UNIT I

Power Measurement Systems and Fundamentals

In order to understand *electrical power measurement systems,* we must first study the fundamentals of measurement. These fundamentals deal mainly with the characteristics and types of measurement systems. Measurement systems are discussed in Chapter 1.

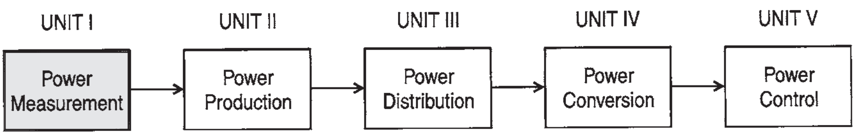
Chapter 2 provides an overview of the *fundamentals* that are important in the study of electrical power systems.

Chapter 3 deals with *measurement equipment and methods* associated with electrical power systems. These measurement systems include single-phase and three-phase wattmeters, power factor meters, ground-fault indicators, and many other types of equipment used in the analysis of electrical power system operation.

Figure I shows a block diagram of the *electrical power systems model* used in this textbook. This model is used to divide electrical power systems into five important systems: (1) *Power Measurement,* (2) *Power Production,* (3) *Power Distribution,* (4) *Power Conversion,* and (5) *Power Control.*

UNIT OBJECTIVES

Upon completion of Unit I, Power Measurement Systems and Fundamentals, you should be able to:



Power Measurement Fundamentals (Chapter 1)
Power System Fundamentals (Chapter 2)
Power Measurement Equipment (Chapter 3)

Figure I. Electrical power systems model

1. Compare the basic systems used for measurement.
2. Convert quantities from small units to large units of measurement.
3. Convert quantities from large units to small units of measurement.
4. Convert quantities from English to metric units.
5. Convert quantities from metric to English units.
6. Explain the parts of an electrical system.
7. Calculate power using the proper power formulas.
8. Draw diagrams illustrating the phase relationship between current and voltage in a capacitive circuit or inductive circuit.
9. Define capacitive reactance and inductive reactance.
10. Solve problems using the capacitive reactance formula and inductive reactance formula.
11. Define impedance.
12. Calculate impedance of series and parallel AC circuits.
13. Determine current in AC circuits.
14. Explain the relationship between AC voltages and current in resistive circuits.
15. Describe the effect of capacitors and inductors in series and in parallel.
16. Explain the characteristics of series and parallel AC circuits.
17. Solve Ohm's law problems for AC circuits.
18. Solve problems involving true power, apparent power, power factor, and reactive power in AC circuits.
19. Explain the difference between AC and DC.
20. Define the process of electromagnetic induction.
21. Describe factors affecting induced voltage.
22. Draw a simple AC generator and explain AC voltage generation.
23. Convert peak, peak-peak, average, and RMS/effective values from one to the other.
24. Describe voltage, current, and power relationships in three-phase AC circuits for wye and delta configurations.
25. Describe the following basic types of measurement systems:
    Analog Instruments
    Comparative Instruments
    CRT Display Instruments
    Numerical Readout Instruments
    Chart Recording Instruments

26. Explain the operation of an analog meter movement.
27. Describe the function of a Wheatstone bridge.
28. Explain the use of the dynamometer movement of a wattmeter to measure electrical power.
29. Describe the use of a watt-hour meter to measure electrical energy.
30. Interpret numerical readings taken by a watt-hour meter.
31. Explain the use of a power analyzer to monitor three-phase power.
32. Describe the measurement of power factor with a power factor meter.
33. Calculate power demand.
34. Explain the monitoring of power demand.
35. Explain the methods of measuring frequency.
36. Explain the use of a synchroscope.
37. Describe the use of a ground fault indicator.
38. Describe the use of a megohmmeter to measure high resistance values.
39. Describe the operation of a clamp-on current meter.
40. Describe a telemetering system.

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Chapter 1

Power Measurement Fundamentals

Electrical power measurements are important quantities, which must be measured precisely. Electrical power systems are dependent upon accurate measurements for everyday operation. Thus, many types of measurements and measuring equipment are associated with electrical power systems. Measurement fundamentals will be discussed in the following sections.

Today, most nations of the world use the metric system of measurement. In the United States, the National Bureau of Standards began a study in 1968 to determine the feasibility and costs of converting the nation to the metric measurement system. Today, this conversion is incomplete.

The units of the metric system are decimal measures based on the kilogram and the meter. Although the metric system is very simple, several countries have been slow to adopt it. The United States has been one of these reluctant countries, because of the complexity of actions required by a complete changeover of measurement systems.

IMPORTANT TERMS

Chapter 1 deals with power measurement fundamentals. After studying this chapter, you should have an understanding of the following terms:

Units of Measurement
Measurement Standards
English System of Units
International System of Units (SI)
Unit Conversion Tables
Base Units

Derived Units
Small Unit Prefixes
Large Unit Prefixes
Conversion Scale
Scientific Notation
Powers of 10
Electrical Power Units

UNITS OF MEASUREMENT

Units of measurement have a significant effect on our lives, but we often take them for granted. Almost everything we deal with daily is measured by using some unit of measurement. For example, such units allow us to measure the distance traveled in an automobile, the time of day, and the amount of food we eat during a meal. Units of measurement have been in existence for many years; however, they are now more precisely defined than they were centuries ago. Most units of measurement are based on the laws of physical science. For example, distance is measured in reference to the speed of light, and time is measured according to the duration of certain atomic vibrations.

The *standards* we use for measurement have an important effect on modern technology. Units of measurement must be recognized by all countries of the world. There must be ways to compare common units of measurement among different countries. Standard units of length, mass, and time are critical to international marketing and to business, industry, and science in general.

The *English system of units,* which uses such units as the inch, foot, and pound, has been used in the United States for many years. However, many other countries use the metric system, which has units such as kilometers, centimeters, and grams. The metric system is also called the *International System of Units,* and is abbreviated SI. Although the English and SI systems of measurement have direct numerical relationships, it is difficult for individuals to change from one to the other. People form habits of using either the English or the SI system.

Since both systems of measurement are used, this chapter will familiarize you with both systems, and with the conversion of units from one to the other. The *conversion tables* of Appendix C should be helpful. The SI system, which was introduced in 1960, has several advantages over the English system of measurement. It is a decimal system that uses units commonly used in business and industry, such as volts, watts, and grams. The SI system can also be universally used with ease. However, the use of other units is sometimes more convenient.

The SI system of units is *based on seven units,* which are shown in Table 1-1. Other units are derived from the base units and are shown in Table 1-2.

Table 1-1. Base Units of the SE System

Measurement Quantity	*Unit*	*Symbol*
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Luminous Intensity	candela	cd
Amount of substance	mole	mol

Table 1-2. Derived Units of the SI System

Measurement Quantity	*Unit*	*Symbol*
Electric capacitance	farad	F
Electric charge	coulomb	C
Electric conductance	siemen	S
Electric potential	volt	V
Electric resistance	ohm	Ω
Energy	joule	J
Force	newton	N
Frequency	hertz	Hz
Illumination	lux	lx
Inductance	henry	H
Luminous intensity	lumen	lm
Magnetic flux	weber	Wb
Magnetic flux density	tesla	T
Power	watt	W
Pressure	pascal	Pa

Some definitions of *base units* are included below:

1. Unit of length: METER (m)—the length of the path that light travels in a vacuum during the time of 1/29,792,458 second (the speed of light).
2. Unit of mass: KILOGRAM (kg)—the mass of the international prototype, which is a cylinder of platinum-iridium alloy material stored in a vault at Sevres, France, and preserved by the International Bureau of Weights and Measures.
3. Unit of time: SECOND (s)—the duration of 9,192,631,770 periods of radiation corresponding to the transition between two levels of a Cesium-133 atom. (This is extremely stable and accurate.)
4. Unit of electric current: AMPERE (A)—the current that, if maintained in two straight parallel conductors of infinite length, placed 1 meter apart in a vacuum, will produce a force of 2×10^{-7} newtons per meter between the two conductors.
5. Unit of temperature: KELVIN (K)—an amount of 1/273.16 of the temperature of the triple point of water. (This is where ice begins to form, and ice, water, and water vapor exist at the same time.) Thus, 0 degrees Centigrade = 273.16 Kelvins.
6. Unit of luminous intensity: CANDELA (cd)—the intensity of a source that produces radiation of a frequency of 540×10^{12} Hertz.
7. Unit of amount of substance: MOLE (mol)—an amount that contains as many atoms, molecules, or other specified particles as there are atoms in 0.012 kilograms of Carbon-12.

As you can see, these are highly precise units of measurement. The definitions are included to illustrate that point. Below, a few examples of *derived units* are also listed:

1. Unit of energy: JOULE (J)—the work done when one newton is applied at a point and displaced a distance of one meter in the direction of the force; 1 joule = 1 newton meter.
2. Unit of power: WATT (W)—the amount of power that causes the production of energy at a rate of 1 joule per second; 1 watt = 1 joule per second.
3. Unit of capacitance: FARAD (F)—the capacitance of a capacitor in which a difference of potential of 1 volt appears between its plates when it is charged to 1 coulomb; 1 farad = 1 coulomb per volt.

4. Unit of electrical charge: COULOMB (C)—the amount of electrical charge transferred in 1 second by a current of 1 ampere; 1 coulomb = 1 ampere per second.

CONVERSION OF SI UNITS

Sometimes it is necessary to make conversions of SI units, so that very large or very small numerals may be avoided. For this reason, decimal *multiples* and *submultiples* of the base units have been developed, by using standard prefixes. These standard prefixes are shown in Table 1-3. Multiples and submultiples of SI units are produced by adding prefixes to the base unit. Simply multiply the value of the unit by the factors listed in Table 1-3. For example:

1 kilowatt = 1000 watts
1 microampere = 10^{-6} ampere
1 megohm= 1,000,000 ohms

Table 1-3. SI Standard Prefixes

Prefix	*Symbol*	*Factor by Which the Unit is Multiplied*
exa	E	1,000,000,000,000,000,000 = 10^{18}
peta	P	1,000,000,000,000,000 = 10^{15}
tera	T	1,000,000,000,000 = 10^{12}
giga	G	1,000,000,000 = 10^{9}
mega	M	1,000,000 = 10^{6}
kilo	k	1,000 = 10^{3}
hecto	h	100 = 10^{2}
deka	da	10 = 10^{1}
deci	d	0.1 = 10^{-1}
centi	c	0.01 = 10^{-2}
milli	m	0.001 = 10^{-3}
micro	μ	0.000001 = 10^{-6}
nano	n	0.000000001 = 10^{-9}
pico	P	0.000000000001 = 10^{-12}
femto	f	0.000000000000001 = 10^{-15}
atto	a	0.000000000000000001 = 10^{-18}

Small Units

The measurement of a value is often less than a whole unit, for example 0.6 V. 0.025 A, and 0.0550 W. Some of the *prefixes* used in such measurements are shown in Table 1-4.

For example, a millivolt (mV) is 0.001 V, and a microampere (μA) is 0.000001 A. The prefixes of Table 1-4 may be used with any electrical unit of measurement. The unit is divided by the fractional part of the unit. For example, to change 0.6 V to millivolts, divide by the fractional part indicated by the prefix. Thus, 0.6 V equals 600 mV, or 0.6 V ÷ 0.001 = 600 mV. To change 0.0005 A to microamperes, divide by 0.000001. Thus, 0.0005 A = 500 μA. When changing a base electrical unit to a unit with a prefix, move the decimal point of the unit to the right by the same number of places in the fractional prefix. To change 0.8 V to millivolts, the decimal point of 0.8 V is moved three places to the right (8.↲0↲0), since the prefix milli has three decimal places. So 0.8 V equals 800 mV. A similar method is used for converting any electrical unit to a unit with a smaller prefix.

Table 1-4. Prefixes of Units Smaller Than 1

Prefix	*Abbreviation*	*Fractional Part of a Whole Unit*
milli	m	1/1000 or 0.001 (3 decimal places)
micro	μ	1/1,000,000 or 0.000001 (6 decimal places)
nano	n	n 1/1,000,000,000 or 0.000000001 (9 decimal places)
pico	p	1/1,000,000,000,000 or 0.000000000001 (12 decimal places)

When a unit with a *prefix* is converted back to a *base unit,* the prefix must be multiplied by the fractional value of the prefix. For example, 68 mV is equal to 0.068 V. When 68 mV is multiplied by the fractional value of the prefix (0.01 for the prefix milli), this gives 68 mV × 0.001 = 0.0068 V. That is, to change a unit with a prefix into a base electrical unit, move the decimal in the prefix unit to the left by the same number of places as the value of the prefix. To change 225 mV to volts, move the decimal point in 225 three places to the left (2 2 5), since the value of the prefix milli has three decimal places. Thus, 225 mV equals 0.225 V.

Table 1-5. Prefixes of Large Units

Prefix	*Abbreviation*	*Number of Times Larger than 1*
Kilo	k	1000
Mega	M	1,000,000
Giga	G	1,000,000,000

Large Units

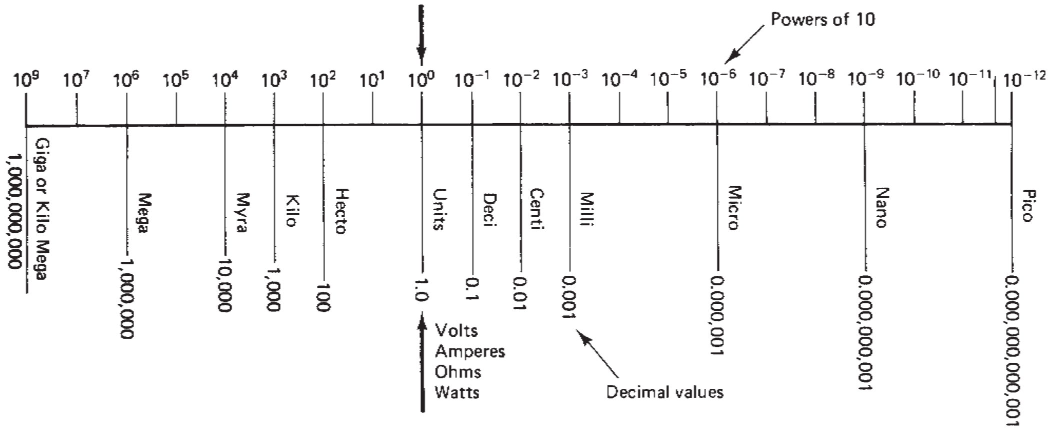
Sometimes electrical measurements are very large, such as 20,000,000 W, 50,000, or 38,000 V. When this occurs, prefixes are used to make these numbers more manageable. Some prefixes used for large electrical values are shown in Table 1-5. To change a large value to a smaller unit, divide the large value by the value of the prefix. For example, 48,000,000 Ω is changed to 48 megohms (MΩ) by dividing by one million: 48,000,000 Ω ÷ 1,000,000 48 MΩ. To convert 7000 V to 7 kilovolts (kV), divide by one thousand: 7000 V ÷ 1000 = 7kv. To change a large value to a unit with a prefix, move the decimal point in the large value to the left by the number of zeros represented by the prefix. Thus 3600 V equals 3.6 kV (3 6 0 0). To convert a unit with a prefix back to a standard unit, the decimal point is moved to the right by the same number of places in the unit, or, the number may be multiplied by the value of the prefix. To convert 90 MΩ to ohms, the decimal point is moved six places to the right (90,000,000). The 90 MΩ value may also be multiplied by the value of the prefix, which is 1,000,000. Thus 90 MΩ × 1,000,000 = 90,000,000 Ω.

The simple *conversion scale* shown in Figure 1-1 is useful when converting standard units to units of measurement with prefixes. This scale uses either powers of 10 or decimals to express the units.

SCIENTIFIC NOTATION

Using *scientific notation* greatly simplifies arithmetic operations. Any number written as a multiple of a power of 10 and a number between 1 and 10 is said to be expressed in scientific notation. For example:

$$81{,}000{,}000 = 8.1 \times 10{,}000{,}000, \text{ or } 8.1 \times 10^{7}$$
$$500{,}000{,}000 = 5 \times 100{,}000{,}000, \text{ or } 5 \times 10^{8}$$
$$0.0000000004 = 4 \times 0.0000000001, \text{ or } 4 \times 10^{-10}$$



Directions for using the conversion scale:

1. Find the position of the term as expressed in its original form. → 20 μA
2. Select the position of the conversion unit on the scale. → Amperes
3. Write the original number as a whole number or in powers of 10. → 20 μA or 20×10^{-6} A
4. Shift the decimal point *in the direction of* the desired unit. → 0.000020 A or 20×10^{-6} A

Decimal point moved six places to the left

Figure 1-1. Simple conversion for large or small numbers

Table 1-6 lists some of the *powers of 10*. In a whole-number *power of 10,* the power to which 10 is raised is positive and equals the number of zeros following the 1. In decimals, the power of 10 is negative and equals the number of places the decimal point is moved to the left of the 1.

