Chapter 11

ELECTRICITY

The history of stage lighting is much older than the history of electricity in the theatre. For example, the Greek plays, now thousands of years old, were played out of doors. However this does not indicate a lack of concern for lighting conditions. Historians report that some of the plays whose action begins at dawn (e.g., the *Agamemnon*) did begin at dawn. Hours later in the dramatic festival the end of the tragedy may have actually happened at sunset. Even if these speculations are not true, it is apparent that the authors of the Greek tragedies were well aware of the effect on an audience of changes in natural lighting. They often used these changes as images in their writing.

Much later, when the theatre moved indoors, artificial lighting became necessary for visibility if not for dramatic purposes. Soon experimenters were devising special oil lamps with reflectors and even color media in the form of bottles filled with colored liquid (wine, perhaps?) Still later, the Elizabethans again depended on natural light which entered their partially indoor theatre through a hole in the roof.

Early lighting

During the eighteenth century when scene painting reached monumental heights with the work of the Bibbiena family, stage lighting was dedicated to the illumination of painted illusion. To this end, the lighting was made as shadowless as possible to avoid revealing any imperfections in the surface of the fabric on which the painting was done. Shadows in the setting were the province of the painter. This lighting was not only flat, but also dim and at very low color temperature—it came from candles and oil lamps. Actors performed in the same kind of light at only slightly brighter levels. One source describes the lighting "equipment" over the actors as a "candle hoop" which "hung in dripping radiance." Concentrating on one's characterization must have been a challenge on that stage.

Limelight

More recently, the limelight was invented. It consisted of a piece of limestone heated to incandescence by means of a gas flame from a blowpipe. The gas was usually acetylene which, when mixed with air in the proper proportions produces a hot clean flame. In other proportions the mix can be highly explosive. Later oxygen was substituted for air, making an even more explosive mixture possible. Leaky piping leveled more than one theatre of the era. At about the same time, gas lighting replaced the candle and oil lamp "borderlights" which hung in the flies not far from highly flammable wing and drop scenery—a situation that would give a modern fire marshal nightmares. Theatre fires were common and often deadly. When, in the nineteenth century, the electric lamp was introduced into the theatre to replace the highly dangerous gas lamps, it was greeted with enthusiasm. However the electrical source offered as a substitute for the limelight did not fare as well. It was the electric arc, a spark set up between two pieces of carbon. The light most resembled that often observed today when an electric welder is in use. It was cold in color, flickering and noisy. On the other hand, the limelight produced a complexion-flattering warm white light that was steady and practically noiseless. Therefore the shift to the arc light was resisted in spite of the explosive danger of the limelight. However, as better electric arcs were developed, the arc light became the standard source for follow spotlights and remained so until quite recently when it has been replaced by the powerful enclosed arcs of high intensity discharge lamps.

Theatre fires

Carbon arc follow spotlight

Sadly, the introduction of the incandescent lamp did little for the development of an incandescent-source spotlight because the early lamps were ill-suited for use with a lens. The incandescent spotlight had to await the development of the concentrated filament lamp in the 1920s. Today the incandescent lamp is being seriously challenged by more efficient discharge sources.

Early incandescent lamps

Electrical current is the energy source for almost every aspect of modern stage lighting. Therefore designers and technicians must understand electrical current to use it effectively and safely.

The Nature of Electrical Current

Early experimenters discovered that there were apparently two kinds of electricity. One could be produced by rubbing amber with cat fur and the other by rubbing glass with silk. These were first termed "resinous" and "vitreous" electricity. Later, Benjamin Franklin suggested that vitreous electricity be called "positive" and resinous "negative. These terms still persist although, as we shall shortly see, they cause some confusion.

"Positive" and "negative" electricity

Modern experimenters have established that there are indeed two kinds of subatomic particles associated with electrical phenomena. The electron, moves about when electricity flows and the proton which provides the attraction that makes the electrons flow.

Electricity and Electrical Current

Although common discourse refers to almost every kind of electrical phenomena as "electricity," scientific accuracy requires that we distinguish between *electricity* and *electrical current*. Therefore the following definitions will prevail in this text:

Electricity

Electricity refers to electrical charges created when a surplus of electrons is built up on some object while a matching deficiency is created elsewhere. No flow takes place until a circuit is completed that allows the electrons to flow and almost instantaneously restores the balance. Such charges are often called static electricity.

Static electricity

Lightning

The most spectacular electrical charge phenomenon is lightning. Lightning bolts are the evidence of a huge unbalance being eliminated by passage of electrons from cloud to cloud or from the earth to a cloud. Man-made charges, minuscule compared to lightning, are often stored in devices known as capacitors. These are essential parts of electronic apparatus such as television sets and strobe lights. Electrical charges can also be unintentionally built up by friction such as those encountered when you scuff over a carpet on a dry day and suddenly discover that a charge has been built up on your body when it is unpleasantly discharged upon grasping a doorknob.

Electrical current

Electrical current is a flow of electrons that takes place when a conductive path is established between the terminals of a source of electrical energy such as a battery or generator. Most of the electrical equipment in the theatre, including lamps, motors etc., is energized by electrical current. It will be the principal subject of the discussion to come.

Electrical flow is a source of energy.

Atoms in their normal state are electrically balanced, having equal positive and negative charges. The positive charges exist as protons and the negative ones as electrons. In many materials one or more electrons are detachable, if energy is applied. When this happens the atom becomes electrically unbalanced because it has more protons than electrons. This imbalance known as an *electrical potential*, a kind of pressure that causes the detached electrons to want to flow back to the protons deficient in electrons giving up the energy that unbalanced them in the process. Thus energy can be derived from electron flow.

Energy is required to produce electricity or electrical current.

Clearly, energy must be supplied to produce either electricity or electrical current. In a dry cell, for example, this energy comes from chemical reactions that cause a surplus of electrons to build up on the negative terminal and a deficiency to be reflected on the positive. In a generator, mechanical energy is supplied, from a water or steam turbine, for example. Note the semantic difficulty: a *surplus* of electrons (negative charges) results in a charge on the *negative* terminal; a deficiency is reflected at the *positive* terminal. When a circuit is established the flow will be from negative terminal to positive terminal. Ben Franklin's arbitrary decision naming the kinds of electricity still haunts us.

A "surplus of negatives"

As we shall repeatedly discover, much electrical engineering is devoted to usefully recovering as much of the energy put into an electrical system as possible.

When electrons flow, they usually flow through something, although if under enough pressure, they will pass through a vacuum. Controlling their flow involves the use of conductors, which allow their flow and insulators, which prevent it. As we shall see, "allow" and "prevent" are relative terms which must always be qualified by indicating the pressure (voltage) driving the electrons.

