But we usually know the voltage. We know, for example, that certain types of batteries supply 9 volts. We know that if we are in France or Germany, the main voltage is typically 230 volts and if we are in North America the voltage is 120 volts. Therefore, we might want to change the equation to predict how much current will flow in a circuit if we know the voltage and resistance. Then we can modify the equation above by using some simple math.

In any equation, there is a balance between the right and left sides of the equal sign (=). If we think of the equal sign as a balance beam, and then we can add, subtract, multiply, or divide one side of the balance beam. As long as we do

the same to the other side, we haven't changed the balance. So, let's start with our original equation and divide both sides by the resistance *R*.

$$V=I\times R$$

$$VR=I\times RR$$

Notice that RR=1, and $I \times 1 = I$, so we can cancel RR, leaving:

$$VR=I\times 1$$

or

$$VR=I$$

Now we can rearrange the formula to put the single variable *I* on the left side. Why? Because in a typical formula the unknown variable, in this case *I*, is on the left. That leaves:

$$I=VR$$

VR is the same as V÷, so it becomes:

$$I=V\div R$$

This equation is just another form of Ohm's law except the unknown variable, the one we're trying to figure out, is the current I.

Many electricians and technicians have a multimeter, so they can measure the voltage and current. But what if we want to figure out the resistance? In that case we can rearrange the equation a slightly different way. We'll start with the original equation, but instead of dividing both sides by the resistance *R*, we'll divide both sides by the current *I*.

$$V=I\times R$$

$$VI=II\times R$$

Again, notice that II=1, and R×1=R, so we can cancel II.

$$VI=1\times R$$

So, we're left with:

$$VI=R$$

Again, we'll rearrange it so that the single variable R is on the left side of the equation.

$$R=VI$$

And finally, we'll replace the fraction bar with the division symbol, and we're left with:

$$R=V\div I$$

Now we have three different equations, all of which are a form of Ohm's law:

$$V=I\times R$$

$$I=V\div R$$

$$R=V\div I$$

The only difference between these three formulas is that there is a different variable on the left side of each equation. In order to solve any equation, there must be only one unknown value and it is easier if we start with an equation where that unknown is on the left. That way, all we have to do is to choose the right equation—the one with the unknown value on the left—and plug in the known values on the right. If, for example, we know the voltage and current and we want to figure out the resistance, we'll use the third equation *(R = V ÷ I). But if we know the voltage and the resistance and we want to figure out the current, we'll use the second equation (I = V ÷ R).*

An easy way to remember these three formulas is to draw a circle with a line through it, and put a "V" on the top and an "I" and an "R" on the bottom, as shown in Figure 2.8:

FIGURE 2.8
This mnemonic helps you recall the three forms of Ohm's law. If you cover the unknown value, it reveals the formula to use. For example, if you cover the V, the formula is I × R. (If there is no operator between the values, that means you need to multiply.) If you cover the I, the formula is V/R, and if you cover the R, the formula is V/I.

This is a mnemonic that can help you remember the three formulas associated with Ohm's law. The way it works is that you cover the value you're looking for and it will reveal the formula. For example, if you cover the V, the formula is I × R. (If there is no operator, that means you need to multiply.) If you cover the I, the formula is V/R; and if you cover the R, the formula is V/I.

Example 2a

Suppose we have a circuit with a 2-amp fuse and a 100-ohm resistor in series (meaning that one terminal of the LED is connected to one terminal of the resistor as shown below). What is the minimum voltage that would cause the fuse to blow?

Answer:

If the fuse blows at 2 amps and the resistor is 100 ohms, then we can use Ohm's law to find out how much voltage will cause 2 amps to flow in the circuit.

$$V=I\times R$$

$$V=2\times 100$$

$$V=200\text{volts}$$

Remember to always include the units of measure in the answer to make sure it is understood properly.

Example 2b

If we have a circuit with a 12-volt battery, a lamp, and a resistor connected in series as shown in Figure 2.9, how much current would flow if the total resistance in the circuit is 150 ohms?

FIGURE 2.9
Circuit with 12-volt battery, lamp, and resistor.

Answer:

$$I=V\div R$$

$$I=12\div 150$$

$$I=0.08\text{amps}(80\text{milliamps})$$

Example 2c

Suppose we have a 24-volt battery, and when we connect it to a circuit and measure the current, we find that it is 10 amps. What is the resistance of the circuit?

Answer:

$$R=V\div I$$

$$R=24\div 10$$

$$R=2.4\Omega$$

VOLTAGE DROP/LINE LOSS

In the real world there is no such thing as a perfect conductor; every component in a circuit or system, including the cable and wiring, has some resistance. It may be small, but it's there. Not only is there resistance in wire, but it also appears across connectors, across the junctions of electronic switches and devices, in the windings of motors and transformers, and more. Sometimes it is small enough that it produces little effect and can be ignored, and other times it has a significant effect. One of those effects is voltage drop, which is sometimes called “line loss.”

Cable usually has relatively low resistance. However, when it conducts current, the combination of the current and the resistance of the cable creates a voltage drop. Voltage is dropped across a cable every time a load is connected and turned on. The question is not whether the drop happens, but how severe the drop is.

If the voltage drop is excessive, then some equipment might not work properly or at all. Many switch-mode power supplies, like those found in computers, consoles, video projectors, digital amplifiers, and so on have an acceptable range of voltage input—typically from about 90 V to 250 V—and excessive voltage drop could cause the applied voltage at the load to drop below the minimum. Another problem with excessive voltage drop is that it is caused by high resistance and/or high current, either of which cause an increase in the heating of the conductors, and that could lead to significant deterioration of the insulation around the conductor, melted connectors, or worse. Excessive voltage drop is a symptom of a problem, which is that too much current is running through a conductor, or that the cross-sectional area of the conductor is too small for the amount of current that it is carrying.

Even feeder cable, like 4/0 AWG (pronounced "four aught"), which is commonly used in North America, or 185 mm^2 (millimeters squared), which is commonly used in Europe and Australia, can have enough resistance when it is used in longer lengths to cause significant voltage drop. The National Electrical Code (NEC) recommends a maximum of 3% voltage drop across the feeder circuit or 3% across the branch or final circuits, but no more than a total of 5% altogether. A current of 250 amps carried through a 300-foot run of 4/0 cable in a 3-phase system would produce a voltage drop of about 3.4% if the temperature is 40° C (104° F).

The voltage dropped across a cable can be calculated using Ohm's law: $V_{Drop} = I \times R$, where I is the current flowing through the cable and R is the resistance of the length of the conductor to and from the load. According to Chapter 9 Table 8 in the NEC, the resistance of 4/0 conductor is 0.0608 ohms per 1000 feet at 75° C (167° F). The resistance can be adjusted for different temperatures using the formula $R_2 = R_1 [1 + \alpha (T_2 - 75)]$, where $\alpha = 0.00323$ for copper, R_1 is the resistance at 75° C, and R_2 is the resistance at the temperature T_2 (in Celsius).

For example, at 40° C (104° F), the resistance of 4/0 is about 0.0539 ohms per 1000 feet {0.0608 × [1 + 0.00323 × (40 − 75)] = 0.0539}. For a 300-foot length of cable, the resistance is 0.01617 Ω [0.05392656 × (300/1000) = 0.01617].

Another way to calculate voltage drop is to use the "specific resistance" of copper, which is the resistance of a one-foot length of copper wire with a cross-sectional area of one circular mil at a given temperature; the higher the temperature, the higher the resistance. One circular mil is very small—it's an area equal to one thousandth of an inch, or, to give some perspective, #18 AWG wire is 1620 mils. The specific resistance of copper at 75°C (167° F) is 12.9 and at 32°C (90° F) it is about 11.

To calculate the voltage drop using the specific resistance of copper, the formula is:

$$VD=2\times K\times I\times L/ACM$$

where K = the specific resistance of copper, I is the current, L is the length in feet (or in meters if K is given in ohms per circular mil-meter), and A_{CM} is the area in circular mils.

This formula assumes the outgoing current is equal to the return current, which is why it has a multiplier of 2 in the formula. That is always the case for branch circuits or final circuits (assuming very little leakage current or fault current!), but it is not the case in 3-phase, 4-wire plus ground systems. In this system, the neutral current can vary from 0 amps if it is a balanced 3-phase load with linear loads (due to phase cancellation) to as high as 170% of the phase current (based on empirical data).

Example 2d

A branch circuit that is 150 feet long is carrying 10 amps. If it is #12 AWG wire, and the cross-sectional area is 6530 circular mils, then the voltage drop at 32°C is:

$$VD=2\times K\times I\times L/ACM$$

$$VD=2\times 11\times 10\times 150/6{,}530$$

$$VD=5.1\ V$$

If it is a 120 V circuit, the voltage that is applied to the load is the supply voltage minus the voltage drop; so the load will have an applied voltage of 114.9 V. The voltage drop can be measured only under load, because, as we can see in the formula, it depends on the current flowing through the conductors. If the load is off, then the current is 0 A and the voltage drop is 0 V.

Table 2.1 Voltage Drop in Across 4/0 AWG Copper Wire at 40° C (104° F) by the Length of the Run and Current.*

Voltage drop for 4/0 cable at 40° C (104° F) and 208 V supply

Length	100 A		150 A		200 A		250 A		300 A	
Feet	Volts drop	%	Volts drop	%	Volts drop	%	Volts drop	%	Volts drop	%
50	0.47	0.22	0.70	0.34	0.93	0.45	1.17	0.56	1.40	0.67
100	0.93	0.45	1.40	0.67	1.87	0.90	2.34	1.12	2.80	1.35
150	1.40	0.67	2.10	1.01	2.80	1.35	3.50	1.68	4.20	2.02
200	1.87	0.90	2.80	1.35	3.74	1.80	4.67	2.25	5.60	2.69
250	2.34	1.12	3.50	1.68	4.67	2.25	5.84	2.81	7.01	3.37
300	2.80	1.35	4.20	2.02	5.60	2.69	7.01	3.37	8.41	4.04
350	3.27	1.57	4.90	2.36	6.54	3.14	8.17	3.93	9.81	4.71
400	3.74	1.80	5.60	2.69	7.47	3.59	9.34	4.49	11.21	5.39
450	4.20	2.02	6.30	3.03	8.41	4.04	10.51	5.05	12.61	6.06
500	4.67	2.25	7.01	3.37	9.34	4.49	11.68	5.61	14.01	6.74

*The cells in red indicate conditions that exceed the recommended 3% voltage drop as a percentage of 120V, per the NEC.

Example 2e

#12 AWG wire has a characteristic resistance of 5.20864 ohms per kilometer. What is the resistance of a 100-meter run?

Answer: 5.20864 ohms per 1000 meters is the same as 0.00520864 ohms per meter. Therefore, to find the total resistance of a length of wire, we can multiply that number by the number of meters in the run.

$$\text{Resistance ohms} = 0.00520864 \text{ ohmspermeter} \times 100 \text{ meters} = 0.520864 \text{ ohms}$$

RESOLVING EXCESSIVE VOLTAGE DROP

There are a few different ways to remedy excessive voltage drop. One way is to decrease the length of the run, which decreases the total resistance of the conductors. The resistance of wire is based on the amount of copper (or whatever the conductive material) through which the current travels. If we shorten the length of the run by half, the resistance will drop by half, which will cut the voltage drop in half.

We can also decrease the resistance of the circuit by increasing the wire size (cross-sectional area). A larger cross-sectional diameter provides a less restrictive path for the flow of current, and therefore decreases the resistance. In the American Wire Gauge (AWG) system, a smaller number actually translates to bigger wire. For example, going from #12 AWG to #10 AWG increases the cross-sectional area from 3.3 mm^2 to about 5.3 mm^2.

There are two different types of loads: passive loads and active loads. Depending on the type of load involved, boosting the voltage can make the problem worse. Passive loads, like incandescent lamps, have a fixed resistance and no active electronics—like transistors, capacitors, or inductors—to compensate for varying voltage conditions. If the voltage applied to a passive load drops, then less current will flow. (That's how dimmers work; the dimmer drops the effective RMS voltage, which drops the current and power is applied to the lamp.) If the applied voltage rises, then more current will flow. If we boost the voltage in a circuit with passive loads in order to compensate for excessive voltage drop, then more current will flow and the voltage drop will increase (remember, $V_{drop} = I \times R$), making the problem worse. Examples of passive loads are incandescent lamps, heating elements, and motors.

An active load has active electronics that ensure the load receives the right amount of power. If the voltage applied to an active load drops, the current will rise so that the power stays the same. If the applied voltage rises, then the current will fall to compensate. If you are on portable generator power, you will often have the option of boosting the voltage using the automatic voltage regulator (AVR). However, boosting the voltage at a portable generator by adjusting the AVR makes the generator run harder and hotter, and can shorten its life. It will also increase the voltage to other loads closer to the supply, which may or may not be a problem.

SERIES RESISTANCE

When two or more components are connected in a circuit end to end, they are connected in series, as illustrated by the resistors illustrated below. (See Figure 2.10.)

FIGURE 2.10
A network of resistors in series.

If we wanted to know how resistors connected in series behave, we could replace this network of resistors with one resistor of the equivalent value. The equivalent resistance of several resistors connected in series is just the sum of the individual resistors.

$$R_{total}=R_1+R_2+\ldots+R_{n-1}+R_n$$

where n = the total number of resistors in series

Example 2f

If a 100' length of 4/0 AWG cable has a resistance of 0.00608 Ω, what is the resistance of four lengths of this cable connected in series? (See Figure 2.11.)

FIGURE 2.11
What is the equivalent resistance of this network of resistors?

Answer: The total resistance can be calculated by adding the value of each resistor in the series.

$$R_{total}=0.00608+0.00608+0.00608+0.00608$$

$$R_{total}=0.02432\ \Omega$$

Example 2g

Six resistors with the following values are connected in series: 120 ohms, 150 ohms, 100 ohms, 100 ohms, 250 ohms, and 500 ohms. What is the equivalent resistance? (See Figure 2.12.)

FIGURE 2.12
What is the equivalent resistance of this network of resistors?

Answer:

$$R_{total}=120+150+100+100+250+500$$

$$R_{total}=1220 \text{ ohms}$$

PARALLEL RESISTANCE

When two or more resistors are all connected across two common nodes as shown in the illustration below, they are connected in parallel. (See Figure 2.13.)

FIGURE 2.13
A network of resistors in parallel.

To find the equivalent resistance of a network of n resistors in parallel, use the formula below:

$$1Rtotal=1R1+1R2+\ldots+1Rn-1+1Rn,$$

where R_{total} is the total resistance, R_1 is the first resistor, R_2 is the second resistor, R_{n-1} is the second to last resistor, and R_n is the last resistor.

Example 2h

An electrician finds excessive voltage drop across a 400’ run of 4/0 AWG feeder cable. The portable power generator has a connection panel with four sets of camlock connectors, so she decides to run four sets of feeder in parallel. If a 400’ run of 4/0 AWG has a resistance of 0.0432 Ω, what is the equivalent resistance of four sets connected in parallel?

Answer:

$$1Rtotal=1R1+1R2+\ldots+1Rn-1+1Rn$$

$$1Rtotal=10.02432\Omega+10.02432\Omega+10.02432\Omega+10.02432\Omega$$

$$1/Rtotal=1\div0.02432+1\div0.02432+1\div0.02432+1\div0.02432$$

$$1/Rtotal=41.12+41.12+41.12+41.12$$

$$1/Rtotal=164.48$$

$$Rtotal=1/164.48=1\div164.48=0.00608\ \Omega$$

Example 2i

Six resistors with the following values are connected in parallel: 120 ohms, 150 ohms, 100 ohms, 100 ohms, 250 ohms, 500 ohms. Find the equivalent resistance in Figure 2.14.

FIGURE 2.14

Answer:

$$1Rtotal=1R1+1R2+1R3+1R4+1R5+1R6$$

$$1R_{total}=1120+1150+1100+1100+1250+1500$$

$$1/R_{total}=1\div120+1\div150+1\div100+1\div100+1\div250+1\div500$$

$$1/R_{total}=0.0083+0.00667+0.01+0.01+0.004+0.002$$

$$1/R_{total}=0.041$$

$$R_{total}=24.39 \text{ ohms}$$

SERIES/PARALLEL RESISTANCE

If a circuit has resistors connected both in series and in parallel, the equivalent resistance can be found by replacing the parallel resistors with the equivalent resistance and then calculating the equivalent resistance of the remaining network of resistors. First, calculate the equivalent resistance of the parallel resistors and then replace them with the equivalent value. Then, redraw the network using the equivalent resistance of the parallel network of resistors and calculate the equivalent resistance of the series resistors.

Example 2j

What is the equivalent resistance of the circuit in Figure 2.15?

FIGURE 2.15

Answer:

Step 1: Calculate the value of the parallel resistor network. From the above example, we know the total resistance is 24.39 Ω.

Step 2: Replace the parallel resistor network with a single resistor of the same value and redraw the network as shown in Figure 2.16.

FIGURE 2.16

Step 3: Sum the series resistors: R_{total} = 100 + 24.39 + 100 = 224.4 Ω.

SHORT CIRCUITS AND GROUND FAULTS

Under normal circumstances, every electrical circuit has resistance. If the resistance is so low that it is negligible (meaning very close to 0 Ω), then it is a short circuit, and a huge amount of current will flow, causing everything in the path of the current to get very hot. If the circuit is built correctly and has overcurrent protection—meaning a fuse or circuit breaker—then it will interrupt the circuit; hopefully before any damage can occur. One of the most common causes of a short circuit is faulty wiring, and the most common cause of faulty wiring is damaged insulation due to aging and deterioration, mechanical damage (cuts, punctures, abrasions, etc.), excessive heat, water or moisture, oil, dirt, and vibration.

It is not surprising that the concept of infinity is a bit challenging to grasp. The opposite of infinity is zero, and the concept of zero is relatively new to humans. Before it was first developed in the third or fourth century A.D. in India, people understood the idea of nothing, yet it wasn't part of their understanding of math. Today, it seems we're in a similar situation with the concept of infinity. Some of us have been told that you can't divide by 0. If you use your calculator to calculate any number divided by 0, it will read “error,” “not a number,” or something similar. Yet, there really is a real-world equivalent of infinity. For example, what is the resistance of an open circuit? If you could measure the resistance of a blown fuse, what would it read? The answer is ∞ Ω (infinity ohms).

Infinity Amps

According to Ohm's law, the current *I* is equal to the voltage *V* divided by the resistance *R* (I = V ÷ R). But what would happen if the resistance in a circuit was 0 Ω? (In real life, there is no such thing as a circuit with 0 Ω because even the most conductive materials, like gold and silver, have a little bit of resistance.)

Yes, I'm aware that your primary school teachers probably told you that you cannot divide by zero. At the risk of dashing your childhood memories of your beloved teachers, they lied to you. But in their defense, they did it for your own sake. After all, when you're young and impressionable, if you were to contemplate the concept of infinity, your little head might explode. So, to help you avoid that mental distress, they told you that you cannot divide by zero. But now that you are older, it's time that you faced the facts; you *can* divide by zero.

To illustrate, look at the sequence below and see if you can identify a pattern:

$$1 \div 1 = 1$$

$$1 \div 0.1 = 10$$

$$1 \div 0.01 = 100$$

$$1 \div 0.001 = 1000$$

$$1 \div 0.0001 = 10{,}000$$

$$1 \div 0.00001 = 100{,}000$$

$$1 \div 0.000001 = 1{,}000{,}000$$

Do you see where this is going? The smaller the divisor is, the larger the answer is. If we keep going, eventually the divisor will be so small that it might as well be zero, and the answer will be so large that it might as well be infinity. The truth is, any number divided by zero is infinity.
You still don't believe it? Okay, what is 1 ÷ 0.000000000000000000000000000001?
The answer is 1,000,000,000,000,000,000,000,000,000,000. That's 30 zeros after the decimal point in the divisor and 30 zeros after the 1 in the answer. What if we put 1000 zeros after the decimal point? Or a million zeros? How about a million million zeros? We could keep going, and we will…unless you admit the truth. One more time; what is any number divided by 0? *Infinity*.

RESISTANCE AND HEAT

Exceeding the ampacity of a circuit will cause components in the path of current to overheat. However, as long as we have overcurrent protection like fuses and circuit breakers that are working properly, the circuit will be interrupted, preventing components from getting dangerously hot and melting down. Yet we sometimes see connectors and other components overheat, arc, and melt. Why does this happen?

It turns out that resistance converts current to heat. An incandescent lamp, for example, has a tungsten filament. Although tungsten is a conductor, it has enough resistance that when current passes through it, it gets hot enough to give off light. This is the process of incandescing. But as long as the current does not exceed the rating of the overcurrent protection device, then it will not blow the fuse or trip the circuit breaker. Sometimes high resistance produces enough heat to cause high enough temperatures to melt connectors and start a fire without triggering the overcurrent protection device. This can happen when connectors are not mated correctly or mate loosely and don't make very good contact between the pins. (See Figure 2.17.)

FIGURE 2.17

When the pins in an electrical connector mate too loosely, they create high resistance. When current passes through high resistance, the electrical energy is converted to heat energy. If the current isn't high enough to trip the overcurrent protection it can melt the connector and possibly start a fire.

UNDERSTANDING CIRCUITS

2.1 Is an electrical receptacle with nothing connected to it an open circuit or a complete circuit?

2.2 Suppose a device has a short circuit (effectively 0 Ω). If you were to connect it to an electrical receptacle and turn it on, how much current would flow?

2.3 If you applied 120 volts to a circuit with infinity resistance, how much current would flow?

2.4 The resistance of the human body is drastically reduced when the skin is wet. If your hands are wet and you are shocked, would more or less current flow through your body compared to being shocked with dry hands?

2.5 In Figure 2.7, if V_T is 240 V, V_1 is 80 V, and V_2 is 80 V, how many volts is V_3?

2.6 Aircraft landing lights (ACLs) are sealed-beam, 28-volt PAR lamps that were popular in concert lighting before automated lighting and LEDs. They are typically wired in series (end to end) and connected to a 120-volt supply. Under those circumstances, how much voltage is dropped across each of the four lamps?

2.7 When you connect a load using an extension cord, if the wire gauge is too small or the cable is too long, the resistance of the conductors will be relatively high. When current passes through it, excessive voltage drop can be created across the extension cord. If the supply voltage is 240 volts, the hot or live conductor drops 2.5 volts, and the neutral drops 2.5 volts, how much voltage would be applied to load?

2.8 In a 24-volt circuit, a lamp draws 6.25 amps. What is the resistance of the filament in the lamp?

2.9 A 12-volt circuit has a 3-amp fuse. How much resistance is needed in the circuit to keep the fuse from blowing?

2.10 If a current of 1 amp is flowing through a 150-ohm resistor, what is the voltage drop across the resistor?

2.11 A 9-volt battery is connected to an axial fan and it draws 0.1 amps (or 100 milliamps). What is the effective resistance of the fan?

2.12 A 150-ohm heating element is connected to a 24-volt circuit. How much current will it draw?

2.13 A current of 5 amps is flowing through a circuit with a 9-volt battery. What is the resistance of the circuit?

2.14 A 24-volt battery is connected to two 100-ohm resistors wired in series (end to end). If a current of 0.12 amps is flowing through the circuit, what is the resistance of the two resistors in series?

2.15 A load draws a current of 6 amps when it is connected to a 12-volt battery. If the voltage is increased to 24 volts, how much current will flow through it?

2.16 If a 12-volt battery produces a current of 0.5 amps (or 500 milliamps), what is the resistance of the circuit?

2.17 How many millivolts (mV) would it take to produce a current of 0.01 amps (or 10 milliamps) in a circuit with resistance of 10 ohms? (Hint: 1000 millivolts = 1 volt.)

2.18 How much current would flow through a 120-Ω resistor if it has a 5-volt power supply?

2.19 If a 12-volt battery causes a current of 0.1 amps to flow, what is the resistance of the circuit?

2.20 How much current will flow in a 1-volt circuit if the resistance is 0.1 ohms?

2.21 How much current will flow in a 1-volt circuit if the resistance is 0.01 ohms?

2.22 How much current will flow in a 1-volt circuit if the resistance is 0.001 ohms?

2.23 How much current will flow in a 1-volt circuit if the resistance is 0.0001 ohms?

2.24 How much current will flow in a 1-volt circuit if the resistance is 0.00001 ohms?

2.25 How much current will flow in a 1-volt circuit if the resistance is 0.000001 ohms?

2.26 How much current will flow in a 1-volt circuit if the resistance is 0.0000001 ohms?

2.27 How much current will flow in a 1-volt circuit if the resistance is 0.00000001 ohms?

2.28 In general, if the voltage is the same, when the resistance goes down, the current goes _____.

2.29 Most multimeters have a "continuity" setting that allows you to test a circuit for electrical continuity. In the continuity mode, the meter will emit a tone when the two leads are connected to a complete circuit. If a meter in continuity mode does not emit a tone when the leads are connected to the two pins of an incandescent lamp or a fuse, what does that tell you?

CHAPTER 3
DC Power

In Thomas Edison's time, the technology to change the voltage in a DC circuit did not exist. But we could change AC voltages, thanks to Lucien Gaulard and John Dixon Gibbs, who invented the transformer late in the nineteenth century. George Westinghouse bought the Gaulard-Gibbs patent after seeing a demonstration of a transformer at the Inventions Exhibition in London and he began building AC generators, transformers, and power distribution systems around 1881. By that time, Edison had already established a number of electrical utilities that provided DC electricity to its customers. When Westinghouse ramped up his business, it set the stage for the battle of the two technologies—AC versus DC. In the end, economy won out. A transformer enables AC to be transmitted at higher voltages and lower current, allowing much smaller and cheaper conductors, which is why the world gravitated towards AC instead of DC.

Today, we can use DC-to-DC inverters to change the voltage in DC circuits, and there's no longer a technological advantage to using AC over DC. And since most everything we use in live event production has a power supply that ultimately converts the incoming power to low-voltage DC, it is possible that we could go back to using DC again. If and when it becomes economically advantageous to do so, it will likely happen.

ELECTRICAL POWER

Electricity is energy, and energy cannot be created, nor can it be destroyed; it can only change forms. Typically, a generating station converts chemical energy to heat energy by burning fossil fuels like coal, natural gas, or diesel, and then using it to boil water and create steam to spin a turbine, which converts heat energy to kinetic energy. The turbine is coupled with an alternator, which converts kinetic energy to electrical energy. In an electrical circuit, electrical energy can be changed to light, heat, sound, or motion. When that happens, “work” is being done. The rate at which electrical energy is being changed to some other form of energy is electrical power, which is measured in watts.

Understanding electrical power is important because it is directly related to the amount of power distribution equipment we need to do our jobs, including the amount of supply we need (i.e., how many amps will our system draw from the feeder transformer or generator supplying power), how many power distribution racks will be needed, how many branch or final circuits, and how many devices can be connected to each branch or final circuit.

Although the vast majority of the time, we are using alternating current, we'll start discussing DC power before being introduced to AC systems. DC power is important to understand and it is much simpler than AC power.

THE DC POWER FORMULA

Power is measured in watts, and the wattage is the rate at which electrical energy is being converted to other forms of energy, like light, sound, heat, or motion. In a DC system, electricity is being converted any time current is flowing through a load. The greater the flow of current, the more power is being used.

Electrical power is also related to voltage and current: the higher the voltage across a load (assuming a complete circuit in which current is flowing through the load), and the greater the current flowing through the load, the more power being used.

In a DC circuit, power is equal to the voltage times the current.

$$P \text{ watts} = V \text{ volts} \times I \text{ amps}$$

We can use basic algebra to arrive at three different versions of this formula. If we start with the original equation and divide both sides by the current *I*, we end up with:

$$PI = V \times II$$

$$PI = V \times II$$

And since II= 1…

$$PI = V \times 1$$

$$PI = V$$

Now let's rearrange this so that the unknown value, V, is on the left…

$$V = PI$$

$$V = P \div I$$

This is another form of the DC power formula. We can also start with the original equation and, instead of dividing both sides by the current I, divide both sides by the voltage V. Then we end up with:

$$PV = V \times IV$$

$$PV = VV \times I$$

$$PV = 1 \times I$$

$$PV = I$$

$$I = PV$$

$$I = P \div V$$

Now we have three different forms of the DC power formula, each of which has a different variable (the unknown value) on the left side:

1. $P = V \times I$
2. $V = P \div I$
3. $I = P \div V$

Depending on which two values we know and which one we don't, we can pick the right formula to solve the problem. An easy way to remember these three formulas is to draw a circle with a line through it, and put a “P” at the top, and “V” and “I” at the bottom, as shown in Figure 3.1:

FIGURE 3.1
This mnemonic helps you recall the three different versions of the DC power formula. If you cover the unknown value, it reveals the formula to use. For example, if you cover the P, the formula is V × I. (If there is no operator between the values, that means you need to multiply.) If you cover the V, the formula is P/I, and if you cover the I, the formula is P/V.

Figure 3.1 shows a mnemonic that can help you remember the three variations of the DC power formula. The way it works is this: if you cover the value you are looking for, the right formula will be revealed. For example, if you cover the P, the formula is V × I. (If there is no operator, that means you need to multiply.) If you cover the V, the formula is P/V, and if you cover the I, the formula is P/V.

Example 3a

If we connect a 12-volt battery to a lamp, measure the current, and find that it draws 2.5 amps, how much power is being used?

Answer:

In this case, we are given the values for V and I, which are 12 volts and 2.5 amps respectively. The unknown value is P, so we'll use the formula P = V × I. Then, we will substitute the known values like this…

$$P=12\times2.5$$

$$P=30\text{ W}$$

Example 3b

If we have a 100-watt power supply and we want to limit the current drawn by any load to no more than 5 amps, what is the maximum voltage we should apply to the load?

Answer:

$$V=P\div I$$

$$V=100\div5$$

$$V=20\text{ V}$$

Example 3c

How much current will be drawn by a 120-watt load if it is connected to a 9-volt battery?

Answer:

$$I=P\div V$$

$$I=120\div9$$

$$I=13.3\text{ A}$$

Example 3d

We have a 500-watt load that we want to power using a 5600 watt-hour battery. How long can we power the load on a single charge? (Hint: the units of measure of the battery capacity are watt-hours, which means you multiply the wattage of the load by the time in hours to get the capacity. Or, if you divide the capacity by the wattage, you will get the time in hours.)

Answer:

$$\text{Battery capacity} = \text{wattage} \times \text{time}$$

$$5600 \text{ watt-hours} = 500 \text{ watts} \times \text{time}$$

$$\text{Time} = 5600 \text{ watt-hours} \div 500 \text{ watts} = 11.2 \text{ hours}$$

THE WEST VIRGINIA FORMULA

The unit of measure of power is watts, the unit of measure of voltage is volts, and the unit of measure of current is amps. If we start with the DC power formula and change all of the variables to their unit of measure, it becomes:

$$\text{Watts} = \text{Volts} \times \text{Amps}$$

This is what some people sometimes refer to as the "West Virginia" formula because, using abbreviations, it becomes $W = V \times A$, which is just an easy way to remember the formula.

The West Virginia formula (or, more correctly, the DC power formula) sometimes works with AC circuits, *but not always*. The formula for AC power is similar to the DC power formula but it has a very important difference, which is related to something called "power factor" (PF). In short, power factor is the ratio of how much current a load is converting to light, sound, heat, or motion compared to how much current it draws. In an AC circuit, some loads draw current but store some of the energy rather than convert it; therefore, the power factor is less than 1. If the load converts 100% of the energy that it draws rather than storing it, then the power factor of the load is 1 (sometimes referred to as "unity") and the AC and DC formulas work out to be the same; otherwise, the DC and AC power calculations would yield much different results. The key is whether or not the power factor is 1 or close to 1. In an AC circuit, the power factor can range from 0 to 1, and in a DC circuit it is always 1. The power factor of a load is not always included in the specifications, but any purely resistive load, like an incandescent lamp, heating element, or resistor always has a power factor of 1; thus, we can safely use the DC power formula. On the other hand, any device that contains capacitors or inductors, such as a switch-mode power supply, might have a power factor other than 1. (See Power Factor in Chapter 6.)

An incandescent lamp is a purely resistive load because it has no capacitors or inductors, only a tungsten filament with relatively high resistance. If we wanted to calculate the resistance of an incandescent lamp, like an HPL, we could figure it out by looking at the specifications. For example, an HPL 750/115 is listed as a 750-watt lamp at 115 volts. Using the West Virginia formula (because, even though we're using AC, this is a purely resistive load, so the power factor is 1), we can calculate the current draw:

$$I = P \div V$$

$$I = 750 \div 115$$

$$I = 6.5 \text{ A}$$

Once we know the current draw, we can use Ohm's law to calculate the resistance of the filament at the rated voltage and current:

$$R = V \div I$$

$$R = 115 \div 6.5$$

$$R = 17.7\ \Omega$$

Example 3e

An HPL 575/120 lamp is listed as a 575-watt lamp at 120 volts. What is the resistance of the filament at the rated voltage and current?

Answer:

The first step is to calculate the current draw using the West Virginia formula:

$$I=P\div V$$

$$I=575\div 120$$

$$I=4.8\ A$$

Once we know the current draw, we can use Ohm's law to calculate the resistance of the filament at the rated voltage and current:

$$R=V\div I$$

$$R=120\div 4.8$$

$$R=25\ \Omega$$

In the two examples above, we used a two-step approach to solve the problem. We can combine those two steps by using substitution. Starting with the West Virginia formula, we can use Ohm's law to substitute for the current *I*.

$$P=V\times I$$

But I = V ÷ R, so we can say

$$P=V\times V\div R$$

$$P=V2\div R$$

Example 3f

An HPL 375/115 lamp is rated 375 watts at 115 volts. What is the resistance of the filament at the rated voltage?

Answer:

$$P=V2\div R$$

$$R=V2\div P$$

$$R=1152\div 375$$

$$R=13{,}225\div 375$$

$$R=35.3\ \Omega$$

We can also start with the West Virginia formula and then substitute for the voltage *V* using Ohm's law.

$$P=V\times I$$

But V = I × R, so we can say

$$P=I\times R\times I$$

$$P=I\times I\times R$$

$$P=I2\times R$$

Now we have a total of five equations related to power. The last two are:

4. $P = V^2 \div R$
5. $P = I^2 \times R$

The equation we use depends on what we know (the knowns) and what we don't know (the unknowns). There are at least four different quantities that we can know about a circuit, including power, voltage, current, and resistance. In order to solve any equation with three values, there must be two known values. Finding the right answer starts with selecting the right equation, which is the one with the unknown on the left and the two knowns on the right.

Example 3g

A circuit is wired with 100 meters of 1.5 mm wire (50 meters from the supply to the load and 50 meters back to the supply). The resistance of the wire is approximately 12 ohms per 1000 meters. When current flows through the conductor, the combination of the current and resistance causes it to heat up. How much power is converted to heat (called the I^2R loss) if the current is 16 amps?

Answer:

$$P=I2\times R$$

The current is 16 amps, and the total resistance of the branch circuit is one-tenth of 12 ohms, or 1.2 ohms. Therefore,

$$P=16\text{ amps}2\times 1.2\ \Omega=256\times 1.2$$

$$P=307.2\text{ watts}$$

Finding the voltage, current, resistance, or power is simply a matter of examining the known values and using the right formula to calculate the unknown value. The chart in Figure 3.2 is useful for identifying the knowns and the unknowns and for choosing the right formula.

FIGURE 3.2
The formula wheel with voltage, resistance, current, and power formulas. To find the unknown, identify the quadrant in which it appears, then find the formula in that quadrant with the two known values.

Power in an AC circuit is not as straightforward as in a DC circuit because of the nature of alternating current. We will discuss AC power later on in this book.

UNDERSTANDING DC POWER

3.1 A 12-volt lamp draws 10 amps at the rated voltage. What is the power of the lamp?

3.2 A lamp is rated 150 watts at 12 volts. How many amps will it draw at the rated voltage?

3.3 How much current is drawn by a lamp rated 250 watts at 24 volts?

3.4 An incandescent lamp has a tungsten filament through which current flows, which causes it to heat up and give off light. That is the process of incandescing. If an incandescent lamp is rated 60 watts at 12 volts, what is the resistance of the filament at the operating temperature?

3.5 If a resistor consumes 100 watts at 12 volts, how much power will it use if it is connected to a 9-volt power supply? (Hint: find the value of the resistor, then the current at 9 volts.)

3.6 A 48-volt battery is rated 1200 mAh (milliamp-hours). If you use it to power a 120-watt load, how long can it run on a full charge?

3.7 A 5600 watt-hour battery is used to power four 120-watt LEDs. How long can they run on a full charge?

3.8 How many 48 V, 1200 mAh batteries would be needed to power four 90-watt, 48 V lamps for eight hours?

3.9 A solar panel can supply 265 watts at full power. If the voltage is 30.96 volts, what is the output current?

CHAPTER 4

Introduction to Alternating Currents

All of the circuit laws, including Ohm's law, apply to both AC and DC circuits. There are other factors, like power factor and harmonics, that don't affect DC circuits but might come into play in an AC circuit. These factors can have a significant impact on a power distribution system by increasing the current draw for a given wattage, increasing the amount of heat that is generated by a circuit, and more. This, in turn, could affect the supply requirements for a given system, the amount of power distribution equipment needed, the number of devices we can connect to a branch circuit or a final circuit, and more. To better understand these concepts and their effects, it helps to understand the AC waveforms and how they are generated.

MAGNETISM

Your primary or middle school teacher may have demonstrated what the lines of flux of magnetism look like by sprinkling iron filings on a plate of glass with a magnet underneath. The filings line up along the magnetic lines of flux, as shown in Figure 4.1.

FIGURE 4.1
You can't see magnetism, but if you sprinkle iron filings over glass with a magnet underneath, the magnetic lines of flux around the magnet become apparent.

These lines of flux represent equal strength of the magnetic field just as a topographic map shows lines of contour showing equal elevation. If you follow one line of magnetic flux from the north pole to the south pole, the strength of the magnetic field stays the same. If, however, you cut across the lines of flux, then the magnetic field gets stronger or weaker, depending on whether you're moving closer or farther away from the magnet. Electricity and magnetism are linked, and they have an effect on one another.

ELECTROMAGNETISM

In the early nineteenth century, very little was known about electricity. One day in the spring of 1820, a Danish physicist named Hans Christian Ørsted, who taught at Copenhagen University, was giving a lecture about the heat generated by a current flowing through a platinum wire. There happened to be a compass on his desk in the vicinity of the wire. When the current started flowing, he noticed that the needle deflected. He discovered that the flow of current produced a magnetic field, a phenomenon known as electromagnetism. After studying the effect for a few months, he learned that the magnetic field around a current-carrying conductor has a specific orientation. The lines of flux of the magnetism surround the conductor in concentric rings and diminish in strength as they get farther from the conductor. (See Figure 4.2.)

FIGURE 4.2
When current flows, it produces a magnetic field around the conductor that is oriented at right angles to the direction of the flow of current.

If you wrap the fingers of your right hand around a current-carrying conductor and stick your thumb out in the direction of the flow of current, your fingers indicate the orientation of the magnetic lines of flux. That's called the right-hand rule, which is a way of visualizing the orientation of the magnetic lines of flux around a current-carrying conductor. (See Figure 4.3.)

FIGURE 4.3
The magnetic field produced by the flow of current is called electromagnetism. If you grasp a conductor with your right hand and point your thumb in the direction of the current flow, your fingers will indicate the direction of the magnetic lines of flux.

Electromagnetism is inextricably linked with the flow of current. Each and every time you set up a power distribution system, connect one or more loads, and turn them on, there is a magnetic field around the conductors. The magnetic fields around a single conductor, like a feeder cable, can be very strong because they typically carry a lot of current: the higher the current, the stronger the magnetic field. But branch circuits or final circuits have at least two or more conductors, one of which carries current to the load and the other carries current back from the load; therefore, the magnetic fields are equal and opposite, and they cancel. The cancellation, however, is not perfect, and there can be hot spots of magnetism along the length of the conductors.

Anyone who has ever set up an audio system knows that this simple fact can result in electromagnetic interference (EMI), which causes hum, and that is the bane of the audio tech's existence. There are many sources of EMI, including the magnetic fields generated by power cables, and it can be tricky to find and reduce or eliminate the noise.

It helps to use good quality, balanced and shielded audio cables and to use techniques that will help minimize magnetic fields and their effects. For example, when you are setting up an audio system, the further away you can keep the signal cables from the power distribution system, the less chance you'll have of inducing noise into the system. It is a good practice to run signal cable, like microphone cables, at least three feet away from power cables, and if they must cross, they should cross at right angles to each other so that the signal cable doesn't cut any lines of flux, which is how noise is induced into the signal cable.

You can also minimize strong electromagnetic fields by not coiling excess feeder cable. Since feeder cable is single-conductor cable that typically carries a lot of current, coiling it creates a very strong magnetic field, which can induce noise into any nearby signal cable, including audio and video cable. If there is excess feeder cable, laying it in a figure “8” will minimize the chance of EMI because one half the magnetic field is in one direction and in the other half is in the opposite direction; so, taken as a whole, the magnetic fields cancel.

FIGURE 4.4
Feeder cable is single-conductor cable, and typically carries a lot of current, which generates a strong magnetic field. If the excess cable is coiled, it increases the strength of the magnetic field, which can cause problems. A better solution is to "figure eight" the excess feeder cable, as shown in Figure 4.4.

This is not necessary with branch circuits or final circuits, or with any cable that carries both outgoing current and return current because, in theory, the magnetic fields cancel.

THE AC GENERATOR

In the early 1800s, an English physicist named Michael Faraday discovered that when the lines of flux of a magnetic field are cut by a conductor and the conductor is part of a complete circuit, it will cause current to flow through the conductor. If it is an open circuit, then it will produce voltage across the conductor. This is known as Faraday's law of induction, and it laid the groundwork for the development of generators, transformers, motors, and solenoids, each of which couple inductively between a magnetic field and an electrical circuit.

To illustrate how it works, suppose we bend some wire in a rectangular loop and insert it in a magnetic field so that two sides of the loop are perpendicular to the lines of flux of the magnetic field, as shown in Figure 4.5. The two leads of the wire connect to slip rings that allow us to rotate the loop and still tap into the circuit to measure the voltage being generated.

FIGURE 4.5
Spinning a loop of wire in a magnetic field will generate voltage across the conductor.

As the wire spins, the two sides of the conductor cut the lines of flux at a right angle to the radius of travel. (See Figure 4.6).

FIGURE 4.6
As the loop of wire spins, it cuts through the magnetic lines of flux. The two arrows show the direction of travel.

When the loop is straight up and down, one of the wires is at the top of the circle (0°) and the other is at the bottom (180°), and the direction of travel at that moment in time is parallel to the lines of flux. That means that they are not cutting across the lines of flux, so no voltage is generated. As the loop spins clockwise, the wires increasingly cut more lines of flux and the voltage rises. When one of the wires is at 90° and the other at 270°, they are both traveling at a right angle to the flux and they generate the peak voltage. As they continue to rotate, the voltage drops as they move closer to parallel to the lines of flux. When they rotate past 180° and 360°, they start generating a negative voltage because they are cutting lines of flux in the opposite direction—one of the wires is moving up through the lines of flux instead of down, while the other is moving down instead of up. Another quarter of a rotation later, the negative peak voltage is reached before it starts rising back to 0 again. After the spins one full cycle, it returns to its original starting point and it starts over again. Figure 4.7 shows eight points of the cycle.

FIGURE 4.7
Rotor position and angle with the associated direction of travel for a 2-pole generator.

The result is that the voltage being generated by this generator follows a cyclical pattern that starts at 0 volts and rises smoothly to a peak value before falling back to 0 volts, and then it goes to a negative peak value before going back to 0 volts again. It repeats this pattern over and over. The waveform it follows is called a sine wave. (See Figure 4.8.)

FIGURE 4.8
In an AC waveform, the voltage fluctuates between a positive peak value and a negative peak value.

The way this simple machine works is an example of a synchronous generator, meaning that speed of rotation is synchronized with the frequency that the voltage waveform repeats itself: the faster the rotation, the faster the sine wave is traced out and repeated. The frequency of repetition of the waveform is an important value, and it is measured in cycles per second—which is the same as hertz (Hz), after the German physicist Heinrich Hertz.

Frequency is standardized worldwide to either 50 or 60 Hz, depending on which part of the world you are in. In North America, parts of South America, and other parts of the world, the frequency is 60 Hz; in Europe, Australia, Asia, Russia, Africa, and parts of South America, the frequency is 50 Hz. The voltage and the types of connectors used also depend on which country you are in.

RMS VALUES

The voltage and current in an AC system are constantly changing at a rate equal to the frequency of the supply. The cycle starts at 0, rises to a positive peak, falls back to zero, goes to a negative peak, then back to 0, and repeats that cycle over and over again, all in a fraction of a second. Yet we always associate AC voltages and currents with a single number, like 120 volts in North America or 230 volts in Europe and Australia. (See Appendix 5: Worldwide Voltages and Frequencies.) Why do we represent a constantly changing value, like AC voltage or current, with a single number?

The answer is that when we call out alternating-current values, it is implied that we're referring to the root-mean-square (RMS) value. RMS is single number that is calculated from a continuously changing, repeating waveform like a sine wave, and it is related to the peak value of the waveform or the amplitude of the waveform.

What, exactly, is the root mean square, or the RMS value of a waveform like a sine wave? It is a way of equating a variable waveform to its equivalent DC value. There is a formula for calculating the RMS value of any periodic waveform, and it involves sampling the waveform at regular intervals, squaring them, calculating the mean value of the squared sample points, and then taking the square root of the result. (It is not important to know that formula or how to use it, although, if you really want to, there's more information in Appendix 8: Useful formulas.)

Why do we use RMS values? Because the first electrical systems that Thomas Edison built and installed in the 1890s were DC systems, but the world soon switched to AC. When that happened, many factories, office buildings, and some homes already had DC systems installed and they simply replaced the source. Since the lamps, sockets, wiring, switches, fuses, and so forth were already in place, they didn't want or need to replace anything except the supply. But it was very important that the new AC supply delivered the same amount of energy as the DC supply it was replacing. Otherwise, the lamps would either burn too brightly but wouldn't last long, or they wouldn't burn bright enough and they would last a very long time.[1] If the RMS value of the AC supply matches the DC value, then the lamp brightness and lamp life would be the same.

The RMS value is essentially the equivalent DC value; i.e., 240 VAC (RMS) delivers the same energy to the load as 240 VDC. The RMS voltage is sometimes referred to as the "heating equivalent" voltage because it would heat electric heating element to the same temperature as would the equivalent DC voltage.

Suppose you had an autotransformer that allowed you to raise or lower the peak value of an AC voltage waveform by turning a dial. (The peak value of a waveform is called the "amplitude.") Now suppose you had two 100-watt incandescent lamps, one of which was connected to 120 VDC and the other connected to your autotransformer. If you wanted to match the brightness of the two lamps you could turn the dial on the autotransformer to change the amplitude of the AC voltage until the lamps were exactly the same intensity. If you did that, you would find that the peak value of the AC voltage was such that, if you applied the formula for the RMS value to that voltage waveform, it would equal the DC value. The peak value of the AC voltage, in this case, would be 169.7 volts because the RMS value for a sine wave is 0.707 times the peak value, and 169.7 × 0.707 = 120. (Note that the peak value and the RMS value are not the same, as some people falsely believe.)

AVERAGE VERSUS RMS

The RMS value of a waveform is not the same as its average value. The average value of a single cycle of a sine wave is 0 volts because the positive half cycle exactly cancels the negative half cycle. Even if we inverted the negative half cycle of the sine wave, which is called "full-wave rectification (See Figure 4.9.), the average value would still not equal the RMS value.

FIGURE 4.9
A fully rectified sine wave where the negative half cycle is inverted to make it positive.

The average value of a fully rectified sine wave is about 63.7% of the peak, while the RMS value of a sine wave is about 70.7% of the peak. They are clearly not the same.

To find the RMS value of a sine wave, we can simply multiply the peak value, V_{peak}, by 0.707.

$$VRMS=Vpeak\times0.707$$

In North America, the standard household voltage is 120 VAC, which means the peak voltage is 169.7 volts (120 ÷ 0.707 = 169.7 volts). In Europe and Australia, where the voltage is 230V, the peak voltage is 325V. (See Figure 4.10).

FIGURE 4.10
The RMS value of a sine wave is the peak value times 0.707. In North America, the peak voltage is 169.73 volts and the RMS value is 120 volts. In Europe and Australia, the peak voltage is 325 volts.

Although the voltage and current in an AC system is constantly changing, we call it by its RMS value. In the real world, even the RMS value and the peak value change slightly from time to time due to loading conditions and events like lightning and faulted lines. When we meter power using a voltmeter or amp meter, the values appear to be relatively steady, but many times that is only because our instruments are not fast enough to capture and display transient conditions like voltage spikes, dips, and high-frequency noise. Also, if you monitor the voltage long enough you will likely find that the RMS value varies slightly over time. Yet we still "name" it by its target value, which is known as the "nominal" value. Nominal is a word derived from the Latin word for "name."

The RMS value of voltage has much more real-world meaning than the average voltage does. It is the alternating current equivalent of the transfer of DC power. In other words, 120 VAC RMS transfers the same amount of power to a load as would 120 VDC. And remember that power is proportional to the square of the voltage ($P = V^2 \div R$), and the square of a negative number is positive. So even a negative voltage transfers a positive value of power.

TRANSFORMERS

A transformer converts voltage from high to low, or from low to high, while passing along approximately the same amount of power from the input to the output (with the exception of losses due to inefficiency, but most transformers are very efficient, typically about 97.5% efficient.) Distribution transformers raise the voltage to allow large amounts of energy to be transported over long distances using relatively low current, which significantly reduces the amount of copper needed for transmission, reduces heat losses (or I^2R losses), reduces the size of the transmission towers, and saves money on copper, labor, and materials. Feeder transformers are typically located in live event production venues and they drop the voltage from relatively high to relatively low, allowing us to use electrical energy more safely.

As an example, if we wanted to transmit 100 megawatts at 480 volts, it would require a conductor capable of carrying 208,333 A (100,000,000 watts ÷ 480 volts = 208,333 A). That would require a massive amount of copper! However, distributing the same 100 megawatts at 345,000 volts would only require a conductor capable of carrying about 290 A (100,000,000 watts ÷ 345,000 volts = 289.9 A), which could be accomplished using a much more reasonably sized conductor.

A transformer has two coils of wire in close proximity to each other. When current flows through the input or "primary" coil, it creates a magnetic field around it. If the transformer is fed AC, (transformers only work with AC), then the magnetic field expands and collapses twice for every single cycle of AC; once during the positive half cycle and once during the negative half cycle. As the magnetic field expands and collapses, the lines of flux of magnetism cut the conductors of the output or "secondary" coil, which produces voltage across the winding. (See Figure 4.11.) If it is connected to a complete circuit, current will flow.

FIGURE 4.11
When AC voltage is applied to the primary winding of a transformer, it creates a magnetic field that expands and collapses twice for every single cycle of AC. The lines of flux cut across the secondary winding, which generates a voltage at the output.

The strength of the magnetic field developed by the primary winding depends on the number of turns of wire, the size of the coils, and the intensity of the current, and the voltage generated at the secondary depends on the ratio of the number of turns in the primary to the number of turns in the secondary. If the voltage increases from the primary to the secondary, it is a step-up transformer, and if the voltage decreases it is a step-down transformer. Transformers are rated according to how many amps they can safely output multiplied by the output voltage, which is called "apparent power." The units of measure of apparent power is volt-amps or kilovolt-amps. For example, if a transformer can safely output a total of 100 amps at 120 volts, then the nameplate rating, which is a label the manufacturer places on the gear outlining the specifications, will be 12,000 volt-amps (VA) or 12 kVA.

On paper, a transformer is indicated by the symbol shown in Figure 4.12.

$$V_p/V_s = N_p/N_s$$

FIGURE 4.12
The symbol for a transformer with an iron core. The ratio of the input (primary) voltage to the output (secondary) voltage is the same as the ratio of the number of turns in the primary to the number of turns in the secondary.

The ratio of number of turns in the primary to the number of turns in the secondary is called the turns ratio. The output voltage is the product of the input voltage and the turns ratio.

$$Vout/Vin=turnssecondaryturnsprimary$$

or

$$Vout=Vin\times turnssecondaryturnsprimary$$

Example 4a

A 120/240V transformer has 50 turns in the primary. How many turns does the secondary winding have?

Answer:

$$120/240=50/X$$

$$X=50\times 240/120=12{,}000\div 120=100 \text{ turns}$$

Example 4b

A transformer has a turns ratio of 8:115 (primary to secondary). What should the input voltage be in order to generate 6900 V at the output?

Answer:

$$Vout=Vin\times turnssecondaryturnsprimary$$

$$6900=Vin\times 1158$$

$$Vpri=6900\times 8\div 115=480 \text{ V.}$$

Example 4c

How many amps can a single-phase 24kVA transformer supply at 120V?

Answer:

$$24kVA=24{,}000VA=120V\times I$$

$$I=24{,}000\div 120=200 \text{ amps}$$

TRANSFORMER TAPS

A transformer tap is a terminal that is connected to one of the windings at some point along its length. (See Figure 4.13.) It effectively changes the number of turns of wire in a coil. For example, if a winding has 100 turns of wire and outputs 240 volts, by soldering a terminal at the midpoint of the winding, we can pick off 120 volts.

FIGURE 4.13
A tap is a terminal connected to a winding at some point along its length.

Some transformers have one or more taps to compensate for variations in the input voltage. If the input voltage is too high or too low, the transformer can be re-tapped to bring the output closer to the desired voltage. In Figure 4.14, the nameplate of a 480V to 120/208V transformer shows that it has seven taps, and the jumper connection at the right shows which one to use based on the incoming voltage. If, for example, the incoming voltage is 490V instead of 480V, then the closest voltage listed is the 491V tap (#2). If the jumper is moved to the #2 tap, then the output voltage will be much closer to 120/208V.

FIGURE 4.14
This transformer has seven taps, each of which changes the effective number of windings, which changes the output voltage. The jumper connection chart on the right shows which tap to use, based on the incoming voltage.

UNDERSTANDING ALTERNATING CURRENT

4.1 (a) Any time current flows, there is a magnetic field around the conductor, and it is oriented in a particular direction. If a multi-conductor cable contains two current-carrying conductors plus ground or earth (ground/earth is normally not conducting), and one conductor carries the outgoing current in one direction while the other carries the return current in the opposite direction (because a circuit is a loop), what is the net (or total) magnetic field around the entire cable? Why?

4.2 A power cord typically has one hot or live conductor, which carries the current to the load, a neutral conductor, which carries the return current from the load back to the supply, and a grounding or earthing conductor, which is there to carry any fault current in the event of a short circuit. (The grounding/earthing conductor is a very important safety feature and should *never* be defeated by "lifting" the ground/earth!) In the event of a ground fault or earth fault (meaning that there is a short circuit or a 0 Ω circuit to ground or earth), then fault current returns to the supply through the grounding or earthing conductor, or in some cases, through the earth. When that happens, is the current in the neutral conductor still equal to the outgoing current in hot/live conductor? Would there then be a net magnetic field around the two conductors?

4.3 A clamp meter measures current passing through a conductor by measuring the magnetic field around it, which is proportional to the current flowing through it. Does a clamp meter work on a multi-conductor cable like an extension cord? Why or why not?

4.4 Michael Faraday was an English physicist who conducted an experiment in 1831 in which he tried to induce current in a conductor by inserting in a magnetic field. He wrapped a conductor around one side of an iron toroid and connected it to a battery. On the other side of the toroid, he wrapped another conductor and connected it to an ammeter. It didn't work the way he expected. However, in the process, he made an important discovery—called Faraday's law—which says that a changing magnetic field induces a change in voltage in a conductor. (See Figure 4.15.) Does this apparatus look like a transformer? Does a transformer work with a DC battery? Why or why not?

4.5 (a) A single cycle of a sine wave is how many degrees? (b) At which point does the positive peak occur? (c) At which point does the negative peak occur?

4.6 Which of the waveforms in Figure 4.16 is a pure sine wave?

4.7 A linear load is one in which the wave shape of the current is draw looks the same as the wave shape of the voltage supplying power to it. If a power supply draws current in pulses as shown in Figure 4.17, is it a linear load?

4.8 An incandescent lamp is connected to a dimmer that switches the circuit off for the first quarter cycle, then turns it on during the second quarter cycle, and repeats for the negative half cycle. (See Figure 4.18.) Is the resulting current waveform a sine wave?

4.9 A linear load is connected to an AC circuit and it draws current in a sine wave. For the first half cycle, the current flows from the supply, through the live conductor to the load, and back through the neutral conductor. In which direction will the current flow during the negative half cycle?

4.10 If the RMS voltage in North America is 120V, how many times during a single cycle is the instantaneous voltage (the voltage at any instant in time) equal to 120 volts? At which point(s) during the cycle is the voltage 120V?

4.11 What is the average value of a single cycle of a sine wave?

4.12 Is the average voltage and the RMS voltage the same? Is the average current and the RMS current the same?

4.13 If a lamp produces a certain amount of light and has a certain lamp life when it is operated at 100 VDC, would it produce the same amount of light and have the same lamp life if was operated at 100 $V_{average}$ AC? What about if the lamp was operated at 100 V_{RMS} AC?

4.14 The nominal voltage in Europe is 230 V and 120 V in North America. It is implied that those voltages are the RMS values. Is the same true of current? If a system draws 150 amps, is it 150 amps peak or 150 amps RMS?

4.15 The generator in Figures 4.5 through 4.7 has two magnetic poles; a north pole and a south pole. It shows a spinning coil of wire inside of a stationary magnetic field. In real life, a generator usually has a stationary coil of wire and a spinning magnet, as shown in Figure 4.19. The stationary part of the generator is called the stator and the rotating part is the rotor. In a two-pole generator, each time the one of the magnetic poles passes the coil of wire, it generates a peak voltage; each time the other pole passes the coil, it produces a peak voltage of the opposite polarity. Therefore, for every single rotation of a two-pole generator, how many cycles of a voltage sine wave does it produce?

4.16 How many revolutions per minute (RPM) would a two-pole generator have to spin in order to create a voltage waveform with a frequency of 60 Hz? 50Hz?

4.17 A four-pole generator has a rotor with two north poles and two south poles, as shown in Figure 4.20. How many complete voltage cycles does it produce for every single rotation or the rotor?

4.18 How many revolutions per minute (RPM) would a four-pole generator have to spin in order to create a voltage waveform with a frequency of 60 Hz? 50Hz?

4.19 True or false: In a sine wave, the values at 0° and 360° are equal.

4.20 If a changing magnetic field can cause current to flow in a conductor, can a feeder cable that is conducting current induce current in an audio cable that is running parallel to it? If so, how could you prevent this from happening?

4.21 The efficiency of a transformer can be measured by comparing the apparent power output to the apparent power input, i.e., apparent $power_{secondary}$/apparent $power_{primary}$ × 100 = % efficiency. If the current flowing into a 277/480V feeder transformer is 187 amps per leg and the output is 417 amps per leg at 120/208V, what is the transformer efficiency?

4.22 If the RMS voltage in Europe is 230 V, what is the peak voltage?

4.23 If the peak voltage in Japan is 141.4 V, what is the RMS voltage?

4.24 If the peak voltage in the United Kingdom is 339 V, what is the RMS voltage?

4.25 What is the apparent power rating of a 3-phase feeder transformer that can output 100 amps per phase at 120 volts?

4.26 If a feeder transformer has a nameplate rating of 75kVA, how many amps per phase can it output at 120 volts?

4.27 A single-phase 120/240V transformer has a nameplate rating of 30 kVA. How many amps can it output at 120V?

4.28 A show has a total power requirement of 150 amps. What is the smallest transformer that will provide enough power with at least 20% to spare?

4.29 Suppose you have a single-phase transformer with a 2:1 turns ratio and its output is measured at 120 V. If you rewired it so that the output becomes the primary and the input is now the secondary, what would the output voltage be?

4.30 According to Ohm's law, current is proportional to voltage in a resistive circuit (V = I × R). In a circuit like this, if the voltage is a sine wave, what would be the waveform of the current?

4.31 (a) How does laying out excess feeder cable in a figure eight minimize EMI? (b) Is it necessary to figure-eight multicore branch cable? Why or why not?

FIGURE 4.15
Does this apparatus look like a transformer?

FIGURE 4.16
Which of these is a sine wave?

FIGURE 4.17
The waveform at the top is the input voltage, and the waveform at the bottom is the current drawn by the load.

FIGURE 4.18
A dimmer keeps the current off for the first part of the positive half cycle and then turns it on for the remainder of the positive half cycle, then repeats the switching action in the negative half cycle.

FIGURE 4.19
A two-pole generator.

FIGURE 4.20
A four-pole generator.

NOTE

1 A 5% increase between the rated voltage of an incandescent lamp and the voltage applied to the lamp results in a 50% decrease in lamp life, and a 5% decrease results in a 50% increase in lamp life. For example, if the rated voltage is 115V and the applied voltage is 120.75V, the rated life will be cut in half.

CHAPTER 5

3-Phase Power

In the late 1800s there were only two main uses for electricity: lights and motors. And before multi-phase power existed, there were no motors that could run on AC because the torque in a motor is proportional to the applied voltage, and at the 0-volt crossing in a single-phase AC supply, the torque drops to 0 and the motor stalls. It wasn't until later on that shaded-pole motors that could run off of single-phase voltage were invented. That's one of the main reasons why the first electrical power distribution systems were DC systems.

At the end of the nineteenth century, Nikola Tesla conceived and patented a design for a poly-phase AC motor. His patent was for a 2-phase system in which two independent circuits provided torque and were 90° out of phase with each other. This allowed for one of the two circuits to provide the torque when the other was at 0 volts and 0 torque. George Westinghouse bought the patent and started producing 3-phase transformers and generators, and eventually, AC systems overtook the DC systems that were being used. Today, the vast majority of power that is generated for commercial applications throughout the world is 3-phase power, and it has become the norm in most live event power distribution systems.

A single-phase generator has a single pair of windings that outputs one voltage waveform. 3-phase power is produced by a single generator that has three sets of windings, each of which is physically oriented 120° apart from one another.Each pair of windings generates its own voltage output and, because they are physically oriented 120° apart from each other, the voltage waveforms are also 120° out of phase with each other, as shown in Figure 5.1.

FIGURE 5.1

A 3-phase generator showing three pairs of windings physically spaced 120° apart from each other. Each pair of windings is connected in series or in parallel to produce a single voltage waveform, each of which is 120° out of phase with each other, as shown in the graph at the bottom of the illustration.

Why 3-Phase and not 2-Phase or 6-Phase?

Early AC electrical systems used 2-phase generators in order to prevent motors from stalling when the voltage passed through 0V; while one of the voltage waveforms was at 0V, the other was at its peak voltage, which provided the torque to keep an AC motor turning. But it was soon learned that 3-phase power was more efficient than 2-phase power. That's because each pair of windings in a 3-phase system forms a circuit that shares a common leg with another circuit (e.g., a load connected across phases A and B forms one circuit, which shares phase B with another load that is connected across phases B and C), and the currents flowing through the common leg are 120° out of phase, leading to slight phase cancellation. That, in turn, reduces the current in that phase, which also reduces the heat generated by the product of the current and resistance, and that reduces the energy losses. The Westinghouse Electric Corporation, led by George Westinghouse, soon began manufacturing 3-phase generators. In the early days of power distribution, there were systems built with different numbers of phases, including 6-phase power. If 3-phase power is more efficient than 2-phase power, and 6-phase power is more efficient than 3-phase power, then why are the vast majority of electrical systems around the world 3-phase systems? Why not 12-phase or 48-phase?
The reason 3-phase systems dominate electrical power distribution is because every additional phase requires circuit breakers, additional transformer windings, and switch gear, which adds cost. There are still 2-phase systems in the downtown area of Philadelphia, Pennsylvania known as Center City, and Hartford, Connecticut, but they are artifacts of the past.

WIRING COLOR CODES

The conductors in a power distribution system are color coded according to the country in which the system is built, installed, or used. In the United States color codes are designated by the National Electrical Code (NEC), but the only requirements are that the neutral conductor (the NEC refers to it as the “grounded conductor”) in 120V/208Y systems should be white, and the grounding conductor should be green, green with yellow stripes, or bare copper wire. There are no designated colors for the phase conductors, but standard practice is that in a 120V/208Y system, the phase conductors are black, red, and blue, in that order, and in a 480Y/277V system, the phase conductors are brown, orange, and yellow and the neutral is gray. The sole exception is that in a 120/240V four-wire delta-connected system, the high leg (also known as the “stinger leg” or “wild leg”) has to be orange. That means that the voltage from the orange leg to the neutral is 208 volts. This is the only system in North America in which it is acceptable to have 208V from a phase conductor to the neutral. The voltage from the other phase conductors to neutral is 120V and the phase-to-phase voltage is 240V.

The entertainment production industry in the United States is fairly rigid in its color coding practice, and most 3-phase 4-wire plus ground systems follow the unwritten standard that the terminals are green, white, black, red, and blue for ground, neutral, phase A, phase B, and phase C, respectively. Most every other country follows a standard that strictly spells out the color for the protective earth (grounding conductor), neutral, and each phase conductor. The codes are complicated by the fact that they were harmonized in Europe and Australia in 2006, and there are still installations using the old standard. A brief overview of the color codes and standard practice in selected countries is shown in Figure 5.2:

	Australia	Canada	China	Europe since 2007; UK since 2004	Europe before 2007	United States
Phase A	Red	Red	Yellow	Brown	Brown or Black	Black
Phase B	White	Black	Green	Black	Brown or Black	Red
Phase C	Blue	Blue	Red	Grey	Brown or Black	Blue
Neutral	Black	White	Light Blue	Blue	Blue	White
Grounding Wire or Protective Earth	Green/Yellow Striped	Green or Bare Copper	Green/Yellow Striped	Green/Yellow Striped	Green/Yellow Striped	Green, Green/Yellow Striped, or Bare Copper

FIGURE 5.2
Electrical wiring color codes around the world. The only color codes that are mandated by the NEC in the United States are the colors for neutral and the grounding wire. The other colors are standard practice but are not required by the NEC.

3-PHASE TRANSFORMERS

Power is typically transmitted from the generating plant at very high voltages in order to reduce the current, which reduces the size of the conductors and saves money. There are a series of step-down transformers that progressively drop the voltage as it is brought into more densely populated areas. By the time it enters the service entrance of a building, it is at an intermediate voltage level. A feeder transformer is typically used to drop the voltage to a safer level for utilization. The majority of feeder transformers are 3-phase transformers, which are like three single-phase transformers in one housing except the primary (input) windings are all connected to each other and the secondary (output) windings are all connected to each other. (See Figure 5.3.) How the windings are wired and connected to a service panel determines the type of service that is available.

FIGURE 5.3
The inside of a 3-phase, 150 kVA feeder transformer showing three pairs of windings.

3-PHASE 4-WIRE PLUS GROUND WYE OR STAR CONNECTION

If the three primary windings in a 3-phase transformer are connected end-to-end-to-end, as shown in Figure 5.4(a) and 5.4(b), it is called a delta connection because, schematically, it forms a triangle, and that resembles the letter Δ (delta) in the Greek alphabet. If the secondary windings are all connected to a common node, then the common node becomes the neutral conductor and the other end of the three windings are the hot or live conductors. The neutral conductor is normally grounded or earthed in order to keep it at ground/earth potential (0 volts). This connection scheme is referred to as 3-phase 4-wire plus ground. In a 4-wire plus ground system, the grounding conductor is the fifth wire; it is considered part of the grounding system. It is also known as a wye-connected secondary or "star," and it is the most common secondary connection used in modern buildings and performance venues in North America, the European Union, Australia, South Africa, and many other parts of the world. On an electrical panel in North America, the nameplate or label might refer to this as "120V/208Y."

FIGURE 5.4
(a) Connection diagram for a 3-phase transformer in a delta-wye (Δ-Y) configuration. The three primary windings on the left are connected end-to-end-to-end, and the three secondary windings are connected at a common node, which is the neutral.

FIGURE 5.4
(b) The same 3-phase transformer shown schematically.

The output of a feeder transformer is typically connected to a disconnect switch, which allows you to safely connect or "tie in" a portable power distribution system by de-energizing the output of the switch. See Figure 5.5. In a theatre, a switch is often referred to as a "company switch" because touring theatre companies use it to supply power for their show. The switch should have a connection panel with connectors that make it quick and easy to terminate feeder cables to supply power to distribution units downstream of the feeder transformer. In North America and other parts of the world, the connectors are usually single-pole locking connectors (commonly called cam-lock connectors) and in Europe, Australia, and parts of the world that were influenced by the UK, they could be multi-pole connectors used with multi-core cable. Either way, if there are five conductors, usually, but not always, then it is a 3-phase system, but it is often referred to as "five-wire" cable. The five wires comprise the three phase conductors, a neutral, and a ground or earth.

FIGURE 5.5
This disconnect switch (also known as a company switch) has a connection panel with five single-pole locking connectors, commonly known as cam-lock connectors. It allows you to tie in portable power distribution safely by disconnecting power from the output using the on/off switch on the right before terminating the feeder cable. The green connector is the grounding conductor, white is neutral, and the black, red, and blue connectors are the three phase conductors in a 3-phase system. It is very important to make sure the switch is off before connecting any feeder cables. Even if the switch is in the off position, you should verify that there is no voltage at the output terminals using a non-contact voltage detector like a Fluke 1AC II or a Klein NCVT-2 because a switch can malfunction, and the act of connecting a cable to a live terminal might cause an arc flash. Once you have confirmed that there is no voltage present, then connect the ground/earth first, then the neutral, and finally the three hot/live conductors.

