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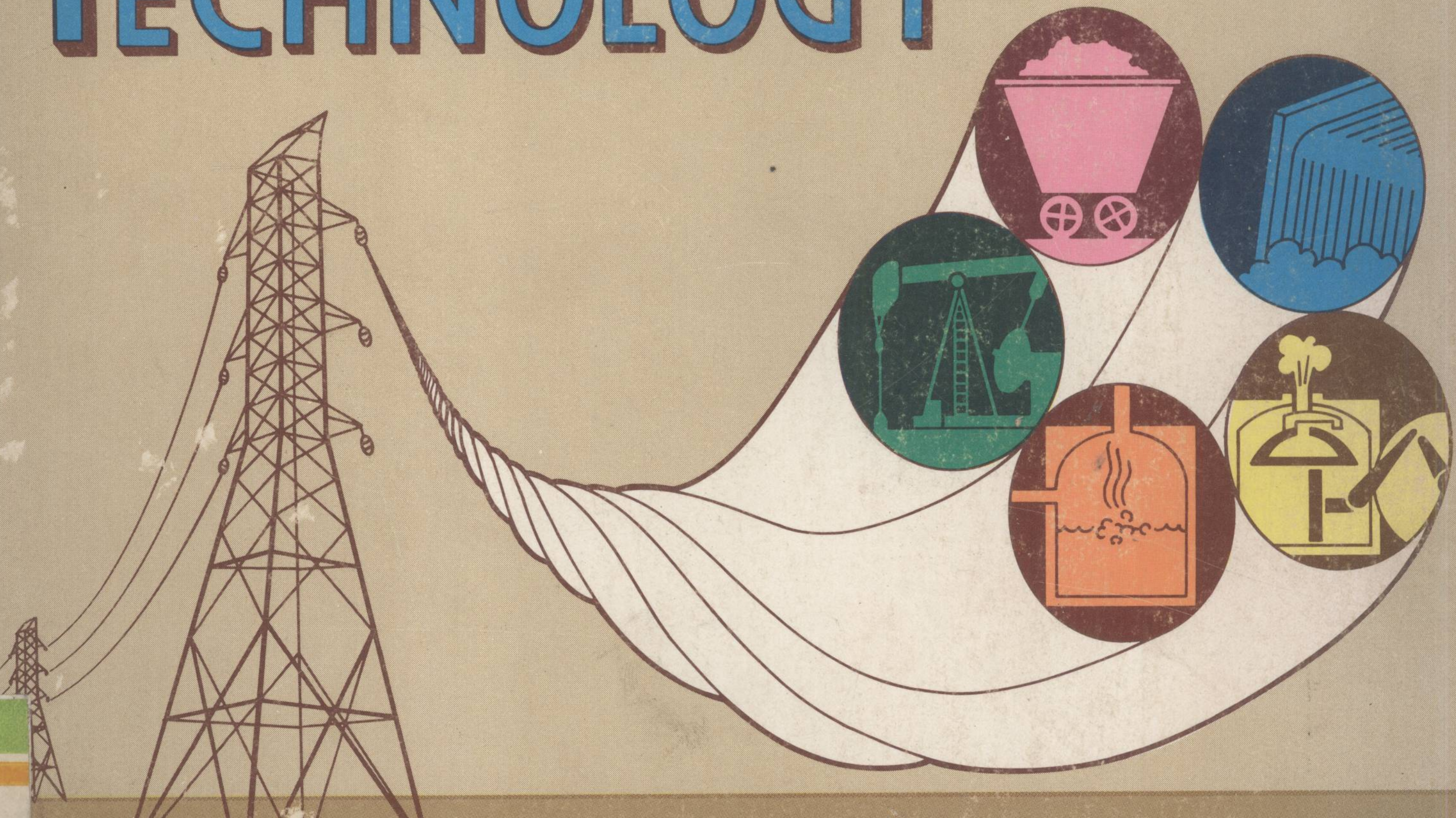
ELECTRICAL POWER SYSTEMS TECHNOLOGY



by
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Electrical
Power Systems
Technology

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Preface

Electrical Power Systems Technology provides a broad overview of the production, distribution, control, conversion, and measurement of electrical power. Through the presentation method used in this book, the reader will be able to develop an understanding of electrical power systems. The units of the book are organized in a systematic manner, beginning with electrical power production methods. The basic fundamentals of each major unit of the book are discussed at the beginning of the unit. These fundamentals provide a framework for the information which follows in each unit.