"Flow" of Electrons

Although it is easy to picture a stream of electrons flowing through a wire much as water flows through a pipe, and this analogy is often used, the best information indicates that the actual flow more nearly resembles a row of dominoes toppling one after the other as they fall. A detached electron moves in a way that causes another to be detached and the first to be reattached. The newly detached electron moves still another and so on throughout the circuit. The effect, however, is the same as a constant flow as far as most applications are concerned. Nevertheless we will occasionally need to remind ourselves of the real nature of electron flow when trying to understand what goes on inside of transistors, silicon controlled rectifiers and other solid state devices.

Conductors

These are materials with an electron on the outer part of each atom that is easily detached. Once detached, these electrons can become part of an electrical current. Conductors vary in the ease with which electrons can be detached. Silver, copper and aluminum are among the best conductors. Other materials such as carbon or tungsten which have quite firmly attached electrons are poor conductors. The term resistance refers to the ease or reluctance with which various materials part with electrons. As resistance increases it takes more and more energy to detach the electrons.

Resistance

Choice of type of conductor depends on the purpose in mind. If the goal is to move a maximum electrical current along the conductor with minimum loss, the best conductor that is economically feasible is chosen, usually copper or aluminum. If, on the other hand, the purpose is to convert electrical current into heat, a high resistance conductor such as tungsten or nichrome is used.

The following is a list of good conductors commonly used in theatrical applications and some of those found in nature which influence the safe use of electrical current:

silver
mercury
lead
aluminum
iron and steel
moist concrete
copper
brass
impure water
zinc
most metals
moist earth

Here is a list of poor conductors some of which are much used in electronics applications:

tungsten
silicon
most nonmetals
carbon
nickel-chromium alloys (Nichrome)

It is important to distinguish between poor conductors and insulators. Poor conductors will carry current and, within limits, will not be harmed by its passage although they will exact a toll in the form of heat converted from the energy of flow of the current. Insulators will not carry current at all up to the point where they break down and are punctured, or char or burn allowing the current to pass.

Insulators compared with poor conductors

Semiconductors

Silicon: the basis of the semiconductor world

A number of materials exhibit the property of conducting current in one direction quite well and almost totally opposing it in the opposite direction. These are known as semiconductors. They are at the very heart of modern solid state electronics, forming the essential parts of dimmers, control circuitry, computers and myriad other devices without which modern technology both within and outside of the theatre could not exist. Although there are a number of elements and alloys that can form semiconductors, by far the majority of those in use are based on the element silicon which has been "doped" with minute amounts of other materials.

In their nonconducting direction semiconductors perform like the insulators described below. They block the flow of current only up to certain voltages. At higher voltages they can break down and conduct, but at the expense of being damaged or destroyed.

Insulators

These are materials which have no detachable electrons. Except under certain rather exotic quantum conditions sometimes called "tunneling," they totally block the flow of current through them up to a point beyond which they are punctured or otherwise damaged and electrons flow. Insulators are used to control the flow of electrons into whatever path the engineer wishes and to provide protection to those who handle current-carrying parts.

Lightning

By far the commonest of all insulators is air, the dryer the better. Mile upon mile of electrical transmission lines depend on the insulating value of air to keep the electrons from straying away from their planned path. Of course, even air has its limits as a lightning bolt clearly demonstrates. Once air has been ionized (electrons have been detached from its atoms, leaving them charged) it becomes a conductor and the lightning bolt carries huge amounts of current until the imbalance created by the storm is eliminated.

Here is a list of insulators commonly found in use in the theatre and in other places where electrical current is in use:

air
almost all plastics
rubber
dry cloth
fiberglass
silicone rubber
glass
porcelain
dry paper
dry wood
pure deionized water
Teflon

Pure water is an insulator

Note that the insulating value of many materials depends on their being dry. Even a slight amount of moisture may change an insulating material into a dangerously conductive one. This is because water, except at its most pure state, is an excellent conductor of current. Remarkably, highly purified and deionized water is used as an insulating coolant for very large xenon lamps where it is circulated through openings in the electrodes to cool them. If this water were conductive, it would short the apparatus and destroy it.

Electron Flow

Path of electron flow

A return path is necessary

Electron flow provides a way of transferring energy from one device to another whether that device is a tiny signaling device in a control board or the power supply for a 1000 horsepower motor. Energy put into the system causes the electrons to be detached creating a surplus of electrons at the negative pole of the generating source and a deficiency at the positive pole. If there is a conductive path between the two related poles, electrons will flow until the imbalance is restored. It is very important to understand the rules of this flow. In order for electrons to be attracted and to flow: *There must be a continuous conducting path from the negative pole of the generating device back to the attracting positive pole of that same device.* If there is no such path, no flow will occur and no energy can be transported. For example, connecting the positive pole of one dry cell to the negative pole of another will not result in any flow. Only if the remaining poles of the two batteries, one negative and one positive are connected, thus creating a complete circle, will the flow occur. Put another way the rule is: *Without a return path, no current will flow.*

Circuit

Each complete path in an electrical device is called a circuit. Many circuits can be interwoven into hugely complicated devices, but ultimately each circuit must be so arranged that it relates its own surplus of electrons to its own deficiency. Note that electrical parts in a complex device may actually serve as parts of several circuits at the same time, the attractions for the electrons sorting themselves out as though each circuit were isolated.

Conservation of energy

When the electrons flow in such a way that they restore the balance, they give up their extra energy and the system returns to a neutral state. If a continuous flow is needed, energy must be constantly fed into the system to maintain the unbalance. As far as physics is concerned, none of the energy inserted into an electrical system is ever lost. It is converted into various forms, but the total amount remains the same. However practical utilization of the energy is another matter. Much of it may be "lost" by being inadvertently converted into a form not wanted by the users of the system. Usually this comes down to the energy being converted into unwanted heat.

The Simple Circuit

Reduced to its most elementary form, a circuit consists of a source of electrical current, conductors to carry the electrons through the complete loop back to the source, insulators to keep the electrons on their path and some device to utilize the energy released as the electrons flow. (Figure 11.1) Usually the circuit also includes a switch to enable the user to turn the flow on or off.

A flashlight is an example of a circuit only slightly more complicated than this. It usually utilizes more than one battery although these act as though they were one.

Note that the order of the parts in a simple circuit makes no difference to its operation. Even if a switch is included it makes no difference where the switch is installed. Also note that the same amount of electrons flows through the entire circuit. Normally it is the current-using device which controls the amount of flow although the capacity of source could also be the limiting device.