A power distribution system is typically used to supply power to individual loads like lights, audio, and video equipment. Its main job is to subdivide the current coming from the feeder transformer through the feeder cable and switch, and to distribute that power to the loads through smaller branch circuit or final circuit conductors. The three feeder cables are run from the switch to the power distribution unit, inside of which are "bus" bars, or copper bars that can carry a lot of current. The branch circuits or final circuits are terminated to the bus bars internally, and they can be wired between any of the three phases and neutral, or between any two phases, depending on the distro and the voltage requirements of the loads. It might apply the voltage to the loads from a phase conductor to the neutral conductor, or from one phase conductor to another phase conductor.

The values of those voltage levels depend on the geographical location, the incoming voltage, and the ratio of the number of turns of wire in the primary winding compared to the number of turns of wire in the secondary winding, which is called the "turns ratio." (See Appendix 5: Worldwide Voltages and Frequencies.) In North America and other

parts of the world, the phase-to-neutral voltage is 120V nominal and 208V nominal from phase-to-phase. In Europe, as well as other parts of the world, the phase-to-neutral voltage is 230V and the phase-to-phase voltage is 400V.The type of connector typically provides a clue about the intended voltage to be applied to the load. For example, in North America, a common Edison connector should only be used with 120V loads, while L6-20 and L6-30 connectors (twist-locking 20-amp and 30-amp connectors, respectively) are used with single-phase 208V loads.

FIGURE 5.6
(a) In North America and other parts of the world, a 3-phase wye-connected service supplies 120 volts from phase to neutral and 208 volts from phase to phase.

FIGURE 5.6
(b) In Europe and other parts of the world, a 3-phase wye-connected service supplies 230 volts from phase to neutral and 400 volts from phase to phase.

PARTIAL PHASE CANCELLATION

If you look at Figure 5.6(a), at first glance, it might appear that the phase-to-phase voltage should be twice the phase-to-neutral voltage. After all, the voltage from phase a to neutral is 120 V and from phase b to neutral is also 120 V, so why isn't the voltage from phase a to phase b 240 V?

In a 3-phase system, any two voltage waveforms are 120° out of phase with each other, so they don't add linearly because of phase cancellation. As a result, the phase-to-phase voltage is 1.732 (or the square root of 3) times the phase-to-neutral voltage. For example, 120 V and 120 V is not 240 V, it's 208 V (120 V × 1.732 = 208 V) because of phase cancellation. And in Figure 5.6(b), 230 V × 1.732 = 398 V (approximately 400 V).

One way to visualize this is to graph the two voltage waveforms and add them point-by-point, as shown in Figure 5.7. On the left-hand side, the two 120 V waveforms are 180° out of phase with each other. When they are subtracted, the result is a single 240 V sine wave. On the right, the two 120 V waveforms are 120° out of phase with each other, and when they are subtracted, the result is a 208 V sine wave.

FIGURE 5.7
Left: Two 120 V sine waves that are 180˚ out of phase with each other are subtracted and the result is a single 240 V sine wave. Right: The two 120 V sine waves are 120˚ out of phase with each other. When they are subtracted, the result is a 208 V sine wave.

Another, more graphical way to look at it is to use vectors. The vectorial difference between the two phase-to-neutral voltages isn't double the length of one of them, it is a little less than double. To illustrate, look at Figure 5.8. It shows a vectorial representation of phase A (OA), phase B (OB), and the vectorial difference between the two (AB), which is the phase-to-phase voltage. Both phase A and phase B originate at the common node O, but phase B is 120° ahead of phase A.

FIGURE 5.8
The vectorial difference of the phase-to-neutral voltage of two phases in a 3-phase system.

The reason that the phase-to-phase voltage is the difference and not the sum is that it is measured from the end of the vector OA to the end of the vector OB. If we trace the path from the end of OA through the common node O, to the end of OB, then we can see that we're traveling in the opposite direction of OA and in the positive direction of OB. Therefore, we are adding the negative of OA, which is the same as subtracting OA from OB.

To calculate the magnitude of AB, we can draw a perpendicular line from the midpoint of AB to O, as shown in Figure 5.9.

FIGURE 5.9
By drawing a perpendicular line from the midpoint of vector AB to O, we can create two right triangles and calculate the magnitude of AB.

This line bisects AB (cuts it in half) and creates two right triangles. (A right triangle is one with a 90° angle.) Note that the angle between OA and OB, which is 120°, is also bisected by the perpendicular line, so we know that each of the two angles is 60°. Looking at one of the right triangles, we now know the measure of one angle and one side, so we can calculate the length of one-half of AB by using the formula for the sine of an angle.

$$\sin \theta = \text{oppositeside} \div \text{hypotenuse},$$

where the hypotenuse (the side opposite the right angle in a right triangle) is OA or OB, depending on which right triangle we're dealing with. (Let's choose OA.)

$$\sin 60° = \text{one-half of AB} \div \text{OA}$$

By multiplying both sides of this equation by OA, we get

$$\text{OA} \times \sin 60° = \text{one-half of AB}$$

Now if we use a calculator or lookup table to find the sin of 60° and multiply both sides of the equation by 2, we get

$$\text{OA } 2 \times 0.866 = \text{AB}$$

or

$$\text{AB} = \text{OA} \times 1.732$$

Remember that AB is the phase-to-phase voltage and OA is the phase-to-neutral voltage. To check our work, let's calculate the phase-to-phase voltage in a 3-phase 4-wire wye or star connected system using the formula above if the phase-to-neutral voltage is 120 volts.

$$\text{VAB} = \text{VOA} \times 1.732$$

$$\text{VAB} = 120 \times 1.732 = 207.85 \text{ volts}$$

The loads to be connected, whether they are lights, audio, or video, will have specific voltage requirements that are spelled out in the specifications for that gear. The combination of the service and the power distribution unit are chosen to apply the proper voltage to the loads. There are portable power distribution units that supply phase-to-neutral voltage, which is 120 volts in North America, and others that supply phase-to-phase voltage to the connected loads, which is 208 volts in North America. There are also some that supply both in the same unit. See Figure 5.10

FIGURE 5.10
A portable power distribution unit can supply phase-to-neutral voltage or phase-to-phase voltage, depending on how it is wired. This unit has Socapex outputs at the top, which might be wired phase-to-neutral or phase-to-phase. The 5-15 (a.k.a. Edison) connectors should be wired phase-to-neutral.

In North America, when a 120V portable power distribution system is used, it is wired so that the connected loads create a circuit from one of the three hot or live conductors, through the load, and back to the supply through the neutral conductor. When a 208V portable power distro is connected to the switch, it is wired so that the connected loads create a circuit across two of the three hot or live conductors. This is referred to as a "single-phase 208-volt" load because, even though it uses two phase conductors, there is only one path for current, and the voltages supplied by the two phase conductors combine to produce a single voltage and current waveform. See Figure 5.11. The neutral conductor is not used in this configuration, but the grounding/earth conductor must always be used!

FIGURE 5.11
A single-phase 208V connection is connected across two phases but there is only one path for current. The voltages from phases A and B combine to create a single voltage and current waveform. Notice that the neutral conductor is not connected because it is not used for single-phase 208V.

The power cable for a 3-phase load has a connector with three poles (a "pole" is a current-carrying terminal) plus a grounding/earthing pin. When a load is connected to all three phase conductors, then it is a 3-phase 208 V load. In this case there are three paths for current in a single load. For example, a 3-phase chain hoist has three windings, each of which is connected across two of the three phases of the supply.

Some equipment in North America operates at the phase-to-neutral voltage (120 V), and some operates at the phase-to-phase voltage (typically 208 V or 240 V) because it requires less current and thus, less copper, fewer circuits, and less power distribution equipment. Generally speaking, if a load would draw above about 16 amps at 120V, then it is a good candidate for 208 V or 240 V operation.

In some commercial buildings and amusement parks in the United States the phase-to-phase voltage is 480 V (or in some cases it is 600 V in Canada) and the phase-to-neutral voltage is 277 V (or 347 V in Canada when the phase-to-phase voltage is 600 V). 277 V is commonly used for architectural lighting, such as fluorescent troffers when they are used in large numbers and exterior lighting where the wire runs are very long, in order to minimize voltage drop. This is an illustration of why different voltages are used for different applications. There is always a trade-off between safety and economy; the higher the voltage, the greater the shock hazard but the less current, and therefore the more economical it is, while lower voltage is a bit safer but draws more current for the same power, and therefore requires more copper and costs more.

In many parts of Europe and some parts of Australia, the 3-phase 4-wire earthed neutral, star connected system is commonly used. All countries belonging to the European Union have agreed to comply with IEC 60038:2009, which standardizes the single-phase voltage to 230 V +10%/–6% (216.2 – 253 V). The nominal phase-to-phase voltage is 398.4 V (usually indicated as 400 V) and the phase-to-neutral voltage is 230 V. Note that the vast majority of equipment used in Europe operates at the single-phase voltage, although there are some electric chain hoists and other equipment that operate at 400 V 3-phase.

A 3-phase 4-wire earthed neutral configuration is also used extensively in the UK and Australia, but the phase-to-phase voltage is usually 415 V and the phase-to-neutral voltage is 240 V. Although both of these countries have agreed to comply with IEC 60038:2009, they did not have to change their distribution voltage because 240 V falls within the allowable limits of 230 V +10%/–6%.

A 3-phase 4-wire earthed neutral configuration is used in many other parts of the world, including China, Mexico, parts of the Middle East, South America, and Russia. In China the phase-to-phase voltage is 380 V while the phase-to-neutral voltage is 220 V, and in Mexico, the Middle East, South America, and Russia the phase-to-phase voltage is 220V while the phase-to-neutral voltage is 127V or 120V.

SINGLE-PHASE THREE-WIRE EARTHED MIDPOINT

In Japan and in some venues in the United States and Canada, a single-phase three-wire earthed midpoint system, also known in the United States and Canada as "split-phase service," is used. It has two phase conductors fed from a single winding of a distribution transformer, and the neutral is tapped at the center of the phase winding and earthed, as shown in Figure 5.12. This configuration leads to a service with four terminals. In the United States and Canada, those conductors are typically green, white, black, and red.

FIGURE 5.12
Single-phase 3-wire earthed midpoint, also known as split-phase service.

The utility can provide this service by running a 3-phase delta transmission system through a neighborhood and then tapping into it with a single-phase center-tapped distribution transformer and running the two phases and the neutral to the building. As long as each distribution transformer is distributed equally between the three phases, the system is in balance. See Figure 5.13.

FIGURE 5.13
Typical 3-phase delta distribution showing single-phase center-tapped feeder transformers feeding individual consumers. Each feeder transformer is connected to two different phases of the 3-phase delta system to evenly distribute the load.

In the parts of the world where this configuration is common, the voltages are typically 240V phase-to-phase and 120V phase-to-neutral.

For a more complete listing of voltages and frequencies around the world, see Appendix 5.

3-PHASE THREE-WIRE DELTA

Sometimes when cable has to be run a long way, a 3-phase 3-wire plus ground delta configuration at a relatively high voltage is used. For example, in motion picture production, portable power generators are often used for shooting on location, and since the generator is very loud, it is often located remotely so that it doesn't interfere with the sound recording. In this case, the generator operator will set the output of the generator to 480 V and set technicians will run a set of feeder cables to a step-down transformer located near the shoot. The primary of the step-down transformer is typically a 480 V delta configuration and the secondary is a 120/208 V wye configuration. (See Figure 5.14.)

FIGURE 5.14
3-phase 3-wire delta connected secondary.

The phase-to-phase voltage in this system is usually 480V in the United States or 600V in Canada, or it can be 208V in the United States and Canada. There is no neutral conductor unless one of the three secondary windings has a center tap, in which case it becomes a high leg delta (see High Leg Delta section below), but it *must* have a grounding conductor or it is not safe. The grounding conductor comes from the generator and provides a means for fault current to make its way back to the supply in order to interrupt the circuit in the event of a ground/earth fault.

3-PHASE 4-WIRE DELTA HIGH LEG

In North America and many parts of South America and the Caribbean, a 3-phase 4-wire plus ground delta high leg configuration is sometimes used. In this configuration, the secondary is wired in a delta but one of the windings has a center tap, which becomes the neutral. The neutral is also grounded at the service. This configuration typically provides 240 volts phase-to-phase while also providing two phase-to-neutral connections at 120 volts, but the voltage from the “high leg” to neutral is higher than the voltage from any of the other two phases to ground; it iss typically 208V. The high leg, also known as the “wild leg” or the “stinger leg,” must be orange in color according to the NEC in order to provide a warning that it is 208V to neutral instead of the normal 120V. A switchboard or panel with a 3-phase 4-wire delta high leg must be marked: “Caution _____ Phase Has _____ Volts to Ground.” (See Figure 5.15.)

FIGURE 5.15
3-phase 4-wire plus ground delta high leg connection with one phase winding grounded at the midpoint. In this illustration, phase B is known as the high leg or the wild leg and it must be orange in color to warn that the voltage to neutral is higher than normal.

Note that, unlike the 3-phase 4-wire wye or star configuration, the voltage from phase A to phase B is the sum of the voltage from phase A to neutral and the voltage from phase B to neutral. That's because they are measured across the same phase winding and they are 180° out of phase with respect to each other, so they combine to 240V, not 208V.

SINGLE-PHASE TWO-WIRE EARTHED END OF PHASE

In most of Europe, South America, China, and Australia, power is commonly supplied using a single-phase two-wire plus earth system. In this configuration the neutral conductor is tapped at the end of the phase winding. In EU countries and Australia, the voltage is 230V +10%/–6% (216.2 – 253V). The wiring scheme is shown in Figure 5.16.

FIGURE 5.16
Single-phase two-wire earthed end of phase system as used throughout Europe, Asia, Australia, and South America.

LOAD BALANCING

A 3-phase system works most efficiently when the loads are equally balanced among the three phases, and an unbalanced 3-phase system can cause a voltage unbalance, which can cause excessive heat in induction motors and rectifiers (a rectifier is an electronic circuit that converts AC voltage and current to pulsing DC by inverting the negative half cycle of the AC waveform), which can shorten their life.

But many times, in entertainment systems, it is virtually impossible to maintain any semblance of balance, particularly if we are using a large number of incandescent lamps with dimmers. Every time a new cue is executed, the load on the phases changes, as does the balance among them. Nevertheless, we try to start with a balanced 3-phase system and if at all possible, we try to maintain a balance to the extent possible. For example, in motion picture production, if there is a portable power generator, part of the generator operator's job is to monitor the voltage imbalance and redistribute the loads in order to maintain as much balance as possible.

When loads are connected to a 3-phase power distribution unit or dimmer rack, they should be equally spread among the three phases. How that's done varies; sometimes the phases are in sequence (circuit 1, phase a; circuit 2, phase b; circuit 3, phase c; circuit 4, phase a; etc.) and sometimes they are grouped in pairs (circuits 1 and 2, phase a, circuits 3 and 4, phase b, circuits 5 and 6, phase c, etc.). There is no standard dictating how this is done, so you should refer to the user manual or check the voltage output using a voltmeter.

If there is no documentation describing the phasing of the gear you're working with, you can use a voltmeter to check the phasing of the circuits. Using the proper category of meter and the proper PPE, measure voltage from the hot or live from one circuit to another. If the voltage 0, then they are on the same phase; if the voltage is the nominal phase-to-phase voltage, then they are on different phases.

UNDERSTANDING 3-PHASE POWER

5.1 A 3-phase 100-amp portable power distribution system has terminals with the following colors: green, blue, grey, black, and brown. In which continent is it intended to be used?

5.2 A venue has a power switch with five terminals that are the following colors: green, white, black, orange, and blue. What is the voltage from the orange conductor to the neutral (white) conductor?

5.3 Using Figure 5.17, answer the following questions:
(a) What is the connection configuration?
(b) How many total amps can it output at the secondary?
(c) How many amps per phase can it output at the secondary?
(d) If the incoming voltage is 460V, which tap should be used?

5.4 Most multimeters have a continuity mode to find out whether or not there is a conductive path from one probe to the other, and they are often used to test fuses and incandescent lamp filaments. In Figure 5.4(b), which shows a schematic diagram of a delta-wye connected feeder transformer, if you were to use a multimeter in continuity mode to check for continuity between the neutral and grounding conductor, would you expect to find a conductive path?

5.5 On the left-hand side of Figure 5.7, the two waveforms are being subtracted. If, instead, they were added, what would be the result? With a single-phase 3-wire earthed midpoint transformer as shown in Figure 5.12, when you measure the voltage from phase to phase, are the voltages across the two windings adding or subtracting?

5.6 If the phase-to-phase voltage on the primary side of a feeder transformer is 480 volts, what is the phase-to-neutral voltage on the primary?

5.7 If the nominal voltage in Europe is specified at 230V +10%/−6%, what is the lowest acceptable voltage and what is the highest acceptable voltage?

5.8 Using a sheet of graph paper, draw a dot in the center of the page. Now draw a vertical line from the dot upward to a point that is six squares above the dot and put an arrow at the end of it. Label that line 120V. Draw another vertical line from the dot downward to a point that is six squares below the dot and put an arrow at the end of it. Label that line 120V and label the dot "Neutral." You have just drawn a vectorial diagram of a single-phase 3-wire earthed midpoint transformer as shown in Figure 5.12. The first arrow is a vector representing the voltage from the center tap to one of the phase conductors, and the other represents the voltage from the center tap to the other phase conductor. What is the phase angle between the two phase conductors?

5.9 Use Appendix 5: Worldwide Voltages and Frequencies and find the following: (a) What is the voltage tolerance in Australia? Los Angeles? (b) If the household/commercial/industrial voltage is 240 V in Australia, what is the acceptable range of voltages?

5.10 A 400/230 V, 3-phase feeder transformer is rated 75 kVA. How much current will it supply per leg at 230 V?

5.11 What size transformer is required to supply a system with 175 kW of load and an average power factor of 0.75? If we want to allow 20% overhead, what size transformer would then be required?

5.12 What size transformer is needed to supply power to a 400-amp 3-phase switch?

5.13 What size transformer is needed to supply power to a 200-amp 3-phase switch?

FIGURE 5.17
Nameplate on a feeder transformer.

CHAPTER 6

Resistive, Capacitive, and Inductive Loads

Everything that is connected to power and draws current is referred to as a “load.” Electrical loads can be classified in three different categories; resistive, inductive, and capacitive. Each of these types of load limits the amount of current that will flow through, although they do it in different ways. Resistance impedes the flow of current and converts electrical energy to heat energy in the process. Inductors and capacitors impede the flow of current through magnetic fields and stored electrical charges, respectively, but instead of converting electrical energy to heat energy, they store electrical energy. Regardless of the type, the load ultimately determines how much current will flow in a circuit, and the current draw is an important part of safe power distribution.

In live event production, it used to be that most of the loads were resistive, like incandescent lights (PAR cans, ellipsoidal reflector spotlights, Fresnel fixtures, etc.). Today, more and more devices have capacitors in them, which means they are capacitive loads. A capacitor is a charge-storage component that is primarily used to help convert incoming AC mains power to low-voltage DC, which is the voltage on which most integrated circuit chips and LED emitters operate. They are also used to filter out high-frequency noise that might be induced in a circuit due to electromagnetic interference. Capacitive loads can include LED fixtures, any device with a switch-mode power supply—like audio and lighting consoles, digital amplifiers, video projectors, automated lights, and so on.

Other devices have inductors, which makes them inductive loads. An inductor is a coil of wire, and it is used in AC circuits for various reasons, including to change the voltage in an AC circuit by creating a strong magnetic field in order to couple it to another coil of wire with a different number of turns, as in a transformer, or to generate torque, as in the case of motors. Inductors are also used to control the flow of current, as in magnetic ballasts or dimmer chokes. Some devices have both capacitors and inductors, in which case the size of the component determines whether the overall load is capacitive or inductive; if the capacitance is stronger than the inductance, then it is a capacitive load, and vice versa. If the capacitance and inductance are equal in strength, then the load behaves as a purely resistive one for reasons that will be discussed next. Many of these devices, like LED fixtures, are relatively new in live event production. As a result, power distribution is changing because the types of load being connected today often have a power supply that converts the AC mains power to low-voltage DC. That's also why it might make sense to return to DC power distribution someday. Let's take a look at each type and how it affects the electrical system.

When two waveforms of the same frequency, like voltage and current, are compared with each other, they can either be in synch or out of synch. Either way, the difference is measured in degrees, and it is called the “phase angle.” If they are completely in synch, or in phase, then the phase angle is 0°. If they are out of phase with each other, then the degree to which they are out of phase can be anywhere between 0° to 360°. (See Figure 6.1.)

FIGURE 6.1
The phase angle between (A) and (B) is 0°; the phase angle between (A) and (C) is 90°; and the phase angle between (A) and (D) is 180°.

Circuits can have resistance, capacitance, inductance, or a mix of any of these. If it has any capacitance or inductance, it is a "reactive" load, meaning that the capacitance or inductance reacts with the voltage and current, and that affects the phase relationship between them and ultimately determines how much current is drawn, just as resistance determines the current draw in a DC circuit.

In a purely resistive circuit, like an incandescent lamp or a reactive load with equal amounts of capacitance and inductance, the voltage and current are always in phase; when the voltage rises, the current rises with it, and when the voltage falls, the current falls too. (See Figure 6.2.)

FIGURE 6.2
In a purely resistive load, the voltage (black) and current (red) are always in phase. When the voltage rises, the current rises, and when the voltage falls, the current falls too.

However, in reactive circuits, the voltage and current are out of phase, which affects the current draw; the more they are out of phase with each other, the higher the current draw for the same load. A circuit can be partially resistive and partially reactive, and the amount of reactance influences the phase angle between the voltage and current and, consequently, the amount of current it draws.

CAPACITORS

A capacitor is a charge storage device, and it is made by placing a conductor in very close proximity to another conductor separated by an insulator, as shown in Figure 6.3.

FIGURE 6.3
A capacitor has two conductors in close proximity separated by an insulator.

If you were to disassemble a commercially built capacitor, you would likely find two conductive plates or pieces of foil separated by a dielectric material like mylar, usually rolled into a cylinder, as in Figure 6.4. The two leads will be connected to the two pieces of foil.

FIGURE 6.4
A capacitor is made of two conductive pieces of foil in very close proximity separated by an insulator.

When the leads of a capacitor are connected to a DC supply, like a battery, the two conductive plates in the capacitor take the polarity of the supply (positive and negative), and because they are very close together, the electrostatic attraction between the plates will cause charged particles to collect on the plates; negatively charged electrons will collect on one plate and positively charged "holes" will collect on the other.(See Figure 6.5.) (In electronic parlance, a "hole" is an atom that is missing an electron, making it positively charged.) When the battery is removed, the charges stay put, resulting in a charged capacitor. In a perfect world, a capacitor would stay charged forever; in the real world, there is no such thing as a perfect insulator, just as there is no such thing as a perfect conductor, so some of the charges will eventually pass through the insulation, and the capacitor will self-discharge over time. Depending on how they are built, capacitors can hold a charge for a long time before self-discharging—some longer than others.

FIGURE 6.5
Symbols for a capacitor (top) and a polarized capacitor.

Capacitors come in many different sizes and shapes, and they are used for different purposes. They are rated in farads, which is a very, very large value; therefore, microfarads (μF) are more commonly used. Ultimately, the value of a capacitor and the frequency of the current results in a value of impedance, which is measured in ohms (Ω). For DC

(frequency = 0 Hz), a capacitor is an open circuit and passes no current. The higher the frequency, the lower the impedance.

In live event production, capacitors can be found in LED fixtures, moving lights, consoles, amplifiers, video projectors, and more. In power supplies, capacitors that are used to help to convert AC to DC are called “smoothing” capacitors. When AC is fed to a power supply, a bridge rectifier— which is four diodes connected in a “bridge” configuration—inverts the negative half cycle of the waveform, making it positive, resulting in pulsing DC. A smoothing capacitor is then used to smooth out the pulses. When the voltage rises, the capacitor is charged to the peak voltage of the pulse and when the voltage falls, the capacitor holds the charge, although it might discharge slightly, resulting in a rippling DC voltage.

Capacitors can also be used to filter noise out of a circuit. Once a capacitor is charged, it behaves like an open circuit to DC. But electrical noise (electromagnetic interference or EMI) is typically very high frequency, usually in the kilohertz, megahertz, or gigahertz range, and the higher the frequency, the more a capacitor behaves like a short circuit. If a capacitor is connected between the output of a DC power supply and its chassis ground, then it will pass DC to the load and shunt or short EMI to the chassis, which converts it to heat and dissipates it in the atmosphere, thus ridding it of the noise.

Capacitors are also used in motor start circuits to help maintain the voltage during startup. Starting a motor from 0 RPM to full speed requires a lot of torque, which can cause the applied voltage to drop, and that, in turn, drops the torque. A charged capacitor can supply much needed energy to boost the torque and maintain voltage across the windings of a motor when it is started.

Stray Capacitance

Capacitance can be difficult to control. Commercial capacitors are built using very tightly controlled parameters, and even then, they can vary from the intended value. Manufacturers sort or “bin” them according to their value, and the tighter the tolerance, the higher the price they can charge. A capacitor that is within 1% of a certain value is worth more than one that is within 10%.

Capacitance can also be created accidentally just by the placement of circuit traces or conductors. A microphone cable, for example, can exhibit stray capacitance of parasitic capacitance because it has two conductors in close proximity separated by an insulator. A circuit board with two traces very close together can also exhibit capacitance. It may not be a great capacitor, but it can have enough capacitance that it can distort a low-voltage signal. Some cables are specially made with very low capacitance in order to preserve the quality of digital signals. (Remember, the higher the frequency, the more a capacitor conducts, and since digital signals are usually very high frequency, a high-capacitance cable can attenuate and distort the signal.) DMX cables, for example, are made with special materials and construction techniques to minimize capacitance.

INDUCTORS

An inductor is simply a coil of wire and it reduces or chokes the flow of current in an AC circuit. It does not, however, have the same effect with DC. (See Figure 6.6.)

FIGURE 6.6
An inductor wound on a toroidal iron core. (Photo courtesy of Leviton.)

When the two leads from a coil of wire, or an inductor, are connected to a DC supply, the current flowing through it creates a strong magnetic field in the center of the coil (see Figure 6.7). Other than that, nothing else happens, and the result is basically a short circuit. But when it is connected to an AC supply, the polarity of the supply changes at twice the frequency of the voltage; during the positive half cycle, one terminal of the inductor is positive and the other is negative, and during the negative half cycle, they swap polarity. The process repeats over and over with each new cycle. With each change in direction of the current, a magnetic field is set up inside of the coil, When the polarity changes, that magnetic field is the opposite polarity of the applied voltage, so it opposes the change in direction of the current. The magnetic field lingers just long enough to "choke" or reduce the amount of current that flows through it. It decays very quickly, but it lasts long enough to reduce the amplitude of the current. When the current finally does start to flow in the opposite direction, it sets up a magnetic field in the other direction. The process repeats every time the polarity changes. As a result, the current is reduced compared to what it would be if there were no inductors in the circuit.

FIGURE 6.7
Cross-sectional view of the magnetic field around an inductor. Note that an inductor does not impede the flow of DC current.

The degree to which the current is reduced by an inductor depends on the value of the inductance, which, as mentioned earlier, is measured in farads (or more commonly, microfarads—μf) and the frequency of the current. The value of inductance is determined by the number of turns of wire in the coil, the size of the coils, the spacing of the coils, and other variables. Ultimately, all of these factors result in a value of impedance, which is measured in ohms, just like resistance is measured in ohms. The difference is that a resistor consumes energy by converting electrical energy to heat, while inductors and capacitors store energy in the form of a magnetic field or an electrostatic field, respectively. Therefore, using inductors to limit the amount of current flowing in a circuit is a much more energy efficient way of controlling it.

Coils of wire, or inductors, are found in many devices that we use in live event production, like ballasts, motors, and transformers. In a schematic drawing, an inductor is indicated by a symbol as shown in Figure 6.8. It used to be that inductors were commonly used as ballast for arc lamps. Unlike an incandescent lamp, an arc lamp has no filament. Instead, it has two electrodes inside of a quartz envelope arranged in such a way that there is a short gap between them. When high voltage is applied to the electrodes, an arc jumps the gap and current conducts. Once current is flowing, the high voltage is removed but it continues to conduct, emitting a bright light in the process.

FIGURE 6.8
Inductor symbols with and without an iron core.

When an arc lamp is in a conductive state, it is basically a short circuit. Lacking any other circuit elements, a huge amount of current would flow. To regulate the current, we could use a large resistor, but a resistor is a very inefficient way of controlling current because it converts electrical energy to heat energy. A better way to do it is to use an inductor because it reduces the flow of current but it stores energy rather than consuming it. The magnetic field produced by an inductor is a form of energy, and because the supply is alternating current, the magnetic field opposes the change in direction of the current every time the polarity changes, thereby "choking" the flow of current.

REACTANCE

In a purely resistive circuit, the voltage and current are always in phase. But introducing reactance causes something different to happen. With an inductor, when voltage is applied, a magnetic field grows around and inside of the coil of wire as the current starts to flow. When the polarity changes, it takes time for the magnetic field to collapse. Until it does, it is oriented to oppose the change in direction of the flow of current in the inductor. Therefore, the current lags behind voltage by the amount of time it takes for the magnetic field to collapse after the voltage changes polarity. The phase angle between the voltage and current varies from 0° to 90°, depending on how inductive it is compared to how resistive it is. In a purely inductive circuit (with no resistance or capacitance), the current lags the voltage by 90°, as illustrated in Figure 6.9.

FIGURE 6.9
In a purely inductive load, the current lags the voltage by 90°. Notice that in the current waveform (in red), a new cycle starts after the voltage cycle has already begun, so the current is lagging the voltage in this illustration.

Capacitors behave in the opposite way. When voltage is applied to a capacitor, free electrons move towards the positively charged plate of the capacitor, which means current is flowing, and then the voltage starts building. Therefore, in a capacitor, the current leads the voltage. In a purely capacitive load, the current leads the voltage by 90°, as illustrated in Figure 6.10.

FIGURE 6.10
In a purely capacitive load, the current leads the voltage by 90°, as in this illustration.

If a circuit or load is partially reactive and partially resistive, then the phase angle will be less than 90° but more than 0°, and the value depends on the amount of reactance compared to the amount of resistance. In real life, there is no such thing as a purely reactive load because there is no such thing as a perfect conductor; every conductor has some resistance, however small. Other components, like connectors, contribute small amounts of resistance as well. The overall resistance might be very small, but it is enough to keep the phase angle from reaching exactly 90°.

The phase relationships between the voltage and current in an inductor and a capacitor can be more easily remembered with the help of the phrase "ELI the ICEman." ELI is a mnemonic for the voltage (or EMF) leading the current (I) in an inductor (L). ICE is a mnemonic for the current (I) leading the voltage (EMF) in a capacitor (C).

The reason this is important to us is because the phase angle between the voltage and current in a circuit is related to the power factor, which, as we will soon see, affects the amount of current that flows in a circuit.

POWER FACTOR

Power factor is a measure of how much of the current being drawn is being put to work compared to the overall current draw. In other words, it is the percentage of the current that is converted from electrical energy to light, sound, heat, or motion compared to the total current being drawn by a load or circuit. Power factor can range from 0 to 1 (or 0% to 100%), depending on the reactance of a load or circuit. A power factor of 1 means that 100% of the current being drawn is being converted to another form of energy (light, heat, sound, or motion), and a power factor of 0 means that 0% of the current being drawn by a load is being converted. Ideally, we want the power factor to be 1 because that means we are getting the most out of our power distribution system rather than drawing current for no good reason.

If the power factor is low, that means that the load is drawing excess current compared to an equivalent load with a higher power factor. The reason is that some of the electrical energy being drawn is stored rather than consumed. Capacitors store energy in the form of electrostatic charges (electrons), and inductors store energy in the form of a magnetic field. This energy is eventually returned to the supply, but in the process, it is using more power distribution capacity than is necessary to drive the load, which requires a larger supply of power (e.g., 400 amps instead of 200 amps), more power distribution equipment, and more circuits.

A tungsten lamp is an example of a purely resistive load with a power factor of 1. It stores no energy because it has no energy storage devices, and 100% of the current that passes through it is converted to light and heat (mostly heat!). An arc lamp uses a power supply to regulate the current because, by itself, the lamp has very low impedance and would draw very high current. The power supply is typically a switch-mode power supply, and as such, it has a lot of

capacitors, which makes it an inherently reactive load. The capacitors store energy and drop the power factor (unless the power supply is power factor-corrected), typically to around 0.5. That means that the load will draw twice as much current as an equivalent load with a power factor of 1. For example, a 1200-watt load with a power factor of 1 draws 10 amps at 120 volts (1200 ÷ 120 = 10), but a 1200-watt load with a power factor of 0.5 draws 20 amps at 120 volts. The "extra" 10 amps are supplying energy to the capacitors, which are storing energy that will eventually be returned to the supply.

Power factor is related to the phase angle between the voltage and current. It is actually the cosine of the phase angle.

Power factor = $\cos\theta$, where θ represents the phase angle between the voltage and current

In a DC system, the power factor is always 1 because the voltage and current are constant, therefore, they can never be out of phase and the phase angle is 0°. The cosine of 0° is 1; therefore the power factor is 1.

In an AC system, power factor can vary from 0 to 1. If the voltage and current are 90° out of phase with respect to each other, then the power factor is 0. The more reactive a circuit or load is, the greater the phase angle between the voltage and current, and the lower the power factor.

In the real world, it is impossible to have a power factor exactly equal to 0 because the conductors have some resistance, however small, and the mere act of drawing current through them will heat them up, thus converting at least some of the electrical energy to heat.

PF = 0.09?

The lowest power factor I have ever encountered was 0.09! The culprit was a string of Christmas tree lights that were powered by a portable power generator. The highly reactive load was causing the voltage to rise to potentially dangerous levels on the generator when it was loaded to more than 50% of its capacity.

The unusually low power factor was caused by the construction of the LED lights, each of which had two capacitors, a bridge rectifier, and an LED emitter. (See Figure 6.11.) Even though each capacitor was small, when they are multiplied by the hundreds, as in this case, they can carry quite a charge, and the size of the generator is relatively small compared to the electrical grid.

FIGURE 6.11
This was one of several LED emitters from a string of Christmas lights with extremely low power factor. The only circuit elements are a bridge rectifier and two capacitors, which explains why the load was highly reactive.

The power factor could have been corrected by adding the right amount of inductance. Instead, the decision was made to use twice as many generators so that they wouldn't have to load them more than 50%. Had the issue gone unchecked, it likely would have destroyed the generators.

AC POWER FORMULA

Phase angles are related to current draw, but you don't often have to know or measure the phase angle because manufacturers will typically supply all the information about the power factor or current draw in the equipment specifications that you need to know about that piece of equipment. What is important is to understand the effect that power factor has on current draw and that you take it into account when you are calculating your power requirements. Therefore, it is important to understand the AC power formula, which is:

$$\text{Power} = \text{Voltage} \times \text{Current} \times \text{Power Factor}$$

or

$$P = V \times I \times PF$$

Notice that, if the power factor is 1, then this formula is the same as the West Virginia (DC power) formula because $P = V \times I \times 1$ is the same as $P = V \times I$. But if the power factor is less than 1, then the current goes up for the same wattage compared to a similar load with a power factor of 1. For example, a 1000-watt load with a power factor of 1 draws 8.3 amps while a 1000-watt load with a power factor of 0.5 draws 16.6 amps. Both are 1000-watt loads but the load with low power factor draws twice as much current. As a result, we will be able to connect only half as many fixtures on a single branch circuit or final circuit, and we will need twice as many branch circuits or final circuits for the same number of fixtures. We will also need twice as much supply. Normally there is a mix of fixtures in a typical show, some with high power factor and others with low power factor.

Before the advent of automated lighting, LED luminaires, and computer-based devices, we could more or less safely ignore power factor because very few devices had low power factor. Tungsten (incandescent) lamps are purely resistive loads, and even with a dimmer, low power factor is typically not an issue. Arc lamps used to be powered primarily by magnetic ballast power supplies, which are simply large inductors, but they were typically power-factor-corrected by the manufacturer by adding an equal amount of capacitive reactance. So, as long as the correction was functioning properly, low power factor was not an issue. But it has become more of an issue in live event production and we should be more cognizant of it. If we are working with AC, which is true the vast majority of the time, then we should be aware of how the power factor can affect current draw and our power distribution systems.

Sometimes, but not often, power factor is provided in the specifications for the gear you are using. If the manufacturer has gone to the trouble and expense of designing and building gear that is power factor-corrected, meaning they designed the gear so that the power factor is 1, then they will often include it in the specification. Other than that, it is rare that power factor is included in the specs. Either way, what's important is to know how much current is drawn by each load.

Manufacturers can provide the current draw in a variety of ways. Sometimes they will provide only the wattage at common voltages and frequencies, and it can vary slightly according to the applied voltage and frequency. In this case, if the power factor is not provided, then we might assume that it is 1; otherwise, we have no way of calculating the current draw, we can only measure it. But if the power factor is anything other than 1, then our calculation will be wrong. If the manufacturer includes both wattage and power factor, then we can use the AC power formula to calculate the current draw.

Some manufacturers provide volt-amps in the specifications, in which case the power factor is “baked in.” The volt-amps, which is technically called “apparent power,” is simply the voltage multiplied by the current. To calculate the current draw, you can divide the apparent power by the voltage, which yields amps. For example, if an automated light has a rating of 2200 volt-amps (or VA) at 240 volts, then the current draw is 9.2 amps (2200 volt-amps ÷ 240 volts = 9.16 amps).

DISPLACEMENT POWER FACTOR

The DC power formula says that power is the voltage times the current. In an AC system, the power at any instant in time (the instantaneous power) is also the product of the voltage and the current. But if the voltage and current are out of phase with each other, then that affects the power over time, which is why the AC power formula includes power factor.

The greater the phase angle between the voltage and current, the lower the power factor. This is referred to as the "displacement power factor" because the voltage and current are displaced from each other, resulting in lower power factor.

To show why, we can create a plot with the voltage and current, and use it to calculate and plot the power, as shown below. This is an illustration of a purely resistive circuit, which means that the voltage and current are in phase with each other (the phase angle is 0°) and the power factor is 1. If we multiply the voltage and the current at each point in time along the graph and plot the result, it displays the power (power = voltage × current). Notice that the power curve lies entirely in the positive half of the graph, which is "real power." In other words, it is energy that is being converted from electrical energy to another form of energy.

Now look at Figure 6.12. In this graph, the voltage and current are 90° out of phase with each other (as in our theoretical purely reactive load where the phase angle is 90°). Now when we multiply the voltage and the current at each point along to graph and plot the power curve, half of it lies in the positive part of the graph and half in the negative part. The negative half of the power curve is the "reactive power," and it exactly cancels the positive half over one full cycle. The result is that the average power over a single cycle (or several cycles) is 0 watts. That is an indication of a power factor of 0; that is, none of the energy is being converted by the circuit or the load. (See Figure 6.13.)

FIGURE 6.12
Voltage, current, and power in a purely resistive circuit. The power curve was plotted by multiplying the instantaneous voltage and the instantaneous current. Notice the power curve (in red) lies entirely above the x-axis, which represents 0 watts. That indicates that it is "real" power.

FIGURE 6.13
In this illustration the voltage and current are 90° out of phase with each other and the power factor is 0. Notice that half of the power curve is positive and half is negative, so the average power over the time period is 0 W. That indicates that there is 0 W of real power being used, or that the power factor is 0.

NON-LINEAR LOADS

The ideal AC waveform is a pure sine wave, and most sources of power—whether it is from a feeder transformer or a portable power generator—supply a pure, undistorted voltage sine wave. However, some loads draw current in such a way that distorts the current waveform. For example, some devices, like certain LED fixtures or devices with switch-mode power supplies, draw current in pulses, in which changes the waveform from a sine wave to a distorted waveform. Loads like this that alter the waveform are known as a “non-linear loads.”

Capacitive loads tend to draw current in pulses because, when a capacitor is charged, it only passes current when the applied voltage is higher than the charge on the capacitor. If you look at Figure 6.14 above, you'll see that the current pulses align with the peaks of the voltage waveform; when the voltage rises above the charge on the capacitor, the load draws current, and when it falls below it, no current flows. A manufacturer can add a circuit to a capacitive fixture that smooths out these pulses and turns the current waveform back into a sine wave, in which case they are “power-factor-corrected” fixtures and linear loads. This used to cost a considerable amount of money, so many non-linear loads were not power-factor-corrected. But has changed recently. Because of the large number of devices being manufactured today that have switch-mode power supplies, like smart phones and tablets, the prices of power supplies in general has fallen due to economies of scale. So, power-factor-correction is now much more affordable, therefore, more devices with switch-mode power supplies, like LED fixtures, are now power-factor-corrected.

FIGURE 6.14
The top waveform is the voltage and the bottom waveform is the current. This device draws current in pulses, altering the current waveform in the process, which makes this a non-linear load.

Capacitors are often used to help convert mains power (120 VAC in North America or 230 VAC in Europe and other parts of the world) to low-voltage DC. Power supplies have a bridge rectifier, which inverts the negative half cycle of an AC waveform and converts it to a positive half cycle, resulting in "pulsing DC." A smoothing capacitor is then used to smooth out those pulses, creating a mostly steady-state DC voltage with some rippling. A voltage regulator eliminates the ripples to finally produce DC voltage and current. Loads that use low-voltage DC, like LED luminaires, computers, consoles, digital amplifiers, and video projectors, are non-linear loads unless they are power-factor-corrected. Other non-linear loads include incandescent lamps connected to phase-controlled dimmers.

DISTORTION POWER FACTOR

Figure 6.13 shows how the power factor is related to the displacement (or phase angle) between the voltage and current waveforms. That is known as "displacement power factor." Power factor is also be affected by current distortion. If a device draws current in pulses or if the current is distorted by dimming or any other cause, then the power factor of the load drops; the more distortion there is, as measured by the total harmonic distortion (THD), the lower the power factor. This is referred to as "distortion power factor." The overall power factor is a combination of displacement and distortion power factor, but they don't combine linearly, they combine vectorially.

HARMONICS

Much like atoms are the building blocks of the universe, sine waves are the building blocks of all other waveforms. If we took a series of sine waves with different frequencies and amplitudes and added them together, we would get another waveform that is completely different than a sine wave. That is waveform synthesis. If we were clever enough, we could carefully select the right frequencies and amplitudes in order to create any waveform we wanted to build, whether it's a square wave, a sawtooth wave, or a waveform with pulses, like that shown in Figure 6.15.

FIGURE 6.15
The lower power factor, shown in the upper righthand corner, is a result of the current distortion created by the load. Notice that the capacitor symbol in the display indicates a capacitive load.

By the same token, we could take any waveform and deconstruct it into its components, which would be a series of sine waves of frequencies that are whole number multiples of the original frequency and with descending amplitudes. The original frequency is called the "fundamental" frequency, and whole number multiples of that frequency are called "harmonics." For example, if the fundamental frequency is 50 Hz, the second harmonic is 100 Hz, the third is 150 Hz, and so on.

By way of illustration, we can add a series of sine waves in a spreadsheet and plot the results. For the sake of brevity, we'll add only the first three sine waves in a series of odd-numbered harmonics, each with an amplitude that is half of the previous one. Figure 6.16 shows the results taken from an Excel chart in which these three sine waves in the series were summed. The result is a complex waveform approaching that of a square wave.

FIGURE 6.16
The complex waveform shown on the right was created by adding pure sine waves that are odd multiples of the fundamental frequency with half of the amplitude of the previous harmonic. If we were to add more sine waves in the series of odd multiples and decreasing amplitude, the resulting waveform would more closely resemble a square wave.

Just as sine waves can be added together to create complex waveforms, every complex waveform can be broken down into a series of pure sine waves. The only waveform that does not have harmonics is a pure sine wave. Decomposing a complex waveform is called Fourier analysis, after the mathematician, Joseph Fourier, who discovered the principle.

EFFECTS OF HARMONICS

Harmonics can introduce at least three issues in a power distribution system: (1) they can cause the neutral conductor to be overloaded, even in a balanced 3-phase system; (2) they can produce more heat than fundamental frequency currents do because of the "skin effect," which means that, because the current is higher in frequency it tends to travel along the skin of the conductor rather than through the center, and that increases resistance, and thus heat; and (3) they can contribute to excessive voltage drop. If there is neutral current in a balanced 3-phase system, that's a symptom of harmonics. Other symptoms include hot conductors, loud feeder transformers, nuisance tripping of circuit breakers, and excessive voltage drop.

In a 3-phase system, all of the phase-to-neutral currents sum in the neutral conductor, as shown in the Figure 6.17.

FIGURE 6.17
In a 3-phase system, all three phase-to-neutral currents sum in the neutral conductor. The black, blue, and red arrows represent the phase currents returning to the supply through the neutral conductor.

When the three phase-to-neutral currents combine in the neutral conductor, the fundamental frequencies cancel because they are 120° out of phase with each other. (See Figure 6.18.) The second-order harmonics (meaning the 2nd, 4th, 6th, etc.) are twice the frequency of the fundamental and when the frequency doubles, so does the phase angle between them. As a result, second-order harmonics are 240° out of phase with each other, but they also cancel. (See Figure 6.19.) Third-order harmonics are three times the frequency of the fundamental and are 360° out of phase with each other, which is the same as 0° degrees, or completely in phase with each other, so they reinforce in the neutral instead of cancel. This causes high neutral current, even in a balanced 3-phase system. (See Figure 6.20.)

FIGURE 6.18

In a balanced three-phase system, the phase-to-neutral currents sum in the neutral conductor. The fundamental frequencies cancel each other out because they are 120° out of phase with each other. The yellow line represents the sum of the three phase currents.

FIGURE 6.19
The secondary harmonics (twice the fundamental frequency) are 240° out of phase with each other and cancel in the neutral conductor. The yellow line indicates the sum of the three phase currents.

FIGURE 6.20
The third-order harmonics (three times the fundamental frequency) are in phase with each other, so they reinforce instead of cancel. The yellow line represents the current in the neutral conductor.

Every third harmonic (3rd, 6th, 9th, etc.) causes current to reinforce in the neutral, so the higher the harmonic content, the higher the neutral current. Harmonics are referred to by their harmonic number, e.g., 2nd, 3rd, 4th, and so on. The more current distortion there is, the higher the harmonics go. Since we don't know how many harmonics there might be, we can say they go to the nth harmonic, and every third harmonic is referred to as the triple-n or “triplen” harmonics.

If there is a lot of distortion, then the current in the neutral conductor can exceed that of any of the phase conductors, so it can be overloaded. The neutral is the only normally current-carrying conductor with no overcurrent protection (no fuse or circuit breaker) because it is connected to the grounding/earthing electrode, which means it provides the 0-volt reference in the electrical system. If that connection is lost, then the 0-volt point can drift, and voltage will be applied to the loads in such a way that some loads would receive more than 120 volts (up to 208 volts) and some would receive less than 120 volts, depending on how well the loads are balanced across the three phases. If the loads are incandescent lamps, then some will dim and some will get very bright, possibly exploding. Therefore, the neutral conductor is never protected by a fuse or circuit breaker. (See Figure 6.21.) If the phase conductors are loaded to their maximum ampacity, then triplen harmonics can contribute to overloading the neutral conductor, and the insulation will start to break down and eventually melt.

FIGURE 6.21
The neutral conductor (with the white tape) is the only normally current-carrying conductor that has no overcurrent protection. Triplen harmonics can cause the neutral conductor to be overloaded.

If a 3-phase system is heavily loaded with non-linear loads, it is good practice to monitor the neutral conductor while the system is being operated. You should know the ampacity of the neutral conductor, which can be found in ampacity tables, and you should use a true RMS meter to measure the current. An average reading meter will measure the fundamental frequency but not the harmonic currents, so it will yield false readings in this case. You can also use an IR thermometer to monitor the temperature of the neutral feeder conductor. In a balanced 3-phase system with no harmonics, the current in the feeder neutral will be 0 amps or very close to it, and the conductor will be at or near room temperature (provided it's not being heated by adjacent current-carrying conductors). If there is high harmonic content, then the temperature could approach the temperature rating of the conductor, which is 105° C for type SC (also known as "Entertainment cable") feeder cable.

Because the neutral feeder conductor can be overloaded and it has no overcurrent protection, sometimes double neutral conductors are run if the switch and the power distribution system has the ability to accept two neutral feeder conductors. However, the entire system should have double neutrals from the supply to the load. Even if the neutral is oversized or doubled, third-order harmonics can cause nuisance tripping and excessive voltage drop, and it can contribute to overheated transformers because of the skin effect. (See section below: The Skin Effect.)

If double neutral terminals are not available, an alternative is to de-rate the system 50%, which has the same effect as doubling the neutral feeder conductor, although all of the conductors are then effectively doubled. For example, if we have a 400-amp switch but we treat it as if it is a 200-amp switch by connecting no more than 200 amps of load, then we have effectively de-rated it by 50%, and the neutral feeder conductor will not be overloaded, even if there is high harmonic current.

THE SKIN EFFECT

When DC current flows through a conductor, it flows across the entire cross-sectional area of the conductor, as shown in Figure 6.22. But the higher the frequency, the more the current tends to travel along the outer skin of the conductor, which is called the "skin effect." At 60 Hz, feeder cable exhibits some skin effect but at 1000 Hz and higher it is much more pronounced. Harmonics are higher in frequency than the fundamental frequency, and the 16th or 17th harmonics are in the 1000s of Hz.

FIGURE 6.22
The higher in frequency, the more current tends to travel along the skin of a conductor. At 60 Hz, feeder cable exhibits a slight skin effect but it becomes more pronounced in the thousands of hertz. The 16th and 17th harmonics are around 1000 Hz.

True RMS Meters

Some voltmeters and amp meters are true RMS-reading meters while other are average-reading meters. An average-reading meter has a bridge rectifier that inverts the negative half of the sine wave and makes it to positive, resulting in a fully rectified waveform, as shown in Figure 6.23. The meter then reads the average value of the waveform and multiplies it by a number that represents the ratio of the RMS value of a sine wave to the average value of a sine wave. That number is 1.14, but only if the waveform is a pure sine wave.

FIGURE 6.23
A bridge rectifier converts the negative half cycle of a sine wave to a positive pulse, resulting in a fully rectified waveform. The average and RMS values are indicated by the dashed lines, and the ratio of the two is approximately 1.14.

Average-reading meters work fine as long as the waveform being measured is a pure sine wave. If, however, there is any waveform distortion, then the ratio changes, and the meter will read inaccurately, resulting in metering errors. The more distorted the waveform, the greater the error. A true RMS meter has a computer that samples the waveform several hundred times each cycle and calculates the actual RMS value regardless of the waveform.

A true RMS meter is usually, but not always, marked as such; sometimes you have to look at the meter specs to find out whether or not it is. If it doesn't specify, chances are that it is an average-reading meter. They work fine for some types of loads but will yield errors reading non-linear loads or any load that generates harmonics and distorts the waveform. Non-linear loads, like LED fixtures without power factor correction, are very common in live event production, so using true RMS meters to get accurate readings of voltage and current is advisable. Current distortion is much more common than voltage distortion, but there are instances where the voltage can be distorted.

You may wonder why average-reading meters are still made, given the low cost of computers and computer chips. One of the challenges facing production electricians is to know whether or not an audio, video, or lighting system has high harmonic content, because the harmonics can cause problems like high neutral current and excessive heat due to the skin effect. Unless you have a very expensive power quality meter, you have to use clues and become an electrical detective to figure out whether or not you need to keep a close eye on the neutral conductor and watch for overheating components or nuisance tripping of breakers. If you have a true RMS meter and an average-reading meter, you can use them both to help solve the puzzle. If, for example, you meter the current in the feeder cable with both devices and they yield the same current values, then you can be

confident that there is little harmonic content. On the other hand, if they yield completely different readings, say 100 amps and 80 amps, then the difference is the harmonic content.

POWER FACTOR CORRECTION

A load with low power factor draws more current compared to the same load with high power factor. That means it requires bigger conductors, connectors, fuses, transformers, and so forth, and it also means it generates more heat due to the higher current, and that requires more heat management like bigger heat sinks and better air flow. Larger conductors and components require more truck space and warehouse space, and they are also heavier, so they require more fuel to transport and labor handle. Therefore, manufacturers of larger devices that draw significant amounts of current are incentivized to build products with high power factor. But how can a manufacturer keep the power factor high if a device is inherently a reactive load? The answer is power factor correction.

Low power factor in reactive loads can be corrected by adding the opposite type of reactance; if it is a capacitive load then inductance is added, and if it is an inductive load, capacitance is added. Transformers, motors, and ballasts are inductive load, which cause the current to *lag* the voltage. In a capacitor, the current *leads* the voltage, so by adding an equal amount of capacitive reactance to an inductive circuit, the voltage and current realign, and that raises the power factor. If the capacitive reactance is equal to the inductive reactance, then the power factor will be 1, which is referred to as “unity.” If the capacitive reactance does not exactly equal the inductive reactance, then they don't fully cancel; the load will still be partially reactive, and the power factor will be less than unity.

Most LEDs and automated lighting fixtures being manufactured today have switch-mode power supplies, some of which are power factor-corrected and some of which are not. These power supplies have a lot of capacitors and are therefore inherently capacitive loads. If they are power factor-corrected, that means the manufacturer added a power factor correction circuit, which includes inductors to smooth out the pulses of current drawn by the load. This is more common in newer gear. Since reactance is frequency-dependent (the amount of reactance varies according to the frequency), then the device may not be completely power factor-corrected, depending on which part of the world it is being used or the frequency of the power. Regardless, power factor-corrected devices typically have a power factor anywhere from 0.9 to 1. Devices that have a switch-mode power supply that is not power factor-corrected typically have a power factor of about 0.5.

Older automated lights (manufactured before about 2005) with arc lamps and some inexpensive automated lights with arc lamps as well as older HMIs might have a magnetic ballast power supply instead of an electronic switch-mode power supply. In that case, they typically have a large power factor-correction capacitor (Figure 6.24) to compensate for the magnetic ballast, which is a large inductor.

FIGURE 6.24
A power factor-correction capacitor in an automated light.

The insulation in the capacitors tend to dry out and deteriorate over time, as it is subjected to repeated cycles of high heat and room temperature cooling. When the insulation fails, then the capacitor can lose its reactance and the power factor of the device will drop. There are two different modes of failure of a capacitor: it can fail as a dead short, in which case it will trip a circuit breaker or flow a fuse immediately, or it can fail as an open circuit, in which case it will likely still work for a long period of time (perhaps weeks or months), but since the power factor will be low, it will draw more current and run hotter. Eventually, it will likely blow the internal fuse. Until then, there is no way to know that the PF capacitor has failed unless the fixture is opened for visual inspection.

COMPLEX POWER

When the voltage and current are 90° out of phase with each other, then the power consumed over a full cycle averages 0 watts and the power factor is 0. Since power times time is energy, and energy cannot be created or destroyed (it can only change forms, e.g., electrical energy to light, heat, sound, or motion), you may wonder what happens to the energy in this situation. After all, if there is no energy being consumed by the load, then it must be going somewhere.

It turns out that when the voltage and current are out of phase, then energy flows back and forth between the supply and the load. The energy flowing to the load is temporarily stored in the form of a magnetic field if it is an inductive load or an electrostatic field if it is a capacitive load. This energy is subsequently returned to the source, minus the losses due to inefficiency, when the voltage changes polarity and the magnetic field collapses or the electrostatic field discharges. The result is that the net power transferred is lower than it would be if the power factor was unity.

The power that is shuttled back and forth between the supply and the load is called “reactive power,” and it is measured in volt-amps reactive (VAR) or kilovolt-amps reactive (kVAR). Reactive power does no work and is therefore sometimes referred to as “wattless power.”

The reason that it is important to us is because reactive power causes more current to flow, which adds to our ampacity requirements. If the power factor is low and the current drawn due to reactive power is ignored, then we can overload our supply, our power distribution system, or branch circuits. For example, the fixture pictured below (Figure 6.25) has a label on the yoke that says the power consumption is 75 watts max. What it doesn't tell you is that the power factor is 0.5. If we use the West Virginia formula to calculate the current draw, the answer will be half of the actual maximum current draw, leading us to believe that we can connect twice as many fixtures to a branch circuit or to a power distribution system.

FIGURE 6.25
The label on this fixture says the maximum power consumption is 75 watts, but it doesn't provide any information about the power factor, which is 0.5. That could lead to errors calculating the current draw, which could lead to overloading a branch circuit or power distribution system.

Power that is converted by the load to light, heat, sound, or motion is called “real power,” and it is measured in watts, kilowatts or megawatts. Reactive power and real power have both a magnitude and a phase angle; the magnitude is measured in watts, and the phase angle between the voltage and current is measured in degrees. Therefore, they can be represented by drawing vectors. When reactive power and real power combine, they don't add linearly, they add vectorially. The phase angle of real power is always 0° (the voltage and current are always in phase), and the phase angle of reactive power is always −90° for inductive loads and +90° for capacitive loads. The vectoral sum of real power and reactive power is “apparent power,” as shown in Figure 6.26.

FIGURE 6.26
Apparent power is the vectoral sum of real power and reactive power. Notice that the phase angle of real power is always 0° and the phase angle of the reactive power is always −90° for inductive loads or +90° for capacitive loads.

Apparent power is measured in volt-amps (VA), or kilovolt-amps (kVA) if it is in the thousands. Since real power and reactive power are 90° apart from each other, and apparent power is the vectorial sum of real power and reactive power, they form a right triangle and they are related by the Pythagorean theorem:

$$\text{Apparent Power}^2=\text{Real Power}^2+\text{Reactive Power}^2$$

The current draw is determined by apparent power because the supply has to deliver enough current for both the real power and the reactive power. It's easy to calculate the apparent power if you know or can measure the voltage and current; it is just the product of the two (VA = volts × amps).

Apparent power is sometimes provided in fixture specifications instead of wattage or current draw because it is an easy way to provide useful information for electricians and technicians about the power requirements for that device. For example, the specifications for a Clay Paky Axcor Profile 600 say that the input power is 800 VA at 230VAC/50Hz. That means that at 230 volts, the fixture draws about 3.5 amps because 800 ÷ 230 = 3.5. Although the apparent power is only given at 230V/50Hz, we can still do a rough calculation of the current draw at any voltage. If, for example, we power this fixture with 120V/60Hz, and we assume the same apparent power (in reality, it might vary slightly because impedance varies with frequency; but it will be close), then the current draw would be about 6.7 amps.

The wattage or the power factor of the Axcor Profile 600 are not given, although it says the LED emitter is 500 watts. If the motors and PC boards use another 75 watts or so, then the total wattage would be 575 watts, which means the power factor would be 0.71 because 575 ÷ 800 = 0.71. (Note: This is a fictional number used for illustration only!)

Example 6a

Suppose we measure 230 VAC and 10.5 amps in a circuit. What is the apparent power?

Answer:

$$\text{Apparent Power}=V\times I=230V\times 10.5A=2{,}415VA$$

FEEDER TRANSFORMERS FOR NON-LINEAR LOADS

Before the proliferation of automated lights, LEDs, and HMIs, most loads used in live event production were linear, with exception of lamps on dimmers. Today, the vast majority of entertainment lighting systems have at least some non-linear loads such as LEDs, switch-mode power supplies, and forward phase-control dimming. This is changing the nature of power distribution systems.

At one workshop, we set up some standard fluorescent soft lights that are often used in television and studio production. We balanced the 3-phase system by putting the same number of fixtures on each phase, and we took current measurements on all three phases and the neutral. Because of the harmonic distortion, which was 77.3% (see Figure 6.27), the current on the neutral was about 173% of each of the phases. Had we loaded the system to more than about 58% of its full capacity, we would have overloaded the neutral conductor (173% × 58% = 100%).

FIGURE 6.27
The display on this power quality meter shows a total harmonic distortion of 77.3%, which caused the current flowing through the neutral to reach about 170% of the phase current in a balanced 3-phase system. The bar graph indicates the amplitude and frequency of each harmonic component from the fundamental frequency (indicated by the number 1 below the first bar) up to, in this case, the 25th harmonic.

This is an example of how the neutral conductor can be overloaded even in a balanced 3-phase system with high harmonic content, and why some power distribution systems in live event production sometimes use double-neutral conductors. But doubling the neutral conductor does no good if the feeder transformer can't handle high neutral currents.

Before the proliferation of desktop computers and switch-mode power supplies, many feeder transformers were built with undersized neutral conductors. When desktop computers became the norm, a lot of feeder transformers were overheating and failing, which led to the development of a rating system for transformers based on the size of the neutral components and its ability to handle neutral current.

K-RATED TRANSFORMERS

A K-rated transformer is a specially constructed delta-wye transformer designed to withstand the heat and effectively manage the harmonics produced by non-linear loads. These transformers are often found in theaters in which a lot of dimmers are used for dimming conventional tungsten lamps. K-rated transformers have bigger conductors, special

winding geometry, heat-managing cooling ducts, bigger iron cores, and an oversized neutral terminal. In addition, the delta-wye configuration isolates triplen harmonic current and keeps them from propagating through the entire electrical system by recirculating in the delta primary windings.

The K factor (factor K in Europe) is a measure of the amount of heat generated in a transformer due to the harmonic content; it is derived from a ratio of the harmonic content of a waveform compared to the overall current. The K rating of a transformer is an indication of how well it can deliver power to non-linear loads without exceeding its temperature range. The values range from 1 to 50, but standard ratings include 4, 9, 13, 20, 30, 40, and 50.

For permanently installed systems in today's production environment, a K-rated transformer and oversized neutral conductor can provide protection against degradation of neutral components due to heating. The K-rating required depends on the harmonic content of the loads to be connected. ANSI/IEEE C57.110 describes the ratings as follows:

- K-1: A transformer designed to handle the heating effects of eddy currents and other losses due to 60 Hz sine wave currents. It may or may not be designed to handle the increased heating effects of harmonic currents.
- K-4: A transformer designed to supply the rated apparent power (in kVA) to a load without overheating if the current is made up of a 60 Hz sine wave plus 16% third harmonic current, 10% fifth harmonic current, 7% seventh harmonic current, 5.5% ninth harmonic current, and so on, up to the 25th harmonic.
- K-9: A transformer designed to accommodate 163% of the harmonic loading of a K-4 rated transformer.
- K-13: A transformer designed to accommodate 200% of the harmonic loading of a K-4 rated transformer.
- K-20, K-30, K-40: Transformers designed to handle successively larger amounts of harmonic content without overheating.

K-rated transformers are designed to handle heat according to how much extra current is flowing in the neutral, but they are not as efficient as standard transformers and they tend to distort the voltage under non-linear loads.

HARMONIC MITIGATING TRANSFORMERS

A harmonic mitigating transformer (HMT) is specially designed to reduce the harmonic currents due to non-linear loads in a 3-phase system. They can be found in some theaters, television studios, motion picture studios, and other applications where high harmonic currents are anticipated. In an HMT, each half of the three secondary windings is wound on a different section of the iron core of the transformer. The windings are arranged in a zigzag configuration (see Figure 6.28) so that the magnetic flux generated by the triplens is cancelled, thus canceling the harmonic currents.

FIGURE 6.28
The windings of a harmonic mitigating transformer are split in two, and each half is wound on a different section of the iron core of the transformer. The magnetic fields due to the triplen currents (represented in this

illustration by the dashed lines) in the winding pairs are in direct opposition to each other, so they cancel, which prevents triplen currents from flowing and keeps current from flowing in the neutral conductor of a balanced 3-phase system.

The primary can be a delta or a wye (or star), and the secondary is a wye. The combination is known as a delta- or wye-zigzag transformer. (See Figure 6.29.)

FIGURE 6.29
Delta-zigzag (top) and wye- or star-zigzag transformer (bottom).

The cancellation of the magnetic fields due to triplen currents reduces the impedance of the transformer and increases the efficiency. The reduced harmonic current also decreases the operating temperature. HMTs cost more than a standard transformer, but they usually have a relatively quick payback. HMTs are also designed to attenuate the 5th, 7th, and 11th harmonics through phase shifting. These harmonics are byproducts of variable frequency drive circuits.

UNDERSTANDING RESISTIVE, CAPACITIVE, AND INDUCTIVE LOADS

6.1 What is the phase angle between the voltage and the current shown in Figure 6.30? Is the current leading or lagging?

6.2 Which load is more reactive, a load with a phase angle of 40° or a load with a phase angle of 30°?

6.3 Most portable power generators are optimized for lagging loads. Are LED typically leading or lagging loads if they have a power factor of 0.5?

6.4 Which is more energy efficient, a 9 Ω resistor or a 9 Ω inductor? Why?

6.5 If the current is leading the voltage, is it a capacitive or an inductive load?

6.6 The reactance of a capacitor depends on the frequency. (a) What is the frequency of DC? (b) How many ohms is a capacitor in a DC circuit? (c) Is a capacitor an open circuit or a short circuit in a DC system?

6.7 (a) How many ohms is an inductor to DC? (b) Is an inductor an open circuit or a short circuit to DC?

6.8 If a capacitor is connected between the output of a DC power supply and its 0-volt reference (typically the chassis), does it draw current or short the output if the only current is DC (0Hz)?

6.9 If a load has low power factor, does it draw more or less current than a load with higher power factor of the same wattage?

6.10 What is the power factor of a tungsten lamp?

6.11 How much current does a 1000-watt load draw at 230V if it has a power factor of .75?

6.12 What is the power factor of a system that draws 29 amps at 120V if the total wattage is 3200 watts?

6.13 How much current is drawn by a load with an apparent power of 2.4 kVA at 240V?

6.14 In a balanced 3-phase system, if current is flowing in the neutral conductor, what does that indicate?

6.15 Name three symptoms of harmonics caused by the skin effect.

6.16 If a 200-amp 3-phase switch is de-rated 50% and the current in the neutral conductor is measured to be 150% of the phase conductor, what is the maximum amount of current that would flow in the neutral?

6.17 In Figure 6.27, the RMS current measures 8.69 amps, and the fundamental frequency reads 5.5 amps. If you use an average-reading meter to measure this load, how many amps will it read?

6.18 If a device has an inductive reactance of 3.8 Ω, how can it be power factor corrected?

6.19 If a load draws 12.5 amps at 208 volts, what is the apparent power?

6.20 If a load has an apparent power that is equal to the real power, what does that say about the power factor?

6.21 If a 120V/208Y feeder transformer is labeled 150 kVA, how many amps can it output per phase?

6.22 In Figure 6.27, the display indicates a K factor of 14.8. (See third row, upper left display.) What is the closest K-rated feeder transformer for a load like this?

6.23 Is it possible to have a power factor greater than 1? Why or why not?

6.24 Why is a luminaire with high power factor smaller and lighter than an equivalent one with a lower power factor?

6.25 In a highly reactive load, the current is high but the consumed (real) power is low. If current represents the flow of energy, what happens to that energy? Where does it go?

6.26 If a load draws 13 amps at 120 volts, what is the apparent power?

6.27 (a) Does a K-rated transformer prevent harmonic current from flowing through an electrical system? (b) How are they different than other transformers?

6.28 How does a harmonic mitigating transformer deal with harmonics flowing in an electrical system?

FIGURE 6.30
What is the phase angle? Is the current leading or lagging?

CHAPTER 7
3-Phase Power Calculations

In North America and other parts of the world where 3-phase, 120V/208Y services are commonly used, it can be challenging, even for some of the most experienced electricians, to understand how to calculate their power requirements because of phase relationships in 3-phase power and how currents combine in a circuit. The voltages in each of the three phases are 120° out of phase with each other, and when current flows through loads that are connected to different phase conductors, then those currents are also 120° out of phase with respect to each other. How they interact is important because, ultimately, it determines our power requirements.

In a 3-phase system with 120V loads, the loads are connected from phase (hot or live conductor) to neutral, and the current flowing through the black, red, and blue phases (using North American colors) all return to the supply through the neutral (white) conductor. If the power factor is 1 and there are no harmonics, then the currents cancel in the neutral conductor because they are 120° out of phase with each other. If there are also single-phase 208V loads, then they will be connected from one phase conductor to another (phase to phase), and the neutral conductor is not a part of the circuit. So, unless there is a mix of 208V loads and 120V loads, the neutral conductor is simply not connected to the circuit. In that case, the neutral conductor is part of each of the 120V circuits, but it is not part of the 208V circuits. (See Figure 7.1.) (Note: The grounding conductor should *always* be connected!)

FIGURE 7.1
A 3-phase system in North America can have 120V loads and 208V loads. The 120V loads are connected from a phase conductor (black, red, or blue) to neutral (white), and 208V loads are connected from one phase conductor to another (black to red, red to blue, or blue to black).

In such a system, each of the connected loads can be thought of as an independent circuit with its own current. If there are two or more loads in the same circuit, then the currents they draw combine to form a single current. If they are connected across the same phase conductors (or a phase conductor and the neutral conductor), then the currents are in phase and they simply add.

For example, suppose we have a lighting rig with 48 120/208V LED color wash fixtures that are power factor corrected (the power factor is 1), and each fixture draws 1 amp at 120 volts or 0.58 amps at 208 volts. If we connect them to a 120V power distro and distribute them equally across the three phases, then each phase conductor will be connected to 16 fixtures, and each of the feeder cables will carry 16 amps. The current in the neutral conductor will cancel, so it will be 0 amps (or very close to it).