This book deals with many important aspects of electrical power, not just one or two areas. In this way, the reader can better understand the *total* electrical power system—from its production to its conversion to another form of energy. Each unit deals with a specific system, such as production, distribution, control, conversion, or measurement. Each system is broken down into subsystems. The subsystems are then explored in greater detail in the chapters which comprise each unit.

For more in-depth understanding of the content of this book, the reader should have a knowledge of basic electrical fundamentals. The mathematical presentations given are very simple and are used only to show practical relationships which are important in electrical power system operation. This book is recommended as a textbook for an "electrical power" or "electrical generators and motors" course. It would be a suitable text for vocational-technical schools, community colleges, universities, and, possibly, some technical high school programs. Many photographs and illustrations are shown to make the presentations that are given easier to understand. The content is presented in such a way that any reader should be able to learn a great deal about the operation of electrical power systems.

STEPHEN W. FARDO
DALE R. PATRICK

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UNIT I

Power Production

The first unit of this book develops a framework for the units which follow. The fundamentals of power production are examined in Chapter 1. Electrical power production systems include modern power systems such as fossil-fuel (coal, oil, gas) systems, hydroelectric systems, and nuclear-fission systems. These systems are discussed in Chapter 2. However, there are also many alternative energy systems that are being studied as potential sources of electrical power. These alternative systems, which include nuclear-fusion, geothermal, solar, wind, fuel cell, coal gasification, tidal, and magnetohydrodynamic (MHD) systems, are discussed in Chapter 3.

Most of the electrical power that is produced is alternating-current (ac) power. Chapter 4 deals with the single-phase and three-phase alternators which are used to produce alternating-current (ac) power. Direct-current (dc) power can be produced by chemical action or rotating machinery, or it can be converted from ac sources (rectification). Chapter 5 deals with the systems used for production of direct current.

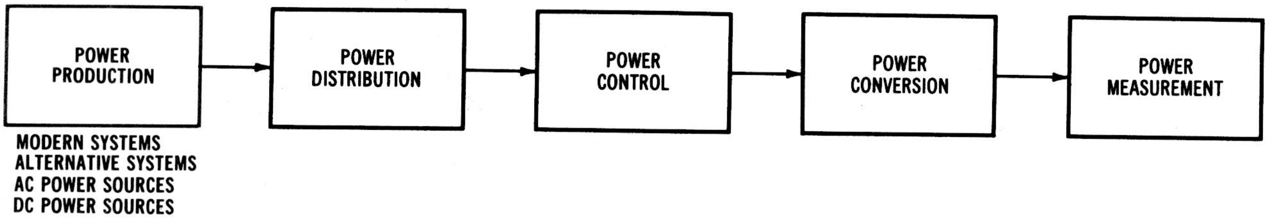


Fig. 1. The electrical power system.

CHAPTER 1

Power System Fundamentals

One of the most important areas of electrical knowledge is the study of electrical power systems. Complex power systems supply the vast need of our country for electrical energy. Due to our tremendous power requirement, we must constantly be concerned with the proper operation of our power production and power conversion systems. This book deals with some of the characteristics of electrical power production and power distribution systems, as well as the power control and power conversion systems needed. In addition, a discussion of electrical power measurement techniques is included.