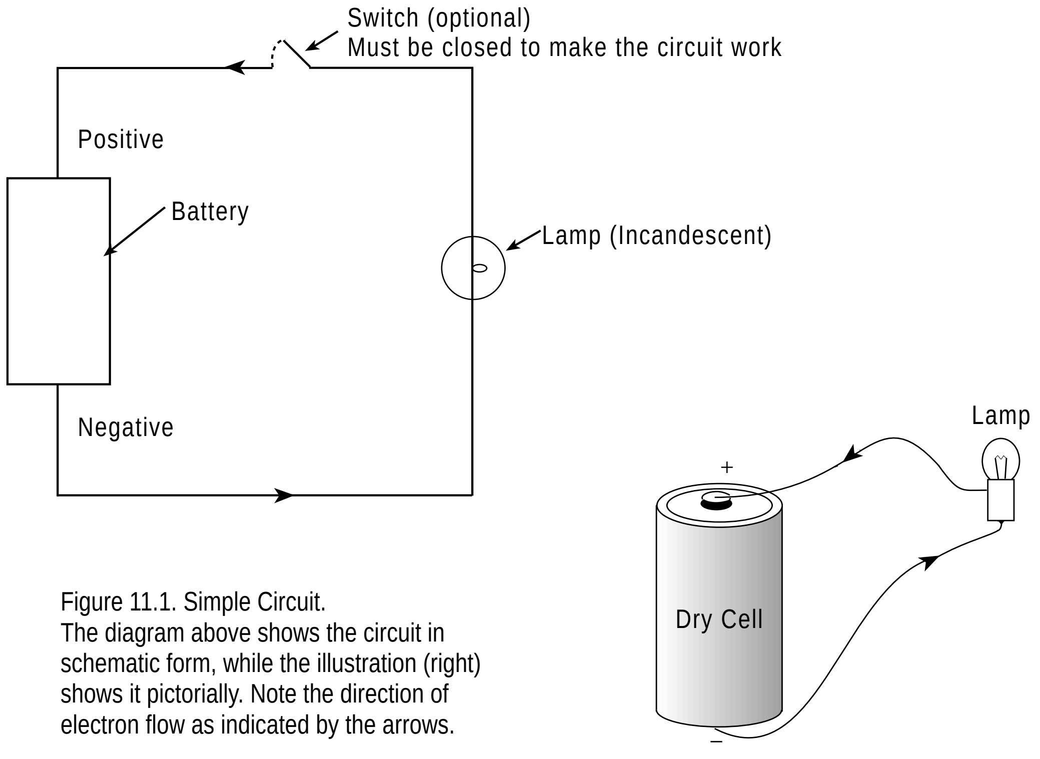

Figure 11.1. Simple Circuit.
The diagram above shows the circuit in schematic form, while the illustration (right) shows it pictorially. Note the direction of electron flow as indicated by the arrows.

Series and Parallel Circuits

Although the variations in electrical circuitry are almost infinite, two general categories must be noted here: the series circuit and the parallel circuit. A series circuit is simply a variation on the simple circuit wherein a number of devices are inserted into the circuit to utilize or control the flow (Figure 11.2). Like the simple circuit, the same number of electrons will flow throughout the entire circuit and a break anywhere in the circle will shut down the whole circuit. The resistances of the parts of the circuit add up to form the total resistance of the circuit (see below for details of electrical mathematics).

Series circuit

A good example of a series circuit is a low-cost string of Christmas tree lights in which there is only one conductor looped from light to light. If one light fails by burning out, the entire string goes dead unless special lamps have been installed that jump over the break when a lamp fails. Series circuits are often used in safety control circuitry in the theatre where the purpose is to be sure that all of the various elements in the circuit are in their proper condition before allowing the action to proceed.

A parallel circuit is one in which there are a number of paths the electrons can follow to make their return to the positive pole (Figure 11.2). This circuit is the most common of all, being used in almost every lighting circuit on stage and in homes and businesses. Opening any one path in a parallel circuit will not shut off the remaining paths. Note that parallel circuits require more wire.

Parallel circuit

Perhaps the most important part of this study of series and parallel circuitry is to develop a clear understanding of the phrases, "in parallel with…" and "in series with…" These describe the relationship between two or more parts of a circuit. When a device is "in series with" another piece or pieces of equipment this means that the device that is in series can exert control over the others. If, for example, a switch is in series with a string of lighting fixtures, that switch can turn the entire string on or off.

"In series with…"

When a device is said to be in parallel with other equipment it has no direct influence over the other things included in the circuit. The lamps in a set of borderlights, for instance, are "in parallel" with each other, and if one lamp burns out, the others remain on.

"In parallel with…"

Sometimes circuits are described as "series-parallel." This means that parts of the circuit may be in series but that other parts are in parallel or that there are several series circuits which are in parallel with each other. Even more complicated patterns may exist.

Series-parallel

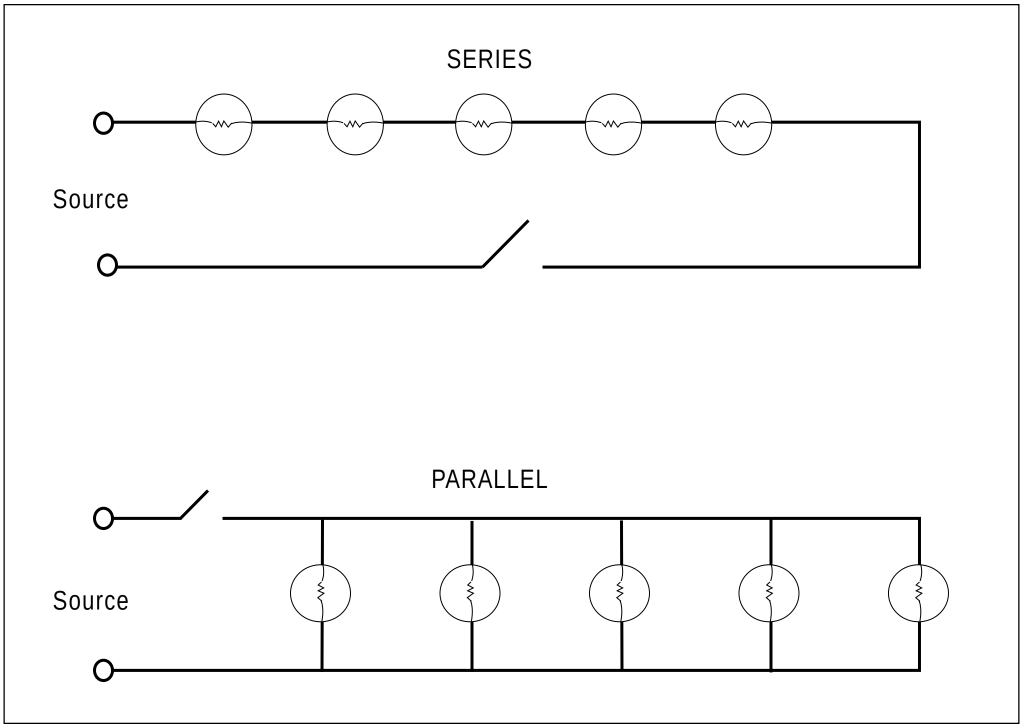

Figure 11.2. Series and Parallel Circuits. Note that in a series circuit there is *only one path* for all of the electrons. Any break in the loop stops the flow completely. The same number of electrons must flow through the entire circuit, giving rise to the phrase "in series with…" which describes the situation where the current in a given piece of equipment is dependent on that flowing through the rest of the circuit.