Table 1-6. Power of 10

	Number	*Power of 10*
	1,000,000	10^6
	100,000	10^5
Whole numbers	10,000	10^4
	1000	10^3
	100	10^2
	10	10^1
	1.0	10^0
	0.1	10^{-1}
	0.01	10^{-2}
	0.001	10^{-3}
Decimals	0.0001	10^{-4}
	0.00001	10^{-5}
	0.000001	10^{-6}

Scientific notation simplifies multiplying and dividing large numbers or small decimals. For example:

$$
\begin{aligned}
&4800 \times 0.000045 \times 800 \times 0.0058 \\
&\qquad = (4.8 \times 10^3) \times (4.5 \times 10^{-5}) \times (8 \times 10^2) \times 5.8 \times (10^{-3}) \\
&\qquad = (4.8 \times 4.5 \times 8 \times 5.8)\ ´\ (10^{3-5+2-3}) \\
&\qquad = 1002.24 \times 10^{-3} \\
&\qquad = 1.00224 \\
&\qquad = \frac{9.5 \times 10^4}{8} \\
&\qquad = 1.1875 \times 10^8 \\
&\qquad = 118{,}750{,}000
\end{aligned}
$$

Other Electrical Power Units

Table 1-7 shows some common units used in the study of electrical power systems. These units will be introduced as they are utilized. You should review this figure and the sample problems included in Appendix A.

Table 1-7. Common Units

Quantity	*SI Unit*	*Symbol*
Angle	radian (1 rad ≅ 57.3°)	rad
Area	square meter	m^2
Capacitance	farad	F
Conductance	siemens (mhos)	S
Electric charge	coulomb	C
Electric current	ampere	A
Energy (work)	joule	J
Force	newton	N
Frequency	hertz	Hz
Heat	joule	J
Inductance	henry	H
Length	meter	m
Magnetic field strength	ampere per meter	A/m
Magnetic flux	weber	Wb
Magnetic flux density	tesla (1 T = 1 Wb/m^2)	T
Magnetomotive force	ampere	A
Mass	kilogram	kg
Potential difference	volt	V
Power	watt	W
Pressure	pascal (1 Pa = 1 N/m2)	Pa
Resistance	ohm	Ω
Resistivity	ohm-meter	Ωm
Specific heat	joule per kilogram-kelvin	J/kg K or J/kg = °C
Speed	meter per second	m/s
Speed of rotation	radian per second (1 rad/sec = 9.55 r/min)	rad/s
Temperature	kelvin	K
Temperature difference	kelvin or degree Celsius	K or °C
Thermal conductivity	watt per meter-kelvin	W/m K/or W/m= °C
Thermal power	watt	W
Torque	newton-meter	N-m
Volume	cubic meter	m^3
Volume	liter	L

Chapter 2

Power
System Fundamentals

One of the most important areas of electrical knowledge is the study of electrical power. Complex systems supply the vast need of our country for electrical power. Because of our tremendous power requirement, we must constantly be concerned with the efficient operation of our power production and power conversion systems. This textbook deals with the characteristics of electrical power production systems, power distribution systems, power conversion systems, and power control systems. In addition, an overview of electrical power measurement systems is included in this unit.

IMPORTANT TERMS

Systems Concept
Electrical System
- Source
- Path
- Control
- Load
- Indicator

Energy
- Kinetic Energy
- Potential Energy

Work
Power
Force
Electrical Power Systems Model
- Electrical Power Measurement
- Electrical Power Production
- Electrical Power Distribution

- Electrical Power Conversion
- Electrical Power Control

Electrical Circuits

- Resistive
- Inductive
- Capacitive

DC Power Calculation
Maximum Power Transfer
Purely Resistive AC Circuit
Counter-Electromotive Force (CEMF)
Magnetic Flux
Actual Power
Phase Angle (8)
Resistive-Inductive (R-L) Circuit
Purely Inductive Circuit (R=0)
Negative Power
Inductance (L)
Inductive Reactance (X_L)
Capacitance (C)
Farad (F)/Microfarad (uF) Units
Electrostatic Field
Capacitive Reactance (X_C)
Vector (phasor) Diagram
Series AC Circuit

- Voltage Values: V_A, V_R, V_L, V_C, V_X

Parallel AC Circuit

- Current Values: I_T, I_R, I_L, I_C, I_X

Impedance (Z)
Total Reactance (X_T)
Impedance Triangle
Admittance (Y) Triangle
Conductance (G)
Inductive Susceptance (B_L)
Capacitive Susceptance (B_C)
Apparent Power (VA)
True Power (W)
Power Factor (pf)
Unity Power Factor (1.0)
Active Power

Reactive Power (VARs)
Three-phase System
Wye Configuration
Delta Configuration
Line Voltage (V_L)
Phase Voltage (V_P)
Line Current (I_L)
Phase Current (I_P)
Power per Phase (P_P)
Total Three-Phase Power (P_T)

THE SYSTEM CONCEPT

For a number of years, people have worked with jigsaw puzzles as a source of recreation. A jigsaw puzzle contains a number of discrete parts that must be placed together properly to produce a picture. Each part then plays a specific role in the finished product. When a puzzle is first started, it is difficult to imagine the finished product without seeing a representative picture.

Understanding a complex field such as electrical power poses a problem that is somewhat similar to the jigsaw puzzle, if it is studied by its discrete parts. In this case, too, it is difficult to determine the role that a discrete part plays in the operation of a complex system. A picture of the whole system, divided into its essential parts, therefore becomes an extremely important aid in understanding its operation.

The *system concept* will serve as the "big picture" in the study of electrical power. In this approach, a system will first be divided into a number of essential blocks. This will clarify the role played by each block in the operation of the overall system. After the location of each block has been established, the discrete component operation related to each block becomes more relevant. Through this approach, the way in which some of the "pieces" of electronic systems fit together should be made more apparent.

BASIC SYSTEM FUNCTIONS

The word *system* is commonly defined as an organization of parts that are connected together to form a complete unit. A wide variety of electrical systems is in use today. Each system has a number of unique features, or characteristics, that distinguish it from other systems. More importantly, however, there is a common set of parts found in each system. These parts play the same basic role in all systems. The terms energy *source,* transmission *path, control, load,* and *indicator* are used to describe the various system parts. A block diagram of these basic parts of the system is shown in Figure 2-1.

Each block of a basic system has a specific role to play in the overall operation of the system. This role becomes extremely important when a detailed analysis of the system is to take place. Hundreds and even thousands of discrete components are sometimes needed to achieve a specific block function. Regardless of the complexity of the system, each block must achieve its function in order for the system to be operational. Being familiar with these functions and being able to locate them within a complete system is a big step toward understanding the operation of the system.

The *energy source* of a system converts energy of one form into something more useful. Heat, light, sound, and chemical, nuclear, and mechan-

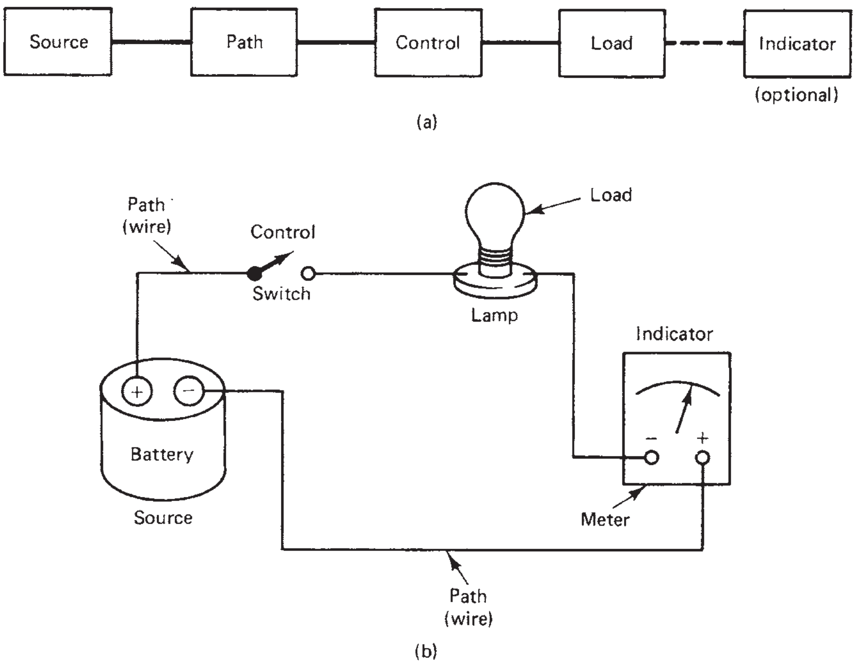


Figure 2-1. Electrical system: (A) Block diagram; (B) Pictorial diagram

ical energy are considered as primary sources of energy. A primary energy source usually goes through an energy change before it can be used in an operating system.

The *transmission path* of a system is somewhat simpler than other system functions. This part of the system simply provides a path for the transfer of energy (see Figure 2-2). It starts with the energy source and continues through the system to the load. In some cases, this path may be a single electrical conductor, light beam, or other medium between the source and the load. In other systems, there may be a supply line between the source and the load. In still other systems, there may be a supply line between the source and the load, and also a return line from the load to the source. There may also be a number of alternate or auxiliary paths within a complete system. These paths may be series connected to a number of small load devices, or parallel connected to many independent devices.

The *control* section of a system is by far the most complex part of the entire system. In its simplest form, control is achieved when a system is turned on or off. Control of this type can take place anywhere between the source and the load device. The term "full control" is commonly used to describe this operation. In addition to this type of control, a system may also employ some type of partial control. Partial control usually causes some type of an operational change in the system, other than an on or off condition. Changes in electric current or light intensity are examples of alterations achieved by partial control.

The *load* of a system refers to a specific part, or a number of parts, designed to produce some form of work (see Figure 2-2). Work, in this case, occurs when energy goes through a transformation or change. Heat, light, chemical action, sound, and mechanical motion are some of the common forms of work produced by a load device. As a general rule, a very large portion of all energy produced by the source is consumed by the load device during its operation. The load is typically the most prominent part of the entire system because of its obvious work function.

The *indicator* of a system is primarily designed to display certain operating conditions at various points throughout the system. In some systems the indicator is an optional part, while in others it is an essential part in the operation of the system. In the latter case, system operations and adjustments are usually critical and are dependent upon specific indicator readings. The term "operational indicator" is used to describe this application. Test indicators are also needed to determine different operating values. In this role, the indicator is only temporarily attached to the sys-

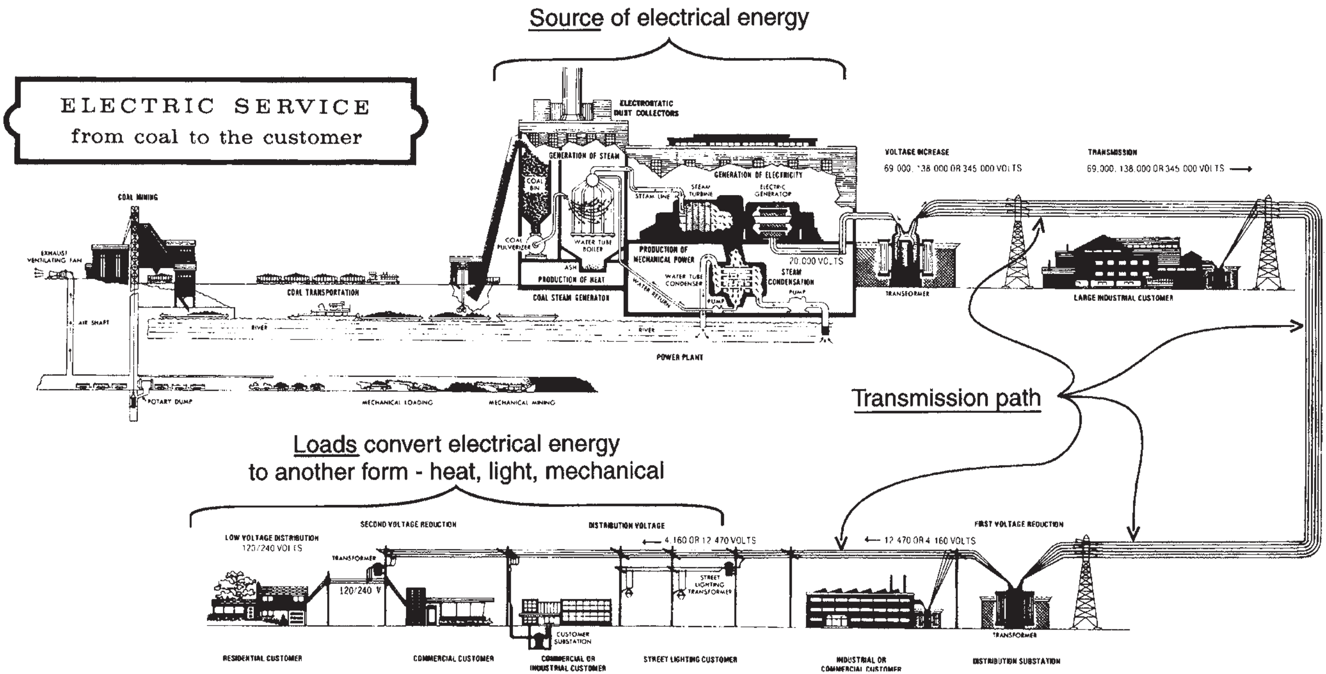


Figure 2-2. Distribution path for electrical power from its source to where it is used (*Courtesy Kentucky Utilities Co.*)

tem, in order to make measurements. Test lights, meters, oscilloscopes, chart recorders, and digital display instruments are some of the common indicators used in this capacity.

A SIMPLE ELECTRICAL SYSTEM EXAMPLE

A flashlight is a device designed to serve as a light source in an emergency, or as a portable light source. In a strict sense, flashlights can be classified as portable *electrical systems.* They contain the four essential parts needed to make this classification. Figure 2-3 is a cutaway drawing of a flashlight, with each component part shown in association with its appropriate system block.

The battery of a flashlight serves as the primary *energy source* of the system. The chemical energy of the battery must be changed into electrical energy before the system becomes operational. The flashlight is a synthesized system because it utilizes two distinct forms of energy in its operation. The energy source of a flashlight is a expendable item. It must be replaced periodically when it loses its ability to produce electrical energy.

The transmission path of a flashlight is commonly through a metal casing or a conductor strip. Copper, brass, and plated steel are frequently used to achieve the transmission function.

The control of electrical energy in a flashlight is achieved by a slide switch or a push-button switch. This type of control simply interrupts the transmission path between the source and the load device. Flashlights are primarily designed to have full control capabilities. This type of control is achieved manually by the person operating the system.

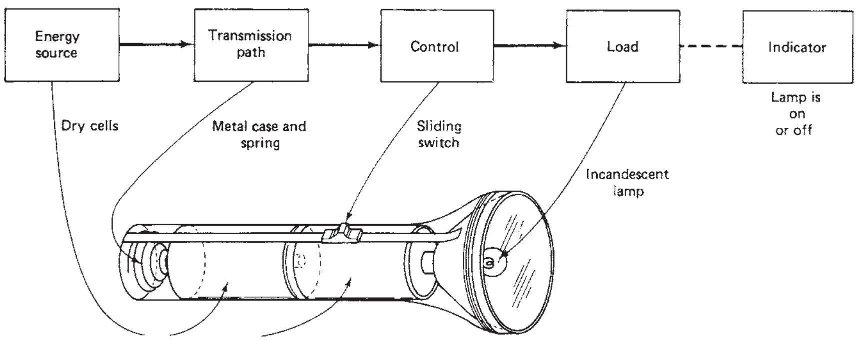


Figure 2-3. Cutaway drawing of a flashlight

The load of a flashlight is a small incandescent lamp. When electrical energy from the source is forced to pass through the filament of the lamp, the lamp produces a bright glow. Electrical energy is first changed into heat energy and then into light energy. A certain amount of the work is achieved by the lamp when this energy change takes place.

The energy transformation process of a flashlight is irreversible. It starts at the battery when chemical energy is changed into electrical energy. Electrical energy is then changed into heat energy and eventually into light energy by the load device. This flow of energy is in a single direction. When light is eventually produced, it consumes a large portion of the electrical energy coming from the source. When this energy is exhausted, the system becomes inoperative. The battery cells of a flashlight require periodic replacement in order to maintain a satisfactory operating condition.

Flashlights do not ordinarily employ a specific indicator as part of the system. Operation is indicated when the lamp produces light. In a strict sense, we could say that the load of this system also serves as an indicator. In some electrical systems the indicator is an optional system part.

ENERGY, WORK, AND POWER

An understanding of the terms "energy," "work," and "power" is necessary in the study of electrical power systems. The first term, "energy," means the capacity to do work. For example, the capacity to light a light bulb, to heat a home, or to move something requires energy. Energy exists in may forms, such as electrical, mechanical, chemical, and heat. If energy exists because of the movement of some item, such as a ball rolling down a hill, it is called kinetic energy. If energy exists because of the position of something, such as a ball that is at the top of the hill but not yet rolling, it is called potential energy. Energy is one of the most important factors in our society.

A second important term is "work." Work is the transferring or transforming of energy. Work is done when a force is exerted to move something over a distance against opposition, such as when a chair is moved from one side of a room to the other. An electrical motor used to drive a machine performs work. Work is performed when motion is accomplished against the action of a force that tends to oppose the motion. Work is also done each time energy changes from one form into another.

Sample Problem: Work

Work is done whenever a force (F) is moved a distance (d), or:

$W = F \times d$, where
W = work in joules
F = force in newtons
d = distance the force moves in meters

Given: An object with a mass of 22Kg is moved 55 meters.

Find: The amount of work done when the object is moved.

Solution: The force of gravity acting on the object is equal to 9.8 (a constant that applies to objects on earth) multiplied by the mass of the object, or:

$$F = 9.8 \times 22 \text{ Kg} = 215.6 \text{ newtons}$$
$$W = F \times d$$
$$= 215.6 \times 55$$
$$W = 11{,}858 \text{ joules}$$

A third important term is "power." Power is the rate at *which* work is done. It concerns not only the work that is performed but the amount of time in *which* the work is done. For instance, electrical power is the rate at which work is done as electrical current flows through a wire. Mechanical power is the rate at which work is done as an object is moved against opposition over a certain distance. Power is either the rate of production of energy or the rate of use of energy. The watt is the unit of measurement of power.