THE ELECTRICAL POWER SYSTEM

The block diagram of an electrical power system is shown in Fig. 1-1. The first block or the *electrical power production* section is an important part of the complete electrical power system. However, once electrical power is produced, it must be distributed to the location where it will be used, so electrical *power distribution* systems (block 2) transfer electrical power from one location to another. Electrical *power control* systems (block 3) are probably the most complex of all the parts of the electrical power system as there are unlimited types of devices and equipment used to control electrical power. Then, the electrical *power conversion* systems (block 4), also called *loads,* convert the electrical power into some other form of energy, such as light, heat, or mechanical energy. Thus, conversion systems are an extremely important part of the electrical power system. Another part of the electrical power system is *power measurement* (block 5). Without electrical power measurement systems, control of electrical power would be almost impossible.

Each of the blocks shown in Fig. 1-1 represents one important part of the electrical power system. Thus, we should be concerned with each part of the electrical power system rather than only with isolated parts. 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 our energy problems that are related to electrical power. We cannot consider only the production aspect of electrical power systems. We must understand and consider each part 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 all electrical power production or power conversion systems are either resistive, inductive, or 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 which is produced is alternating current. Direct-current (dc) circuits will be discussed later in greater detail in Chapter 5.

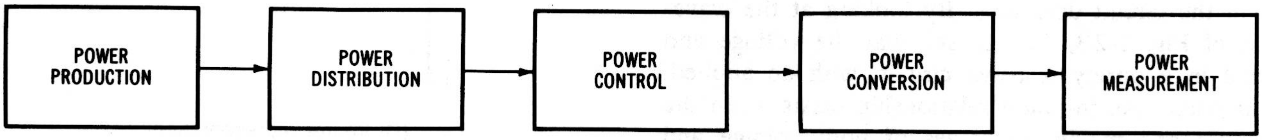
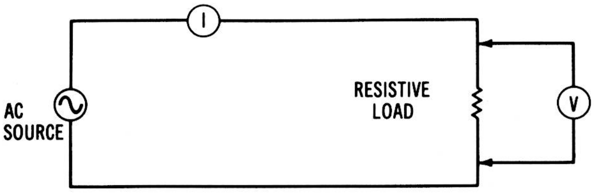
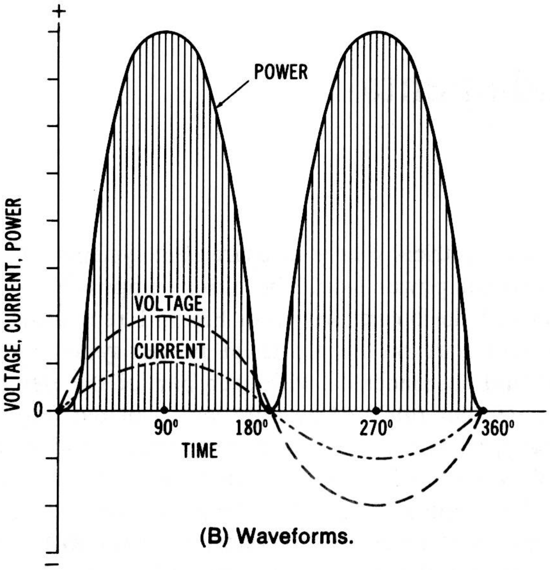


Fig. 1-1. Block diagram of an electrical power system.



(A) Circuit diagram.



(B) Waveforms.

(C) Vector representation.

Fig. 1-2. Resistive circuit.