In parallel circuitry there can be as m any paths as desired. Breaking any one of them merely causes the load in that path to cut off without disturbing the remainder. Thus the phrase "in parallel with…" refers to a situation where each piece of equipment that is part of the circuit is independent of the current flowing through the others.

Modern electronic dimmers are a typical example of the way these terms are applied: The main current-carrying part of the dimmer is *in series* with the load (the lamps). This makes it possible for the dimmer to control all of the lamps attached to it. However, the dimmer control circuitry requires its own supply of power, albeit small. This control power is *in parallel* with the lamp load and remains on whether the lamps are dimmed out or remain on.

Electrical Mathematics

The terms that appear in electrical formulae and in descriptions of electrical apparatus are:

Resistance (Ohm): The opposition that a conductor applies to a stream of electrons flowing through it. All conductors have resistance except a few esoteric substances which have zero or near-zero resistance when cooled to very low temperatures. Resistance appears in electrical formulas as "R." Its unit of quantity is the Ohm, named for Georg Simon Ohm, an early experimenter with electricity.

Impedance: This is a resistance-like opposition to flow encountered only when alternating current is flowing. It is measured in Ohms and functions like resistance in most, but not all cases. It is explained below.

Voltage: Voltage is also named after an early experimenter, Alessandro Volta. It is the pressure that causes the detached electrons to flow and is also known as Electromotive Force (EMF). Voltage appears in formulas as "E" for EMF. Note that "V" is also sometimes used but not in any context of physics, where "V" has long been reserved for "velocity."

Ampere: This is the unit of quantity. It refers to the number of electrons flowing through a conductor. It is an absolutely measurable quantity described as the number of electrons needed to deposit 0.001118 grams of silver per second when the current is flowing through a neutral silver nitrate solution. This could be translated into an actual, but incredibly large, number of electrons. The ampere is abbreviated "I" because the letter "A" is already used in an even more basic formula in physics": F = MA (force equals mass times acceleration). "Ampere" is almost always shortened to "amp." Current carrying capacity is often labeled "ampacity."

Ohm's Law

The most basic of all electrical formulae is Ohm's law:

$$E = I \times R$$

i.e., *voltage equals amperage times resistance*.

Every student of electrical phenomena should memorize this formula which describes the relationship between the elements of a simple circuit. Note that if one knows any two of these elements, the third can be easily calculated. Simple algebraic variations on Ohm's law are as follows:

$$I = \frac{E}{R} \quad \text{or} \quad R = \frac{E}{I}$$

The lighting technician may occasionally need to determine the resistance of parallel or series circuits. The formulae are as follows:

For series circuits: $R = r + r + r + r \ldots$

For parallel circuits: $\frac{1}{R} = \frac{1}{r} + \frac{1}{r} + \frac{1}{r} \ldots$

In which R = total resistance of the circuit and r = the individual resistance of the components

The Power Formula

Ironically, although Ohm's law is the basic formula for all electrical circuits, the theatre lighting technician will seldom use it directly. Instead he or she will use the power formula. This happens because manufacturers and suppliers of equipment for the theatre have already made the most basic calculations using Ohm's law and have labeled their products in watts or amperes.

Power formula

The Watt: All of the electrical units so far defined deal with elements of the flow of electrons in a circuit. However none of them deal directly with the amount of power being carried by that circuit and delivered to whatever device is utilizing it. The watt is the unit that does this. Simple logic indicates that the amount of energy carried by a stream of electrons will be the product of the number of electrons times the force that causes them to move. This is analogous to the energy carried by a stream of water in a pipe, which would be the product of the amount of water and the pressure driving it.

Energy transfer is described in watts.

The mathematical definition of a watt is: 1 amp x 1 volt = 1 Watt. The formula is:

$$W = E \times I$$

In which W = the energy carried, i.e., watts; E the voltage driving the electrons and I the number of electrons moving stated in amperes. It is common for this equation to be written W = V x A using the first letters of the names of the quantities instead of the scientific notation. Either is correct as long as the users know that V = voltage, not velocity and A = amperes, not acceleration.

The Kilowatt and the Kilowatt Hour

Kilowatt

Kilowatt hour (kWh)

A watt represents a very small amount of energy—even a small night-light lamp is rated at four watts. Therefore the common way of counting watts is by thousands, termed *kilowatts*. Both watt and kilowatt express the amount of energy being transferred at any given moment, not the total amount over a period of time. Since multiplying the quantity per second by time is a more practical way of measuring energy, the term *kilowatt hour* (kWh) has been devised. It represents any sum of wattage that adds up to 1000 and flows for one hour. For example a 100 watt lamp running for 10 hours would use a kilowatt hour of electrical current as would a 2000 watt lamp operating for one half hour.

Cost of operation

Electrical current is sold by the kWh. The hourly cost of operating any electrical device can be calculated once the wattage is known and the kWh rate being charged. If, for example, a spotlight draws 2000 watts and the cost of power is 12¢ per kWh, each hour of operation of the spotlight will cost 24¢. If a number of luminaires or other equipment are being operated at the same time, the cost of operation will equal the sum of the individual devices times the cost per kWh. Note that actual calculations of cost of operation can become much more complicated because of dimming. Although electrically dimming a lamp reduces the amount of current it draws, the dimmers themselves and any auxiliary equipment such as ballasts may also draw current. The result is a complex computation.