If we take those same 48 fixtures and connect them to a 208V distro, now they will be connected from phase to phase instead of from phase to neutral. If they are equally distributed across the three phase conductors, then 16 fixtures will be connected from the black conductor to the red conductor, 16 will be connected from red to blue, and 16 will be connected from blue to black. Each fixture will draw 0.58 amps, so each branch circuit will carry about 9.3 amps (16 × 0.58 amps = 9.28 amps). However, each of the feeder cables supplies current to two different branch circuits, as illustrated in Figure 7.2; the black feeder cable supplies the black-red branch circuit and the blue-black branch circuit; the red feeder cable supplies the black-red branch circuit and the red-blue branch circuit; and the blue feeder cable supplies the red-blue branch circuit and the blue-black branch circuit.

FIGURE 7.2
In a balanced 3-phase system, each feeder cable supplies two circuits; the black feeder supplies the black-red and the blue-black branch circuit, the red feeder supplies the black-red and the red-blue branch circuits, and the blue feeder supplies the blue-black and the red-blue branch circuits.

But remember, the current flowing through each of the three branch circuits is 120° out of phase with the other. So, even though the current flowing through each feeder cable is the combination of two of the branch circuit currents, it is not the simple arithmetic sum of the two branch circuit currents because they don't add linearly. In other words, because of phase cancellation, the combined current of two branch circuit currents is less than 9.3 amps plus 9.3 amps. And that is what can trip up some electricians who have a fuzzy understanding of 3-phase power.

It is not difficult to calculate 3-phase power requirements if you understand the path that current takes in a 3-phase system and the phase relationship between the currents. Once you understand that, then it is a matter of using the correct power formula, the right voltage (phase-to-neutral or phase-to-phase) and understanding whether your answer is the number of amps per leg or the total number of amps.

3-PHASE POWER CALCULATIONS

In a 3-phase system, each of the three phases can be thought of as an independent power supply with a common node as shown in Figure 7.3.

FIGURE 7.3
3-phase power is effectively three separate sources of power with a common connection at the neutral.

The common point of connection, which is the neutral, is earthed or grounded, which adds stability to the system by providing a 0-volt reference. *The illustration doesn't show the phase relationship between the three power sources, but it is very important to note that they are all 120° out of phase with each other.* That is key to understanding how a 3-phase system works. If they were all in phase with each other, then there would be no voltage difference between them and connecting a load across phases would draw no current.

When you connect a load from phase to neutral, the neutral conductor is by definition 0 volts because it is earthed, so it creates a voltage differential and current flows from the supply through the load, and back through the neutral conductor. If you connect a load across two different phases, the applied voltage is the combination of the two power sources, which are 120° out of phase with each other. Since there is a voltage difference, current flows from one phase conductor, through the load, and through the other phase conductor.

Suppose, for example, that you connect a 2080-watt moving light to a 208V distro and that creates a circuit that is fed from the black phase and the red phase, as shown in the illustration below. The connection completes a circuit as illustrated by the red dashed line, and the current $I_{black\text{-}red}$ begins to flow.

FIGURE 7.4
When a load is connected from phase to phase, a path for current is created through two of the phases and the load, as indicated by the black and red dashed line.

If we connect second moving light between the red and blue phases, as shown in Figure 7.4, then a second path for current, $I_{red\text{-}blue}$, is created, as indicated by the red and blue dashed line in Figure 7.5. Notice that the two currents, $I_{black\text{-}red}$ and $I_{red\text{-}blue}$, combine in the red phase. In the real world, the leg that is carrying both currents is the red feeder cable and the current flowing through it is the combination of $I_{black\text{-}red}$ and $I_{red\text{-}blue}$.

FIGURE 7.5
When a second load is connected across the red and blue phases, it creates a second path for current, Ired-blue, as indicated by the red and blue dashed line. The two currents, Iblack-red and Ired-blue, combine in the common leg, which is the red feeder cable.

Remember that the two currents, $I_{black-red}$ and $I_{red-blue}$, are 120° out of phase with each other; therefore, they don't simply add the way you might think. When two waveforms are out of phase with each other and you combine them in a single conductor, there is partial phase cancellation, meaning the amplitude of the resulting waveform is less than the simple addition of the amplitude of the two individual waveforms.

Suppose, for example, the value of $I_{black-red}$ is 100 amps and $I_{red-blue}$ is also 100 amps. If they were completely in phase with each other, they would combine to 200 amps, and if they were completely out of phase with each other they would combine to 0 amps. In this case, since they are 120° out of phase with each other, they combine to a value somewhere between 0 and 200 amps. But what is that value?

If you recall from Chapter 4, when two 120V waveforms that are 120° out of phase with each other combine in a wye-connected secondary, the phase-to-phase voltage is the phase-to-neutral voltage times 1.732 (120V × 1.732 = 208V). It is similar when you combine two current waveforms *of equal magnitude*. In this case, 100A × 1.732 = 173.2A, so instead of doubling the current, it is 173.2 amps, which is slightly less than doubled due to partial phase cancellation.

If you're having trouble visualizing this, it might help to use vectors. A vector is an arrow whose size indicates magnitude and orientation indicates the phase angle, and since current has both a magnitude and a phase angle, it can be represented by a vector. The vectors in the illustration below represent the currents $I_{black-red}$ and $I_{red-blue}$, each of which are 100 amps and 120° out of phase with each other. The resulting current, or the combination of the two currents, is indicated by the vector from the head of I_1 to the head of I_2. (See Figure 7.6.)

FIGURE 7.6
I1 and I2 are both 100 amps but they are 120° out of phase with each other. When the two currents combine in a single conductor, the resulting amplitude is the length of the vector from the head of I_1 to the head of I_2.

We can figure out the magnitude of the resulting current—let's call it I_{total}—by using a little math trickery. Notice that the three vectors form a triangle. In the illustration below, we have drawn a line from the origin, 0, to the midpoint of I_{total} (M), which breaks the triangle into two right triangles. (A right triangle is one with a 90° angle.) This line also bisects the 120° angle, or cuts it in half, so we know the new angle is 60°, as shown in Figure 7.7.

FIGURE 7.7
By drawing a line from O to the midpoint of I_{total} (M), we have created two right triangles. The resulting triangles now have a 60° angle.

A right triangle has a fixed relationship between the three sides and the three angles. If we know the length of one side and one of the angles (in addition to the 90° angle), then we can figure out the length of the other two sides. In this case, we know one of the angles is 60° and the length of one side is 100 amps. If we call the side we're trying to calculate "X," then the formula to find X is:

$$\sin 60° = X \div I1$$

Using a calculator with trigonometric functions, we can find the sin of 60°, which is 0.866, and we know I_1 is 100, so:

$$0.866 = X \div 100$$

Now if we multiply both sides by 100, we get:

$$100 \times 0.866 = 100 \times X \div 100$$

And 100 ÷ 100 = 1, and 100 × 0.866 is 86.6, so X = 86.6. But X is only half of the magnitude of the vector representing I_{total}, so I_{total} is 2 × X, which is 2 × 86.6 or 173.2 amps.

What this means is that in a 3-phase system, when two currents of the same magnitude—in this case 100 amps—that are 120° out of phase and they combine in the same conductor, then the magnitude of the current doesn't double, but it is multiplied by 1.732 due to partial phase cancellation. That is why, in this case, 100 amps plus 100 amps doesn't equal 200 amps, but it equals 173.2 amps.

With that in mind, if we add a third load between the blue phase and the black phase, then we complete a third circuit with current $I_{blue\text{-}black}$, as shown in Figure 7.8.

FIGURE 7.8
Three independent phase-to-phase circuits cause current to flow, and each feeder cable carries the current from two circuits at a time. But those two currents are 120° out of phase with each other.

Now all three feeder cables have two currents combining, each of which are of equal magnitude and are 120° out of phase with each other. So, in a balanced 3-phase system, the current flowing through each feeder cable is 1.732 times the current drawn by any one of the three loads. Not so coincidentally, that number, 1.732, is the square root of 3, which often appears in 3-phase systems. For example, the phase-to-phase voltage in a 3-phase system is the phase-to-neutral voltage times the square root of 3. In North America, 208V is 120V times the square root of 3, and in Europe, 400V is 230V times the square root of 3.

BALANCED 3-PHASE LOAD CALCULATIONS

In a balanced 3-phase system, each of the three feeder conductors carries the vectoral sum of two currents, and because of partial phase cancellation, they multiply by a factor of the square root of 3. So, the formula for calculating the power in a balanced 3-phase system has to be adjusted to compensate for phase cancellation as follows:

$$P3\varnothing = V \times I \times PF \times 3,$$

where $P_{3\varnothing}$ is the power in watts that is connected to the 3-phase system, and PF is the collective power factor of the load.

It is important to know that when you use the 3-phase power formula, you have to use the phase-to-phase voltage in order to get the right answer; otherwise, your calculations will be incorrect.

Example 7.1

Let's try an example to illustrate how to calculate the current draw in a 3-phase system. Suppose we're hired to be the master electrician for a North American tour that has 30 moving lights, each of which is rated 2080 watts at 208 volts with a power factor of 0.99. Since we have a number of fixtures that are divisible by 3, we can build a balanced system using standard 3-phase power. We want to know the current draw in order to find out, among other things, how much supply we need for the moving lights and whether or not the venues in which we will be playing will be able to supply enough power. We'll start by writing down the formula and filling in the known values.

$$P3\varnothing = V \times I \times PF \times 3$$

$$30\times2080W=208V\times I\times0.99\times1.732$$

Then we'll divide by sides by (208 × 0.99 × 1.732) to clear the right side of the equation.

$$62{,}400(208 \times 0.99 \times1.732)=(208\times I\times0.99\times1.732)(208\times0.99\times1.732)$$

On the right side of the equation, 208 × 0.99 × 1.732 divided by (208 × 0.99 × 1.732) equals 1, so they cancel, leaving

$$62{,}400(208\times0.99\times1.732)=I$$

Now we'll rearrange the equation to put the unknown value, I, on the left side of the equation.

$$I=62{,}400\div208\times0.99\times1.732$$

$$I=62{,}400\div356.66$$

$$I = 175 \text{ amps per leg}$$

When you use this formula to solve for the current draw, it yields the current in each of the three legs in a balanced 3-phase system. To find the total current draw you have to multiply by 3, so in this case, the total current draw is 525 amps. But keep in mind that building power supplied by a switch is typically specified in amps per phase, e.g., 400 amps 3-phase means a total of 1200 amps, while portable power generators are typically specified in total amps.

UNBALANCED 3-PHASE LOAD CALCULATIONS

The power formula above works for a balanced 3-phase system, but sometimes it is not possible to distribute the load equally among the three phases. Suppose, for example, that you have five or ten followspots on a 3-phase service. How do you calculate the current draw on each of the three phases?

Sometimes we don't bother to calculate unbalanced loads, and we can safely avoid it by distributing the load as evenly as possible and then using the heaviest of the three values for the purpose of calculating the current draw. For example, if we have five followspots, then we can distribute the load with two of them across the black and red phases, two across the red and blue phases, and one across the blue and black phases. Suppose these followspots are 3000 watts each, which means that two phases will be loaded to 6000 watts while one has 3000 watts. For the purposes of calculating our power requirements we can use a value of 6000 watts for all three phase combinations and then use the 3-phase power formula. Then we'll get a result that says each of the three legs is conducting about 100 amps, when in reality, as we'll see shortly, the black and the blue phases will actually be conducting about 88 amps, so they have a built-in overhead of almost 15%. This works because it is better to overestimate our current requirements rather than to underestimate them so that there is room for error or adjustments. Also, we would never use feeder cable of different size for different legs; we would never use a set of feeder cable with one 4/0 conductor, one 3/0 conductor, and one 2/0 conductor, or any other mix of conductor sizes, so this approach allows us to properly size the feeder cable and the supply.

If, however, you want to calculate the current in each phase of an unbalanced 3-phase load, or if you have other loads to mix in with the unbalanced load to get closer to a balanced load, there is a formula that you can use.

Suppose we have a system like the one illustrated in Figure 7.9, where I_a, I_b, and I_c are the currents flowing through the phase conductors (which also happen to be the three feeder cables in a 3-phase system), I_{a-b}, I_{b-c}, and I_{c-a} are the current flowing through the loads, and the power factor is 1.

FIGURE 7.9
An unbalanced 3-phase load.

The first step is to calculate the current flowing through the loads, which is I_{a-b}, I_{b-c}, and I_{c-a}, as follows:

Ia-b=P÷V×PF=15,000W÷208V×1=72A

Ib-c=P÷V×PF=10,000W÷208V×1=48A

Ic-a=P÷V×PF=20,000W÷208V×1=96A

These values are not the same as the currents flowing through the feeder cables, but each of them contributes to it. I_a, which is the current in one of the feeder cables, is carrying both I_{a-b} and I_{c-a}; I_b is carrying I_{a-b}, and I_{b-c}; and I_c is carrying I_{b-c} and I_{c-a}. But remember, I_{a-b}, I_{b-c}, and I_{c-a} are 120° out of phase with each other, so they don't add linearly, they add vectorially. If it was a balanced 3-phase load, then we could just use the 3-phase power formula, but since it is an unbalanced load, that complicates matters. But there is a way of calculating the results that involves trigonometry. It is not important for us to know the details (although if you're a math geek like I am, and you wish to know the details, they are in Appendix 6). The bottom line is that we can use the following equations to calculate the current in each phase conductor:

Ia=(Ia-b)2+(Ic-a)2-[2×Ia-b×Ic-a×cosine120°]

Ib=(Ib-c)2+(Ia-b)2-[2×Ib-c×Ia-b×cosine120°]

Ic=Ic-a2+Ib-c2-2×Ic-a×Ib-c×cosine120°

where I_{a-b} is the current flowing through the loads that are connected from the phase a terminal to the phase b terminal, I_{b-c} is the current flowing through the loads that are connected from the phase b terminal to the phase c terminal, and I_{c-a} is the current flowing through the loads that are connected from the phase c terminal to the phase a terminal, as shown in Figure 7.9.

In North America and other parts of the world, I_a, I_b, and I_c correspond to the current in the black, red, and blue phases, and the phase-to-phase voltage is 208V. In Europe, Australia, and other parts of the world, the phase colors will be brown, black, and grey, and the phase-to-phase voltage is 400V, although it is rare to use 400V gear in our industry.

Example 7.2

Suppose we have 10 Barco UDX-U32 laser projectors that we will power from a single 3-phase 120V/208Y service. The specifications say that the projectors consume about 3000 watts at 208V, and they have a power factor of 1. What is the current draw on each phase conductor if we distribute the load with four projectors connected from phase a to the phase b, three from phase b to phase c, and three from phase c to phase a?

Answer:

Based on the specs, we can calculate the current draw for each projector:

$$I=P\div(V\times PF)=3000W\div(208V\times 1)=14.42 \text{ amps}$$

Therefore, if we load four units from phase a to be, three from b to c, and three from c to a, then we have the following values for I_{a-b}, I_{b-c}, and I_{c-a}:

$$Ia\text{-}b= 4 \times 14.42 = 57.7 \text{ amps}$$

$$Ib\text{-}c= 3 \times 14.42 = 43.26 \text{ amps}$$

$$Ic\text{-}a= 3 \times 14.42 = 43.26 \text{ amps}$$

Therefore,

$$Ia=57.72+43.262-[2\times 57.7\times 43.26\times \text{cosine}120°]$$

$$Ia=3{,}329.29+1{,}871.43-[2\times 57.7\times 43.26\times -.5]$$

$$Ia=5{,}200.72--2{,}496.1]$$

$$Ia=7{,}696.82=87.7 \text{ amps}$$

$$Ib=43.262+57.72-[2\times 43.26\times 57.7\times \text{cosine}120°]$$

$$Ib=1{,}871.43+3{,}329.29-[2\times 43.26\times 57.7\times -.5]$$

$$Ib=5{,}200.72--2{,}496.1]$$

$$Ib=7{,}696.82=87.7 \text{ amps}$$

$$Ic=43.262+43.262-[2\times 43.26\times 43.26\times \text{cosine}120°]$$

$$Ic=1{,}871.43+1{,}871.43-[2\times 43.26\times 43.26\times -.5]$$

$$Ic=3{,}742.86--1{,}872.43]$$

$$Ic=5{,}615.29=74.9 \text{ amps}$$

Example 7.3

Typically, in a show we have a mixture of devices, some of which are powered by phase-to-neutral voltage (120V in North America) and others by phase-to-phase voltage (208V in North America). What if you have a mix of each? Suppose, for example, that we add 150 LED color wash fixtures to the system in Example 7.2, and each of LED fixtures draws 1 amp at 120V and has a power factor of 0.5. How much current does each phase conductor draw now?

Answer:

If we distributed the LED fixtures equally among the three phases, then we will end up with 50 fixtures connected from phase a to neutral, 50 from phase b to neutral, and 50 from phase c to neutral. That will add a certain amount of current to each of the phase conductors, and the current will be in phase with the current generated by the video

projectors that are connected to the same phases. Therefore, we can calculate the current draw due to the LED fixtures and add it to the current we calculated in Example 7.2. Therefore,

$$I_a=87.7+50=137.7 \text{ amps}$$

$$I_b=87.7+50=137.7 \text{ amps}$$

$$I_c=74.9+50=124.9 \text{ amps}$$

QUICK CHECK

To simplify our power calculations, we can either use the 3-phase power formula or the single-phase power formula even if some of the loads require a phase-to-neutral (120V in North America) connection and others require a phase-to-phase (208V) connection. The key is to use the right voltage with the right formula. The 3-phase power formula requires that we use the phase-to-phase voltage, and the single-phase power formula requires that we use the phase-to-neutral voltage.

For example, suppose we have 30 moving lights, each of which is rated 2080 watts at 208 volts with a power factor of 0.99, as in Example 7.1, and then we add 90 LED color wash fixtures that are rated 120 watts at 120 volts with a power factor of 0.5. To calculate the current draw, we can use the 3-phase power formula like this:

$$P_{3\varnothing}=V\times I\times PF\times 3$$

$$30\times 2080W+90\times 120W=208V\times I\times 0.99\times 1.732+(208V\times I\times 0.5\times 1.732)$$

$$62{,}400+10{,}800=356.7\times I+180.13\times I$$

$$73{,}200=356.8\times I$$

$$I=73{,}200\div 356.8=205.2 \text{ amps per leg}$$

Even though we have to connect the LED fixtures from phase to neutral, we arrive at the correct answer using the 3-phase formula and the phase-to-phase voltage. We could have arrived at the same answer by using the single-phase power formula, like this:

$$P=V\times I\times PF$$

$$30\times 2080W+90\times 120W=120V\times I\times 0.99+(120V\times I\times 0.5)$$

$$62{,}400+10{,}800=118.8\times I+(60\times I)$$

$$73{,}200=178.8\times I$$

$$I=73{,}200\div 118.8=616.2 \text{ total amps}$$

Or 205.4 amps per leg

Other than a rounding error, the answers are the same.

UNDERSTANDING 3-PHASE POWER CALCULATIONS

7.1 If the voltage waveforms in a 3-phase system are 120° out of phase with each other, then what is the phase relationship between the three phase currents if all of the connected loads are linear?

7.2 If a single-phase 208V device draws 10 amps, then how many amps will be drawn if two of these devices are connected to the same two phase conductors?

7.3 If a single-phase 208V device is connected to the black (phase a) and red (phase b) conductors and it draws 10 amps, then how many amps is the black conductor carrying and how many amps is the red conductor carrying?

7.4 If a single-phase 208V device draws 10 amps, then how many amps will be drawn through each of the three feeder conductors if there are two devices connected from black to red, two connected from red to blue, and one connected from blue to black?

7.5 If a 3-phase, 208V chain hoist draws 1.8 amps per phase and has a power factor of 0.62, (a) what is the real power consumption? (b)What is the apparent power?

7.6 A 3-phase system has 15 automated lights, each of which is rated 2080VA with a power factor of 1, and 90 LED color-wash fixtures rated 180W with a power factor of 0.5. How much current will be drawn in each of the three feeder cables?

7.7 A 3-phase system has 10 automated lights, each of which is rated 2080W at 208V, and 40 575W ellipsoidals with 120V tungsten lamps. How much current will be drawn in the three feeder conductors?

7.8 A 3-phase system has 12 automated lights, each of which is rated 1040W at 120V, and 48 575W ellipsoidals with 120V tungsten lamps. How much current will be drawn in the three feeder conductors?

7.9 How many 2080W luminaires can be supplied by a 400A, 3-phase switch if they have a power factor of 0.97, they operate at 208V, and you want to allow 20% overhead?

CHAPTER 8
Portable Power Generators

A generator converts one form of energy to another. It takes liquid fuel energy and combusts it, which turns the engine or "prime mover" and converts it to mechanical energy. An alternator is coupled with the prime mover and converts the mechanical energy to electrical energy. Today, most portable power generators are diesel powered and, in the United States, they often comply with Q3 (California code for air quality).

Unlike a gas engine, a diesel engine doesn't have spark plugs. As long as a diesel engine has fuel and air, and as long as you can turn the engine over, then it will start. Diesel engines are more reliable than gas engines, they're more robust, and they last longer, but they also have their own peculiarities.

The generator described in Chapter 4 had a rotating coil of wire and a stationary two-pole magnet. In real life it is usually the other way around, probably because it is more practical to build a stationary winding with a rotating electromagnet than the other way around. So, the part that rotates, which is called the "rotor," is usually the magnet, and the part that's stationary, which is called the "stator," is where the windings are located. This is what is known as a rotating field generator. (See Figure 8.1.)

FIGURE 8.1
A two-pole generator showing the windings in the stator and the rotating magnetic poles of the rotor.

Each pole of the rotor is wrapped with a coil of wire through which DC current is passed, causing it to become magnetized. That current is called the "exciter current" because it excites the electromagnet. It is typically supplied by a lead-acid battery during startup and by a belt-driven alternator during normal operation. The higher the exciter

current, the stronger the magnetic field and the higher the voltage output of the generator. Most generators have a voltage regulator that adjusts the output voltage by controlling the exciter current. If the output voltage is too low, then it can be increased by increasing the exciter current using the voltage regulator. If the generator has an automatic voltage regulator (AVR), then it maintains the output voltage to a preset value by monitoring it and using a feedback loop to adjust the exciter current automatically.

A stator winding is typically made up of two coils wired in series that act as a single coil. One of the windings is on one side of the stator and the other is on the opposite side. The purpose is to balance the forces during the rotation of the rotor. Every time one of the magnetic poles passes a winding, it is either attracted or repelled from the winding, depending on the polarity, and that force that is transferred to the bearings on the rotor. If there were only one coil, then the force on the bearing would be unbalanced, much like an unbalanced washing machine, and the rotor would not spin smoothly. The bearing would also have more friction and it would fail prematurely. Arranging the windings on opposite sides of the stator helps balance the forces, reduces friction on the bearings, and helps to extend their life. A 3-phase generator has three sets of stator windings arranged around the stator 120° apart from each other.

A two-pole generator produces one cycle of a sine wave for each full rotation of the rotor. Each time the north pole passes one of the windings, it creates a positive peak. And when it passes the winding on the opposite side of the stator, it creates a negative peak. This is an example of a synchronous generator, meaning that the position and speed of the rotor are synchronized with the voltage waveform: the faster the rotation, the faster the voltage waveform repeats.

Some generators have more than two poles, including portable generators that are commonly used in live event production. A four-pole generator, for example, generates two complete cycles of the waveform for every single revolution of the rotor. (See Figure 8.2.) Therefore, when it rotates at 1800 revolutions per minute (RPM), it generates a 60 Hz waveform and when it rotates at 1500 RPM, it generates 50 Hz waveform. Although most portable power generators allow you to make fine adjustments to the output frequency, they are typically designed to supply power at 50Hz or 60Hz. To operate at a different frequency requires modifications, including replacing the voltage regulator, recalibrating the governor, and more.

FIGURE 8.2
A four-pole, 3-phase generator operating at 1800 RPM produces 60 Hz and at 1500 RPM it produces 50 Hz.

Portable power generators that are used in live event production are typically four-pole, 3-phase generators, although they can be switched to single-phase operation. A 3-phase generator has six stator windings, and each winding has two terminals that are brought out to a terminal block. The terminals are connected to a switch that allows you to

select three-phase operation or single-phase zig-zag operation. In North America and other locations where 120/208V power is used, these generators supply 120/208V in 3-phase mode or 120/240V in single-phase mode.

GENERATOR SPECIFICATIONS

Portable power generators are capable of outputting a limited number of amps at a particular voltage. The specifications will typically spell out the maximum total amps at a given voltage, but there is more than one way to do so. It might be specified by the number of amps, e.g., 1200 amps @ 120/208V 3-phase, or by the kilovolt-amps (kVA), e.g., 144 kVA @ 120/208V 3-phase. The kVA rating, or apparent power, is the phase-to-neutral voltage multiplied by the total amps, so the output in amps can be derived from the kVA rating. For example, if a generator is rated 150 kVA, then it can output a maximum of 1250 amps total at 120/208V because 150,000 kVA ÷ 120 volts = 1250 amps, or about 417 amps per leg, although it is likely to have a 400-amp breaker.

The terminology portable power generator operators use can be different than that of electricians. A generator's ampacity is specified by the total number of amps it can output, while an electrician typically specifies three-phase power by quoting the number of amps available from each of the three phases. For example, a generator operator would specify an 1800-amp, three-phase generator while an electrician would call a switch with the same capacity a 600-amp three-phase switch.

There are other terms in generator specs that are important to understand as well. Often times, the output is listed as “standby” power and/or “prime” power. Backup generators are designed to provide backup power in the event that the grid power or building power is lost. These generators are not expected to run 24/7/365, so they are designed to run harder for short periods of time. Standby generators can operate at 100% of the standby rating until grid power is restored, but they are not designed to be loaded more than their rating for any period of time.

In live event, motion picture, and television production, we often use generators as the primary source of power, not as a backup. The prime power rating of a generator is based on the assumption it will be running for long periods of time and that the load will vary from 50% to 100% of the generator rating. It can run loaded up to about 110% of the prime power rating, but not for more than one hour in every 12-hour period.

The specs might also reference kW, as in 1200 kW @ 120/208V 3-phase. That number is likely based on the condition that the power factor of your load is 0.8. Power factor is a measure of how much of the current being drawn by the load is being converted to useful work. “Work” in this context means it is being converted from electrical power to light, heat, sound, or motion. Those are the only things we can do with electricity when we connect a load to a source of power, with one exception; some loads store energy and eventually return it to the source. Energy can be stored either in the form of a magnetic field—which is what an inductor does—or in the form of an electrostatic field—which is what a capacitor does.

For example, some loads, like certain LED fixtures and HMIs with electronic ballasts that are not power factor corrected, have low power factor and draw more current than they consume, meaning that less than 100% of the current is converted to light, heat, sound, or motion. The ratio of the amount of current being consumed to the amount of current being drawn is the power factor. It can range anywhere from just above 0 to 1 (or just above 0% to 100%), but it has nothing to do with the generator. It is entirely determined by the load, and whether or not it has inductors and/or capacitors. (See Chapter 6: Power Factor.)

This can be better understood by looking at the generator capability curve. This is a graph that shows the relationship between the wattage, the power factor of the connected load, and the performance of the generator. (See Figure 8.3.) A generator capability curve looks something like a semi-circle plotted on an X-Y plane. The semi-circle describes the apparent power of the generator, which is the maximum amount of current it can output at a particular voltage, versus the phase angle of the load. If you draw a vector from the origin (0 on the plot) straight up so that it touches the semi-circle, the length of that vector represents the kVA, and the angle, in this case 0° because it is straight up, represents the phase angle between the voltage and current. The phase angle is also related to the power factor; the cosine of the phase angle is the power factor. (See Chapter 6: Power Factor.) For example, if the angle is 36.9°, then the power factor is 0.8 because the cosine of 36.9° is 0.8.

FIGURE 8.3
The semi-circle in the generator capability curve represents the apparent power in kVA, and it is plotted against the real power and the reactive power.

The Y-axis on the plot represents the real power that the load is drawing and that the generator is producing. It is the part of the current that is being converted to light, sound, heat, or motion, and it is measured in watts or kilowatts. If the power factor is 1, then the apparent power and real power are equal. If the power factor is anything other than 1, then the apparent power is greater than the real power; the lower the power factor, the lower the real power, but the apparent power is always the same.

The X-axis represents the reactive power that the load draws and that the generator is producing. Reactive power is current that is drawn by the load but is not converted to work; it is temporarily stored before being returned to the supply. Reactive power is measured in volt-amps reactive or kilovolt-amps reactive (kVARs). If the power factor is 1, then the reactive power is 0. If the power factor is anything other than 1, then the reactive power is greater than 0.

If the power factor is anything other than 1, then the apparent power, the real power, and the reactive power form a right triangle known as the "power triangle." The apparent power is the hypotenuse of the right triangle (the side opposite the right angle), and the relative length of the X and Y components are the reactive power and the real power, respectively. For example, for a 100 kVA generator, if the phase angle is 25°, then the power factor is 0.91 (cosine of 25° is 0.906), the real power is 90.6 kW, and the reactive power is 42.3 kVAR. (See Figure 8.4.) If the load is inductive, then the apparent power vector will be in the right side of the plot. If it is more capacitive, then it will be on the left.

FIGURE 8.4
If the power factor is anything other than 1, then the apparent power, the real power, and the reactive power form a right triangle, which is known as the "power triangle."

Notice that because the power triangle is a right triangle, the Pythagorean theorem applies:

Apparent power2= real power2+ reactive power2

For example, using the previous example with a 100 kVA generator and a load with a power factor of 0.91:

Apparent power2= real power2+ reactive power2

100 kVA2= 90.6 kW2+ 42.3 kVAR2

The apparent power represents the limit of the generator output, which is limited by the stator current. If too much current flows through the stator winding, it will overheat, and the insulation will start to break down, thus damaging the generator. The apparent power is the combination of real power and reactive power, so the lower the power factor, the lower the real power and the higher the reactive power. For example, our 100 kVA generator in the example above can only output enough power to supply 90.6 kW of load if the power factor is 0.91 because the reactive power draws additional current that adds to the heat load of the stator winding. The apparent power is always 100 kVA, but the real power is a function of the power factor of the load because the rest of the capacity of the generator is being taken up by the reactive power.

If the power factor of the load gets below 0.8 lagging (meaning it is an inductive load), then the generator capacity is reduced by the ability of the rotor winding to handle current. The current that flows through the rotor winding (the exciter current) is controlled by the automatic voltage regulator, and the higher the current, the stronger the magnetic field, and thus, the higher the voltage output of the generator. The more inductive the load, the lower the power factor and the higher the exciter current needs to be to keep the voltage constant. When the power factor gets below 0.8, the exciter current reaches its limit, resulting in a reduction of the apparent power rating of the generator. So that part of the capability curve is modified by the red area in Figure 8.5, meaning the generator output is de-rated according to the modification of the apparent power curve.

FIGURE 8.5
If the power factor of the load is below 0.8, then the exciter current becomes the limiting factor and the generator capacity is reduced.

For example, if a 100 kVA generator has a connected load with a power factor of 0.5, then the apparent power, according to the generator capability curve, is reduced to about 83.2 kVA, the maximum real power is about 40 kW, and the reactive power is about 73 kVAR.

Notice that the red area starts to come into play when the power factor reaches 0.8 lagging and beyond. That's why some generator manufacturers list the power factor as 0.8 in their specs. It doesn't mean your load has a power factor of 0.8, it means that if the power factor of your load is below 0.8 lagging, then you will have to de-rate the generator according to the capability curve.

There's another limitation for capacitive loads (leading power factor). Capacitive loads send reactive power back to the supply, which means the rotor current has to be reduced to maintain the same output voltage. But if the rotor

current is too low, then the output voltage can become unstable, so there's another area of the capability curve that is out of bounds, as shown in Figure 8.6. The yellow area of the curve is in the area of leading power factor (a capacitive load), which also reduces the capacity of the generator because a capacitive load sends reactive power back to the generator, making the output voltage unstable.

FIGURE 8.6
The red areas indicate conditions in which the exciter current is too high or too low, resulting in a reduction of the capability of the generator. The yellow area indicates a leading power factor, which causes instability in the output voltage.

Generator specs also sometimes include “kWm” and/or “ekW” ratings, and they are related to how generators work. There are two parts to a generator; the “prime mover,” which is the part that supplies the mechanical power, and the alternator, which converts the mechanical power to electrical power. The first law of thermodynamics, which is known as the conservation of energy, says that energy cannot be created nor destroyed; it can only change forms. When the generator burns fuel, it converts chemical energy to heat energy, and when the fuel vapor combusts, it expands and pushes the mechanical parts of the engine, converting it to mechanical energy. That, in turn, rotates the engine, which is coupled to the alternator, and the alternator converts it to electrical energy.

Mechanical energy can be measured in different ways, and in an engine it is usually measured in horsepower. The horsepower was James Watt's attempt in the late 1700s to define a standard unit of measure that would come in handy for comparing his steam engine to the amount of work that can be accomplished by the energy it was replacing, which was a team of horses. It is somewhat subjective, but it establishes a standard means of measuring the mechanical output of an engine.

Watt is also the namesake of the electrical unit of measurement of power, which is a watt. It is an easy conversion from mechanical power (kWm) to electrical power (ekW): one horsepower is equal to 746 electrical watts. So, if the specs for a generator lists the mechanical output power of the engine in horsepower, then we can multiply it by 746 to figure out how much raw electrical power the engine is capable of producing. And if 100% of that mechanical power is converted to electrical power, then 746 kWm would translate to 746 ekW.

The capacity of the alternator may or may not exactly match the power of the engine. Sudden increases in the electrical load put high demands on the torque of the engine, so the engine may be oversized compared to the alternator in order to handle the dynamics of the load. Otherwise, the engine may be overwhelmed, it may stall, or worse—it could put enough mechanical strain on it to damage parts of the engine. Manufacturers often anticipate this, so they sometimes design generators with an engine that is capable of outputting more mechanical power than the alternator can output electrical power. That way, it has enough power in reserve that when a lot of load is turned on, the engine will rev up, producing a big cloud of thick black smoke, and then recover.

For example, a MultiQuip SG1400C4F diesel studio generator has an engine with a prime power rating of 282 HP, which translates to 210.4 kilowatts mechanical (kWm). If you look at the alternator specs for the same generator, it says it can output 1400 amps at 120/208V 3-phase, which translates to 168 kVA (1400 amps × 120 volts = 168 kVA).

GENERATOR POWER FACTOR

Generator specs will often include power factor, which is typically at 0.8, but that spec has nothing to do with the power factor of the connected load. It is either the minimum lagging power factor that the generator can handle without being de-rated (see capability curve above) or the ratio of the electrical power output to the mechanical power output. In our example above, the 1400-amp generator with a power factor of 0.8 has a diesel engine rated 282 horsepower, which translates to 210.4 kWm. The alternator is rated 1400 amps at 120/208V 3-phase, which translates to 168 kVA. The ratio of the apparent power to the mechanical power is 0.8 (168,000/210,400 = 0.8).

These specs can lead to confusion about how to properly size a portable power generator. The electrical power factor is always determined by the connected load, not the generator. If, for example, you connect a tungsten lighting system to a portable power generator that lists the power factor at 0.8, the power factor of the load is still unity (1).

If a generator specs wattage instead of amps or kVAs, then it is likely based on a load with a power factor of 0.8. If the connected load has a power factor that is higher or lower than 0.8, then the maximum wattage that can be connected can be determined by looking at the capability curve.

Generators operate at peak efficiency when they are more heavily loaded. For that reason, it is important to size generators properly for a given load. Not only are they more fuel efficient when they are more heavily loaded, but when a diesel-powered generator is operating a very low capacity, there is unburnt fuel that passes through the turbocharger into the exhaust, causing a “slobbering effect,” also known as “fuel stacking” or “wet stacking.” The result is that the fuel leaks inside of the engine compartment and the generator can run erratically. The solution is to add more load to the generator to blow out the fuel and it will run better.

PORTABLE POWER GENERATOR MAINTENANCE AND OPERATION

A properly outfitted portable power generator should have an operation manual on board that includes a log to log the hours of operation, the date, location, starting and stopping hours, and the maximum number of amps. This is required in parts of the United States, like California. The operation manual should also spell out the grounding procedures and have a copy of the license to operate or the required permits. Heavy fines can be levied against violators of permitting regulations. Besides the operation manual, the generator should have an onboard fire extinguisher. Before turning on the generator, locate the fire extinguisher, take it out of its compartment, read the inspection tag and make sure has been recently inspected, and place the fire extinguisher in a readily accessible location, not inside of a compartment that might be hard to access in the event that the generator catches fire. (See Figure 8.7.) The fire extinguisher should be the right class for electrical fires, which is a class C.

FIGURE 8.7
Before starting a portable power generator, locate the fire extinguisher; then, remove it from its compartment, confirm that it has recently been inspected, and place it nearby in an accessible location.

There are two electrical systems in a generator; the low voltage DC system and the high voltage AC system. Care should be taken not to confuse them. Lead acid batteries supply the low voltage DC and they are used to start the generator. There may be only one battery, or—in the case where the starter works on 24VDC—two batteries connected in series. Once the generator is running, an onboard alternator uses engine power to recharge the batteries.

There are many different types of generators and prime movers, but most of the ones used for live event production are diesel-powered. Diesel engines have a turbocharger that forces a mixture of air and exhaust gases into the combustion chamber of the engine to increase its efficiency. Because the exhaust gases are very hot, the turbocharger gets very hot, so the engine should be idled before shutting it off in order to allow the operating temperature to drop. Unless there is an emergency, the engine should never be turned off without idling it first; otherwise, the bearings in the turbocharger could seize. At the end of the day, when the generator is no longer needed, turn off the circuit breaker and disconnect the cables while the generator is idling and let it idle for five or ten minutes before turning it off.

Once the generator has been given sufficient time to cool and it is turned off, it should then be refueled to its capacity. It is important to refuel it after each use because the fuel system recirculates fuel through the engine and back into the tank. Excess fuel that is not combusted is very hot when it goes back into the tank. When the engine is turned off, the fuel in the tank cools, causing condensation, leading to water and moisture in the tank. Getting water in the fuel tank of a diesel engine is inevitable, but it can be minimized by refilling and keeping the tank full after each use.

Caution: When diesel fuel is being dispensed, a static electricity discharge can potentially create a spark and cause a fire or explosion. Always use a U.L. listed fuel nozzle, which are designed to prevent the build-up of static electricity, to refuel a generator.

There are always contaminants in fuel, so a portable power generator will typically have several fuel filters. A primary filter separates water and fuel, and it has a petcock or valve that allows you to drain the water. There are more fuel filters that filter out contaminants like rust, fungus, and algae, the latter two of which are especially problematic in hot, humid climates. Rust is produced in the fuel tank by the presence of water, and it continually feeds into the fuel

system. There are fuel additives that can help reduce the level of contaminants, but the filters should be changed on a regular basis, typically about every 100 hours of operation.

The air filter and oil filter should be changed regularly, along with the oil. (See Figure 8.8.) The frequency of oil changes depends on the circumstances and the type of oil that is used, but it can range from about 150 hours to about 300 hours.

FIGURE 8.8
The fuel filters, air filter, oil filter, and oil should be changed on a regular basis.

OPERATING PROCEDURE

To operate a portable power generator safely, follow these procedures:

1. Locate the generator properly. Plan the location of the generator and power distribution equipment to avoid having to run cables across active roadways, doorways, and walkways. Where cables have to cross driveways, parking lots, or any other location involving vehicular or pedestrian traffic, make sure the cables are protected from damage and minimize trip hazards by running the cables through cable ramps.

   Make sure the generator is on level ground or level it using blocks or jacks to ensure proper fuel pickup. The fuel pump inside of the fuel tank has a pickup line, and if the generator is not level—which often happens if it parked against the curb on a street with a crown—then the fuel will tip to the low side of the street. The pickup line is on the side of the generator away from the curb, which means the fuel level will be higher on the side of the tank where the pickup line cannot reach it, and it will run out of fuel before the tank is empty. It is also important to place the generator so that the exhaust will not go into a building, an alley, or other enclosed area where it can collect and cause respiratory problems. There should be no flammable materials nearby because sparks can fly out of the exhaust and ignite them. For example, do not park the generator under a tree with low hanging branches that could be ignited by hot exhaust fumes. (See Figure 8.9.)

2. Once you have positioned the generator, find the fire extinguisher (every portable power generator should have one!), which is typically located in a compartment. Check the inspection tag to make sure it is current, and leave it in an accessible location. In the unfortunate event that the generator or nearby flammable materials catch fire, you should be able to get to the fire extinguisher very quickly without having to spend any time searching for it or opening a compartment to get to it.

3. Walk completely around the generator and make sure there are no leaks, especially fuel leaks, or any other obvious warning signs.

4. Check the fuel level. Fuel consumption depends on the operating load; the more load that is turned on, the higher the fuel consumption. The approximate fuel consumption is spelled out in the specifications, typically something like X liters or gallons per hour at 50% load, Y liters or gallons per hour at 75% load, and Z liters or gallons per

hour at 100% load. Generators are more efficient when they are more fully loaded, although it is a good idea to reserve 20% capacity for overhead, so, ideally, the generator load will vary between 50% and 80% of its capacity. You should never let a generator run out of fuel because the sludge at the bottom of the tank will foul the fuel lines and fuel filters, requiring expensive maintenance or repair when that happens. And sometimes you can get a generator from an unfamiliar supplier who has not taken care to fill the tank properly before delivery. And even in cases where you are not directly responsible for the operation of the generator, if you are in charge of power distribution, lighting, audio, or video, then you are the person who will get the blame if it stops working.

5. Check the oil before starting the engine. It is a simple task that could prevent serious damage to the engine. Most portable power generators have a petcock or a valve for the oil system that can inadvertently be opened by bumping it, and all the oil will drain out of the engine. Diesel engines also consume oil. The older the power plant is, the more oil it consumes. The oil is checked using a dipstick, much like checking the oil in a car. (See Figure 8.10.) Refer to the user manual for the manufacturer's recommendations for oil type and engine capacity.

6. Make sure the main circuit breaker on the generator and all of the circuit breakers on the power distribution panels are turned off before starting the generator.

7. Before starting the generator, make sure the voltage selection switch is set properly. Many portable generators that we use in live event production have a voltage selection switch that enables you to choose between different voltage and phase configurations. (See Figure 8.11.) For example, in North America, the voltage selection switch might allow you to choose three-phase 277/480V operation, three-phase 120/208V operation, or single-phase “zig-zag” 120/240V operation. The setting you choose depends on the task at hand. If you're lighting a movie and you want to locate the generator far away from the set because It is loud, then you can choose the 480V setting and use a feeder transformer near the set to drop the voltage to 120/208V. The higher voltage to the feeder transformer reduces the current draw, and therefore reduces the voltage drop or line loss. This allows you to locate the generator far enough away from the set so that the noise it makes will not be an issue for the audio techs. Once the engine is running, the setting of the voltage selection switch should not be changed under any circumstances. Even if the breaker is off, if the engine is running there could be residual voltage on the system. If it is switched under load, the contacts can arc and cause damage to the system and/or injury to the operator.

8. Connect the feeder cable to the connectors on the output terminal panel, making sure to connect the grounding/earthing conductor first, then the neutral, and then the hot conductors. Take care to match the colors of the conductors to that of the connectors on the connection panel. In North America, the connectors are typically single-pole locking connectors or “cam-lock connectors.” If it is a three-phase generator, there will be five color-coded conductors; green for ground, white for neutral, black, red, and blue for the hot conductors. If there are several connectors of the same color, they are connected in parallel to the same bus, so it doesn't matter which set you use because all the same colors connect to the same bus. There might also be convenience outlets with Edison connectors or, as shown in Figure 8.12, stage pin connectors.

9. Start the generator by turning the key and let it warm up sufficiently. Typically, this takes about five or 10 minutes or so. While it is warming up, listen carefully for any abnormal noises. If the generator doesn't sound normal, turn it off and investigate.

10. Before energizing any connected load, check the voltage and frequency to confirm that it is correct. Many portable power generators have a built-in panel meter that displays voltage, current, frequency, RPM, and more. If the voltage is not set properly, adjust it using the voltage regulator on the generator.

11. Check that the amp meter for all phases indicates 0 amps.

12. Check that the oil pressure and engine temperature are normal. (Refer to the user manual for normal ranges.)

13. Check the tachometer and make sure the generator is running at normal speed. Normal speed for a 4-pole generator—which is typically what is used in live event production—is 1800 RPM in North America and 1500 RPM in Europe, Australia, and Asia.

14. Once all the proper settings and readings are confirmed, throw the switch to put the generator online.

FIGURE 8.9
Portable power generators should be located on level ground or leveled with blocks or jacks; otherwise the fuel pickup line may not be able to reach the fuel before the tank runs dry. Also, the generator should not be parked where the exhaust fumes can collect or go into a building, and it should not be parked under trees or other structures that could be ignited by hot exhaust fumes.

FIGURE 8.10
Always check the oil before starting the engine. The dipstick indicates the oil level, the low level, and the full limit level.

FIGURE 8.11
The voltage selection switch on a 3-phase generator should be set before starting the generator and should never be changed while the generator is operating.

FIGURE 8.12
The output terminal panel of a portable power generator typically has single-pole locking connectors and some convenience outlets.

MONITORING THE OPERATION OF PORTABLE POWER GENERATORS

Generators have lots of moving parts and potentially dangerous voltage. Therefore, they should be closely monitored by qualified personnel when they are being used, and unqualified people should be kept at a healthy distance from them. Panel instruments help make the task of monitoring their operation a bit easier. Modern portable power generators are typically equipped with a control panel with several monitoring instruments. (See Figure 8.13.) These typically include a voltmeter and amp meter for each of the three phases, a frequency meter, a DC voltmeter to monitor the battery voltage, an engine temperature gauge, and an oil pressure gauge. It might also include a tachometer that shows the engine speed in RPM. There will probably be other indicator lamps such as:

FIGURE 8.13
Many portable power generators have built-in panel meters for voltage, current, frequency, RPM, and more.

- voltage selection switch to indicate the output voltage and phasing; e.g., 120/240 V single-phase, 120/208 V 3-phase, or 277/480 V 3-phase
- charging fault indicator to monitor the alternator and battery charging circuit
- low coolant indicator
- low oil pressure indicator
- high engine temperature indicator
- overcrank indicator
- overspeed indicator
- engine start indicator

In addition to monitoring the indicator panel, the voltage and current at the generator should also be monitored. If the voltage drops below the nominal level, minor adjustments can be made using the voltage regulator. If it changes drastically (more than about +/−10%), then it is a good idea to investigate further and possibly shut down the generator until the cause can be determined.

LOAD BALANCING

The loads on multi-phase generators should be balanced, to the extent possible, between phases. In motion picture production, part of the job of the generator operator is to monitor the generator, including the load balance. According to *On-Site Power Generation: A Comprehensive Guide to On-Site Power,* a generator should be balanced to within about 5%. Load imbalance can be calculated using the following formula:

$$\text{Load imbalance} = \text{maximum deviation from average current}\text{average current}$$

If the imbalance exceeds 5%, it can cause the voltage between the phases to become unbalanced, and the generator operator will seek to more evenly distribute the loads to achieve better balance. In other facets of the industry—like live music or theatre—load balancing is virtually impossible to achieve with any consistency because every cue

randomly distributes the loads across the phases. But it is always a good idea to start by connecting the loads in a way that is as evenly balanced across the phases as possible.

PORTABLE POWER GENERATOR GROUNDING/EARTHING AND BONDING

One of the most common questions about using portable power generators is whether or not to ground/earth using a grounding/earthing rod. The correct answer is that it depends on the circumstances.

In the United States, the National Electrical Code says that the frame of a portable power generator is *not required* to be connected to a grounding electrode if "(1) The generator supplies only equipment mounted on the generator, cord-and-plug-connected equipment through receptacles mounted on the generator, or both, and (2) The normally non–current-carrying metal parts of equipment and the equipment grounding conductor terminals of the receptacles are connected to the generator frame." It is easy to check to make sure that non-current-carrying metal parts of the equipment and the equipment grounding conductor (the green color-coded conductor) are connected to the generator frame. Just use a multimeter and put it in continuity mode: place one probe on the green terminal and the other on the generator frame. Then, the meter should emit a tone indicating that you have continuity. If not, first make sure the probe on the generator frame is in contact with the metal and not touching thick paint. If it still indicates no continuity, then it is not bonded properly.

The code is silent about generators that supply equipment via a feeder cable connected to a portable power distribution system but remember that the purpose of a grounding/earthing rod is twofold: (1) for lightning and line surge protection, and (2) for 0-volt reference. The frame of the generator can serve as the 0-volt reference as long as it is bonded correctly to the neutral at the supply. If the generator is supplying power to a building or structure that also has its own power, then the generator should be bonded to the building grounding/earthing electrode to create a uni-potential plane and to ensure that there is not a difference in potential between the building steel and other conductive parts like truss, pipes, and stages.

LIGHTNING PROTECTION

Under no circumstances is it safe to operate a portable power generator if there is lightning in the vicinity. But what is considered the "vicinity?" Lightning can travel about 10 to 15 miles, but the right time to shut down a portable power generator supplying power to a portable stage varies according to the situation.

According to the Event Safety Alliance (www.eventsafetyalliance.org), the standard of care is that if there is lightning within an eight mile radius, anyone outdoors should seek shelter. Depending on how long it takes to evacuate a facility and how fast a weather disturbance is moving, the timing of the decision should allow time for everyone to evacuate the premises before lightning enters the eight-mile zone. That could translate to a much larger radius depending on the size of the crowd, the proximity of shelter, and the speed and direction of the storm.

According to meteorologist Dr. Kevin Kloesel, a lightning shelter should be a "substantial building" that has plumbing and wiring or an enclosed metal vehicle. Unsafe structures, he says, include "open garages, car ports, covered patios, picnic shelters, beach pavilions, golf shelters, tents of any kind, baseball dugouts, sheds, and partially enclosed vending areas." And unsafe vehicles are "golf carts, construction equipment with open canopies, tractors, forklifts, bucket trucks or cherry pickers, convertibles, motorcycles, or any other open cab vehicle."

There are weather apps that approximate the distance from your location to the closest lightning, but they rely on having a good internet connection, which has been known to fail at the most inappropriate times. When there are large crowds, cellular service tends to be slow or non-existent because there is a limited amount of bandwidth that is being shared by everyone in the vicinity. Perhaps more importantly, many of these apps have a delay of up to 15 minutes depending on the tilt angle of the radar it uses. A better solution is to hire the services of a professional meteorologist to monitor the weather and provide alerts in the event of a weather disturbance. They have better tools and the knowledge to better interpret weather data.

If a generator has to be shut down because of lightning, it should remain off for at least 30 minutes after lightning has left the vicinity. (See Figure 8.14.)

FIGURE 8.14
Portable power generators should be shut down if there is lightning within an 8-mile radius and should remain turned off for at least 30 minutes after lightning activity in the vicinity has ceased.

TO DRIVE A ROD, OR NOT TO DRIVE A ROD?

Ultimately, the question about whether or not to drive a grounding/earthing rod is best answered by the local authority having jurisdiction (the AHJ, better known in the United States as the electrical inspector). It depends on the local codes and regulations, which vary from municipality to municipality and from country to country. In some locations, like Los Angeles, driving a grounding rod is not allowed because the density of infrastructure almost guarantees that if you pick a random location and drive an 8-foot grounding rod, you are likely to hit underground electrical, water, gas, sewage, cable, traffic control, or some other underground infrastructure. In those instances, other means of protection should be used, such isolating the frame of the generator from the earth or connecting the grounding/earthing conductor to a metal light pole or other conductive structure that is in good contact with the earth.

Note: Always call the local utility companies before digging or driving a grounding rod. All underground services should be located before installing electrodes. Before connecting a grounding/earthing electrode conductor to a fire hydrant, check with the local fire marshall or authority having jurisdiction. Always follow local codes and regulations!

If the generator is being used to supplement building power, then the generator grounding/earthing conductor should be connected to the grounding/earthing electrode of that building. If the generator is supplying power to equipment that is not in the proximity of building power, then it should not be connected to interior water pipes, building steel, or a building grounding/earthing electrode.

In the county of Los Angeles, the Fire Department Public Safety Film Unit issued portable generator guidelines in 2013 (Addendum 23E to Safety Bulletin #23) entitled "Guidelines for Meeting National Electrical Code (NEC) Grounding Requirements for Portable Generators Supplying Portable Equipment in the Motion Picture and Television Industry." It sites NEC 250.34 and says, "The frame of the generator mounted to a truck or trailer may serve as the grounding electrode (in place of the earth) for the portable power distribution system. A ground rod is not required if the generator units and vehicles they are mounted to are insulated from the earth."

The reason that this is safe is because a grounding/earthing rod is primarily for lightning protection, and the motion picture and television industry has strict policies against shooting while there is lightning. The "30/30 rule" says that when you see a flash of lightning, count the seconds until you hear the thunder. If the thunder occurs before you reach the count of 30 seconds, then the strike was less than 6 miles away, and you should shut down the generator and wait 30 minutes from the last lightning strike to ensure the danger of lightning strike has passed.

"Insulated from the earth" means that no conductive parts of the trailer are in direct contact with the earth. If a portable power generator is mounted on a vehicle or trailer with rubber tires, then it can be insulated from the earth by insulating the trailer jack from the earth and making sure there are no chains or other conductive parts touching the

ground. The jack can be insulated from the earth by placing it on a sheet of wrapped in rubber, as shown in Figure 8.15. Also, rubber mats should be placed around metal stairs, if there are any.

FIGURE 8.15
If a trailer mounted portable generator has rubber tires, then it can be isolated from the earth by preventing the jack from making direct contact with the earth. This photo shows the trailer jack resting on a sheet of plywood wrapped in rubber.

In the event of a fault to a conductive metal part, isolating the generator from the earth prevents the completion of a low impedance path back to the source through a person touching the energized conductive part. Otherwise, a faulty ground could energize a conductive part—like the chassis of a light—and if someone touches it, they could complete a path through the earth and back to the supply through the grounding/earthing rod as shown in Figure 8.16.

FIGURE 8.16
In the event of a ground fault, the grounding/earthing rod becomes a path for fault current through a person touching an energized conductive metal chassis.

If there are multiple generators located within 20 feet of each other, or if multiple generators are supplying power to a stage or set in which two or more pieces of portable equipment are indoors and within 12 feet of each other or indoors and 20 feet of each other, then the generator grounding/earthing conductors should be bonded to each other with a copper conductor that is sized according to NEC Table 250.122.

Table 8.1 The Size of an Equipment Grounding Conductor for Bonding Multiple Generators is Based on NEC Table 250.122

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size (AWG) for Copper Wire
20	12

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size (AWG) for Copper Wire
60	10
100	8
200	6
300	4
400	3

If a generator is supplementing power in a building or structure that has power, then the generator's grounding conductor should be bonded to the building grounding electrode and it should be sized according to NEC Table 250.66. The building grounding electrode is usually near the service entrance or the electrical meter.

Table 8.2 A generator supplementing power in a powered building or structure is required to be bonded to the building grounding electrode with a bonding conductor sized according to Table 8.2 (From NEC Table 250.66.)

NFPA 70 Table 250.66
Grounding Electrode Conductor for Alternating-Current Systems

Size of Largest Ungrounded Service-Entrance Conductor or Equivalent Area for Parallel Conductors[a] (AWG/kcmil)		Size of Grounding Electrode Conductor (AWG/kcmil)	
Copper	**Aluminum or Copper-Clad Aluminum**	**Copper**	**Aluminum or Copper-Clad Aluminum**
2 or smaller	1/0 or smaller	8	6
1 or 1/0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250	4	2
Over 3/0 through 350	Over 250 through 500	2	1/0
Over 350 through 600	Over 500 through 900	1/0	3/0
Over 600 through 1100	Over 900 through 1750	2/0	4/0
Over 1100	Over 1750	3/0	250

In Canada, the practice of grounding portable power generators is very different. The Entertainment Electrical Safety Committee of Ontario (EESCO) has published "Grounding of Generators in the Entertainment Industry," and it says that all generators over 12 kW should be grounded, and those that are under 12 kW should be grounded if they are not frame grounded or if they use something other than cord and plug connected loads. Grounding should be accomplished with one of four acceptable grounding electrodes including: (a) two 10' ground rods spaced 10' apart from each other and driven to full depth, (b) an approved ground plate, which is typically 10" × 16" × 1/4", buried at a depth of at least two feet, (c) a buried metal water pipe such as a fire hydrant or water faucet, or (d) and existing metal object equivalent in size and depth to (a) or (b).

Other requirements for grounding generators include using the correct size of grounding conductor and using approved connectors, using a grounding conductor that is dedicated to that purpose that is no more than 50 meters long with no more than two in-line single-pin connections. The sizing requirements are spelled out in ESA SPEC-003 Table 3 as follows:

Table 8.3 Sizing Grounding Conductors for Generators from ESA SPEC-003 Table 3

Ampacity of Overcurrent Protection	Size of Copper Grounding Conductor AWG
100 or less	4
101 to 200	2
201 to 300	2/0
301 and above	4/0

In the United Kingdom, the requirements for earthing temporary systems, including generators, vary depending on the electrical environment. British Standards (BS 7909 - "Code of practice for temporary electrical systems for entertainment and related purposes") requires an assessment regarding whether or not the earthing terminal of a generator should be connected to an earthing electrode, the electrode of a building, or both, and whether or not the circuit protective conductor (CPC) of multiple temporary electrical systems should be interconnected. The determination has to do with the earthing arrangements, which can be TN-S (separate terra or earth and neutral

conductors), TN-C-S (a combination of a combined earth and neutral conductor for part of the system and separate earth and neutral for another part), or TT (multi-point earth with different earthing electrodes for the supply and for the distribution system). For more information, refer to BS 7909.

FIGURE 8.17
Earthing arrangements in Europe. *(A) TN-S network with a separate protective earth and neutral conductor; (B) TN-C network with a combined protective earth and neutral conductor; (C) TN-C-S network with a combined protective earth and neutral from the generator but a separate protective earth and neutral downstream from the distro; (D) TT network with two earthing connections.]*

MULTIPLE GENERATORS SUPPLYING POWER TO A SINGLE LOCATION

If more than one generator is being used to supply power to a stage or a remote location, then the grounding/earthing connections should be bonded to each other. This applies when there is more than one generator within 20 feet of another generator or when they are supplying equipment that is not more than 20 feet apart.

OPERATING THREE-PHASE GENERATORS IN SINGLE-PHASE MODE

Three-phase generators typically have a switch that allows you to select between 120/240 V single-phase operation, 120/208 V 3-phase operation, or 277/480 V 3-phase operation. Running a three-phase generator in single-phase mode reduces its output by 1/3 because the output is reduced to two phases instead of three, as shown in Figure 8.18. For example, an 1800 A 3-phase generator operated in single-phase mode has an output of 1200 A.

FIGURE 8.18
Left: The wiring diagram for a 3-phase generator showing three phases and the neutral. Right: The wiring diagram for a 3-phase generator operated in single-phase mode showing two phases and the neutral. Phase A and B are wired in series, limiting the output to 2/3 of the output in 3-phase mode.

UNDERSTANDING PORTABLE POWER GENERATORS

8.1 A movie set has four 20kW Fresnels powered by a portable generator. (a) How much total current will they draw at 120 V? (b) If a 3-phase feeder transformer is brought in and fed from the portable generator, how much current will the lighting system draw per leg if the generator is switched to 240 V? (c) How much current will be drawn per leg at 480 V?

8.2 If a portable power generator has an engine that is rated at 350 HP, how many mechanical watts can it produce?

8.3 If a portable power generator has a fuel capacity of 200 gallons and consumes 6.5 gallons per hour at 75% load, how many hours will it run at 75% load?

8.4 Why is it important not to change the voltage selection switch on a generator while it is running?

8.5 A 3-phase generator running in single-phase mode only outputs 2/3 of its capacity because two of the three phase windings are wired in series, which means one of the three is cold while the other two are hot. If a 3-phase generator outputs 1200 amps total in the 3-phase setting, how many total amps can it output in singe-phase zig-zag mode?

8.6 If an 1800 kVA 3-phase generator is set to single-phase zig-zag operation, how many amps can it output at 120 V?

8.7 (a) A movie set has four 20k Fresnels powered by a portable generator. If the lights are powered with an electronic ballast that has a power factor of 0.7, how much current will they draw at 240 V? (b) What size generator is needed to supply them properly if it is to be run in single-phase zig-zag mode?

8.8 If a system has 16 LED luminaires, each of which is 720 watts with a power factor of 0.5, what size generator would you need to supply them?

8.9 Why is it important to allow a generator to cool under no load conditions before turning it off?

8.10 Why is it important to refill the fuel tank in a generator after each use?

8.11 How often should the filters on a portable power generator be changed?

8.12 A portable power generator is carrying 180 amps in phase A, 135 amps in phase B, and 220 amps in phase C. (a) What is the average current? (b) What is the maximum deviation from the average current? (c) What is the percent of imbalance?

8.13 A 41.7-horsepower 3-phase motor has an efficiency of 94%. If there are 746 watts per horsepower, how many watts is the motor?

8.14 If a lightning storm is moving at 15 miles per hour and your weather app has a 15-minute delay, how many miles can the storm travel in the time it takes for you to get updates?

CHAPTER 9
Battery Power

Mark Thompson, a resident of Matthews, North Carolina, had charged the lithium-polymer batteries for his drone 50 times by his estimation and he never had a problem.

“In fact,” he said, “I've never even had one feel warm to the touch.”

Still, he was in the habit of making sure he didn't leave them unattended while they were charging. But on one particular day in October of 2019, he forgot the lithium batteries were on the charger, and he left his home for 20 minutes. By the time he got back, his living room was engulfed in fire.

This is not an isolated incident. Lithium batteries are particularly volatile because they have a very high energy density and they are built in such a way that there are several modes of failure. According to the U.S. Federal Aviation Administration Office of Security and Hazardous Materials Safety, there have been approximately 265 lithium battery-related incidents that were recorded involving smoke, fire, extreme heat, or explosion between 1991 and August 2019. That doesn't include incidents not related to air transport.

Battery power is becoming more common in live event production because of advances in battery technology, the increasing efficiency of loads like LEDs, and the increasing use of wireless control. (See Figure 9.1.) They are used in in a variety of applications including emergency backup systems, uninterruptable power supplies (UPS), wireless receivers, wireless microphones, video cameras, drones, luminaires, and more. Although batteries can provide convenient power and offer a number of advantages, they also come with hazards—including the possibility of shock, fire, explosion, and chemical exposure—as well as environmental concerns. We can best control those hazards by understanding the differences between battery types, the risks involved, and how to mitigate them.

FIGURE 9.1
Battery power is increasingly being used in live event production. Portable battery packs can supply power for lights, cameras, and accessories for short periods of time in locations that are challenging for building power or portable power generators to supply.

BATTERY CHEMISTRY

A battery creates a chemical reaction that converts chemical energy to electrical energy when it is connected to a complete circuit. There are a number of different battery types, including alkaline, lead-acid, and lithium; each of which uses different chemicals and materials to accomplish the task, and each of which has advantages and disadvantages.

LEAD-ACID BATTERIES

Lead-acid batteries have not changed a lot since they were invented in 1859. They have the lowest energy density of these three battery types, but they are relatively inexpensive and can be recharged. Lead-acid batteries can be classified as a starter type or deep-cycle type. Starter batteries are used to supply a lot of current and power for a short amount of time in order to crank an engine. These are the type that are used in cars and other vehicles. Deep-cycle batteries are used to supply a sustained current over a longer period of time. These batteries are typically found in golf carts, wheelchairs, uninterruptable power supplies, and other devices.

Lead-acid batteries have a number of individual cells, each of which is made up of a positive electrode and a negative electrode. The positive electrode is made of lead peroxide and the negative is made of lead, which is why lead-acid batteries are very heavy. The cells are submersed in an electrolyte, which is diluted sulfuric acid in either liquid form or gel. Lead-acid batteries with a liquid electrolyte are referred to as “wet-cell” batteries.

When a lead-acid battery is charged, it “outgasses,” meaning it produces hydrogen gas and oxygen gas, and consumes water. The gases produced when a lead-acid battery is charged have to be vented to the outside of the case. Under normal conditions, hydrogen is colorless, odorless, tasteless, and highly flammable; therefore, lead-acid batteries should be charged only in well-ventilated areas or outdoors.

Conventional lead-acid batteries are called “flooded” or “wet-cell” batteries because they have a vent and a filler well to allow for the topping off of the cells with distilled water. Before opening a battery vent cap, it is important to wear safety goggles and rubber gloves to protect against the splashing of sulfuric acid. After fully charging a wet-cell battery, the water level should be checked. If any of the lead plates are exposed, then just enough distilled water should be added to cover them and no more than that.

Maintenance-free lead-acid batteries are sealed but they have a pressure-relief valve that vents hydrogen gas when the internal pressure reaches a certain threshold. These are called valve-regulated lead-acid batteries (VRLA) or, more commonly, maintenance-free batteries.

Wet-cell batteries produce about 60 times more hydrogen gas when they are charging compared to VRLA batteries; therefore, proper ventilation is important. Wet-cell battery banks are often housed in specially built enclosures or rooms with forced air ventilation to prevent ignition because hydrogen gas is highly flammable.

NICKEL-BASED BATTERIES

In nickel-cadmium (Ni-Cad) batteries, the lead and lead peroxide electrodes found in lead-acid batteries are replaced with nickel oxide hydroxide and cadmium. Ni-Cads are typically sealed, and they have a much higher energy density than lead acid batteries. Until the middle of the 1990s, they were by far the most popular type of battery for portable electronic, but they have some drawbacks—one of which is that they suffer from charge memory or “memory effect.” That means that, if they are consistently recharged before they are completely depleted, they will no longer provide any charge beyond that point, thereby reducing their capacity. They can be reconditioned, to an extent, by fully charging them, fully draining them, allowing them to cool off, and then recharging them again. Even with regular reconditioning, the batteries will eventually lose capacity and have to be replaced.

Another drawback is that they are relatively expensive compared to nickel-metal hydride (NiMH), which is the current popular replacement for Ni-Cad batteries. Also, cadmium is a toxin and an environmental hazard, and if Ni-Cad batteries are disposed of in a landfill or incinerated, they can leach cadmium into the soil and water table or release it into the air.

Nickel metal hydride batteries are similar to Ni-Cad batteries except they essentially replace the cadmium electrode in Ni-Cads with an alloy that absorbs hydrogen. They are not as energy dense as lithium-ion batteries and they also have a higher self-discharge, losing about 20% of their capacity in the first 24 hours and about 10% per month after that.

LITHIUM-BASED BATTERIES

Lithium-ion (Li-ion) batteries use a lithium compound for the positive electrodes and graphite for the negative electrodes. They are often used in live event production for a variety of applications because they have a very high energy density and they have dropped in price considerably since they were invented in 1991. Improvements in electrode materials have increased their capacity from 1100 milliamp-hours (mAh) to over 3000 mAh. (See Figure 9.2.) Spent lithium batteries are not considered hazardous waste, although they are easily recycled (and recycling is definitely encouraged!).

FIGURE 9.2
This portable Li-ion battery is rated 28.4 Ah at 30V. It can power a typical 1 × 1 LED panel at full intensity for about four to seven hours, depending on the wattage.

Lithium-ion polymer batteries are similar to Li-ion batteries except they use a gelled electrolyte instead of a liquid electrolyte. They have a higher energy density and it can be manufactured in a smaller package than Li-ion, but they also cost more.

Lithium-ion batteries are easier to maintain than other types of batteries because they don't require exercising (charging and discharging fully) nor do they suffer from the memory effect (limited charge capacity due to repeated partial discharge). They have a relatively flat discharge curve and low self-discharge (internal discharge from inactivity), so they lend themselves well to reliable charge metering. But they are higher in cost, and, according to the Federal Aviation Administration (FAA) of the U.S. Department of Transportation, “Lithium metal batteries are highly flammable and capable of ignition. Ignition…can be caused when a battery short circuits, is overcharged, is heated to extreme temperatures, is mishandled, or is otherwise defective.”

Lithium batteries pose a greater risk of ignition because they have higher energy density and their physical construction makes them more susceptible to damage. The demand for small, lightweight, and powerful batteries has led to the development of batteries that are less than rugged—unlike lead-acid batteries, which are large, heavy, and much more ruggedized. Cylindrical Li-ion batteries typically have several individual battery cells in a single package. Separators are used to keep the cells from shorting out; and if a separator fails—whether due to puncturing, overheating, or a manufacturing defect—it causes adjacent cells to short, which causes a large amount of current to flow and heat the battery. That, in turn, can cause other separators to fail. The result is a chain reaction, leading to what battery manufacturers call “venting with flame” or “rapid disassembly.” This is more common in lithium batteries than in other types of batteries because the separators are thinner and not as durable.

PRIMARY AND SECONDARY BATTERIES

Non-rechargeable batteries are known as “primary batteries” and rechargeable batteries are known as “secondary batteries.” Many audio techs use non-rechargeable batteries in wireless microphones because they don't trust rechargeable batteries to hold a charge for the duration of the show. But new battery technology and battery charger technology is changing that. All of the Broadway theaters now use rechargeable batteries, thanks to the efforts of the Broadway Green Alliance (www.broadwaygreen.org). The theaters have two sets of batteries and while one set is being used on stage, the other set is charging. They are alternated every show, and at the end of the year, both sets are properly disposed of and two new sets of batteries are purchased.

BATTERY CAPACITY

Batteries are rated according to the voltage they supply and their amp-hour rating (Ah), milli-amp-hour rating (mAh), or watt-hour rating (Wh). (See Figure 9.3.) The standard amp-hour rating is the number of amps that a battery can supply over a period of 20 hours when they are fully charged. For example, a 10 amp-hour battery can supply 1/2 amp for 20 hours. The battery may or may not be designed to supply half an amp, but that is the standard that manufacturers use to determine the capacity of a battery. It might be designed to deliver 10 amps for 1 hour, or one amp for 10 hours, depending on the voltage and wattage of the load it is supplying. A 100-watt, 12-volt load draws 8.3 amps, and a fully charged 10 amp-hour battery should run it for about 1 hour and 12 minutes (10 amp-hours/8.3 amps = 1.2 hours or 1 hour and 12 minutes).