Resistive Circuits

The simplest type of electrical circuit is a resistive circuit, such as the one shown in Fig. 1-2. The purely resistive circuit offers the same type of opposition to alternating-current power sources as it does to pure direct-current power sources. In dc circuits,

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

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

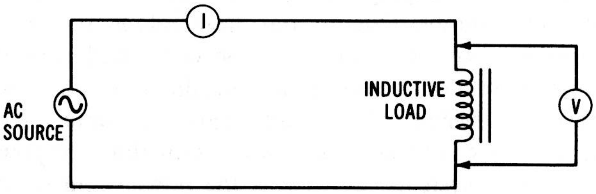
$$\text{Resistance (R)} = \frac{\text{Voltage (V)}}{\text{Current (I)}}$$

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

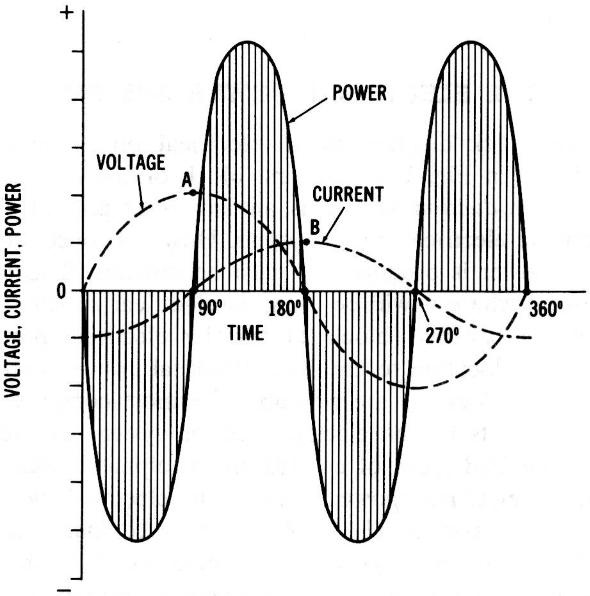
These basic electrical relationships show that when voltage is increased, the current in the circuit increases proportionally. Also, as resistance is increased, the current in the circuit decreases. By looking at the waveforms of Fig. 1-2B, we can see that the voltage and current in a purely resistive 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 Fig. 1-2B. Thus, when an ac circuit contains only resistance, its behavior is very similar to a dc circuit. Purely resistive circuits are seldom encountered in the design of electrical power systems, although some devices are primarily resistive in nature.

Inductive Circuits

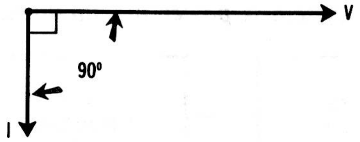
The property of inductance (L) is very commonly encountered in electrical power systems. This circuit property, shown in Fig. 1-3, adds more complexity to the relationship between voltage and current in an ac circuit. All motors, generators, and transformers exhibit the property of inductance. This property is evident due to a counter-electromotive force (cemf) which is produced when a magnetic field is developed around



(A) Circuit diagram.



(B) Waveforms.



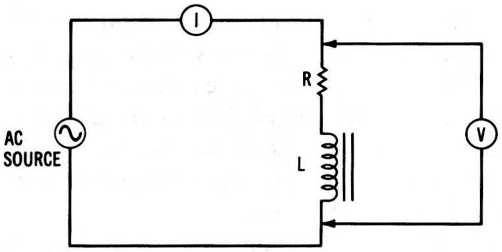
(C) Vector representation.

Fig. 1-3. Inductive circuit.

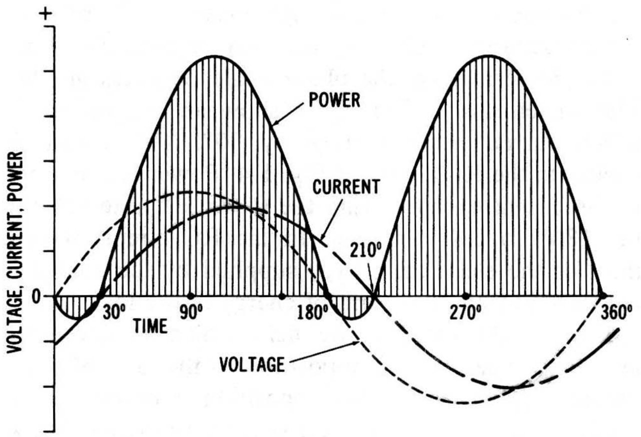
a coil of wire. The magnetic flux produced around the coils affects circuit action. Thus, the inductive property (cemf) produced by a magnetic field offers an opposition to change in the current flow in a circuit.