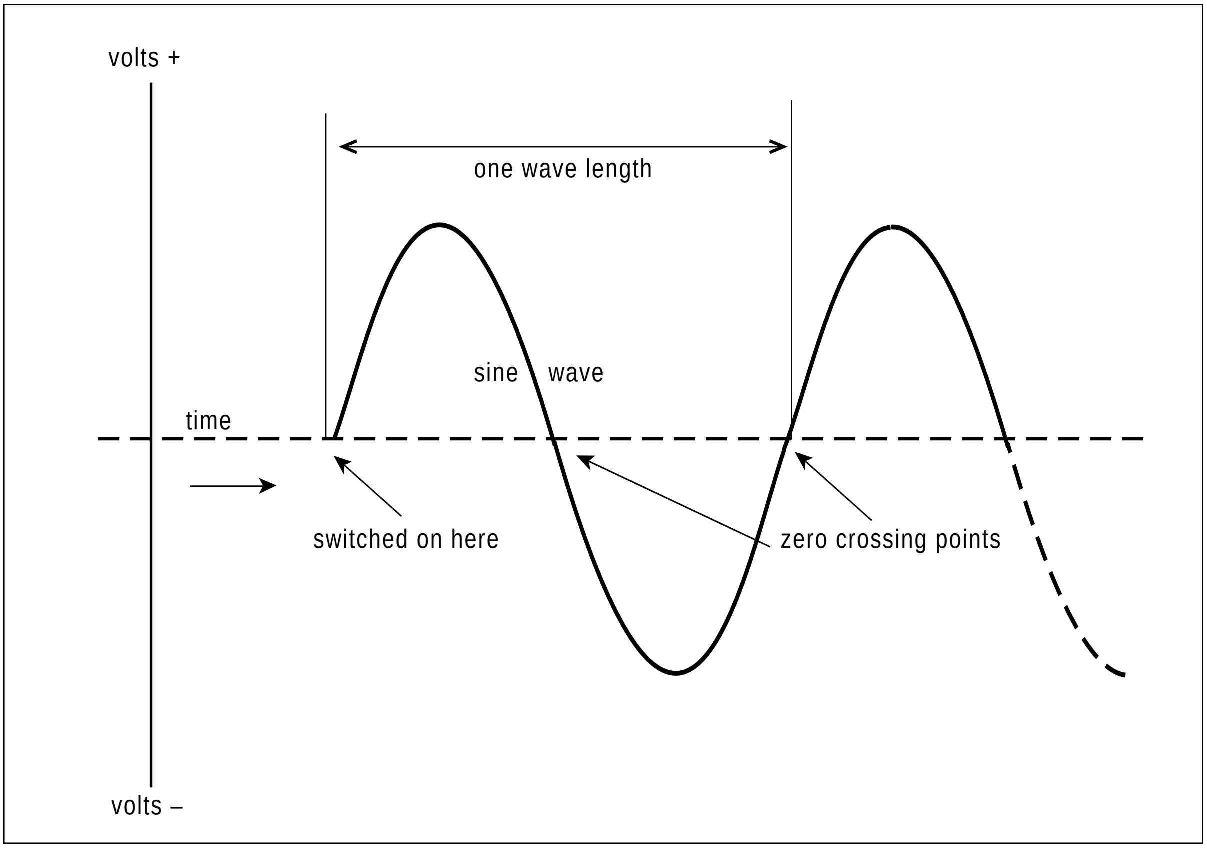

Figure 11.3. Alternating Current. This diagram illustrates the standard alternating current produced by power generators throughout the world. The sine waveform is the natural result of the rotating coil(s) in the generator (See Figure 11.4). This constantly changing voltage will induce voltages in any conductor within its magnetic field.

The Heat Formula

Electrically generated heat

Whenever current flows through a conductor, with the exception of rare superconductor situations, some of the energy being transmitted is converted into heat. Unless heat is being sought, such as inside an incandescent lamp, this heat represents wasted energy and also may prove hazardous. The formula which describes how electrical current is converted into heat is:

$$H \text{ (in calories per second)} = 0.24\, I^2R$$

Note that voltage does not appear directly in the formula although it has figured into the determination of the amperage. The factor, 0.24 is simply a constant that causes the product to come out in calories. *It is particularly important to note the 1^2 part of this formula*. It figures prominently in electrical safety.

Generation and Distribution of Electrical Current

The generation and distribution of electrical current are interlocked because large generating equipment must often be located in remote locations for the reasons mentioned below. The conditions imposed by long-distance transmission of power directly influence the way electrical current is used in the theatre and everywhere else. Long distance transmission of power has, until quite recently, required that the power be in the form of *alternating current* (AC) i.e., current that swings regularly in the manner shown in Figure 11.3. Although high voltage direct current (DC) is now used to transmit huge amounts of energy over long distances with greater efficiency than AC, most distribution of current still utilizes AC circuitry.

Alternating current

We begin with an examination of the alternating current generator. This device can be as small as the alternator in your car or as huge as those at Boulder Dam. It works on a very basic principle of physics: *When a conductor is placed in a moving or changing magnetic field an electrical potential is developed in that conductor. If a path is provided, current will flow and energy may be derived from that flow.* It is important to note that the energy comes from energy of movement imparted to the generator, not from the magnetic field which merely provides the condition for the conversion. Therefore all generators must be provided with a source of energy of motion (a prime mover). The larger the generator, the larger the prime mover must be. Typical prime movers are water power created by a huge hydraulic dam or the energy developed by a huge steam turbine which must, in turn, be driven by a boiler fueled by coal, oil or even atomic energy.

Prime movers

The demand for power in our mechanized society is far larger than the output of even the largest single generating station. Therefore generating plants across the country are interconnected so that many power sources can function as one. Such power grids are able to accommodate mammoth changes in the amount of energy demanded as large cities turn on all of their street lights at once or large plants start or stop, many at the same moment. Normally these grids can also pick up the load if a part

Power grids

of the system is suddenly destroyed, such as in a major earthquake. However, the sensitive and precise electrical control apparatus of these grids have their limits. Under certain rare but possible conditions, an entire grid can sequentially become overloaded and go out of service creating a widespread blackout. This can create one of the many kinds of emergencies that a theatrical lighting system must be equipped to handle. Emergency lighting will be further discussed later in this chapter and in the next.

Parts of Generators

All generators must fulfill the basic requirement above: they must subject one or more conductors to a moving or changing magnetic field. This means, in the case of generators, that either the conductors or the magnet must move, but not necessarily both. In small generators such as those in automobiles, the magnet(s) remain fixed and coils of insulated wire attached to the driven shaft rotate. This moving portion is called an *armature*. The current induced in the armature is transferred to the fixed part of the generator by a series of brass or copper rings mounted around