FIGURE 9.3
Batteries are rated according to how many amps they can supply over a period of 20 hours. The ratings can be in amp-hours (Ah), milli-amp-hours (mAh), or watt-hours (Wh).

BATTERY SAFETY

Batteries store energy, and any type of energy storage device, including batteries, can be a potential fire or explosion hazard. In addition, batteries can also present a shock hazard and a chemical hazard.

Sometimes lithium-ion batteries, battery packs, and chargers have built-in safety features, including thermal protection, over-pressure protection, overcharge protection, overtemperature protection, and overcurrent protection. Most commercial battery chargers and devices that use lithium batteries have built-in battery management that limits the amount of charge a battery can receive so they should be used only for that specific battery type, according to manufacturer's specifications. Non-rechargeable batteries should never be placed in a battery charger, nor should any lithium-type battery be placed in a charger designed for NiCad or NiMH batteries.

ELECTRIC SHOCK HAZARD

Batteries can present a serious or life-threatening shock hazard, especially when they are configured in series or parallel circuits; connecting them in series increases the voltage, and connecting them in parallel increases the amount of energy that can be released in the event of a short circuit or shock. Like any electrical system, care should be taken

to prevent personnel from making direct contact with any exposed conductor, terminal, or any uninsulated part of a battery circuit. *NFPA 70E: Standard for Electrical Safety in the Workplace* spells out the boundaries of approach for DC voltage systems in Table 130.4(D)(b), including the limited approach boundary (the boundary inside of which no unqualified personnel should be if there is a live exposed conductor) and the restricted approach boundary (the boundary inside of which you should be wearing shock protection, like voltage-rated rubber gloves, if there is a live exposed conductor). According to the table, the boundaries of approach for less than 100 VDC are "not specified," meaning the hazard is not significant. (It is important to note that the threshold for AC is 50 VAC, or half that of DC voltage.) From 100 VDC to 300 VDC, the restricted approach boundary simply says to avoid contact, and for 301 VDC and above, the restricted approach boundary is at least one foot. These guidelines relate to the shock hazard; however, there may be other hazards such as arc flashes, arc blasts, and chemicals.

TRANSPORTING LITHIUM BATTERIES

In 1996, the United States enacted legislation to protect the environment against batteries containing mercury and cadmium. The Mercury-Containing and Rechargeable Battery Management Act, or the Battery Act, banned the manufacture of batteries containing large amounts of mercury and required manufacturers to disclose the contents of batteries containing cadmium and to develop programs for their collection and proper disposal. Similar legislation was enacted in the European Union in 1991 (Directive 91/157/EEC) and in 2006 (Directive 2006/66/EC).

In the United States, lithium batteries are regulated by the U.S. Department of Transportation (DOT) and are considered hazardous material. As such, they have to follow established guidelines concerning the safe transport of lithium batteries by air, rail, highway, and water on both commercial shipping as well as those that are being conveyed on passenger craft.

As of January 2008, spare lithium batteries are not allowed in checked baggage.

Spare lithium batteries are allowed in carry-on baggage.

Larger lithium batteries rated between 100 and 300 watt-hours with equivalent lithium content (ELC) of eight to 25 grams are limited to one installed in a device plus two spares.

Lithium-ion batteries rated for more than 300 watt-hours or with ELC of more than 25 grams are forbidden.

These and other guidelines for transportation of personal lithium batteries can be found on the DOT's Pipeline & Hazardous Materials Safety Administration website at: http://www.phmsa.dot.gov/hazmat or at www.Safe.Travel.dot.gov/whats_new_batteries.html.

For transportation of larger shipments of lithium batteries, a detailed guidance document with revised 2012 regulations can be found on the web site of the International Air Transport Association (www.iata.org). See IATA Guidance Document: Transport of Lithium Metal and Lithium Ion Batteries at bit.ly/tgBicj.

PROPER DISPOSAL

Some batteries (but not all) are considered hazardous waste, but all batteries should be disposed of properly. Recycling batteries keeps toxins such as lead, cadmium, and mercury out of landfills and thus prevents them from leaching into the soil or venting into the atmosphere where they can cause serious health problems.

Recycle spent batteries by collecting them and taking them to a household hazardous waste collection center or recycling center.

To locate collection and recycling centers in the United States and Canada, visit bit.ly/aH1MLn.

Some retailers accept batteries for recycling including Best Buy, Home Depot, Radio Shack, Sears, Staples, Target, and Wal-Mart.

Never incinerate batteries of any type.

Fully discharge lithium batteries to consume the lithium content before recycling.

Recommended Guidelines for the Use and Handling of Lithium-based Batteries in the Entertainment Industry

Note: Always follow manufacturers guidelines when using lithium batteries.

Background
Lithium batteries are frequently used in many aspects of the Entertainment Industry including (but not limited to): flashlights, computers, cell phones and similar devices, battery belts and packs, wireless transmitters, radios, musical instrument accessories, block camera batteries, digital SLR cameras, and solar power systems.

Identification
Lithium batteries are available in three different types: lithium metal, lithium-ion (Li-ion or LiOn); and lithium polymer (Li-ion polymer or LiPo). In addition, there are at least six different types of material used for the anode and cathode in Li-ion batteries. Their chemical names include lithium cobalt oxide ($LiCoO_2$), lithium manganese oxide ($LiMn_2O_4$), lithium iron phosphate ($LiFePO_4$), lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$), lithium nickel cobalt aluminum oxide ($LiNiCoAlO_2$), and lithium titanate ($Li_4Ti_5O_{12}$).
Lithium-type batteries can be labelled "lithium," "lithium metal," "lithium Ion," "lithium polymer," or "LiPo."

Safety Guidelines
NEVER mix batteries by type, age, or manufacturer.
NEVER allow lithium-based batteries to be damaged whether by puncture, crushing, squeezing, impact, excessive mechanical shock, vibration, or dropping.
NEVER expose lithium-based batteries to high heat.
NEVER allow conductive materials to bridge or short the contacts of the battery.
NEVER leave charging lithium batteries unattended.
NEVER charge any battery that is not designed to be re-charged.
NEVER carry lithium-based batteries in pockets of clothing.
ONLY use batteries in approved devices, as specified by the manufacturer.
ONLY use approved batteries in a device, as specified by the manufacturer.
NEVER put lithium-based batteries in sealed containers such as flashlights, battery belt cells, underwater housings, etc.
ALWAYS secure lithium-based batteries to prevent their movement and to prevent contact with conductive materials.

UNDERSTANDING POWER SOURCES CONCEPTS

9.1 Why should lead-acid batteries be charged in well-ventilated areas or outdoors?

9.2 Why should Ni-Cad batteries be fully discharged before recharging?

9.3 Which of the following can cause Li-ion batteries to vent with flame?

a. puncturing
b. overheating
c. manufacturing defects
d. all of the above

9.4 A battery has a rating of 4800 mAh. If it is used in a device that draws 0.75 amps, how many hours will the battery last if it starts with a full charge?

9.5 A 1 × 1 LED panel light has a maximum power consumption of 200 watts. If you use two 14.4 V, 90 Wh batteries, how long will it run on a full charge?

9.6 On the Broadway show *Wicked*, the technicians use wireless microphones with Sennheiser SK2012 transmitters. The transmitters use one AA Ansmann 2800 mAh rechargeable battery, and they are powered on for four hours and fifteen minutes. If the transmitter uses 376.25 milliamps, what is the minimum battery capacity that will work?

9.7 According to the *NEC 70E: Standard for Electrical Safety in the Workplace*, what is the restricted approach boundary for 100 VDC?

9.8 Why does the U.S. Department of Transportation (DOT) not allow spare lithium batteries in checked baggage?

9.9 Why is it not a good idea to mix lithium battery types, batteries of different ages, or different manufacturers?

9.10 Why is it unsafe to carry lithium-based batteries in the pockets of clothing?

CHAPTER 10

Electrical Safety

Have you ever been shocked before? Chances are very good that you have. Did you survive? Of course you did. But others have not been so lucky. Why is it that when some people get shocked, they walk away from it and others do not? There are many variables, and the better we understand those variables, the better we are positioned to protect ourselves in the future. And ask yourself this question: If you have been shocked in the past—and most of us have—what are the odds that you will be shocked in the future? And if you are shocked at some point in the future, don't you want to control the circumstances to the best of your ability? But how can we do that? The answer starts with Ohm's law.

According to Ohm's law, when you get shocked, the amount of current that flows through your body depends on the voltage and the resistance of your body. And it is the current that can harm you. The voltage matters only because it is part of what determines how much current will flow. You can experience a shock with a very high voltage and still survive if the current if very low. For example, a neon transformer applies about 10,000 volts, but the current is only a few milliamps (a few thousandths of an amp). Back in the day, we used to install neon above the dance floor in nightclubs. And it was not highly unusual for a tech to accidentally touch the terminals and get zapped, yet none of us were ever seriously injured by the shock.

Some people have been shocked and survived because the circumstances just happened to be in their favor on that particular occasion—either the resistance was high, or the voltage was low. On the other hand, there are documented cases of people who were killed by an electric shock of less than 80 volts, and one in particular was killed by only 30 volts. These are highly unlikely but not impossible events. The key is the surrounding circumstances; In order to protect yourself against being severely injured if you are shocked in the future is to understand the factors that control the current and take steps to minimize the effects.

ELECTRIC SHOCK

There are many factors that can influence the severity an electrical shock, but the most important factors are the amount of current that flows through the body and the length of time it flows. The path that current takes through the human body is also a determining factor in the severity of injury. The most damage is caused by electricity passing through vital organs like the lungs, heart, brain, and kidneys. Table 10.1 is from the U.S. Department of Human Services ("Worker Deaths by Electrocution: A Summary of NIOSH Surveillance and Investigative Findings") and it estimates the effects of 60 Hz AC current passing through the chest.

Table 10.1 The effects of 60 Hz electrical current passing through the chest

Effect	Current

* Contact with 20 milliamps of current can be fatal. As a frame of reference, a common household circuit breaker may be rated at 15, 20, or 30 amps.

Source: U.S. Department of Human Services *Worker Deaths by Electrocution: A Summary of NIOSH Surveillance and Investigative Findings, Public Health Service Centers for Disease Control and Prevention National Institute for Occupational Safety and Health, May 1998*

Effect	Current
Barely perceptible	1 mA
Maximum current an average person can grasp and "let go"	16 mA
Paralysis of respiratory muscles	20 mA
Ventricular fibrillation threshold	100 mA
Cardiac standstill and internal organ damage	2 Amps
Common fuse or breaker open circuit*	15/20 Amps

* Contact with 20 milliamps of current can be fatal. As a frame of reference, a common household circuit breaker may be rated at 15, 20, or 30 amps.

Source: U.S. Department of Human Services *Worker Deaths by Electrocution: A Summary of NIOSH Surveillance and Investigative Findings, Public Health Service Centers for Disease Control and Prevention National Institute for Occupational Safety and Health, May 1998*

EFFECTS OF 60 HZ ELECTRICAL CURRENT PASSING THROUGH THE CHEST

A current of about 0.5 milliamps is enough to startle a person. Although this level of current will most likely not cause any serious damage, if you are working at height without fall protection, it could lead to a serious fall. Around 10 milliamps is all it takes for 1.5% of men, 40% of women, and 92.5% of children to contract their muscles to the point where they cannot let go, which is approaching the threshold of the "let-go current," as shown in Table 10.1. At 20 mA, 92.5% of men and 100% of women and children cannot let go. At 30 mA, no one can let go. The maximum current level allowable for virtually every person to be able to let go is 6 mA, which is the trip value of class A ground fault circuit interrupters (GFCIs), and those are designed to protect human life. A current of 10 mA to 60 mA passing through the human body can cause difficulty in breathing. Should someone become frozen to a live conductor, they could stop breathing long enough to suffocate.

If you are shocked, the duration of the shock will influence how badly you are injured; the longer the event, the worse it is. Table 10.1 does not include information about the length of time the shock lasts, but the IEC chart in Figure 10.1 does.

FIGURE 10.1

Log-log graph of the effect of alternating current I of duration T passing from left hand to feet*

- *AC-1: imperceptible*
- *AC-2: perceptible but no muscle reaction*
- *AC-3: muscle contraction with reversible effects*
- *AC-4: possible irreversible effects*
  - *AC-4.1: up to 5% probability of heart fibrillation*

- *AC-4.2: 5-50% probability of fibrillation*
- *AC-4.3: over 50% probability of fibrillation*

*Defined in IEC publication 60479-1.

Source: Redrawn based on Weineng Wang, Zhiqiang Wang, Xiao Peng, "Effects of the Earth Current Frequency and Distortion on Residual Current Devices", *Scientific Journal of Control Engineering*, Dec 2013, Vol 3 Issue 6 pp 417–422.

THE IMPEDANCE OF THE HUMAN BODY

The amount of current that flows through the body, and therefore, the severity of the shock, depends on the impedance of the circuit. When you are being shocked, you become part of the circuit; it is the impedance of your body that helps determine the amount of current. Depending on the conditions, the impedance of the human body can vary from a few hundred ohms to several thousand ohms. The conditions that can affect the impedance include the amount of surface area of the skin that comes in contact with the live conductor, whether the skin is wet or dry, the path that the current takes through the body, and the amount of pressure applied, as well as body shape, age, weight, and gender. Wet skin is a lot more conductive than dry skin, which is why it is much more dangerous to use electricity in the proximity of moisture or water. The table below shows some values of impedance in ohms for various parts of the body.

According to Table 10.2, if you grasp a 1–1/2" pipe with two hands, then the impedance is approximately 500 Ω to 1,500 Ω. If we use 1000 ohms as an average value, then, according to Ohm's law, a 120-volt shock would cause 120 milliamps of current to flow through the body, while a 240-volt shock would cause 240 milliamps to flow. The graphic in Figure 10.2 shows that less than 100 milliamps can be fatal. According to the book *Introduction to Electrical Engineering* (Irwin & Kerns, 2000), for an electrical shock with a frequency of 60 Hz, a shock in the range 100 to 200 milliamps is most likely to be fatal.

Table 10.2 The impedance of the human body varies from a few hundred to several thousand ohms depending on the conditions*

	Impedance	
	Dry	**Wet**
Finger touch	40 kΩ—1 MΩ	4—15 kΩ
Hand holding wire	10—50 kΩ	3—6 kΩ
Finger-thumb grasp[a]	10—30 kΩ	2—5 kΩ
Hand holding pliers	5—10 kΩ	1—3 kΩ
Palm touch	3—8 kΩ	1—2 kΩ
Hand around 1–1/2" pipe (or drill handle)	1—3 kΩ	0.5—1.5 kΩ
Two hands around 1–1/2" pipe	0.5—1.5 kΩ	250—750 kΩ
Hand immersed	—	200—500 Ω
Foot immersed	—	100—300 Ω
Human body, internal, excluding skin	—	200—1000 Ω

* Table 10.2 shows some values for various conditions.

a Data interpolated.

Source: This table was compiled from Kouwenhoven and Milner. Permission obtained from estate of Ralph Lee by Cadick, Capelli-Schellpfeffer, Neitzel, and Winfield. Reprinted from John Cadick, Mary Capelli-Schellpfeffer, Dennis Neitzel, and Al Winfield, *Electrical Safety Handbook*, 4th edn (McGraw Hill, 2012).

FIGURE 10.2
The effects of electrical shock. The range from 100 to 100 milliamps is most likely to be fatal. Higher currents can contract the heart until the current is removed; then the heart might start beating again on its own.

It doesn't take a lot of current to cause a fatality. The human body produces electrical pulses that pace the heart on the order of one millionth of an amp (1 μA). As little as 100 to 200 milliamps passing through the heart can interrupt its natural rhythm and cause it to go into fibrillation, meaning it doesn't beat regularly. When that happens, the heart flutters and can't deliver the necessary oxygen to the blood, eventually causing death.

When we are shocked, we have no control over the voltage of the source of power, but we do have a certain amount of control over the impedance we present to the circuit, and thus the amount of current that will flow. We can control the impedance by wearing shock protection, especially leather or rubber gloves, depending on the circumstances, and rubber-soled or EH-rated shoes. Both of those items cover the two most common points of contact. Protective apparel like this can help to increase the impedance and decrease the amount of current that flows through our body in the event that we accidentally come in contact with live conductors or stray voltage. Otherwise, it is just the impedance of the human body that determines how much current flows.

Most of the time, wearing leather gloves and EH-rated shoes while setting up and running a typical show are sufficient to protect against the risk of electric shock. This is the most basic level of protection that you should use when you are handling energized cables and power distribution equipment and metering voltages. In the event that the insulation has been damaged (See Figure 10.3.) or a ground fault has caused a conductive part—like a scaffold, truss, or staging structure—to become energized, leather gloves (as long as they are dry) and EH-rated shoes will protect against 120V shock and perhaps even 208V, 230V, or 240V shocks. EH-rated shoes are designed to be able to withstand up to 14,000 volts at 60 Hz for one minute and allow less than 3 mA to pass through them as long as they are dry.

FIGURE 10.3
Damaged insulation, like this sliced feeder cable jacket, creates a shock hazard when the power distribution system is energized. Leather gloves, as long as they are dry, and rubber-sole shoes help protect against these hazards.

But depending on the task at hand, we may or may not need to wear a higher level of protection, like voltage-rated rubber gloves and EH-rated shoes. Any time we are within the restricted approach boundary as defined by the *NFPA 70E: Standard for Electrical Safety in the Workplace* (or the Canadian equivalent, *Z462, Workplace Electrical Safety*), we should be wearing the proper category of personal protective equipment (PPE), including shock protection and arc flash/arc blast protection. This only applies if there is a live, exposed conductor. For example, if you open a company switch to do a visual inspection, even if the switch is off, the incoming conductors at the top of the switch are still live.

The restricted approach boundary is a certain distance around a live exposed conductor defined by the voltage involved. Most of the time we are dealing with voltages that call for class 00 (rated to 500V) rubber gloves (208V phase-to-phase in North America and 230V phase-to-neutral in other parts of the world), and the restricted approach boundary is one foot. (Note: It is very important to remember that there is also a risk of arc flash and arc blast: before you open a company switch for visual inspection or otherwise, make sure you are wearing all of the right personal protective equipment, including arc flash/arc blast protection.)

We can also help protect against electrical shock due to accidental contact with energized parts by using insulated tools, removing metal ornaments like jewelry (especially dangling jewelry like necklaces or earrings) and using a carpet or rubber mat to stand on in the event the floor is bare concrete. (I used to travel with a rubber yoga mat. It is not voltage-rated, but it is handy and much better than a bare concrete floor!) It goes without saying that you should never stand in water when working on live electrical equipment because wet skin has a much lower resistance than dry skin.

In addition to a potential for shock, a live exposed conductor can also produce an arc flash. We can protect ourselves against the hazards of arc flash and electrical fire by wearing arc-rated clothing, including arc-rated long pants and an arc-rated long-sleeve shirt. Arc-rated apparel is made of engineered materials like meta-aramid (which goes by the trade name Nomex), para-aramid, and poly-benzimidazole (PBI). For many common tasks a production electrician is required to do, natural fiber like cotton, wool, rayon, or silk, is sufficient protection, but nylon or other synthetic fabrics are not because they have a low melting point and, in the event of an arc flash, they can melt into the skin. (See Arc-Rated Clothing below.)

Also, any time there is work going on overhead, we should wear head protection because of the risk of head injury due to falling objects. (See Figure 10.4.) There are those who don't like to wear head protection and say that if a rig falls on your head a hard hat won't help. That may or may not be true, but it is far more likely that a shackle pin, wrench or spanner, or some other object will fall on your head, in which case a hard hat could mean the difference between being startled or being severely injured. Electricians should wear class G or class E head protection, or the international standards equivalent. A class G helmet is designed to withstand the impact of falling objects and reduce the danger of exposure to electrical conductors up to 2,200 V, and a class E helmet is designed to withstand the impact of falling objects and reduce the danger of exposure to electrical conductors up to 20,000 V. There are also non-

melting head liners, which are important for protection against injury due to an arc flash or electrical fire, but they are not required for the majority of work we do in live event production.

FIGURE 10.4
Hard hats should be worn when there is work being performed overhead in order to protect against the impact of falling objects. (Photo courtesy of Joan Melzig, M&M Production Management.)

By taking precautions and working intelligently, we can better protect ourselves against the risk of shock and electrocution. According to Ohm's law, if we can raise our impedance, then we will lower the current passing through our body in the unfortunate event that we come into contact with a live circuit. If the past is any indication, the chances of getting shocked in the future are pretty high; accordingly, wearing protective clothing—especially gloves and EH-rated shoes—is important.

ELECTRICAL SAFETY

To protect against the hazards of electricity, avoid working with or around live electrical circuits and equipment. Most circuits can be de-energized by turning them off using a disconnect, a circuit breaker, or a switch. To insure that the circuit remains de-energized while work is being done, it should be locked and tagged by the person doing the work, or in some cases where more than one person is involved, it can be locked and tagged by a person in charge of an organized procedure. This is called a lockout/tagout (LOTO) procedure.

In North America there are standards designed to help ensure the safest possible working conditions when performing minor maintenance, service, adjustment, cleaning, or an inspection of electrical equipment. In the USA, it is the *NFPA 70E – Standard for Electrical Safety in the Workplace*, and the equivalent in Canada is *CSA Z462, Workplace Electrical Safety Standard.* These documents provide methods for evaluating the hazard associated with a particular task or procedure, calculating the "boundaries of protection" or the safe working distance when working on or near electrical conductors or circuit parts which are energized or might become energized, and they give guidance about lockout/tagout procedures and wearing the appropriate personal protective equipment for a particular project or task.

There is no direct equivalent standard in Europe or Australia. However, the principles of evaluating hazards, applying locks and tags to prevent the accidental energizing of equipment, and use of personal protective equipment are universal. The purpose of NFPA 70E is to raise awareness, to help people evaluate the risks involved in working with and around electricity, to help train people how to recognize the hazards of the job, and to help protect themselves against those hazards.

There is no national enforcement of NFPA 70E in the U.S., although the Occupational Safety and Health Administration (OSHA) takes many of its codes and regulations from NFPA 70E, and it does enforce them with fines

and other penalties. One of the procedures covered in the standard involves working on circuits by turning them off and locking and/or tagging them while the work is being performed.

LOCKOUT/TAGOUT

A lockout/tagout procedure should be performed any time a circuit needs to be worked on for maintenance, repair, or troubleshooting. It involves turning off the circuit and using a lock to prevent it from accidentally being re-energizing before the work is completed. The details of a lockout/tagout procedure are described in *NFPA 70E Article 120, Establishing an Electrically Safe Work Condition*.

There are two different classifications of lockout/tagout; a simple lockout/tagout, and a complex lockout/tagout. (Note: There used to be three classifications, the third of which was called "individual qualified employee control," but it has since been eliminated. It was used when equipment was de-energized for minor maintenance, servicing, adjusting, cleaning, or inspection by a qualified individual, and the work could be done without placing a lock or tag on the disconnect provided it was adjacent to the work, the employee could clearly see it while performing the work, and the work didn't extend beyond one shift. However, this classification was eliminated in the 2012 version of *NFPA 70E*.)

Both procedures call for the application of a lock and a tag to the disconnect after de-energizing a circuit and before working on the equipment. You should make sure you have identified all the possible sources of power using up-to-date drawings of the electrical system and/or identification tags. Sometimes there is an emergency backup power supply, especially for egress lighting in theatres and performance spaces. You should also turn everything off before opening the disconnect. Interrupting a circuit under load, especially a circuit drawing lots of current, is dangerous. (To see what happens when you interrupt a circuit under load, visit http://youtu.be/hIkNY5xjy5k.)

The lock can be a keyed lock or a combination lock, but it should identify the person who installed it. Locks made for this purpose have a place to write your name and contact information, along with a statement prohibiting unauthorized operation or removal. The key or the combination should always stay with the person who installed it so that it cannot be used to unlock the disconnect before the work is completed.

After turning off the power and applying the lock and tag but before touching any circuit part, test the voltage using the proper category of voltmeter. (See Categories of Meters in Chapter 10.) Make sure the voltmeter is working properly before each use by testing it using a proving unit such as that shown in Figure 10.5. Then test the voltage from each phase to ground or earth, and phase-to-phase. After verifying that the circuit is not live, test the voltmeter again using the proving unit to ensure that it is still fully functional. This method of testing the meter before and after verifying a circuit is not live is known as the three-point test. It helps to ensure an accurate reading.

FIGURE 10.5
A proving unit is used to help ensure a voltmeter is functioning properly before and after using it to test a circuit.

SIMPLE LOCKOUT/TAGOUT VERSUS COMPLEX LOCKOUT/TAGOUT

A simple lockout/tagout procedure can be performed when there is only one circuit involved and the work is being done by a single "qualified" person. A qualified person is basically someone who has electrical skills and knowledge and has been trained to recognize the hazards of the job. The procedure is to de-energize the load and place a lock on the equipment to prevent it from being re-energized until it is ready to be returned to service. In a simple lockout/tagout, the worker is responsible for his or her own lockout/tagout.

If there are multiple sources of energy, multiple crews, multiple crafts, multiple locations, multiple employers, different means of disconnection, or a particular sequence requirement, or if the work will continue beyond one work shift, then a complex lockout/tagout procedure should be performed. Then a qualified person should be appointed to have overall responsibility. It also requires a written plan of execution, and it involves planning, coordination, application of the lockout/tagout devices, removal of the lockout/tagout devices, and release for return to service. (See Figure 10.6.)

FIGURE 10.6
A lockout/tagout procedure ensures that equipment is de-energized, locked out, and tested for no voltage before anyone works on it.

In cases where the equipment doesn't allow the use of a lock, the tagout procedure is used with at least one other safety precaution. Most disconnects will accommodate a padlock in order to lock the switch in the "off" position, and in the United States equipment that was installed after January 2, 1990 is required to accept a lockout device. The lock can be a keyed lock or a combination lock, and the key or combination should stay with the person who installed the lock or, in the event of an established procedure, with the person in charge. The lock has to have a label or some other means of identifying the individual who installed it, and it should be accompanied by a tag stating that unauthorized personnel are prohibited from removing the device or operating the disconnect. It should also be suitable for the environment and for the duration of the work to be performed.

If the circuit or systems has stored energy, such as a spring-loaded mechanism in large circuit breakers, counterweights, or power factor-correction capacitors, it should be released. A small capacitor can be de-energized by discharging it through a resistor in series with an LED. For example, automated lights with a magnetic ballast power supply and a power factor correction capacitor can be discharged this way. Other times, the circuit must be turned off and left alone for several days while it self-discharges. That was the case when a performing arts center with an underground train station was remodeled. They had to wait 72 hours after de-energizing the circuit in order to let it self-discharge.

Before working on a de-energized circuit, it should be verified that equipment cannot be restarted by testing the operation of the gear. The voltage should then be measured using the three-point method to confirm the circuit is not live and grounding devices should be installed for the duration of the work should they be required.

There is a sample lockout/tagout procedure in Annex G of *NFPA 70E* that describes in detail each step to be taken during a lockout. If you are involved in the installation, maintenance, or repair of electrical equipment, then it is a good idea to obtain a copy by visiting www.nfpa.org. There are many other requirements and procedures involved in a lockout/tagout procedure. This text is not intended to replace the *NFPA 70E*.

ARC FLASH AND ARC BLAST

In addition to the hazards of electric shock, production electricians face other hazards as well, including arc flash and arc blast. (See Figure 10.7.) According the NFPA, most electrical accidents that require admission to the hospital are caused by arc flash burns, not electrical shock. In the United States alone, over 2000 people each year are admitted to burn centers with severe burns due to arc flash. Air is usually an insulator, but when the voltage between two

conductive parts is high enough, the air between them can become ionized; when it does, it becomes conductive. This can happen if the difference in voltage is high enough or the distance between the two parts short enough. Once an arc starts, the surrounding air becomes more conductive and more current will flow, causing a chain reaction. The result is ionized gas—plasma—in the form of a ball of fire that engulfs the surrounding air and then dissipates in a very short amount of time, assuming the overcurrent protection does its job. The temperature of the air can reach 19,427°C (35,000°F). If anyone is unfortunate enough to be in the arc flash zone, they could be severely burned.

FIGURE 10.7
Sequence photograph of a 480-volt arc flash shown at 1-millisecond intervals. (Photo courtesy of Ferraz Shawmut.)

When an arc flash occurs, the air temperature goes from ambient to extremely high in a very short amount of time, resulting in an explosive blast with tremendous pressure. (See Figure 10.8). These ultra-high temperatures will cause copper and other metals to vaporize and expand. When copper goes from solid to vapor, it expands up to 67,000 times, producing a shower of molten metal. The blast can reach thousands of pounds per square foot and can rupture eardrums, cause lungs to collapse, cause concussions, and damage internal organs.

FIGURE 10.8
Arc flash picture taken at 10,000 frames per second. (Courtesy of Ferraz Shawmut High-Power Labs.)

The likelihood of an arc flash increases as the voltage increases: the higher the voltage for a given arc distance the more likely it could happen. The size of the plasma ball produced by an arc flash depends on the available fault current. In general, the larger the conductors, the higher the available fault current and the worse the accident will be.

An arc flash can be triggered by dust or other impurities in the air, or corrosion of insulators that can cause sparking and create an arc, causing it to flash over. Water condensation or dripping water can also create a conductive path for an arc to flash over. Sometimes arcs are caused by a person accidentally touching a live part or dropping a tool into live equipment. Conductors can also flash over if the voltage is high enough and the gap to another conductor or ground is short enough. And sometimes the insulating material breaks down, allowing an arc to jump through it or around it.

An arc flash can be very dangerous. Given the nature of live event production power distribution, it is a real possibility. I have personally witnessed it in a 400-amp company switch. Fortunately, no one was hurt in that case, but it was really eye-opening. There are other people in the entertainment industry who have not been so fortunate.

WORKING LIVE

Working on live gear can be extremely dangerous and should not be attempted by anyone who is not qualified, authorized, competent, and confident; even then, it should be conducted using only the right category of personal protective equipment (PPE). That being said,, it should be a last resort only and it should be carried out with the utmost of caution. If there is no other option (for example, if there is no disconnect switch or if shutting down power would create a hazard such as shutting down an emergency alarm) then there are things you can do to help protect yourself and those around you.

First, you should get written permission from the safety office (when applicable), management, or the owner of the property. The exception is when the work to be performed is strictly for testing, troubleshooting, voltage measurement or visual inspection and the restricted approach boundary will not be crossed. The signed permit should include a description of the work to be done and justification for working live. There is a sample permission form entitled "Energized Electrical Work Permit" in one of the appendices of *NFPA 70E*.

SHOCK PROTECTION BOUNDARIES

Before exposing a live exposed conductor, such as when a company switch is opened, a shock hazard analysis should be performed to determine the boundaries of protection. The boundaries spell out the closest approach distances that should be maintained away from a live exposed conductor and they define the requirements for the use of personal protective equipment inside of the boundaries.

There are two shock protection boundaries; the limited approach boundary, which is the boundary inside of which no unqualified personnel should be allowed, and the restricted approach boundary, which is the boundary inside of which an increased risk of shock exists, and the proper category of shock protection should be worn. Any time any part of your body is inside of the restricted approach boundary, you should be wearing insulated gloves or insulated gloves and insulated sleeves at a minimum. The distances of these boundaries are determined by the voltage of a live exposed conductor and are determined by using Table 130.4(C)(a) of the *NFPA 70E*, which is reproduced below for convenience.

Table 10.3 NFPA 70E: Standard for Electrical Safety in the Workplace Table 130.4(D)(a), Approach Boundaries to Energized Electrical Conductors or Circuit Parts for Shock Protection for Alternating-Current Systems

Table 130.4(D)(a) Approach Boundaries to Energized Electrical Conductors or Circuit Parts for Shock Protection for Alternating-Current Systems (All dimensions are distance from energized electrical conductor or circuit part to employee.)

(1)	(2)	(3)	(4)
	Limited Approach Boundary[b]		Restricted Approach Boundary[b]; Includes Inadvertent Movement Adder
Nominal System Voltage Range, Phase to Phase[a]	Exposed Movable Conductor[c]	Exposed Fixed Circuit Part	
<50 V	Not specified	Not specified	Not specified
50 V–150 V[d]	3.0 m (10 ft 0 in.)	1.0 m (3 ft 6 in.)	Avoid contact
151 V–750 V	3.0 m (10 ft 0 in.)	1.0 m (3 ft 6 in.)	0.3 m (1 ft 0 in.)
751 V–15 kV	3.0 m (10 ft 0 in.)	1.5 m (5 ft 0 in.)	0.7 m (2 ft 2 in.)
15.1 kV–36 kV	3.0 m (10 ft 0 in.)	1.8 m (6 ft 0 in.)	0.8 m (2 ft 7 in.)
36.1 kV–46 kV	3.0 m (10 ft 0 in.)	2.5 m (8 ft 0 in.)	0.8 m (2 ft 9 in.)
46.1 kV–72.5 kV	3.0 m (10 ft 0 in.)	2.5 m (8 ft 0 in.)	1.0 m (3 ft 3 in.)
72.6 kV–121 kV	3.3 m (10 ft 8 in.)	2.5 m (8 ft 0 in.)	1.0 m (3 ft 4 in.)
138 kV–145 kV	3.4 m (11 ft 0 in.)	3.0 m (10 ft 0 in.)	1.2 m (3 ft 10 in.)
161 kV–169 kV	3.6 m (11 ft 8 in.)	3.6 m (11 ft 8 in.)	1.3 m (4 ft 3 in.)
230 kV–242 kV	4.0 m (13 ft 0 in.)	4.0 m (13 ft 0 in.)	1.7 m (5 ft 8 in.)
345 kV–362 kV	4.7 m (15 ft 4 in.)	4.7 m (15 ft 4 in.)	2.8 m (9 ft 2 in.)
500 kV–550 kV	5.8 m (19 ft 0 in.)	5.8 m (19 ft 0 in.)	3.6 m (11 ft 10 in.)
765 kV–800 kV	7.2 m (23 ft 9 in.)	7.2 m (23 ft 9 in.)	4.9 m (15 ft 11 in.)

Note (1): For arc flash boundary, see 130.5(A).

Note (2): All dimensions are distance from exposed energized electrical conductors or circuit part to employee.

[a] For single-phase systems above 250V, select the range that is equal to the system's maximum phase-to-ground voltage multiplied by 1.732.

[b] See definition in Article 100 and text in 130.4(D)(2) and Informative Annex C for elaboration.

[c] *Exposed movable conductors* describes a condition in which the distance between the conductor and a person is not under the control of the person. The term is normally applied to overhead line conductors supported by poles.

[d] This includes circuits where the exposure does not exceed 120V.

Source: National Fire Protection Association; NFPA 70E: Standard for Electrical Safety in the Workplace, 2018 Edition; Quincy, Massachusetts: 2018.

In North America, most of the time, we in the live event production industry are working around voltages in the range of 100 to 3000 volts, which means the limited approach boundary for a moveable conductor is 3 meters. A moveable conductor is defined as one in which the distance between the conductor and a person is "not under control of the person." The limited approach boundary for a fixed conductor, like a bus bar, is one meter, and the restricted approach boundary just says, "Avoid contact." So as long as you don't touch a live exposed conductor under 300 volts, then you are unlikely to be shocked because of arcing. However, unqualified personnel, meaning the talent, craft services or catering, some management, etc., should not be within three meters of the live exposed conductor.

Sometimes we work around higher voltages, like 480-volt to 600-volt transformers or generators. In that case, then the boundaries of protection change to the range from 301 volts to 1000 volts. Then the limited approach boundary for moveable or fixed conductors is the same (three meters and one meter respectively), but the restricted approach boundary is 0.3 meters (one foot).

Overhead power lines are the single most common cause of electrocution in the workplace. Sometimes they are not insulated, and you should assume that is the case unless the utility or a qualified person who is a registered engineer confirms that it is insulated. Otherwise, the boundaries of approach apply. The voltage of these transmission lines is not always readily apparent, although there is sometimes a sign on the transmission tower stating the voltage of

overhead power lines. If not, there usually a unique number on the transmission tower that identifies it and a phone number to call to find out the voltage. Once voltage is known, then the safe approach distance can be determined.

The Occupational Safety and Health Administration gives the minimum clearance distances based on the voltage of a power line in Standard 1926.1408 – Power Line Safety. Table 10.4 sums up the standard. The clearance requirement includes any extension of your body like tools, scaffold supports, grip stands or poles, and so forth.

Table 10.4 Overhead power lines are the leading cause of electrocution on the job*

Minimum clearance distances for power lines (reproduced from OSHA Standard 1926.1408 Table A)

Voltage (nominal, kV, alternating current)	Minimum clearance distance (feet)
Up to 50	10
50 to 200	15
200 to 350	20
350 to 500	25
500 to 700	35
700 to 1000	45
Over 1000	(as established by the utility owner/operator or registered professional engineer who is a qualified person with respect to electrical power transmission and distribution).

* Note: OSHA Standard 1926.1408 Table A spells out the minimum safe approach distances for power lines.
Source: National Fire Protection Association; NFPA 70E: Standard for Electrical Safety in the Workplace, 2018 Edition; Quincy, Massachusetts: 2018.

ARC FLASH BOUNDARY

The arc flash boundary is the distance from a live exposed conductor inside of which, in the event of an arc flash you are likely to receive second-degree burns unless you are wearing the right personal protective equipment. Technically, it is the distance at which the incident energy is 5 joules per square centimeter or 1.2 calories per square centimeter or greater. The distance can be calculated by performing an arc flash hazard analysis, and it also determines the category of risk, and the proper personal protective equipment to use. (See Personal Protective Equipment below.) To calculate the arc flash boundary, you need to know the voltage, the size or the transformer in MVA, the impedance of the transformer feeding the system (both are given on the nameplate of the transformer), and the circuit breaker clearing time. As of 2012, electrical apparatus is required to have signage spelling out this information including the nominal system voltage, the arc flash boundary, minimum arc rating of the clothing to be worn, and either the amount of energy that would be released in the event of a fault and the corresponding working distance or the arc flash PPE category as it is spelled out in NFPA 70E Table 130.7(C)(15)(A)(b) or Table 130.7(C)(15)(B).

For the types of systems we deal with in the entertainment industry, the arc flash boundary can vary from less than a meter to a few meters. (See Figure 10.9.)

FIGURE 10.9

The shock protection boundaries include the limited approach boundary and the restricted approach boundary, and they depend on the voltage of a live exposed conductor. The arc flash boundary depends on the available fault current in the event of a fault.

There are two tables in NFPA 70E that provide the hazard/risk categories for certain tasks. They are *Table 130.7(C)(15)(A)(a) Arc Flash Hazard Identification for Alternating Current (ac) and Direct Current (dc) Systems* and *Table 130.7(C)(15)(A)(b) Arc-Flash Hazard PPE Categories for Alternating Current (ac) Systems.* These tables are used to figure out the category of risk for certain common tasks and the type of personal protective equipment required for that task. Part of the former is reproduced in Table 10.5. (To view the entire table, please see *NFPA 70E*.) These are tasks that entertainment production electricians and technicians may be required to perform.

Table 10.5 Arc flash hazard identification for alternating current (ac) and direct current (dc) systems

Table 130.7(C)(15)(A)(a) Arc flash hazard identification for alternating current (ac) and direct current (dc) systems*

Task	Equipment condition[a]	Arc flash PPE requirement
Reading a panel meter while operating a meter switch	Any	No
Normal operation of a circuit breaker (CB), switch, contactor, or starter	All of the following: The equipment is properly installed The equipment is properly maintained All equipment doors are closed and secured All equipment covers are in place and secured There is no evidence of impending failure	No

* *Note: Hazard identification is one component of risk assessment. Risk assessment involves a determination of the likelihood of occurrence of an incident, resulting from a hazard that could cause injury or damage to health. The assessment of the likelihood of occurrence contained in this table does not cover every possible condition or situation. Where this table indicates that arc flash PPE is not required, an arc flash is not likely to occur.*

a *The phrase properly installed, as used in this table, means that the equipment is installed in accordance with applicable industry codes and standards and the manufacturer's recommendations. The phrase properly maintained, as used in this table, means that the equipment has been maintained in accordance with the manufacturer's recommendations and applicable industry codes and standards. The phrase evidence of impending failure, as used in this table, means that there is evidence of arcing, overheating, loose or bound equipment parts, visible damage, deterioration, or other damage.*

Source: Reproduced from NFPA 70E. See NFPA 70E for complete table.

Table 130.7(C)(15)(A)(a) Arc flash hazard identification for alternating current (ac) and direct current (dc) systems*

Task	Equipment condition[a]	Arc flash PPE requirement
	One or more of the following: The equipment is not properly installed The equipment is not properly maintained Equipment doors are open or not secured Equipment covers are off or not secured There is evidence of impending failure	Yes
For ac systems: Work on energized electrical conductors and circuit parts, including voltage testing	Any	Yes
For dc systems: Work on energized electrical conductors and circuit parts of series-connected battery cells, including voltage testing	Any	Yes
Removal or installation of CBs or switches	Any	Yes
Removal or installation of covers for equipment such as wireways, junction boxes, and cable trays that does not expose bare energized electrical conductors and circuit parts	All of the following: The equipment is properly installed The equipment is properly maintained There is no evidence of impending failure	No
	Any of the following: The equipment is not properly installed The equipment is not properly maintained There is evidence of impending failure	Yes

* *Note: Hazard identification is one component of risk assessment. Risk assessment involves a determination of the likelihood of occurrence of an incident, resulting from a hazard that could cause injury or damage to health. The assessment of the likelihood of occurrence contained in this table does not cover every possible condition or situation. Where this table indicates that arc flash PPE is not required, an arc flash is not likely to occur.*

a *The phrase properly installed, as used in this table, means that the equipment is installed in accordance with applicable industry codes and standards and the manufacturer's recommendations. The phrase properly maintained, as used in this table, means that the equipment has been maintained in accordance with the manufacturer's recommendations and applicable industry codes and standards. The phrase evidence of impending failure, as used in this table, means that there is evidence of arcing, overheating, loose or bound equipment parts, visible damage, deterioration, or other damage.*

Source: Reproduced from NFPA 70E. See NFPA 70E for complete table.

Table 130.7(C)(15)(A)(a) Arc flash hazard identification for alternating current (ac) and direct current (dc) systems*

Task	Equipment condition[a]	Arc flash PPE requirement
Removal of bolted covers (to expose bare, energized electrical conductors and circuit parts)	Any	Yes
Opening hinged door(s) or cover(s) (to expose bare energized electrical conductors and circuit parts)	Any	Yes
Perform infrared thermography and other noncontact inspections outside the restricted approach boundary. This activity does not include opening of doors or covers.	Any	No
Work on control circuits with exposed energized electrical conductors and circuit parts, 120 volts or below without any other exposed energized equipment over 120 V including opening of hinged covers to gain access	Any	No
Work on control circuits with exposed energized electrical conductors and circuit parts, greater than 120 V	Any	Yes
Insulated cable examination with no manipulation of cable	Any	No
Insulated cable examination with manipulation of cable	Any	Yes
Work on exposed energized electrical conductors and circuit parts of equipment directly supplied by a panelboard or motor control center	Any	Yes

* *Note: Hazard identification is one component of risk assessment. Risk assessment involves a determination of the likelihood of occurrence of an incident, resulting from a hazard that could cause injury or damage to health. The assessment of the likelihood of occurrence contained in this table does not cover every possible condition or situation. Where this table indicates that arc flash PPE is not required, an arc flash is not likely to occur.*

a The phrase properly installed, as used in this table, means that the equipment is installed in accordance with applicable industry codes and standards and the manufacturer's recommendations. The phrase properly maintained, as used in this table, means that the equipment has been maintained in accordance with the manufacturer's recommendations and applicable industry codes and standards. The phrase evidence of impending failure, as used in this table, means that there is evidence of arcing, overheating, loose or bound equipment parts, visible damage, deterioration, or other damage.

Source: Reproduced from NFPA 70E. See NFPA 70E for complete table.

There is a similar, but more industry-specific guide from Contract Services Administration Trust Fund (CSATF), which is a non-profit organization that provides training and guidance for the motion picture and television production industry. Safety Bulletin #23 Addendum D is reproduced in Table 10.6 for your convenience.

Table 10.6 CSATF Safety Bulletin #23 gives guidance for the use of PPE for tasks commonly performed in the motion picture and television production industries

Industry Wide Labor-Management Safety Committee Safety Bulletin #23 Guidelines for Working with Portable Power Distribution Systems and Other Electrical Equipment "Addendum D" - Common Motion-Picture/Television Tasks and Associated Personal Protective Equipment

120V/208V or 120V/240V Power Systems Supplied by Utility or Generators			
Task	**PPE category**	**Voltage-rated tools**	**Voltage-rated gloves**
Metering (including power source, feeder circuit, and branch circuit)	0	Y	Y
Connecting/Disconnecting Single Conductor Cable (energized)	1	Y	Y
Replacing Dimmer Modules	1	Y	Y
Operating Circuit Breakers or fused switches (covers on)	0	N	N
Connecting to Systems	1	Y	Y
277V/480V Power Systems Supplied by Utility or Generators	**PPE Category**	**Voltage-Rated Tools**	**Voltage-Rated Gloves**
Metering Utility Fed Systems (including feeder circuit)	2	Y	Y
Connecting/Disconnecting Single Conductor Cable (energized)	Not Allowed		
Replacing Dimmer Modules	Equipment Not Available		
Operating Circuit Breakers or fused switches (covers on)	0	N	N

* According to ASTM F 1506-00 + AR Coveralls Acceptable

Source: Contract Services Administration Trust Fund Safety Bulletin #23 (www.csatf.org)

Industry Wide Labor-Management Safety Committee Safety Bulletin #23 Guidelines for Working with Portable Power Distribution Systems and Other Electrical Equipment "Addendum D" - Common Motion-Picture/Television Tasks and Associated Personal Protective Equipment

120V/208V or 120V/240V Power Systems Supplied by Utility or Generators			
Task	**PPE category**	**Voltage-rated tools**	**Voltage-rated gloves**
Connecting to Systems	2	Y	Y
PPE Equipment	**Category 0**	**Category 1**	**Category 2**
Non-Melting* or Long Sleeve, Untreated, Natural Fiber Shirt+	X		
Non-Melting* or Natural, Untreated Fiber or Denim Long Pants+	X	X	
Eye Protection	X	X	X
Arc Rated Face Shield (Double Layer Switching Hood)			X
Hard Hat		X	X
AR Long Sleeve Shirt (or AR Coveralls)		X	X
AR Long Pants (or AR Coveralls)		X	X
Hearing Protection			X
Leather Work Shoes	X	X	X
Leather Gloves (Gauntlets) As Needed		As Needed	X

* According to ASTM F 1506-00 + AR Coveralls Acceptable
Source: Contract Services Administration Trust Fund Safety Bulletin #23 (www.csatf.org)

PERSONAL PROTECTIVE EQUIPMENT (PPE)

If you are working inside of a limited approach boundary or arc flash boundary, it is imperative for your own protection that you use the right personal protective equipment (PPE). The shock protection boundaries have to do with the voltage, and the arc flash boundary has to do with the amount of energy that might be released if there is an arc flash, and the two are independent of each other. The arc flash boundary and the category of PPE are determined by calculating the incident energy in calories per square centimeter from a specified distance that would be released in the event of an arc flash. The amount of energy that would be released depends on the size of the feeder transformer in megavolt-amps (MVA) and the amount of time the arc is exposed to the worker as measured in seconds. The time of exposure depends on the type of fuse or circuit breaker. (More complete information is spelled out in Informative Annex D: Incident Energy and Arc Flash Boundary Calculation Methods in *NFPA 70E*. Alternatively, you can use *Table 130.7(C)(15)(A)(a) Arc Flash Hazard Identification for Alternating Current (ac) and Direct Current (dc) Systems* and *Table 130.7(C)(15)(A)(b) Arc-Flash Hazard PPE Categories for Alternating Current (ac) Systems* in NFPA 70E to determine the hazard/risk category and the requirements for the use of rubber insulating gloves and insulated and insulating hand tools. Parts of those tables are reproduced above.)

ARC-RATED CLOTHING

The American Society for Testing Materials (ASTM) developed a rating system for arc-rated clothing called the Arc Thermal Performance Value (ATPV). It is based on the amount of heat energy in calories per square centimeter that it will protect against. For example, a garment with an ATPV of 5 means that it will protect against heat energy up to 5 calories per square centimeter. The higher the ATPV value, the better it protects against heat energy.

There are arc-rated shirts, arc-rated pants, and arc-rated coveralls. They are made with fabrics like meta-aramid, para-aramid, and poly-benzimidazole (PBI) and provide protection against arc flash. Clothes that are designed to withstand more than 4 calories per square centimeter are considered to be arc-rated, and they are manufactured under trade names like Indura, Nomex, etc. These items can ignite, but they will not continue to burn.

Arc-rated clothing and other arc-rated PPE is rated from category 1 to 4. Category 1 PPE protects against up to 4 calories per square centimeter; category 2 protects against up to 8 calories per square centimeter; category 3 protects

up to 25 calories per square centimeter; and category 4 protects against up to 40 calories per square centimeter. (See Table 10.7). Their use is required for hazard/risk category ratings of 1 to 4, and that is the case any time there is a possibility of exposure to an arc flash of more than 1.2 calories per square centimeter (5 joules per square centimeter), which is the threshold for a second-degree burn.

Table 10.7 Table 130.7(C)(16) Personal Protective Equipment (PPE) from NFPA 70E

PPE Category	PPE
1	**Arc-Rated Clothing, Minimum Arc Rating of 4 cal/cm^2** (see Note 1) Arc-rated long-sleeve shirt and pants or arc-rated coverall Arc-rated face shield (see Note 2) or arc flash suit hood Arc-rated jacket, parka, rainwear, or hard hat liner (AN) **Protective Equipment** Hard hat Safety glasses or safety goggles (SR) Hearing protection (ear canal inserts) Heavy duty leather gloves (see Note 3) Leather footwear (AN)
2	**Arc-Rated Clothing, Minimum Arc Rating of 8 cal/cm^2** (see Note 1) Arc-rated long-sleeve shirt and pants or arc-rated coverall Arc-rated flash suit hood or arc-rated face shield (see Note 2) and arc-rated balaclava Arc-rated jacket, parka, rainwear, or hard hat liner (AN) **Protective Equipment** Hard hat Safety glasses or safety goggles (SR) Hearing protection (ear canal inserts) Heavy duty leather gloves (see Note 3) Leather footwear
3	**Arc-Rated Clothing Selected so That the System Arc Rating Meets the Required Minimum Arc Rating of 25 cal/cm^2** (see Note 1) Arc-rated long-sleeve shirt (AR) Arc-rated pants (AR) Arc-rated coverall (AR) Arc-rated arc flash suit jacket (AR) Arc-rated arc flash suit pants (AR) Arc-rated arc flash suit hood Arc-rated gloves (see Note 3) Arc-rated jacket, parka, rainwear, or hard hat liner (AN) **Protective Equipment** Hard hat Safety glasses or safety goggles (SR) Hearing protection (ear canal inserts) Leather footwear

AN: as needed (optional). AR: as required. SR: selection required.
Notes:
(1) Arc rating is defined in Article 100.
(2) Face shields are to have wrap-around guarding to protect not only the face but also the forehead, ears, and neck, or, alternatively, an arc-rated arc flash suit hood is required to be worn.
(3) If rubber insulating gloves with leather protectors are used, additional leather or arc-rated gloves are not required. The combination of rubber insulating gloves with leather protectors satisfies the arc flash protection requirement.
Source: National Fire Protection Association; NFPA 70E: Standard for Electrical Safety in the Workplace, 2018 Edition; Quincy, Massachusetts: 2018.

PPE Category	PPE
4	**Arc-Rated Clothing Selected so That the System Arc Rating Meets the Required Minimum Arc Rating of 40 cal/cm^2** (see Note 1) Arc-rated long-sleeve shirt (AR) Arc-rated pants (AR) Arc-rated coverall (AR) Arc-rated arc flash suit jacket (AR) Arc-rated arc flash suit pants (AR) Arc-rated arc flash suit hood Arc-rated gloves (see Note 3) Arc-rated jacket, parka, rainwear, or hard hat liner (AN) **Protective Equipment** Hard hat Safety glasses or safety goggles (SR) Hearing protection (ear canal inserts) Leather footwear

AN: as needed (optional). AR: as required. SR: selection required.
Notes:
(1) Arc rating is defined in Article 100.
(2) Face shields are to have wrap-around guarding to protect not only the face but also the forehead, ears, and neck, or, alternatively, an arc-rated arc flash suit hood is required to be worn.
(3) If rubber insulating gloves with leather protectors are used, additional leather or arc-rated gloves are not required. The combination of rubber insulating gloves with leather protectors satisfies the arc flash protection requirement.
Source: National Fire Protection Association; NFPA 70E: Standard for Electrical Safety in the Workplace, 2018 Edition; Quincy, Massachusetts: 2018.

The required ATPV rating of that clothing is based on the HRC rating, and it is spelled out in NFPA 70E Table 130.7(C)(15)(A)(b), some of which is reproduced here in Table 10.8 for convenience.

Table 10.8 NFPA 70E Table 130.7(C)(15)(A)(b), Arc-flash hazard PPE categories for alternating current (ac) systems

Equipment	Arc Flash PPE category	Arc-Flash boundary
Panelboards or other equipment rated 240 V and below. Parameters: Maximum of 25 kA short-circuit current available; maximum of 0.03 sec (2 cycles) fault clearing time; working distance 455 mm (18 in.)	1	485 mm (19 inches)
Panelboards or other equipment rated >240 V and up to 600 V. Parameters: Maximum of 25 kA short-circuit current available; maximum of 0.03 sec (2 cycles) fault clearing time; working distance 455 mm (18 in.)	2	900 mm (3 feet)
600-V class switchgear (with power circuit breakers or fused switches) and 600 V class switchboards. Parameters: Maximum of 35 kA short-circuit current available; maximum of up to 0.5 sec (30 cycles) fault clearing time; working distance 455 mm (18 in.)	4	6 meters (20 feet)
Other 600-V class (277 V through 600 V, nominal) equipment. Parameters: Maximum of 65 kA short-circuit current available; maximum of 0.03 sec (2 cycles) fault clearing time; working distance 455 mm (18 inches)	2	1.5 meters (5 feet)

Source: NFPA 70E Table 130.7(C)(15)(A)(b)

There a number of common HRC 0 tasks, such as operating a circuit breaker, that do not require arc-rated clothing. But everyday tasks like this should be carried out by production electricians wearing non-melting, natural fibers like untreated cotton, wool, rayon, silk, or blends of these fibers with a fabric weight of at least 4.5 ounces per square yard. (Rayon is cellulose-based, which is made from wood pulp.) These fibers are flammable but non-melting. On the other hand, polyester, acetate, acrylic, nylon, polyethylene, polypropylene, and spandex are all materials that have a low melting temperature and will melt and drip. These fibers should not be worn because in the event of an arc flash, they will make injuries worse. And according to the Occupational Health and Safety Administration (OSHA), “the clothing cannot contribute to an employee's injury,” which means that it should not be worn.

HAND PROTECTION

The two most common points of contact are your hands and feet. If there is a possibility of electric shock, then you should wear shock protection, which includes gloves and voltage-rated shoes. For certain tasks, rubber voltage-rated gloves with the proper voltage rating and leather protectors are required. Otherwise, thick leather gloves will protect against inadvertent contact with live exposed conductors due to broken or damaged insulation, stray voltage, etc. They also help protect your hands against everyday hazards like sharp edges, road case hazards, scrapes, cuts, etc.

When you are setting up a power distribution system, all the power should be off, and you should confirm that it is off before you start making cable connections. However, should the power inadvertently be turned on while you are making a connection, it can cause an arc flash. (See Figure 10.10.) If you are wearing gloves, you have a much better chance of avoiding severe injury.

FIGURE 10.10
This person received second-degree burns to the hand when the pins in a 19-pin circular connector rotated and created a 208V short, resulting in an arc flash. Thick leather gloves likely would have prevented severe injury.

In some cases, the arc flash boundary is outside of the limited approach boundary. If you are outside of the limited protection boundary but inside of the arc flash boundary, then you can wear heavy-duty leather gloves for arc flash protection if they are made entirely of leather with a thickness of at least 0.03 inches (0.7 millimeters). They can be unlined or lined with non-flammable, non-melting material.

In other cases, the arc flash boundary is inside of the limited protection boundary. If you are inside the limited protection boundary, then you can wear rubber insulating gloves with leather protectors and that satisfies the requirement for arc flash protection. (See Figure 10.11.)

FIGURE 10.11
Rubber insulating gloves and leather protectors should be worn any time there is a possibility of electric shock.

FOOT PROTECTION

When you are shocked, sometimes the return path for current is through the earth, as illustrated in Figure 10.12. EH-rated (electrical hazard) shoes provide additional protection against electric shock in dry conditions by insulating you from the earth. They are rated to withstand up to 14,000 V at 60 Hz for up to one minute and allow less than 3 mA to flow in dry conditions. (See Figure 10.13.)

FIGURE 10.12
When a person is shocked, often times the path for return current goes through the earth, as shown in this illustration.

FIGURE 10.13
EH-rated shoes are made with non-conductive soles and heels, and are rated to withstand up to 14,000 V at 60 Hz for up to one minute. They will not conduct more than 3 mA in dry conditions.

OTHER PPE

In addition to arc-rated clothing, hand, and foot protection, there are other forms of PPE. These include:

- Eye protection - For a hazard/risk category of 0 or 1, safety glasses or goggles should be worn.
- Face protection - For a hazard/risk category of 2, 3, or 4, an arc-rated flash suit hood or arc-rated face shield should be used along with an arc-rated head covering called a balaclava. If a face shield is worn, it should wrap around to protect the face, chin, forehead, ears, and neck, and safety glasses or safety goggles should be worn under the face shield.
- Hearing protection - Ear canal inserts are required any time you are inside the arc-flash boundary. Since a face shield should be worn for HRC ratings of 1 and above, and since it is required to wrap around the face to protect the ears, there are no particular requirements for the type of ear canal inserts to be used. The face shield will provide protection against melting earplugs.
- Hard hat - For any HRC from 1 to 4, a hard hat with an arc-rated hard hat liner is required. For shock hazard protection, a class G (general) or E (electrical) hard hat is required. A class G hard hat is for impact protection and reduces the danger of shock up to 2,200 V. A class E hard hat is for impact protection and reduces the danger of shock up to 20,000 V.

METERING SAFELY

When you are setting up a power distribution system, it is important to meter the system in order to confirm the voltages before turning on the loads; otherwise, you could inadvertently apply the wrong voltage and damage expensive equipment, or worse, injure yourself or someone else. In order to measure voltage, you have to have access to live exposed conductors, like wires or terminals, because you have to touch the leads of your voltmeter to them. That means there is a risk of shock, and you should take that risk very seriously. If you are not qualified, authorized, and competent to perform the task, you should not attempt it. If you are, then you should understand the risks involved and take steps to protect yourself against shock, arc flash, and arc blast by wearing the proper PPE. The level of risk depends on the task at hand; the higher the voltage, the greater the risk, and the further upstream you are in the power distribution system (upstream is towards the source of power), the larger the conductors, fuses, and circuit breakers, and the greater the risk of arc flash and arc blast. For many of the tasks involved in live event production, it is sufficient to wear thick leather gloves and leather shoes with rubber soles, preferably shoes with an EH (electrical hazard) rating, which are designed to withstand up to 14,000 volts at 60 Hz for one minute, allowing less than 3.0 milliamps of current to flow if they are dry. Other times, you will need voltage-rated rubber gloves (usually class 00 or class 0) with leather covers, arc-rated clothing, EH-rated shoes, eye protection, arc-rated face shield, hearing protection, and head protection. Arc-rated clothing is flame resistant and is rated to prevent second-degree burns.

Regardless of the circumstances, it is a good idea to wear leather gloves and EH-rated shoes when you are measuring voltage because there might be stray voltage or damaged insulation, creating a shock hazard, and your hands and feet are the most common points of contact and the most common path for fault current. To avoid having to suit up and don higher categories of PPE, you can meter the voltage using the test ports in a portable power distribution system if they are available. Test ports are small openings on the face of the distro that allow you to insert probes without exposing you to live conductors. (See Figure 10.14.) The test ports are connected to the bus (a bus is a large copper bar) through very small wires, which reduces the risk of arc flash and arc blast.

FIGURE 10.14
If your power distribution system has test ports, then metering voltage does not require voltage-rated gloves or arc flash and arc blast protection because the ports are small openings and are connected to the circuit conductors by way of very small gauge wires. The smaller conductors limit the amount of energy that could be released in the event of a short circuit.

If test ports are not available, then it is safe to meter the power as far downstream in the electrical system as possible where the conductors are smaller and farther away from the source of power.

CATEGORIES OF METERS

The electrical grid may appear to be stable and unchanging, but there are lots of events like voltage spikes, surges, sags, and swells caused by large loads coming online or going offline, crossed transmission lines, broken lines, and other issues. Some events, like lightning, are transient, meaning they can temporarily put very high voltage on the grid. If the wrong type of meter is in contact with a conductor while there is a high voltage surge, it could cause an arc flash and result in injury to the user. In one case, an electrician was measuring voltage in an electrical panel and the meter exploded, killing the electrician and a fire official who was standing behind him. According to an article in Electrical Construction & Maintenance magazine titled "The Case of a Deadly Arc Flash," the meter "could not withstand the voltage transients present on such systems, and the fuse was unable to interrupt the fault current that resulted from an internal failure." It also said that the electrician "did not recognize that the meter lacked appropriate safety ratings and was unsuitable for the intended measurement."

The meter you use to measure voltage, current, or any other electrical value is part of your personal protective equipment (PPE). They are categorized according to how well they protect you, so it is very important that you use the right category of meter for the task at hand. There are four categories of meters and the category is based on the level of protection. The higher the category, the greater the level of protection. (See Figure 10.15.)

FIGURE 10.15
Meters are categorized according to how well they protect against voltage spikes and surges. There are four categories of meters; the higher the category, the more protection it provides.

Categories of meters are defined by an international standard issued by the IEC (International Electrotechnical Commission) in *IEC-61010-1: Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use*. The categories are based on their intended use and their ability to withstand transient overvoltages. The closer to the source of power they are used, the higher the category of meter should be used because energy from a transient or surge is naturally dampened as it flows through the system, and the smaller the conductors, the less energy is available. The categories of meter are:

- Category IV — for use with transmission, generation, and the primary side of feeder transformers. This includes portable power generators, electrical meters, primary overcurrent protection equipment, and any outdoor conductors.
- Category III — for use with distribution circuits, including feeders, dimmer racks, the secondary side of feeder transformers, breaker panels, company switches, disconnects, and similar equipment.
- Category II — for use with single-phase loads connected to receptacles, luminaires, appliances, branch circuits, and receptacles more than 10 meters from a category II source or more than 20 meters from a category IV source.
- Category I — for use with low-voltage electronics and signal-level measurements like PC boards and components.

For most work in live event production, a category III or higher meter is sufficient. If you work with portable power generators or feeder transformers you should probably use a category IV meter. (See Figure 10.16.)

FIGURE 10.16
This meter is a category III up to 600 volts and a category IV up to 300 volts.

When you are setting up a power distribution system, you should check the system voltage before energizing any of the connected equipment to make sure the voltage is correct, and the power distribution system is set up correctly. Otherwise, you run the risk of damaging equipment, which can be very dangerous and very expensive. (See Figure 10.17.)

FIGURE 10.17
After you set up a power distribution system, you should check the system voltage before energizing any equipment or turning on any circuit breakers; otherwise, you run the risk of damaging equipment, which can be very dangerous and very expensive. This dimmer rack was destroyed because the applied voltage was too high, resulting in an arc flash. (Photo courtesy of Zeb Cochran.)

TRUE RMS VERSUS AVERAGE READING METERS

There are “true RMS” meters and “average reading” meters, including voltmeters and amp meters. In live event production, it is important understand the difference because using an average reading meter with certain types of loads can yield errors. To understand why, it helps to understand RMS values.

The value of AC voltage and current is always quoted in RMS, which is its equivalent to a DC value. The RMS value is calculated using the square root of the mean of the squares of several sample points in a single cycle of the waveform. If, for example, the AC waveform was sampled 1000 times during a single cycle, each sample was squared, those squares were summed and divided by the number of samples, then the square root is taken, the result is a single value that represents the equivalent DC value, and that's the RMS value. So, when we say 240 volts or 120 volts, what we really mean is 240 volts RMS or 120 volts RMS. This applies when we say 20 amps or 200 amps. When we use a meter to measure AC voltage or current, the readings are displayed in RMS values. But some meters don't actually measure RMS values.

An average reading meter is designed to read the average value of the waveform after it has been fully rectified (converted from AC to pulsing DC by inverting the negative half cycle using diodes). Since we don't use average values to describe AC voltage or current, the manufacturers of average-reading meters build the meter so that it applies a multiplier and it displays the RMS value instead of the average value. The multiplier is a fixed value based on the relationship between the ratio of the RMS value to the average value of a pure sinewave. But many of the waveforms we measure in live event production are not pure sinewaves because they can be distorted (See Figure 10.18.), which changes the relationship between the RMS value and the average value. This leads to reading errors for any waveform except pure sinewave. If there is any distortion of the waveform at all, then an average-reading meter will yield errors.

FIGURE 10.18
In live event production, the current is often distorted, as shown in the waveform at the bottom of the display. An average reading meter will read this Current is typically measured using a clamp meter. Some allow you to also measure voltage and resistance.

A true RMS meter has a microprocessor that calculates the RMS value by sampling the waveform several thousand times per cycle. If the waveform is a pure sinewave, then both types of meters will read the same value (provided they are properly calibrated). But an average reading meter is only accurate when it is reading a pure sinewave while an RMS meter is accurate reading any waveform.

If you are using a meter that does not have a marking that says, "true RMS meter," then it is an average reading meter. We should use true RMS amp meters and volt meters in live event production because we often encounter distorted waveforms, especially current distortion.

UNDERSTANDING ELECTRICAL SAFETY

10.1 According to the IEC chart in Figure 10.1, what is the least amount of current that can cause heart fibrillations?

10.2 When someone is shocked, the typical reaction time is about 1.5 seconds. According to the IEC chart in Figure 10.1, what is the least amount of current that could cause heart fibrillation for a 1.5-second shock?

10.3 There is a significant difference between the impedance of the human body when the skin is wet and when the skin is dry. Which condition makes you more susceptible to electrocution?

10.4 Name at least three factors that influence the impedance of the human body.

10.5 If a person with dry hands wraps two hands around a 1– 1/2" pipe, what is the range of impedance?

10.6 (a) If a person wraps two dry hands around a 1–1/2" pipe as in 10.5 above and the pipe is energized to 120 V, how much current will flow? (b) If this is a one-second shock, is it enough current to cause heart fibrillation? (c)

How much current would flow if their skin is wet? (d)If the pipe is energized to 230 V, then how much current will flow?

10.7 When an electric guitar player touches the strings of the guitar, he/she is connected to electrical ground through a combination of connections from the bridge of the guitar to the shield of the guitar cable, which is connected to the chassis of the amplifier, which is connected to electrical ground. Should the guitar player then come in contact with his/her free hand with a conductive part, like a truss, scaffold, etc., that has stray voltage, they are completing a circuit from hand to hand. How much current will flow if the resistance is 1000 Ω and the voltage is 120V?

10.8 How can you increase your impedance should you accidentally contact a live conductor? Hint: You have to do this in advance.

10.9 Why should you not wear synthetic fiber like polyester, nylon, Dacron, etc., when you are setting up and working with power distribution?

10.10 If someone is being shocked, at what level of current might they be unable to let go of the energized part?

10.11 Suppose you are grasping a 1–1/2" metal pipe with two dry hands and your impedance is 1500 Ω. What is the voltage that could cause 23 mA to flow, which is enough to make your muscles seize?

10.12 Can the arc flash boundary ever be larger than (or outside of) the limited protection boundary?

10.13 Suppose you are wearing leather gloves and they are dry. If they have a resistance of 50,000 Ω and the resistance of your body is 1000 Ω, that creates an equivalent resistance of 51,000 Ω. If you accidentally come in contact with a 120-volt live conductor, how much current will flow? What if the conductor is energized to 230V?

10.14 In the scenario in question 10.12 above, is the resulting current enough to cause heart fibrillation? Is it enough to cause your muscles to seize?

10.15 If someone is being shocked, at what level of current do they have difficulty breathing?

10.16 What is the most common cause of electrical accidents on the job?

10.17 What is the temperature that the air can reach in the event of an arc flash?

10.18 What happens to copper when it is exposed to the kinds of temperatures produced by an arc flash?

10.19 Name at least three things that can contribute to arc flash.

10.20 What is the definition of the flash protection boundary?

10.21 To measure voltage, you usually have to have access to a live exposed conductor. If the voltage you are measuring is 480 V and there is a live, exposed, fixed conductor, what is the limited approach boundary?

10.22 Under which conditions should arc-flash PPE be worn to turn on a company switch?

10.23 In Table 10.5, does the CSATF guidance for metering voltage, including feeder circuits and branch circuits, recommend wearing voltage-rated gloves and use voltage-rated tools?

10.24 Why is it safer to meter power further downstream in a power distribution system?

10.25 Why is it important to wear thick leather gloves and rubber-soled shoes (preferably EH-rated) for most metering tasks in live event production?