The opposition to change of current is evident in the diagram of Fig. 1-3B. In an inductive circuit, we can say that voltage leads current or that current lags voltage. If the circuit were purely inductive (contains no resistance), the voltage would lead the current by 90° (Fig. 1-3B) and no power would be converted in the circuit. However, since all actual circuits have resistance, the inductive characteristic of a circuit might typically cause the condition shown in Fig. 1-4 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.

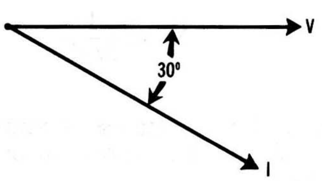
In terms of power conversion, a purely inductive circuit would not convert any power in a circuit. All ac power would be delivered back to the power source. Refer back to Fig. 1-3B and note points A and B on the waveforms. These points show that at the peak of each waveform, the corresponding value of the other 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 to another form of energy. Therefore, the power converted in a purely inductive circuit (90° phase angle) would be equal to zero.



(A) Circuit diagram.



(B) Waveforms.



(C) Vector representation.

Fig. 1-4. Resistive-inductive (RL) circuit.

Compare the purely inductive waveforms to those of Fig. 1-4B. In the practical resistive-inductive (RL) circuit, part of the power supplied from the source is converted in the circuit. Only 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 to another form of energy.

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 counterelectromotive 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 alternating current establishes the rate of change of the current. Inductive reactance (X_L) may be expressed as:

$$X_L = 2\pi fL$$

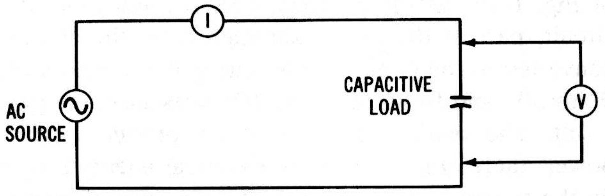
where,

X_L is the inductive reactance in ohms,
2π is 6.28, the mathematical expression for one sine wave of alternating current (0°–360°),
f is the frequency of the ac source in hertz,
L is the inductance of the circuit in henrys.

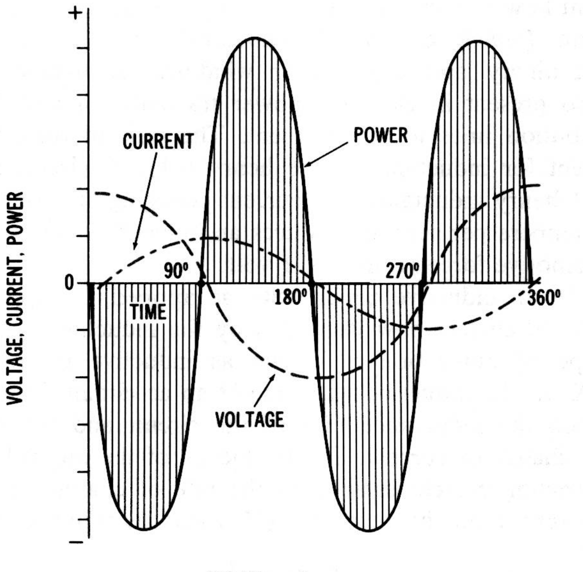
Capacitive Circuits

Fig. 1-5A 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 also have many applications in electrical power systems.

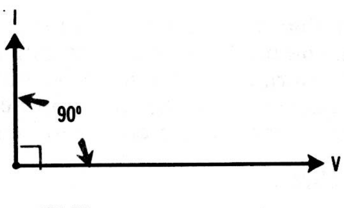
The operation of a capacitor in a circuit is dependent upon its ability to charge and discharge. When a capacitor charges, an excess of electrons (negative charge) is accumulated on one plate and a deficiency of electrons (positive charge) is created on the other plate. Capacitance (C) is determined 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 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.