Sample Problem: Power

Power is the time rate of doing work, which is expressed as:

$$P = \frac{W}{t}, \text{ where}$$

P = power in watts
W = work done in joules
t = time taken to do the work in seconds

Given: An electric motor is used to move an object along a conveyor line. The object has a mass of 150 kg and is moved 28 meters in 8 seconds.

Find: The power developed by the motor in watts and horsepower units.

Solution:

$$
\begin{aligned}
\text{Force (F)} &= 9.8 \times \text{mass} \\
&= 9.8 \times 150 \text{ kg} \\
F &= 1470 \text{ newtons}
\end{aligned}
$$

$$
\begin{aligned}
\text{Work (W)} &= F \times d \\
&= 1470 \times 28 \text{ m} \\
W &= 41{,}160 \text{ joules}
\end{aligned}
$$

$$
\begin{aligned}
\text{Power (P)} &= W/t \\
&= 41{,}160/8 \\
P &= 5{,}145 \text{ watts}
\end{aligned}
$$

$$\text{Horsepower} = \frac{P}{746}, \text{ since}$$

1 horsepower = 746 W.

hp = 5,145/746 = 6.9 hp

The Electrical Power System

A block diagram of the electrical power systems model used in *this* textbook is shown in Figure 2-4. Beginning on the left, the first block is Electrical Power Measurement. Power measurement is critical to the efficient operation of electrical power systems. Measurement fundamentals and power measurement equipment are discussed in Unit I of this textbook. The second block is Electrical Power Production. Unit II presents the electrical power production systems used in our country. Once electrical power has been produced, it must be distributed to the location where it is used. Electrical Power Distribution Systems are discussed in Unit III. Power distribution systems transfer electrical power from one location to another. Electrical Power Conversion Systems (Unit IV), also called electrical loads, convert electrical power into some other form, such as light, heat, or mechanical energy. Thus, power conversion systems are an extremely important part of the electrical power system. The last block, Electrical Power Control (Unit V), is probably the most complex of all the parts of the electrical power system. There are almost unlimited types of devices, circuits, and equipment used to control electrical power systems.

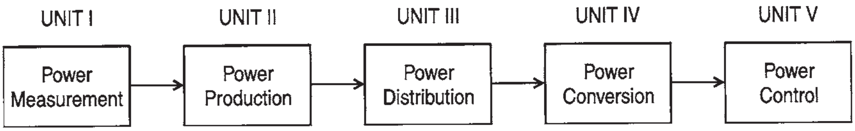


Figure 2-4. Electrical Power Systems Model

Each of the blocks shown in Figure 2-4 represents one important part of the electrical power system. Thus, we should be concerned with each one as part of the electrical power system, rather than in isolation. In this way, we can develop a more complete understanding of how electrical power systems operate. This type of understanding is needed to help us solve problems that are related to electrical power. We cannot consider only the production aspect of electrical power systems. We must understand and consider all parts of the system.

TYPES OF ELECTRICAL CIRCUITS

There are several basic fundamentals of electrical power systems. Therefore, the basics must be understood before attempting an in-depth study of electrical power systems. The types of electrical circuits associated with electrical power production or power conversion systems are (1) resistive, (2) inductive, and (3) capacitive. Most systems have some combination of each of these three circuit types. These circuit elements are also called loads. A load is a part of a circuit that converts one type of energy into another type. A resistive load converts electrical energy into heat energy.

In our discussions of electrical circuits, we will primarily consider alternating current (AC) systems at this time, as the vast majority of the electrical power that is produced is alternating current. Direct current (DC) systems will be discussed in greater detail in Chapter 7.

POWER IN DC ELECTRICAL CIRCUITS

In terms of voltage and current, power (P) in watts (W) is equal to voltage (in volts) multiplied by current (in amperes). The formula is $P = V \times I$. For example, a 120-V electrical outlet with 4 A of current flowing from it has a power value of

$$P = V \times I = 120 \text{ V} \times 4 \text{ A} = 480 \text{ W}.$$

The unit of electrical power is the watt. In the example, 480 W of power are converted by the load portion of the circuit. Another way to find power is:

$$P = \frac{V^2}{R}$$

This formula is used when voltage and resistance are known, but current is not known. The formula $P = F \times R$ is used when current and resistance are known. DC circuit formulas are summarized in Figure 2-5. The quantity in the center of the circle may be found by any of the three formulas along the outer part of the circle in the same part of the circle. This circle is handy to use for making electrical calculations for voltage, current, resistance, or power in DC circuits.

It is easy to find the amount of power converted by each of the resistors in a series circuit, such as the one shown in Figure 2-6. In the circuit shown, the amount of power converted by each of the resistors, and the total power, are found as follows:

1. Power converted by resistor R_1:
   $P_1 = I^2 \text{ x } R_1 = 2^2 \times 20\ \Omega = 80 \text{ W}$

2. Power converted by resistor R_2:
   $P_2 = I^2 \times R_2 = 2^2 \times 30\ \Omega = 120 \text{ W}$

3. Power converted by resistor R_3:
   $P_3 = I^2 \times R_3 = 2^2 \times 50\ \Omega = 200 \text{ W}$

4. Power converted by the circuit:
   $P_T = P_1 + P_2 + P_3 = 80 \text{ W} + 120 \text{ W} + 200 \text{ W}$
   $= 400 \text{ W}$, or

   $P_T = V_T \times I = 200 \text{ V} \times 2 \text{ A} = 400 \text{ W}$

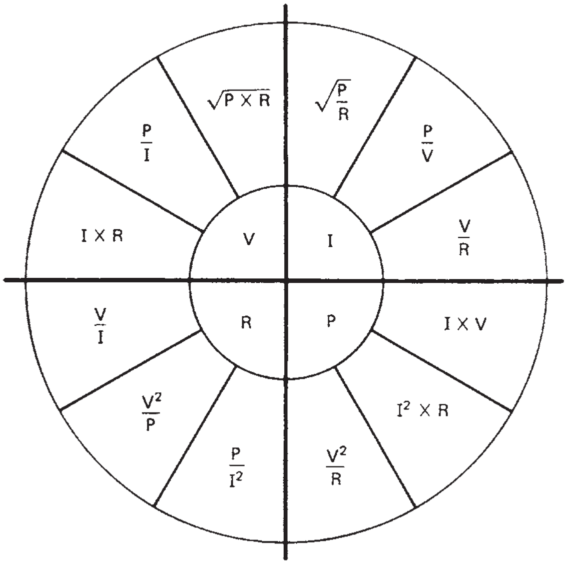


Figure 2-5. Formulas for finding voltage, current, resistance, or power

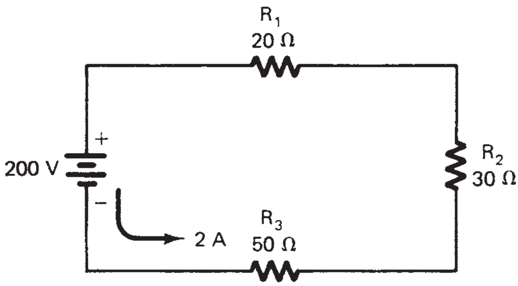


Figure 2-6. Finding power values in a series circuit

When working with electrical circuits, you can check your results by using other formulas.

Power in parallel circuits is found in the same way as power in series circuits. In the example shown in Figure 2-7, the power converted by each of the resistors, and the total power of the parallel circuit, are found as follows:

1. Power converted by resistor R_1:

$$P_1 = \frac{V^2}{R_1} = \frac{30^2}{5} = \frac{900}{5} = 180 \text{ W}$$

2. Power converted by resistor R_2:

$$P_2 = \frac{V^2}{R_2} = \frac{30^2}{10} = \frac{900}{10} = 90 \text{ W}$$

3. Power converted by resistor R_3:

$$P_3 = \frac{V^2}{R_3} = \frac{30^2}{20} = \frac{900}{20} = 45 \text{ W}$$

4. Total power converted by the circuit:

$$P_T = P_1 = P_2 + P_3 = 180 \text{ W} + 90 \text{ W} + 45 \text{ W} = 315 \text{ W}$$

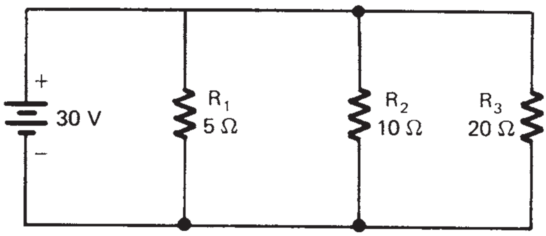


Figure 2-7. Finding power values in a parallel circuit.

The watt is the basic unit of electrical power. To determine an actual quantity of electrical energy, one must use a factor that indicates how long a given power value continued. Such a unit of electrical energy is called a watt-second. It is the product of watts (W) and time (in seconds). The watt-second is a very small quantity of energy. It is more common to measure electrical energy in kilowatt-hours (kWh). It is the kWh quantity of electrical energy that is used to determine the amount of electrical utility bills. A kilowatt-hour is 1000 W in 1 h of time, or 3,600,000 W per second.

As an example, if an electrical heater operates on 120 V, and has a resistance of 200, what is the cost to use the heater for 200 h at a cost of 5 cents per kWh?

1. $$P = \frac{V^2}{R} = \frac{120^2}{20\Omega} = \frac{14{,}400}{20\Omega} = 720 \text{ W} = 0.72 \text{ kW.}$$

2. There are 1000 W in a kilowatt (1000 W = 1 kW).

3. Multiply the kW that the heater has used by the hours of use:

   kW × 200 h = kilowatt-hours (kWh)
   0.72 × 200 h = 144 kWh

4. Multiply the kWh by the cost:
   kWh × cost = 1.44 KWh × 0.05 = $7.20

Some simple electrical circuit examples have been discussed in this chapter. They become easy to understand after practice with each type of circuit. It is very important to understand the characteristics of series, parallel, and combination circuits.

MAXIMUM POWER TRANSFER

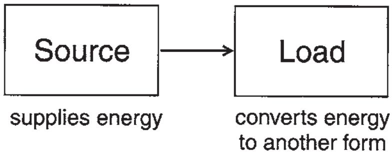
An important consideration in relation to electrical circuits is *maximum power transfer.* Maximum power is transferred from a voltage source to a load when the load resistance (RL) is equal to the internal resistance of the source (RS). The source resistance limits the amount of power that can be applied to a load. Electrical sources and loads may be considered as diagrammed in Figure 2-8.

For example, as a flashlight battery gets older, its internal resistance increases. This increase in the internal resistance causes the battery to supply less power to the lamp load. Thus, the light output of the flashlight is reduced.

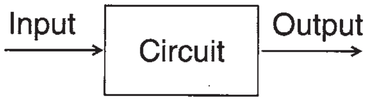
Figure 2-9 shows an example that illustrates maximum power transfer. The source is a 100 V battery with an internal resistance of 5 Ω. The values of I_L, V_{out}, and power output (P_{out}) are calculated as follows:

$$I_L = \frac{V_T}{R_L + R_S}; \quad V_{out} = I_L \times R_L; \; P_{out} = I_L \times V_{out}$$

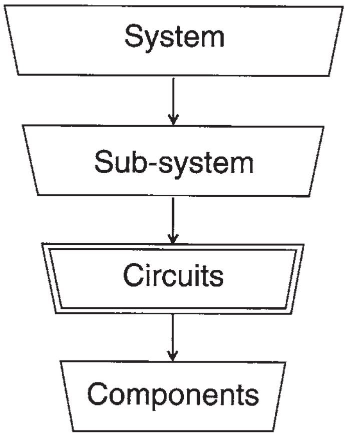
Notice the graph shown in Figure 2-9. This graph shows that maximum power is transferred from the source to the load when $R_L = R_S$. This is an important circuit design consideration for power sources.



(A) Circuits have a source and a load.



(B) Circuits have an input and an output.

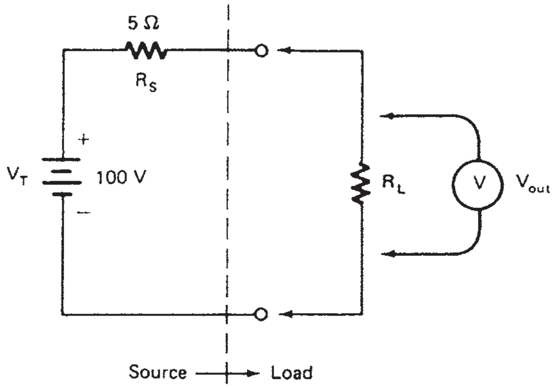


(C) Circuits are a part of any electrical system.

Figure 2-8. Electrical circuits and systems: (A) Circuits have a source and a load; (B) Circuits have an input and an output; (C) Circuits are a part of any electrical system.

OVERVIEW OF ALTERNATING CURRENT (AC) CIRCUITS

The following discussion provides an overview of the three basic types of alternating current (AC) circuits. These basic circuits are: (1) resistive, (2) inductive, and (3) capacitive. The basic characteristics of each of these circuits should be examined to gain a fundamental understanding of electrical power systems.



R_L	I_L	V_{out}	Power Output (W)
0	$\frac{100\ V}{5\ \Omega} = 20\ A$	$20\ A \times 0\ \Omega = 0\ V$	$20\ A \times 0\ V = 0\ W$
2.5 Ω	$\frac{100\ V}{7.5\ \Omega} = 13.3\ A$	$13.3\ A \times 2.5\ \Omega = 33.3\ V$	$13.3\ A \times 33.3\ V = 444\ W$
5 Ω	$\frac{100\ V}{10\ \Omega} = 10\ A$	$10\ A \times 5\ \Omega = 50\ V$	$10\ A \times 50\ V = 500\ W$
7.5 Ω	$\frac{100\ V}{12.5\ \Omega} = 8\ A$	$8\ A \times 12.5\ \Omega = 60\ V$	$8\ A \times 60\ V = 480\ W$
10 Ω	$\frac{100\ V}{15\ \Omega} = 6.7\ A$	$6.7\ A \times 10\ \Omega = 67\ V$	$6.7\ A \times 67\ V = 444\ W$

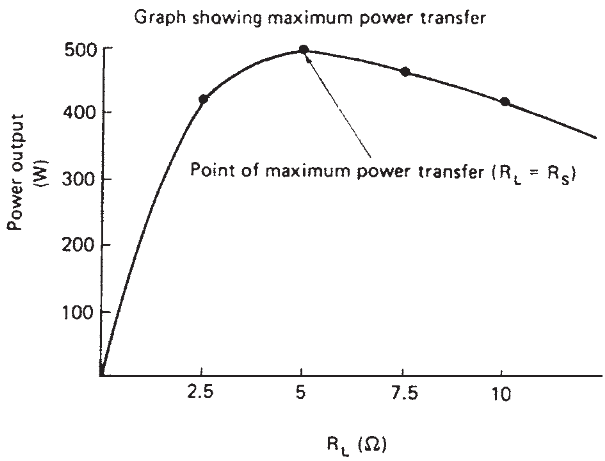


Figure 2-9. Problem that shows maximum power transfer

Resistive AC Circuits

The simplest type of AC electrical circuit is a resistive circuit, such as the one shown in Figure 2-10A. The purely resistive circuit offers the same type of opposition to AC power sources as it does to pure DC power sources. In DC circuits,

$$\text{Voltage (V)} = \text{Current (I)} \times \text{Resistance (R)}$$

$$\text{Current (I)} = \frac{\text{Voltage (V)}}{\text{Resistance (R)}}$$

$$\text{Resistance (R)} = \frac{\text{Voltage (V)}}{\text{Current (I)}}$$

$$\text{Power (P)} = \text{Voltage (V)} \times \text{Current (I)}$$

These basic electrical relationships show that when voltage is increased, the current in the circuit increases proportionally. Also, as resistance is increased, the current in the circuit decreases. By looking at the waveforms of Figure 2-10B, we can see that the voltage and current in a purely resistive circuit, with AC applied, are in phase. An in-phase relationship exists when the minimum and maximum values of both voltage and current occur at the same time interval. Also, the power converted by the circuit is a product of voltage times current ($P = V \times I$). The power curve is also shown in Figure 2-10B. Thus, when an AC circuit contains only resistance, its behavior is very similar to that of a DC circuit. Purely resistive circuits are seldom encountered in electrical power systems designs, although some devices are primarily resistive in nature.

Inductive AC Circuits

The property of inductance (L) is very commonly encountered in electrical power systems. This circuit property, shown in Figure 2-11A, adds more complexity to the relationship between voltage and current in an AC circuit. All motors, generators, and transformers exhibit the property of inductance. The occurrence of this property is due to a counter electromotive force (cemf), which is produced when a magnetic field is developed around a coil of wire. The magnetic flux produced around the coils affects circuit action. Thus, the inductive property (cemf) produced by a magnetic field offers an opposition to change in the current flow in a circuit.