10.26 Why is it safer to meter power through the test ports in a power distribution system?

10.27 Which category of meter should be used to meter power at a portable power generator?

10.28 What is the difference between an average-reading meter and a true RMS meter?

10.29 If a non-linear load draws a total of 8.7 amps with 77.3% total harmonic distortion, and the fundamental frequency accounts for 5.5 amps, what reading will be displayed on an average-reading amp meter monitoring this load?

CHAPTER 11
Grounding/Earthing and Bonding

In the 1970s, when amplified musical instruments and public address systems were relatively new, few people well understood how to build and maintain safe portable power distribution systems. As a result, there were several musicians, including Leslie Harvey of Stone the Crows and Keith Relf of the Yardbirds, who died by electrocution because they were using equipment with a faulty ground/earth. Today, we know more about proper grounding/earthing and bonding techniques and electrical safety, yet the issue is still often misunderstood. Volumes have been written on the subject and aspects of it are still evolving. But proper grounding/earthing and bonding is the very foundation of a safe electrical system and understanding how grounding/earthing and bonding works is critical for the safety of live events.

GROUNDING/EARTHING AND BONDING

In an electrical circuit, current always tries to return to its source. How it returns is a matter of considerable importance from the standpoint of safety. When you plug in a light or some other electrical device, you use a power cable that has a green (or green with a yellow stripe) conductor. That conductor, which is called the equipment grounding conductor (EGC) in North America or the circuit protective conductor (CPC) in the United Kingdom, is connected to the chassis inside of the fixture. Its job is to cause the circuit breaker to trip or the fuse to blow in the event of a ground fault, thereby clearing the fault and removing the danger of electric shock. (A ground fault is any unintentional contact between a live conductor and a grounded object like a conductive housing, chassis, or junction box.) If that conductor is broken or compromised in any way and there's a ground fault, it creates a shock hazard because someone can touch the energized chassis and complete the circuit through the person's body, causing injury or death.

That concept is not hard to understand but it is a bit clouded by terminology. The green or green and yellow conductor is commonly called the “ground” in North America, but it has nothing whatsoever to do with earth, ground, the floor, or anything remotely related to the plane on which we stand. It is actually a “bonding” conductor that bonds the conductive metal of the chassis to the circuit in the event of a fault where the line conductor contacts it, thus completing the circuit. If it is working correctly, it will immediately overload the circuit so that the circuit breaker will trip or the fuse will blow.

The word “ground” is a sort of a catch-all, covering several completely different unrelated purposes. The practice of connecting our electrical systems to the earth is primarily for lightning protection or overvoltage protection and to create a good 0-volt reference; and the practice of bonding every conductive part within touching distance of an electrical circuit is to clear a fault to that conductive part. These functions have nothing to do with each other, yet we often use the same word for them. So, let's explore each of these practices.

GROUNDING/EARTHING

In the production electrician's world, electrical systems are grounded/earthed, which means that the system is solidly connected to the earth by means of a grounding/earthing electrode. Electrodes can take many forms, but the one that you might be most familiar with is a grounding/earthing rod or a plumbing pipe that is electrically continuous for a minimum length, as specified by local codes and regulations. The rod is made of solid copper, and by driving it into the earth you ensure that it takes the same voltage as the earth, which, by definition, is 0 volts. A listed clamp is then used to connect a bare copper conductor or a conductor with green or green and yellow marking, and that is then connected to one side of the electrical system. You should be able to measure the impedance to the earth using an earth clamp meter, and it should be less than about 25 ohms.

Why do we connect electrical systems to earth? We do so primarily for two reasons; lightning or overvoltage protection, and stable 0-volt reference.

Lightning constitutes an incredible amount of energy, and if it strikes a transmission line or moves in such a way as to enter a building, then it will be very destructive unless it has an easy path to the earth, which is where it really wants to go anyway. (Remember, current always tries to return to its source, which, in this case it the earth.) In Thomas Edison's time, earthing was controversial. The New York Board of Fire Underwriters believed that earthing electrical systems caused more fires than it prevented, but in the 1903 edition of the NEC, they recommended earthing electrical systems. Ten years later in 1913, they started requiring it, probably because empirical evidence demonstrated that earthing reduced the incidence of fire due to lightning strikes.

The earth can be a relatively good conductor, depending on the soil composition, moisture content, mineral content, and other factors at any given location. When lightning strikes a building, it enters the building either through the electrical conductors or the building steel, both of which should be solidly connected to the earth. The energy takes the low-impedance path into the earth, where it spreads out and dissipates in the form of heat in a faction of a second. Because the mass of the earth is so large, the heat spreads far enough that it does little or no damage. Without a solid connection to the earth, the energy is concentrated in one small area of the building, which is likely to cause a fire. (See Figure 11.1.)

FIGURE 11.1
Lightning constitutes a huge amount of energy. If it has a low-impedance path to the earth, it will take it, whereupon it spreads out and dissipates in the form of heat. The impedance to earth in this building was high enough that a lightning strike destroyed the wiring and almost caused a fire.

Besides lightning, overvoltage can be caused by line surges and other events. For example, strong winds or a vehicle hitting a utility pole can cause high voltage transmission lines to break and fall on a lower voltage line, energizing it to a much higher voltage. Power surges can be caused by large loads coming on or off line. Many buildings have a transient voltage suppression system (TVSS) that shorts high voltage to ground/earth.

ZERO-VOLT REFERENCE

Another reason for connecting an electrical system to earth is to provide a stable 0-volt reference. Voltage is only meaningful when it is referenced to another point. When a bird lands on a high-voltage wire, it doesn't get electrocuted because it does not have a zero-voltage reference or a connection to another point in the circuit with a different potential. If the bird happens to straddle the gap between the high-voltage line and the metal transmission tower or another line, sparks will fly. That is because the voltage needs a reference in order to be meaningful.

Voltmeters have two probes for the same reason. If you were to take only one of the probes and touch it to a high voltage terminal, it wouldn't read any voltage at all because there is no point of reference.

We typically take zero volts as the absolute reference for voltage measurement. The exception is when we want to know the voltage across a load. That's an important bit of information because many devices require a certain amount of voltage to operate properly. But sometimes we want to know the system voltage, so we measure from a 0-volt reference. For example, when we measure 230 volts at the supply, that means that the system voltage is 230 volts higher than our 0-volt reference or ground/earth.

Since the earth is the largest object that is easily accessible, it can be used as a very stable voltage reference. Because it is so large, it takes a huge amount of energy to raise the voltage above 0V, and even then, as in the case of lightning strike to the earth, it would only change momentarily before falling back to 0 volts when the energy is dissipated. The earth is a very large current sink, and as long as we can establish good contact with it, we have a good zero-volt reference. Every power distribution system has at least one point that is electrically connected to the earth by means of a grounding/earthing electrode as mandated by electrical codes and regulations. We call this zero-volt reference "ground" in North America and "earth" in Europe and Australia. (See Figure 11.2.) When a building is constructed, whether it is a theater, arena, studio, or other venue, it has to meet code requirements, which, in the National Electrical Code, include a requirement for a primary and secondary connection to the earth unless the primary grounding electrode has an impedance of 25 ohms or less.

FIGURE 11.2
The earth is the zero-volt reference for power distribution systems. In North America and other countries, it is called "ground," and in Europe, Australia, and other countries it is called "earth."

TYPES OF GROUNDING/EARTHING ELECTRODES

A grounding/earthing electrode can take different forms, including rods, plates, advanced driven rods, concrete encased electrodes, a building foundation, water pipe, or electrolytic electrodes.

A driven rod 8 to 10 feet long and at least 5/8" in diameter is one of the most common electrodes. Most have a steel core and are covered with 5 to 10 mils of copper (a mil is one-thousandth of an inch) in order to protect the steel from corrosion. The life expectancy is only 5 to 10 years, depending on the soil conditions. They are relatively inexpensive,

but they can be challenging to install. In the United States, the rod must be at least 8 feet long and it should have at least 8 feet in contact with the soil. In some cases where the soil is rocky and it is difficult to drive it straight down, it is acceptable to drive it at an angle of up to 45 degrees from perpendicular. Alternatively, it can be buried horizontally at a depth of at least 30 inches. (See Figure 11.3.)

FIGURE 11.3
A ground/earthing rod is 8 to 10 feet long and at least 5/8" in diameter. It must have at least 8 feet of contact with the earth. It can be driven at an angle of up to 45˚ or it can be buried horizontally at a depth of at least 30 inches.

A plate electrode is a square sheet of copper with at least 2 square feet of surface area (one square foot per side). It has to be buried at a depth of at least 30 inches. Like a rod electrode, it has a life expectancy of about 5 to 10 years. (See Figure 11.4.)

FIGURE 11.4
A plate electrode must have at least 2 square feet of surface area (one square foot per side) and has to be buried at a depth of at least 30 inches.

An advanced driven rod looks like a drill bit with a carbide tip. It is modular with 4-foot sections so that it is easier to install using a drill hammer. It has a life expectancy of about 15 to 20 years.

A concrete encased electrode (sometimes called a Ufer ground, named after the engineer who invented the technique) can be the rebar in a building foundation, a wire, or wire mesh embedded in the concrete foundation of a building. According to the *Standard Handbook for Electrical Engineers*, when a large ground fault occurs, the current heats the moisture in the concrete, which can cause the concrete to expand and crack the foundation.

Water pipes can also be used as grounding electrodes, although they sometimes have a tar coating, which can prevent a good connection, or use plastic fittings, which completely insulates entire sections of the pipes. In some locations, plastic fittings are purposely designed into the system to prevent the flow of current and minimize electrolysis. If a water pipe is used as a grounding electrode, then it has to have at least 10 feet of metal pipe in direct contact with the earth, the joints must be electrically continuous, bonding jumpers must be installed around insulating joints and meters, and the connection to the pipe must be within 5 feet of where it enters the building.

An electrolytic electrode is one with a hollow copper shaft filled with salts. This creates an electrolytic solution that seeps into the soil and over time it makes better contact with the earth. It is installed using an auger to drill a hole, which is then backfilled with conductive material once the electrode has been installed. Although this type of electrode is high in cost, it has a life expectancy of about 30 to 50 years.

GROUNDING/EARTHING SEPARATELY DERIVED SYSTEMS

Portable power generators and transformers are “separately derived systems,” meaning that they have no electrical connection between the input and the output. Therefore, the grounding/earthing and bonding should be checked to make sure it is carried through to the secondary, and it may have to be re-established.

In a transformer, the neutral is typically bonded to the metal transformer enclosure (See Figure 11.5.), meaning that it is mechanically and electrically connected, using a bonding jumper, and the grounding/earthing conductor is connected to a grounding/earthing bus. Alternatively, the neutral and grounding/earthing conductors can be bonded at the first means of disconnect or overcurrent protective device.

FIGURE 11.5
A separately derived system showing the ground/earth connection. The bonding jumper creates a low impedance path for fault current back to the supply.

How a portable power generator should be grounded/earthed depends on the local codes and regulations, which can vary from municipality to municipality and from country to country. Sometimes one or more full-sized grounding/earthing rods are required, sometimes driving a grounding/earthing rod is prohibited, and sometimes driving a grounding/earth rod is optional.

Note: Before driving a rod or digging a hole, call the proper authorities to ensure that it is safe to dig.

In some locations, such as Los Angeles, driving a grounding rod is not allowed because the infrastructure is so dense that if you drive a rod you are highly likely to hit underground electrical, gas, water, cable, sewage, traffic control, or some other buried cables or pipes. In those instances, other means of grounding/earthing should be used, such as the grounding/earthing electrode of a nearby building, a buried metal water pipe, a metal light pole, or other conductive structure that is in good contact with the earth.

The County of Los Angeles Fire Department Public Safety Film Unit issued portable generator guidelines in 2013 (Addendum 23E to Safety Bulletin #23) entitled "Guidelines for Meeting National Electrical Code (NEC) Grounding Requirements for Portable Generators Supplying Portable Equipment in the Motion Picture and Television Industry." It sites NEC 250.34 and says, "The frame of the generator mounted to a truck or trailer may serve as the grounding electrode (in place of the earth) for the portable power distribution system. A ground rod is not required if the generator units and vehicles they are mounted to are insulated from the earth."

"Insulated from the earth" means that no conductive parts of the trailer, like safety chains and the jack, are touching the pavement, as shown in Figure 11.6. This practice prevents the completion of a low impedance path back to the source through a person touching an energized conductive part in the event of a ground fault. In addition, the system should only be energized only in the presence of trained, qualified personnel.

FIGURE 11.6
If a trailer mounted portable generator isolated from the earth as shown in this picture, then according to "… *Grounding Requirements for Portable Generators Supplying Portable Equipment in the Motion Picture and Television Industry*," a grounding/earthing rod is not required in Los Angeles county if it is insulated from the earth. It should only be energized in the presence of trained, qualified personnel.

Part of the reason that this is allowed is because a grounding/earthing rod is primarily for lightning protection, and the motion picture and television industry has strict policies against shooting in the presence of lightning. The 30/30 rule says that when you see a lightning strike, count the seconds until you hear the thunder. If the thunder occurs before you reach the count of 30 seconds, then the strike was less than 6 miles away, and you should shut down the generator and wait 30 minutes from the last lightning strike before the danger of lightning strike has passed. (The National Oceanic and Atmospheric Administration recommends seeking shelter if there is lightning in an 8-mile radius.) Other reasons for not requiring a grounding rod have to do with line surges and other grid-related events, but since a portable power generator is isolated from the power grid, it is not an issue.

If there are multiple generators located within 20 feet of each other, or if multiple generators are supplying power to a set in which two or more pieces of portable equipment are within 12 feet of each other while indoors or 20 feet of each other while outdoors, then the generators have to be bonded to each other with a copper conductor that is sized in accordance with NEC Table 250.122. (See Table 11.1.) The purpose is to prevent a difference in potential between the two generator frames and their 0-volt references, which could be a shock hazard. Should there be a difference in potential, it will equalize through the bonding conductor.

Table 11.1 The size of an equipment grounding conductor for bonding multiple generators

Table 250.122 Minimum size equipment grounding conductors for grounding raceway and equipment

Rating or setting of automatic overcurrent device in circuit ahead of equipment, conduit, etc., not exceeding (Amperes)	Size (AWG or kcmil)	
	Copper	Aluminum or copper-clad aluminum*
15	14	12
20	12	10
60	10	8
100	8	6
200	6	4
300	4	2
400	3	1

Note: Where necessary to comply with 250.4(A)(5) or (B)(4), the equipment grounding conductor shall be sized larger than given in this table.
* *See installation restrictions in 250.120.*
Source: Based on NEC Table 250.122.

Table 250.122 Minimum size equipment grounding conductors for grounding raceway and equipment

Rating or setting of automatic overcurrent device in circuit ahead of equipment, conduit, etc., not exceeding (Amperes)	Size (AWG or kcmil)	
	Copper	Aluminum or copper-clad aluminum*
500	2	1/0
600	1	2/0
800	1/0	3/0
1000	2/0	4/0
1200	3/0	250
1600	4/0	350
2000	250	400
2500	350	600
3000	400	600
4000	500	750
5000	700	1200
6000	800	1200

Note: Where necessary to comply with 250.4(A)(5) or (B)(4), the equipment grounding conductor shall be sized larger than given in this table.
* *See installation restrictions in 250.120.*
Source: Based on NEC Table 250.122.

If a generator is supplementing power in a building or structure that has power, then the generator's grounding conductor should be bonded to the building grounding electrode and it should be sized according to NEC Table 250.66. The building grounding electrode is usually near the service entrance or the electrical meter. (See Table 11.2.)

Table 11.2 A generator supplementing power in a powered building or structure is required to be bonded to the building grounding electrode with a bonding conductor sized according to this table.

Table 250.66 Grounding Electrode Conductor for Alternating-Current Systems

Size of Largest Ungrounded Service-Entrance Conductor or Equivalent Area for Parallel Conductors[a] (AWG/kcmil)		Size of Grounding Electrode Conductor (AWG/kcmil)	
Copper	Aluminum or Copper-Clad Aluminum	Copper	Aluminum or Copper-Clad Aluminum[b]
2 or smaller	1/0 or smaller	8	6
1 of 1/0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250	4	2
Over 3/0 through 350	Over 250 through 500	2	1/0
Over 350 through 600	Over 500 through 900	1/0	3/0
Over 600 through 1100	Over 900 through 1750	2/0	4/0
Over 1100	Over 1750	3/0	250

Notes:
1. Where multiple sets of service-entrance conductors are used as permitted in 230.40, Exception No. 2, the equivalent size of the largest service-entrance conductor shall be determined by the largest sum of the areas of the corresponding conductors of each set.
2. Where there are no service-entrance conductors, the grounding electrode conductor size shall be determined by the equivalent size of the largest service-entrance conductor required for the load to be served.
a This table also applies to the derived conductors of separately derived ac systems.
b See installation restrictions in 250.64(A).
Source: From NEC Table 250.66.

This is a very short summary of the two-page document and is not intended to replace it. Read it thoroughly and follow the local codes.

In Canada, the practice of grounding portable power generators is very different. The Entertainment Electrical Safety Committee of Ontario (EESCO) has published "Grounding of Generators in the Entertainment Industry." It says that all generators over 12 kW should be grounded, and those that are under 12 kW should be grounded if they are not frame grounded or use other than cord and plug connected loads. Grounding should be accomplished with one of four

acceptable grounding electrodes including: (a) two 10' ground rods spaced 10' apart from each other and driven to full depth, (b) an approved ground plate, which is typically 10" × 16" × 1/4", buried at a depth of at least two feet, (c) a buried metal water pipe such as a fire hydrant or water faucet, or (d) and existing metal object equivalent in size and depth to (a) or (b).

Note: Always call the local utility companies before digging or driving a grounding rod. All underground services should be located before installing electrodes. Before connecting a grounding/earthing electrode conductor to a fire hydrant, check with the local fire marshal or authority having jurisdiction. Always follow local codes and regulations!

The other requirements for grounding generators include using the correct size of grounding conductor and using approved connectors. The grounding conductor should be dedicated for that purpose and it can be no more than 50 meters long. It must not have more than two in-line single-pin connections. The sizing requirements are spelled out in ESA SPEC-003 Table 3 and reproduced in Table 11.3 as follows:

Table 11.3 Sizing grounding conductors for generators from EESCO "Grounding of Generators in the Entertainment Industry."

1.1 Ampacity of overcurrent protection	**Size of copper grounding conductor AWG**
100 or less	4
101 to 200	2
201 to 300	2/0
301 and above	4/0

Note: When different electrical systems are in proximity to each other and do not share the same grounding electrode they shall be bonded together. See EESCO document "Bonding of Electrical Systems in the Entertainment Industry."
Source: ESA SPEC-003 Table 3.

In the United Kingdom, the requirements for earthing temporary systems, including generators, vary depending on the electrical environment. British Standards (BS 7909 - "Code of practice for temporary electrical systems for entertainment and related purposes") requires an assessment be made regarding whether or not the earthing terminal of a generator should be connected to an earthing electrode, the electrode of a building, or both, and whether or not the circuit protective conductor (CPC) of multiple temporary electrical systems should be interconnected. The determination has to do with the earthing arrangements, which can be TN-S (separate terra or earth and neutral conductors), TN-C-S (a combination of a combined earth and neutral conductor for part of the system and separate earth and neutral for another part), TT (multi-point earth with different earthing electrodes for the supply and for the distribution system). For more information, refer to BS 7909. (See Figures 11.7a–11.7d.)

FIGURE 11.7a
TN-S: separate protective earth (PE) and neutral (N) conductors from transformer to consuming device, which are not connected together at any point after the building distribution point. The integrity of the earthing in a TN-S should be tested and verified. The generator neutral should be connected to the main earthing terminal at the generator and the CPC of the distro should be connected to it.

FIGURE 11.7b
TN-C: combined PE and N conductor all the way from the transformer to the consuming device.

FIGURE 11.7c
TN-C-S: combined PEN conductor from transformer to building distribution point, but separate PE and N conductors in fixed indoor wiring and flexible power cords.

FIGURE 11.7d
TT: one point of the source of supply is directly earthed, the exposed conductive parts are connected to earth electrodes electrically independent of the earth electrodes of the source.

GROUNDING/EARTHING ELECTRODE CONDUCTOR

The conductor that connects an electrical system to the grounding/earthing electrode is known as the grounding/earthing electrode conductor. It is normally non-conducting, meaning that the only time it should be conducting current is when something is wrong, such as a ground/earth fault, lightning strike, or overvoltage situation. Since it should only have to conduct current for very short periods of time during an anomaly, it can be smaller in size than the phase conductors. Table 11.4 shows acceptable sizes according to the National Electrical Code. The requirements may vary in your region, so check the local codes and regulations.

Table 11.4 Grounding electrode conductor acceptable sizes for AC systems.(For complete table, see National Electrical Code Table 250.66.)

Size of largest ungrounded Conductor or Equivalent Area for Parallel Conductors (AWG/kcmil) - Copper	Size of grounding Electrode Conductor (AWG/kcmil) – Copper
2 or smaller	8
1 or 1/0	6
2/0 or 3/0	4
Over 3/0 through 350	2

Source: National Electrical Code 2017, Table 250.66.

The grounding/earthing electrode conductor should be routed so that it is only as long as necessary and no longer with no bends or loops because that can increase the impedance to earth and the lower the impedance, the more effective it is. Once a grounding/earthing electrode has been established and the grounding/earthing electrode conductor installed, the resistance to ground/earth should be measured using tools designed especially for this purpose, like clamp-on ground tester. It induces voltage in a closed loop, which includes the grounding electrode conductor and measures the resulting current. By using Ohm's law, it can determine the impedance to the earth. If it is more than 25 ohms, the *NEC* requires a secondary grounding electrode to be connected in parallel to lower the resistance to ground. Ideally, the resistance to ground should be as low as possible. In some cases, it is engineered to be less than 5 ohms.

MAIN BONDING JUMPER

All of the normally non-conducting metal parts of a power distribution system should be interconnected in such a way that, in the event that they become energized, a complete circuit to the part will cause enough fault current to flow that it trips the circuit breaker and removes the voltage. If the impedance of the circuit is low enough, then it will interrupt the circuit because of overcurrent protection (fuse or circuit breaker) will open. Part of that circuit includes a main bonding jumper (MBJ), and it makes a very important connection between the equipment grounding conductor and the neutral conductor. (See Figure 11.8.) Without it, there is no way to clear a fault to a conductive chassis of the equipment. If a metal part becomes energized—which can happen when insulation breaks down, a wire breaks or melts, etc.—then it will stay energized because there is no path for fault current back to the supply, which creates a shock hazard. The presence or absence of the MBJ can be verified before energizing a power distribution system by checking for continuity between the grounding conductor and the neutral conductor at the supply. If there is no continuity, then the MBJ is missing and it should not be used until it is rectified. Ordinarily, that means bringing in a licensed commercial electrician to install an MBJ.

FIGURE 11.8
The path for fault current includes the main bonding, which connects the equipment grounding conductor to the neutral conductor. Without it, a fault to a conductive chassis would put voltage on it but it would not trip the circuit breaker. The main bonding completes the circuit in the event of a ground fault, thereby causing the circuit breaker to trip.

There were several American servicemen who were electrocuted over a period of time in Afghanistan and Iraq, reportedly because of missing main bonding jumpers. When the water pump shorted to the metal housing, it energized the plumbing pipes, and when the servicemen went to take a shower and touched the water valve, they inadvertently completed the path for fault current through their bodies and back to the electrical supply through the earth, through the grounding/earthing electrode, and through the grounding/earthing electrode conductor.

To ensure that the main bonding jumper is in place, you should be able to use a continuity checker to confirm that there is continuity between any non-conducting metal part of the electrical system and the neutral conductor. If there is no continuity, then there is no path for fault current back to the supply and the overcurrent protection device will not work.

EQUIPMENT GROUNDING CONDUCTOR/CIRCUIT PROTECTIVE CONDUCTOR

A safe power distribution system always includes an equipment grounding conductor (EGC), also known as a circuit protective conductor (CPC) in Europe, Australia, and Asia. In the United States and Canada, it is the green conductor or the conductor with green marking, and in Europe, Australia, and Asia it is marked green with a yellow stripe in the power cord, branch circuit, or feeder set.

All non-conductive metal parts of a power distribution system should be bonded by the use of the equipment grounding conductor/circuit protective conductor. It serves to provide a low-impedance path to the supply in the event of a ground fault to the conductive metal. It also keeps these metal parts at ground (0 V) potential. The practice of maintaining a ground potent at all metal parts of the electrical system is referred to as an equipotential plane or zone, or equipotential bonding.

If the system is properly bonded through a low-impedance path, then, in the event of a ground fault, the EGC or CPC will cause a large fault current to flow, thereby tripping the overcurrent protection device and de-energizing the circuit. The main bonding jumper serves to carry the ground fault current from the EGC to the neutral conductor, thereby completing the circuit.

If the circuit is not properly bonded, then a ground fault will cause the metal chassis or housing to be energized but no current will flow; the overcurrent device will be of no help. If anyone touches the chassis or housing while

simultaneously touching a grounded object, like a microphone, guitar strings, or metal chassis, then that person will complete the circuit and current will flow through the person and back to the supply through the earth. (See Figure 11.9.) It is a potentially lethal situation.

FIGURE 11.9
The EGC or CPC help prevent accidental injury by causing enough current to flow in the event of a fault to trip the circuit breaker. In this illustration, a fault to an improperly bonded normally non-current-carrying metal part causes it to become energized. The person touching the energized part completes the path to ground and becomes part of the path for the fault current. The red line indicates the path for fault current.

The grounding connection on any electrical equipment should never be altered. A so-called "ground lift adapter" is sometimes used to lift the ground/earth conductor. Those devices are actually grounding adapters to connect a 3-wire device (grounded) to an older 2-wire (ungrounded) system in a way that connects the grounding conductor to the metal parts of a bonded receptacle. (See Figure 11.10.)

FIGURE 11.10
A faulty ground allows normally non-conductive metal parts to stay energized, creating a potentially lethal situation. A grounding adapter like this should never be used to lift a ground. These are made to connect a 3-wire grounded device to a 2-wire ungrounded system in a way that connects the grounding conductor to the metal parts of a grounded receptacle. Notice the wording on the adapter that says, "Caution: Connect tab to grounded screw."

When power distribution equipment, lighting, audio, and video gear are functioning properly, the grounding/earthing terminal on the power connector properly connects the normally non-conducting metal parts to the grounding/earthing system. Broken grounding/earthing terminals or conductors can isolate normally non-conductive metal parts. Otherwise, in a fully functioning device, the neutral conductor is connected to the EGC at the supply, and the EGC is bonded to the case of the gear. In a lighting fixture, the case is typically connected to yoke, metal clamp (when one is used), and metal truss (provided the truss is not insulated from the clamp using an insulated protector), which means that the truss or pipe on which lighting is hung is also bonded. The more lights that are hung on the truss, the better it

is bonded, assuming the power cables on the lights don't have faulty grounding/earthing connection and the fixtures aren't isolated from the truss by a protective sleeve. Sometimes plastic or PVC sleeves are used to prevent the bolt from a C-clamp from damaging the truss. If a non-conductive truss protector is used, then the continuity between the electrical system grounding conductor and the truss should be verified using a continuity tester. If there is no continuity, then the truss should be bonded using a grounding clamp that is connected to electrical ground or by removing at least one truss protector.

GROUNDED VERSUS GROUNDING VERSUS BONDING

The terminology in the National Electrical Code can be confusing, particularly when it refers to the neutral as the "grounded" conductor and the equipment grounding conductor (EGC) as the "grounding" conductor. In a 4-wire plus ground/earth wye or star connected system, the neutral conductor (the white or gray wire in North America, the blue wire in Europe, the black wire in India and Australia, and the light blue wire in China) is connected to earth at the supply or the service panel, so it is referred to as the "grounded conductor." British standards simply refer to it as the neutral conductor.

None of the phase conductors are grounded, so they are referred to as "ungrounded conductors." Grounding is a continual process—the green conductor is continually grounding the conductive metal parts to which it is bonded, so it is called the "grounding conductor" and is usually green or green with a yellow stripe, or it can be a bare copper wire in the United States and Canada. "Bonded" means it is connected both mechanically and electrically to create a conductive path. All normally non-conducting metal parts in an electrical system such as metal enclosures, conduit, and water pipes should be bonded to create an equipotential plane or zone and to ensure the circuit breaker trips in the event of a ground fault.

In a low-voltage signal cable like a shielded audio cable or video cable, then the shield is usually connected to the chassis, which is "signal ground" or the 0-volt reference for the signal voltage. The EGC can also be connected to the same chassis. The symbols for ground/earth are shown in Figure 11.11.

FIGURE 11.11
Symbols for signal ground, earth ground, and chassis ground.

GROUND LOOPS

Audio hum and noise are the bane of the audio professional's existence. Those pesky noise problems are sometimes related to electrical system grounding/earthing because they can be caused by current flowing in a loop that includes the grounding conductor and the shield of the signal cable. Ground loops can degrade video and lighting control signals as well. Following good grounding practices and understanding how ground loops occur will keep the system safe and help minimize or eliminate problems with ground loops.

An audio system is powered by a cable that includes an equipment grounding conductor or circuit protective conductor, which is bonded to the chassis. The audio cable has a shield that connects to pin 1 of the 3-pin XLR connector. When it is plugged in, it connects to the chassis, both at the sending and the receiving end. This all forms a complete conductive path, and voltage can be induced by electromagnetic coupling to the power cable, causing current to flow through the ground loop. (See Figure 11.12.) That current produces its own magnetic field, which couples to the amplifier and causes a loud 60-Hz hum.

FIGURE 11.12
A ground loop enabled by a connection between the equipment grounding/earthing conductor, the chassis, and signal ground/earth.

The easiest—and the most dangerous—way to interrupt a ground/earth loop is to lift the ground using a three-to-two prong adaptor. This breaks the current path, but it puts personnel at great risk of electrocution. A ground/earth fault can energize the equipment and put voltage on the chassis, and any unfortunate person who happens to make contact with the equipment and ground/earth at the same time can be seriously injured or killed.

A much better way to resolve the problem is to use an audio isolation transformer like an IL-19. This is a 1:1 transformer, which means it has no electrical connection between the input and output, and that breaks the loop and stops the hum. Some audio engineers claim that an isolation transformer alters the sound, and it is possible that the frequency response is not flat. In that case, a short adapter can be built without a pin-1 connection, which also breaks the loop but doesn't change the sound. The adapter should be used at the receiving end of the cable to create a "telescoping shield."

ISOLATED GROUND

Some electrical loads generate "noise" that can propagate through an electrical system. For example, motors, fluorescent lights, and dimmers can generate electromagnetic interference that can induce noise in a grounding conductor. When that happens, anything that is powered by the same circuit or that share the grounding conductor might experience problems like hum, buzz, or distortion because of "dirty power." Audio amplifiers and video equipment are particularly susceptible to electromagnetic interference (EMI). Many of these problems can be avoided or resolved by using an isolated ground system.

An isolated ground system minimizes the electrical noise in the isolated system, and provides "clean power" for audio, video, or other equipment. Such a system is built by using an isolation transformer to power part of an electrical system. Since a transformer is a separately derived system, there is no electrical connection between the input (primary side) of the transformer and the output (secondary side) of the transformer, and noise that appears on both the phase conductor and the neutral conductor relative to ground (common-mode noise) is not passed along. Since it is a separately derived system, the grounding connection has to be reestablished.

An isolation transformer can be a 1:1 transformer or step-down transformer. An electrostatically shielded transformer provides additional filtering of common-mode noise and increases the isolation. The transformer should be sized to power all of the connected equipment plus some overhead for growth and a margin of error.

Typically, an isolation transformer is reserved for the exclusive use only one type of gear, like the audio or video, and other types of loads are not allowed to use it. The "clean power" is run to isolated grounding receptacles, which have a green triangle (usually with an orange background) symbolizing isolated ground and indicating that the circuit is reserved for certain equipment.

All the receptacles in an isolated ground system have a grounding terminal to which the isolated equipment grounding conductor is terminated. The isolated grounding conductor is insulated from the junction box or chassis to which the

isolated receptacle is mounted. When there are multiple receptacles, the isolated equipment grounding conductor can pass through panelboards, junction boxes, raceways, wireways, or any other normally non-conducting metal parts without contacting the metal. The chassis must still be bonded to the building equipment grounding conductor to ensure that there is a path for fault current back to the source and that a ground fault will trip the overcurrent device. (See Figure 11.13.)

FIGURE 11.13
An isolated ground system minimizes electrical noise and reduces interference with the operation of audio, video, or other electronic equipment.

BALANCED POWER SYSTEMS

In the United States, the *NEC* allows for the use of 120V balanced power from a separately derived system (meaning that it has its own service, whether from a different feeder transformer, generator, or another system) that provides two balanced phases of opposite polarity. (See Figure 11.14.) The line-to-ground voltage is 60 volts, but because the two lines are inverted in phase, the line-to-line voltage is 120 volts. The purpose of this system is to ensure that any noise that is picked up equally on the two phases is cancelled. It does so because the noise is summed to the ground, and if it is equal in magnitude but opposite in phase, the result is zero.

FIGURE 11.14
A balanced power transformer cancels noise on the ground because the two phase conductors are opposite in polarity.

These systems are only allowed in commercial or industrial buildings where their use can be restricted to qualified personnel. They can use standard panelboards as long as the voltage rating exceeds the voltage of the system and is clearly marked on the outside of the panel or inside the doors of the panel. Two-pole breakers must be used because each branch circuit has two live wires.

Receptacles and permanently installed equipment in this system have to have an equipment ground that is connected to an equipment grounding bus in the panelboard, and it must be marked "Technical Equipment Ground." It has to be connected to the grounded conductor (neutral) but it doesn't have to be bonded to the panelboard enclosure. Also, receptacles have to be protected by GFCIs (see the section titled "Ground Fault Circuit Interrupters" in Chapter 12, page 235) and must be marked as follows:

> WARNING – TECHNICAL POWER
>
> Do not connect to lighting equipment.
>
> For electronic equipment use only.
>
> 60/120 V 1-∅AC
>
> GFCI protected

There must also be a standard 125-volt, single-phase, 15- or 20-amp outlet within six feet of every 60/120V technical power outlet. Isolated ground receptacles can be used provided they are installed according to applicable codes. There are more requirements for meeting code for balanced power systems, but the details are beyond the scope of this book. Refer to *NEC Article 647 – Sensitive Electronic Equipment* for more information.

GROUNDING/EARTHING ELECTRODES FOR ISOLATED GROUNDING AND TECH POWER

According to the *NEC*, the grounding electrode for separately derived systems should be as close as possible to the point at which the grounding electrode conductor is connected to the electrical system. This point of connection is typically inside of the isolation transformer or tech power transformer. The electrode should be either an underground

metal water pipe that is in direct contact with the earth for at least 3 meters (10 feet) or the metal frame of the building or structure. If a water pipe is used, it has to have continuity to the point of connection and if there are any insulating joints or obstructions that interrupt the continuity, is has to be made continuous by using bonding jumpers. If the metal frame of the building or structure is used, the structural member has to be in direct contact with the earth for at least 3 meters (10 feet) or more. The metal structure can also be the bolts that hold down a structural steel column if they are connected to a compliant concrete-encased electrode, but the bolts have to be connected to the concrete-encased electrode by an approved method including welding. If none of these electrodes are available, then you can use a concrete encased electrode, a ground ring, rod and pipe electrodes, plate electrodes, or any other listed electrode. Electrodes that are *not* permitted are gas pipes and aluminum electrodes.

UNDERSTANDING GROUNDING/EARTHING CONCEPTS

11.1 If a large bird with a leg span of 12 inches (one foot) lands on a 69 kV transmission line and the impedance of the transmission line is about 1 ohm per mile with a current of 300 A, what is the voltage from one of the bird's feet to the other? (One mile equals 5280 feet.)

11.2 In the circuit below, what is the voltage reference if we place one probe at point D and one probe at point C? (Assume the first probe is the reference probe.) What voltage will we read? (Figure 11.15)

11.3 What is the main purpose of a grounding electrode?

11.4 If a water pipe is used as a grounding/earthing electrode, why is it important to bond to it within 5 feet of where it enters the building?

11.5 Why should the grounding/earthing and bonding be checked in a separately derived system?

11.6 If the frame of a generator mounted to a truck or trailer serves as the grounding electrode in place of the earth, why does it help to insulate the trailer from the earth?

11.7 What is the purpose of grounding or earthing the neutral conductor?

11.8 Is it required to drive a grounding/earthing rod when you're using a portable power generator?

11.9 Why is it sometimes not a good idea to drive a grounding/earthing rod?

11.10 If you're working outside and you see a lightning strike, why should you time the sound of thunder? What is the significance of the 30/30 rule?

11.11 (a) If multiple generators are operating within 20 feet of each other, why is it important that they are bonded? (b) Why is it important to bond to a building or structure to which a generator is supplying power? (c) Does the requirement for bonding to a building or structure include bonding to a portable stage?

11.12 What is the grounding/earthing requirement for portable power generators in Ontario, Canada?

11.13 Why is it acceptable to use a smaller grounding/earthing conductor than the phase conductors?

11.14 If a grounding/earthing conductor is too long, or it has loops in it, how does that affect the grounding/earthing system?

11.15 Why is the main bonding jumper such an important part of an electrical system?

11.16 How does an equipment grounding conductor or circuit protective conductor help clear a ground/earth fault?

11.17 If using a “ground lift adapter” to interrupt ground loops can create a potentially lethal situation, then why are they made? What is the intended purpose of these devices?

11.18 Can ground/earth loops interfere with lighting or video equipment?

11.19 What is the problem with using two bonding jumpers at different locations in the same electrical system?

11.20 In an isolated ground/earth system, why is it important to bond the isolated ground/earth and the building ground/earth? (See Figure 11.13.)

11.21 What would happen if a live conductor were to make electrical contact with a metal equipment enclosure, metal conduit, or metal stage and the electrical system is not properly bonded?

11.22 Where is the grounding/earthing electrode typically located in a building?

FIGURE 11.15
If D is the reference, what is the voltage from D to C?

CHAPTER 12

Overcurrent Protection

The very first electrical standard in the United States was called “Electric Light Wires, Lamps, etc.,” and it was written by the New York Board of Fire Underwriters in 1881. It had five simple rules for installers: (1) use wires with 50% more ampacity than the connected load, (2) use wires that are “insulated and doubly coated with some approved material,” (3) fasten the wires with approved non-conducting fasteners every 2-1/2” for incandescent lamps and every 8” for arc lamps, 8” from all other wires or metal conductive surfaces in the open where they can be inspected, (4) protect arc lamps with glass globes to prevent sparks or hot carbon from causing a fire, and (5) use a shut-off switch at the point of entrance of the electricity into a building and turn off the power when not in use. It went on to say that installers had to submit an application to use electric lights and it must be accompanied by a statement with the number of lamps to be used, an estimate from “some known electrician” of the “quantity of electricity required,” a sample of at least three feet of the wire to be used, a certificate of the ampacity of the wire, and information about where the electricity would be generated, whether or not the circuit would have a ground, and the details of the installation.

Electrical power distribution comes with inherent risks, but the risks can be mitigated by taking precautions. Those precautions spelled out by the Board in 1881 are still effective today, and many more have been added since then. Edison well understood the potential hazards of bringing electricity into homes and businesses. Though he wrote a letter to the New York Board of Fire Underwriters exclaiming that his DC power generation, distribution, and lighting system were “absolutely free from any possible danger from fire,” he recognized that if the current exceeded the ampacity of the wire then it would indeed present a hazard. Therefore, he invented the fusible link or fuse to minimize that hazard. As early as 1883, Edison's systems used a “breakdown plug,” or what we now call a fuse.

FUSES

A fuse is a calibrated weak link in a circuit that will predictably and reliably melt if a certain level of current is reached for a certain amount of time. When the fuse element melts, the circuit is interrupted and the current ceases to flow.

Fuses don't always blow as soon as the current exceeds its rating. There is an inverse-time relationship between the amount of current and the time it takes to blow; the higher the current, the faster the fuse will open.

The part of a fuse that melts is the “fuse wire,” which is an alloy with a relatively low melting temperature. The minimum fusing current is the least amount of current that will cause the fuse wire to melt.

Fuses have both a current rating and a voltage rating. The current rating is the most amount of current that a fuse can handle without eventually blowing, while the voltage rating is the maximum voltage a fuse can safely withstand after the fuse has blown. If the voltage rating is exceeded, for example, if a 125V fuse is used in a 240V circuit, then there is the possibility that when it blows, an arc could develop across the terminals and the circuit could continue to conduct, thus defeating the purpose of the fuse in the first place. A properly rated fuse is designed to withstand the open circuit voltage for 30 seconds after the fuse blows or to have an interrupt resistance of at least 1k ohms.

When the current passing through a fuse exceeds the current rating, an overcurrent condition has occurred. The amount of time it takes for the fuse wire to melt from the time the overcurrent condition occurs is the "melting time" of the fuse. When the flow of current is interrupted, an arc develops between the terminals of the fuse. As the break between the terminals grows, it eventually interrupts the arc. The time it takes after the fuse wire melts and the arc stops is the arcing time of the fuse. The combination of the melting time and the arcing time is the "operating time" of the fuse, which is typically less than a few milliseconds or less than half a cycle. (See Figure 12.1.)

FIGURE 12.1
When a fuse interrupts a circuit, an arc is developed across the terminals before the gap grows large enough to interrupt it.

In a power distribution system, power is supplied through a fused disconnect switch, which is sometimes called a company switch or a bull switch. Because of the high ampacity of most of these switches, they use high rupturing capacity (HRC) fuses. (See Figure 12.2.) These fuses have a ceramic or epoxy-glass enclosure to withstand the very high temperatures generated by the arc, and they are usually filled with a quartz-sand filler, which crystallizes with heat, essentially turning to glass and helping to quench the arc. They are hermetically sealed to prevent the oxidation of the fuse wire and they contain the arc in the event of a short circuit. There are different types of HRC fuses, including ultra-fast, which are designed for the protection of solid-state devices, quick response for loads with little or no inrush current, and delayed action for loads with high inrush current.

FIGURE 12.2
A high rupture capacity fuse is filled with quartz sand to quench the arc produced by interrupting a circuit under load.

CURRENT LIMITING

The main purpose of a fuse is to protect a circuit and all of the components connected to it. If there is a short circuit (meaning the impedance is 0 Ω or very close to it), then the current will be very high (approaching infinity amps), producing intense heat that can result in a fire.

A current limiting fuse limits the peak current at any instant in time (the instantaneous peak current) by interrupting the circuit in less than 1/2 of a cycle (0.008 seconds for 60 Hz or 0.01 seconds for 50 Hz). As a result, the short circuit current is reduced significantly, which reduces the potential for fire and helps make the electrical system safer.

LOW-VOLTAGE, LOW CURRENT FUSES

Low-voltage (under 600V) fuses used in North America typically comply with Underwriters Laboratories (UL) and/or Canadian Standards Association (CSA) standard 248-14, while those used in Europe comply with International Electrotechnical Commission (IEC) standard 60127-2. UL and CSA standards are harmonized but they differ from IEC standards. Table 12.1 shows the allowable continuous operating current for various types of fuses at 23°C.

Table 12.1 Allowable continuous operating current for fuses at 23°C

Standard	Voltage rating	Allowable continuous operating current (23°)
UL/CSA	125V	Less than 70% of I_{rated}
UL/CSA	250V	Less than 75% of I_{rated}
IEC	125V	Less than 70% of I_{rated}
IEC	250V	Less than 100% of I_{rated}
IEC	32V–250V	Less than 80% of I_{rated}

Source: Courtesy of Wickmann, www.wickmann.com.

If the rated current of a fuse is too low for the application, then it is likely to nuisance trip because of fluctuations and spikes in the line voltage and the resulting current. If it is too high, it will not do its job of protecting the circuit and it could be a potential fire hazard. Replacement fuses should be of the same fuse type, since UL and CSA ratings are different from IEC ratings. For a 250V fuse, for example, a 1.4-amp UL/CSA fuse is approximately the same as a 1-amp IEC-rated fuse. Therefore, if a fuse manufactured to UL standards is replaced with a fuse manufactured to IEC standards, then the circuit will no longer be protected properly. And it goes without saying that it is never a good idea, regardless of the circumstances, to bypass a fuse with a chewing gum wrapper or any other conductive material.

There are several different types of low-voltage fuses that are classified according to how quickly or how slowly they will open in a fault or overcurrent situation. A fast-acting fuse will blow more quickly than a time-delayed or time-lag fuse, although, as you can see by Table 12.2, you can overload a fast-acting normal fuse by 50% and it might still take several minutes to blow. Time-delayed fuses are used in situations where there is high inrush current and the steady-state operating current is lower. Examples include discharge lamps, motors, transformers, and other highly capacitive or inductive loads.

Table 12.2 Miniature fuse time-current characteristics for UL/CSA and IEC standards

% Rated current	Current range	UL/CSA 248-14		IEC 60127-2				
		Fast-acting normal blow	Time-delay	Quick-acting I	Quick-acting II	Time-lag III	Time-lag IV	Time-lag V
100%	0–10 A	•	•					
135%	0–10 A	< 1 hour	< 1 hour					
150%	50 mA–6.3 A 32 mA–6.3 A 1 A–6.3 A			< 1 hour	< 1 hour	< 1 hour	< 1 hour	< 1 hour
200%	0–10 A 0–3 A	< 2 min	< 5 s					
210%	50 mA–6.3 A 32 mA–6.3 A 1 A–6.3 A			< 30 min	< 30 min	< 2 min	< 30 min	< 2 min
275%	50 mA–3.15 A 4 A–6.3 A 32 mA–100 mA 125 mA–6.3 A 1 A–6.3 A			10 ms–2 s 10 ms–3 s	10 ms–500 ms 50 ms–2 s	200 ms–10 s 600 ms–10 s	1 s–80 s	200 ms–10 s 600 ms–10 s
400%	50 mA–3.15 A 32 mA–100 mA 125 mA–6.3 A 1 A–3.15 A 4 A–6.3 A			3 ms-300 ms	3 ms–100 ms 10 ms–300 ms	40 ms–3 s 150 ms–3 s	95 ms–5 s 150 ms–5 s	40 ms–3 s 150 ms–3 s
1000%	50 mA–6.3 A 32 mA–6.3 A 32 mA–100 mA 125 mA–6.3 A 1 A–3.15 A 4 A–6.3 A			< 20 ms	< 20 ms	10 ms–300 ms 20 ms–300 ms	10 ms–100 ms 20 ms–100 ms	10 ms–300 ms 20 ms–300 ms

Source: Courtesy of Wickmann, www.wickmann.com.

CIRCUIT BREAKERS

All electrical circuits need overcurrent protection whether it is a fuse or a circuit breaker. A circuit breaker is a resettable switch that opens and closes a circuit manually or automatically in the event of an overload or short circuit. They are necessitated by the governing body in virtually every location in the world like the National Electrical Code (NEC) in the United States, the Canadian Standards Association (CSA) in Canada, the "Wiring Regs" or BS7671: Requirements for Electrical Installations in the United Kingdom, and the International Electrotechnical Commission (IEC) in the European Union, and well as other standards around the world.

In the live event production industry, we are normally dealing with low-voltage (600 volts and under) circuit breakers, and usually the molded case variety (MCCB for molded case circuit breaker), although miniature circuit breakers are occasionally found in automated luminaires and similar devices. There are different types of circuit breakers including thermal, thermal-magnetic, magnetic, and electronic circuit breakers, and they can behave differently.

CIRCUIT BREAKER RATINGS

Regardless of the type, circuit breakers all have a voltage rating, an amp rating, and an ampere interrupting capacity (AIC) rating. If the circuit voltage exceeds the circuit breaker voltage rating, it may not be able to extinguish the arc generated when the circuit is interrupted. The amp rating is the largest continuous (meaning three hours or more) current that they can carry in free air without tripping. The AIC is the maximum current a breaker can safely interrupt without failing. The mechanism for interrupting the circuit includes to metal contact closures, and any current in excess of the AIC rating puts them at risk of overheating and welding themselves closed, thus preventing them from interrupting the circuit.

In North America, molded case circuit breakers comply with UL-489 or CSA C22.2 No. 5. They have standard current ratings of 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 110, 124, 150, 175, 200, 225, 250, 300, 350, 400 amps and higher. There are also adjustable-trip circuit breakers.

In Europe, miniature circuit breakers are designed and built to IEC 60898-1, which defines the rated current I_n at an ambient air temperature of 30 ˚C. Standard current ratings are 6, 10, 13, 16, 20, 25, 32, 40, 50, 63, 80, 100, and 125 amps. They also have a letter designating the trip type, either B, C, or D, based on the instantaneous trip value, which is a multiple of the rated current. Type B circuit breakers will trip instantaneously when the current is between 3 to 5 times the rated current, type C breakers will trip instantaneously for current of 5 to 10 times the rated current, and type D breakers will trip instantaneously for current of 10 to 20 times the rated current. (See Figure 12.3.)

FIGURE 12.3
In Europe, miniature circuit breakers are classified according to the range of current needed to trip them instantaneously. Type B circuit breakers will trip instantaneously when the current is between 3 to 5 times the rated current, type C breakers will trip instantaneously for current of 5 to 10 times the rated current, and type D breakers will trip instantaneously for current of 10 to 20 times the rated current.

SINGLE-POLE, DOUBLE-POLE, AND THREE-POLE CIRCUIT BREAKERS

A pole is a current-carrying terminal. A single-pole circuit breaker has only one set of switching contacts and is used to interrupt a circuit at one point. For example, when a branch circuit or final circuit is overloaded or short-circuits and the breaker trips, it only needs to interrupt the hot or live conductor. Since the neutral conductor has no voltage, the load is completely de-energized when the circuit breaker is open.

A double-pole breaker has two switching contacts and is used to protect phase-to-phase circuits. When it trips, it interrupts both phase conductors, thereby removing all sources of voltage from the circuit. A three-pole breaker has three switching contacts and is typically used in three-phase circuits or to protect a three-phase load. Multi-pole breakers can be manufactured with two or three actuator mechanisms internally linked or by "ganging" or externally tying two or three actuator levers together. (See Figure 12.4.)

FIGURE 12.4
A multi-pole breaker, like this two-pole breaker, can have an internally linked actuator lever or they can be "ganged" together externally.

THERMAL CIRCUIT BREAKERS

Thermal-type circuit breakers sense current using a bi-metallic strip through which the current flows. The strip is laminated with two dissimilar metals, each with a different coefficient of expansion. The current flowing through the metals causes them to heat up due to their resistance and they expand as they heat. Because the two metal strips have

different coefficients of expansion, they expand at different rates, causing the laminated strip to bend. When the current reaches a predetermined magnitude, the bi-metallic strip will bend far enough to trigger a spring-loaded actuator switch, which then opens the contacts and breaks the circuit. (See Figure 12.5.)

FIGURE 12.5
A thermal circuit breaker has a bi-metallic strip that heats up when current flows through it. It is calibrated to interrupt the circuit in the event of an overload or short circuit.

The behavior of thermal circuit breakers is affected by the ambient air temperature because a higher starting temperature results in less temperature rise needed to reach the tripping threshold. Thermal breakers are somewhat forgiving of short current spikes because it takes time for the current to heat up the bi-metallic strip. A spike of a few cycles may not trip the breaker, which is desirable when it is expected, as with Xenon strobe fixtures and motors. Some thermal circuit breakers also have a magnetic relay to sense short circuit currents (as opposed to overloading) and they react more quickly. These thermal-magnetic circuit breakers offer both overload protection (with a slower response) and short circuit protection (with a faster response time).

MAGNETIC CIRCUIT BREAKERS

Magnetic circuit breakers sense current through the magnetic field in a coil of wire, which attracts a spring-loaded iron core. If the current is high enough, then the magnetic field will be strong enough to pull the iron core far enough to trigger the switching contact. (See Figures 12.6 and 12.7.) This solenoid is very fast acting and more accurate than a thermal breaker because it is unaffected by the ambient air temperature.

FIGURE 12.6

A magnetic circuit breaker senses current using a coil of wire that creates a magnetic field in proportion to the current. The magnetic field pulls a spring-loaded core, and if the current is high enough, then the magnetic field will be strong enough to cause the iron core to trip the switching contact at a predetermined current. (a) A cross-sectional view of a magnetic circuit breaker with no load. (b) The same breaker with some load but under the trip threshold. (c) The same breaker beyond the threshold tripping current.

FIGURE 12.7
Magnetic circuit breaker showing the solenoid, spring-loaded piston, armature, and actuator.

Some magnetic circuit breakers are filled with viscous fluid to introduce a slight delay to the reaction of the solenoid. This allows for brief periods of inrush currents and surges but still provides for overload protection. Large short circuit currents are sufficient to overcome the hydraulic delay and trip the circuit breaker almost instantaneously.

Electronic circuit breakers replace the magnetic solenoid with a much faster and more accurate Hall sensor and digital processing. They are unaffected by the ambient air temperature and they can be designed to filter out harmonics, thus eliminating nuisance tripping due to harmonic currents.

RESIDUAL CURRENT DEVICES

Some power distribution systems in Europe use multi-point earthing, and the return path for fault current is through the earth. If the impedance of the earth is high enough, then the fault current will be proportionately lower and the circuit breaker protecting the circuit will not trip, which can be a very dangerous situation. For that reason, a residual current device (RCD), which senses “leakage current” and interrupts the circuit, is often required to be used. They are also required for handheld mains powered equipment like followspots, musical instruments, and so on.

An RCD can detect an imbalance of as little as 30mA between the live and neutral conductors, which indicates leakage current due to shock or an earth fault, in which case it will interrupt the circuit within 30 milliseconds. The detection mechanism is a toroidal current transformer through which all of the current-carrying conductors are passed. (See Figure 12.8) Under normal circumstances, the vectoral sum of the outgoing current and the return current is 0A, and the magnetic fields produced by the opposing currents cancel. However, in the event of an earth fault, not all of the outgoing current is returned through the neutral conductor, so the outgoing current is higher than the return current, thus producing a magnetic field inside of the toroid, which causes the current transformer to produce voltage that then triggers the solenoid and opens the switching contacts.

FIGURE 12.8
A residual current device has a current transformer through which the line and neutral conductors are run. If the vectoral sum of the outgoing and return currents is zero, then no voltage is generated in the current transformer. In the event of an earth fault, the current transformer generates a voltage that causes the solenoid to open the switching contacts. An RCD must trip within 30 milliseconds if the leakage current is 30 milliamps or more.

According to BS 7909:2011, an RCD must trip at 30 mA of leakage or more, and it must have an operating time of no more than 40 msec (but it is usually 30 msec). There must not be more than six final circuits (or branch circuits in North American parlance) protected by a single RCD, and tripping the RCD must not introduce hazards such as the dowsing of working lights, safety lighting, or emergency lighting. The standard suggests that type A RCDs should be used when possible. These are devices that can be used with AC waveforms that have a DC component due to distortion. It also says that type B RCDs should be considered for loads that use pulse-width modulation, which include LEDs, switch-mode power supplies, and variable speed motors.

GROUND FAULT CIRCUIT INTERRUPTERS

In 1962, Professor Charles Dalziel of the University of California at Berkeley learned about RCDs through his work in the area of electrical safety when he attended a meeting in Geneva, Switzerland. He subsequently teamed with a manufacturing company to help develop an improved version of an RCD with a lower trip level that incorporated transistors. (See Figure 12.9.) By using an electronic control circuit instead of an electromechanical relay, they could more accurately monitor the differential current. Thus, they were able to build a device with a trip level of 15 milliamps. They called it a ground fault circuit interrupter (GFCI). By 1968, the National Electrical Code required the use of GFCIs in the circuits used for the underwater lighting of swimming pools.

FIGURE 12.9

A class A GFCI is a personnel protection device that can detect leakage current and interrupt a circuit in a specified amount of time. It has a "must trip" value of 6 milliamps and a "must not trip" value of 4 milliamps.

CLASS A GFCIS

Millions of GFCIs have been manufactured and installed around the world since they were invented in the 1960s. A harmonized tri-national standard defining Class A GFCIs was jointly issued by ANCE in Mexico as NMX J 520, CSA in Canada as CSA C22.2, and by UL in the United States as UL 943 in 2008. The standard describes Class A GFCIs as devices designed to interrupt a circuit when a ground fault current exceeds 6 milliamps, but it must not trip for less than 4 milliamps of leakage current. GFCIs are inverse-time devices, so they react faster to higher currents. The time it takes for a class A GFCI to trip follows the formula $T = (20/I)^{1.43}$, where I is in milliamps. A current of 6 mA will cause it to trip in about 5.6 seconds, while a current of 20 mA will cause it to trip in about 1 second. This is the minimum requirement, but most class A devices perform above the minimum requirement by about 50%, so a leakage current of 6 mA will cause the device to trip within about 2.8 seconds or less. Since RCDs and earth leakage circuit breakers (ELCBs) have higher trip currents, they do not meet the standard of a Class A GFCI in North America. They are, however, considered personnel protection devices in some other countries.

CLASS C, D, AND E GFCIS

Originally, GFCIs were class B devices, meaning they had a minimum trip current of 20 milliamps. They were used in swimming pool lighting circuits, but they are now obsolete. Today, there class C, D, and E GFCIs, all of which have a trip value of 20 mA but are categorized according to the voltages involved and the trip time. Class C GFCIs are for use in circuits with voltages of no more than 300 V from phase to ground, so they are fine for 480/277V systems. If the load protected by a class C GFCI does not have double insulation, then there is also a requirement to monitor the grounding conductor and open the circuit if it is lost. Class D GFCIs are for use in circuits with voltages of no more than 300 V to ground, which covers 600 V systems. They are required to have a large enough grounding conductor to provide a low impedance path for fault current to prevent more than 150 V across the body. Class E devices are similar to class D except they trip faster, eliminating the need for a larger grounding conductor.

In 2009, *American National Standard E1.19, Recommended Practice for the Use of Class A Ground-Fault Circuit Interrupters (GFCIs) Intended for Personnel Protection in the Entertainment Industry* was published. This recommended practice spells out when, where, and how to use GFCIs in places of assembly, the production of film, video, and broadcast, theatrical productions, carnivals, fairs, and similar events in North America. It covers electrical services of 100 amps or less, 120–240VAC single- and three-phase 60-Hz circuits where the voltage to ground does not exceed 150VAC. Note that since the voltage to ground in Europe is 230VAC or 240VAC, this standard specifically excludes those systems. In brief, the standard calls for the use of GFCIs in any circuit used outdoors, in wet or damp locations, or any time the circuit is in proximity to moisture or water unless the circuit is for egress lighting, exit lighting, or emergency lighting systems, or if tripping the GFCI could cause injury.

It used to be that the components inside of a GFCI, which include sense coils, an integrated circuit chip, an SCR, a solenoid, bridge rectifier, resistors, capacitors, and more, could fail and the device would no longer provide shock protection, yet it would still provide power to the load. That's why all GFCIs have a test/reset button. In 2015, the UL standard 943 for GFCIs was modified and provisions were added to make them safer by denying power to the load or give an audible or visual indication of a failure should any of the vital components fail.

The IC chip in a GFCI requires a constant voltage supply to operate, and the voltage comes from the circuit that it is protecting. If this circuit is on a dimmer, then the IC chip will stop functioning when the dimmer is set below a certain value; thus, GFCIs don't work on dimmed circuits. There used to be special GFCIs that had a separate power input for the control circuit, and they could be used in dimmer racks, but they are no longer manufactured.

Some loads, like HMI ballasts and audio amplifiers, are challenging to use with GFCIs. That's because they use capacitors to filter noise by draining noise current to the chassis, and that is read as leakage current in GFCIs, so they “nuisance trip.” To minimize nuisance tripping, put the load as close to the GFCI as possible to minimize the leakage contributed by the power cable. There are portable GFCIs that allow you to connect a load directly to the GFCI regardless of its location. (See Figure 12.10.) If a device cannot be made to work with GFCI protection when it should be, then try keeping it dry, isolate it, guard it, put it behind a crowd barrier or high enough that no one can reach it, or otherwise make sure it is not accessible.

FIGURE 12.10
A portable GFCI allows you to eliminate leakage contributed by a long cable, thus minimizing the chance of nuisance tripping.

UNDERSTANDING OVERCURRENT PROTECTION

12.1 The higher the overcurrent, the less time it takes for a fuse to blow or a circuit breaker to trip. If we want to clear a fault as quickly as possible to make it safer, should the impedance of the grounding conductor be high or low?

12.2 Fuses have a current rating and a voltage rating. Why do they have a voltage rating?

12.3 What is an HRC fuse and where is it typically used?

12.4 A properly rated fuse is designed to withstand the open circuit voltage for _____ seconds or to have an interrupt resistance of at least _____ ohms.

12.5 What is the purpose of a time-delay fuse?

12.6 What is the purpose of filling a fuse with quartz-sand?

12.7 (a) If a circuit breaker has an AIC rating of 10kA and it is protecting a circuit with an impedance of 8Ω, how much voltage would cause the current to exceed the AIC rating? (b) What could cause that much voltage to be applied to the circuit?

12.8 How does the ambient air temperature affect a thermal breaker?

12.9 Why are thermal circuit breakers more forgiving of voltage spikes and surges?

12.10 What is the purpose of combining thermal overload protection with magnetic circuit protection?

12.11 How does a magnetic circuit breaker sense current?

12.12 Which type of circuit breaker is more accurate, thermal or magnetic?

12.13 How does the ambient temperature affect magnetic circuit breakers?

12.14 Type B miniature circuit breakers will trip instantaneously when the current is between ___ and ___ times the rated current.

12.15 What is an RCD?

12.16 What is a GFCI?

12.17 What is the difference between an RCD and a GFCI?

12.18 What is the difference between a Class A and a Class C GFCI?

12.19 Does *ANSI E1.19, Recommended Practice for the Use of Class A Ground-Fault Circuit Interrupters (GFCIs) Intended for Personnel Protection in the Entertainment Industry* cover European power distribution systems?

12.20 When and where should GFCIs be used?

12.21 Should GFCIs be used on branch circuits with lighting that is on the ice in a rink?

12.22 When should GFCIs not be used?

12.23 Do GFCIs work on dimmed circuits?

12.24 Can a GFCI operate properly and still provide shock protection if there is no equipment grounding conductor?

12.25 If you accidentally touch a hot/live conductor and the neutral conductor at the same time on a circuit with GFCI protection, will the GFCI interrupt the circuit?

CHAPTER 13
Dimming Systems

Two of the most important inventions in the history of theatre and live event production were electronic dimming and LEDs. And just as electronic dimmers changed theatrical production forever, LEDs are changing theatrical production and every other segment of the lighting industry. The first practical LEDs were introduced in the early 1960s but they because of their small size and low light output, they had limited use. These early LEDs were used primarily as panel indicator lights.

In 2000, Dr. Roland Haitz, then a research scientist at Agilent Technologies, presented a white paper in which he observed that LEDs have increased in brightness by a factor of 20 every 10 years since they were introduced. This observation, now known as “Haitz law,” may or may not still be true by the time you read these words. What is true, however, is that LEDs are now making an indelible mark in the live event production industry. But it wasn't always that way.

In 1997, a new company made its debut at LDI, the largest trade show for the entertainment lighting industry in North America. Their entire display consisted of two LED luminaires about the size of a PAR 36 and a PAR 46. They were hardly bright enough to compete with any of the other lights at the trade show that year. Some of us at the show that year scoffed at the idea of using LEDs in stage lighting. But that company, called Color Kinetics, got the last laugh when a mere 10 years later Philips bought them for $791 million.

Such was the power of Haitz law. For many years after that show, LED luminaires remained the dimmer siblings of the entertainment lighting world. In December 2009, at a Daughtry show, I came to the realization that LED luminaires had crossed the threshold from “inferior” brightness to at least equal brightness compared to other more conventional light sources. If you look at the picture of that show below, you'll see six GLP Impression LED fixtures mounted on stirrups, three above stage left and three above stage right. You'll also see eight Martin MAC 2000 fixtures sitting on the upstage floor and splayed across the back of the stage. From my vantage point in the arena, it looked to my naked eye that the Impressions were every bit as bright as the MAC 2000s. It doesn't look like that in the picture because the camera sees things differently than the human eye, but to the thousands of people in the audience, they were equally bright. (See Figure 13.1.)

FIGURE 13.1
Daughtry show in December 2009 with LED luminaires and arc lamps. (Photo by Morgen Loven.)

But brightness wasn't the only obstacle LEDs had to overcome. Early LED luminaires suffered from poor color rendering and color fidelity, flicker on camera, high cost, and steppy dimming. Those issues have been resolved in many cases to the point where they now dominate the theatrical lighting landscape, at least in terms of new products. Incandescent luminaires will eventually be phased out because it will become increasingly difficult to find replacement lamps at a reasonable price. As a result, power distribution is changing along with it.

LED DIMMING

LEDs operate on low-voltage DC with a constant current. Accurately varying the current (and dimming level) is very difficult, so LEDs are typically dimmed by modulating the width of an on/off, which is referred to as pulse-width modulation (PWM). A power supply converts the incoming AC to low voltage DC, and then it switches the current on and off within a fixed period of time, typically in the range of about 1 to 3 milliseconds. The percentage of time that the LED is on compared to the time it is off is the "duty cycle," and it determines the perceived brightness. The resulting current waveform is a square wave, and the dimming level controls the duty cycle. The wider the width of the pulse, the brighter the output of the LED; the narrower the width of the pulse, the dimmer the output. (See Figure 13.2.) At full brightness, the current is steady DC and at blackout there is no current at all.

FIGURE 13.2
Pulse-width modulation showing 20%, 50%, and 100% duty cycle, which corresponds to dimming level in an LED.

The inverse of the PWM period is the PWM frequency, and it typically ranges from 300 Hz to 1000 Hz or higher. Lower frequencies can cause interaction between the frame rates of video or film and the pulsing LEDs, which translates to flicker, especially as lower duty cycles or dimming levels. Whole number multiples of camera frame rates produce less interaction.

LED luminaires typically have on-board dimming, which means that many systems designers are changing the way they design performing arts centers, performance halls, theaters, and other performance spaces. Instead of using centralized dimming in a series of racks located in an electrical closet or dimmer room, non-dimmed circuits are supplied at each hanging location. If an incandescent luminaire is required, then a dimming might be installed in a raceway in a distributed dimming system.

PHASE-CONTROLLED DIMMING

LED fixtures are rapidly transforming the entertainment lighting landscape, but there are still literally millions of "conventional" incandescent luminaires in use in theaters around the world, and they are controlled with dimmers. (See Figure 13.3(a) and 13.3(b).) The dimmers used most often in theatre, concert touring, and other live event productions are usually phase-controlled dimmers. They use an electronic switch controlled by a DMX control signal to turn the voltage off and on once in each half cycle of the voltage sine wave (120 times every second in a 60 Hz system or 100 times every second in a 50 Hz system). The dimming level controls the length of time the voltage is held on compared to the length of time it is held off.

FIGURE 13.3
Portable dimmer rack (a) rear view and (b) front view. (Photo courtesy of ETC.)

In Figure 13.4, the dimmer is set to around 25% (depending on the setting of the dimming curve, i.e., linear, exponential, etc.) and the control signal at the bottom of the illustration is off at 0° and turns on at 45°, then it turns off again at 180° and on again at 225°. It repeats this sequence for every cycle of the voltage sinewave until the dimming level changes. Note that the switching in the negative half cycle mirrors that of the positive half cycle; otherwise, the voltage waveform will generate a DC offset, which can damage the components in the circuit.

FIGURE 13.4
Modified voltage waveform showing the switching action of a forward phase-control dimmer. The control signal at the bottom of the illustration turns a switch on and off at precisely the right time to create a dimming level of about 25%.

The switching device can be either a TRIAC (triode for alternating current) or an SCR (silicon-controlled rectifier). Both are solid-state switches that are controlled by a low-voltage control signal. The control signal is generated by the lighting console in response to the programmer or operator, who sets the dimming level. The console then outputs that signal to the dimmer in the form of a DMX control signal through the DMX port. The processor in the dimmer translates it to a timing signal that is referenced to the zero crossing of the AC voltage. That timing signal turns the switch on at precisely the right phase angle, and that is called the "firing angle." The voltage is turned on, and when the phase angle reaches 180° in the positive half cycle or 360° in the negative half cycle, the voltage goes back to zero and stays off until the next switching cycle. The resulting modified voltage waveform controls the dimming level of the light.

A TRIAC is a bi-directional switch, meaning it can conduct current in both the positive and negative directions. On the other hand, an SCR is a uni-directional switch; it can conduct in only one direction. In order to conduct for the full voltage cycle, dimmers with SCRs have two of them connected in inverse-parallel (one connected in one direction and the other in the opposite direction). (See Figure 13.5.) That way, the first conducts during the positive half cycle while the second is off, and the second conducts during the negative half cycle while the first is off. This allows one SCR to cool off while the other is conducting. Dimmers with SCRs tend to be more robust than dimmers with TRIACs because the SCRs are used with a 50% duty cycle. On the other hand, SCRs cost more than TRIACs.

FIGURE 13.5
A forward phase-controlled dimming circuit showing two SCRs (SCR1 and SCR2) connected in inverse parallel fashion. The control signal regulates the duty cycle of the current flow, thus dimming the lamp.

In a forward phase-controlled dimmer, when the voltage is switched on during the middle of a cycle, the current rises very quickly to catch up with the voltage. As a result, it produces a current spike and overshoots the level where it should be. (See Figure 13.6) The sharp edges of the modified waveform cause mechanical vibration of the filament, which produces an audible frequency referred to as "filament sing." The frequency and amplitude are dependent upon the dimmer level and the resonant frequency of the filament, but it is loudest when the dimming level is about half.