(A) Circuit diagram.



(B) Waveforms.



(C) Vector representation.

Fig. 1-5. Capacitive circuit.

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 Fig. 1-5B 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 Fig. 1-5B, 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 Fig. 1-5B, the positive and negative power waveforms will cancel one another out.

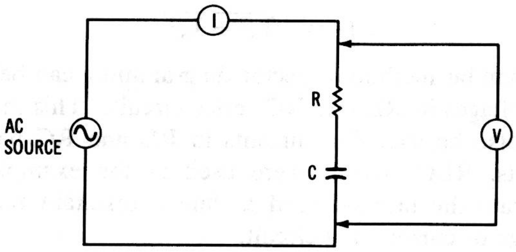
Since all circuits contain some resistance, a more practical circuit is the resistive-capacitive (RC) circuit shown in Fig. 1-6. In an RC circuit, the current leads the voltage by some phase angle between 0° and 90°. As capacitance increases, with no corresponding increase in resistance, the phase angle becomes greater. The waveforms of Fig. 1-6B show an RC circuit in which current leads voltage by 30°. This circuit is similar to the RL circuit of Fig. 1-4. Power is converted in the circuit except during the 0° 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 to another form of energy in the load.

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

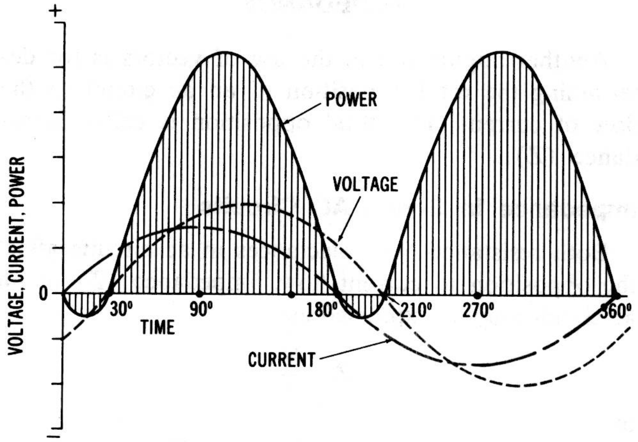
$$X_C = \frac{1}{2\pi fC}$$

where,

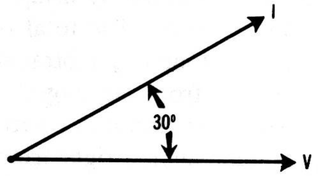
X_C is the capacitive reactance in ohms,
2π is the mathematical expression of one sine wave (0° to 360°),
f is the frequency of the source in hertz,
C is the capacitance in farads.



(A) Circuit diagram.



(B) Waveforms.



(C) Vector representation.

Fig. 1-6. Resistive-capacitive (RC) circuit.

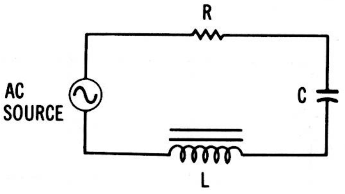
VECTOR AND PHASOR DIAGRAMS

In Figs. 1-3 through 1-6, a vector diagram was shown for each circuit condition that was illustrated. Vectors are straight lines which have a specific direction and length. They may be used to represent voltage or current values. An understanding of vector diagrams (sometimes called 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.

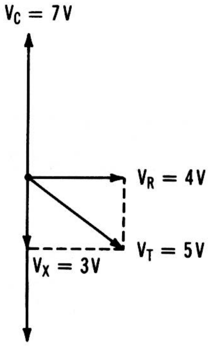
Ordinarily, when beginning a vector diagram, a horizontal line is drawn with its left end as the reference point. Rotation in a counterclockwise direction from the reference point is then considered to be a positive direction. Note that in the preceding diagrams, the voltage vector was the reference. 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 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 Fig. 1-7. 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, the resultant voltage applied to the circuit can be found. Since these



(A) Circuit diagram.