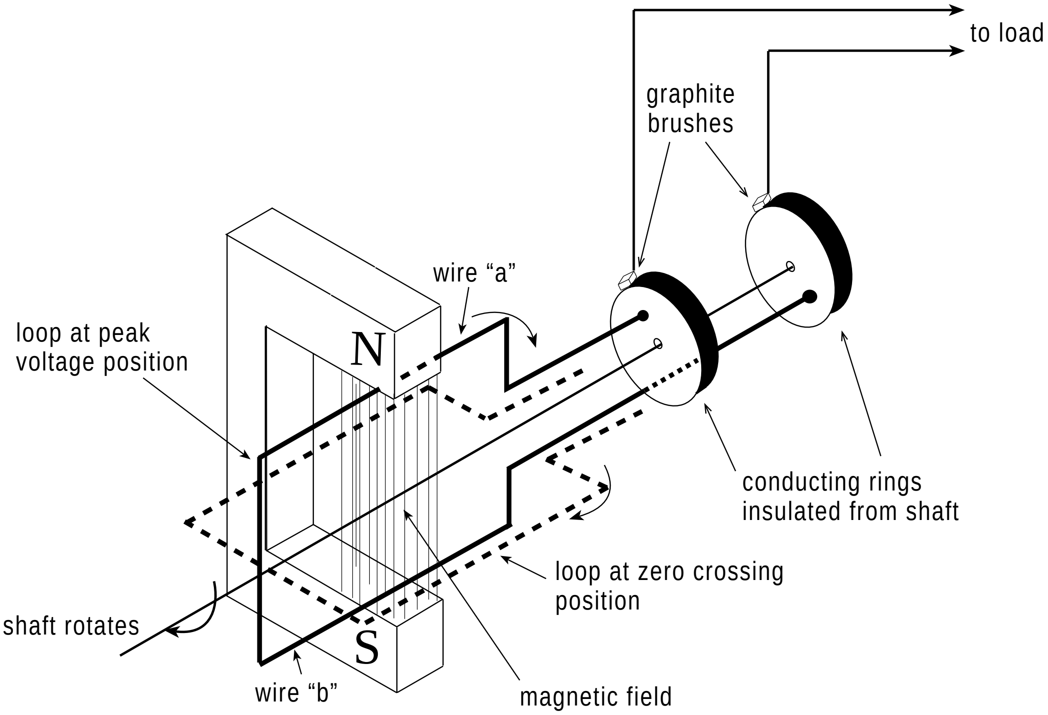

Figure 11.4. The AC Generator. Generation is based on the fact that any conductor exposed to a moving or changing magnetic field will have voltage induced into it. In this simple generator, the conductor is the moving part. Note the wire loop which moves with the rotating shaft. The dotted outline denotes the position of the loop at a zero crossing when no voltage is being generated. As the loop rotates to the point where wire "a" passes the "N" pole of the magnet (the heavily outlined position), the voltage rises to its positive maximum. As the loop continues to rotate, voltage drops again toward zero and reverses. Then, as "wire "b" rotates toward the "N" pole, the voltage reaches a negative peak. Finally, as the rotation continues, the negative voltage dwindles toward zero as the loop moves into its original position.

The electrical energy is removed from the moving part of the generator by the slip-ring arrangement diagrammed. The graphite brushes slide over the moving surface of the rings transferring the current to the fixed wiring supplying the load.

the shaft which contact “brushes.” These are blocks of graphite that slide over the surface of the moving rings and collect the current. Graphite is used because it is slippery and a conductor of electrical current. This arrangement is known as the *commutator*. In large generators the magnets are moved and the coils of wire in which the current is induced remain stationary.

Armature

Commutator

While actual generators in power plants are much more complicated, one can visualize how alternating current is produced by imagining a single loop of insulated wire being rotated between the poles of a simple horseshoe magnet, its current commutated by a simple slip ring arrangement. See Figure 11.4. If one begins with the loop of wire exactly at a neutral position with reference to the magnetic field between the poles of the magnet and imagines the coil rotating clockwise, the following sequence of voltages will be generated: (Note that we must keep track of the two halves of the loop labeled “a” and “b.”) As “a” moves toward the “N” pole a positive voltage will be generated in the loop (Figure 11.4). This voltage will increase as the conductor approaches the point of maximum magnetic field peaking as it passes the “N” pole and declining as it continues to rotate toward the next neutral position. Continuing the rotation, the voltage in the loop reverses because “b” is now approaching the “N” pole. This reversal point is known as the *zero crossing* and is vital to the operation of most modern theatrical dimmers. As it passes the pole the voltage reaches a negative peak. Then the loop continues rotating, again passing the point where it started.

Zero-crossing point

Cycle

The rotating coil produces the fluctuating voltage.

A single complete pattern of voltages containing one positive and one negative peak is known as a *cycle* (Figure 11.3). The frequency with which these cycles occur will depend on the speed of rotation of the shaft carrying the wire loop. In the real world of power generation the speed of rotation of the generator is carefully controlled to maintain 60 Hertz (cycles per second) alternating current. (60 Hz. AC) which is the standard in the USA. Some European countries utilize 50 Hertz current which means that their generators rotate slower than ours. The name *Hertz* has been substituted for *cycle* to honor an early experimenter in electrical phenomena.

60 Hz current

Hertz

If one could see the electrons moving in a conductor carrying alternating current, one would see electrons rushing first in one direction then the other changing direction each 1/120th of a second. While this may seem fast, electrons are capable of changing direction billions of times per second making 60 Hertz seem slow.

If nothing distorts the pattern of voltage produced by the generator, its graph (Figure 11.3) will display a sine wave. This is a geometrical form that may be created by plotting the values of the sines of all of the angles the coil passes through as it rotates, measured from the zero-crossing point. The sine wave is a fundamental reference to which many other wave forms are compared.

Phase

When it is necessary to describe how two waves relate to each other it is common to refer to their *phase* (ø), a term which refers to the point in the cycle under discussion. For example, two voltages might be referred to as “180 degrees out of phase.” This means that the positive pulse of one wave lines up exactly in time with the negative pulse of the other causing them to cancel each other. Note how the number of degrees relates to the position of the generating coil. Other phase relationships are common and often significant when they occur in dimming apparatus.

3 phase current

Also, in the real world, power generators normally have three coils moving with relationship to the magnetic field. This results in greater efficiency and produces what is known as three phase 60 Hertz alternating current (3ø 60Hz AC). It is standard throughout the USA, Canada and in many other locations. 50 Hz current is standard in much of Europe and also in other countries. The phase relationship between the three voltages is 120° reflecting the fact that the three generating coils are located at 120° intervals around the generator shaft (or multiple coils are arranged to produce the same effect.)

Continuous DC

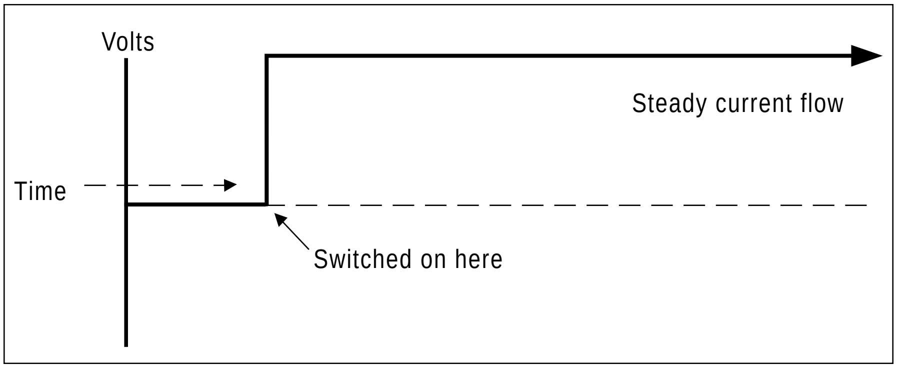

Figure 11.5. Steady Direct Current. Note that, once turned on, this current has no further changes in voltage until turned off. This means that it produces an unchanging magnetic field that cannot induce voltage in any nearby conductors except at the moment of turning on or off. This type of DC is produced by batteries and perfectly filtered DC power supplies.