FIGURE 13.6
In a forward phase-controlled dimmer, the voltage (in red) turns on in the middle of the cycle and the current (in yellow) rises quickly to try to catch up. As a result, it overshoots its target, finally settling down to its correct level.

To help address this issue, a choke is inserted in series with the load to limit how fast the current rises, thus limiting the overshoot. The larger the choke, the more it limits the change in current. Rise time is a measure of the effectiveness of the choke and it is measured in microseconds, or µsec (10^{-6} seconds). The greater the rise time, the less mechanical vibration the quieter the dimming system. In North America, inexpensive dimmers can have a rise time of about 80 µsec or less, and standard dimmers usually have a rise time of about 350 µsec. Improved performance dimmers have a rise time of about 500 or 600 µsec, and high-rise time dimmers have a rise time of up to 800 µsec. Bigger chokes cost more to produce, therefore, high-rise dimmers are sold at a premium. They're also heavier because they have more copper windings. (See Figure 13.7.)

FIGURE 13.7
Dimmer modules with chokes. On the left is a single-channel dimmer module with 800-µsec chokes; on the right is a dual-channel dimmer module of the same capacity but with 350-µsec chokes. Note the difference in

size between the high-rise choke and the standard choke. (Photo courtesy of Leviton.)

REVERSE PHASE-CONTROL

Forward phase-controlled dimmers use switching devices like TRIACs or SCRs that can turn the voltage on at any time during the cycle, but they can turn off only at the zero-crossing point when there is no current flowing. That's because interrupting a circuit under load draws an arc, which can destroy some electronic components. So, while TRIACs and SCRs are good at forward phase-control—switching on during the voltage cycle—they can't be used for reverse phase-controlled dimming—switching the voltage off during the voltage cycle. But there are devices that can be used for that purpose.

An insulated gate bipolar transistor, or IGBT, is a type of switching transistor that can handle relatively large currents. It can be turned on or off at any time during the voltage cycle, hence it can be used for reverse phase-controlled dimming.

Reverse phase-controlled dimming is similar to forward phase-controlled dimming except the switch is on at the beginning of each half cycle and it turns off at some point during each half cycle. (See Figure 13.8.) Just as with forward phase-controlled dimming, the two half cycles have to mirror each other or a DC offset will be produced, possibly damaging circuit components. It does so by turning off the voltage at two points separated by 180°. For example, if the positive half cycle is switched off at 60°, then the negative half cycle is switched off at 240°.

FIGURE 13.8
Reverse phase-controlled dimming showing the voltage waveform being turned off at 135° and turned on at 180°, then turned off again at 315° and back on at 360°.

Because the voltage is switched off during the voltage cycle instead of being switched on, there is no current spike, no overshoot, and no need to use chokes to control the rise time. So reverse phase-controlled dimmers are lighter in weight than forward phase-control dimmers with chokes. But IGBTs and similar high-current switching transistors are more expensive than SCRs or TRIACs, so reverse phase-controlled dimmers are typically more expensive than conventional dimmers.

SINEWAVE DIMMING

High-current handling transistors can also be used to dim loads by using pulse-width modulation (PWM) instead of phase-control. A sinewave dimmer turns the voltage on and off several thousand times during each cycle, varying the width of the pulse, which ultimately controls the dimming level. The output is a sinewave, but the amplitude varies according to the dimming level, which is a function of the duty cycle of the PWM. (See Figures 13.9 and 13.10.) For example, when the duty cycle of each voltage pulse is 50%, the dimming level is 50%. Since the sine waveform is maintained, it does not generate harmonics.

FIGURE 13.9
A sinewave dimmer varies the amplitude of a sinewave using pulse-width modulation. A transistor switches the voltage on and off several thousand times during each voltage cycle. The duration of the voltage and current pulse determines the voltage level.

FIGURE 13.10
A sinewave dimmer waveform illustrating 50% pulse-width and the resulting voltage amplitude.

The switching frequency of sinewave dimmers is in the range of about 30 kHz to 50 kHz. The advantage of higher switching frequencies is that they can operate with smaller inductors and transformers.

Sinewave dimmers are considered linear loads, meaning that they draw current in a linear fashion; if the voltage input is a sinewave, then the current is drawn in a sinusoidal waveform. The advantages of having a linear load are many. First of all, a sinewave dimmer produces no third-order harmonics, and by extension, they produce no overcurrent in the neutral conductor of a balanced three-phase system even when they are dimming. They also produce no filament sing, they require no chokes to control the rise time, and they are much quieter than conventional dimmers. But large current handling transistors are expensive and sinewave dimmers command a premium price. (See Figure 13.11.)

FIGURE 13.11
The Swisson XSD Sinewave Dimmer pack.

DIMMER CURVES

The human eye sees differently than a camera or a light meter. An increase or decrease in light intensity looks different to a human than it does to a light meter or a camera. When the intensity is doubled, it doesn't appear to the human eye that it is twice as bright. To trick the eye into seeing a linear change in intensity, the dimming level actually has to follow an exponential dimming curve.

A linear dimmer curve means that a 50% increase in the signal controlling the intensity results in a 50% increase in the light output. But the human eye perceives it as more than a 50% increase. An exponential dimmer curve means that a 50% increase in the control signal level results in a 25% increase in intensity as measured by a meter because $0.5^2 = 0.25$. But an exponential increase in intensity looks linear to the eye.

Most dimmers provide the ability to select a dimming curve, and it might be linear, exponential (or "square law"), or an "S" curve. (See Figure 13.12.) An S-curve stretches out the low end and the high end of the dimming curve to provide more control in the parts of the dimming curve that are most sensitive. This is especially important with LEDs since they are pulse-width modulated, and at the low end of the dimming curve, the pulses are very short and hard to control.

FIGURE 13.12
Linear, square law, and S-curves.

UNDERSTANDING DIMMING SYSTEMS

13.1 If a movie set is lit with LED fixtures and the monitor displays rolling bands of color, what is the best course of action to resolve the problem?

13.2 If a LED video wall has a refresh rate of 400 Hz and the PWM frequency of the LED luminaires on camera is 300 Hz, how many times does the video display refresh for each time the LEDs pulse?

13.3 Why are LEDs usually dimmed by PWM instead of conventional forward phase-controlled dimmers?

13.4 If an LED has a power supply that uses pulse-width modulation with no power factor correction, is it a linear load or a non-linear load?

13.5 How does the frequency of a pulse-width modulated LED affect flicker on video or film?

13.6 What would happen if a TRIAC or SCR were used to dim an incandescent lamp using reverse phase-control?

13.7 How does the intensity of a dimmed lamp change with the firing angle?

13.8 What would happen if the positive and negative half cycles of a dimmer did not mirror each other?

13.9 Why does it take two SCRs to make one dimmer channel work?

13.10 How does a choke reduce or eliminate noise in a dimmer?

13.11 Why is reverse phase-control dimming chokeless?

13.12 (a) How do forward phase-controlled dimmers and reverse phase-controlled dimmers create harmonics in an electrical system? (b) Why doesn't a sinewave dimmer generate harmonics?

13.13 High harmonic content produced by a non-linear load causes current to flow in the neutral conductor of a 3-phase system whether or not the three phases are equally balanced. Is there anything wrong with current flowing in the neutral conductor?

13.14 What causes filament sing?

13.15 (a) What is meant by the rise time of a dimmer? (b) What changes the rise time in a dimmer?

13.16 If a forward phase-controlled dimmer switches on at 35°, at what phase angle should it turn back on and off again to avoid creating a DC offset?

13.17 What is the fundamental frequency, second harmonic frequency, and third harmonic frequency of a 50-Hz square wave?

13.18 Why do triplen harmonics sum in the neutral conductor while the fundamental and second harmonics do not?

13.19 If the duty cycle of a sinewave dimmer is 25%, what is the dimming level? (Assume a linear dimming curve.)

CHAPTER 14
Portable Power Distribution

Modern power distribution systems have evolved over decades and listed devices are now relatively safe, reliable, and easy to use, provided they are used with caution according to the manufacturer's specifications by trained, qualified personnel who understand how to use them properly. Because the electrical distribution systems we use are capable of delivering massive amounts of current, we should also thoroughly understand the hazards involved and how to mitigate them, the components that are used to distribute power, and how to assemble them according to the best practices and safety requirements, as well as the local codes and regulations.

Electrical power distribution systems generally have the same or similar elements whether they are to be used in the theater, concert and touring applications, motion picture production, corporate events, or other events. (See Figure 14.1.) The power source is either the electrical power grid or a portable power generator. If power comes from the electrical grid, then it is sometimes referred to as "building power," and it is fed to the power distribution system through a feeder transformer. The feeder transformer is often connected to a portable power distribution unit (also known as a PPD, PD, or "distro") through a disconnect switch, which is usually called a "company switch" or, in motion picture production, a "bull switch." The switch allows electricians to safely tie in their portable power distribution using feeder cables by de-energizing the switch or turning off the power to the switch before making the connections. The power distribution unit is the dividing line between the feeder circuits and the branch circuits or final circuits.

FIGURE 14.1
Electrical power distribution from the supply to the loads, including a feeder transformer, disconnect switch, portable power distribution units, and cabling.

PORTABLE POWER DISTRIBUTION UNITS

Touring shows typically have at least one or more portable power distribution units (PPD, or simply PD) connected by large-gauge, single-conductor feeder cable to the building electrical supply or a portable power generator. (See Figures 14.2 and 14.3.) A PD subdivides the current into individual branch circuits or final circuits with overcurrent protection—typically circuit breakers—that supply power to each of the electrical devices in the system. Many of these PDs are 19” rack-mountable and are housed in flight cases with heavy-duty casters for ease of transportation. They are typically assembled at the factory from modular components according to the end-user's requirements. The end product is specified according to its total input and throughput rating in amps per phase as well as the connector types. For example, a 200A 3-phase distro is capable of distributing up to 200 amps for each of the three phases for a total of 600 amps. It will typically have enough output connectors that if every output was loaded 100%, it would trip the main circuit breaker because there are more output connectors than the main breaker can handle. This is because the manufacturer is relying on the user never turning on all of the loads at once or never loading the outputs more than 50%. This is not obvious, nor is it spelled out in the specs, but some quick calculations will confirm it. For example, a 200-amp, 3-phase distro with six Edison duplex receptacles and 12 L21-30 connectors can supply up to 600 amps, but it is capable of being connected to up to about 158kW, which would draw about 1,320 amps or about 440 amps per phase.

FIGURE 14.2
The PD on the right shows the digital LED phase, voltage, and load indicators (top module), main circuit breaker (second module from top), convenience outlets (third from top), two modules with Socapex multi-circuit outputs, and main inputs with cam-type locking connectors (bottom). The PD at the left shows 12 L14-30 twist-lock connectors for three-phase four-wire plus ground outputs. (Photo courtesy of Motion Labs, Inc., www.motionlabs.com.)

FIGURE 14.3
Top, left to right: Motion Labs Lighting PD, Indu Electric Tourpack Distro, Leprecon PD. Bottom, left to right: Lex Products Powerrack, PRG S-4000, CW Limited PD.

Portable PDs that are used to supply power on stage are required by code to be internally lined with noncorrosive metal, have a circuit breaker for the main input, and have overcurrent protection for each branch circuit or final circuit. Most have parallel output connectors or "passthroughs" to enable the connection of multiple PDs in a daisy-chain fashion. Some have double neutrals to better handle non-linear loads, which cause high current to flow in the neutral conductor, even in a balanced 3-phase system. A double neutral means that there are two neutral conductor connectors and an oversized neutral bus, thereby ensuring that the neutral conductor will never be overloaded. (The neutral current in a system with high harmonic content can get as high as about 173% of the phase current, but not higher.) Of course, using a PD with double neutrals is only effective at preventing overloading the neutral conductor if the switch has double neutrals and the feeder transformer has an oversized neutral bus.

On some PDs, the gender of the neutral and ground connectors are reversed relative to the other connectors. This is referred to as a "reverse ground neutral" (RGN) system, and it minimizes the possibility of creating a bolted short (direct connection) between a phase conductor and thereby creating an arc flash. Since about 8% of the male population is color blind, it is easy for some people to mistake the colors green and blue. It is also difficult to distinguish those two colors under certain types of lighting like sodium-vapor lights. Therefore, by changing the gender of the connectors, it makes it impossible to inadvertently make the wrong connection without using a turn-around (male-to-male or female-to-female gender changer).

FLEXIBLE CORDS AND CABLES

Flexible cords and cables, or more commonly "extension cords" or "stinger cables," are often used to extend the length of a power cable or to connect power from a distribution unit to an electrical device. There are different types of cables that can be used for this purpose, the primary distinction being the type of outer covering they have, which determines how rugged they are and how they can be used.

Cables are made for specific purposes, and they are classified by letter type according to their intended use. Type "S" cables are designed for "extra hard usage," meaning they are better able to withstand the abuse of being tossed around, stepped on, run over by golf carts, forklifts, and other vehicles. Type "SJ" cables, on the other hand, are designed for "hard usage," meaning that if they are abused in the same manner, the outer covering is likely to be damaged, leading

to a potentially hazardous condition. Therefore, they should be protected from damage by the support of a rigid structure like a pipe, truss, scaffold, and so on. Until the 2020 edition of the NEC, Article 520.68 said that type SJ cables can be used for power cords up to 1 meter in length, breakout assemblies not to exceed 20 feet in length, or for two-fers. Changes in the 2020 edition now allow the use of type SJ cable in lengths not to exceed 100 feet as long as it is supported by a rigid structure. They are still not supposed to be run along the ground where they can be stepped on or run over. Article 520 covers applications in theaters, audience areas of motion picture and television studios and similar locations, and Article 530, which covers motion picture and television studios and similar locations, also says that type SJ cables should be protected from damage.

In the United Kingdom, "ordinary duty" flexible cable (H05RN-F cable with a voltage rating of at least 300/500 V) is allowed to be used indoors while "heavy duty" flexible cable (H07RN-F with a voltage rating of at least 450/750 V) must be used for outdoor applications. Heavy duty cable is more durable, and it is resistant to abrasion and water.

Cables are marked on the jacket with the wire gauge, and usually with the cable type, the rated voltage, the temperature rating (or the temperature at which the outer covering begins to deteriorate), and the manufacturer name or trademark. (See Figure 14.4.)

FIGURE 14.4
Cables are marked with the wire gauge, cable type, rated voltage, the temperature rating, and the manufacturer name or trademark.

BRANCH CIRCUITS OR FINAL CIRCUITS

Multi-core or multi-conductor cable is often used to run branch circuits or final circuits from a PD or dimmer rack to the connected devices, and 19-pin circular (See Figure 14.5.) or the less common rectangular connectors (See Figure 14.6.) are often used to terminate the cable at the PD. Socapex is one brand of 19-pin circular connector, and it originally came from a French aerospace company called Amphenol. The connectors are available in solder- or crimp-type contacts for in-line (cable mount) or panel mount use. They are often used with 14-conductor or 18-conductor cable; in the 14-conductor cable, the grounding conductor is common to all the circuits, and in the 18-conductor cable each circuit has its own grounding conductor. In either case there are six individual circuits (six hot or live conductors, six neutral conductors, plus grounding conductors, or in the case of 208V circuits, 12 hot or live conductors plus grounding conductors), and each circuit is protected from overcurrent by a circuit breaker.

FIGURE 14.5
Male 19-pin circular connector. (Photo courtesy of Creative Stage Lighting.)

FIGURE 14.6
The Harting rectangular multi-pin connector has mostly been replaced by the 19-pin circular connector for distributing multiple branch circuits in a single cable.

In 1997, the United States Institute for Theatre Technology (USITT) published a recommended practice called *RP-1: Contact Function Assignments for Multi-circuit Circular Pin Connectors Used for the Distribution of Multiple Lighting Circuits*. Its purpose was to standardize the pin assignments for 19-pin and 37-pin connectors in the entertainment industry. (Thirty-seven-pin connectors were used for 0–10V lighting control and 12-circuit multicables, but they are less common today because of the prevalence of digital control.)

The pin connections are organized in two rings: an inner ring and an outer ring (plus the center pin, which is unused and therefore not connected). The pins in the outer ring are used for the hot (ungrounded) conductors and the

grounded (neutral) conductors. They are arranged in adjacent pairs (hot, neutral) and are numbered clockwise in the female connector and counterclockwise in the male connector from the user's point of view. The pins in the inner ring are used for the equipment grounding conductor, and they are paired with the closes hot/neutral pins (see pinout diagram in Figure 14.7). The center pin is not connected. The odd-numbers pins from 1 to 11 are the ungrounded or phase conductors, and the even-numbered pins 2 through 12 are the grounded or neutral conductors.

FIGURE 14.7
19-pin Socapex pinout as shown looking at the pins and sockets.

All of the conductors (pins 13 through 18) should be connected to each other, and they should make first and break last. This is usually accomplished by the design of the connectors, which extends the length of the female pins in the inner ring so that they make first contact when the connectors are mated and last contact when they are broken apart. At least one of the equipment grounding conductors should be at least the same gauge as the largest ungrounded conductor. It is permissible to use only two equipment grounding conductors but using all six is also permitted. (See Table 14.1.)

Table 14.1 19-pin circular connector six-circuit pinout

Contact no.	Function	Contact no.	Pinout
1	Circuit #1 ungrounded conductor	11	Circuit #6 ungrounded conductor
2	Circuit #1 grounded conductor	12	Circuit #6 grounded conductor
3	Circuit #2 ungrounded conductor	13	Circuit #1 grounding conductor
4	Circuit #2 grounded conductor	14	Circuit #2 grounding conductor
5	Circuit #3 ungrounded conductor	15	Circuit #3 grounding conductor
6	Circuit #3 grounded conductor	16	Circuit #4 grounding conductor
7	Circuit #4 ungrounded conductor	17	Circuit #5 grounding conductor
8	Circuit #4 grounded conductor	18	Circuit #6 grounding conductor
9	Circuit #5 ungrounded conductor	19	Not connected
10	Circuit #5 grounded conductor		

Source: TMB (www.tmb.com/tech-data/6-circuit-connector-pin-out/)

Multiconductor cable used for power distribution should be listed for extra hard usage, and they are available in a variety of wire gauges, although the most commonly used in live event production include #12 (4mm), #14 (2.5mm), or #16 AWG (1.5mm).

BREAKOUTS OR SPIDERS

Once a multiconductor cable delivers power to the vicinity of the loads, it has to be separated into individual circuits and fed to each load. This is typically done with a breakout or spider assembly (See Figure 14.8.), which is an adapter

with a male multi-pin connector on one end and several individual cables terminated with female connectors on the other end.

FIGURE 14.8
A 19-pin connector-to-True1 six-circuit breakout or spider.

Each of the connectors should be a listed two-pole three-wire device and the cable should be a listed junior hard service cord. (A "pole" in this context means a current-carrying terminal. The third pin is the grounding pin, which, under normal circumstances should not carry any current.) There are a variety of two-pole three-wire connectors used in the industry around the world, such as Edison connectors (NEMA 5-15 and 5-20), stage pin, twist-lock, IEC, CEEform, Schuko, and more. The longest conductor in the breakout should be no more than six meters (20 feet). Also, since junior hard service cord is not designed to withstand abuse such as being stepped on or run over by a forklift or a heavy road case, it should not be run along the ground. Instead, it should be protected by a support structure like a truss or pipe. Lastly, each branch circuit should be protected by an overcurrent device rated appropriately for the gauge of wire but no more than 20 amps.

BRANCH CIRCUIT CONDUCTOR AMPACITIES

The ampacity of multiconductor cables is spelled out in the codes and regulations. In the United States, NEC Article 520 deals with *Theaters, Audience Areas of Motion Picture and Television Studios, Performance Areas and Similar Locations,* and Table 520.44(C)(3) defines the ampacity of listed extra-hard usage cords and cables with temperature ratings of 75°C (167°F) and 90°C (194°F) based on an ambient air temperature of 30°C (86°F) for up to three current-carrying conductors in contact with each other. It is reproduced in Table 14.2 below.

Table 14.2 Ampacity of Listed Extra-Hard-Usage Cords and Cables with Temperature Ratings of 75° C (167° F) and 90° C (194° F)* Based on an Ambient Temperature of 30° C (86° F)

AWG	Temperature Rating		Maximum Rating of Overcurrent Device
	75°C (167° F)	90°C (194° F)	
14	24	28	15
12	32	35	20
10	41	47	25
8	57	65	35

* *Ampacity shown is for multiconductor cords and cables where only three copper conductors are current carrying as described in 400.5. If the number of current-carrying conductors in a cord or cable exceeds three and the load diversity factor is a minimum of 50%, the ampacity of each conductor shall be reduced, as shown in Table 14.3.*

Source: National Fire Protection Association; NFPA 70: National Electrical Code, 2017 Edition; Quincy, Massachusetts: 2016.

AWG	Temperature Rating		Maximum Rating of Overcurrent Device
	75°C (167° F)	90°C (194° F)	
6	77	87	45
4	101	114	60
2	133	152	80

* *Ampacity shown is for multiconductor cords and cables where only three copper conductors are current carrying as described in 400.5. If the number of current-carrying conductors in a cord or cable exceeds three and the load diversity factor is a minimum of 50%, the ampacity of each conductor shall be reduced, as shown in Table 14.3.*

Source: National Fire Protection Association; NFPA 70: National Electrical Code, 2017 Edition; Quincy, Massachusetts: 2016.

Table 14.3 Ampacity de-rating chart for multiple conductors in a single cable [reproduced from Table 520.44(C)(3)(a)]

Number of Conductors	Percent of Ampacity
4–6	80
7–24	70
25–42	60
43+	50

Source: National Fire Protection Association; NFPA 70: National Electrical Code, 2017 Edition; Quincy, Massachusetts: 2016.

AMPACITY DE-RATING FACTORS

When current flows through a conductor, a by-product of the current and the resistance of the copper is heat. The material that makes up the jacket or insulation has a specific melting point, and if that temperature is reached, then it starts to change the molecular structure of the material, breaking it down, and changing its characteristics. That is one of the main factors that limits the ampacity of any conductor, and it is indicated by the temperature rating of the outer covering or insulation, which is the maximum temperature at any point along its length that it can withstand before it starts to deteriorate. The temperature rating is marked on the jacket of cables and listed in the specifications.

There are factors other than the wire gauge that influence the ampacity of cables, including the number of current-carrying conductors in contact with each other, the ambient air temperature, harmonic content, and the presence of surrounding material that limits heat dissipation. These factors can influence the operating temperature and reduce or de-rate the ampacity of conductors beyond the standard limits.

Because the heat generated by the current flowing through one conductor raises the temperature of adjacent conductors, there are de-rating factors for cables with multiple current-carrying conductors. For example, Table 14.2 [reproduced from] says that the ampacities shown are for multiconductor cables with no more than three current-carrying conductors in contact with each other. The 19-conductor cable we use for live event production actually has 12 current-carrying conductors in contact with each other, so the next part of the table (shown in Table 14.3) shows the de-rating factors according to the number of current-carrying conductors in a single cable.

In the case of 19-conductor cables, the 30% de-rating factor puts the ampacity of #12 AWG (4mm) conductors at 22.4 amps for 60°C cable and 24.5 amps for 90°C cable, which is more than is allowed for applications outside of Article 520.

There are also de-rating guidelines for ambient air temperature, harmonic content, and conductors that are run in conduit, raceways, or cable ramps.

CABLE VOLTAGE RATINGS

In addition to ampacity rating, cables also have a voltage rating. The voltage rating is the maximum voltage the outer covering or insulation can withstand before it exceeds the dielectric strength or insulating value. If the applied voltage exceeds the rated voltage, the insulation can develop pinholes and leak current.

WEATHER PROTECTION

If an enclosure, like a junction box or fixture housing, is to be permanently installed outdoors, it is typically required by local codes and regulations to be identified for outdoor use, usually by carrying a compliance marking like an IP (ingress protection) rating or a NEMA enclosure rating. This is especially important for electrical apparatus since moisture or water can cause problems ranging from the slow deterioration of connections and insulation to rapid short-circuiting, not to mention creating a shock hazard. The IP rating system is an international standard that rates an enclosure based on how well it protects against the ingress of foreign objects, like particles or parts of the body, and moisture or water. In North America, the National Electrical Manufacturers Association (NEMA) has a similar rating system for rating enclosures, called the NEMA rating. Both systems classify enclosures according to how well they protect against the elements and harsh environments.

IP RATINGS

The International Protection Code, or IP Code, is a two-digit rating with optional suffixes for additional information about the enclosure. The code is always preceded by the letters "IP," which stands for international protection or ingress protection, and is followed by a two-digit number. The first number can range from 0 to 6, and it indicates how well it protects against the ingress of solid objects such as dust, dirt, bird feathers, fingers, and hands. The second number can range from 0 to 8, and it indicates how well it protects against the ingress of water or moisture. (See Figure 14.9.) The minimum IP rating for an enclosure to be permanently installed outdoors is 65, which means it is dust tight and protects against jetting water. An IP rating of 68 means that an enclosure can be immersed in water up to a depth of 1.5 meters for up to half an hour. A rating of IP2X (where X can be any number from 0 to 8) means it protects against someone touching the inside of the enclosure. More information about IP ratings can be found in IEC 60529 and in Appendix 7.

FIGURE 14.9
IP ratings are a two-digit code and an optional suffix describing the degree of protection of an enclosure from the elements or a harsh environment. The first digit describes the degree of protection against solid objects, and the second describes the degree of protection against the ingress of water.

NEMA ENCLOSURE RATINGS

Like IP ratings, NEMA enclosure ratings describe the application of enclosure types and the degree of protection against the environment. NEMA ratings range from type 1 to type 13, and although they don't correspond to IP ratings, there are similarities. NEMA 4, 6, or 6P, for example, provides protection to the level of IP-65, but there is no NEMA enclosure equivalent to IP-68. The complete list of NEMA enclosure ratings can be found in Appendix 7 in the back of this book or in NEMA Standards Publication 250-2008, “Enclosures for Electrical Equipment (1000 Volts Maximum).”

Although power distribution and electrical apparatus that is installed outdoors requires an outdoor rating, there is an exception in the United States that is spelled out in the National Electrical Code Article 520.10, which covers theaters, audience areas of motion picture and television studios, performance areas, and similar locations. It says, “Portable stage and studio lighting equipment and portable power distribution equipment not identified for outdoor use shall be permitted for temporary use outdoors, provided the equipment is supervised by qualified personnel while energized and barriered from the general public.” Article 100 defines a qualified person as, “One who has skills and knowledge related to the construction and operation of the electrical equipment and installations and has received safety training to recognize and avoid the hazards involved.” It also references *NFPA 70E: Standard for Electrical Safety in the Workplace*, in which it says that a qualified person is someone who has been trained to recognize the hazards of the job and can demonstrate the ability to use certain personal protective equipment. In this application it doesn't spell out how long “temporary” can be, so it is entirely up to the authority having jurisdiction.

DEVICE CONNECTORS

PDs can be assembled using many different types of output connectors, and the type that is ultimately used depends on the situation and the country in which it is to be used. Connector types vary from country to country, and sometimes they even vary within the same country. For example, in the United States you may find production companies using Edison, stage pin, twist-lock, PowerCon, or True1 connectors.

A connector has both a voltage rating and an ampacity rating. The voltage rating ensures that a connector will be able to withstand the applied voltage without arcing between conductive parts, and the ampacity rating indicates the maximum current it can conduct without degrading the insulation due to the heat generated by the current.

Around the turn of the twentieth century, Harvey Hubbell II was walking along a sidewalk in New York City as the shops were closing. He encountered a penny arcade wherein the janitor was sweeping up after closing time. Looking through the window, he noticed how the janitor had to disconnect the power cable from a game that was hard-wired to the power supply in the wall in order to move it and sweep under it. At the time, there were no connectors, and switches were expensive, so the bare ends of the conductors were wrapped around terminal posts protruding from the wall. Each time the janitor tried to unwrap the wires, he would get a shock. The incident gave Hubbell the idea to build a connector that would mate with a receptacle in the wall. On January 2, 1912, Hubbell applied for a patent for a separable attachment plug. (See Figure 14.10.) The two-pole two-wire connector was patented in 1913. It is essentially (and ironically) the same Edison-type connector, without the grounding wire, that is now commonly used in North America for household applications and some commercial and theatrical applications.

FIGURE 14.10
Harvey Hubbell's patent for a separable attachment plug, granted in 1913.

STAGE PIN CONNECTORS

The stage pin connector is one of the most commonly used electrical connector in North American theaters. (See Figure 14.11.) They are available with voltage ratings from 125V to 250V and amp ratings from 20A to 100A.

FIGURE 14.11
Stage pin connectors are often used to power devices in the theater.

One of the main advantages of the stage pin connector is that it has a low profile, it can lie flat, it is less obtrusive, and presents less of a trip hazard. The pins of the male connectors have slots that can be spread a bit to increase the pressure when it is fitted into to the female socket, which makes a better electrical connection. A pin spreader is used to restore the proper spacing when they are compressed. If the pins are not sufficiently spread, then it makes poor contact with the female socket, which raises the resistance, and that can create arcing, heating, and pitting of the pins and sockets. That, in turn, causes higher resistance, leading to a deteriorating situation until the connector overheats and the plastic melts. The pins and sockets should be periodically inspected, and if they show signs of burning or arcing, they can be cleaned with sandpaper or other abrasive material to remove the carbon buildup.

In 2012, the Technical Standards Program of PLASA (www.plasa.org) published *ANSI E1.24-2012: Entertainment Technology Dimensional Requirements for Stage Pin Connectors* (revised in 2017) to standardize the pin spacing used in these connectors so that connectors made by different manufacturers will be compatible. The illustration in Figure 14.12 is from E1.24-2012 (R2017) Annex A - Pin Connector Chart (Normative).

FIGURE 14.12
Pin configurations for stage pin connectors. Reproduced with permission from ANSI E1.24-2012(R2017).

NEMA CONNECTORS

In North America, electrical connectors rated up to 60 amps and 600 volts are manufactured to comply with ANSI/NEMA WD 6-2016. Of the many different NEMA classifications, only a few are commonly used in our industry. Among them are the NEMA 5-15 (also known as an Edison plug), 5-20, L5-15, L5-20, and L6-20. In certain applications, other types are commonly used as well.

The first number in the NEMA classification is a code that indicates the voltage rating and wiring configuration, and the second number indicates the current rating in amps. The letter P appended to the classification means that it is a plug, and the letter R indicates that it is a receptacle. For example, a NEMA 5-XP is a 125V, two-pole three-wire plug (the third wire is the equipment grounding wire). A NEMA 5-15P, commonly referred to as an Edison plug, is a two-pole three-wire plug rated for 125 volts and 15 amps. (See Figure 14.13.)

FIGURE 14.13
NEMA 5-15P 125V 15A two-pole three-wire connector, also known as an Edison connector.

NEMA 6-X is rated for 250V maximum and it is a two-pole three-wire device. The more common NEMA connectors in theatre and live event production are the L5-15, L5-20, L6-16, and L6-20. The prefix L means that it is a locking connector, commonly known as a twist-lock connector. These connectors have curved blades and lock by inserting the blades into the receptacle and twisting. (See Figure 14.14.)

FIGURE 14.14
NEMA L6-20 250V 20A twist-lock connector.

There are over a hundred more NEMA configurations, and the ones shown in Figure 14.15 are some of the more common ones encountered in theatre and live event production. The letter W indicates the location of the pole used for the grounded neutral conductor, which is whiter in color than the other poles. The letter G indicates the equipment ground/earth.

FIGURE 14.15
Common NEMA wiring device configurations in theatre and live event production.

UL Listed or Recognized?

Underwriters Laboratory is one of several nationally recognized testing laboratories (NRTLs) as listed by the Occupational Safety and Health Administration of the U.S. Department of Labor. Manufacturers can send a complete product to an NRTL such as UL and pay to have it tested and evaluated against recognized safety standards. If the product is found to be reasonably free of the risk of fire, electric shock, and related hazards, and it is manufactured under UL's Follow-Up Services program, then it is UL Listed. Such products always bear the UL Listing Mark, the manufacturer's name or trademark. (See Figure 14.16.)

FIGURE 14.16
The UL Mark on a product is the manufacturer's representation that the complete product has been tested and evaluated by UL to recognized safety standards and that it is reasonably free of the risk of fire, electric shock, and related hazards.

The UL Listing Mark has “UL” inscribed in a circle with the word “LISTED” in capital letters underneath it. If it is listed in the United States then it will have the letters “US” at the four o'clock position, and if it is listed in Canada it will have the letter “C” at the eight o'clock position.

A UL Recognized product, on the other hand, is for components rather than finished products. The mark is an indication that the component has been tested and evaluated to meet the criteria for limited, specific use. Such a component is intended to be

used in completed products that should be submitted for testing and evaluation as a complete product to receive a UL listing. UL listings can be found on the UL Website at www.ul.com.

POWERCON AND TRUE1 CONNECTORS

PowerCon and PowerCon True1 are the trade names of power connectors made by Neutrik. They are both a locking three-wire connector that are popular for power cable terminations. (See Figure 14.17.) The difference between them is that the True1 connector makes the ground/earth first and breaks last, which means that it can be connected or disconnected live or under load. The connectors have no exposed conductive parts, and a keyed input and output prevents the possibility of connecting the wrong cables. The input and outputs are also color coded for easy identification. The connectors use UL- and cUL-recognized components, meaning that they have been tested and evaluated for limited, specific use. PowerCon connectors are also VDE (German testing laboratory) certified.

Figure 14.17
Left to Right: Neutrik PowerCon 32A three-wire plug, receptacle, and PowerCon True1 20A plug.

15-AMP PLUGS

In the United Kingdom, the 15-amp Duraplug is commonly used in the theatre for dimmed loads. (See Figure 14.18.) It conforms to BS546, which is an obsolete standard, although its use is still permitted under the wiring regulations. The connector became popular because it was the only appliance connector without a built-in fuse, which is unnecessary in the theatre because of the overcurrent protection in dimmers. The lack of a fuse also makes it easier to troubleshoot. The 15A plug is a 250V two-pole three-wire connector.

FIGURE 14.18
The 15-amp Duraplug is commonly used in the theatre in the United Kingdom, even though it is manufactured to the obsolete BS546 standard.

CEE-FORM (PIN & SLEEVE) CONNECTORS

The CEE 17 connector is commonly used in the United Kingdom. and other parts of Europe for hard power or non-dimmed power in theater and live event production. Hire companies use them in a variety of applications, including automated lighting. In North America, the same connectors are known as pin-and-sleeve, or more commonly, "Hubbell" connectors, even though Hubbell is a brand with a wide variety of products, including pin-and-sleeve connectors. They are very popular in hotel ballrooms and convention centers.

CEE-form connectors in general comply with IEC 60309 European Approved Wiring Devices, which defines heavy-duty pin-and-sleeve plugs and receptacles. (See Figure 14.19.) They are explosion-proof, chemical resistant, and rated IP 44 (also available in IP 67). They are color coded according to their voltage rating: yellow for 100/130V, blue for 200/250V, and red for 380/415V, although there are now 16-amp, 230V CEE plugs available in black.

FIGURE 14.19
The CEE 17 16-amp connector is very popular in Europe and the United Kingdom for hard power or non-dimmed power.

CEE 17 devices are available in a variety of ratings, including 16-amp, 32-amp, and 63-amp. The 16-amp device is probably the most popular in live event production.

IEC CONNECTORS

IEC 60320 is a standard that includes a range of plugs and receptacles, including the C13 receptacle and the C14 plug, colloquially known simply as IEC connectors. (See Figure 14.20.) In North America, they are commonly used for desktop computers, lighting consoles, and other appliances. In Europe, they are sometimes used for hard power or non-dimmed loads, including luminaires.

FIGURE 14.20
IEC C13 receptacles and C14 plugs are commonly referred to simply as IEC connectors. They are used in North America to power lighting consoles, desktop computers, and appliances. In Europe they are used for a variety of applications, including powering some luminaires.

SCHUKO CONNECTORS

The CEE 7/4 or Type F connector, commonly known as the Schuko connector, is a two-pole three-wire connector with round pins and earthing clips on the side of the connector. Schuko is short for *schukokontakt,* meaning "protective contact" in German. The name stems from the fact that a pair of earthing clips in the plug make contact with the protective earth in the recessed socket before the live and neutral pins are engaged.

In other parts of Europe, including France, Belgium, and the Czech Republic, the CEE 7/5 connector is used, which is similar to the CEE 7/4 connector except it has a male protective-earth pin on the socket. (See Figure 14.21.) The CEE

7/7 connector can accommodate both CEE 7/4 and 7/5 sockets, and therefore is commonly used throughout Europe.

FIGURE 14.21
A CEE 7/7 connector showing the two round pins and protective earth clip with a hole to mate with the male protective-earth pin in the CEE 7/5 recessed socket.

Hybrid CEE 7/7 connectors are commonly used on luminaires and dimmers in many parts of Europe. They are rated for 250 volts and up to 16 amps.

AUSTRALIAN CONNECTORS

The connectors that are used in Australia and New Zealand conform to AS/NZS 3112 and are used for most every powered device in live event production. They are round connectors with three flat pins, two of which are angled at 30° towards the center line. (See Figure 14.22.) The earthing pin is at the bottom of the connector and it is not angled. The most common of these connectors is rated for a maximum of 10 amps at 250V.

FIGURE 14.22
These Australian connectors are used for a variety of devices used in live event production.

Some Australian male connectors have a female socket built into the back of the connector, giving them the ability to piggyback several connectors on one socket. Care should be used not to overload the circuit if multiple connectors are used in this manner.

There are many more types of connectors in use throughout the world, but the connectors discussed here are a sample of some of the more common ones used in North America, Europe, and Australia.

TWO-FERS

A twofer is an adapter that allows you to connect two loads in parallel to the same circuit. They are used to save cabling by providing a means of quickly connecting two devices into the same power cable. If the circuit is on a dimmer, then both lights will dim to the same level. If it is a non-dim circuit, then the loads can operate independently of each other. When fixtures are paralleled on the same circuit, the main concern is that the circuit is not overloaded, so the current draw for each fixture should be known and used to calculate the total current draw.

FEEDER CABLE

Feeder cables are the conductors that connect from the supply to the distribution unit(s), whether they are circuit breaker panels, portable power distribution units, or dimmer racks. Feeder cables are typically single-core conductors, although they can be multi-core conductors up to 125 amps. Either way, it is important that they are the correct gauge or cross-sectional area in order to sufficiently handle the current. It is also important that they have the right type of insulation for the application.

In permanent installations, power distribution systems are typically designed by a licensed electrical engineer and installed by licensed electricians. In portable applications, the system is typically designed by (hopefully very qualified and experienced) shop personnel and assembled on site by stagehands or touring personnel. In the United States, the NEC gives guidelines for the proper construction and operation of feeder cable in *Article 520: Theatres, Audience Areas of Motion Picture and Television Studios, Performance Areas, and Similar Locations*. In the United Kingdom, the applicable standard is *BS 7671: Requirements for Electrical Installations*, colloquially known as "the wiring regs."

In the United States, type SC feeder cable (type PPC is the equivalent cable in Canada) is commonly used for portable power distribution systems. (See Figure 14.23.) It is "extra-hard usage" (type "S") cable, which is flexible cable yet durable enough to withstand the abuse of touring. It is jacketed with a thermoset outer covering, which is a type of polymer that cures or hardens through the addition of heat to form a stronger, more durable compound. It can be used indoors or out, and it is available in sizes ranging from 6 AWG to 250 kmil or 250,000 circular mils (millionths of an inch) in temperature ratings of 60°C, 75°C, 90°C, or 105°C (140°F, 167°F, 194°F, or 221°F respectively). Type SC cable is rated 105°C, although the NEC only recognizes up to 90°C cable, probably because the maximum temperature rating of the lugs terminating the cable is 90°C.

FIGURE 14.23
Single-conductor feeder cable type PPC (type SC in the United States), rated 105°C, 600V.

In most situations, feeder cable should be sized according to the "maximum load that the switchboard is intended to control in a given installation," meaning that a dimmer rack, breaker panel, or portable power distribution unit need not be fed to its full nameplate capacity if it is not fully loaded. In that case, the feeders must be protected by an overcurrent device with an amp rating equal to or smaller than the ampacity of the cable. But in motion picture production, television studios, and similar locations, as long as it is supervised by qualified personnel while it is energized, the overcurrent device protecting feeder cable can be up to 400% of the ampacity of the cable. For example, #2AWG feeder can be used with a 400A switch since it has an ampacity of at least 100 amps.

In the United States, NEC Table 400.5(A)(2) is used to find the ampacity of feeder cable based on the wire gauge and the temperature rating of the outer covering based on an ambient air temperature of no more than 30°C (86°F). (See Figure 14.24.) If it is higher than that, then the cable should be de-rated according to Table 310.15(B)(2). If there are four or more current-carrying conductors in contact with each other, then they should be de-rated according to Table 400.5(A)(3).

Table 400.5(A)(2) Ampacity of Cable Types SC, SCE, SCT, PPE, G, G-GC, and W. [Based on Ambient Temperature of 30°C (86°F). See Table 400.4.]

Copper Conductor Size (AWG or kcmil)	Temperature Rating of Cable								
	60°C (140°F)			75°C (167°F)			90°C (194°F)		
	D[1]	E[2]	F[3]	D[1]	E[2]	F[3]	D[1]	E[2]	F[3]
12	—	31	26	—	37	31	—	42	35
10	—	44	37	—	52	43	—	59	49
8	60	55	48	70	65	57	80	74	65
6	80	72	63	95	88	77	105	99	87
4	105	96	84	125	115	101	140	130	114
3	120	113	99	145	135	118	165	152	133
2	140	128	112	170	152	133	190	174	152
1	165	150	131	195	178	156	220	202	177
1/0	195	173	151	230	207	181	260	234	205
2/0	225	199	174	265	238	208	300	271	237
3/0	260	230	201	310	275	241	350	313	274
4/0	300	265	232	360	317	277	405	361	316
250	340	296	259	405	354	310	455	402	352
300	375	330	289	445	395	346	505	449	393
350	420	363	318	505	435	381	570	495	433
400	455	392	343	545	469	410	615	535	468
500	515	448	392	620	537	470	700	613	536
600	575	—	—	690	—	—	780	—	—
700	630	—	—	755	—	—	855	—	—
750	655	—	—	785	—	—	885	—	—
800	680	—	—	815	—	—	920	—	—
900	730	—	—	870	—	—	985	—	—
1000	780	—	—	935	—	—	1055	—	—

[1]The ampacities under subheading D shall be permitted for single-conductor Types SC, SCE, SCT, PPE, and W cable only where the individual conductors are not installed in raceways and are not in physical contact with each other except in lengths not to exceed 600 mm (24 in.) where passing through the wall of an enclosure.

[2]The ampacities under subheading E apply to two-conductor cables and other multiconductor cables connected to utilization equipment so that only two conductors are current-carrying.

[3]The ampacities under subheading F apply to three-conductor cables and other multiconductor cables connected to utilization equipment so that only three conductors are current-carrying.

Table 400.5(A)(3) Adjustment Factors for More Than Three Current-Carrying Conductors in a Flexible Cord or Flexible Cable

Number of Conductors	Percent of Value in Table 400.5(A)(1) and Table 400.5(A)(2)
4–6	80
7–9	70
10–20	50
21–30	45
31–40	40
41 and above	35

FIGURE 14.24
NEC Table 400.5(A)(2) shows the ampacity of cables including type SC, based on the wire gauge and temperature rating of the outer covering with an ambient air temperature of no more than 30°C (86°F. Table 400.5(A)(3)

The conductors should be run together but not taped or otherwise bundled because of mutual heating. In practice, #2AWG feeder cable sets are typically taped together every foot or so, and that is referred to as "banded" feeder cable. This is typically done for the convenience of having a full set of feeder cable in a single package. It is never done with 2/0 AWG or 4/0 AWG because it would be too heavy. From a technical standpoint, the points at which banded cables are taped together created hot spots that contribute to the deterioration of the jacket.

Feeder cable should be marked with the appropriate color within six inches of the end of the cable (see the section titled "Wiring Color Codes" in Chapter 5). In some cases, the connectors are color coded and other times colored tape is used. (See Figure 14.25.)

FIGURE 14.25
Feeder cable should be color coded within six inches of the end of the cable.

Multiple feeder cables can be linked together for longer runs, but no more than three connector pairs can be used in the first 100 feet (30 meters). After that, one connector pair can be used for each additional 100 feet (30 meters). Feeder cable conductors can be paralleled provided that they are exactly the same length and wire gauge. In the United States, if the rating of the main circuit breaker in a power distribution system is over 200 amps, then the grounding conductor should be sized according to table 250.122 in the NEC.

In Europe, cable is sized by calculations based on the current drawn by the load, and there are several correction factors given in the wiring regs. (See Figure 14.26.) The correction factors include the voltage drop due to the cable run, the ambient temperature, the number of conductors grouped together, and the temperature rating of the insulation. Multiconductor feeder cable is used unless the ampacity is 120 amps or higher, in which case single-conductor cable is used. H07RN-F cable is commonly used for power distribution because it is weather and oil resistant, and it is suitable for portable applications. It has ethylene propylene rubber insulation and a neoprene jacket, and it is rated 450/750 V. The base ampacity (before derating factors are applied) is given below.

Current carrying capacity for 60°C rubber and 90°C rubber insulated flexible cables to BS 7919

Conductor	Current carrying capacity and associated voltage drop							
C.S.A.	60°C rubber insulated				90°C rubber insulated#			
	1 two-core cable* or 2 single core cables touching†		1 three-core, four-core or five-core cable		1 two-core cable* or 2 single core cables touching†		1 three-core, four-core or five-core cable	
	d.c. or single phase a.c.		three phase a.c.		d.c. or single phase a.c.		three phase a.c.	
mm²	A	mV/A/m	A	mV/A/m	A	mV/A/m	A	mV/A/m
4	30	12	26	10	42	13.2	37	11
6	39	7.8	34	6.7	55	8.5	49	7.3
10	51	4.6	47	4.0	76	5.1	66	4.3
16	73	2.9	63	2.5	103	3.2	89	2.7
25	97	1.8d 1.85a	83	1.55	136	2.03d 2.04a	119	1.73
35	140	1.31d 1.32a	102	1.15	200	1.42d 1.46a	146	1.23
50	175	0.91d 0.93a	124	0.84	250	1.00d 1.02a	177	0.93
70	216	0.64d 0.67a	158	0.58	310	0.71d 0.73a	225	0.64
95	258	0.49d 0.53a	192	0.44	369	0.54a 0.57d	273	0.49
120	302	0.38d 0.43a	222	0.36	432	0.42d 0.46a	316	0.39
150	347	0.31d 0.36a	255	0.30	497	0.34d 0.39a	363	0.32
185	394	0.25d 0.32a	291	0.26	564	0.27d 0.33a	414	0.27
240	471	0.19d 0.27a	343	0.21	673	0.21d 0.28a	487	0.23
300	541	0.15d 0.24a	394	0.185	773	0.167d 0.25a	560	0.195
400	644	0.115d 0.21a	-	-	885	0.127d 0.22a	-	-
500	738	0.090d 0.20a	-	-	1017	0.100d 0.20a	-	-
630	861	0.068d 0.185a	-	-	1190	0.074d 0.190a	-	-

Notes:

1 The tabulated current ratings are for cables in free air but may also be used for cables resting on a surface.

2 These ratings are not applicable to cables wound on reeling drums or covered over or coiled up. Refer to Table 4F2A Notes 2 & 3 of BS 7671.

3 Where the conductor is to be protected by a semi-enclosed fuse to BS 3036, see item 5.1 of the preface to Appendix 4 of BS 7671.

* Two-core only up to and including 25mm². Single-core ratings for 25mm² and above.

† Larger voltage drop will result if the cables are spaced.

\# Where a conductor operates at a temperature exceeding 70°C it shall be ascertained that the equipment connected to the conductor is suitable for the conductor operating temperature. (See BS 7671 Regulations 512.1.2)

Correction Factors

For Alternative Ambient Temperatures

60°C rubber insulated cables

Ambient Temperature	25°C	30°C	35°C	40°C	45°C	50°C	55°C
Correction Factor	1.04	1.0	0.91	0.82	0.71	0.58	0.41

90°C rubber insulated cables

Ambient Temperature	35°C	40°C	45°C	50°C	55°C	60°C	65°C	70°C	75°C	80°C	85°C
Correction Factor	0.95	0.91	0.86	0.82	0.76	0.70	0.64	0.57	0.50	0.40	0.28

FIGURE 14.26
H07RN-F cable specs, courtesy of AEI Cables.

Regardless of where you are located, conductors should never be connected to a live source; power should be off before making the connection. If there is no means of disconnecting power before terminating cables, extreme caution should be used, and the procedures for working live should be closely followed. (See Chapter 10, *Working Live*.)

Single-conductor feeder cable should always be connected and disconnected in the proper sequence; to make a connection, make sure that the power is turned off, and then connect the grounding conductor first, grounded (neutral) conductor second, and ungrounded or phase conductors last. To break a connection, make sure that the power is turned off, and the break the connections in the reverse order as making a connection; break the ungrounded or phase conductors first, the grounded (neutral) conductor next, and the grounding conductor last.

Because feeder cables typically carry a lot of current, there is a strong magnetic field in the proximity of the conductors. Care should be taken not to coil excess single-conductor feeder cable while it is conducting current because the coils reinforce the magnetic field and create a strong source of electro-magnetic interference that can induce noise into audio and video systems. Instead, excess cable can be wrapped in a figure-eight pattern so that the magnetic flux from one half of the figure-eight will cancel that of the other. The loops of the figure-eight should be relatively large with the fewest number of coils as is practical in order to prevent concentrating the heat from the flow of current. (See Chapter 4, Electromagnetism.)

SINGLE-POLE CONNECTORS

The connectors used with single-conductor feeder cable or tails are typically locking cam-type or keyed single-pole connectors. (See Figure 14.27.) They should be listed by a recognized testing laboratory such as Underwriters Laboratory (UL) or ETL in the United States, or Canadian Underwriters Laboratory (CUL) in Canada. In Europe, they should bear a CE (European Conformity) mark, which means that they are certified by the manufacturer to conform to the applicable standards.

FIGURE 14.27
Keyed single-pole locking cam-type connectors are used to connect single-conductor feeder cable. They should be listed with a recognized testing laboratory such as UL or ETL in the United States or CUL in Canada.

These connectors are manufactured under a variety of names by different manufacturers. Cam-Lok is the trade name of the single-pole cam-type locking connectors manufactured by Crouse-Hinds. Cam-type locking connectors are the de facto industry standard in North America for portable single-pole connectors. In Europe, keyed single-pole connectors (KSPC) like PowerLock connectors made by Veam (formerly Litton-Veam) and Power Link connectors made by LK Connectors are preferred, but Cam-Lok and equivalents are also used, typically by touring shows from outside of Europe. PowerLock and Power Link connectors have an IP protection rating of 2X, meaning that they provide finger protection against personnel coming into contact with a live component of the connector and receiving an electric shock. This is achieved by a plastic cap over the contacts that closes when the connector is not mated. Cam-Loks have no such protection, although most power distribution systems using Cam-Loks have a spring-loaded safety cover on the female connectors to prevent the accidental contact with a live conductor. (See Figure 14.28 and 14.30.)

FIGURE 14.28
Cam-type receptacle with safety cover to prevent accidental contact with a live conductor.

FIGURE 14.29
PowerLock connectors made by Veam and Power Link connectors made by LK Connectors have a rating of IP 2X against electric shock and a mated condition IP rating of 67.

FIGURE 14.30
Panel-mount Cam-Lok connectors. Note the spring-loaded safety covers on the output connectors (top).

When they are mated, PowerLock and Power Link connectors are rated IP 67, meaning that they are dust-tight and protect against the ingress of water when immersed up to one meter for up to 30 minutes. Cam-lock connectors are rated NEMA 3R, which means they are constructed for either indoor or outdoor use and provide a degree of protection to personnel against incidental contact with the live components and against falling dirt, rain, sleet, and snow, and they are not damaged by the external formation of ice. (See Figures 14.29.) Nevertheless, it is common practice to wrap cam-lock connectors that are exposed to the elements with plastic wrap or polyethelene plastic wrapping and elevate them on an apple box or crate to keep them dry and prevent immersion in collected water.

NEUTRAL CONDUCTOR SIZING

The grounded or neutral conductor is the normal path for the return current. Depending on the application and the type of connected load, it is sometimes sized differently than the phase conductors in a 3-phase system. If there are any non-linear loads in a 3-phase system, and in today's systems there almost always are, then the neutral current can be higher than the current in any of the three phase conductors. And since the neutral conductor, by design, has no fuse or circuit breaker, care should be taken to prevent it from being overloaded. There are two ways to make sure that doesn't happen; the entire power distribution system can be de-rated up to 50% or double neutral conductors can be used provided the feeder transformer can handle high neutral current and the power distribution system has double neutrals. De-rating the power distribution system or doubling the neutrals ensures that it can handle higher neutral current, including both the fundamental frequency current and the harmonic frequency currents. Currents as high as about 170% of the phase current have been measured in balanced 3-phase systems with non-linear loads that have a total harmonic distortion of about 77%, as shown in Figure 14.31.

FIGURE 14.31
This bar graph of the harmonic spectrum of an electrical system was measured in a balanced 3-phase system. It caused about 170% of the phase current to flow in the neutral conductor.

The branch circuits or final circuits don't need an oversized neutral conductor because they are not 3-phase systems with a neutral.

UNDERSTANDING PORTABLE POWER DISTRIBUTION

14.1 Why do conductors have overcurrent protection?

14.2 How much current can a 400A 3-phase switch supply?

14.3 A 200A 3-phase distro has 24 20-amp, two-pole branch rated circuit breakers, three 30-amp, three-pole branch rated circuit breakers, and six 20-amp, single-pole branch rated circuit breakers. If all of the outputs are loaded 100%, how much current would the distro draw?

14.4 In the circuit below, what voltage would you read if you placed one lead of a voltmeter on point A and one on point B? What would the voltage read from point B to point C? C to D? D to A? (Figure 14.32)

Figure 14.32
Reading voltage across circuit elements.

14.5 How much voltage is dropped across a 100-foot 12/3 AWG (three-conductor #12AWG) multi-conductor cable if it has 16 amps flowing through it? (Assume K = 10.5)

14.6 Two different cables with the same wire gauge have temperature ratings of 60°C and 90°C respectively, which one has the highest ampacity?

14.7 Why are harmonics a de-rating factor for the ampacity of cables?

14.8 (a) How many current-carrying conductors are in contact with each other in a 19-conductor multicable with Socapex connectors? (b) What is the de-rating factor for this cable?

14.9 What is the meaning of the voltage rating of a cable or conductor?

14.10 What is the minimum IP rating for lighting fixtures to be permanently installed outdoors?

14.11 (a) What is the voltage and current rating of an L14-30 connector? (b) How many poles does it have?

14.12 (a) According to NEC Table 400.5(A)(2) (Figure 14.24), what is the ampacity of a single type SC 4/0 conductor in free air if the ambient air temperature is 30°C (86°F) or less? (b) What is the ampacity of 4/0 if there are four current-carrying conductors in contact with each other?

14.13 (a) What are the most common types of cable used for portable single-conductor feeder cable or tails in the United States? (b) In Canada? (c) In the United Kingdom?

14.14 If the voltage drop for 90°C rubber insulated 95mm^2 (H07RN-F) cable is 0.49 millivolts per amp per meter, what is the voltage drop if the cable is 50 meters in length and the current is 200 amps?

14.15 How are PowerLock single-pole connectors safer than Cam-Lok connectors?

14.16 (a) How many circuits are there in a multicore cable that is terminated with a 19-pin Socapex connector? (b) How many current-carrying conductors does it have? (c) What is the derating factor of that cable according to Table 14.3?

14.17 (a) What happens to the resistance of a connector if the terminals make poor contact with the receptacle? (b) How does that affect the heat that is generated?

14.18 What is the voltage and current rating of an L6-20 connector?

14.19 How many connector pairs can be used in the first 100 feet (30 meters) of single-conductor feeder cable in the United States?

14.20 What protection is provided by a NEMA 3R enclosure? (See Appendix 7: IP Ratings and NEMA Ratings.)

14.21 What degree of protection is provided by an enclosure rated IP 65? (See Appendix 7: IP Ratings and NEMA Ratings.)

CHAPTER 15
Show Prep, Setup, and Monitoring

Congratulations! We've been hired as the production electrician for the All Bets Off rock band, who are scheduled to tour medium-sized theaters across North America before continuing on to other parts of the world. Our job is to make sure the lighting and electrics work flawlessly. That means we have to supervise a crew who will go to the shop and pull the gear, test it, set the DMX addresses and/or IP addresses and subnet masks, label the gear and the road cases, build cable looms, and load it all into the semi-trailer before it is hauled to the first gig, where we will oversee the load-in, setup, and load-out for every show. And before any of this can happen, we have to generate the paperwork that will be the basis for the "shop order" or gear list.

The lighting designer or LD, Johnny Lumenz, has sent along a Vectorworks (VW) CAD plot in both a native VW format (.vwx) and a PDF file along with a Lightwright (LW) file of the paperwork. His "For Bid Only" equipment list includes eight Martin Quantum Wash fixtures, nine Clay Paky Axcor Wash 600 fixtures, and six Vari-Lite VL6000 Beam fixtures. There will also be two High End Systems FQ-100 fog machines, and four followspots are to be provided locally at each venue.

After studying the plot, we begin thinking about how we will go about designing a power distribution system. It should be designed make the most efficient use of time and labor by laying the cabling out logically and making it as quick and easy to set up and break down as possible. We start by editing a LW file, adding all of the relevant fixture and circuiting information. We will also assign unit numbers and circuits as well as label multicables (also known colloquially as "Socapex" or "soco") for easy identification while the system is being set up. This will all help us figure out how many portable power distribution racks or PDs will be needed, how many multicables are needed, how much total power is needed, which will tell us how much feeder cable will be needed. Once the power distribution is laid out and we have determined that the lighting plot will fit the power budget for the tour, then we can lay out the data distribution system.

EQUIPMENT SCHEDULE

An equipment list was developed by the lighting designer for bidding purposes, but it is missing some pertinent information, including the power requirements. After spending some time looking up the specs, a spreadsheet, like the one shown in Table 15.1 that summarizes the specs as listed by the manufacturer, can be completed to help with power calculations.

Table 15.1 Manufacturer's specifications for the list of equipment in the lighting plot

Qty	Instrument type	Power specifications
8	Martin Quantum Wash automated fixtures	120 V, 60 Hz, 7.4 A, 880 W, PF 0.999; 208 V, 60 Hz, 4.2 A, 860 W, PF 0.995
9	Clay Paky Axcor Wash 600 automated fixtures	800 VA @230Vac - 50Hz

Source: Compiled from the manufacturer's web sites: www.martin.com, www.claypaky.it, www.vari-lite.com, and www.highend.com.

Qty	Instrument type	Power specifications
6	Vari-Lite VL6000 Beam fixtures	10.1 A at 210V
2	High End Systems FQ-100 fog machines	1500 watts maximum, 120V

Source: Compiled from the manufacturer's web sites: www.martin.com, www.claypaky.it, www.vari-lite.com, and www.highend.com.

This list is indicative of how different manufacturers specify the power requirements for lighting equipment differently. Some provide the "true power" in watts (W) and power factor (PF), some provide the "apparent power" in volt-amps (VA), some provide the current in amps (A) at a specified voltage (V), some provide the wattage and not power factor, and some provide little information about the current draw at all. As production electricians, it is up to us to interpret all of the data (or lack thereof) in order to ensure the safety and success of the tour.

Ultimately, we want to know how much current each fixture draws so we'll know how to circuit them without overloading a circuit and tripping a circuit breaker. It will also help us figure out how to distribute the loads as equally as possible across the three phases in a 3-phase power distribution system.

Notice that some of the gear can operate at any voltage between 90V to 250V, while some can only run a specific voltage, like 120V or 208V. Given the choice, we'll want to use a higher voltage because it will then draw less current, which means we can use less copper and perhaps fewer PD units, and that translates to less time, labor, weight, fuel and transportation costs, which saves money.

With that in mind, you can calculate the current drawn by each fixture, starting with the Quantum Wash fixtures. In this case, you are calculating the branch current as opposed to the feeder current because you want to know the current drawn by an individual fixture, not a group of fixtures across three phases. So, you'll use the single-phase power formula.

$$P=V\times I\times PF$$

$$860W=208V\times I\times 0.995$$

$$I=860\div 208\times 0.995=4.2 \text{ amps}$$

Now we'll move on to the Axcor Wash 600 fixtures. These are specified in terms of the apparent power in volt-amps. This is a way of specifying the current draw at any voltage without having to consider the power factor because apparent power is the vectoral sum of the true power and the "reactive power." So, regardless of the power factor, the fixture will draw a certain number of amps at a given voltage, which is really all we are interested in. If you divide the apparent power by the applied voltage it will yield the current (volt-amps divided by volt equals amps). The power factor could be high, or it could be low; it is not known. But we do know the current draw.

Notice that it specifies the apparent power at 230V and 50Hz. Since you'll be touring in North America, we will have to use 208V at 60Hz. The apparent power in that case might be slightly different, but not enough to make a significant difference. Besides, there is no other information, and you have to start somewhere.

To calculate the branch current draw, simply divide the apparent power by the applied voltage.

$$I=\text{Apparent Power}\div V$$

$$I=800\div 208=3.8A$$

The *VL6000* Beam fixture specs spell out the branch current draw as 10.1 amps at 210 volts. Just as with the Axcor fixtures, the applied voltage will be slightly different, but not significantly different. So, the branch current draw will likely be very close to 10.1 amps.

That only leaves the two fog machines, which are specified at *1500* watts maximum at 120 volts, and that translates to 12.5 amps each. If the power distro is designed for 208V loads only, then we'll need to make sure we have some 120V circuits available for them. All of this information will be used to create a worksheet that to help assign circuits and more.

In the process of assigning circuits, the goals are to balance the loads as evenly as possible across the three phases and use the PDUs as efficiently as possible, allow for spare circuits in the rig just in case any of them malfunction, ensure that no multicable or branch circuits are overloaded, and to ensure that the supply and feeder circuits are not loaded to

more than 80% of their rated capacity (or to leave 20% for overhead). There is no single foolproof way to do this, and different electricians might use different techniques. Here is one approach.

To assign circuits, start with the Instrument Schedule from LW showing the hanging location or position, the unit number, fixture type, fixture mode, channel number, DMX starting address, and the current draw at the applied voltage. Then we'll go down the list and assign a circuit based on the current draw and the fixture location, which determines which multicable will be used because we want to avoid using jumpers to reach from one truss or location to another. The numbering scheme here is PDU/multicable/circuit where the PDU is a number, the multicable is assigned a letter, and each circuit is a number.

In this case, the PD is a 400A with six Socapex outputs (labeled A through F), each of which has six 208V 20-amp circuits (numbered 1-6). The phasing of the outputs is important because we want to balance the loads across the three phases as evenly as possible. Most PDUs are circuited so that circuits 1 and 4 are black-red, circuits 2 and 5 are red-blue, and circuits 3 and 6 are blue-black.

Starting with the Quantum Wash fixtures, we could assign three fixtures to a single 20A circuit and still leave 20% for overhead (80% of 20 amps is 16 amps, and 3 × 4.2A = 12.6A), but since this is a smaller rig and there will likely be enough circuits to assign only two per branch circuit, that might be a better route to go. That will also make the rig a bit more reliable since tripping a branch circuit breaker will only bring down two lights instead of three. Now go down the row and assign two fixtures per circuit (with the help of some twofers, unless the fixtures have PowerCon or True1 in and out connectors, in which case we can "daisy-chain" the power, or connect the output of one fixture to the input of the next, up to the limit of circuit), and continue in sequential order to maintain balance across the three phases. We may or may not need to make adjustments after the first pass, but we have to start somewhere. The results of the first pass are shown in Table 15.2.

Table 15.2

Position	Unit#	Instrument type	Address	Specs	Load	Circuit	Mode
DS truss	101	Quantum Wash	1/1	860W	4.2A @ 208V	1-A-1	extended
DS truss	102	Quantum Wash	1/34	860W	4.2A @ 208V	1-A-1	extended
DS truss	103	Quantum Wash	1/67	860W	4.2A @ 208V	1-A-2	extended
DS truss	104	Quantum Wash	1/100	860W	4.2A @ 208V	1-A-2	extended
US truss	105	Quantum Wash	1/133	860W	4.2A @ 208V	1-B-1	extended
US truss	106	Quantum Wash	1/166	860W	4.2A @ 208V	1-B-1	extended
US truss	107	Quantum Wash	1/199	860W	4.2A @ 208V	1-B-2	extended
US truss	108	Quantum Wash	1/232	860W	4.2A @ 208V	1-B-2	extended
US truss	201	Axcor Wash 600	2/1	800VA	3.8A @ 208V	1-B-3	basic
US truss	202	Axcor Wash 600	2/37	800VA	3.8A @ 208V	1-B-3	basic
US truss	203	Axcor Wash 600	2/73	800VA	3.8A @ 208V	1-B-4	basic
US truss	204	Axcor Wash 600	2/109	800VA	3.8A @ 208V	1-B-5	basic
US truss	205	Axcor Wash 600	2/145	800VA	3.8A @ 208V	1-B-6	basic
US riser	206	Axcor Wash 600	2/181	800VA	3.8A @ 208V	1-C-1	basic
US riser	207	Axcor Wash 600	2/217	800VA	3.8A @ 208V	1-C-2	basic
US riser	208	Axcor Wash 600	2/253	800VA	3.8A @ 208V	1-C-3	basic
US riser	209	Axcor Wash 600	2/289	800VA	3.8A @ 208V	1-C-3	basic
SR floor	301	VL6000	3/1	10.1 A at 210V	10.1A @ 208V	1-D-1	16-bit
SR floor	302	VL6000	3/24	10.1 A at 210V	10.1A @ 208V	1-D-2	16-bit
SR floor	303	VL6000	3/47	10.1 A at 210V	10.1A @ 208V	1-D-3	16-bit
SL floor	304	VL6000	3/70	10.1 A at 210V	10.1A @ 208V	1-D-4	16-bit
SL floor	305	VL6000	3/93	10.1 A at 210V	10.1A @ 208V	1-D-5	16-bit
SL floor	306	VL6000	3/116	10.1 A at 210V	10.1A @ 208V	1-D-6	16-bit

Notice that in going from the Quantum Wash fixtures on the DS truss to the same fixture type on the US truss, we had to use a different multicable to avoid using jumpers from one truss to another; otherwise, it will create a cabling mess. So, it is necessary to keep track of the circuit and phase assignments to maintain balance across the three phases.

Now those numbers can be used to build an electrical schedule to see how well the system is balanced across phases. Each color pair (black-red, red-blue, and blue-black) represents the branch circuit connection from the PD to the light fixture. If we add the branch currents in each color pair, we can see how the load is distributed. Remember that circuits 1 and 4 are connected across the black and red phases, circuits 2 and 5 across red and blue, and circuits 3 and 6 across blue and black. (See Table 15.3.)

Table 15.3 Circuit Assignments According to PDU, Cable, and Phase

PDU	Cable	Circuit	Black-Red	Red-Blue	Blue-Black
1	A	1	8.4	-	-
1	A	2	-	8.4	-
1	A	3	-	-	-
1	B	1	8.4	-	-
1	B	2	-	8.4	-
1	B	3	-	-	7.6
1	B	4	3.8	-	-
1	B	5	-	3.8	-
1	B	6	-	-	3.8
1	C	1	3.8	-	-
1	C	2	-	3.8	-
1	C	3	-	-	7.6
1	D	1	10.1	-	-
1	D	2	-	10.1	-
1	D	3	-	-	10.1
1	D	4	10.1	-	-
1	D	5	-	10.1	-
1	D	6	-	-	10.1
Total Current Draw			44.6	44.6	39.2

After compiling the information, it appears that the system is pretty well balanced with a difference of only 5.4 amps between the highest and lowest groups of fixtures. The load could be better distributed by moving fixtures from the color pair with the heaviest load to the color pair with the lightest load until the best possible balance is achieved. This is particularly important when we are using a portable power generator because a small imbalance can translate to a mechanical imbalance in the diesel engine, which produces more friction in the bearings and resulting in more heat and wear. In this case, by moving one of the Axcor Wash 600 fixtures from black-red to blue-black, the totals would be 40.8, 44.6, and 43 amps. So we'll go with that.

The total current draw calculated in the table above is not the current drawn on the each of the three feeder conductors; it is the current drawn on the branch circuits. The feeder cables carry a combination of current that is common to each branch circuit; e.g., the black feeder carries 40.8 amps from the black-red circuit and 43 amps from the blue-black circuit, But remember, these currents are 120° out of phase of each other, so, they do not simply add. We need a way to figure out how they combine.

There are two approaches to find the answer. One option is to use the highest of the three branch currents as the load on all three color pairs and use it to calculate the 3-phase current draw. In this case, it is 44.6 amps, and if all three branch currents carried 44.6 amps, then the current flowing through the feeder cable would be 77.25 amps (44.6 × 1.732) per leg. That is a quick and easy way, if slightly less accurate, to estimate your supply and distro requirements.

The other option would be to calculate the unbalanced 3-phase current, which is a lot more complex than calculating a balanced 3-phase load. (See Appendix 6: Unbalanced 3-Phase Load Calculations). Using this method, we find the current to be 74 amps on the black phase, 72.6 amps on the red phase, and 75.9 amps on the blue phase, which confirms that the approximation we used above (77.25 amps on all three phases) is a pretty good estimate.