(B) Vector diagram.

$V_L = 10\text{ V}$

$V_X = V_L - V_C$

$= 10\text{ V} - 7\text{ V}$

$= 3\text{ V}$

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

$= \sqrt{4^2 + 3^2}$

$= \sqrt{16 + 9}$

$= \sqrt{25}$

$= 5\text{V}$

(C) Problem solution.

Fig. 1-7. Voltage vector relationship in a series RLC circuit.

vectors form a right triangle, the value of V_T can be expressed as:

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

where,

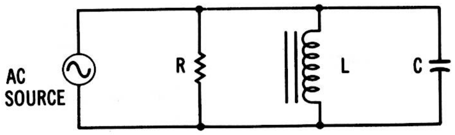
V_T is the total voltage applied to the circuit,
V_R is the voltage across the resistance,
V_X is the total reactive voltage ($V_L - V_C$ or $V_C - V_L$, depending on which is the larger).

The solution to this problem is shown in Fig. 1-7C.

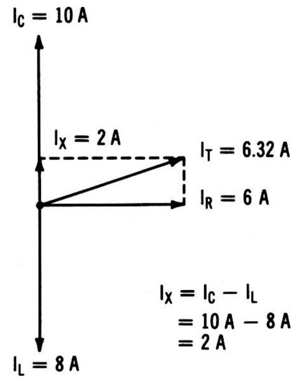
Use of Vectors for Parallel Circuits

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 Fig. 1-8. 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, the total current of the circuit (I_T) may be found. These vectors form a right triangle; therefore, total current can be expressed as:

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



(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.

Fig. 1-8. Current vector relationship in a parallel RLC circuit.

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

Another application in the use of vectors is for determining the total opposition of an ac circuit to the flow of current. This total opposition is called impedance (Z).

Impedance in Series AC Circuits

Both resistances and reactances in ac circuits affect the opposition to current flow. Impedance (Z) of an ac circuit may be expressed as:

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

or

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

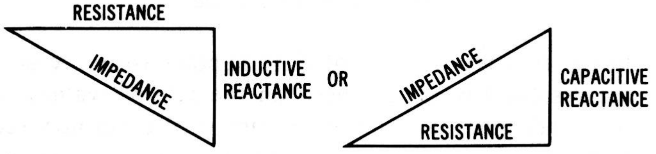
This formula may be clarified by using the vector diagram shown in Figure 1-9B. The total reactance (X_T) of an ac circuit may be found by subtracting the smallest reactance (X_L or X_C) from the largest reactance. The impedance of a series ac circuit is determined by using the preceding formula since a right triangle (called an impedance triangle) is formed by the three quantities which oppose the flow of alternating current. A sample problem for finding the total impedance of a series ac circuit is shown in Fig. 1-9D.

Impedance in Parallel AC Circuits

When components are connected in parallel, the calculation of impedance becomes more complex. Fig. 1-10A shows a simple RLC parallel circuit. Since the total impedance in the circuit is smaller than the resistance or reactance, an impedance triangle such as the one shown in Fig. 1-9C cannot be developed. A simple method used to find impedance in parallel circuits is the *admittance* triangle shown in Fig. 1-10B. The following quantities may be plotted on the triangle: admittance $= \frac{1}{Z}$, conductance $= \frac{1}{R}$, inductive susceptance $= \frac{1}{X_L}$, 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

(A) Circuit diagram.

(B) Vector diagram.



(C) Impedance triangles.