Other Kinds of Current

Continuous DC: The current, typically derived from a battery, consists of a steady flow of electrons moving in the same direction. (See Figure 11.5) When the current is turned on, it immediately jumps to its full value and remains at that level until turned off or otherwise altered. Since it is unchanging, except for the brief moment when it is turned on or off, continuous DC cannot produce any of the effects arising from the actions of changing or moving magnetic fields. Since most modern electrical apparatus depends on the fluctuations of alternating current for its operation, including most modern dimmers, direct current can be a threat to this equipment.

Power supplies

The theatre utilizes direct current from batteries as a supply for lanterns, torches and the like where supply wiring would be inappropriate and for emergency lighting unless a special generator is provided. Also, continuous DC is necessary to the operation of a wide variety of electronic apparatus. This is usually supplied by a "*power supply," a device which converts AC into DC and filters to remove any pulsations. Power supplies are often built into electronic gear although they are also available as separate units. They can be built to supply voltages ranging from a few volts needed for most transistor-operated devices to high and po-

Pulsating DC

tentially deadly voltages such as those used in the picture tubes of televisions and computers.

Power supplies are also needed to control the current flow and operate some types of discharge lamps used in the theatre. For example, xenon lamps, some of which draw as much as 10,000 watts, require a very smooth DC supply for their operation plus a "spike" of high-voltage DC to start them. Other HID lamps have similar requirements. It is important to note that the starting pulses are particularly dangerous.

Pulsing DC: This kind of current is produced by DC generators such as automotive generators, and by devices called rectifiers, which convert AC into DC. It consists of a series of positive-only (or negative-only) pulses whose shape may resemble that of one half of an AC wave. (See Figure 11.6) Pulsing DC is used unfiltered in some types of electrical welders and battery chargers but it is usually filtered to smooth it into continuous DC.

It is vitally important for the theatre technician to know what kind of current is being supplied and to determine whether it meets the needs of equipment about to be attached to it. For example, attaching a transformer-operated device to a DC supply might destroy it.

Square waves

Other Electrical Wave Forms: Electronic equipment can be devised to shape the wave to almost any specification. For instance, certain kinds of equipment utilize square waves. Digital data sent to dimmers from control consoles is in the form of a stream of square wave pulses of varying length.

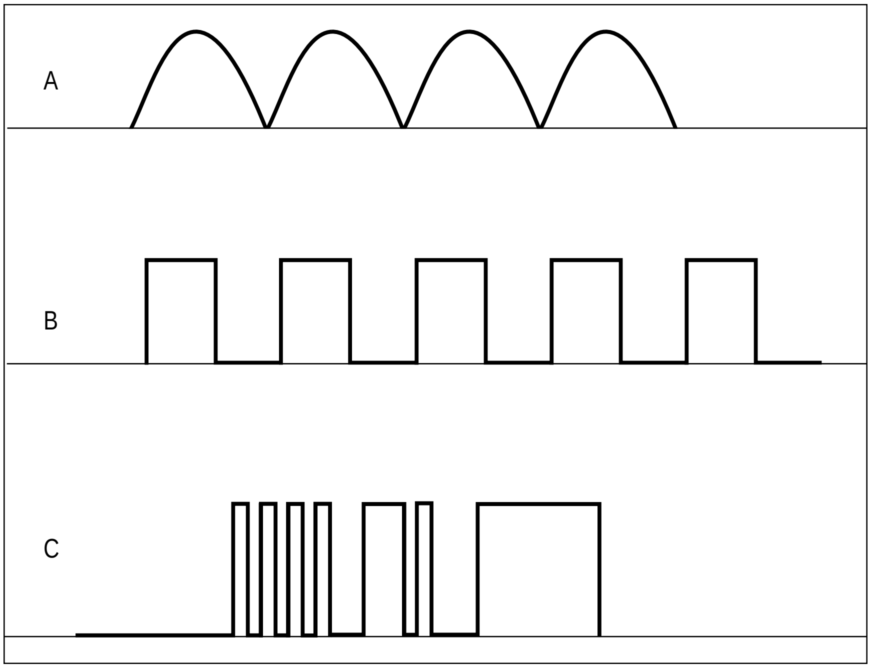

Figure 11.6. Pulsing Direct Current. Diagram A shows the kind of DC produced by a generator such as might be found in an older auto. Note that this particular wave form is basically a sine wave but with the negative pulses reversed in polarity; the reverse is also possible. Pulsating DC is used mainly for charging batteries which will smooth out the pulses when current is drawn from them. Diagram B illustrates the kind of pulsating DC produced by a square wave generator of high quality. Such DC serves many purposes in electronic circuitry. Diagram C shows the kind of irregular but very carefully designed string of pulses that make up the data stream of a computer. A piece of DMX512 data might look something like this.

Calculating AC Power

RMS voltage

The amount of energy transferred by an alternating current circuit can be determined by the power formula, but with this qualification: The voltage figure used in the calculation cannot be the peak voltage because this is reached for only a fraction of a second twice in each cycle. Instead, the peak voltage must be averaged by dividing it by the square root of 2, i.e., 1.41. This results in a figure known as the RMS (root mean square) voltage. Once this calculation has been done, the rest of the mathematics can proceed as though the current were DC. This problem is simplified by the fact that most meters designed for use with AC are built to make the RMS calculation automatically and display the voltage or amperage equivalent of DC. However it is important to remember that the maximum voltage found in AC circuits is the peak voltage, not the RMS voltage. This can make a significant difference when determining the amount of insulation needed to safely operate the circuit. The difference between RMS and peak voltage for a 120-volt circuit is only the difference between 120 volts and about 170 volts which is easily covered by the standard requirement that all insulation for lighting circuits be tested to 600-volt AC. However if the RMS voltage is 5000 volts, as it might be in the power supply for a strobe light, the peak voltage will be 7050 volts. This is enough to significantly change the design of the insulation in the strobe.

Peak voltage determines insulation needed.

Transformers

Power distribution

The invention of the transformer made possible long-distance transmission of electrical energy. Transformers make it possible to raise the voltage of a transmission circuit to a very high number while reducing the amperage proportionately, or the reverse. The total wattage remains unchanged except for a tiny loss in the transformer. Consider the effect of raising the voltage and reducing the amperage on the task of transferring 1,000,000 watts of power over a long line, say from Boulder Dam to Los Angeles. We will assume that the line has a resistance of 500 ohms.