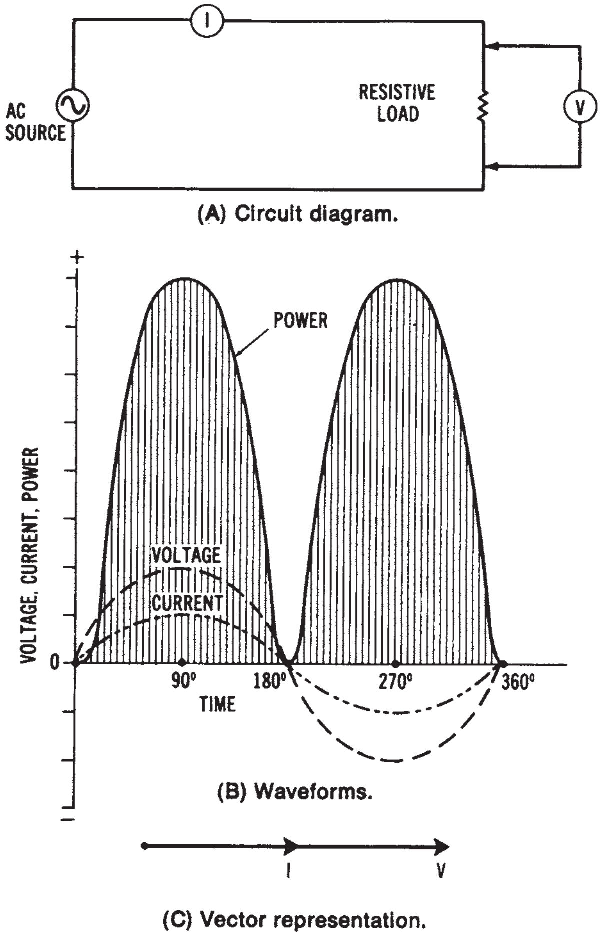


Figure 2-10. Resistive circuit: (A) Circuit diagram; (B) Waveforms; (C) Vector representation

<u>Sample Problem: Energy Stored in an Inductor</u>

A coil stores energy in its magnetic field because of current flow through it. The amount of energy is defined by the equation:

$$W + \frac{1}{2} \times L \times I^2\text{, where}$$

W = energy stored in joules
L = coil inductance in henries
I = current flow through the coil in amperes

Given: a 10-henry coil has 5.8 amperes of current flowing through it.
Find: the amount of energy stored in the coil.
Solution:

$$W = \frac{1}{2} \times L \times I^2$$

$$= \frac{1}{2} \times 10 \times (5.8)^2$$

$$W = 168.2 \text{ joules}$$

The opposition to change of current is evident in the diagram of Figure 2-11B. In an inductive circuit, we can say that voltage leads current or that current lags voltage. If the circuit were purely inductive (containing no resistance), the voltage would lead the current by 90° (Figure 2-11B), and no actual power would be converted in the circuit. However, since all actual circuits have resistance, the inductive characteristic of a circuit typically causes the condition shown in Figure 2-12 to exist. Here, the voltage is leading the current by 30°. The angular separation between voltage and current is called the "phase angle." The phase angle increases as the inductance of the circuit increases. This type of circuit is called a "resistive-inductive (RL) circuit."

In terms of power conversion, a purely inductive circuit would not convert any actual power in a circuit. All AC power would be delivered back to the power source. Refer back to Figure 2-11B, and note points A and B on the waveforms. These points show that the value at the peak of each waveform is zero. The power curves shown are equal and opposite in value and will cancel each other out. Where both voltage and current are positive, the power is also positive, since the product of two positive values is positive. When one value is positive and the other is negative, the product of the two values is negative; therefore, the power converted is negative. Negative power means that electrical energy is being returned from the load device to the power source without being converted into another form of energy. Therefore, the power converted in a purely inductive circuit (900 phase angle) would be equal to zero.

Compare the purely inductive circuit waveforms (Figure 2-11B) to those of Figure 2-12B. In the practical resistive-inductive (RL) circuit, part of the power supplied from the source is converted in the circuit. Only

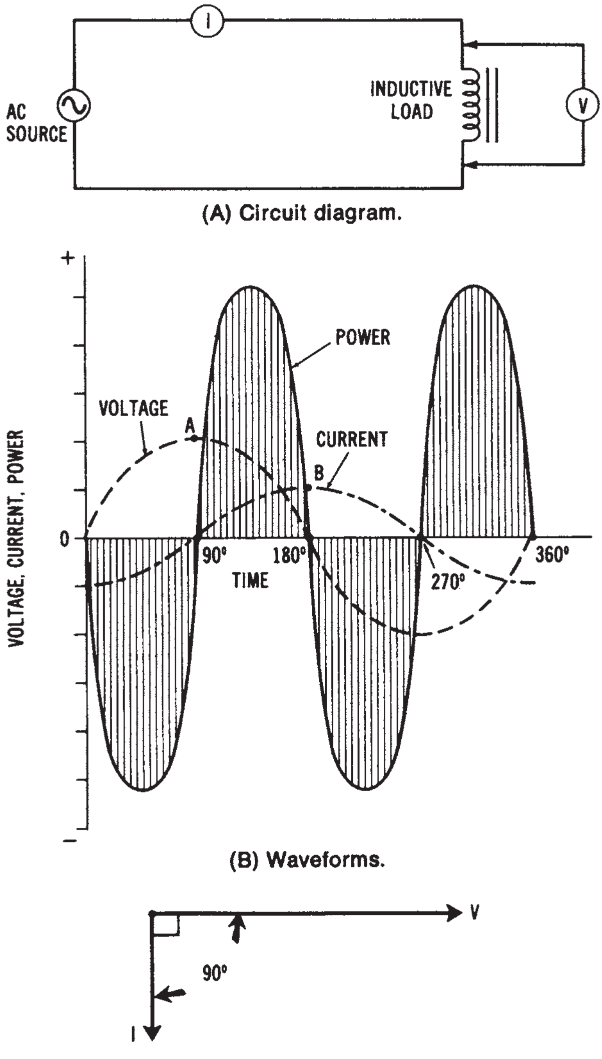


Figure 2-11. Inductive circuit: (A) Circuit diagram; (6) Waveforms; (C) Vector representation

during the intervals from 0° to 30° and from 180° to 210° does negative power result. The remainder of the cycle produces positive power; therefore, most of the electrical energy supplied by the source is converted into another form of energy.

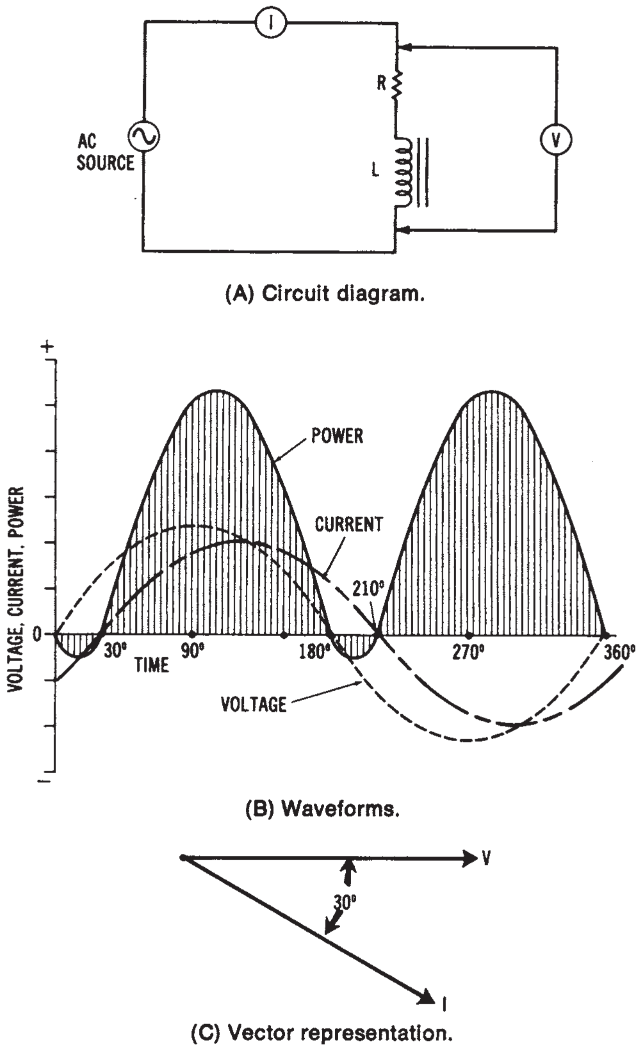


Figure 2-12. Resistive-inductive (R-L) circuit: (A) Circuit diagram; (B) Waveforms; (C) Vector representation

Any inductive circuit exhibits the property of inductance (L), which is the opposition to a change in current flow in a circuit. This property is found in coils of wire (which are called inductors) and in rotating machinery and transformer windings. Inductance is also present in electrical power transmission and distribution lines to some extent. The unit of measurement for inductance is the *henry (H).* A circuit has a 1-henry inductance if a current changing at a rate of 1 ampere per second produces an induced counter electromotive force (cemf) of 1 volt.

In an *inductive circuit* with AC applied, an opposition to current flow is created by the inductance. This type of opposition is known as *inductive reactance (X_L),* The inductive reactance of an AC circuit depends upon the inductance (L) of the circuit and the rate of change of current. The frequency of the applied AC establishes the rate of change of the current. Inductive reactance (X_L) may be expressed as:

$$X_L = 2\pi fL$$

where:

X_L is the inductive reactance in ohms,

2π is 6.28, the mathematical expression for one sine wave of AC (0° to 360°),

f is the frequency of the AC source in hertz, and

L is the inductance of the circuit in henries.

Sample Problem:

Given: frequency = 60 Hz, and inductance = 20 henries.

Find: inductive reactance.

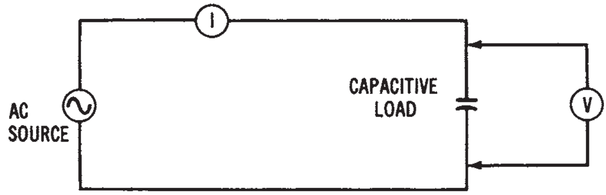
Solution:

$$X_L = 2\pi \times 60 \text{ Hz} \times 20 \text{ H}$$
$$X_L = 7536\ \Omega$$

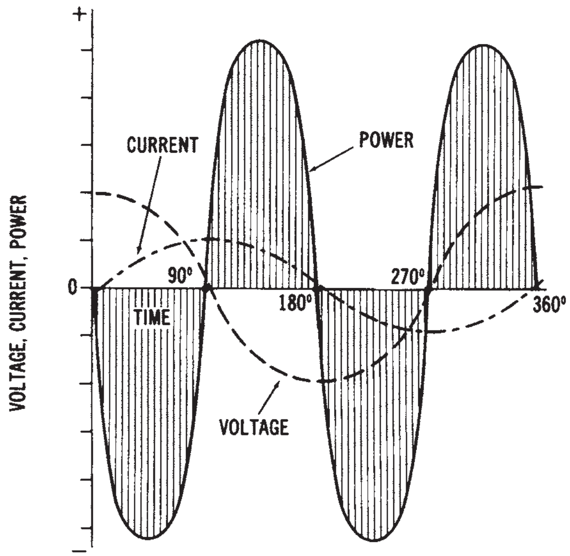
Capacitive AC Circuits

Figure 2-13A shows a *capacitive* device connected to an AC source. We know that whenever two conductive materials (plates) are separated by an insulating (dielectric) material, the property of *capacitance* is exhibited. Capacitors have the capability of storing an electrical charge. They have many applications in electrical power systems.

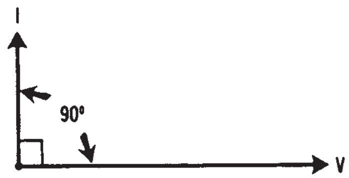
The operation of a capacitor in a circuit is dependent upon its ability to charge and discharge. When a capacitor charges, an excess of electrons (negative charge) is accumulated on one plate, and a deficiency of electrons (positive charge) is created on the other plate. *Capacitance* (C) is determined by the size of the conductive material (plates) and by their separation (determined by the thickness of the dielectric or insulating material). The type of insulating material is also a factor in determining capacitance. Capacitance is directly proportional to the plate size, and inversely



(A) Circuit diagram.



(B) Waveforms.



(C) Vector representation.

Figure 2-13. Capacitive circuit: (A) Circuit diagram; (B) Waveforms; (C) Vector representation

proportional to the distance between the plates. The unit of capacitance is the *farad (F).* A capacitance of 1 farad results when a potential of 1 volt causes an electrical charge of 1 coulomb (a specific mass of electrons) to accumulate on a capacitor. Since the farad is a very large unit, *microfarad (μF)* values are ordinarily assigned to capacitors.

Sample Problem: Energy Stored in a Capacitor

Energy is stored by a capacitor in its electrostatic field when voltage is applied to the capacitor. The amount of energy is defined by the equation:

$$W = \frac{1}{2} \times C \times V^2, \text{ where}$$

W = energy stored in a capacitor in joules,
C = capacitance of the capacitor in farads, and
V = applied voltage in volts.

Given: a 100 μF capacitor has 120 volts applied.
Find: the amount of energy stored in the capacitor.
Solution:

$$W = \frac{1}{2} \times C \times V^2$$

$$W = \frac{1}{2} \times 100^{-6} \times 120^2 = 72 \text{ joules}$$

If a direct current is applied to a capacitor, the capacitor will charge to the value of that DC voltage. After the capacitor is fully charged, it will block the flow of direct current. However, if AC is applied to a capacitor, the changing value of current will cause the capacitor to alternately charge and discharge. In a *purely capacitive circuit,* the situation shown in Figure 2-13B would exist. The greatest amount of current would flow in a capacitive circuit when the voltage changes most rapidly. The most rapid change in voltage occurs at the 0° and 180° positions where the polarity changes. At these positions, maximum current is developed in the circuit. When the rate of change of the voltage value is slow, such as near the 90° and 270° positions, a small amount of current flows. In examining Figure 2-13B, we can observe that current leads voltage by 90° in a purely capacitive circuit, or the voltage lags the current by 90°. Since a 90° phase angle exists, no power would be converted in this circuit, just as no power was developed in the purely inductive circuit. As shown in Figure 2-13B, the positive and negative power waveforms will cancel one another out.

Since all circuits contain some resistance, a more practical circuit is the *resistive-capacitive (RC)* circuit, shown in Figure 2-14A. In an RC circuit, the current leads the voltage by some phase angle between 0° and 90°. As capacitance increases with no corresponding increase in resistance, the phase angle becomes greater. The waveforms of Figure 2-14B show an RC circuit in which current leads voltage by 30°. This circuit is similar to the RL circuit in Figure 2-12. Power is converted in the circuit except during the 00 to 30° interval and the 180° to 210° interval. In the RC circuit shown, most of the electrical energy supplied by the source is converted into another form of energy in the load.

Due to the *electrostatic field* that is developed around a capacitor, an opposition to the flow of AC exists. This opposition is known as capacitive reactance (X_C). Capacitive reactance is expressed as:

$$X_C = \frac{1}{2\pi fC}$$

where:

X_C is the capacitive reactance in ohms,
2π is the mathematical expression of one sine wave (0° to 360°),
f is the frequency of the source in hertz, and
C is the capacitance in farads.

<u>Sample Problem</u>:

Given: frequency = 50 Hz, and capacitance = 200 μF.
Find: capacitive reactance.
Solution:

$$X_C = \frac{1}{2\pi \times 50 \times 200^{-6}}$$

$$X_C = 15.92\Omega$$

VECTOR AND PHASOR DIAGRAMS FOR AC CIRCUITS

In Figures 2-10C, 2-11C, 2-12C, 2-13C and 2-14C, a *vector diagram* was shown for each circuit condition that was illustrated. *Vectors* are straight lines that have a specific direction and length. They may be used to rep-

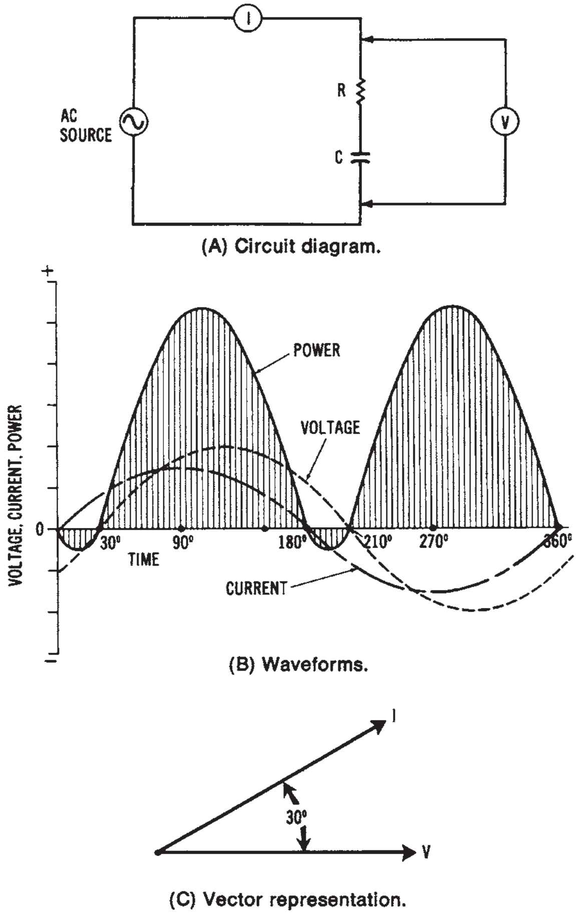


Figure 2-14. Resistive-capacitive (RC) circuit; (A) Circuit diagram; (6) Waveforms; (C) Vector representation

resent voltage or current values. An understanding of vector diagrams (sometimes caned *phasor diagrams)* is important when dealing with alternating current. Rather than using waveforms to show phase relationships, it is possible to use a vector or phasor representation.