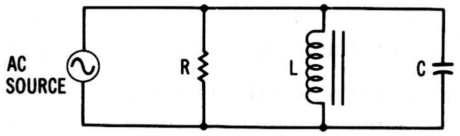
$$X_T = X_C - X_L = 12\Omega - 3\Omega = 9\Omega$$

$$Z = \sqrt{R^2 + X_T^2} = \sqrt{12^2 + 9^2} = \sqrt{144 + 81} = \sqrt{225} = 15\Omega$$

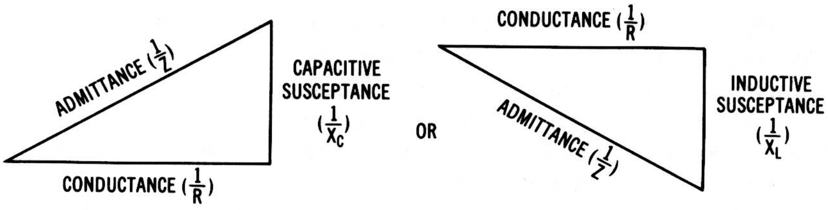
(D) Problem solution.

Fig. 1-9. Impedance in series ac circuits.

(A) Circuit diagram.

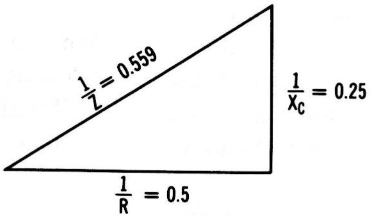


(B) Admittance triangles.



IF R = 2Ω, X_C = 4Ω, FIND Z:

(C) Problem solution.



$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_C}\right)^2} = \sqrt{(0.5)^2 + (0.25)^2} = \sqrt{0.25 + 0.0625} = \sqrt{0.3125} = 0.559$$

$$Z = \frac{1}{0.559} = 1.79\Omega$$

Fig. 1-10. Impedance in parallel ac circuits.

triangle. The sample problem of Fig. 1-10C shows the procedure used to find total impedance of a parallel RC circuit.

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 ($P = V \times I$). This formula is true also 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 using meters to measure power in an ac circuit, apparent power is the voltage reading multiplied by the current reading. The actual power which is converted to 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 to apparent power. This ratio is called the *power factor* and is expressed as:

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

or

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

where,

pf is the power factor of the circuit,
P is the true power in watts,
VA is the apparent power in voltamperes.

The maximum value of power factor is 1.0, or 100%, which would be obtained is a purely resistive circuit. This is referred to as *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 Fig. 1-11. There are two components which affect the power relationship in an ac circuit. The in-phase (resistive) component which results in power conversion in the circuit is called *active power.* Active power is the true power of the circuit and is measured in watts. The second component is that which results from an inductive or capacitive reactance and is 90° 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).

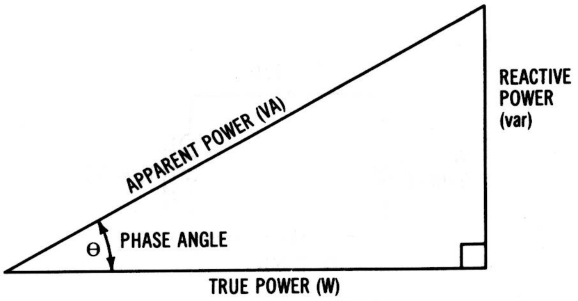


Fig. 1-11. Power triangle.

The power triangle of Fig. 1-11 shows true power (watts) on the horizontal axis, reactive power (var) at a 90° angle from the true power, and voltamperes (VA) as the longest side (hypotenuse) of the right triangle. Note the similarity between this right triangle, the voltage triangle for series ac circuits of Fig. 1-7, the current triangle for parallel ac circuits of Fig. 1-8, the impedance triangles of Fig. 1-9, and the admittance triangles of Fig. 1-10. 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 the trigonometric tables.

We also know that the cosine of an angle of a right triangle is expressed as:

$$\text{cosine}\ \theta = \frac{\text{adjacent side}}{\text{hypotenuse}}.$$

Thus, in terms of the power triangle:

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

Therefore, true power can be expressed as:

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

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).