Now that we have calculated our current draw, we want to pad it by adding 20% overhead. We do this for many reasons. First, the manufacturer's specifications are produced under ideal conditions using tightly controlled voltage

and frequency in a very tightly controlled environment where the ambient air temperature and humidity are ideal. Secondly, the fixtures are tested when they are brand new and all of the components, like the lamp or light engine, power supply, conductors, etc., are in peak working condition. Thirdly, the condition of our rig and the situation in which it is operated is likely to vary widely. The voltage will vary slightly from venue to venue, the connectors will have varying degrees of connectivity and resistance, the atmosphere will likely vary, and other conditions will change. Lastly, we never know when we might have a situation where we need to accommodate changes to the system. So, we'll follow the 80% rule and make sure we are using no more than 80% of our power distribution capacity.

This 20% overhead is a pad, not a code requirement. There are codes that require that a circuit, feeder, and/or service is rated 125% of the continuous load (as opposed to non-continuous), but it doesn't apply to an assembly, like a portable power distribution unit, is listed for 100% rating. This is sometimes referred to as “fully-rated,” and most portable power distribution units fit this description.

SHOP PREP

Once the power and data are laid out, the LW file is documented properly, and labels are printed out, then a shop order can be generated, and the crew can go into the shop to prep the gear. In the shop, all of the lighting gear will be pulled, tested, configured, and labeled before being installed on pre-rig truss or placed in road cases, loaded on trucks, and driven to the venue for the show. Cables can be laid out and taped or tied together to create a cable loom or “hod,” and they will be labeled properly before being wrapped and taped up for transport, which saves a lot of setup time in the venue. And just as importantly, we'll have a chance to put a workbox together with all of the spare lamps, parts, and expendables we'll need for the run of the show. Don't forget the cappuccino machine for the workbox! (See Figures 15.1 and 15.2.)

FIGURE 15.1
Shop prep crew reviewing the documentation before pulling and prepping the gear. (Left to right: Rob Baxter, Rolf Lee, Seth Weldon, Chris Szabo, Henry Parks.)

FIGURE 15.2
Hand-written notes keeping track of how the trucks are packed can help the load-in go more efficiently.

PRIOR TO LOAD-IN

Before the trucks are unloaded, the power source(s) should be checked to make sure they are safe to use and suitable for the load. A quick visual inspection of switches and the feeder transformers supplying them can reveal a lot. The nameplate rating of the transformers will indicate the output rating, voltage, and wiring scheme. A 400A 3-phase switch requires a transformer with a minimum rating of 150kVA, and that is what is typically used for lighting. A 200A 3-phase switch is commonly used for audio systems, and it should be supplied by a transformer with a minimum rating of 75kVA. A 100A 3-phase switch should be supplied by a transformer with a minimum rating of 37.5kVA. If we have a power distribution system with double neutrals, then the feeder transformer should be oversized and/or K-rated (the K rating indicates how much heat due to harmonic current that a transformer can handle and the ratings range from 1, which is intended for loads that do not generate harmonics, to 50, which is intended for loads with the highest harmonics) and the switch should have double neutral terminals.

Feeder transformers should be almost silent under no load. If we find that it is humming loudly under no load, then it could be in failure mode and it should be used with caution and it should be monitored closely during operation. The nameplate rating will specify the maximum “rise temperature,” and if it appears to run hot under load compared to similar sized transformers operating under the same load, then it should also be monitored more closely.

Next, we'll locate the switches associated with each feeder transformer and visually inspect them. We will be checking to make sure the switches are properly installed, properly maintained, that the doors are closed and secured, and that there is no evidence of impending failure. We'll make sure the switch is turned off and that there is no voltage at the output connectors. We can use a voltmeter to verify that there is no voltage at the output if we are wearing thick leather gloves or voltage-rated rubber gloves; otherwise, a non-contact voltage detector can be used. In either case,

we'll use the three-point method (test the tester by using a known source of power, test for the absence of voltage at the switch, and then test the tester again) to ensure that our testing instrument is working.

If the switch is safely locked out to prevent anyone from accidentally turning it on or if it is not connected to any source of power (for example, if it is a portable rental just coming off the truck), then it can be opened to visually inspect it. In that case, make sure it is fused properly, and that there is no debris or mechanical problems, and that it looks like everything is in order. Sometimes we find strands of wire, metal shavings, or other debris that could cause problems or otherwise present a hazard that could interfere with the safe operation of the switch. The size of the fuse depends on the size of the feeder transformer and the feeder cables supplying it. For a 3-phase system, the three fuses should be equal to or less than the current that can be supplied by the feeder transformer. For example, a 150kVA feeder transformer can supply up to 416A per leg (150,000 ÷ 208 ÷ 1.732 = 416), so the switch can be fused up to 400A per leg (because they are typically made in round numbers).

SAFETY MEETING

Just prior to load-in, we'll have a quick safety meeting with all of the electricians. We'll remind them to work safely, and we'll review the emergency procedures, locate fire exits, fire extinguishers, and first-aid kits, and we'll make sure everyone is clear about their assignments. Load-in can be hectic, and there's a lot of pressure to get the rig up and working. But it is important to make sure the power distribution system is safe and finding problems with it now could save a lot of time later on. So, we'll stress the importance of performing a visual inspection of all of the gear, and depending on the circumstances, we'll ask the crew to spend extra time for a careful inspection. The safety meeting also gives the crew an opportunity to ask questions or get clarification about any confusion they may have. We'll encourage questions and model open communication between crew members. (See Figure 15.3.)

FIGURE 15.3

An early morning safety meeting to remind the crew of the importance of working safely and reviewing safety procedures, identifying fire exits, fire extinguishers, and first-aid kits is the first step in preventing accidents.

LOAD-IN

While we are loading in, we'll take the opportunity to inspect all of our power distribution equipment in case any problems got through shop prep undetected. As it is coming off the truck and being assembled, we'll visually inspect the cables, connectors, and all of the components of the power distribution system. We are looking for damaged insulation, damaged or broken terminals on the connectors, and signs of excessive heat like burn marks, rainbow-colored metal, and melted plastic. We will also check to make sure that each set of feeder cables is the same gauge because the outer covering of different cable types can have different thicknesses, so it is not always easy to tell by sight or feel whether or they are the same gauge.

After the power distribution system is assembled but before we connect the feeder cable to the switch, we'll double check to make sure all of the circuit breakers are turned off so that we don't energize the switch and the fixtures at the same time. We want to turn it on in steps to better monitor and control the situation.

TYING IN

The feeder cable will be tied in by a qualified person as defined by the local codes and regulations. In some places, like Canada and Oregon, only a licensed commercial electrician is allowed to terminate feeder cable to a supply. If you are qualified (and authorized, competent, confident) and do tie in the power, it is important to follow the proper sequence for connecting single-conductor cables. First, make sure the switch is off before making any connections. A switch typically has a lever on the side (although sometimes it has a breaker handle with all three phases ganged together) that opens and closes the switch. (See Figure 15.5.) The lever is mechanically linked to a set of contacts, and the linkage relies on components that often includes a cotter pin. Any of these components, including the cotter pin, could malfunction, in which case the position of the lever, whether it is in the on or off position, has no effect. So, the switch could appear to be turned off but is not. Therefore, it is important to test the output for the absence of voltage before tying in the feeder cable.

If we use a voltmeter, then we should assume there is voltage at the outputs until we verify that there is not. So, we'll put on thick leather gloves and make sure we are wearing EH-rated shoes, and then we'll test the voltmeter with a known live source of power. It could be a live outlet, or it could be a proving unit, which is a small, portable tester. Once we confirm that the meter working by measuring voltage, then we can put the probes on the output terminals of the switch to verify there is no voltage, and then we'll test the voltmeter again to make sure it is still working. It is possible that the leads could be broken, so the meter will register 0V even when there is voltage. This three-point method greatly reduces the possibility of error.

Alternatively, we could use a non-contact voltage detector, in which case we still need to use the three-point method, but we won't have to lift the cover of the camlock connector to test the output of the switch for the presence of voltage.

Once we verify that there is no voltage at the output terminals, then we can make the connections to the switch. The grounding conductor should be connected first, followed by the neutral conductor, and then the three ungrounded conductors (or phase conductors) should be connected last. It is a good idea to work in pairs. The first person can make the connections and the second should double-check to make sure they are connected properly. According to the National Eye Institute, about one out of twelve males is, and it is very easy for people with color deficiency to confuse colors, especially blue and green. Also, the ambient lighting conditions can make it difficult to distinguish between different colors, especially green and blue. If you have ever terminated feeder cable under mercury-vapor lamps, then you know how it can affect the perception of colors. The colors of connectors can also fade from exposure to sunlight. All of these things can contribute to difficulty in matching the correct connector colors. That is why some PDs change the gender of the ground and neutral connectors, which prevents accidentally terminating the blue feeder to the green terminal and vice versa. This is known as RGN (reverse ground neutral). (See Figure 15.4.)

FIGURE 15.4
The colors of connectors can be challenging to make out properly when they are illuminated by colored light or light with low color temperature like sodium vapor lamps. They can also be bleached by the sun, making them more difficult to read the proper colors.

FIGURE 15.5
A 200A three-phase four-wire plus ground company switch. Notice that it is a UL listed assembly and the labels indicate the proper order to connect cables and that it should be connected by qualified personnel.

Another item to check is to make sure each camlock connector is terminated properly. They should be inserted completely and rotated clockwise until they stop and lock. Some brands rotate 120° while others rotate 180°.

When the show is over, all of the circuit breakers and switches, including the main breakers and branch circuit breakers on the distros, should be turned off before breaking the connections. Under no circumstances should any connections be made or broken under load because if there is any current flowing through them, it will draw an arc, which can cause an arc flash.

Some older facilities may have no convenient way to tap into the building power. In these rare instances where there is no means of disconnect and the only option is to do a live tie in, then it should only be attempted by a qualified person using the proper PPD. *This is a dangerous procedure and should only be attempted as a last resort, and it should only be undertaken by qualified, experienced personnel using the proper PPE.* (See *NFPA 70E – Working on or Near Live Parts* and Chapter 8: Electrical Safety.) It is normally done using feeder "tails" (single-conductor leads with bare wire on one end and connectors on the other) that are tied into the terminals while the switch is energized. The conductors are normally terminated to lugs using a hex key (commonly called an Allen wrench). (See Figure 15.6.) If you are unsure about how to safely do this, call in an experienced electrician who has the proper training, experience, and PPE for the job.

FIGURE 15.6
Feeder cable terminated at a lug via a hex-keyed set screw.

TURNING ON THE SWITCH

Once all of the feeder cables are properly connected and we have double-checked to make sure that all of the breakers on all of the distros are off, then we can energize the switch. Although there is no special PPE required for turning on a switch that is in good condition with the door closed, it is a good idea to wear leather gloves. That is because, once the switch is energized, then the cables are too, and there is always a possibility that the insulation is damaged or there could be stray voltage due to a ground fault and a faulty ground. To turn on the switch, stand to the side, turn your head, hold your breath, and flip the lever to the on position. We don't need to make a big show of this, but it is good practice just in case the switch malfunctions or there is a ground fault in the system, in which case there could be an arc flash.

Great Balls of Fire

I was once touring with a show that was playing a variety of venues, including medium-sized theatres. I was the LD, and the dimmer tech had recently graduated from college; it was his very first tour. His job was to put the power distro and dimming system together while I set up FOH. One morning, we went into a theatre, and the house electrician terminated the feeder cable to a 400-amp, three-phase switch and left it in the off position. Then he left the building. The dimmer tech finished assembling all of the cables and distro, and when he went to turn on the switch, there was an extremely loud pop, which, to me, sounded like a shotgun, and as I was walking downstage to FOH, out of the corner of my eye I saw what appeared to be a big ball of fire. (See Figure 15.7.) To this day, I don't understand how it escaped the closed switch, but luckily, it went over his head and he was visibly shaken but uninjured. Once you witness an arc flash, it makes an indelible impression upon you that you will never forget. From then on, I always had a healthier respect for the power of electricity.

FIGURE 15.7
When the dimmer tech turned on the switch, there was a very loud blast and a ball of fire shooting out of the switch.

METERING THE VOLTAGE

After turning on the switch and before turning on any breakers, the voltage should be metered using a hand-held meter of the proper category (usually a category III or IV). If the PD has test ports for this purpose, they should be used because they are designed to protect you from the hazards involved in metering voltage. They are small openings in which your voltmeter probes can be inserted, and they are connected to the bus in the PD with very small gauge wire. (See Figure 15.8.) The depth of the ports minimizes the possibility of shorting the probes, and the small gauge wire restricts the energy that could be transferred should there be a short, however remote the possibility.

FIGURE 15.8
A test port allows you to more safely meter the voltage at a portable power distribution unit by inserting the probes of your voltmeter into a small opening with a terminal connected to the bus bars via a small gauge wire.

If we are working with a three-phase system, the voltage should be tested from all three phases to ground (black to green, red to green, and blue to green), from phase to phase (black to red, red to blue, and blue to black), and from neutral to ground (white to green). We want to verify that the voltages are within a few volts of the nominal voltage,

which, in North America) and other parts of the world) is 120V phase to neutral and 208V phase to phase. (See Appendix 5: Worldwide Voltages.) The voltage from neutral to ground should be 0V or very close to it if the supply is being shared with other distribution systems. For example, if the same feeder transformer supplies power to the house lights through a breaker panel and the switch we are tied into, then there could be voltage drop across the neutral conductor due to the current drawn by the house lights. In that case, there might be a few volts between neutral and ground at the distro. But in no case should there be more than 3 or 4 volts between the two because that would indicate excessive voltage drop or induced voltage on the grounding conductor. If the all phases test correctly from phase to phase and from phase to ground, then all of the circuit breakers can be turned on.

MONITORING THE POWER SYSTEM

After metering the voltage and turning on all of the loads, we will check the current on all of the conductors to make sure they are not overloaded and that none of the components are overheating. Using a clamp meter, we will measure the current on each conductor starting with the feeder cable from the supply to the distro. We want to be sure to wear thick leather gloves and EH-rated shoes to prevent shock in the event that the insulation is damaged. Also, we'll avoid touching grounded or bonded conductive surfaces while measuring current for the same reason, and we will not allow our knees to make contact with the floor because they have no shock protection like our shoes do. All five individual conductors should be metered, including the neutral and grounding conductor, and it will help to make a note of each measurement for future reference. Every supply and set of feeder cables should be monitored this way on a regular basis, perhaps hourly.

Next, we'll use an infrared camera, like the Flir One, to see if any of the power distribution components are close to their temperature rating. The camera creates a heat map showing the relative temperature of the image, and by comparing the relative temperature of the feeder set and connectors, we will be able to see if any individual component needs attention. (See Figure 15.9.)

FIGURE 15.9
Left: An infrared camera scan shows the surface temperature of a 4/0 AWG cable carrying 225 amps, well below the ampacity. Although the surface temperature of the jacket is below the 105° C rating, the copper is at a higher temperature, and the lug that connects the conductor to the bus in the distro is rated 90° C. Right: The temperature in same conductor one hour later has now risen beyond the temperature rating of the jacket. It was soon taken out of service.

TURN OUT THE LIGHTS, THE PARTY'S OVER

When the show is over, all the loads should be turned off in the proper sequence. Arc lamps should be turned off at the console or using RDM and allowed to cool for five minutes before shutting down the power. If the power to the fixture is before the lamps are dowsed, then the airflow across the lamps will stop and the temperature will rise instead of fall, and that will likely damage the lamps. After they have been given sufficient time to cool, the individual branch circuit breakers can be turned off one at a time, and then the main breaker should be turned off.

UNDERSTANDING SHOW PREP, SETUP, AND MONITORING

15.1 (a) If a fixture can operate at a range of different voltages, will a higher voltage result in higher or lower current? Why? (b) Which option will save more resources?

15.2 If a fixture is rated 1000 VA at 208V, 60 Hz, and it draws 4.8 amps, what is its power factor?

15.3 If a fixture draws 6.5 amps at 230 V, 50 Hz, what is its apparent power?

15.4 If you want to leave 20% overhead on a 30-amp circuit, how many amps can you use?

15.5 The percent of imbalance in a 3-phase load can be calculated by first calculating the average current of the three phases, then calculating the maximum deviation from the average, and the dividing the deviation by the average and multiplying by 100 to get the percentage of imbalance. A 3-phase system is drawing 74 amps in black phase, 72.6 amps in the red phase, and 75.9 amps in the blue phase. (a) What is the average current draw? (b) What is the maximum deviation from the average? (c) What is the percent of imbalance?

15.6 How many amps per phase can a 300 kVA feeder transformer supply?

15.7 If a feeder transformer is humming loudly under no load, what might that mean?

15.8 Why is it important to make sure all of the circuit breakers are off before energizing the switch?

15.9 (a) To properly terminate a single-pole locking connector, insert it and twist it until it can't be turned any further. How many degrees should it turn? (b) Why is it important to make sure it is fully inserted and twisted until it stops?

15.10 What is the implication of a feeder transformer that is humming loudly under no load?

15.11 (a) If the battery in your digital voltmeter is dead, it will be obvious because the display will not work. If one of the leads has a broken wire or broken connection and you place one probe on a live 120V terminal and the other on ground, what will the display read? (b) How can you ensure that your meter is working properly?

15.12 Why is it important for a second person to double-check the feeder cable connections before energizing a switch?

15.13 What is RGN and why is it sometimes used?

15.14 How many degrees of rotation does it take to fully terminate a camlock connector?

15.15 What happens when a circuit is interrupted under load?

15.16 What is the purpose of the test ports in a portable power distribution unit?

15.17 (a) If all of the circuit breakers in a power distribution system are off, what should the voltage read between the ground and neutral terminals? (b) If there is voltage between the ground and neutral when the breakers are off, what might that indicate? (c) If there is more than about 4 volts between the ground and neutral when all of the circuit breakers are off, what might that indicate?

15.18 If an amp meter doesn't require accessing live conductors like metering voltage does, why is it important to wear thick leather gloves and EH-rated shoes while metering current?

15.19 Why is it important to meter the current in all five conductors of a four-wire plus ground system?

15.20 Why is it important to wait five minutes after dousing the arc lamps before turning off the power?

APPENDIX 1
The Physics of Electricity

"Electricity is actually made up of extremely tiny particles called electrons, that you cannot see with the naked eye unless you have been drinking."

— Dave Barry

WHAT IS ELECTRICITY?

For thousands of years, lightning (electricity) puzzled, mystified, and terrified people. Over the last few hundred years, scientists such as André-Marie Ampère, Alessandro Volta, Michael Faraday, Benjamin Franklin, and many others pieced together an understanding of electricity and helped to unlock its secrets. Step by step, bit by bit, they built a plausible model of electricity that fit mathematical formulas and provided a real-world explanation of the phenomenon. Even after they had a basic understanding of the key relationships and the fundamentals of electricity, early pioneers such as Joseph Swan, Thomas Edison, Nikola Tesla, and George Westinghouse still struggled to harness its power for daily use in a safe and efficient manner.

During that time—the late 1800s and early 1900s—one of the first practical uses of electricity was to illuminate common areas such as city streets and town squares. New York City quickly became entangled—quite literally—in wires carrying electricity, telephone, and telegraph signals. Several times, horrified bystanders witnessed the accidental electrocution of workers in the naked light of day, and electricity gained a reputation for being both mysterious and dangerous. Thomas Edison played on the fear of the public to protect his economic interests by promoting direct current (DC) power distribution as being safer than alternating current (AC) power distribution, while George Westinghouse grew his business on the principles of AC and its inherent economic advantages over DC. The ensuing controversy did nothing to ease the public's apprehension about electricity, nor did it help to clarify its nature or promote its understanding.

To this day, many people have little understanding of the nature of electricity. Some of us still have difficulty answering the question, "What is electricity?" After all, we can't see it, hear it, or smell it. And we certainly don't want to taste it or feel it.

An electrician might understand how to hook up a power distribution system but may not fully understand exactly how electricity behaves. By studying the physics of electricity, we can better understand how it behaves, how to use it safely and effectively, and how to comply with codes and regulations.

ELECTRONS IN MOTION

The short answer to the question "What is electricity?" is that it is the transfer of energy through the motion of charge-carrying electrons. Lightning is an example of electricity and of electrons—lots and lots of them—in motion. Electricians are generally concerned with a much more controlled situation where electricity flows through a given path in a safe, predictable manner. But the electricity we use in shows, gigs, and events is no different than that of a lightning strike, a static discharge, or a flashlight battery supplying power to an LED. Each is an example of the transfer of energy through the motion of electrons.

But, from where do these electrons come? The answer can be found in one of the most basic building blocks of the universe—the atom.

THE ATOM

The word "atom" comes from the Greek word *atomos,* meaning indivisible. It is the smallest particle that still retains the properties of the element from which it comes. When you were in primary school, you were probably taught the classic model of an atom with a nucleus at the center and electrons orbiting around it. (See Figure A1.1.) The nucleus is made up of a number of protons and neutrons, and they are held together by nuclear forces. The specific number of neutrons, protons, and electrons depends on the element. For example, copper atoms normally have 29 protons, 35 neutrons, and 29 electrons.

FIGURE A1.1
The classic model of an atom showing the nucleus at the center and electrons in orbit around the nucleus. (Not to scale.)

If you took your side cutters and cut a small strand of copper from a cable, it would contain billions of copper atoms. If you then cut that piece in half, and then in half again, and over and over until you got down to a single piece that still looked and acted like copper, then you would have a single atom. (See Figure A1.2.) But you would have to be pretty good with those cutters. One atom of copper is approximately 10^{-12} meters in diameter. Put another way, it takes about 254 billion copper atoms placed side by side to make 1 inch. Good luck with that.

FIGURE A1.2
It would take approximately 254 billion copper atoms to span a 1-inch width of copper wire.

Atoms are literally everywhere. They make up the air you breathe, the water you drink, the clothes you wear, and the food you eat. They are the building blocks of the universe.

SUBATOMIC PARTICLES

Despite what the early Greeks thought, atoms can be divided. It turns out that they are made up of even smaller subatomic particles called electrons, neutrons, and protons. These subatomic particles are very important to the understanding of electricity. Electrons carry a negative charge, protons have a positive charge, and neutrons have no charge at all. (See Figure A1.3.) It is the interaction of these charges that causes the phenomenon we call electricity.

FIGURE A1.3
Atoms are made up of particles call neutrons, protons, and electrons. Neutrons carry no charge, protons are positively charged, and electrons are negatively charged. (Not to scale. Note that color was added by the author to distinguish between the different particles.)

THE LAW OF ELECTROSTATIC ATTRACTION AND REPULSION

Notice that the copper atom has the same number of electrons as it has protons. The charge on a single electron is the same strength as a single proton but it is opposite in polarity. In most atoms, the number of electrons is the same as the number of protons, so the charges cancel each other resulting in an overall charge of zero. Sometimes an atom can lose an electron or two because some other force external to the atom—like a battery—can pull it away. In that case, the charges in the atom are no longer balanced and it becomes positively charged.

One of the fundamental laws of nature is that opposite charges attract and like charges repel. Two protons will repel each other and so will two electrons. But a proton and an electron will be attracted to one another. (See Figure A1.4.) That is the law of attraction and repulsion. How strongly they are attracted depends on the strength of the charges and how close they are to each other. A single proton carries a fixed positive charge and a single electron carries a fixed negative charge, so the strength of the total charge depends on the number of protons or electrons involved. The force of attraction between an electron and an atom with two protons, for example, is twice as strong as the force of attraction between an electron and an atom with a single proton.

The force of attraction between two opposite charges also varies with the distance between the charges, but not in the way you might expect. If the distance between the charges is doubled, then the force of attraction or repulsion drops by a factor of four; if the distance is halved, then the force will increase by a factor of four. That is what is called an inverse exponential relationship because the larger the distance, the smaller the force, and drops by the square of the distance.

FIGURE A1.4
Opposite charges attract (b); like charges repel [(a) and (c)]. (Not to scale.)

Since opposite charges attract, electrons stay in orbit around the nucleus of an atom because of electrostatic attraction to the protons. However, some of the electrons are orbiting so far away from the nucleus that the bond is relatively weak. To give you an idea of the relative distances involved, suppose we could expand a copper atom so that the nucleus was the size of a golf ball. Then you would have to go about 2.41 kilometers (a mile and a half) before you would find the outermost electrons. (See Figure A1.5.)

FIGURE A1.5
If the nucleus of an atom were the size of a golf ball, the outermost electrons would be orbiting 2.41 kilometers (1.5 miles) away.

If an external force, like the positive terminal of a battery, is applied to the end of a piece of copper wire, if the external force is strong enough, then the electrons furthest from the nucleus of the copper atoms in the wire can be pulled away and freed from the atom. When that happens, the atom becomes "ionized" and it now carries a positive charge because it is missing a negatively charged electron. The freed electrons that are pulled away from the nucleus of the atoms "drift" toward the external force. Since electrons are so small, it takes billions of them to make up any

appreciable amount of electricity. When all of these particles are moving through the confined space of a conductor, they tend to bump into each other, causing friction, which causes heat. The more particles there are moving through the conductor, the more they bump, and the more heat generated.

The motion of the electrons results in the transfer of energy, and what we know as electrical current. The amount of current flowing through a circuit is measured in amps or amperes. The collisions among all of the electrons results in friction, and is what causes electrical resistance. The amount of resistance in a circuit is measured in ohms. When electrical current encounters resistance, it produces heat. That is why it can be very hot when you walk into a dimmer room or when you touch a conductor that has been conducting a lot of current. If there is too much current flowing through a conductor, it will heat up everything in its path because higher current means there are more electrons flowing, thus there is more "friction" and heat. The temperatures can approach or exceed the melting point of the insulation or jacket of the conductors, and that can cause it to begin to deteriorate. The deterioration may not be readily apparent unless it is a catastrophic meltdown, but excessive heat leads to the premature breakdown and failure of the insulation or jacket of conductors. It could also lead to arcing and pitting of connectors and other problems. It might take months or years before reaching complete failure, or it might take hours or minutes. But any time a cable or wire is conducting current, it is heating up. If the temperature is too high, it is essentially "baking" the insulation around it.

CONDUCTIVE PROPERTIES OF MATERIALS

In order for current to flow, there has to be a conductive path through which the current can flow. Some materials are better conductors of electricity than others because of the structure of the atoms from which they are made. The better conductor a material is, the less it opposes the free flow of electricity; conversely, the worse a conductor it is, the more it opposes the free flow of electricity.

Copper, gold, silver, aluminum, and other metallic elements are good conductors. Carbon, wood, glass, and rubber are poor conductors of electricity and are considered good insulators because they strongly inhibit the free flow of electricity. (See Figure A1.6.) Materials such as germanium and silicon will conduct electricity under certain conditions, like raising their temperature or placing them in the presence of an electric field. These materials are known as semiconductors. Water is normally a good conductor because of the impurities like salt and minerals, but purified water is much less conductive. Air is normally a good insulator but in the presence of very high voltage, it can become ionized—meaning the atoms have lost one or more electrons—and then it can arc and conduct.

Table A1.1 shows how resistive each material is (symbolized by the Greek letter ρ or rho). The inverse of resistivity is called conductivity, which is also shown in the table (symbolized by the Greek letter σ or sigma). Notice that the values given are temperature-dependent; in this case, the table is for a temperature of 20°C.

FIGURE A1.6
A typical utility pole has various conductors and insulators. The copper or aluminum wires and the metal transformer housing are good conductors; the wooden pole and the glass or ceramic insulators are poor conductors.

Table A1.1 Resistivity and conductivity of materials at 20°C

Material	**Resistivity ρ (ohm·m)**		**Conductivity σ × 10^7/Ω·m**
Silver	1.59	$\times 10^{-8}$	6.29
Copper	1.68	$\times 10^{-8}$	5.95
Gold	2.2	$\times 10^{-8}$	4.5
Aluminum	2.65	$\times 10^{-8}$	3.77
Tungsten	5.6	$\times 10^{-8}$	1.79
Iron	9.71	$\times 10^{-8}$	1.03
Platinum	10.6	$\times 10^{-8}$	0.943
Solder (63/37 Sn/Pb)	14.4	$\times 10^{-8}$	0.694
Lead	22	$\times 10^{-8}$	0.45
Mercury	98	$\times 10^{-8}$	0.10
Nichrome (Ni, Fe, Cr alloy)	100	$\times 10^{-8}$	0.10
Carbon (graphite)	3–60	$\times 10^{-5}$	—
Germanium	1–500	$\times 10^{-3}$	—
Silicon	0.1-60	...	—
Glass	1–10 000	$\times 10^{9}$	—
Quartz (fused)	7.5	$\times 10^{17}$	—
Hard rubber	1–100	$\times 10^{13}$	—

Source: D.C. Giancoli, *Physics,* 4th ed. (Prentice Hall, 1995).

CURRENT CONVENTION

We started out by saying that electricity is the transfer of energy through the motion of negatively charged electrons. What, then, is considered to be the direction of the flow of electricity? Is it the same as the direction of the flow of negatively charged electrons, or is it the direction in which a positive charge might flow?

Before very much was known about electricity, electricity was thought to be an invisible fluid. Later on, it was learned that it was actually the flow of very small particles. What do you suppose was thought to be the polarity of those particles? Probably positive. Wouldn't that be a natural assumption? Standard current convention was established at that time. Thus, the convention was that current flows in the direction of positive charges, which is opposite the direction of the flow of electrons.

The important thing to remember is that current flows from the positive terminal of a power supply to the negative terminal. The primary exception is the U.S. Navy, who uses the opposite current convention. This may seem counterintuitive, but a "convention" is just an agreement amongst a group that provides a convenient way of thinking about how it works and how to describe it. But it is really relative. As long as we are consistent, we can choose either "convention"; however, most of the world considers current to flow from positive to negative.

SUMMARY

Electricity is the transfer of energy through the flow of electrons. Electrons are subatomic particles with a negative charge orbiting around the nucleus of an atom. When an external force like a voltage is applied to a conductor, the electrons can be pulled free of the atom. Electrons are so small that it takes billions to produce any appreciable amount of electricity. The friction produced by a huge number of electrons bumping into each other produces heat.

The atoms of some materials give up their electrons more easily than others. Some materials, such as gold, silver, and copper, are better conductors than others, such as carbon, wood, glass, and rubber. Still others, such as germanium and silicon, are semi-conductors, meaning they can be nonconductors or conductors depending on certain conditions. Electrical current flows from the positive terminal of a power supply to the negative terminal.

UNDERSTANDING THE PHYSICS OF ELECTRICITY

A1.1 What is electricity?

A1.2 What is the name of the negatively charged particle in an atom?

A1.3 When current passes through resistance, it produces heat. If you have two conductors with the same amount of current, and one of the conductors had a lower resistance than the other, which would get hotter?

A1.4 If current passing through resistance produces heat, would a current-carrying conductor get hotter or cooler if you shortened its length?

A1.5 If electrical resistance is caused by sub-atomic particles bumping into each other and causing friction, which has less resistance, a conductor with a larger cross-sectional diameter or a conductor with a smaller cross-sectional diameter?

A1.6 What the purpose of the insulation around a conductor?

A1.7 What would happen to the insulation around a conductor if the resistance of the conductor is too high or the current flowing through the conductor is too high?

A1.8 When an electron is pulled away from the orbit of an atom, the atom becomes _____.

A1.9 What is the polarity of the charge of an ionized atom?

A1.10 What makes some materials better conductors than other materials?

A1.11 If lightning is the flow of electricity, what is the conducting medium?

A1.12 In order for current to flow, there has to be a _____?

A1.13 What prevents current from flowing where we don't want it to?

A1.14 What is the likely consequence of running a power distribution system over full capacity?

A1.15 What is an example of an insulating material?

A1.16 Which is more conductive, tungsten or iron?

A1.17 What is the inverse of resistivity?

A1.18 Why is the direction of current convention opposite that of the flow of electrons?

A1.19 Is conventional current flow toward or away from the positive terminal of a battery?

A1.20 How do rubber gloves help prevent electric shock?

A1.21 Why is it important to inspect cables and connectors before putting them into service?

A1.22 If the insulation on a cable is cut, cracked, punctured, or broken to the extent that you can see bare copper wire, why is it a hazard?

APPENDIX 2
The History of Alternating Current System

If Michael Faraday was alive today, we might say that he hacked electricity and magnetism. In 1821, he knew that the flow of current produced a magnetic field, and he wondered if a magnetic field could produce the flow of current. The next year, he wrote in his laboratory notebook, "Convert magnetism into electricity."[1]

A few years later in 1831, he conducted an experiment where he wrapped one side of an iron ring with several turns of insulated wire, and on the other side of the ring, he did the same. One of the coils of wire was connected to a battery and the other was connected to a galvanometer (or an amp meter or ammeter) so he could detect the flow of current. (See Figure A2.1.) When he connected the battery to the first coil and current started to flow, he thought the magnetic field in the first coil would magnetize the iron ring, thereby inserting a magnetic field inside of the second coil of wire, which would then induce the flow of current in the second coil. Instead, the needle on the galvanometer moved momentarily when the battery was first connected, but then it fell to 0. It did the same thing again when the battery was disconnected.

FIGURE A2.1
Faraday wanted to see if a magnetic field create the flow of current. He wrapped insulated wire connected around one side of an iron ring and connected it to a battery, then wrapped the other side of the ring with insulated wire connected to a galvanometer.

Even though he didn't get the result he was looking for—current flowing steadily through the secondary winding—Faraday eventually understood the behavior. When the battery is first connected to the primary winding, the current rises from zero to its maximum, and the magnetic field also grows from zero to its maximum. As the magnetic field grows, the lines of flux of the magnetic field expand and cut the turns of wire in the secondary, thereby inducing voltage in the secondary winding. Since the secondary winding is a complete circuit, the induced voltage causes current to flow. When the current reaches its maximum value, the magnetic field stops growing, the lines of flux no longer cut across the secondary winding, and no voltage is induced. And when the battery is disconnected, the current falls back to 0, the magnetic field collapses, and the lines of flux once again cut across the secondary winding until the current reaches 0. In the end, Faraday deduced that as the lines of flux of a magnetic field cut through a conductor, it will generate voltage. The value of the voltage is proportional to the rate of change and the intensity of the magnetic flux. This is known as Faraday's law of induction.

How does all of this relate to supplying power for a show, a gig, or an event? It is the principle by which alternating current is generated. A generator typically has a rotor with magnetic poles, and it spins in close proximity to stationary windings. The rotary action causes the lines of flux of the magnetic fields to cut the conductive windings, and it generates electricity.

You may also have noticed that Faraday's apparatus in this experiment looks like a transformer, and it is. He didn't realize it, but by discovering the principle of induction, he led other people to invent the transformer, which was an important step in harnessing electric power distribution.

A transformer has the ability to change the voltage of alternating current without changing the amount of power passing through it. This is important because there is a trade-off between safety and economy—the higher the voltage, the more dangerous it is, but it requires less current to transmit the same power; therefore, it can be done with smaller diameter wires, which translates to lower cost. And because electricity is typically transmitted over tens or hundreds of miles, cost is a significant issue. Conversely, the lower the voltage, the more current is required to transmit the same amount of power, so it's safer but more costly. Transformers allow you to change the voltage as needed. So power is generated at moderate voltages, and then distribution transformers are used to raise the voltage to very high levels, typically in the hundreds of thousands or a million volts, for distribution. When the power lines approach more populated areas, a series of step-down transformers are used to drop the voltage back down to more reasonable levels. By the time the power lines are brought into a building in the United States, like your venue, it is typically 480 volts. In Canada that voltage is typically 600 volts, 415 volts in the United Kingdom, or 380 volts in other parts of Europe. Every region of the world has its own standards for voltage and frequency, although there has been some standardization through the years.

The venues we work in typically have a feeder transformer, and its size determines how much power it can provide and how many amps it can supply. Ultimately, that determines how much gear we can power.

WHY WE USE AC INSTEAD OF DC

Near the end of the nineteenth century, Thomas Edison perfected the incandescent lamp (following Joseph Swan's blueprint of a carbon filament, platinum wire leads, and a vacuum-enclosed glass bulb), extending its useful life to several hundred hours. (See Figure A2.2.) The newly established Edison Electric Illuminating Company was rapidly growing, feeding on the demand for electric light and power throughout the United States and Europe.

FIGURE A2.2
Thomas Edison in his New Jersey lab (c. 1918–1919; courtesy of the National Archives).

At the time, the entire world used direct current (DC), meaning the voltage was constant, as opposed to alternating current (AC) where the voltage varies according to a sinewave. But George Westinghouse, who had been very successful in the railroad industry, saw what he thought was the future of the electrical power industry. At the Inventions Exhibition in London in 1881, he saw a "secondary generator"—known today as a transformer—invented by Lucien Gaulard and John Dixon Gibbs. Westinghouse bought the Gaulard-Gibbs patent and began building AC generators and power distribution systems.

There was a lot of debate and discussion at that time about AC, but it suffered from one major drawback: there were no motors that could run on AC power. Therefore, all the advantages of AC power distribution were negated by the lack of its ability to provide locomotion, which was, at the time, one of the major uses of electricity.

DC power distribution, however, was not without drawbacks of its own. There were severe limitations as to how far it could be economically distributed; therefore, small coal-fired "dynamos" had to be used within a half mile (about 800 meters) of where the electricity was to be used. A dynamo is a generator that converts mechanical energy to electrical energy in the form of DC voltage. These dynamos were loud and dirty, and they required an operator to shovel the coal, stoke the fire, make sure the boiler had water, and generally take care of the system. Dynamos were generally ill-suited for urban life, which is exactly where they were needed the most. To make matters worse, DC motors were inefficient and required regular maintenance. They used commutators and brushes, both of which wore out and required constant maintenance. A commutator is an assembly on a dynamo that periodically changes polarity of the circuit to make sure the voltage is always positive; otherwise, the rotation of the dynamo would invert the polarity and produce alternating current. The brushes were conductive pieces of copper or carbon that allowed the shaft of the dynamo to rotate while still maintaining electrical contact. For all of its shortcomings, DC electricity was still far superior to gas lamps and manual labor, both of which were a way of life at the time.

In 1884, a young Serbian named Nikola Tesla arrived in New York from his native Europe to go to work for Thomas Edison. He was there by virtue of a recommendation from Edison's associate, Charles Batchelor, who wrote, “My Dear Edison: I know two great men and you are one of them. The other is this young man.” (See Figure A2.3.)

Two years earlier, Tesla had a vision of a polyphase alternating current system that could drive an AC motor. Until his revelation, there were no motors that could operate with AC power because the torque is proportional to the applied voltage, and when the voltage in an AC waveform falls to 0, the motor would stall. Tesla's revelation was to more than one voltage waveform, thus the “polyphase,” one of which would supply full torque when the other was at 0 torque. He had worked out the solution mathematically, and he had a burning desire to build a prototype and make it a reality. Eventually, he relayed his idea to Edison, who said in no uncertain terms that he wasn't interested, that it was a waste of time, and that he thought AC was more dangerous than DC.

Despite Edison's rebuff, Tesla continued working for him, hoping that one day he would have a chance to realize his polyphase AC system. Edison offered Tesla a $50,000 bonus—about $1.3M in 2020 dollars—if he improved the efficiency of his DC generators. But when Tesla succeeded in doing so, Edison reneged, saying that his offer was in jest and that Tesla didn't understand American humor.

Shortly afterward, Tesla left the Edison company and with the help of outside investors started his own company to build AC induction motors and generators. The investors eventually took over the company and forced him out because they grew impatient. Penniless, Tesla resorted to manual labor, digging ditches for a year to support himself while searching for another investor. He finally met a financial backer, Charles F. Peck, who he convinced that he had an idea worth pursuing. In 1887 Tesla filed seven patents related to polyphase AC power generation, distribution, and locomotion. He had invented and built an AC motor.

George Westinghouse recognized the value of Tesla's work and bought the patents for about $60,000 (about $1.6M in 2020) in cash and stock in his Westinghouse Corporation, in addition to a royalty of $2.50 for each horsepower of electrical capacity he sold. Tesla and Westinghouse were now partners. (See Figure A2.4.)

FIGURE A2.3

Nikola Tesla in front of a high-frequency transformer at East Houston Street in New York. (Courtesy of www.teslasociety.com; Dr. Ljubo Vujovic, Secretary General, Tesla Memorial Society of New York.)

But they had much work to do in order to establish the acceptance of AC. It threatened not only Thomas Edison's DC-centric empire, but also the rich and powerful men of Wall Street who provided Edison's financial backing, including J. P. Morgan. Thus, the stage was set for the so-called "War of Currents" between Edison, a staunch proponent of DC, and the team of Tesla and Westinghouse, who had no doubt that AC power distribution was superior. The advantages of AC power distribution were undeniable: it provided a practical means of transmitting electricity efficiently over long distances, allowing the centralization of power generation, and it significantly reduced the cost of electrical transmission by reducing the size of transmission wires. But at that time, it was also unproven.

FIGURE A2.4
George Westinghouse, shown here, and Nikola Tesla were allies in the effort to make alternating current the standard for electrical power distribution.

The 1893 Chicago World's Fair was to be the first high-profile battleground for the opposing technologies. Edison and Westinghouse both bid on the job of supplying power to light the fair, but a shortage of copper caused a sharp increase in price. Suddenly, the circumstances dramatically favored the solution with the least use of the metal. Edison's million-dollar bid was halved by Westinghouse, and Westinghouse won the job. In the end, close to 28 million people witnessed the illumination of 93,000 incandescent lamps and 5000 arc lamps, all driven by an AC polyphase power system.

One of the attendees at the Chicago World's Fair was British physicist Lord Kelvin. It just so happened that Kelvin was the head of an international commission to select a design for a soon-to-be-constructed power plant at Niagara Falls. Up until that time, he was a firm believer in DC power distribution. But the demonstration of polyphase AC power distribution at the fair convinced him otherwise. After witnessing the AC power system at the fair, he

successfully convinced the commission to award the Niagara Falls contract to Westinghouse. With the reputations of Tesla and Westinghouse riding on the outcome and millions of dollars at stake, the project was successfully completed in 1896. If the world was not yet convinced that AC power distribution was superior, the Niagara Falls project was the final deciding factor. From that point on, the vast majority of electric appliances and equipment was manufactured for AC operation.

That still holds true today. AC allows vast amounts of electricity to be produced in remote locations, transformed to very high voltage, transmitted over very long distances with relatively low current using relatively small conductors, and transformed back to a lower voltage at the point of consumption.

The key to the successful implementation of AC power was the development of the alternating current synchronous motor, which was born in the mind of the young Serbian, Nikola Tesla.

IS AC MORE DEADLY THAN DC?

Near the end of the nineteenth century when Westinghouse was challenging Edison's dominance of commercial power generation and distribution, Edison set out to convince the public that AC was far more dangerous—deadly, even—than DC. He quietly supplied financial support and resources to an electrical engineer and consultant named Harold Brown, who was publicly campaigning for legislation against AC generators and equipment in New York. As part of his campaign, Brown put on public displays designed to demonstrate just how much more dangerous AC was compared to DC. In his first public display, he electrocuted a large black retriever in a lecture hall at Columbia College at 50th and Madison Avenue in New York City, much to the disgust of the members of the audience, which included members of the press, the New York City Board of Electrical Control, and various other interested parties. Many of them walked out in the middle of the demonstration, but Brown persisted until an agent of the American Society for the Prevention of Cruelty to Animals forbade him to electrocute another dog. The demonstration ended but Brown continued his deadly campaign, successfully electrocuting large dogs, calves, and horses in public.

After one of Brown's demonstrations, a story ran in The New York Times describing the grim event. George Westinghouse wrote a letter to the newspaper in response to the article, defending AC. Brown, in turn, wrote a letter to the newspaper challenging Westinghouse to a bizarre contest.

> "I challenge Mr. Westinghouse to meet me in the presence of competent electrical experts and take through his body the alternating current while I take through mine a continuous current….We will commence with 100 volts, and will gradually increase the pressure 50 volts at a time, I leading with each increase, until either one or the other has cried enough, and publicly admits his error."[2]

Westinghouse didn't honor him with a reply.

Is AC really more dangerous than DC? There are many factors that come into play when a person receives a shock. The severity of the shock depends on the size, weight, age, and body fat of the person, as well as voltage, frequency, duration of shock, contact area, contact pressure, temperature, and moisture of the skin. Generally speaking, the impedance of the skin is the first line of defense against a fatal shock. It helps prevent current from flowing through the heart and causing fibrillation. The higher the impedance, the lower the current for a given voltage. Like any other electrical circuit, the flow of current through a human body behaves according to Ohm's law.

It turns out that for AC current, the impedance of our skin decreases as the frequency increases, but the frequencies most likely to cause ventricular fibrillation are between 50 Hz and 60 Hz.

NOTES

1 Jill Jonnes, *Empires of Light: Edison, Tesla, Westinghouse, and the Race to Electrify the World*, Jill Jonnes (Random House, 2003).

2 Jonnes, J.; *Empires of Light: Edison, Tesla, Westinghouse and the Race to Electrify the World*; New York, New York; Random House; 2004.

APPENDIX 3
A (Very) Short History of Portable Power Distribution

Power distribution systems in the live event production industry have evolved over the years through a great deal of trial and error, all the while borrowing heavily from the computer, manufacturing, and aerospace industries. Theatre was the original live event production and it was an early adopter of electric light and electrical technology. The Great White Way, a section of Broadway between 42nd and 53rd Streets, was so nicknamed because of the Charles F. Brush arc lamps that were installed in 1880.

The television and motion picture industries were the next in our industry to push the technology envelope. They pioneered portable lighting, grip, and power distribution equipment and even helped develop motorized lighting. (Cecil B. DeMille's *The Greatest Show on Earth* in 1952 used Century Lighting FeatherLite Fresnels with motorized pan and tilt, and similar units were installed in NBC Studio 8H in Rockefeller Center in the late 1950s or early 1960s.)

When concert touring came into vogue in the late 1960s and early 1970s, the concert and touring industry took up the mantle of pioneering new technology—not necessarily out of desire but rather out of necessity. When the big rock concert hit the road, the techs found that they had to invent the technology and systems that would allow them to meet the challenges before them.

ROCK AND ROLL ROAD SHOWS

Before the days of manufactured and standardized systems, anyone who wanted to take their show on the road had to build their own systems from scratch. E. H. B. “Chipmonck” Monck was one of the lighting designers who helped develop the first methods and techniques for touring large systems. (See Figure A3.1.) He had a background in theatre and ended up lighting Bob Dylan at the Newport Folk Festival, and many other artists, such as the Doors, the Byrds, and Crosby, Stills, and Nash. He was instrumental in helping to build the stages and lighting systems at the first Woodstock in 1968 and he was the lighting designer/director on many early tours, including that of the Rolling Stones.

When Monck started touring in 1963, he said technicians commonly used the single-conductor AA asbestos insulated wire, the same wiring that was used for stage lighting instruments like Lekos and PAR cans at the time. AA is “non-impregnated” with a braided asbestos outer covering. (We now know that asbestos can cause lung disease and cancer, but that was not well-known at the time.) Since there were no commercial stage lighting manufacturers designing and building products for portable use back then, all of the power distribution had to be custom-made from components that were available at the time.

FIGURE A3.1
Monck (center) explains to Roy Lamb (right) that he still needs to tape the five individual conductors together. They are building custom cable assemblies using AA #12AWG single-conductor cable, circa 1970.

To make matters even more difficult, the power available in the buildings at the time varied in size and configuration. In Paris in 1966, while Monck was touring with the Chamber Brothers, they encountered a four-phase six-wire system. (See Figure A3.2.) This was well after most of the world had settled on 3-phase power, but the Chamber Brothers concert was being held in an older venue.

FIGURE A3.2
Monck (left) and David Noffsinger tie in to a 380V service in a wooden enclosure in Sweden during a stop on the Rolling Stones' STP tour circa 1970. Notice the feeder cable on the floor—it is welding cable with Tweco welding connectors.

Because of the voltage difference in Europe, the group toured with three of their own 10kVA 2:1 step-down dry type GE transformers. Tweco welding connectors and welding cable were commonly used for feeder cable and connectors at the time because there were no specialized cable and connectors for portable applications. Two-wire power distribution systems (no equipment ground) were also the norm. Bob See, who started a production company called See Factor Industry, Inc. in 1970, worked in the New York City area in the 1960s and 1970s. According to See, Norman Leonard, who was the house electrician at Madison Square Garden, was responsible for introducing system grounding conductors to the touring industry. By virtue of the fact that he was a licensed electrician and he carried the license for the building, he had the power to allow or disallow shows to go on. And he insisted that any show coming in to the Garden must be properly grounded.

"Norman Leonard single-handedly changed the industry," See said. "When the circus would come in, they had to re-wire everything. He demanded that every piece of cable be three-wire. Various tours came through and they got nailed (meaning they had to address the issue before they were allowed to perform). And all of a sudden, the industry was aware that if you're going to play the Garden, you had better be 'Garden-proof.' He would not let the gear in the building unless it was three-wire. Grounding became a major league issue. He would go up and make you drop a truss and he would put a meter on it and see if you had any current coming down the truss. If he saw any current on the ground, he would make you tear the whole system apart and find out what was going on. And if you just came from a gig outdoors, all of the wire was damp. And back then, it was asbestos, so you could get current going through it. Electrically speaking, today we are safer because of him."

By the time Monck started touring with the Rolling Stones in 1969, "power was no longer an issue," he said. But power distribution systems were far from the level of sophistication they have reached today.

WELDING CABLE IN LIVE EVENT PRODUCTION

As late as 1984, when the Olympics came to Los Angeles, the NEC recognized only type S or type SO cable for single-conductor feeders, and it had been put in the code only that year. Ironically, there was no such thing as single-conductor type S or type SO cable at the time because manufacturers didn't make it. Most production houses used welding cable with single pole welding or cam-type connectors. But it wasn't suited for such use because it was 90-volt, intermittent-duty cable, which means it should not be conducting current 100% of the time. But that's not now show power distribution systems operate, which makes it risky to use welding cable for powering shows. Manufacturers interested in capturing some of the entertainment market started making 600-volt welding cable, and most production houses on the west coast bought and used it.

But that spring, a Los Angeles County inspector red-tagged a temporary building being used for the live broadcast of the Olympics because it was powered via welding cable and terminated in cam-style connectors at the building. Soon

thereafter, city officials received a letter asking for permission to use a particular brand of continuous-duty cable that was rated for 600 volts. Up until that time, the City of Los Angeles had never officially addressed the matter of acceptable feeder cable types: it had never come up, so they simply ignored the issue. But the letter asking permission to use this particular type of feeder cable forced the city to take action.

Their resolution was to grant permission to use it only during the Olympics, but not afterward. They completely disallowed the use of welding cable, much to the chagrin of all of the production companies possessing this particular type of cable, who would now have to trash it. Without the weight of the NEC behind the use of the new 600-volt feeder cable, there was no other choice. But the problem was that the NEC wouldn't write the new cable into the code unless it was UL-listed for that particular purpose. In 1987, type W and type G were added to the ampacity table for feeder cable [Table 400.5(B)], but the table didn't list ampacities for single conductors, only two- and three-conductor cables. Also, these cables were rated for 2000 volts, they were double-jacketed, and they were very heavy. No one wanted to use them.

Over time, type W and type G cables were used as the basis to get single-conductor feeder into the ampacity table. Once that hurdle was cleared, a cable manufacturer convinced UL to list their cable, albeit not as a particular cable type, but having it marked “for use in accordance with Articles 520 and 530 of the NEC.” This cable had blue insulation and was as flexible as welding cable. It seemed to be a success. But the issue was far from resolved.

The blue insulation on this cable was made of thermoplastic (PVC), not thermoset (rubber), as is the case for the entertainment cable we currently use. As the name implies, thermoset is set by heat, and then it stays set under the worst of conditions. Thermoplastic, on the other hand, retains its plasticity as it heats, cools, and reheats, over and over again. A cigarette would burn this cable, and the hot city streets of L.A. would melt it. The infamous blue cable that now permeated the industry had to be discarded.

But in the meantime, a precedent was set. Over the next revision cycle of the NEC, a USITT committee with Mitch Hefter, Ken Vannice, Randy Davidson, Mike Lanni, Mike Skinner, Dick Thompson, Mark Bauserman, Steve Terry, and others wrote proposals to allow other single-conductor cables that were listed and met other necessary requirements. The result was that type SC (thermoset or rubber), SCT (thermoplastic or PVC), and SCE (thermoplastic elastomer) cable were accepted. Type SC, sometimes called entertainment cable, is now the most commonly used cable for portable single-conductor applications.

APPENDIX 4
International Systems of Units (Si), Prefixes, and Scientific Notation

SI PREFIXES

As a matter of convenience, very large and very small numbers are often abbreviated using prefixes like "kilo," "mega," "milli," etc. These are examples of prefixes that are standardized according to the International Systems of Units (SI). For example, kilo is a prefix meaning 1000; therefore, a kilowatt is 1000 watts. The more common prefixes are listed in the table below.

SI Prefix	Abbreviation	Scientific notation	Engineering notation	Decimal equivalent
pico	P	10^{-12}	10^{-12}	0.000 000 000 001
nano	n	10^{-9}	10^{-9}	0.000 000 001
micro	μ	10^{-6}	10^{-6}	0.000 001
milli	m	10^{-3}	10^{-3}	0.001
centi	c	10^{-2}	n/a	0.01
deci	d	10^{-1}	n/a	0.1
–	n/a	10^{0}	n/a	1
deca	da	10^{1}	n/a	10
hecto	h	10^{2}	n/a	100
kilo	k	10^{3}	10^{3}	1000
mega	M	10^{6}	10^{6}	1,000,000
giga	G	10^{9}	10^{9}	1,000,000,000
tera	T	10^{12}	10^{12}	1,000,000,000,000

SCIENTIFIC NOTATION

Scientific notation is shorthand for very large or very small numbers. For example, 150,000 can be written as 15×10^4. In general, any number can be written as $a \times 10^b$, where a can be any number, and b indicates a power of ten. 2 kilowatts, for example, may be expressed in scientific notation as 2×10^3 watts, which is the same as $2 \times (10 \times 10 \times 10)$. In this example, the number "3" is the exponent and "2" is the coefficient. A negative exponent indicates that you divide by 10 rather than multiply by 10. For example, $5 \times 10^{-3} = 5 \div (10 \div 10 \div 10) = 0.005$.

ENGINEERING NOTATION

Engineering notation is similar to scientific notation except the exponent is limited to powers of three. Thus, in engineering notation, we can speak of watts, kilowatts, and megawatts, but not 2×10^4 watts. Exponents that are multiples of three correspond to the prefixes nano (10^{-9}), micro (10^{-6}), milli (10^{-3}), kilo (10^3), mega (10^6), and giga (10^9).

APPENDIX 5
Worldwide Voltages and Frequencies

Country	Frequency and tolerance (Hz ± %)	Household voltage (V) and wiring	Commercial voltage (V) and wiring	Industrial voltage (V) and wiring	Voltage tolerance (± %)
Afghanistan	50	220/380 (A) 220 (L)	380/220 (A)	380/220 (A) (3)	n/a
Algeria	50±1.5	220 (L) (1) 220/127 (E)	380/220 (A) 220/127 (A)	10kV 5.5kV 380/220 (A)	±5–10
Angola	50	220 (L) (1)	380/220 (A)	380/220 (A) (3)	n/a
Antigua	60	230 (L) (1)	400/230 (A)	400/230 (A)	n/a
Argentina	50±1.0	225 (L) (1) 220 (L) (1)	390/225 (A) 380/220 (A) 220 (L)	13.2kV 6.88kV 390/225 (A) 380/220 (A)	±10
Australia	50±0.1	415/240 (A) (E) 240 (L)	415/240 (A) 440/250 (A) 440 (N) (6)	22kV 11kV 6.6kV 415/240 (A) 440/250 (A)	±6
Austria	50±0.1	380/220 (A) (B) 220 (L)	380/220 (A) (B) 220 (L)	20kV 10kV 5kV 380/220 (A)	±5
Bahamas	60	240/120 (G) 120 (L)	240/120 (G) 120 (L)	415/240 (A) (3) 208/120 (A)	n/a
Bahrain	50 & 60	400/230 (A) 230 (L) 120 (L)	400/230 (A) 380/220 (A) 230 (L) 220/110 (K)	11kV 400/230 (A) 380/220 (A)	±6
Bangladesh	50±4	400/230 (A) 230 (L)	11kV 400/230 (A)	11kV 400/230 (A)	±5
Barbados	50±0.4	230/115 (G) (K) 200/115 (A) (E)	230/115 (G) (K) 200/115 (A) (E)	11kV 3.3kV 230/115 (G) 200/115 (A)	±6
Belgium	50±3	380/220 (A) 220/127 (A) 220 (F)	380/220 (A) 220/127 (A) 220 (F)	15kV 6kV 380/220 (A) 220/127 (A) 220 (F)	±5 day; ±10 night
Belize	60	220/110 (K)	220/110 (K)	440/220 (A) (3)	n/a
Bermuda	60±0.1	240/120 (K) 208/120 (A)	240/120 (K) 208/120 (A)	4.16/2.4kV 240/120 (K) 208/120 (A)	±5
Bolivia	50±1	230/115 (H)	230/115 (H)	230/115 (H) (3)	±5
Botswana	50	220 (L) (1)	380/220 (A)	380/220 (A) (3)	n/a
Brazil	60	220 (L) (1) 127 (L) (1)	380/220 (A) 220/127 (A)	380/220 (A) 220/127 (A)	n/a

Bulgaria	50±0.1	380/220 (A) 220 (L)	380/220 (A) 220 (L)	20kV 15kV 380/220 (A)	±5
Burma	50	230 (L) (1)	400/230 (A) 230 (L)	11kV 6.6kV 400/230 (A)	n/a
Cambodia	50	208/120 (A) 120 (L)	380/220 (A) 208/120 (A)	380/220 (A) (3) 208/120 (A)	n/a
Cameroon (FR)	50±2	200 (L) (1)	380/220 (A)	15kV 380/220 (A)	±5
Canada	60±0.02	240/120 (K)	600/347 (A) 480 (F) 240 (F) 240/120 (K) 208/120 (A) (G) 416/240 (A) (D)	12.5/7.2kV 600/347 (A) 208/120 (A) 600 (F) 480 (F) 240 (F)	+4 −8.3
Cayman Islands	60±0.01	240/120 (K)	240/120 (K) (G)	480/240 (G) 480/227 (A) 240/120 (G) 208/120 (A)	±10

Chad	50	200 (L) (1)	200 (L) (1)	380/220 (A) (3)	n/a
Chili	50	200 (L) (1)	380/220 (A) (1)	380/220 (A) (3)	n/a
China (PR)	50	220 (L)	380/220 (A)	380/220 (A)	±10
Columbia	60±1	240/120 (G) 120 (L)	240/120 (G) 120 (L)	13.2kV 240/120 (G)	±10
Costa Rica	60	120 (L) (1)	240/120 (K)	240/120 (G) (3)	n/a
Cyprus	50±2.5	240 (L) (1)	240 (L) (1)	11kV 415/240 (A)	±6
Czech Republic	50±0.1	380/220 (A) 220 (L)	380/220 (A) 220 (L)	22kV 15kV 6kV 3kV 380/220 (A)	±10
Denmark	50±0.4	380/220 (A) 220 (L)	380/220 (A) 220 (L)	30kV 10kV 380/220 (A)	±10
Dahomey	50±1	380/220 (A) 220 (L)	380/220 (A) 220 (L)	15kV 380/220 (A)	±10
Dominican Republic	60	110 (L) (1)	220/110 (K) (1) 110 (L) (1)	220/110 (G) (3)	n/a
Ecuador	60	127 (L) (1) 120 (L) (1) 110 (L)	240/120 (K) 208/120 (A) 220/127 (A) 220/110 (K)	240/120 (K) 208/120 (A) 220/127 (A) 220/110 (K)	n/a
Egypt (AR)	50±1	380/220 (A) 220 (L)	380/220 (A) 220 (L)	11kV 6.6kV 380/220 (A)	±10
El Salvador	60±1	240/120 (K)	240/120 (K) (G)	14.4kV 2.4kV 240/120 (G)	±5
Ethiopia	50	220 (L) (1)	380/220 (A)	380/220 (A) (3)	n/a
Falkland Islands	50±3	230 (L) (1)	415/230 (A)	415/230 (A) (3)	±2.5
Fiji Islands	50±1	415/240 (A) 240 (L)	415/240 (A) 240 (L)	11kV 415/240 (A)	n/a

Finland	50±0.1	240 (L) (1)	380/220	660/380 (A) 500 (B) 380/220 (A) (D)	±10
France	50±1	380/220 (A) 220 (L) 220/127 (E) 127 (L)	380/220 (A) 380/220 (D) 380 (B)	20kV 15kV 380 (B)	±10
Gambia	50	230 (A) (1)	230 (A) (1)	400/230 (A) (3)	±5 (1)
Germany (Federal Republic or West Germany)	50±0.3	380/220 (A) 220 (L)	380/220 (A) 220 (L)	20kV 10kV 6kV 380/220 (A)	±10
Germany (DDR or East Germany)	50±0.3	380/220 (A) 220 (L) 220/127 (A) 127 (L)	380/220 (A) 220 (L)	10kV 6kV 660/380 (A) 380/220 (A)	±5
Ghana	50±5	250 (L) (1)	250 (L) (1)	440/250 (A) (3)	±10
Gibraltar	50±1	415/240 (A)	415/240 (A)	415/240 (A) (3)	±6
Greece	50±1	220 (L) (1)	6.6kV 380/220 (A)	22kV 20kV 15kV 6.6kV 380/220 (A)	±5
Grenada	50	230 (L) (1)	400/230 (A)	400/230 (A) (3)	n/a
Guadaloupe	50 & 60	220 (L) (1)	380/220 (A)	20kV 380/220 (A)	n/a
Guam (Mariana Islands)	60±1 −0.08	240/120 (K) 208/120 (A) 240 (L) 120 (L)	240/120 (K) 208/120 (A)	13.8kV 4.0kV 480/277 (A) 480 (D) 240/120 (H) 208/120 (A)	+8 −10
Guatemala	60±1.7	240/120 (K)	240/120 (K)	13.8kV 240/120 (G)	±10
Haiti	60	230 (L) (1) 220 (L) (1) 115 (L)	380/220 (A) 230/115 (K) 220 (L)	380/220 (A) 230/115 (G)	n/a

Honduras	60	110 (L)	220/110 (K) 110 (L)	220/110 (K) (3)	n/a
Hong Kong (and Kowloon)	50±2	346/200 (A) 200 (L)	11kV 346/200 (A) 200 (L)	11kV 346/200 (A)	±6
Hungary	50±2	380/220 (A) 220 (L)	380/220 (A) 220 (L)	20kV 10kV 380/220 (A)	+5 −10
Iceland	50±0.1	380/220 (A) 220 (L)	380/220 (A) 220 (L)	380/220 (A) (3)	n/a
India (4) Bombay	50±1	440/250 (A) 230 (L)	440/250 (A) 230 (L)	11kV 440/250 (A)	±4
India – New Delhi	50±3	400/230 (A) 230 (L)	400/230 (A) 230 (L)	11kV 400/230 (A)	±6
India – Ramakrishna-puram (2)	50±3 25 dc	400/230 (A) 230 (L) 460/230 (P)	400/230 (A) 230 (L) 460/230 (P)	22kV & 11kV n/a n/a	±6
Indonesia	50+1	220/127 (A)	380/220 (A) 220/127 (A)	380/220 (A) (3)	±5
Iran	50±5	220 (L) (1)	380/220 (A)	20kV 11kV 400/231 (A) 380/220 (A)	±15
Iraq	50	220 (L) (1)	380/220 (A)	11kV	n/a
Ireland, Northern	50±0.4	230 (L) 220 (L) (1)	400/230 (A) 380/220 (A)	400/230 (A) (3) 380/220 (A)	±6
Ireland, Republic of	50	220 (L) (1)	380/220 (A)	10kV 380/220 (A)	n/a
Israel	50±0.2	400/230 (A) 230 (L)	400/230 (A) 230 (L)	22kV 12.6kV 6.3kV 400/230 (A)	±6
Italy	50±0.4	380/220 (A) 220/127 (E) 220 (L)	380/220 (A) 220/127 (E)	20kV 15kV 10kV 380/220 (A) 220 (C)	±5 (urban) ±10 (rural)
Ivory Coast	50	220 (L) (1)	380/220 (A)	380/220 (A) (3)	n/a
Jamaica	50±1	220/110 (G) (K)	220/110 (G) (K)	4/2.3kV 220/110 (G)	±6

Japan, East (4)	50±0.2 (5)	200/100 (K) 100 (L)	200/100 (K) 100 (L)	6.6kV 200/100 (H) 200 (G) (J)	±10
Japan, West (4)	60±0.1 (5)	210/105 (K) 200/100 (K) 100 (L)	210/105 (H) (K) 200/100 (K) 100 (L)	22kV 6.6kV 210/105 (H) 200/100 (H)	±10
Jordan	50	380/220 (A) 220 (L)	380/220 (A)	380/220 (A) (3)	n/a
Kenya	50	240 (L) (1)	415/240 (A)	415/240 (A) (3)	n/a
Korea	60	100 (L)	200/100 (K)	n/a	n/a
Kuwait	50	240 (L) (1)	415/240 (A)	415/240 (A) (3)	n/a
Laos	50±8	380/220 (A)	380/220 (A)	380/220 (A) (3)	±6
Lebanon	50	220 (L) (1) 110 (L) (1)	380/220 (A) 220 (L) 190/110 (A) 110 (L)	380/220 (A) (3) 190/110 (A)	n/a
Lesotho	50	220 (L) (1)	380/220 (L)	380/220 (L) (3)	n/a
Liberia	60±3.3	240/120 (K)	240/120 (K)	12.5/7.2kV 416/240 (B) 240/120 (K) 208/120 (D)	±1.7
Libya	50	230 (L) (1) 127 (L) (1)	400/230 (A) 220/127 (A) 230 (L)	400/230 (A) (3) 220/127 (A)	n/a
Luxembourg	50±0.5	380/220 (A) 220 (L)	380/220 (A) 220 (L)	20kV 15kV	±5 to 10
Madagascar (formerly Malagassy Republic)	50±2	220 (L) (1) 127 (L) (1)	380/220 (A) 220/127 (A)	5kV 380/220 (A) 220/127 (A)	±3
Malawi	50	230 (L) (1)	400/230 (A)	400/230 (A) (3)	n/a
Malaysia	50±1.0	240 (L) (1)	415/240 (A)	415/240 (A) (3)	+5 −10
Mali	50	220 (L) (1) 127 (L) (1)	380/220 (A) 220/127 (A) 220 (L) 127 (L)	380/220 (A) (3) 220/127 (A)	n/a

Manila	60±5	240/120 (H) (K) 240/120 (H)	240/120 (H) (K) 240/120 (H)	20kV 6.24kV 3.6kV 240/120 (H)	±5
Martinique	50	127 (L) (1)	220/127 (A) 127 (L)	220/127 (A) (3)	n/a
Mauritius	50±1.0	230 (L) (1)	400/230 (A)	400/230 (A) (3)	±6
Mexico	60±0.2	220/127 (A) 220 (L) 120 (M)	220/127 (A) 220 (L) 120 (M)	13.8kV 13.2kV 480/277 (A) 220/127 (B)	±6
Monaco	50	380/220 (A) 220 (L) 220/127 (A) 127 (L)	380/220 (A) 220 (L)	380/220 (A) (3)	n/a
Montserrat	60	230 (L) (1)	400/230 (A)	400/230 (A) (3)	n/a
Muscat & Oman	50	240 (L) (1)	415/240 (A) 240 (L)	415/240 (A) (3)	n/a
Morocco	50	220/127 (A) 200/115 (A)	380/220 (A)	380/220 (A) (3)	n/a
Nepal	50±1	220 (L) (1)	400/220 (A) 220 (L)	11kV 400/220 (A)	±10
Netherlands	50±0.4	380/220 (A) 220 (E) (L)	380/220 (A)	10kV 3kV 380/220 (A)	±6
Netherlands Antilles	50 & 60	220 (L) (1) 127 (L) (1) 120 (L) (1) 115 (L) (1)	380/220 (A) 230/115 (A) 220/127 (A) 208/120 (A)	380/220 (A) (3) 230/115 (G) 220/127 (A) 208/120 (A)	n/a
New Guinea	50±2	240 (L) (1)	415/240 (A) 240 (L)	22kV 11kV 415/240 (A)	±5
New Zealand	50±1.5	400/230 (A) (E) 230 (L) 240 (L)	415/240 (A) (E) 400/230 (A) (E) 230 (L)	11kV 400/230 (A) 415/240 (A) 440 (N) (5)	±5
Nicaragua	60	240/120 (G) (K)	240/120 (G) (K)	13.2kV 7.6kV 240/120 (G)	n/a

Nigeria	50±1	230 (L) (1) 220 (L) (1)	400/230 (A) 380/220 (A)	15kV 11kV 400/230 (A) 380/220 (A)	±5
Niger	50	220 (L) (1)	380/220 (A)	380/220 (A)	n/a
Norway	50±0.2	230 (B)	380/220 (A) 230 (B)	20kV 10kV 5kV 380/220 (A) 230 (B)	±10
Pakistan	50	230 (L) (1)	400/230 (A) 230 (L)	400/230 (A) (3)	n/a
Panama	60±0.17	240/120 (K)	480/277 (A) 240/120 (K)	12kV 480/277 (A) 208/120 (A)	±5
Paraguay	50	220 (L) (1)	440/220 (K) 380/220 (A)	440/220 (G) (3) 380/220 (A)	n/a
Peru	60	225 (B) (M)	225 (B) (M)	10kV 6kV 225 (B)	n/a
Philippines	60±0.16	220/110 (K)	13.8kV 4.16kV 2.4kV 220/110 (H)	13.8kV 4.16kV 2.4kV 220/110 (H)	±5
Poland	50	220 (L) (1)	380/220 (A)	15kV 6kV 380/220 (A)	n/a
Portugal	50±5	380/220 (A) 220 (L)	15kV 5kV 380/220 (A) 220 (L)	15kV 5kV 380/220 (A) 220 (L)	±1
Puerto Rico	60±10	240/120 (L)	480 (F) 240/120 (L)	8.32kV 4.16kV 480 (F) 415/240 (A) (3)	±10
Qatar	50	240 (L) (1)	415/240 (A) 240 (J)	415/240 (A) (3)	±6
Rhodesia	50±2.5	225 (L) (1)	390/225 (A)	11kV 390/225 (A)	±6.6

Romania	50±1	220 (L) (1)	380/220 (L)	20kV 10kV 6kV 380/220 (A)	±5
Rwanda	50±1	220 (L) (1)	380/220 (A)	15kV 6.6kV 380/220 (A)	±5
Sabah	50±0.5	240 (L) (1)	415/240/(A)	415/240 (A) (3)	±6
Saudi Arabia	60±0.5	220/127 (A) 127 (L)	380/220 (A) 220/127 (A) 127 (L)	380/220 (A) (3) 220/127 (A)	±5
Senegal	50	127 (L) (1)	220/127 (A) 127 (L)	220/127 (A) (3)	n/a
Sierra Leone	50	230 (L) (1)	400/230 (A) 230 (L)	11kV 400/230 (A)	n/a
Singapore	50±0.5	400/230 (A) 230 (L)	6.6kV 400/230 (A)	22kV 6.6kV 400/230 (A)	±3
Somali Republic	50	230 (L) 220 (L) 110 (L) (1)	440/220 (K) 220/110 (K) 230 (L)	440/220 (G) (3) 220/110 (G)	n/a
South Africa	50±2.5 25 (8)	433/250 (A) (7) 400/230 (A) (7) 380/220 A) 220 (L)	11kV 6.6kV 3.3kV 433/250 (A) (7) 400/230 (A) (7) 380/220 (A)	11kV 6.6kV 3.3kV 500 (B) 380/220 (A)	±5
Spain	50±3	380/220 (A) (E) 220 (L) 220/127 (A) (E) 127 (L)	380/220 (A) 220/127 (A)	15kV 11kV 380/220 (A)	±7
Sri Lanka Ceylon	50±2	230 (L) (1)	400/230 (A) 230 (L)	11kV 400/230 (A)	±6
St. Kitts & Nevis	60	230 (L) (1)	400/230 (A)	400/230 (A) (3)	n/a
St. Lucia	50	240 (L) (1)	400/230 (A)	11kV 415/240 (A)	n/a

St. Vincent	50	230 (L) (1)	400/230 (A)	3.3kV 400/230 (A) (3)	n/a
Sudan	50	240 (L) (1)	415/240 (A) 240 (L)	415/240 (A) (3)	n/a
Surinam	50 & 60	115 (L) 127 (L) (1)	230/115 (K) 220/127 (A) 220/110 (K)	230/115 (G) (3) 220/127 (A) 220/110 (G)	n/a
Swaziland	50±2.5	230 (L) (1)	400/230 (A) 230 (L)	11kV 400/230 (A)	±6
Sweden	50±0.2	380/220 (A) 220 (L)	380/220 (A) 220 (L)	20kV 10kV 6kV 380/220 (A)	±10
Switzerland	50±0.5	380/220 (A) 220 (L)	380/220 (A) 220 (L)	16kV 11kV 6kV 380/220 (A)	±10
Syria	50	220 (L) (1) 115 (L) (1)	380/220 (A) 220 (L) 200/115 (A) 115 (L)	380/220 (A) (3) 200/115 (A)	n/a
Taiwan (Formosa)	60±4	380/220 (A) 220 (L) 220/110 (K) 110 (L)	380/220 (A) 220 (L) 200/115 (A) 115 (L)	380/220 (A) (3) 200/115 (A)	n/a
Tanzania	50	400/230 (A)	400/230 (A)	11kV 400/230 (A)	n/a
Thailand	50	220 (L) (1)	380/220 (A) 220 (L)	380/220 (A) (3)	n/a
Togo	50	220 (L) (1)	380/220 (A)	20kV 5.5kV 380/220 (A)	n/a
Tonga	50	415/240 (A) 240 (L) 110 (L)	415/240 (A) 240 (L) 110 (L)	11kV 6.6kV 415/240 (A)	n/a
Trinidad & Tobago	60±0.5	230/115 (K)	400/230 (A) 230/115 (G)	12kV 400/230 (A)	±6
Tunisia	50±2	380/220 (A) 220 (L)	380/220 (A) 220 (L)	15kV 10kV 380/220 (A)	±10

Turkey	50±2	220 (L) (1)	380/220 (A)	15kV 6.3kV 380/220 (A)	±10
Uganda	50±0.01	240 (L) (1)	415/240 (A)	11kV 415/240 (A)	±4.5
United Arab Emirates Dubai	50±0.5	220 (L) (1)	380/220 (A) 220 (L)	6.6kV 380/220 (A)	±2 to 3
United Arab Emirates Abu Dhabi	50	415/240 (A)	415/240 (A)	415/240 (A) (3)	n/a
United Kingdom (excluding Northern Ireland)	50±1	240 (L) (1)	415/240 (A)	22kV 11kV 6.6kV 3.3kV 415/240 (A)	±6
Uruguay	50±1	220 (B) (L)	220 (B) (L)	15kV 6kV 220 (B)	±6
USA (4) Charlotte, NC	60±0.06	240/120 (K) 208/120 (A)	480/265 (A) 240/120 (K) 208/120 (A)	14.4kV 7.2kV 2.4kV 575 (F) 460 (F) 240 (F) 460/265 (A) 240/120 (K) 208/120 (A)	+5 −2.5
USA Detroit, MI	60±0.2	240/120 (K) 208/120 (A)	480 (F) 240/120 (H) 208/120 (A)	13.2kV 4.8kV 4.16kV 480 (F) 240/120 (H) 208/120 (A)	+4
USA Los Angeles, CA	60±0.2	240/120 (K)	4.8kV 240/120 (G)	4.8kV 240/120 (G)	±5
USA Miami, FL	60±0.3	240/120 (K) 208/120 (A)	240/120 (K) 240/120 (H) 208/120 (A)	13.2kV 2.4kV 480/277 (A) 480 (F)	±5
USA New York, NY	60	240/120 (K) 208/120 (A)	240/120 (K) 208/120 (A) 240 (F)	12.47kV 4.16kV 480/277 (A) 480 (F)	n/a

USA Pittsburgh, PA	60±0.03	240/120 (K)	480/265 (A) 240/120 (K) 208/120 (A) 460 (F) 230 (F)	13.2kV 11.5kV 2.4kV 460/265 (A) 208/120 (A) 460 (F) 230 (F)	±5 (lighting) ±10 (power)
USA Portland, OR	60	240/120 (K)	480/277 (A) 240/120 (K) 208/120 (A) 480 (F) 240 (F)	19.9kV 12kV 7.2kV 2.4kV 480/277 (A) 208/120 (A) 480 (F) 240 (F)	n/a
USA San Francisco, CA	60±0.08	240/120 (K)	480/277 (A) 240/120 (K)	20.8kV 12kV 4.16kV 480/277 (A) 240/120 (G)	±5
USA Toledo, OH	60±0.08	240/120 (K) 208/120 (A)	480/277 (C) 240/120 (H) 208/120 (K)	12.47kV 7.2kV 4.8kV 4.16kV 480 (F) 480/277 (A) 208/120 (A)	±5
Russia	50	380/220 (A) 220 (L) 220/127 (A) 127 (L)	380/220 (A) 220 (L)	380/220 (A) (3)	n/a
Venezuela	60	240/120 (G) 208/120 (A)	240/120 (G) 208/120 (A)	13.8kV 12.47kV 4.8kV 2.4kV 240/120 (G) 208/120 (A)	n/a
Vietnam	50±0.1	220 (L) (1) 120 (L) (1)	380/220 (A) 208/120 (A)	15kV 380/220 (A)	±10
Yemen (PDR)	50±1	250 (L) (1)	440/250 (A)	440/250 (A) (3)	±4

Yugoslavia (now Bosnia and Herzogovina, Croatia, Kosovo, Montenegro, North Macedonia, Serbia, and Slovenia)	50	380/220 (A) 220 (L)	220 (L)	10kV 6.6kV 380/200 (A)	n/a
Zaire, Republic of	50	220 (L) (1)	380/220 (A)	380/220 (A) (3)	n/a
Zambia	50±2.5	230 (L) (1)	400/230 (A)	400/230 (A) (3)	±3.75

Notes:

1. The supply to each house is normally single-phase, utilizing one phase line and the neutral of systems (A) or (G).
2. Frequencies below 50Hz and D.C. supplies are in limited areas only. The supplies given indicates the diversity of possibilities which may exist.
3. Information on higher voltage supplies to factories not available.
4. More than one area of the country has been given to illustrate the differences which exist. These may not be the only supplies available.
5. Frequency is 50Hz (eastern area) and 60Hz (western area). Dividing line is a North/South line through Shizuoka on Honshu Island.
6. Some areas are supplied via a single-wired earthed return (SWER) system (see Figure A5.1).
7. Only a few towns have this supply.
8. Refers to isolated mining districts.
9. Information not available at time of printing.