Ordinarily, when beginning a *vector diagram,* a horizontal line is drawn with its left end as the reference point. Rotation in a counterclockwise direction from the reference point is then considered to be a positive direction. Note that in the preceding diagrams, the voltage vector was the reference. For the inductive circuits, the current vector was drawn in a clockwise direction, indicating a lagging condition. A leading condition is shown for the capacitive circuits by the use of a current vector drawn in a counterclockwise direction from the voltage vector.

Use of Vectors for Series AC Circuits

Vectors may be used to compare voltage drops across the components of a series circuit containing resistance, inductance, and capacitance (an RLC circuit), as shown in Figure 2-15. In a *series AC circuit,* the current is the same in all parts of the circuit, and the voltages must be added by using vectors. In the example shown, specific values have been assigned. The voltage across the resistor (V_R) is equal to 4 volts, while the voltage across the capacitor (V_C) equals 7 volts, and the voltage across the inductor (V_L) equals 10 volts. We diagram the capacitive voltage as leading the resistive voltage by 90° and the inductive voltage as lagging the resistive voltage by 90°. Since these two values are in direct opposition to one another, they may be subtracted to find the resultant reactive voltage (V_X). By drawing lines parallel to V_R and V_X, we can find the resultant voltage applied to the circuit. Since these vectors form a right triangle, the value of V_T can be expressed as:

$$V_T = \sqrt{V_R^2 + V_X^2}$$

where:

V_T is the total voltage applied to the circuit,
V_R is the voltage across the resistance, and
V_X is the total reactive voltage ($V_L - V_C$ or $V_C - V_L$, depending on which is the larger).

Sample Problem:

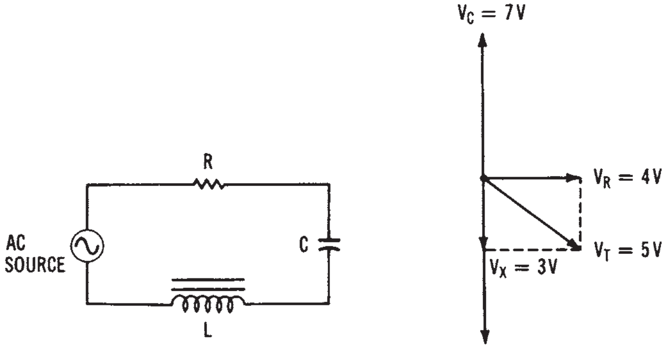
Given: resistive voltage = 25 volts, and reactive voltage = 18 volts.
Find: total applied voltage.
Solution:

$$V_T = \sqrt{V_R^2 + V_X^2}$$

$$V_T = \sqrt{25^2 + 18^2}$$

$$V_T = \sqrt{625 + 324}$$

$$V_T = 30.8 \text{ V}$$



(A) Circuit diagram. **(B) Vector diagram.**

$$
\begin{aligned}
V_L &= 10\text{ V} \\
V_X &= V_L - V_C \\
&= 10\text{ V} - 7\text{ V} \\
&= 3\text{ V}
\end{aligned}
\qquad
\begin{aligned}
V_T &= \sqrt{{V_R}^2 + {V_X}^2} \\
&= \sqrt{4^2 + 3^2} \\
&= \sqrt{16 + 9} \\
&= \sqrt{25} \\
&= 5\text{V}
\end{aligned}
$$

(C) Problem solution.

Figure 2-15. Voltage vector relationship in a series RLC circuit: (A) Circuit diagram; (B) vector diagram; (C) problem solution

Use of Vectors for Parallel AC Circuits

Vector representation is also useful for parallel AC circuit analysis. Voltage in a *parallel AC circuit* remains the same across all the components, and the currents through the components of the circuit can be shown using vectors. A *parallel RLC circuit* is shown in Figure 2-17.

The current through the capacitor *(I_C)* is shown leading the current through the resistor *(I_R)* by 90°. The current through the inductor *(I_L)* is shown lagging I_R by 90°. Since I_L and I_C are 180° out of phase, they are subtracted to find the total reactive current *(I_X)*. By drawing lines parallel to I_R and I_X, we can find the total current of the circuit *(I_T)*. These vectors form a right triangle; therefore, total current can be expressed as:

$$I_T = \sqrt{I_R^2 + I_X^2}$$

Sample Problem:

Given: resistive current = 125 amperes, and reactive current = 65 amperes.

Find: total current.

Solution:

$$I_T = \sqrt{I_R^2 + I_X^2}$$

$$I_T = \sqrt{125^2 + 65a^2}$$

$$I_T = \sqrt{5625 + 4225}$$

$$I_T = 99.25 \text{ A}$$

A similar method of vector diagramming can be used for voltages in RL and RC series circuits. This method may also be used for currents in RL and RC parallel circuits. RLC circuits were used in the examples to illustrate the method used to find a resultant reactive voltage or current in a circuit.

IMPEDANCE IN AC CIRCUITS

Another application of the use of vectors is determining the total opposition of an AC circuit to the flow of current. This total opposition is called impedance (Z) and is measured in ohms.

Impedance in Series AC Circuit

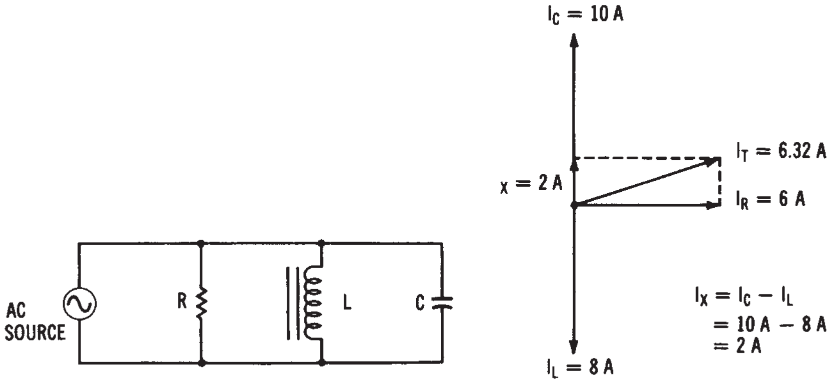
Both resistances and reactances in AC circuits affect the opposition to current flow.

Impedance (Z) of an AC circuit may be expressed as:

$$Z = \frac{V_T}{I}$$

or

$$Z = \sqrt{R_2 + (X_L - X_C)^2}$$



(A) Circuit diagram.

(B) Vector diagram.

$$
\begin{aligned}
I_T &= \sqrt{I_R^2 + I_X^2} \\
&= \sqrt{6^2 + 2^2} \\
&= \sqrt{36 + 4} \\
&= \sqrt{40} \\
&= 6.32 \text{ A}
\end{aligned}
$$

(C) Problem solution.

Figure 2-16. Current vector relationship in a parallel RLC circuit: (A) Circuit diagram; (B) Vector diagram; (C) problem solution

<u>Sample Problem</u>:

Given: an AC circuit has the following component values: R = 100, L = 1 H, C = 10μF, and 1 = 60 Hz.

Find: total impedance of the circuit.

Solution:

$$
\begin{aligned}
X_L &= 2\pi \times f \times L \\
&= 6.28 \times 60 \text{ Hz} \times 1 \text{ H} \\
X_L &= 376.8\ \Omega
\end{aligned}
$$

$$X_C = \frac{1}{2\pi \times f \times C}$$

$$X_C = \frac{1}{6.28 \times 60 \times 0.1^{-6}} = 265.4\Omega$$

$$Z = \sqrt{R_2 + (X_L - X_C)^2}$$

$$\sqrt{100^2 + (376.8 - 265.4)^2}$$

$$\sqrt{10{,}000\ \Omega + 12{,}410\ \Omega}$$

$$Z = 149.7\ \Omega$$

This formula may be clarified by using the vector diagram shown in Figure 2-17. The total *reactance (X_T)* of an AC circuit may be found by subtracting the smallest reactance (X_L or X_C) from the largest reactance. The impedance of a series AC circuit is determined by using the preceding formula, since a right triangle (called an *impedance triangle*) is formed by the three quantities that oppose the flow of alternating current. A sample problem for finding the total impedance of a series AC circuit is shown in Figure 2-17.

Impedance in Parallel AC Circuits

When components are connected in parallel, the calculation of impedance becomes more complex. Figure 2-18 shows a simple parallel RLC circuit. Since the total impedance in the circuit is smaller than the resistance or reactance, an impedance triangle, such as the one shown in the series circuit of Figure 2-17, cannot be developed. A simple method used to find impedance in parallel circuits is the *admittance triangle,* shown in Figure 2-18B. The following quantities may be plotted on the triangle:

$$\text{admittance} = \frac{1}{Z}\ ,\ \text{conductance} = \frac{1}{R}\ ,\ \text{inductive susceptance} = \frac{1}{X_L}$$

$$\text{and capacitive susceptance} = \frac{1}{X_C}$$

Notice that these quantities are the reciprocals of each type of opposition to alternating current. Therefore, since total *impedance (Z)* is the smallest quantity in a parallel AC circuit, it becomes the largest value on the admittance triangle. The sample problem of Figure 2-18 shows the procedure used to find total impedance of a parallel RC circuit.

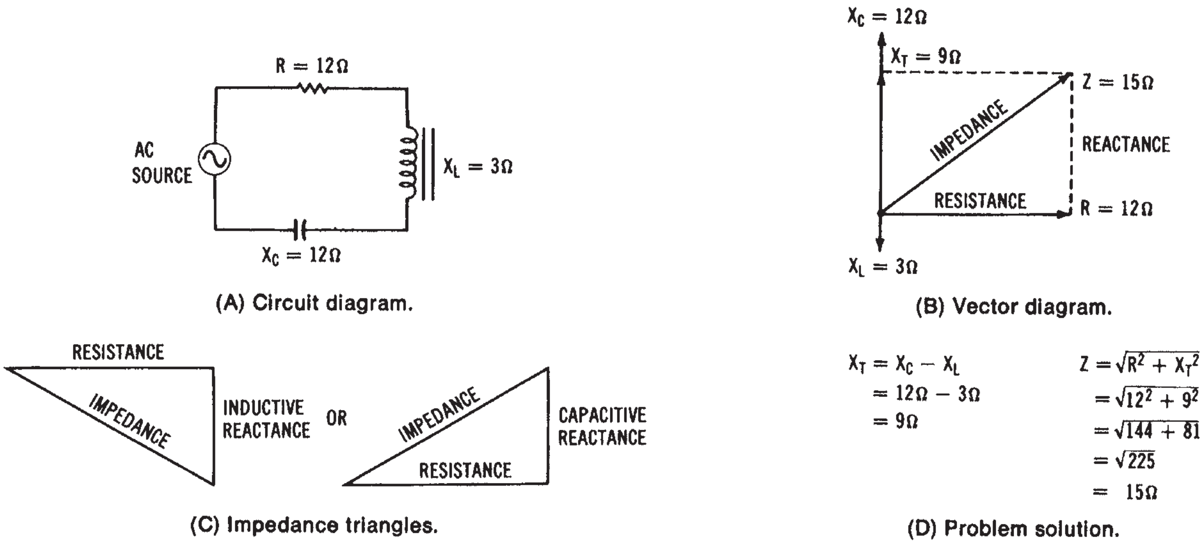


Figure 2-17. Impedance in series AC circuits: (A) Circuit diagram; (B) Vector diagram; (C) Impedance triangles, {DJ problem solution

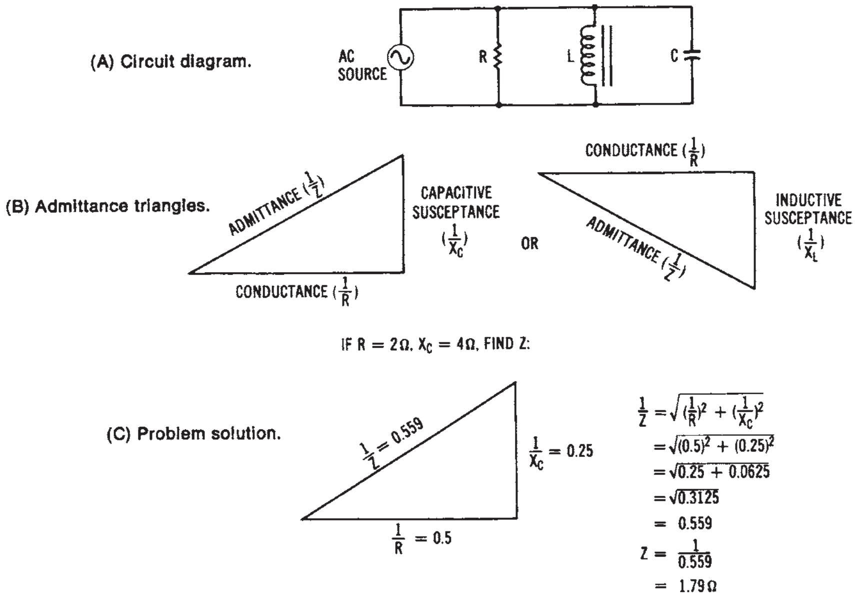


Figure 2-18. Impedance in parallel AC circuits: (A) Circuit diagram; (8) Vector diagram; (C Impedance triangles, (D) Problem solution

POWER RELATIONSHIPS IN AC CIRCUITS

An understanding of basic *power relationships* in AC circuits is very important when studying complex electrical power systems. In the previous sections, resistive, inductive, and capacitive circuits were discussed. Also, power converted in these circuits was discussed in terms of power waveforms, which were determined by the phase angle between voltage and current. In a DC circuit, power is equal to the product of voltage and current (P = V × I). This formula is also true for purely resistive circuits. However, when a reactance (either inductive or capacitive) is present in an AC circuit, power is no longer a product of voltage and current.

Since reactive circuits cause changes in the method used to compute power, the following described techniques express the basic power relationships in AC circuits. The product of voltage and current is expressed in volt-amperes (VA) or kilovolt-amperes (kVA), and is known as *apparent power.* When meters are used to measure power in an AC circuit, apparent power is the voltage reading multiplied by the current reading. The actual power that is converted into another form of energy by the circuit is measured with a wattmeter. This actual power is referred to as *true power.* Ordinarily, it is desirable to know the ratio of true power converted in a circuit into apparent power. This ratio is called the *power factor* and is expressed as:

$$pf = \frac{P}{VA}$$

or

$$\%pf = \frac{P}{VA} \times 100$$

where:

pf is the power factor of the circuit,
P is the true power in watts, and
VA is the apparent power in volt-amperes.

Sample Problem:

Given: a 240 volt, 60 hertz, 30 ampere electric motor is rated at 6000 Watts.

Find: power factor at which the motor operates.

Solution:

$$\%pf = \frac{P}{VA} \times 100$$

$$\frac{6000\text{ W}}{240\text{V} \times 30\text{A}} = 100$$

$$\%\ pf = 83.3\%$$

The maximum value of the power factor is 1.0, or 100%, which would be obtained in a purely resistive circuit. This is referred to as the *unity power* factor.

The phase angle between voltage and current in an AC circuit determines the power factor. If a purely inductive or capacitive circuit existed, the 90° phase angle would cause a power factor of zero to result. In practical circuits, the power factor varies according to the relative values of resistance and reactance.

The power relationships we have discussed may be simplified by looking at the power triangle shown in Figure 2-19. There are two components that affect the power relationship in an AC circuit. The in-phase (resistive) component that results in power conversion in the circuit is called *active power.* Active power is the *true power* of the circuit and it is measured in watts. The second component is that which results from an inductive or capacitive reactance, and it is 900 out of phase with the active power. This component, called *reactive power,* does not produce an energy conversion in the circuit. Reactive power is measured in volt-amperes reactive *(vars).*

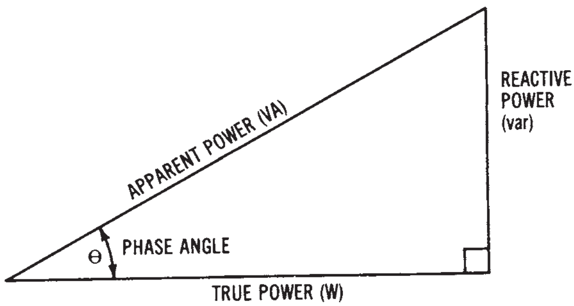


Figure 2-19. Power triangle

The power triangle of Figure 2-19 shows *true power (watts)* on the horizontal axis, *reactive power (var)* at a 90° angle from the true power, and volt-amperes (VA) as the longest side (hypotenuse) of the right triangle. Note the similarity among this right triangle, the voltage triangle for series AC circuits in Figure 2-15B, the current triangle for parallel AC circuits in Figure 2-16B, the impedance triangles in Figure 2-17C, and the admittance triangles in Figure 2-18B. Each of these right triangles has a horizontal axis that corresponds to the resistive component of the circuit, while the vertical axis corresponds to the reactive component. The hypotenuse represents the resultant, which is based on the relative values of resistance and reactance in the circuit. We can now see how important vector representation and an understanding of the right triangle are in analyzing AC circuits.

We can further examine the power relationships of the power triangle by expressing each value mathematically, based on the value of apparent power (VA) and the phase angle (θ). Remember that the *phase angle* is the amount of phase shift, in degrees, between voltage and current in the circuit. *Trigonometric ratios,* which are discussed in Appendix A, show that the sine of an angle of a right triangle is expressed as:

$$\text{sine } \theta = \frac{\text{opposite side}}{\text{hypotenuse}}$$

Since this is true, the phase angle can be expressed as:

$$\text{sine } \theta = \frac{\text{reactive power (var)}}{\text{apparent power (VA)}}$$

Therefore,

$$\text{var} = \text{VA} \times \text{sine } \theta.$$

We can determine either the phase angle or the var value by using trigonometric functions. We also know that the cosine of an angle of a right triangle is expressed as:

$$\text{sine } \theta = \frac{\text{adjacent side}}{\text{hypotenuse}}$$

Thus, in terms of the power triangle:

$$\text{sine } \theta = \frac{\text{true power (W)}}{\text{apparent power (VA)}}$$

Therefore, true power can be expressed as:

$$\text{W} = \text{VA} \times \text{cosine } \theta.$$

Sample Problem:

Given: a circuit has the following values: applied voltage = 240, current = 12 amperes, power factor = 0.83.