Avoiding heat losses

If the power is transferred at ordinary household line voltage of 120 volts (which we will round off to 100 volts for easy figuring):

1,000,000 watts @ 100 volts = 10,000 amperes

Heat losses figuring according to the heat formula $c = .24 \times I^2 R$:

$$c = 0.24 \times 10{,}000^2 \times 500 = .24 \times 100{,}000{,}000 \times 500 =$$
$$1{,}200{,}000{,}000 \text{ calories per second}$$

Most of this heat would be generated in the Mojave desert which scarcely needs it and the power to Los Angeles would be reduced to a trickle. This would make the cost of transmission prohibitive. This calculation explains why power from early DC power plants never got distributed far from the source.

However using transformers to boost the power at the generating station to a high voltage, say 1,000,000 volts, and then reducing it back down to the 100 volts needed in the city would result in the following savings:

1,000,000 watts @ 1,000,000 volts = 1 ampere

Losses are: $0.24 \times 1 \times 500 = 120$ calories per second

(a very tolerable loss)

This is the almost incredible mathematics of high-voltage transmission of AC power. In the real world, power is usually generated at about 18,000 volts and stepped up by a huge transformer capable of handling large amounts of power and putting out, say 500,000 volts. This change is accomplished with only a tiny heat loss and a bit of hum from the transformer. Then the power is sent over the long transmission line which is heavily insulated and carefully protected from lightning. While this line is hugely expensive, it has a long life and very low operating cost. At the other end voltage is stepped down to a less dangerous but still efficient for short-distance distribution 6.000-8.000 volts. At the transformer behind your house, or in the transformer vault of the theatre building, the voltage is further reduced to the range used inside. Transformers are the key device is each of these voltage changes.

High voltage DC lines

Some modern long distance transmission lines designed to handle very large amounts of power are now often operated as DC lines because at very high voltages, 500,000 and upwards, losses caused by radiation from the AC lines become significant. Modern converters make it possible to efficiently step up the voltage as AC, convert it to DC for transmission and reconvert to AC at the receiving end of the line enjoying substantial savings along the way.

Early transformer-based dimmers

Magnetic amplifier

Transformer action not only determines the availability of power for the theatre, but has also figures repeatedly in the development of lighting control devices within the theatre. In the recent past, much of theatre lighting control depended on direct-control autotransformer dimmers. During this same time, remote control dimmers known as saturable core reactors were installed in a few locations. These too, operated on transformer action. Somewhat later another transformer-like device called the magnetic amplifier came into use. Although all of these dimmers are now obsolete, some of them are still in use. Transformers are also found in the circuitry of a number of control devices and remotely controlled equipment in the theatre and are sometimes used to create special voltages, for example for some types of HID lamps. Thus we need to understand something about their operation.

How Transformers Work

Two fundamental facts about the relationship between magnetism and electrical current must be clarified:

1. Whenever current flows through a conductor, a magnetic field will exist surrounding that conductor. This field varies in strength with the current and will change as the current changes, therefore AC produces a constantly changing field around conductors carrying it. The field also varies in strength inversely with the distance from the conductor.
2. If a conductor is placed within a moving or changing magnetic field, a voltage will be *induced* in that conductor and, if a circuit is present, current will flow making it possible to derive energy from that current. Note that movement and change of strength have an identical effect on any conductors in the field.

This effect is known as *inductance.*

Inductance

Back EMF

If a length of insulated conductor is stretched out into a line and its resistance to both AC and DC is measured, these figures will be the same. If that same conductor is made into a coil its "resistance" to AC will increase dramatically while its DC resistance remains as first measured. Coiling the wire has concentrated the AC-induced changing magnetic field surrounding the conductor. This field affects the coil itself inducing a voltage that is opposite to and, if there are sufficient coils, nearly equal the voltage being fed into the wire from the outside source. The opposing voltage is called *back EMF* and its resistance-like effect on AC current flow is known as *impedance*. This is the arrangement inside of a transformer where the input coil is known as the *primary*. Its impedance is adjusted so that only a minuscule current will flow through it when no current is being taken from the other coil(s) as described below.

Back EMF
Impedance
Primary

If another coil of insulated wire, known as a *secondary*, is placed within the concentrated and changing field produced by the primary, a voltage will be induced into it. If a circuit is attached to the ends of the coil, current will flow and energy can be taken from it. This energy will come from the primary which will draw current from its source in proportion to the energy withdrawn. More than one secondary coil may be operated simultaneously from the same primary.

Secondary

Multiple secondaries

A very important effect of this arrangement is that the voltage relationship between the primary and the secondary will be proportional to the number of turns of wire in each coil. If there are more turns in the secondary than in the primary, the voltage will be increased making the transformer a *step-up* transformer. If the turns ratio is reversed, the transformer will become a *step-down* device. Note that within limits, such as quantity of insulation, the same transformer may be operated as either a step-up or a step-down device by reversing the roles of the primary and secondary.

Step-up and step-down transformers

While this transfer and transformation of energy will take place if the two coils of wire are simply placed next to each other, this arrangement is very inefficient. In practical transformers, the coils are carefully wrapped and sometimes even interlaced, around a core made up of soft iron plates. This core concentrates the magnetic field and increases efficiency many times over.

Stepping up or down cannot increase the amount of energy available, indeed there are slight losses, but it can rearrange the relationship between voltage and amperage and effect the changes discussed below.

Another very important effect of using transformers is that they convert the electrical energy coming into them into magnetic energy and then, like a generator, create a new electrical voltage and current which must, however, have the same frequency as the original current. Otherwise, the only connection with the supply current is the energy itself. Not only can the voltage-amperage relationship be completely changed, but also any other conditions such as grounding or phase relationships.

Isolation transformer

An example of this capability is the *isolation transformer*. This is a transformer with a 1:1 ratio between its primary and secondary. Therefore it does not change voltage at all. However if the primary is grounded as it will be when fed from a standard utility supply, the secondary will remain totally ungrounded ("floating"). This floating secondary is advantageous when powering equipment that must be handled "live," while repairs are effected or, worse, whose outer framework may be live. Supplying the equipment through an isolation transformer will afford the repair person extra safety from shock if he or she becomes inadvertently grounded while working on the equipment. Note that the test bench area should be insulated, including the floor even when an isolation transformer is in use.

Working safely on "hot" equipment

Multiple Coil Transformers

Transformers are often built with multiple secondary coils, each producing a different voltage and/or circuit pattern. Obviously, the total power transferred through such a transformer will be the sum of that used in each secondary and should not exceed the capacity of the primary.

Given these facts about electrical current and the equipment required to handle it, we will now follow the course of electrical energy from the power plant to the stage.