FIGURE A5.1

Source: Earl W. Roberts, *Overcurrent and Undercurrents: All About GFCIs, AFCIs, and Similar Devices*, (Reptec, 2004).

APPENDIX 6
Unbalanced 3-Phase Load Calculations

To calculate the current draw in a balanced, three-phase system, we can use the formula:

$$I=P\div(V\text{x } 3)$$

But for an unbalanced load, that formula doesn't work.

Suppose, for example, that we have five 3120-watt followspots that run at 208 volts with a power factor of 1. We can divide them into two groups of two fixtures with one left over, so we'll connect one from the black phase to the red phase, two from red to blue, and two from blue to black, as shown in Figure A6.1 below.

FIGURE A6.1
How can we calculate the current draw in an unbalanced 3-phase system as shown in the illustration?

We know that each followspot will draw 15 amps (3120 ÷ 208 = 15), so the current in the black-red circuit is 15 amps, the current in the red-blue circuit is 30 amps, and the current in the blue-black circuit is 30 amps. But it's the current in each of the phase conductors or feeder conductors that we're interested in because we have to size them correctly and know how much supply we need. The current in the black feeder is the combination of the black-red current and the blue-black current; the current in the red feeder cable is the combination of the black-red current and the red-blue current; and the current in the blue feeder cable is the combination of the red-blue current and the blue-black current. But remember, the black-red current is 120° out of phase with the red-blue and blue-black, so we can't just add the numbers. What we can do, however, is to use vectors to solve for the current in each of the feeder cables.

The illustration (Figure A6.2) is a vector diagram representing the current drawn by the group of fixtures connected from black to red ($I_{bk\text{-}red}$), the group from red to blue ($I_{red\text{-}bl}$), and the group from blue to black ($I_{bl\text{-}bk}$). Each of arrows is proportional to the magnitude of those currents, and the direction of the arrows indicates the phase angle, which is why they are each drawn 120° with respect to each other.

FIGURE A6.2
A phasor diagram showing the three load currents and the resultant currents in phase A, B, and C.

The current I_{black} can be represented by a vector from the head of $I_{bk\text{-}red}$ to the head of $I_{bl\text{-}bk}$, as shown in the next illustration, and the length of that vector compared to the other vectors will be proportional to the magnitude of the current flowing through the black feeder cable. If we can calculate the length of that vector, then we will know how much current is flowing through it.

Solving for the magnitude of I_{black} ($|I_{black}|$) is a simple calculation if you know trigonometry and you can use the law of cosines.

$$|Iblack|2 = |Ibk\text{-}red|2 + |Ibl\text{-}bk|2 - (2 \times |Ibk\text{-}red| \times |Ibl\text{-}bk| \times \cos 120°)$$

$$Ibk\text{-}red = 3.12 \text{ kW} \div 208 \text{ V} = 15 \text{ A}$$

$$Ibl\text{-}bk = 6.24 \text{ kW} \div 208 \text{ V} = 30 \text{ A}$$

$$|Iblack|2 = 152 + 302 - (2 \times 15 \times 30 \times [-0.5])$$

$$|Iblack|2 = 225 + 900 - (-450)$$

$$|Iblack|2 = 1{,}575$$

$$|Iblack| = 1{,}575$$

$$|Iblack| = 39.7 \text{ A}$$

We can calculate $|I_{red}|$ and $|I_{blue}|$ using the same formula.

$$|Ired|2 = |Ibk\text{-}red|2 + |Ired\text{-}bl|2 - (2 \times |Ibk\text{-}red| \times |Ired\text{-}bl| \times \cos 120°)$$

$$Ibk\text{-}red = 3.12 \text{ kW} \div 208 \text{ V} = 15 \text{ A}$$

$$Ired\text{-}bl = 6.24 \text{ kW} \div 208 \text{ V} = 30 \text{ A}$$

$$|Ired|2 = 152 + 302 - (2 \times 15 \times 30 \times [-0.5])$$

$$|Ired|2 = 225 + 900 - (-450)$$

$$|Ired|2 = 1{,}575$$

$$|Ired| = 1,575$$

$$|Ired| = 39.7\ A$$

$$|Iblue|2=|Ibl\text{-}bk|2+|Ired\text{-}bl|2– (2 \times |Ibl\text{-}bk| \times |Ired\text{-}bl| \times \cos 120°)$$

$$Ibl\text{-}bk = 6.24\ kW \div 208\ V = 30\ A$$

$$Ired\text{-}bl = 6.24\ kW \div 208\ V = 30\ A$$

$$|Iblue|2= 302+ 302– (2 \times 30 \times 30 \times [–0.5])$$

$$|Iblue|2= 900 + 900 – (–900)$$

$$|Iblue|2= 2,700$$

$$|Iblue| = 2700$$

$$|Iblue|= 52\ A$$

APPENDIX 7
IP Ratings and Nema Ratings

The International Electrotechnical Commission (IEC) standard for rating an electrical enclosure or housing for its protection against the ingress of foreign objects and moisture is the IP rating system. In the United States, the National Electrical Manufacturers Association (NEMA) has a similar rating system for rating enclosures, called the NEMA rating. Both systems classify enclosures according to how well they protect against the elements and harsh environments.

IP CODE

The International Protection Code, or IP Code, is a two-digit code with optional suffixes for additional information about the rating. It is always preceded by the code letters IP, which stands for international protection or ingress protection. (See Figures A7.1 and A7.2.)

FIGURE A7.1
The two-digit numeric indicators are coded as shown. The first number after the code letters indicates the degree of protection against the ingress of solid objects such as dust, dirt, bird feathers, fingers, and hands. The second number indicates the degree of protection against the ingress of water or moisture

FIGURE A7.2
IP ratings are designated with a two-digit code and an optional suffix describing the degree of protection of an enclosure from the elements or a harsh environment.

0: Not protected
1: ≥ 50 mm diameter
2: ≥ 12.5 mm diameter
3: ≥ 2.5 mm diameter
4: ≥ 1.0 mm diameter
5: Dust protected
6: Dust tight

The second number indicates the degree of protection against the ingress of water or moisture. It can range from 0 to 8, and the highest rating is 8. The numbers are interpreted as follows:

0: Not protected
1: Protection against vertically dripping water
2: Protection against dripping water at up to a 15° angle from the vertical
3: Protection against water spray at up to a 60° angle from the vertical
4: Protection against splashing water from all directions
5: Protection against low-pressure jetting water from all directions
6: Protection against a powerful jet of water from all directions
7: Protection against temporary immersion in water less than 1 meter deep
8: Protection against continuous immersion in water at a specified depth

The first optional letter indicates the degree of protection to personnel and tools. It ranges from A to D, and the letters are interpreted as follows:

A: Protection against contact with back of hand
B: Protection against contact with finger
C: Protection against contact with tool such as a screwdriver
D: Protection against contact with wire

The supplementary optional letter indicates the degree of protection specific to four items as indicated below:

H: Protection against high-voltage apparatus
M: Enclosure was in motion during water testing
S: Enclosure was stationary during water testing
W: Protection against weather

For example, if a fixture has an IP rating of 65, then it is dust tight and rated for the protection against jetting water. This rating is commonly used for equipment intended to be used outdoors. The IP standard also provides for specific means of testing enclosures. A dust-tight enclosure, for example, is tested with talcum powder sifted for specific dimensions with a specific density of powder in the chamber. More information about IP ratings can be found in IEC 60529. The document can be purchased from the IEC Web store at www.iec.ch.

NEMA RATINGS

NEMA ratings describe the application of enclosure types and the degree of protection against the environment. There are NEMA ratings for hazardous locations involving corrosive chemicals, combustibles, and gas, vapors, and dust, and there are NEMA ratings for nonhazardous locations. Since we normally avoid hazardous locations for live event production, we will only discuss the ratings for nonhazardous locations, which include NEMA types 1 through 6.

- **Type 1** enclosures are for indoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt.
- **Type 2** enclosures are for indoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, dripping water, and light splashing of water.
- **Type 3** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, windblown dust, rain, sleet, snow, and the external formation of ice on the enclosure.
- **Type 3R** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, rain, sleet, snow, and the external formation of ice on the enclosure.
- **Type 3S** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, windblown dust, rain, sleet, snow, and protect the external mechanism(s) from becoming inoperable when laden with ice.
- **Type 3X** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, windblown dust, rain, sleet, snow, and an additional level of protection against corrosion and the external formation of ice on the enclosure.
- **Type 3RX** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, rain, sleet, snow, and will be undamaged by the external

formation of ice on the enclosure that provides an additional level of protection against corrosion as well as protection against the external formation of ice on the enclosure.

- **Type 3SX** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, windblown dust, rain, sleet, and snow. They also provide an additional level of protection against corrosion as well as protection against the external mechanism(s) becoming inoperable when laden with ice.
- **Type 4** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, windblown dust, rain, sleet, snow, splashing water, hose-directed water, and the external formation of ice on the enclosure.
- **Type 4X** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of windblown dust, rain, sleet, snow, splashing water, hose-directed water, corrosion, and the external formation of ice on the enclosure.
- **Type 5** enclosures are for indoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, settling airborne dust, lint, fibers, flying particles, dripping water, and the light splashing of water.
- **Type 6** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, hose-directed water, the entry of water during occasional temporary submersion at a limited depth, and the external formation of ice on the enclosure.
- **Type 6P** enclosures are for indoor or outdoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, hose-directed water, the entry of water during prolonged submersion at a limited depth, corrosion, and the external formation of ice on the enclosure.
- **Type 12** enclosures (without knockouts) are for indoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, circulating dust, lint, fibers, flying particles, dripping water, and the light splashing of water.
- **Type 12K** enclosures (with knockouts) are for indoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, circulating dust, lint, fibers, flying particles, dripping water, and the light splashing of water.
- **Type 13** enclosures are for indoor use and provide protection to personnel against access to hazardous parts and against the ingress of falling dirt, circulating dust, lint, fibers, flying particles, dripping water, the light splashing of water, and the spraying, splashing, and seepage of oil and noncorrosive coolants.

For a complete description of NEMA enclosure ratings, see NEMA Standards Publication 250-2008, “Enclosures for Electrical Equipment (1000 Volts Maximum).” It is available from IHS (www.global.ihs.com).

IP VERSUS NEMA

According to NEMA, IP ratings cannot be converted to NEMA enclosure types and vice versa. But Figure A7.3 can be used to compare the two. If the box is marked, that means that the NEMA enclosure type exceeds the requirements for the IP designation in the left-hand column. The first seven rows of the IP rating (0X through 6X) indicate the degree of protection against hazardous parts and foreign objects, and the last nine rows (X0 through X8) indicate the degree of protection against the ingress of water.

CONVERSION OF NEMA ENCLOSURE TYPE RATINGS TO IEC 60529 ENCLOSURE CLASSIFICATION DESIGNATIONS (IP)
(CANNOT BE USED TO CONVERT IEC CLASSIFICATION DESIGNATIONS TO NEMA TYPE RATINGS)

IP First Character	NEMA Enclosure Type																										IP Second Character
	1		2		3		3R		3S		4		4X		5		6		6P		12		12K		13		
IP0_																											IP_0
IP1_																											IP_1
IP2_																											IP_2
IP3_																											IP_3
IP4_																											IP_4
IP5_																											IP_5
IP6_																											IP_6
																											IP_7
																											IP_8
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	

A = A shaded block in the "A" column indicates that the NEMA Enclosure Type exceeds the requirements for the respective IEC 60529 IP First Character Designation. The IP First Character Designation is the protection against access to hazardous parts and solid foreign objects.

B = A shaded block in the "B" column indicates that the NEMA Enclosure Type exceeds the requirements for the respective IEC 60529 IP Second Character Designation. The IP Second Character Designation is the protection against the ingress of water.

FIGURE A7.3

APPENDIX 8
Useful Formulas

Ohm's law:

V = I × R
I = V ÷ R
R = V ÷ I

Single-phase AC power formula:

P (watts) = *V* (volts) × *I* (amps) × Power Factor
V (volts) = P (watts) ÷ [*I* (amps) × Power Factor]
I (amps) = P (watts) ÷ [*V* (volts) × Power Factor]
Power Factor = P (watts) ÷ [*V* (volts) × *I* (amps)]

Three-phase AC power formula:

$P_{3\varnothing}$ (watts) = *V* (volts) × *I* (amps) × Power Factor × 1.732
V (volts) = $P_{3\varnothing}$ (watts) ÷ [*I* (amps) × Power Factor × 1.732]
I (amps) = $P_{3\varnothing}$ (watts) ÷ [*V* (volts) × Power Factor × 1.732]
Power Factor = $P_{3\varnothing}$ (watts) ÷ [*V* (volts) × *I* (amps) × 1.732]

Power factor:

PF = cosine (phase angle) × 100
PF = Power (watts) ÷ [*V* (volts) × *I* (amps)]
PF = Real Power (watts) ÷ Apparent Power (VA)

Apparent power:

Apparent Power (VA) = *V* (volts) × *I* (amps)
I (amps) = Apparent Power (VA) ÷ *V* (volts)
V (volts) = Apparent Power (VA) ÷ *I* (amps)

Peak Voltage:

$V_{peak} = V_{rms} \times 1.414$

RMS Voltage:

$V_{rms} = V_{peak} \times 0.7071$

Inductive reactance:

X_L (ohms) = $2\pi fL$
where X_L is the inductive reactance
π is pi (3.14)
f is the frequency in hertz
L is the inductance in henrys

Capacitive reactance:

$X_C = 12 \times \pi \times f \times C$
where X_C is the capacitive reactance
f is the frequency

C is the capacitance in farads

Series resistance:

$R_{total} = R_1 + R_2 + \ldots + R_{n-1} + R_n$
where n = the total number of resistors in series

Parallel resistance:

1Rtotal=1R1+1R2+…+1Rn-1+1Rn
where R_{total} is the total resistance
R_1 is the first resistor, R_2 is the second resistor, R_{n-1} is the second to last resistor, and R_n is the last resistor

Generator speed and frequency:

Speed of rotation (RPM) × number of poles = 120 × frequency (Hz)

Voltage drop:

Voltage drop = 2 × L × R × I,
where L = the length of the wire in one direction in feet or meters
R = the resistance of the wire in ohms/unit length (feet or meters)
I = the current in amps

Note: The resistance of wire is usually given in ohms per 1000 feet or 1000 meters (kilometers) at a given temperature. In that case, divide the distance of the run by 1000 to find the resistance of the length of wire. For example, if the resistance is given as 0.049 ohms per 1000 feet and the distance is 300 feet, then the total resistance of the run is 0.0147 (0.049 × 300 ÷ 1000).

Voltage drop:

VD=2×K×I×LACM
where K = specific resistance of copper [12.9 at 75°C (167° F); 11 at 32°C (90° F)]
I = current in amps
L = length of cable in feet
A_{CM} = area of the cross section of cable in circular mils

APPENDIX 9
Answers to Practice Problems

CHAPTER 1 ANSWERS

1.1 voltage
1.2 The equivalent is an on/off switch.
1.3 amps or amperes
1.4
1.5 30 volts
1.6 0 volts
1.7 opposition
1.8 This is to reduce the risk of shock.
1.9 There is less risk because the conductors are smaller and reduce the amount of energy that can be delivered in the event of a lightning strike, voltage surge, or shock.
1.10 It is important to minimize the possibility of applying the wrong voltage to the load.
1.11 The variable *I* (current) is measured in amps.
1.12 This is because an amp meter measures the total current inside of the clamp, and if a cable has outgoing and return current in the same cable, you will not be able to read the current drawn by the load without using a line splitter to clamp a single conductor.
1.13 the cross-sectional area or wire gauge, the temperature rating of the jacket or insulation, the number of current-carrying conductors in contact with each other, the ambient air temperature, and whether or not the conductors are enclosed, or they are in free air
1.14 320 amps
1.15 Ohm's law
1.16 resistance
1.17 resistance
1.18 0
1.19 1400 VA
1.20 700 watts
1.21 0.994

FIGURE A9.1

CHAPTER 2 ANSWERS

2.1 An electrical receptacle with nothing connected to it is an open circuit.

2.2 According to Ohm's law, the current is the voltage divided by the resistance, so in this case, the current is the applied voltage divided by 0, which is infinity amps. In practical terms, this is a dead short, in which case the supply would try to deliver as much current as it possibly could, but the overcurrent protection should interrupt the circuit before damage occurs. Otherwise, the components in the circuit would overheat to the point of catastrophic failure, and the weakest point in the circuit would eventually fuse.

2.3 Infinity resistance is an open circuit, so no current would flow.

2.4 Lower resistance results in higher current for the same voltage, which is why electricity presents a greater hazard in the proximity of moisture or water.

2.5 In Figure 2.4, if V_T is 240V, V_1 is 80V, and V_2 is 80V, then V_3 is 80V. ($V_T - V_1 - V_2 - V_3 = 0$V, so 240V − 80V − 80V − $V_3 = 0$, and $V_3 = 80$V.)

2.6 If four ACLs are connected in series on a 120V circuit, then 30V is dropped across each of the four lamps. (120V − $V_1 - V_2 - V_3 - V_4 = 0$V, and $V_1 = V_2 = V_3 = V_4$, so 120V − 4X = 0V and X = 30V.)

2.7 If one of the conductors creates a 2.5V drop and the other creates a 2.5V drop, then 235V would be applied to the device in a 240V circuit. (If 240V − 2.5V − 2.5V − $V_3 = 0$V, then $V_3 = 235$V.)

2.8 In a 24-volt circuit, if a lamp draws 6.25 amps then the resistance of the lamp is 3.7 Ω. ($R = V \div I$, or $R = 24 \div 6.5 = 3.7$ Ω.)

2.9 4 Ω is the least amount of resistance that would limit the to 3 A or less and keep the fuse from blowing. ($R = V/I$, or $R = 12/3 = 12 \div 3 = 4$ Ω.)

2.10 The voltage drop is 150 volts. ($V = I \times R$; $V = 1 \times 150 = 150$ V.)

2.11 If the voltage is 9 V and the current is 0.1 A, then the effective resistance of the fan is 90 Ω. ($R = V/I$, or $R = 9/0.1 = 9 \div 0.1 = 90$ Ω.)

2.12 If the voltage is 24 volts and the resistance is 150 Ω, the current is 0.16 A. ($I = V/R$, or $I = 24/150 = 24 \div 150 = 0.16$ A.)

2.13 If the current is 5 A and the voltage is 9 V, the resistance is 1.8 Ω. ($R = V/I$, or $R = 9/5 = 9 \div 5 = 1.8$ Ω.)

2.14 If the voltage is 24 V and the current is 0.12 A, then the resistance is 200 Ω. ($R = V/I$, or $R = 24/0.12 = 24 \div 0.12 = 200$ Ω.) Therefore, two 100-ohm resistors wired in series is 200 Ω.

2.15 If a load draws 6 A when a 12-volt battery is connected to it, then the resistance is 2 Ω. If the voltage is increased to 24 V and the resistance is 2 Ω, then the current will be 12 A.

2.16 If the voltage is 12 V and the current is 0.5 A, then the resistance is 24 Ω.

2.17 If the current is 10 milliamps and the resistance is 10 ohms, then the voltage is 100 mV. ($V = I \times R$; $V = 0.01 \times 10 = 0.1$ V = 100 mV.)

2.18 0.04 A

2.19 If a 12-volt battery causes a current of 0.1 amps to flow, then the resistance is 120 Ω.

2.20 10 A

2.21 100 A

2.22 1000 A

2.23 10,000 A

2.24 100,000 A

2.25 1,000,000 A

2.26 10,000,000 A

2.27 100,000,000 A

2.28 up

CHAPTER 3 ANSWERS

3.1 120 watts

3.2 12.5 amps

3.3 10.4 amps

3.4 2.4 Ω

3.5 $100 \div 12 = 8.3$ amps; $R = 12 \div 8.3 = 1.44$ Ω; $P = V^2 \div R = 81 \div 1.44 = 56.3$ W

3.6 29 minutes

3.7 11.7 hours or 11 hours and 40 minutes

3.8 $4 \times 90 = 360$ watts; $360 \div 48 = 7.5$ amps; $7.5 \div 1.2 = 6.25$; therefore, 7 batteries would be needed

3.9 8.6 amps

CHAPTER 4 ANSWERS

4.1 The net magnetic field is 0 because the two magnetic fields should be equal and opposite, so they cancel.

4.2 If there is a ground fault or earth fault and the resulting flow of current returns to the supply through the grounding or earthing conductor or through the earth, then the outgoing current through the live conductor is greater than the return current through the second conductor, so there is a magnetic field around the two conductors.

4.3 A clamp meter will not work on a multi-conductor cable like an extension cord because the magnetic field from the outgoing current in one conductor is cancelled by the magnetic field from the return current in the other conductor.

4.4 Faraday's apparatus was a transformer. It has a primary winding and a secondary winding. Transformers do *not* work with DC because the lines of flux of the magnetic field are not cutting through the conductors once current reaches its steady-state value.

4.5 (a) A single cycle of a sine wave has 360 degrees. (b) The positive peak occurs at 90°. (c) The negative peak occurs at 270°.

4.6 The only sinewave is (b).

4.7 Yes, the current waveform in a linear load like an incandescent lamp is a sinewave if the voltage waveform is a sinewave.

4.8 If an incandescent lamp is connected to a dimmer that switches the circuit off for the first quarter cycle, then turns it on during the second quarter cycle, and repeats for the negative half cycle, the resulting current waveform is not a sinewave. The resulting waveform would look like this:

4.9 In the negative half cycle, the current will flow through neutral conductor, through the load, and back to the supply through the live conductor.

4.10 If the RMS voltage is 120V, the instantaneous voltage passes through 120 volts twice; once at 45° and once at 135°.

4.11 The average value of a single cycle of a sinewave is 0.

4.12 No, the average voltage and the RMS voltage are not the same. No, the average current and the RMS current are not the same.

4.13 If a lamp produces a certain amount of light and has a certain lamp life when it's operated at 100 VDC, it would not produce the same amount of light and have the same lamp life if was operated at 100 $V_{average}$ AC, but it would if the lamp was operated with 100 V_{RMS} AC.

4.14 Yes, when current is specified, it is implied that it is the RMS value. If a system draws 150 A, then it is 150 A RMS?

4.15 In Figure 4.19, one cycle of a sinewave is produced for every single rotation of the loop of wire.

4.16 3600 RPM (60 cycles per second × 60 seconds per minute = 3600); 3000 RPM (50 cycles per second × 60 seconds per minute = 3000)

4.17 2

4.18 1800 RPM

4.19 true

4.20 Yes. Keep audio cables away from feeder cable or run them perpendicular to the feeder cable instead of parallel to the cable.

4.21 (417 amps × 3 phases × 120V) ÷ (187 amps × 3 phases × 277V) × 100 = 96.6%

4.22 325V peak

4.23 100V RMS

4.24 240V RMS

4.25 36,000 VA or 3.6 kVA

4.26 208A per phase

4.27 250 amps

4.28 The transformer can only be loaded to 80% in order to satisfy the requirements, so it needs to be capable of outputting enough current so that 150 amps is 80% of the output. If we call the output X amps, we can say that 150 amps equals 80% of X amps, or X = 150 ÷ 0.8 = 187.5 amps. Therefore, the transformer should have a rating of at least 187.5A × 120V = 22,500 VA or 22.5 kVA.

4.29 If the output is 120V and it's a 2:1 transformer, then the input voltage must be 240V. Rewiring it so that the input becomes the output and vice versa would make it a 1:2 transformer, and if the input is 240V then the output would be 480V.

4.30 The current would also be a sine wave.

4.31 (a) The magnetic field in one half of the figure-eight is in one direction, and the magnetic field in the other half is in the opposite direction. Taken as a whole, the two magnetic fields cancel, but there are still two local hot spots of strong magnetism. (b) It is not necessary because multicore cable has circuits with current flowing in opposite directions, so the magnetic fields cancel.

CHAPTER 5 ANSWERS

5.1 Europe

5.2 208V

5.3 (a) delta-wye; (b) 375 amps; (c) 125 amps per phase; (d) tap 5

5.4 Yes, there is continuity.

5.5 0 volts; subtracting (See Figure 5.8; the vectors are subtracting)
5.6 277 volts
5.7 230V – 6% = 230 – 13.8 = 216.2V; 230 + 10% = 230 + 23 = 253V
5.8 120°
5.9 ±6; ±5; 225.6V to 254.4V
5.10 109 amps per phase
5.11 233.3 kVA; 291.7 kVA
5.12 144 kVA
5.13 72 kVA

CHAPTER 6 ANSWERS

6.1 90° leading
6.2 The load with a phase angle of 40°.
6.3 LEDs are typically leading loads because their power supplies have smoothing capacitors.
6.4 A 9 Ω inductor is more energy efficient than a 9 Ω resistor because a resistor converts electrical energy to heat, which is typically dissipated and lost, while an inductor converts electrical energy to magnetism, stores it, and eventually returns to the supply.
6.5 If the current is leading the voltage, then it is a capacitive load.
6.6 (a) The frequency of DC is 0 Hz. (b) A capacitor in a DC circuit is ∞ Ω (infinity ohms). (c) A capacitor in a DC system is an open circuit.
6.7 (a) An inductor is 0 Ω in a DC circuit. (b) It is a short circuit to DC.
6.8 No, it would not draw current because a capacitor is an open circuit to DC.
6.9 It draws more current.
6.10 1
6.11 5.8 amps
6.12 0.92
6.13 10 amps
6.14 The aggregate load is non-linear and it is generating harmonics.
6.15 (1) excessive noise and heat in the feeder transformer, (2) excessive voltage drop due to higher resistance in the conductors, (3) nuisance tripping of the circuit breakers, (4) hot conductors and connectors
6.16 150 amps because 50% of 200 amps is 100 amps, and 150% of 100 amps is 150 amps.
6.17 5.5 amps because an average-reading meter only reads the fundamental (60 Hz) current.
6.18 By adding a capacitor with a reactance of 3.8 Ω.
6.19 2600 VA or 2.6 kVA (208V x 12.5A = 2600 VA)
6.20 That it is unity or PF = 1.
6.21 416.7 amps per leg (150,000VA ÷ 120V = 1,250 amps total, or 1,250 ÷ 3 = 416.7 amps per phase) and it will probably be fused at 400 amps.
6.22 K-20 because the next lowest rating, K-13, is a bit low.
6.23 No, it's not possible to have a power factor greater than 1 because a power factor greater than 1 means that the real power (watts) is greater than the apparent power (volt-amps), which is impossible. Real power is work that is done, and apparent power is the combination of real power and reactive power, and since reactive power does no work, then a power factor greater than 1 means that you would get more work out of the system than was put in.
6.24 A luminaire with a high power factor is smaller and lighter than an equivalent one with a lower power factor because it requires less current so it can use smaller wires, fuses, components, and hardware.
6.25 In a highly reactive load, the current is high but the consumed (real) power is low. Current is the flow of energy, but the energy moves back and forth between the load and the supply. The only consumed energy is due to the resistive portion of the load and line losses (due to the resistance of the copper conductors).
6.26 If a load draws 13 amps at 120 volts, the apparent power is 1560 watts.
6.27 (a) No, a K-rated transformer does not prevent harmonic current. (b) The neutral conductor and neutral bus are oversized to accommodate higher neutral current, and there is more space inside of the transformer to help it dissipate the added heat generated by higher neutral current.
6.28 An HMT has a special winding configuration that helps to cancel triplen harmonics.

CHAPTER 7 ANSWERS

7.1 If the voltage waveforms in a 3-phase system are 120° out of phase with each other, then the current waveforms are also 120° out of phase if the loads are linear.
7.2 20 amps
7.3 The black conductor is carrying 10 amps and the red conductor is carrying 10 amps. (A circuit is a loop, and the current circulates in this loop, so the 10 amps is found in each of the two phase conductors.)
7.4 (black feeder 26.5 amps; red feeder 34.6 amps; blue feeder 26.5 amps)
7.5 (a) P3∅=V×I×PF×3; P3∅=208×1.8×0.62×3=402 watts (b) 402 ÷ 0.62 = 648.4 VA
7.6 140 amps
7.7 97.1 amps, 92.3 amps, 102.3 amps
7.8 111.3 amps per leg
7.9 The switch can output 1200 amps, and 80% of 1200 is 960 total amps, or 320 amps per phase. So, if X = the number of fixtures, then X × 2080W = 208 × 320 × 0.97 × 1.732, or X = (208 × 0.97 × 1.732) ÷ 2080 = 53.8 fixtures. Rounding off, that would be 53 fixtures, or 18 fixtures connected across the black and red phases, 18 connected red to blue, and 17 connected blue to black.

CHAPTER 8 ANSWERS

8.1 (a) 666.7 A at 120 V; (b) 333.3 A at 240 V; (c) 166.7 A at 480 V.
8.2 1 HP = 745.7 watts, therefore, 350 HP = 350 × 745.7 = 261 kWm.
8.3 200 gallons ÷ 6.5 gallons/hour = 30.77 hours, or 30 hours and 46 minutes
8.4 It's important not to change the voltage selection switch while a generator is running because doing so can cause arcing in the terminal block and cause it damage.
8.5 800 amps
8.6 1200 amps
8.7 (a) 476 amps; (b) At least 172 kVA (476A × 240V = 114,240 VA; 114,240 VA × 3/2 = 171.360 kVA)
8.8 23,040 VA or larger (16 × 720W = 11,520W; 11,520W ÷ 120V ÷ 0.5 = 192 A total; 120V × 192A = 23,040 VA)
8.9 It's important to allow a generator to cool under no load before turning it off because the bearings could seize if it cools too quickly.
8.10 It's important to refill the fuel tank in a generator after each use because a partially filled tank has air with moisture that will condense and mix the fuel, causing rust and other issues.
8.11 Air filters should be changed 100 hours of operation and oil filters should be changed about every 150 hours to about 300 hours.
8.12 (a) 173.3 amps [(180 + 135 + 220) ÷ 3 = 178.3]; (b) 43.3 amps (173.3 − 120 = 43.3); (c) 24.3% (43.3 ÷ 178.3 × 100 = 24.3%)
8.13 19 watts [746 ÷ (41.7 × .94) = 19]
8.14 3.75 miles [15 miles per hour ÷ (15 minutes ÷ 60 minutes/hour) = 3.75 miles

CHAPTER 9 ANSWERS

9.1 When a lead-acid battery is charged, it outgasses, producing hydrogen and oxygen, and hydrogen is flammable.
9.2 Ni-Cad batteries should be fully discharged before recharging because they have a charge memory (memory effect), and if they are consistently recharged before they are completely depleted, they will no longer fully charge, thereby reducing their capacity.
9.3 d. All of the above (puncturing, overheating, manufacturing defects)
9.4 6.4 hours or 6 hours, 24 minutes (4.8 Ah ÷ .75 amps = 6.4 hours)
9.5 About 54 minutes (2 × 90 Wh ÷ 200 watts = .9 hours or 54 minutes)
9.6 1599 mAh (376.25 mA × 4.25 hours = 1599 mAh)
9.7 Avoid contact
9.8 Because they are highly flammable and capable of ignition if they short circuit, are overcharged, heated to extreme temperatures, mishandled, or are defective.
9.9 Because a weak cell can cause the over cells to overheat and vent with flame.
9.10 Because they are capable of ignition.

CHAPTER 10 ANSWERS

10.1 The least amount of current that can cause heart fibrillation is about 31 mA or 0.031 amps.
10.2 The least amount of current that could cause heart fibrillation for a 1.5 second shock us about 38 mA or 0.038 amps.
10.3 Wet skin makes you more susceptible to electrocution.
10.4 Some factors that influence the impedance of the human body include the amount of area of surface the skin contacts with a live conductor, whether the skin is wet or dry, the amount of pressure applied, the path current takes through the body, body shape, age, weight, and sex.
10.5 If a person wraps two dry hands around a 1-1/2" pipe, the impedance of the body can range from about 500 Ω to 1,500 Ω.
10.6 (a) If a person wraps their dry hand around a 1-1/2" pipe as in 8.2 above and the pipe is energized to 120 V, then the current will range from 80 to 240 mA (120 ÷ 1,500 = 0.08; 120 ÷ 500 = 0.24). (b) Yes, if it is a one-second shock, then it is likely to cause heart fibrillation. (c) 48 to 160 mA (120 ÷ 750 = .16; 120 ÷ 250 = .48) (d) If the pipe is energized to 230 V, then the current will range from 153 mA to 460 mA. (230 ÷ 1,500 = 0.153; 230 ÷ 500 = 0.46).
10.7 If the resistance is 1000 Ω and the voltage is 120V, then 0.12 amps or 120 mA will flow (120 ÷ 1000 = .12)
10.8 You can increase your impedance by wearing thick leather gloves or rubber voltage-rated gloves.
10.9 You should not wear synthetic fiber when you are setting up and working with power distribution because it has a low melting point, and it is a petroleum-based product that feeds the flame in the event of an arc flash.
10.10 At 20 mA, 92.5% of men and 100% of women and children can't let go, and at 30 mA, no one can let go.
10.11 If you are grasping a 1-1/2" metal pipe with two dry hands and your impedance is 1500 Ω, then 34.5 volts could cause 23 mA to flow (34.5 ÷ 1500 = 0.023).
10.12 Yes, the arc flash boundary can be larger than (or outside of) the limited protection boundary.
10.13 2.4 mA; 4.5 mA
10.14 No; no
10.15 If someone is being shocked, approximately 15 mA to 23mA can cause difficulty breathing.
10.16 The most common cause of electrical accidents on the job is overhead power lines.
10.17 The air can reach temperatures of about 19,427°C (35,000°F) in the event of an arc flash.
10.18 When copper is exposed to extremely high temperatures produced by an arc flash, it can vaporize, going from a solid state to a vapor.
10.19 An arc flash can be triggered by dust or other impurities in the air, or corrosion of insulators, water condensation, dripping water, accidental touching of live parts, dropping a tool into live equipment, high voltage between a conductor and ground, and mechanical failure.
10.20 The arc flash boundary is the distance from a live exposed conductor inside of which, in the event of an arc flash you are likely to receive second degree burns unless you are wearing the right personal protective equipment.
10.21 If the voltage being measured is 480 V, then the limited approach boundary is one foot.
10.22 Arc-flash PPE should be worn to turn on a company switch if the equipment is not properly installed, if the equipment is not properly maintained, if the equipment doors are open or not secured, if the equipment covers are off or not secured, or if there is evidence of impending failure.
10.23 Yes (voltage-rated tools and category 0 voltage-rated gloves).

CHAPTER 11 ANSWERS

11.1 If the impedance of the transmission line is 1 ohm per mile, and there are 5,280 feet per mile, then the impedance is 0.000189 Ω (1 ÷ 5280 = 0.000189). If the current is 300 A, then the voltage from one of the bird's feet to the other is 0.57 V. (V = I × R; V = 300 A × 0.000189 Ω = 0.057 V)
11.2 If we place one probe at point D and one probe at point C, then the voltage reference is 2 V (assuming the first probe is the reference probe). The voltage will be read as 116 V. (118 V − 2 V = 116 V)
11.3 The main purpose of a grounding electrode is for lightning protection or overvoltage protection, and secondarily, for a 0-volt reference.
11.4 If a water pipe is used as a grounding/earthing electrode, it is important to bond to it within 5 feet of where it enters the building because it might be converted to PVC or Pex (plastic), have an insulating gasket, or otherwise become electrically isolated from the building.
11.5 The grounding/earthing and bonding should be checked in a separately derived system because there is no electrical connection between the input and the output of a separately derived system, therefore it may not be carried through to the secondary and it may have to be re-established.
11.6 If the frame of a generator mounted to a truck or trailer serves as the grounding electrode in place of the earth, it helps to insulate the trailer from the earth to prevent a path for return current through the earth in the event of a ground fault.
11.7 The purpose of grounding/earthing the neutral conductor is to provide a stable 0 V reference.
11.8 The requirements related to driving a grounding/earthing rod when you're using a portable power generator depend on the local codes and regulations. Be sure to read and follow local codes.

11.9 It is sometimes not a good idea to drive a grounding/earthing rod because of the density of infrastructure, including underground electrical, gas, water, sewer, cable, traffic signal control cables, telephone, and other cables, pipes, and structures.

11.10 If you're working outside and you see a lightning strike, you should time the sound of thunder to gauge the distance of the strike. The 30/30 rule expresses the idea that if there is a lightning strike within about six miles of the electrical system, then it should be shut down and you should wait at least 30 minutes after the last lightning strike to start it up again. Note that NOAA recommends seeking shelter if lightning is within an 8-mile radius.

11.11 (a) It is important to bond multiple generators that are operating within 20 feet of each other so that there is an equipotential grounding/earthing zone and there are no two metal parts at a different voltage with respect to each other. If there is a difference in potential, it will equalize itself through the grounding/earthing conductors. (b) It's important to bond to a building or structure to which a generator is supplying power for the same reason—to create an equipotential grounding/earthing zone with no differences in voltage between the two. (c) The requirement for bonding to a building or structure includes bonding to a portable stage.

11.12 According to the Entertainment Electrical Safety Committee of Ontario (EESCO), all generators over 12 kW should be grounded, and those that are under 12 kW should be grounded if they are not frame grounded or use other than cord and plug connected loads. Grounding should be accomplished with one of four acceptable grounding electrodes including: (a) two 10’ ground rods spaced 10’ apart from each other and driven to full depth, (b) an approved ground plate, which is typically 10” × 16” × 1/4”, buried at a depth of at least two feet, (c) a buried metal water pipe such as a fire hydrant or water faucet, or (d) and existing metal object equivalent in size and depth to (a) or (b).

11.13 It is acceptable to use a smaller grounding/earthing conductor than the phase conductors because the grounding/earthing conductor only has to conduct current long enough to trip the circuit breaker and interrupt the circuit, which, if the grounding/earthing system is properly functioning, only takes a very brief amount of time. That's why it's important to have a low impedance to ground/earth, so that a high fault current flows in the event of a ground/earth fault.

11.14 If a grounding/earthing conductor is too long, or it has loops in it, it increases the impedance of the grounding/earthing system, which causes less current to flow in the event of a ground/earth fault, and therefore it takes longer to interrupt the circuit.

11.15 The main bonding jumper is an important part of an electrical system because it establishes the path for fault current back to the supply in the event of a fault to the metal housing of the electrical system. Without it, the metal parts will stay energized instead of tripping the overcurrent protective device.

11.16 The equipment grounding conductor or circuit protective conductor helps clear a ground/earth fault by providing a low impedance path for fault current back to the supply, which, in turn, causes the overcurrent protective device to interrupt the circuit.

11.17 Using a “ground lift adapter” to interrupt ground loops can create a potentially lethal situation. Their intended purpose is to make the ground/earth, not to break it. It connects a 3-wire system to a 2-wire system that has no ground/earth by connecting the grounding/earthing pin to the green tab, which is then bonded to the metal junction box on the receptacle with a metal screw.

11.18 Ground/earth loops can interfere with lighting and/or video equipment. They can cause noise in video systems and unstable or unreliable operation in lighting systems.

11.19 The problem with using two bonding jumpers at different locations in the same electrical system is that it creates a dual path for return current through both the neutral and the grounding/earthing conductors. This is known as “objectionable current.” The grounding/earthing conductor should only have current flowing through it in the event of a ground/earth fault.

11.20 In an isolated ground/earth system, it's important to bond the isolated ground/earth and the building ground/earth in order to create an equipotential voltage plane or zone where no two pieces of metal are at different potentials or voltages, and to create a low impedance path to the supply in the event of a ground fault from the building supply.

11.21 If a live conductor were to make electrical contact with a metal equipment enclosure, metal conduit, or metal stage when the electrical system is not properly bonded, then the metal conductive parts would stay energized instead of tripping the circuit breaker or blowing the fuse.

11.22 The grounding/earthing electrode is typically located near the service entrance of a building or near the service panel on the wall opposite the service entrance.

CHAPTER 12 ANSWERS

12.1 To clear a fault as quickly the impedance of the grounding conductor should be as low as possible.

12.2 Fuses have a voltage rating because once they open, they have to be able to withstand the applied voltage. If they are not rated for the applied voltage, then they can arc and continue to conduct, thereby defeating the purpose of the fuse.

12.3 An HRC fuse is a high rupture capacity fuse designed to interrupt high currents without damaging itself or the electrical system. They are typically used in power distribution systems to interrupt feeder currents.

12.4 A properly rated fuse is designed to withstand the open circuit voltage for 30 seconds or to have an interrupt resistance of at least 1000 ohms.

12.5 The purpose of a time-delay fuse is to allow normal inrush currents for loads like motor, capacitors, and incandescent lamps without blowing the fuse.

12.6 The purpose of filling a fuse with quartz-sand is to quench the arc of a fuse when it blows. The arc produces intense heat, which turns the sand into glass, and glass is an insulator.

12.7 (a) 80,000V (10,000 × 8 = 80,000V); (b) Lightning, crossed transmission lines

12.8 A thermal breaker senses current through a bi-metallic strip, which bends in proportion to the heat caused by current flowing through it. The ambient air temperature affects how much heat needs to be added to reach the trip level; the higher the air temperature, the lower the trip current.

12.9 Thermal circuit breakers are more forgiving of voltage spikes and surges because quick spikes and surges don't heat the bi-metallic strip enough to cause the circuit breaker to trip.

12.10 The purpose of combining thermal overload protection with magnetic circuit protection is to provide both overload protection and short circuit protection in one device.

12.11 A magnetic circuit breaker operates by sensing the magnetic field generated by the current flowing through the circuit. When it exceeds the rated current, it closes the armature which opens the switching contacts.

12.12 Magnetic circuit breakers are more accurate than thermal circuit breakers because they are not influenced by the ambient air temperature.

12.13 The ambient temperature affects thermal circuit breakers by adding to the thermal load and changing the reaction by the bi-metallic strip. The ambient air temperature does not affect magnetic circuit breakers.

12.14 Type B miniature circuit breakers will trip instantaneously when the current is between 3 and 5 times the rated current.

12.15 An RCD (residual current device) is a device designed to interrupt a circuit when there is 30 mA or more of leakage current. It senses the difference between the outgoing current and the return current by passing the conductors through a toroid wrapped with wire, which sends a signal to a solenoid controlling the switching contacts.

12.16 A GFCI (ground fault circuit interrupter) is a device designed to interrupt a circuit when there is 6 mA or more of leakage current. It senses the difference between the outgoing current and the return current by passing the conductors through a toroid wrapped with wire, which sends a signal to an integrated circuit chip controlling the switching contacts.

12.17 The main difference between an RCD and a GFCI is that an RCD interrupts a circuit if there is 30 mA or more of leakage current, and a GFCI interrupts a circuit if there is more than 6 mA of leakage current but not less than 4 mA.

12.18 The difference between a Class A and a Class B GFCI is that a class A interrupts a circuit when there is 6 mA or more of leakage current, which means it's a personnel protection device, but a class C GFCI interrupts a circuit if there is 20 mA or more of leakage current.

12.19 *ANSI E1.19, Recommended Practice for the Use of Class A Ground-Fault Circuit Interrupters (GFCIs) Intended for Personnel Protection in the Entertainment Industry* does not cover European power distribution systems.

12.20 GFCIs should be used any time there is water or moisture in close proximity to a circuit or an electrical system (about 8 feet) or when circuits are located in wet locations. This includes outdoors (unless the stage is covered and there's no chance it can get wet), in pools, fountains, stages with water effects, and other locations where there is a likelihood that the circuits could get wet.

12.21 GFCIs should be used for branch circuits for lighting on an ice rink because ice is conductive.

12.22 GFCIs should not be used if tripping them can create a hazard, such as with emergency lighting circuits, life-support systems, etc.

12.23 GFCIs have an integrated circuit that is powered by the hot/live conductor. If it is dimmed, the voltage level will eventually drop below the operating voltage of the IC chip and the GFCI will stop working, thus the circuit will be unprotected.

12.24 A GFCI can operate without an equipment grounding conductor. The circuit senses the difference in current between the outgoing current and the return current, which does not include the grounding conductor.

12.25 If you accidentally touch a hot/live conductor and the neutral conductor at the same time, then all of the outgoing current will be returned through the neutral conductor and the GFCI will not offer any shock protection.

CHAPTER 13 ANSWERS

13.1 Increase the PWM frequency of the LED luminaires.

13.2 1.3 times

13.3 Because they operate on low-voltage DC and constant current, and it is difficult to control the current and dimming level with conventional dimming techniques.

13.4 Non-linear

13.5 The lower the PWM frequency, the more likely it is to cause flicker on video or film.

13.6 Reverse phase-control dimming requires the switch to interrupt the circuit under load, which would draw an arc and damage the TRIAC or SCR.

13.7 The firing angle varies between 0° and 89° in the positive half cycle and from 90° to 359° in the negative half cycle. The higher the firing angle, the dimmer the light source.

13.8 Unmatched positive and negative half cycles would cause a DC offset and that would produce excess heat, which would eventually damage the switching device.

13.9 A single SCR would only work with one half cycle of the waveform because they are directional devices and they can only conduct in one direction.

13.10 It opposes the sudden change in the flow and direction of current because it is an inductor.

13.11 Because the current is interrupted, instead of rising quickly it drains from the circuit and does not cause filament sing; therefore, it does not need a choke.

13.12 (a) Forward and reverse phase-controlled dimmers alter the current waveform and create a complex wave, which is rich in harmonics. (b) A sinewave dimmer maintains the sinewave shape and does not create current distortion or harmonics.

13.13 Current flowing in the neutral conductor is not an issue unless it exceeds the ampacity of the neutral conductor because the neutral is the only normally current-carrying conductor without a fuse or circuit breaker.

13.14 Filament sing is caused by a spike in current when a forward phase-controlled dimmer switches on during each half cycle, and that causes the filament to vibrate and produce sound.

13.15 (a) The rise time is the time is takes for the current to rise to its peak level when a forward phase-controlled dimmer switches on during each half cycle. (b) Adding a choke can change the rise time in a forward phase-controlled dimmer; the larger the choke, the longer the rise time and the less the filament will sing.

13.16 215°

13.17 The fundamental frequency is 50 Hz; the second harmonic frequency is 100 Hz; the third harmonic frequency is 150 Hz.

13.18 Triplen harmonics sum in the neutral conductor because they are multiples of three times the frequency of the fundamental (3×, 9×, 15×, etc.), and when the frequency multiplies, so does the phase angle between phases. Since the phase angle of the fundamental frequency is 120°, the phase angle of the triplens is always 360°, which is the same as 0°, meaning they are in phase and reinforce instead of cancel.

13.19 Assuming a linear dimming curve, the dimming level would be 25%.

CHAPTER 14 ANSWERS

14.1 Conductors have overcurrent protection because they have a limited ampacity, and the OCP protects against overloading and short circuits.

14.2 A 400-amp, 3-phase switch can supply 400 amps per phase, or a total of 1200 amps.

14.3 369 amps per phase (20A × 208V × 24 ÷ 120V = 832 total amps; 30A × 208 × 3 ÷ 120V = 156 total amps; 20A × 6 = 120 total amps; 832A + 156A + 120A = 1,108A total, or 369A per phase)

14.4 From point A to B, the voltage will read 120 V; from B to C it will read 2 V; from C to D it will read 116 V; and from D to A it will read 2 V.

FIGURE A9.2

14.5 5.4 volts ($V_D = 2KIL/A_{CM}$; $V_D = 2 \times 10.5 \times 16 \times 100 / 6{,}320 = 5.3$ V)

14.6 The cable with the 90°C temperature rating.

14.7 Harmonics are higher in frequency, therefore they exhibit more skin effect, which increases resistance and heat. The ampacity of conductors should be de-rated if they are carrying high harmonic content.

14.8 (a) There are six circuits and 12 current-carrying conductors in contact with each other. (b) According to Table 520.44(C)(3)(a), the ampacity should be de-rated 30% (70% of full ampacity).

14.9 The voltage rating is the maximum voltage the outer covering or insulation can withstand before it exceeds the dielectric strength or insulating value.
Making or breaking a connection under load can cause an arc flash, and feeder cable is typically connected to a high-ampacity supply, it is larger in diameter, and therefore it is capable of conducting a lot of energy.

14.10 IP65

14.11 (a) The voltage rating is 125V phase to ground and 250V phase to phase, and it is a 30-amp connector. (b) It has three poles.

14.12 (a) 405 amps; (b) 320 amps

14.13 (a) type SC; PPC; H07RN-F

14.14 4.9 volts (.49 × 200 amps × 50 meters ÷ 1000 = 4.9)

14.15 Powerlock connectors have a plastic cam that insulates the copper contacts when they are not mated, which provides finger protection against personnel coming into contact with a live component of the connector and receiving an electric shock.

14.16 (a) six; (b) 12; (c) 70%

14.17 (a) The resistance increases; (b) It creates more heat.

14.18 An L6-20 connector is rated 250 volts, 20 amps.

14.19 No more than three connector pairs can be used in the first 100 feet (30 meters), and after that, one connector pair can be used for each additional 100 feet (30 meters).

14.20 NEMA 3R provides protection to personnel against access to hazardous parts and against the ingress of falling dirt, rain, sleet, snow, and the external formation of ice on the enclosure.

14.21 IP65 enclosures are dust tight and protect against continuous immersion in water less than one meter deep.

CHAPTER 15 ANSWERS

15.1 (a) Higher operating voltage results in lower current draw because, according to the power formula, a higher voltage value for the same power and power factor results in a lower current value. (b) Operating at higher voltage reduces the current draw, which means you can connect more fixtures to a single branch circuit, use fewer circuits and perhaps fewer power distribution units, and less total supply.

15.2 Trick question! There is not enough information to know the power factor. You would have to also know the power in watts to calculate it.

15.3 1495 VA (230 V × 6.5 A = 1495 VA)

15.4 24 amps (30 A × .8 = 24)

15.5 (a) (74 + 72.6 + 75.9) ÷ 3 = 222.5 ÷ 3 = 74.2; (b) The maximum deviation is 1.7 amps (75.9 − 74.2 = 1.7); (c) (1.7 ÷ 74.2) × 100 = 2.3%

15.6 833.3 amps per phase (300 kVA × 1000 ÷ 120 V = 2500 total amps or 833.3 amps per phase)

15.7 The feeder transformer could be in failure mode, meaning it is starting to fail and it could fail at any time.

15.8 It's important to turn on circuits and loads one at a time for a controlled turn-on in case something is shorted, mis-wired, or otherwise malfunctioning.

15.9 (a) Either 120° or 180°, depending on the brand. (Look inside the male connector and see the groove to make sure.); (b) If it's not fully inserted and twisted it can be a high-resistance connection, which can cause it to heat up.

15.10 A feeder transformer should be relatively silent under load. If it is humming loudly under no load then it is likely in failure mode, meaning it could fail at any time.

15.11 (a) The display will read 0 volts even if there is voltage on the terminals. (b) You can ensure the meter is working properly by using the three-point method, which is to test the tester on a circuit that you know is hot, then meter the circuit in question to verify there is no voltage, then test the tester on the hot circuit again.

15.12 One out of twelve males (over 8%) is color blind, so it's easy for that segment of the population to confuse colors, which can lead to a dead short in the system, and energizing the switch with a short will cause an arc flash.

15.13 RGN is the practice of reversing the gender of the ground and neutral feeder conductors to prevent someone from accidentally connecting a hot conductor to the ground or neutral terminals of a switch or a portable power distribution unit.

15.14 The degrees of rotation to fully terminate a camlock connector depends on the brand; some rotate 120° and some rotate 180°.

15.15 When a circuit is interrupted under load, it draws an arc, which could cause an arc flash, depending on the amount of current being drawn at the time.

15.16 The purpose of test ports is to provide a safer means of metering voltage in a power distribution system.

15.17 (a) If all of the circuit breakers are off, the voltage between the ground and neutral should be about 0 volts. (b) If there is voltage in that situation, then it could be that the neutral is shared with another system, and the voltage is due to current flowing in the neutral, which produces voltage drop. (c) If the voltage is more than 3 or 4 volts, then it could be due to excessive voltage drop.

15.18 In the event that the insulation is damaged, metering the voltage without shock protection could lead to shock or electrocution.

15.19 It's important to meter the current in all five conductors to know whether or not the neutral conductor is overloaded, whether or not there is harmonic content in the system, whether or not there is a secondary bond that is causing current to return through the grounding conductor (which could cause conductive surfaces to have stray voltage and become a shock hazard), and to know if there is excessive leakage or induced current in the grounding conductor.

15.20 Turning off the power before allowing arc lamps to cool could cause them to rise in temperature even after the power has been turned off, and that could cause them to break at the pinch seal.

APPENDIX 1 ANSWERS

A1.1 What is electricity? Electricity is the transfer of energy through the motion of charge-carrying electrons.

A1.2 What is the name of the negatively charged particle in an atom? An electron.

A1.3 When current passes through resistance, it produces heat. If you have two conductors with the same amount of current, and one of the conductors had a lower resistance than the other, which would get hotter? The conductor with the highest resistance would get hotter.

A1.4 If current passing through resistance produces heat, would a current-carrying conductor get hotter or cooler if you shortened its length? The conductor would get cooler if you shortened its length.

A1.5 If electrical resistance is caused by sub-atomic particles bumping into each other and causing friction, which has less resistance, a conductor with a larger cross-sectional diameter or a conductor with a smaller cross-sectional diameter? A conductor with a larger cross-sectional diameter has lower electrical resistance.

A1.6 What the purpose of the insulation around a conductor? The purpose of insulation surrounding a conductor is to prevent electrical shock and to prevent faults to ground and other conductors.

A1.7 What would happen to the insulation around a conductor if the resistance of the conductor is too high or the current flowing through the conductor is too high? If the resistance of a conductor is too high or the current flowing through the conductor is too high, then the insulation will start to break down. If it gets hot enough it can melt the insulation.

A1.8 When an electron is pulled away from the orbit of an atom, the atom becomes _____. When an electron is pulled away from the orbit of an atom, it becomes ionized.

A1.9 What is the polarity of the charge of an ionized atom? The polarity of an ionized atom is positive.

A1.10 What makes some materials better conductors than other materials? Some materials are better conductors than other materials because of their atomic structure.

A1.11 If lightning is the flow of electricity, what is the conducting medium? Lightning is electricity flowing through the air. The conducting medium is air. When the voltage is high enough, as it is with lightning, the air can become ionized and conduct electricity.

A1.12 In order for current to flow, there has to be a _____? In order for current to flow, there must be a conductive path from the supply, through the circuit, and back to the supply. In other words, there has to be a complete circuit.

A1.13 What prevents current from flowing where we don't want it to? Insulation prevents current from flowing where we don't want it to.

A1.14 What is the likely consequence of running a power distribution system over full capacity? The likely consequence of running a power distribution system over full capacity is that it will produce too much heat that will destroy or deteriorate components like connectors and insulation (assuming it doesn't trip a circuit breaker or blow a fuse first).

A1.15 What is an example of an insulating material? Examples of insulating materials include glass, quartz, rubber, plastic, air, silicon rubber, etc.

A1.16 Which is more conductive, tungsten or iron? Tungsten is more conductive than iron.

A1.17 What is the inverse of resistivity? The inverse of resistivity is conductivity.

A1.18 Why is the direction of current convention opposite that of the flow of electrons? Current convention was established before the knowledge that it was produced by the flow of negative charges.

A1.19 Is conventional current flow toward or away from the positive terminal of a battery? Conventional current flow is from the positive terminal of a battery, through the circuit, then towards the negative terminal of the battery.

A1.20 How do rubber gloves help prevent electric shock? Rubber gloves help prevent electric shock by insulating your hands from a current-carrying conductor.

A1.21 Why is it important to inspect cables and connectors before putting them into service? It important to inspect cables and connectors before putting them into service to insure the integrity of the insulation has not been compromised by cuts, cracks, holes, or breaks, and that connectors are not broken or mismatched.

A1.22 If the insulation on a cable is cut, cracked, punctured, or broken to the extent that you can see bare copper wire, why is it a hazard? If the insulation on a cable is cut, cracked, punctured, or broken to the extent that you can see bare copper wire, the cable is a shock hazard.

References

Beaty, H.W., Fink, D.G.; *Standard Handbook for Electrical Engineers*, 15th Edition; New York, NY: McGraw-Hill; 2007.

Bhatia, A.; *Battery Room Ventilation and Safety*; Continuing Education and Development, Inc.; Woodcliff Lake, NJ: 2018, March 20.

Bowker, N.; *Guidance Notes: Cable Colour Changes*; Eastbourne, UK: PLASA; 2005.

British Standard Institution; *BS 7671:2001—Requirements for Electrical Installations*; London: BSI; 2004.

British Standards Institution; *BS 7909:2011—Code of Practice for Temporary Electrical Systems for Entertainment and Related Purposes*; London: BSI; 2011.

Cadick, J., Capelli-Schellpfeffer, M., Neitzel, D., Al Winfield; *Electrical Safety Handbook*, 4th Edition; New York, NY: McGraw-Hill; 2012.

Colour Blindness. Retrieved from http://www.colourblindawareness.org/colour-blindness/

Earley, M.W., Coache, C.D., Cloutier, M., Sargent, J., Hohengasser, E., Frost, G., Vigstol, D.; *National Electrical Code® Handbook*. 2020 Edition; New York, NY: McGraw Hill; 2008.

El-Sherif, N.; "Now That Industrial GFCIs Are Here, Inspectors Have a Proactive Option for Shock Protection"; *IAEI Magazine*; 2014, January/February; International Association of Electrical Inspectors.

Entertainment Electrical Safety Committee of Ontario; *Grounding of Generators in the Entertainment Industry*; Ontario, Canada: EESCO; 2013.

Entertainment Services and Technology Association; *American National Standard E1.19- 2015: Recommended Practice for the use of Class A Ground-Fault Circuit Interrupters (GFCIs) Intended for Personnel Protection in the Entertainment Industry*; New York: ESTA; 2017.

Entertainment Services and Technology Association; *American National Standard E1.24- 2012 (R2017): Entertainment Technology Dimensional Requirements for Stage Pin Connectors*; New York: ESTA; 2017.

Giancoli, D.C.; *Physics*, 4th Edition. Englewood Cliffs, NJ: Prentice Hall; 1995.

Hughes, R.; *Home a "Total Loss" after Battery Explodes, Causes Fire;* 2019, October 8; http://wcnc.com.

Hughes, T.P.; *Networks of Power: Electrification in Western Society, 1880–1930*; Baltimore, MD; John Hopkins University Press; 1983.

International Association of Electrical Inspectors; *Soares Book on Grounding and Bonding*, 13th Edition; Richardson, TX: IAEI; 2017.

Irwin, J.D., Kerns, D.V.; *Introduction to Electrical Engineering*; Englewood Cliffs, NJ: Prentice Hall; 1995.

Jonnes, J.; *Empires of Light: Edison, Tesla, Westinghouse and the Race to Electrify the World*; New York, NY; Random House; 2004.

Mobsby, N.; *Practical Dimming*. Cambridge, UK: Entertainment Technology Press; 2006.

National Fire Protection Association; *NFPA 70: National Electrical Code*, 2017 Edition; Quincy, MA: NFPA; 2016.

National Fire Protection Association; *NFPA 70E: Standard for Electrical Safety in the Workplace*, 2018 Edition; Quincy, MA: NFPA; 2018.

Ott, H.W., Whitlock, B., Shirk, D., Olson, B., Muncy, N., Ebersole, D., Schluter, B., Herrick, J., Williams, M.; *Integrating Electronic Equipment and Power into Rack Enclosures*; Fairfield, NJ: Middle Atlantic Products; 2010.

Roberts, E.W.; *Overcurrents and Undercurrents: All About GFCIs, AFCIs, and Similar Devices*; Mystic, CT: Reptec; 2004.

Siemens Industry, Inc.; *Degrees of Protection for Enclosures of Electrical Equipment*; Norcross, GA; 2019, May.

Terry, S.; "*New Power Tools Provide Quality and Efficiency"; Protocol Magazine*; Portland, OR; Fall 2007.

Underwriters Laboratory; UL Mark Artwork; www.marks.ul.com

USITT Recommended Practice RP1: Contact Function Assignments for Multi-Circuit Circular Pin Connectors Used for the Distribution of Multiple Lighting Circuits; United States Institute for Theatre Technology, Inc., 6443 Ridings Road, Syracuse, NY 132206-1111.

van Beek, M.; *Electrical Safety for Live Events*; Cambridge, England; Entertainment Technology Press; 2004.

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