Find: true power of the circuit.

Solution:

$$\begin{aligned} \text{W} &= \text{VA} \times \text{cosine } \theta \\ &= 240 \text{ V} \times 12 \text{ A} \times 0.83 \\ \text{W} &= 2390 \text{ watts} \end{aligned}$$

Note that the expression

$$\frac{\text{true power}}{\text{apparent power}}$$

is the *power factor* of a circuit; therefore, the power factor is equal to the cosine of the phase angle (pf = cosine θ).

Right triangle relationships can also be expressed as equations that determine the value of any of the sides of the power triangle when the other two values are known. These expressions are as follows:

$$W = \sqrt{VA^2 - var^2}$$

$$VA = \sqrt{W^2 - var^2}$$

$$var = \sqrt{VA^2 - W^2}$$

<u>Sample Problem</u>:

Given: total reactive power = 54 var, applied; voltage = 120 volts; current = 0.5 amperes.

Find: true power of the circuit.

Solution:

$$W = \sqrt{VA^2 - var^2}$$

$$\sqrt{(120 \text{ x } 0.5)^2 - 54^2}$$

$$\sqrt{3600 - 2916}$$

26.15 watts

Appendix B should be reviewed in order to gain a better understanding of the use of right triangles and trigonometric ratios for solving AC circuit problems.

POWER RELATIONSHIPS IN THREE-PHASE AC CIRCUITS

To illustrate the basic concepts of three-phase power systems, we will use the example of a three-phase AC generator. This type of generator will be discussed in more detail in Chapter 6. A simplified pictorial diagram of a three-phase generator is shown in Figure 2-20. A three-phase voltage diagram is shown in Figure 2-21.

In Figure 2-20, poles A′, B′, and C′ represent the beginnings of each of the phase windings, while poles A, B, and C represent the ends of each of the windings. These windings may be connected in either of two ways. These methods of connection, called the wye configuration and the delta configuration, are the basic types of three-phase power systems. These three-phase connections are shown schematically in Figure 2-22. Keep in mind that these methods of connection apply not only to three-phase AC generators, but also to three-phase transformer windings and three-phase motor windings.

In the wye connection of Figure 2-22A, the beginnings or the ends of each winding are connected together. The other sides of the windings become the AC lines from the generator. The voltage across the AC lines (V_L) is equal to the square root of 3 (1.73) multiplied by the voltage across the phase windings (V_P), or:

$$V_L = V_P \times 1.73.$$

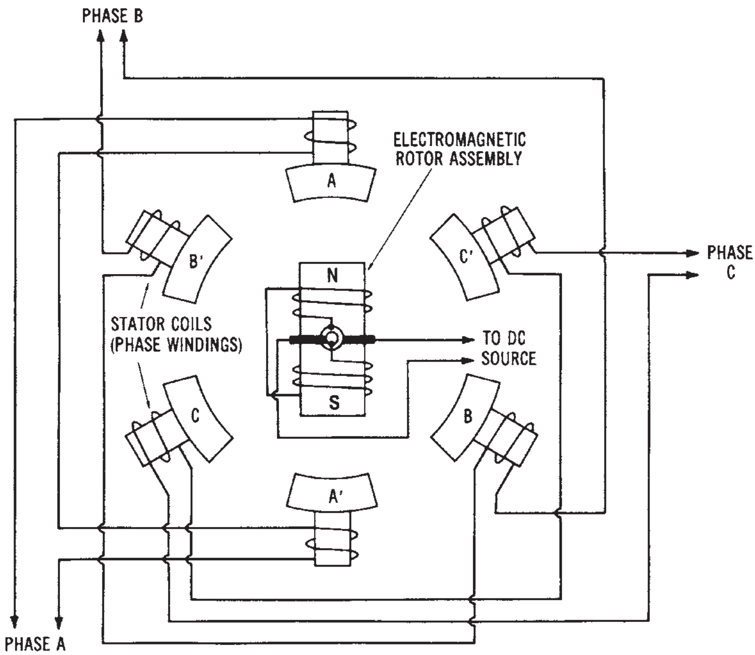


Figure 2-20. Simplified drawing showing the basic construction of a three-phase AC alternator

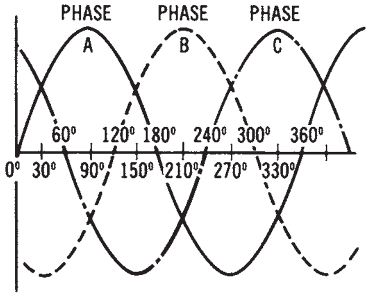


Figure 2-21. Three-phase output waveform developed by an alternator

__Sample Problem__:

Given: phase voltage = 120 volts for a three-phase wye system.

Find: line voltage.

Solution:

$$
\begin{aligned}
V_L &= V_P \times 1.73 \\
&= 120\text{ V} \times 1.73 \\
V_L &= 208\text{ volts}
\end{aligned}
$$

The line currents *(I_L)* are equal to the phase currents *(I_P)*, or:

$$I_L = I_P$$

In the *delta* connection of Figure 2-22B, the end of one phase winding is connected to the beginning of the adjacent phase winding. The *line voltages (V_L)* are equal to the *phase voltages (V_P)*. The *line currents (I_L)* are equal to the *phase current (I_P)* multiplied by 1.73.

The power developed in each phase *(P_P)* for either a wye or a delta circuit is expressed as:

$$P_P = V_P \times I_P \times pf$$

__Sample Problem__:

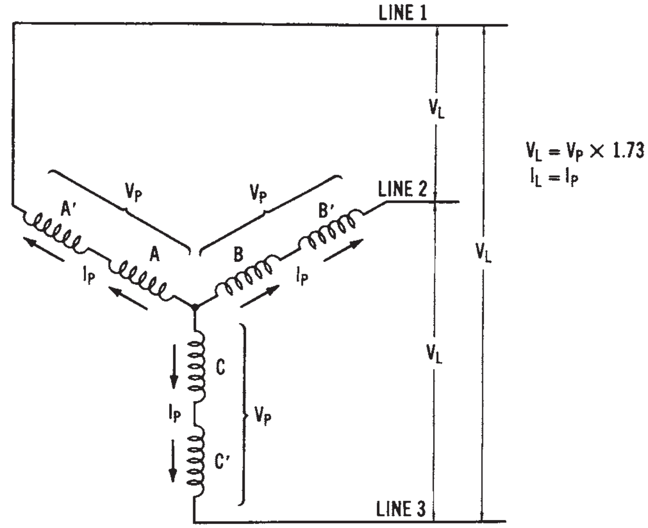
Given: a three-phase delta system has a phase voltage of 240 volts, a phase current of 20 amperes, and a power factor of 0.75.

Find: power per phase.

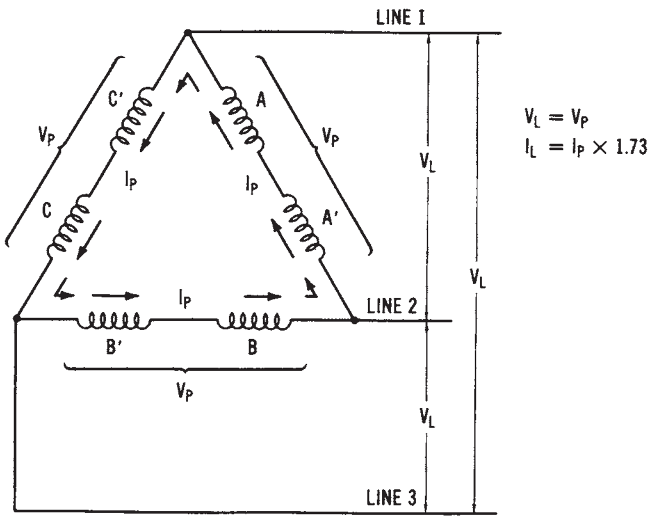
Solution:

$$
\begin{aligned}
P_P &= V_P \times I_P \times pf \\
P_P &= 240\text{ V} \times 20\text{ A} \times 0.75 \\
P_P &= 3600\text{ watts}
\end{aligned}
$$

where pf is the power factor of the load.



(A) The wye (or star) connection.



(B) The delta connection.

Figure 2-22. The two methods of connecting three-phase stator coils together: (A) The wye (or star) connection; (B) The delta connection

The *total power (P_T)* developed by all three phases of a three-phase system is expressed as:

$$\begin{aligned} P_T &= 3 \times 277 \text{ V} \times 10 \text{ A} \times 0.85 \\ &= 3 \times V_p \times I_p \times pf \\ &= 1.73 \times V_L \times I_L \times pf. \end{aligned}$$

<u>Sample Problem</u>:

Given: a three-phase wye system has a phase voltage of 277 volts, a phase current of 10 amperes, and a power factor of 0.85.

Find: total three-phase power.

Solution:

$$P_T = 3 \times 277 \text{ V} \times 10 \text{ A} \times 0.85$$
$$P_T = 7063.5 \text{ watts}$$

We can summarize three-phase power relationships as follows:

$$\begin{aligned} \text{Volt-amperes per phase } (VA_P) &= V_P I_P \\ \text{Total volt-amperes } (VA_T) &= 3\ V_P I_P \\ &= 1.73\ V_L I_L \end{aligned}$$

<u>Sample Problem</u>:

Given: a three-phase delta system has a line voltage of 208 volts and a line current of 4.86 amperes.

Find: total three-phase volt-amperes.

Solution:

$$VA = 1.73 \times 208 \text{ V} \times 4.86 \text{ A}$$
$$VA = 1748.8 \text{ volt-amperes}$$

$$\text{power factor (pf)} = \frac{\text{true power (W)}}{1.73\ V_L I_L}$$

$$= \frac{W}{3\ V_P I_P}$$

$$\text{power per phase (Pp)} = 3\ V_P I_P \times pf$$

$$= 1.173\ V_L I_L \times pf$$

where:

V_L is the line voltage in volts,
I_L is the line current in amperes,
V_P is the phase voltage in volts, and
I_P is the phase current in amperes.

<u>Sample Problem</u>:

Given: a three-phase wye system has the following values: phase voltage = 120 V, phase current = 18.5 A, and power factor = 0.95.

Find: total three-phase power of the circuit.

Solution:

$$\begin{aligned} P_T &= 3 \times V_P \times I_P \times pf \\ &= 3 \times 120\text{ V} \times 18.5\text{ A} \times 0.95 \\ &= P_T = 6{,}327\text{ W} = 6.327\text{ kW} \end{aligned}$$

Calculations involving three-phase power are somewhat more complex than single-phase power calculations. We must keep in mind the difference between phase values and line values to avoid making mistakes.

SUMMARY

In this chapter, we have examined some of the fundamentals of electrical power systems. We need to have some understanding of the three basic types of circuits—*resistive, inductive,* and *capacitive*—in order to understand the operation of power-producing systems, such as generators, chemical cells, and other power-conversion systems (such as electric lights and electric motors).

Resistive circuits exhibit similar characteristics with either applied AC or DC. The power converted in a resistive circuit is expressed in all cases as:

$$P = V \times I$$

The property of *inductance* occurs in systems because of coils of wire or windings that exhibit electromagnetic characteristics. The current developed in an inductive AC circuit *lags* behind the applied AC voltage because of this electromagnetic effect or *counter electromotive force (cemf).*

The power developed in an inductive circuit is dependent upon the *power factor (pf)* of the circuit. Power factor is a ratio of *apparent power* (volt-amperes) and *true power* (watts) of a circuit, an expressed as:

$$\text{Pf} = \frac{\text{true power}}{\text{apparent power}}$$

Capacitance causes current to *lead* voltage in an AC circuit. The *electrostatic field* produced by a capacitor is responsible for this effect. The power developed in a capacitive circuit is expressed as:

$$\text{P} = \text{V} \times \text{I} \times \text{pf}$$

just as in an inductive circuit.

The *power relationships,* as well as voltage and current relationships, in AC circuits, may be simplified by using *vector or phasor diagrams.* These diagrams allow us to examine, by a visual analysis, the effect of resistance, inductance, or capacitance on a circuit.

Both *single-phase* and *three-phase* AC power systems are used extensively. Electrical power systems involve:

1. Electrical power *sources,* such as generators.
2. *Distribution* of electrical power, mainly by specialized conductors.
3. *Control* of electrical power by various methods.
4. Electrical power *conversion* systems or loads, such as electrical lights and motors.
5. *Measurement* of electrical-power-related quantities with specialized equipment.

The units of this book discuss each of these five aspects of electrical-power systems.

Chapter 3

Power Measurement Equipment

Chapter 3 provides an overview of the types of equipment used to *measure* electrical power quantities. Specific applications of measurement equipment are discussed further in the chapters that follow. There are many different types of equipment used to *measure* quantities associated with electrical power.

IMPORTANT TERMS

Upon completion of this chapter, you should have an understanding of the following terms:

Measurement Systems
Analog Instruments
Comparative Instruments
CRT Display Instruments
Numerical Readout Instruments
Chart Recording Instruments
Volt-Ohm-Milliammeter (VOM)
Meter Movement
d'Arsonval Principle
Multifunction Meter
Single-Function Meter
Meter Scale
Wheatstone Bridge
Unknown Resistance (R_X)
Standard Resistance (R_S)
Wattmeter
Watt-Hour Meter

True Power
Apparent Power
Power Factor
Three-Phase Power Analyzer
Power Factor Meter
Power Demand Meter
Average Power
Peak Power
Frequency Measurement
Synchroscope
Phase Sequence
On-Line Operation
Ground Fault Indicator
Megohmmeter
Clamp-on Meter
Telemetering

MEASUREMENT SYSTEMS

All *measurement systems* have certain basic characteristics. Usually, a specific quantity is monitored, either periodically or continuously. Therefore, some type of visual indication of the quantity being monitored must be available. For this purpose, several types of instruments for measuring electrical and physical quantities are available. The basic types of measurement systems can be classified as: (1) *analog instruments,* (2) *comparative instruments,* (3) *cathode ray tube (CRT) display instruments,* (4) *numerical-readout instruments,* and (5) *chart-recording instruments.*

Analog Instruments

Instruments that rely upon the motion of a hand or pointer are referred to as *analog instruments.* The *volt-ohm-milliammeter (vom)* is one type of analog instrument. The vom is a *multifunction, multirange* meter. Single-function analog meters can also be used to measure electrical or physical quantities. The basic part of an electrical analog meter is called the *meter* movement and is shown in Figure 3-1. The movement of the pointer along a calibrated *scale* is used to indicate an electrical or physical quantity. For example, physical quantities such as air flow or fluid pressure can be monitored by analog meters.

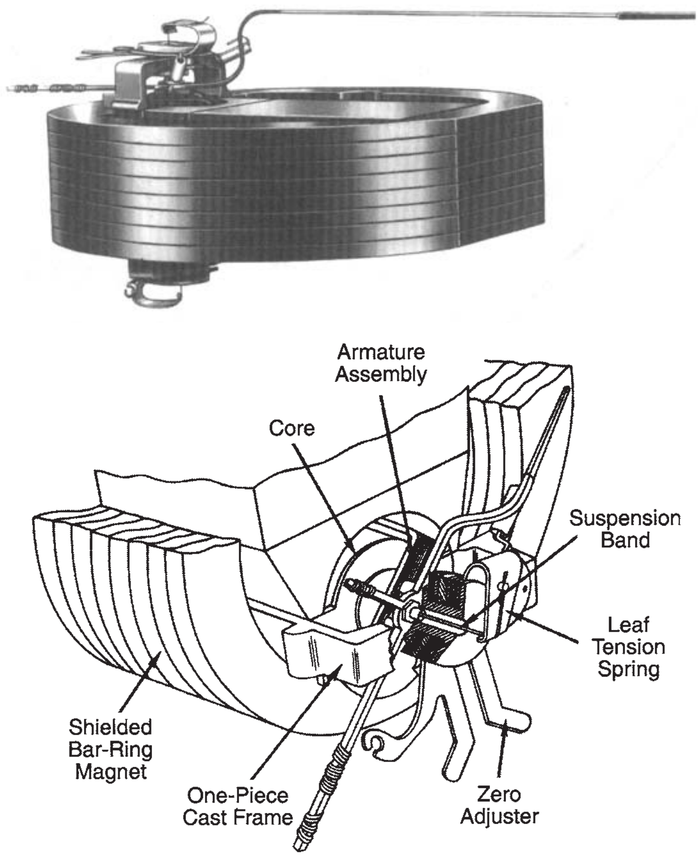


Figure 3-1. Moving-coil meter movement for analog meters (*Courtesy Triplett Corp.*)

Many meters employ an *analog movement* called the *d'Arsonval,* or *moving-coil,* type. The basic operational principle of this type of movement is shown in Figure 3-2. The pointer or needle of the movement remains stationary on the left portion of the calibrated scale until a current flows through the electromagnetic coil that is centrally located within a permanent magnetic field. When current flows through the coil, a reaction between the electromagnetic field of the coil and the stationary, permanent magnetic field develops. This reaction causes the hand (pointer) to deflect toward the right portion of the *scale.* This basic moving-coil meter movement operates on the same principle as an electric motor. It may be used for either *single-function meters,* which measure only one quantity, or for *multifunction meters.*

The basic meter movement may be modified so that it will measure almost any electrical or physical quantity.

Comparative Instruments

Another group of measuring instruments can be classified as *comparative instruments.* Usually, a comparative instrument is designed to compare a component of known value to one with an unknown value. The accuracy of comparative instruments is ordinarily much better than that of analog instruments, described above.

A *Wheatstone bridge* is a typical type of comparative instrument. The technique used for measurement with a Wheatstone bridge is illustrated in Figure 3-3. A voltage source is used in conjunction with a resistive bridge circuit and a sensitive zero-centered moving-coil meter movement. The bridge circuit is completed by adding the external *unknown resistance (R_x)* that is to be measured. When R_s is adjusted, so that the resistive path formed by R_x and R_s is equal to the path formed by R_1 and R_2 no current will flow through the meter. In this condition, the meter will indicate zero (referred to as a *null),* and the bridge is said to be balanced. The value of

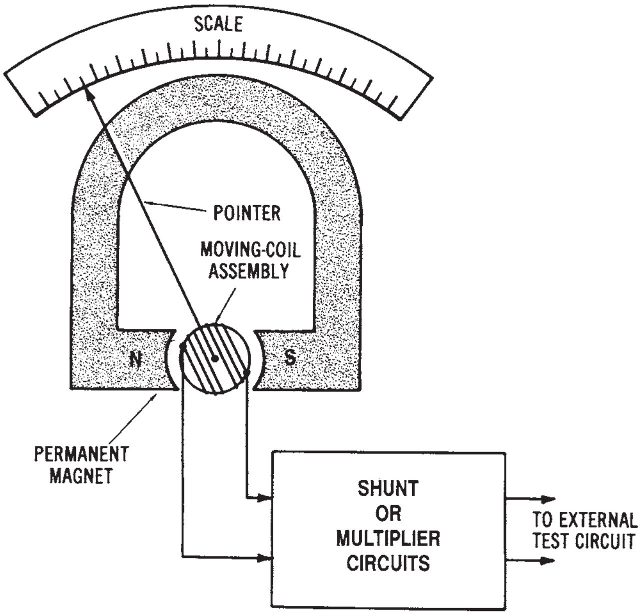


Figure 3-2. Operating principle of a meter movement

standard resistance (R_s) is marked on the meter, so that the value of the *unknown resistance (*R_x*)* can be determined. Resistors R_1 and R_2 form the "ratio arm" of the indicator. The value of an unknown resistance (R_x) may be mathematically expressed as:

$$R_x = \frac{R_1}{R_2} \times R_s$$

Sample Problem:

Given: in the bridge circuit of Figure 3-3, R_1 = 500 ohms, R_2 = 2000 ohms, and R_s = 1000 ohms.

Find: the value of unknown resistance (R_x).

Solution:

$$R_x = \frac{R_1}{R_2} \times R_s$$

$$\frac{5002}{20000} \times 1000\ \Omega$$

$$R_x = 250 \text{ Ohms}$$

The *Wheatstone bridge* will measure most values of resistance with considerable accuracy. Several other types of comparative instruments also use the Wheatstone bridge principle.

Cathode Ray Tube (CRT) Instruments

A cathode ray tube display instrument, usually called an *oscilloscope,* is an important type of instrument. Using an oscilloscope makes it possible to visually monitor the voltages of a system. The basic operational part of the oscilloscope is the cathode ray tube. Figure 3-4 shows the construction and electron gun arrangement of a CRT.

Several different types of CRT display instruments are available. *General-purpose oscilloscopes* are used for electronic servicing and for displaying simple types of waveforms. *Triggered-sweep oscilloscopes* are used when it is preferable to apply an external voltage to the oscilloscope for comparative purposes. Other oscilloscopes, classified as laboratory types, have very high sensitivity and good frequency response over wide ranges. A CRT display instrument may be used to measure AC and DC voltages, frequency, and phase relationships, and for various timing and numerical-control applications as well. *Memory* and *storage type* instruments are available for use for more sophisticated measurement purposes.

Numerical-readout Instruments

Many modern instruments employ *numerical readouts.* These simplify the measurement processes and permit more accurate measurements to be made. Numerical-readout instruments rely upon the operation of *digital* circuitry in order to produce a numerical display of the measured quantity. They are very popular measuring instruments.

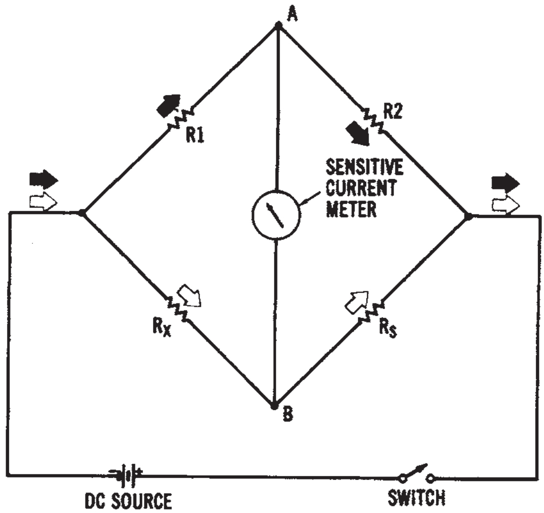


Figure 3-3. Schematic diagram of a Wheatstone bridge

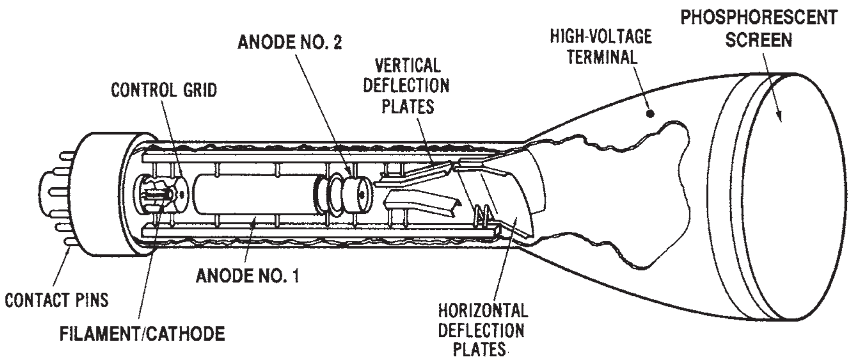


Figure 3-4. Construction of a cathode ray tube

Chart-recording Instruments

The types of instruments discussed previously are used when no permanent record of the measured quantity values is needed. However, instruments can be employed that provide a permanent record of the quantity values. Also, values measured over a specific time period can be recorded. A *chart-recording instrument* is such an instrument. The types of chart recorders include both *pen and ink* recorders and *inkless* recorders.

Pen and ink recorders have a pen attached to the instrument. This pen is controlled by either electrical or mechanical means, which cause it to touch a paper chart and leave a permanent record of the measured quantity on the chart. The charts utilized may be either roll charts (which revolve on rollers under the pen mechanism) or circular charts (which revolve on an axis under the pen). Chart recorders may use more than one pen to record several quantities simultaneously. In this case, each pen mechanism is connected so as to measure a specific quantity. The pen of a chart recorder is a capillary tube device that is actually an extension of the basic meter movement. The pen must be connected to a constant source of ink. The pen is moved by the torque that is exerted by the meter movement, just as the pointer of a hand-deflection type of meter is moved. The chart used for recording the measured quantity usually contains lines that correspond to the radius of the pen movement. Increments on the chart are marked according to time intervals. The chart must be moved under the pen at a constant speed. Either a spring-drive mechanism, a synchronous AC motor, or a DC servomotor can be used to drive the chart. Recorders are also available that use a single pen to make permanent records of measured quantities on a single chart. In this case, either coded lines or different colored ink can be used to record the quantities.

Inkless recorders may use a voltage applied to the pen point to produce an impression on a sensitive paper chart. In another process, the pen is heated to cause a trace to be melted along the chart paper. The obvious advantage of inkless recorders is that ink is not required.

Chart-recording instruments are commercially available for measuring almost any electrical or physical quantity. For many applications, the recording system is located a great distance from the device being measured. For accurate system monitoring, a central instrumentation system may be used. Power plants, for instance, ordinarily use chart recorders at a centralized location to monitor the various electrical and physical quantities involved in the power plant operation.

The operation of a typical *roll-chart* recording instrument involves several basic principles. The user should assure that the chart roll has enough paper to last throughout the duration of the time that it is to be used. The ink supply should be checked. If ink is needed, the well should be filled to the proper level. Also, the pen should be checked for proper pressure on the roll chart and for accurate adjustment along the incremental scale of the roll chart. The user should also assure that the meter is properly connected to the external circuit (which is needed for making the desired measurement).

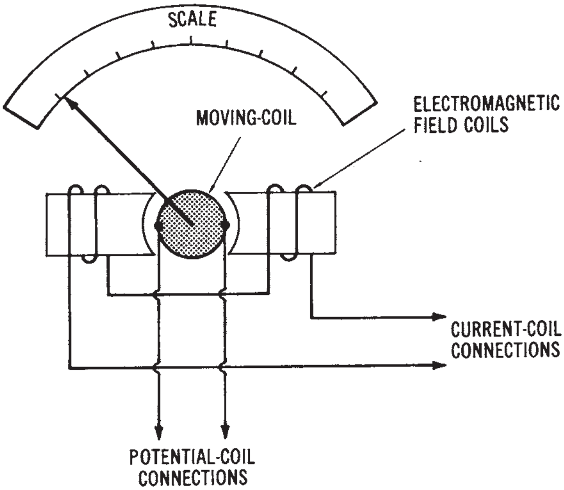
MEASURING ELECTRICAL POWER

Electrical power is measured with a *wattmeter*. A meter movement called a dynamometer movement, shown in Figure 3-5, is used in most wattmeters. Note that this movement has two electromagnetic coils. One coil, called the *current coil*, is connected in series with the load to be measured. The other coil, called the *potential coil*, is connected in parallel with the load. Thus, the strength of each electromagnetic field affects the movement of the meter pointer. The operating principle of this movement is similar to that of the moving-coil type of movement, except that there is a fixed electromagnetic field rather than a permanent-magnetic field.

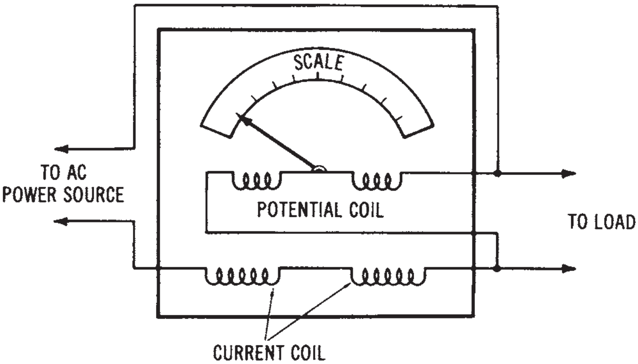
When we measure DC power, the total power is the product of voltage times current ($P = V \times I$). However, when measuring AC power, we must consider the *power factor* of the load, since $P = V \times I \times pf$). The *true power* of an AC circuit may be read directly with a wattmeter. When a load is either inductive or capacitive, the true power will be less than the *apparent power* ($V \times I$).

MEASURING ELECTRICAL ENERGY

The amount of electrical *energy* used over a certain period of time may be measured by using a watt-hour meter. A *watt-hour meter,* illustrated in Figure 3-6 relies upon the operation of a small motor mounted inside its enclosure. The speed of the motor is proportional to the power applied to it. The rotor is an aluminum disk that is connected to a numerical register, which usually indicates the number of kilowatt-hours of electrical energy used. Figure 3-7 shows the dial-type face plate that is frequently used on watt-hour meters. Other types of watt-hour meters have a direct



(A) Basic dynamometer movement.



(B) Wattmeter movement using dynamometer movement.

Figure 3-5. Measuring electrical power: (A) Basic dynamometer movement, showing potential coil and current coil connections; (B) Wattmeter movement using dynamometer movement, showing source and load connections; (C) Thermal pens for a chart recorder (Courtesy Esterline Angus); (D) Programmable thermal array recorder (Courtesy Soltec Corp.)

numerical readout of the kilowatt-hours used. Study Figure 3-7 to learn to read a watt-hour meter.

The *watt-hour meter* is connected between the incoming power lines and the branch circuits of an electrical power system. In this way, all

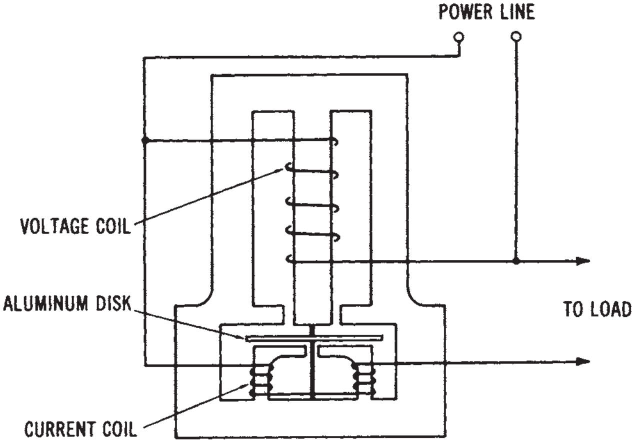


Figure 3-6. Construction diagram of a watt-hour meter

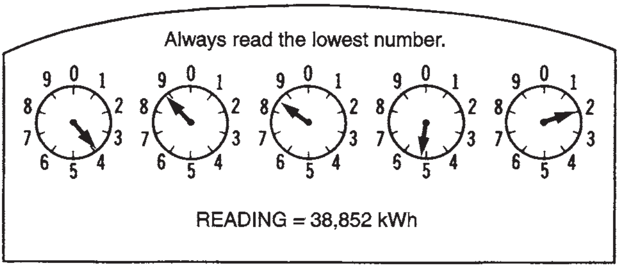


Figure 3-7. Reading the dials of a watt-hour meter

electrical energy that is used must pass through a watt-hour meter. The same type of system is used for home, industrial, or commercial service entrances.

The operation of a *watt-hour meter* is, in many ways, similar to the conventional wattmeter. A potential coil is connected across the incoming power lines to monitor voltage, while a current meter is placed in series with the line to measure current. Both meter sections are contained within the watt-hour meter enclosure. The voltage and current of the power system affect the movement of an aluminum-disk rotor that is part of the watt-hour meter assembly. The operation of the watt-hour meter may be considered as similar to that of an AC induction motor. The stator is an electromagnet that has two sets of windings—the voltage windings and the current windings. The field developed in the voltage windings causes a current to be induced into the aluminum disk. The torque produced is proportional to the voltage and the in-phase current of the system. Therefore, the watt-hour meter will monitor the *true power* converted in a system.

MEASURING THREE-PHASE ELECTRICAL ENERGY

For industrial and commercial applications, it is usually necessary to monitor the *three-phase energy* that is utilized. It is possible to use a combination of single-phase wattmeters to measure the total three-phase power, as shown in Figure 3-8. The methods shown are ordinarily not very practical, since the sum of the meter readings would have to be found in order to calculate the total power of a three-phase system. *Three-phase power analyzers* are designed to monitor the true power of a three-phase system.

Measuring Power Factor

Power factor is the ratio of the *true power* of a system to the *apparent power* (volts × amperes). To determine power factor, we could use a relationship of pf = W/VA. However, it would be more convenient to use a *power factor meter* in situations where the power factor must be monitored.

The principle of a *power factor meter is* shown in Figure 3-9. The power factor meter is similar to a wattmeter, except that it has two armature coils that rotate because of their electromagnetic field strengths. The armature coils are mounted on the same shaft so that their alignment is about 90° apart. One coil is connected across the AC line (in series with a resistance), while the other coil is connected across the line through an inductance. The resistive path through the coil reacts to produce a flux proportional to the *in-phase* component of the power. The inductive path reacts in proportion to the *out-of-phase* component of the power.

If a *unity (1.0) power factor* load is connected to the meter, the current in the resistive path through coil A will develop full torque. Since there is no out-of-phase component, no torque will be developed through the inductive path. The meter movement will now indicate full-scale or unity power factor. As the power factor decreases below 1.0, the *torque* developed by the inductive path through coil B becomes greater. This torque will be in opposition to the torque developed by the resistive path. There-

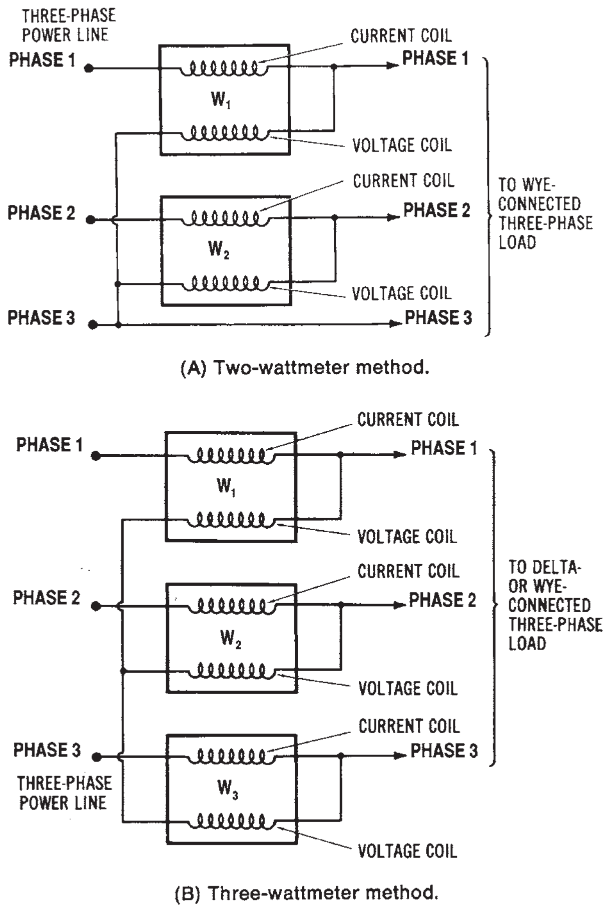


Figure 3-8. Using single-phase wattmeters to measure three-phase power: (A) Two-wattmeter method; (B) Three wattmeter method

fore, a power factor of less than 1.0 will be indicated. The scale must be calibrated to measure power factor ranges from zero to unity.

Power-demand Meters

Power-demand monitors are instruments used to perform an important industrial function. Power demand is expressed as:

$$\text{power demand} = \frac{\text{peak power (kW)}}{\text{average power used (kW)}}$$

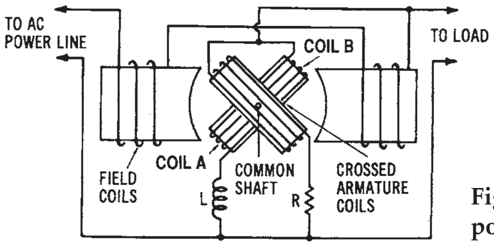


Figure 3-9. Schematic diagram of a power factor meter circuit

Sample Problem:

Given: an industry uses 5000 kW peak power and 3880 kW average power over a 24-hour period.

Find: the industry's demand factor over the 24-hour period.

Solution:

$$\text{Demand} = \frac{\text{Peak Power}}{\text{Avg. Power}}$$

$$= \frac{5000\text{kW}}{3800\text{kW}}$$

$$\text{Demand} = 1.31$$

This ratio is important since it indicates the amount above the *average power* consumption that a utility company must supply to an industry. Power demand is usually calculated over a 15-, 30-, or 60-minute interval, and then converted into figures that represent longer periods of time.

Industries may be penalized by a utility company if their *peak power demand* far exceeds their *average demand*. *Power-demand monitors* help industries to better utilize their electrical power. A high peak demand means that the equipment for an industrial power-distribution system must be rated higher. The closer that the peak demand approaches the value of the average demand, the more efficient the industrial power system is in terms of power utilization.

FREQUENCY MEASUREMENT

Another power measurement that is very important is frequency. The frequency of the power source must remain stable, or the operation of many types of equipment can be affected. Frequency refers to the number of cycles of voltage or current that occur in a given period of time. The unit of measurement for frequency is the hertz (Hz), which means cycles per second. A table of frequency bands is shown in Figure 3-10. The standard power frequency in the United States is 60 hertz. Some other countries use 50 hertz.

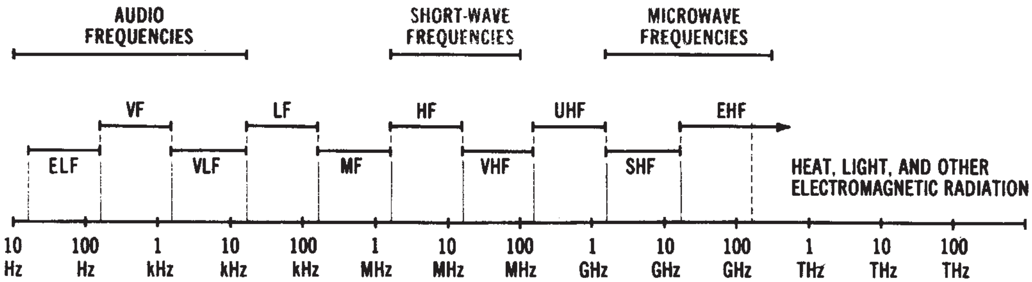
Frequency can be measured with several different types of meters. An electronic counter is one type of frequency indicator. *Vibrating-reed* instruments are also commonly used for measuring power frequencies. An *oscilloscope* can also be used to measure frequency. *Graphic recording instruments* may be used to provide a visual display of frequency over a period of time. The electrical power industry commonly uses this method to monitor the frequency output of its alternators.

SYNCHROSCOPES

The major application for a *synchroscope* is in electrical power plants. Most power plants have more than one alternator. In order to connect two or more alternators onto the same AC line, the following conditions must be met: (1) their voltage outputs must be equal, (2) their frequencies must be equal, (3) their voltages must be in phase, and (4) the phase sequence of the voltages must be the same.

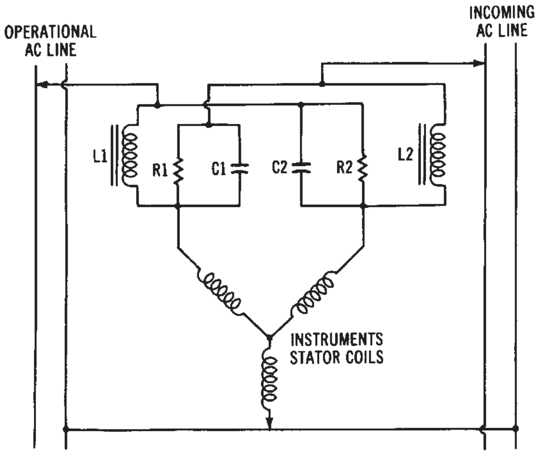
Voltage output levels may be checked easily with a voltmeter of the transformer-type that is used to monitor high voltages. Frequency is adjusted by varying the speed of an alternator and is also easy to monitor. The phase sequence is established on each alternator when it is installed and connected to the electrical power system. In addition, before alternators are paralleled, the output voltages of both alternators must be monitored, to ensure that they are in phase. This is done by using a synchroscope (see Figure 3-11).

A *synchroscope* is used to measure the relationship between the phases of the system and the alternator that is to be put in parallel or "*on-line*." A synchroscope also indicates whether the alternator is running faster or slower than the system to which it is being connected. The basic design of the indicator utilizes a phase-comparative network of two RLC circuits, which are connected between the operating system and the alternator to be paralleled. The meter scale shows whether the new alternator is running too slow or too fast (see Figure 3-11B). When an in-phase relationship exists, along with the other three factors previously

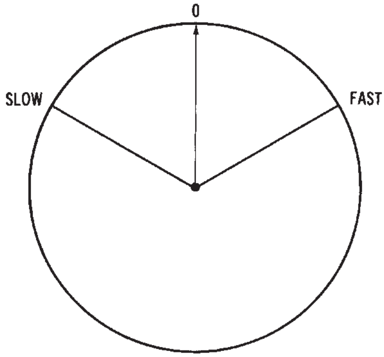


BAND		FREQUENCY RANGE
EXTREMELY LOW FREQUENCY	(ELF)	30 Hz TO 300 Hz
VOICE FREQUENCY	(VF)	300 Hz TO 3 kHz
VERY-LOW FREQUENCY	(VLF)	3 kHz TO 30 kHz
LOW FREQUENCY	(LF)	30 kHz TO 300 kHz
MEDIUM FREQUENCY	(MF)	300 kHz TO 3 MHz
HIGH FREQUENCY	(HF)	3 MHz TO 30 MHz
VERY-HIGH FREQUENCY	(VHF)	30 MHz TO 300 MHz
ULTRA-HIGH FREQUENCY	(UHF)	300 MHz TO 3 GHz
SUPER-HIGH FREQUENCY	(SHF)	3 GHz TO 30 GHz
EXTREMELY HIGH FREQUENCY	(EHF)	30 GHz TO 300 GHz

Figure 3-10. Classification of frequency bands



(A) Schematic diagram.



(B) Indicator scale.

Figure 3-11. Synchroscope: (A) Schematic diagram; (B) Indicator scale

discussed, the alternator may be put "on-line" or connected in parallel with a system that is already operational. The addition of another alternator to the system will allow a higher power capacity to be produced by the electrical power system.

GROUND-FAULT INDICATORS

Ground-fault indicators are used to locate faulty system or equipment grounding conditions. The equipment of electrical power systems must be properly grounded. Proper grounding procedures, principles, and ground-fault interrupters are discussed in Chapter 10.

A *ground-fault indicator* may be used to check for faulty grounding at various points in an electrical power system. Several conditions can exist that might be hazardous. These faulty wiring conditions include: (1) hot and neutral wire reversed, (2) open equipment ground wire, (3) open neutral wire, (4) open hot wire, (5) hot and equipment ground wires reversed, or (6) hot wire on the neutral terminal and the neutral is unconnected. Each of these conditions would present a serious problem in the electrical power system. Although proper wiring eliminates most of these problems, a periodic check with a *groundfault indicator* will ensure that the electrical wiring is safe and efficient.

MEGOHMMETERS

Megohmmeters are used to measure high resistances that are beyond the range of a typical ohmmeter. These indicators are used primarily for checking the quality of insulation on electrical power equipment (mainly motors). The quality of equipment insulation varies with age, moisture content, and the applied voltage. A megohmmeter is similar to a typical ohmmeter, except that some types use a *hand-cranked* permanent-magnet DC generator as a voltage source, rather than a battery. The operator cranks the DC generator while making an insulation test. Figure 3-12 shows a diagram of a megohmmeter circuit. This circuit is essentially the

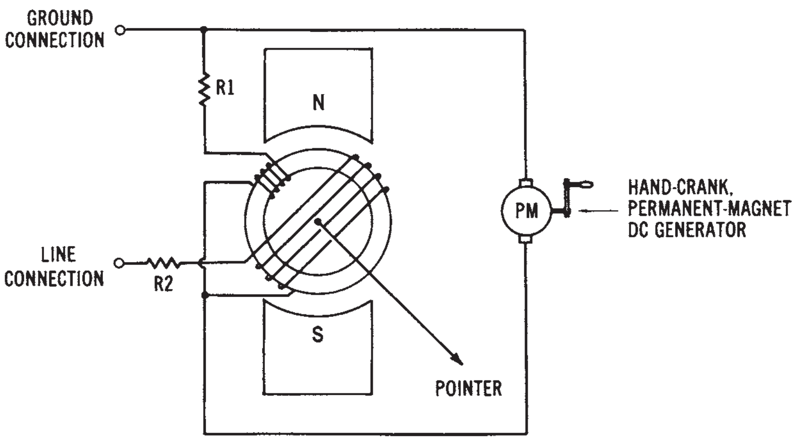


Figure 3-12. Circuit diagram of a megohmmeter, analog type

same as in any series ohmmeter, with the exception that a DC generator is used as the voltage source. *Digital* megohmmeters are also available.

Periodic *insulation tests* should be made on all large power equipment. As insulation breaks down with age, the equipment starts to malfunction. A good method is to develop a periodic schedule for checking and recording insulation resistance. Then, it can be predicted when a piece of equipment will need to be replaced or repaired. A resistance-versus-time graph (see Figure 3-13) can be made, and the trend shown on the graph can be noted. A downward trend (a decrease in insulation resistance) over a specific time period indicates that an insulation problem exists.

CLAMP-ON METERS

Clamp-on meters are popular for measuring current in power lines. This indicator may be used for periodic checks of the current by clamping it around a power line. It is an easy-to-use and convenient maintenance and testing instrument.

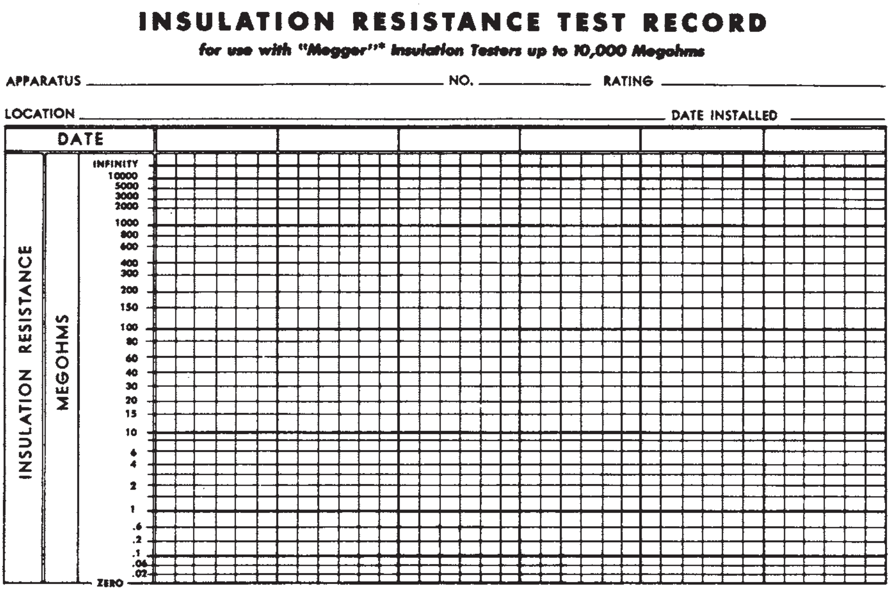


Figure 3-13. Resistance versus time chart to be used with a megohmmeter (Courtesy *Biddle Instruments*)

The simplified circuit of a *clamp-on* analog current meter is shown in Figure 3-14. Current flow through a conductor creates a magnetic field around the conductor. The varying magnetic field induces a current into the iron core of the clamp portion of the meter. The meter scale is calibrated so that when a specific value of current flows in a power line, it will be indicated on the scale. Of course, the current flow in the power line is proportional to the current induced into the iron core of the clamp-on meter. The *clamp-on meter* may also have a voltage and resistance function that utilizes external test leads. Thus, the meter can be used to measure other quantities.

TELEMETERING SYSTEMS

When a quantity being measured is indicated at a location some distance from its transducer or sensing element, the measurement process is referred to as *telemetering*. Many types of metering systems fit this definition. However, telemetering systems are usually used for *long-distance* measurement, or for centralized measurement systems. For instance, many industries group their indicating systems together to facilitate process control. Another example of telemetering is the centralized monitoring (on a regional basis) of electrical power by utility companies. These systems are similar to other measuring systems, except that a transmitter/

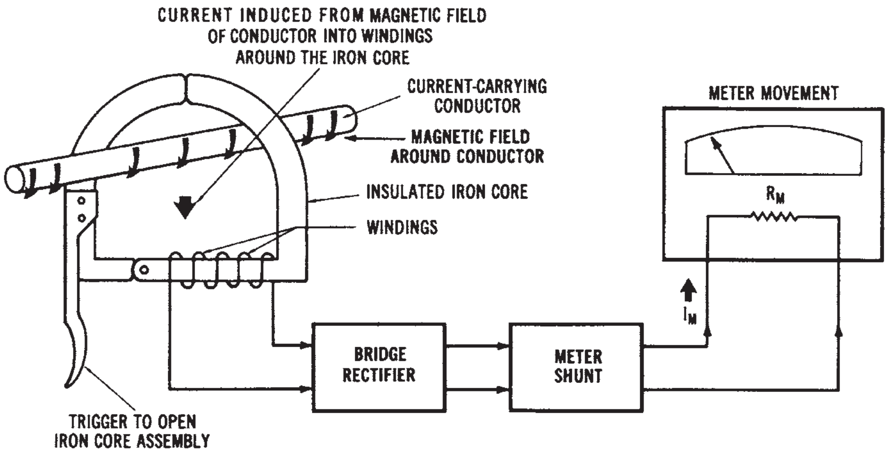


Figure 3-14. Circuit diagram of a damp-on current meter

receiver communication system is usually involved.

Many types of electrical and physical quantities can be monitored by using *telemetering* systems. The most common transmission media for telemetering systems are: (1) wire-such as telephone lines, (2) superimposed signals—which are 30- to 200-kHz signals carried on electrical power distribution lines, and (3) radio frequency signals—from AM, FM, and phase-modulation transmitters. The block diagram of one type of *telemetering* system is shown in Figure 3-15. In this type of system, a DC voltage from the transducer is used to modulate an AM or FM transmitter. The radio frequency (RF) signal is then received at another location and converted back into a DC voltage to activate some end device. The end device, which may be located at a considerable distance from the transducer, might be a chart recorder, a hand-deflection meter, or possibly a process controller. *Digital telemetering* is also used, since binary signals are well suited for data transmission. In this system, the transducer output is converted to a binary code for transmission.

Telemetering is the measurement of some quantity at an area that is distant from its origin. For instance, it is possible, by using telemetering systems, to monitor on one meter the power used at several different locations. Almost any quantity value, either electrical or non-electrical, can be transmitted by using some type of telemetering system. A basic telemetering system has: (1) a *transmitting* unit, (2) a *receiving* unit, and (3) an *interconnection* method. Electrical power systems frequently utilize telemetering systems for the monitoring of power.

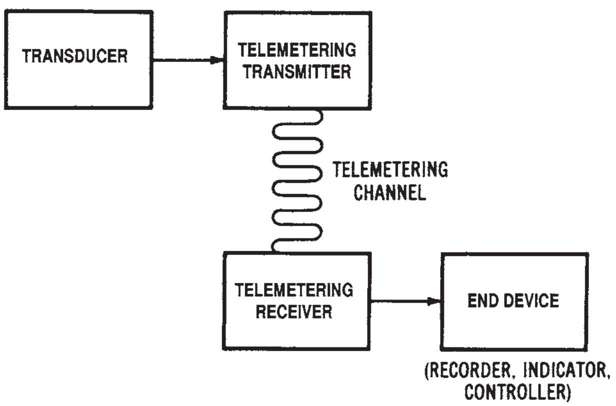


Figure 3-15. Block diagram of a basic telemetering system