ENCYCLOPEDIA ARTICLE

Print View | Email a Link

Alternating current

Contents [Hide]

Electric current that reverses direction periodically, usually many times per second. Electrical energy is ordinarily generated by a public or a private utility organization and provided to a customer, whether industrial or domestic, as alternating current. See also: Electric power generation

One complete period, with current flow first in one direction and then in the other, is called a cycle, and 60 cycles per second (60 Hz) is the customary frequency of alternation in the United States and in the rest of North America. In Europe and in many other parts of the world, 50 Hz is the standard frequency of alternation. On aircraft a higher frequency, often 400 Hz, is used to make possible lighter electrical machines.

When the term alternating current is used as an adjective, it is commonly abbreviated to ac, as in ac motor. Similarly, direct current as an adjective is abbreviated dc.

For further study:

BIOGRAPHIES

Ferranti, Sebastian Ziani de

View all 2 related biographies...

DICTIONARY

- **alternating current**

Advantages

The voltage of an alternating current can be changed by a transformer. This simple, inexpensive, static device permits generation of electric power at moderate voltage, efficient transmission for many miles at high voltage, and distribution and consumption at a conveniently low voltage. With direct (constant) current it is not possible to use a transformer to change voltage. On a few power lines, electrical energy is transmitted for great distances as direct current, but the electrical energy is generated as alternating current, transformed to a high voltage, rectified to direct current and transmitted, and then changed back to alternating current by an inverter, to be transformed down to a lower voltage for distribution and use. See also: Direct-current transmission

In addition to permitting efficient transmission of energy, alternating current provides advantages in the design of generators and motors, and for some purposes gives better operating characteristics. Certain devices involving chokes and transformers could not be operated on direct current. Also, the operation of large switches (called circuit breakers) is facilitated because the instantaneous value of alternating current automatically becomes zero twice in each cycle, and an opening circuit breaker need not interrupt the current but only prevent current from starting again after its instant of zero value. See also: Alternating-current generator; Alternating-current motor; Circuit breaker

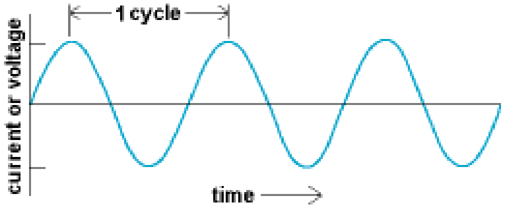
Sinusoidal form

An alternating current waveform is shown diagrammatically in **Fig. 1**. Time is measured horizontally (beginning at any arbitrary moment) and the current at each instant is measured vertically. In this diagram it is assumed that the current is alternating sinusoidally; that is, the current i is described by Eq. (1),

$$i = I_m \sin 2\pi f t \qquad (1)$$

where I_m is the maximum instantaneous current, f is the frequency in cycles per second (hertz), and t is the time in seconds. See also: Sine wave

Diagram of sinusoidal alternating current.



Add to 'My Saved Images'

Measurement

Quantities commonly measured by ac meters and instruments are energy, power, voltage, and current. Other quantities less commonly measured are reactive volt-amperes, power factor, frequency, and demand (of energy during a given interval such as 15 min).

Energy is measured on a watt-hour meter. There is usually such a meter where an electric line enters a customer's premises. The meter may be single-phase (usual in residences) or three-phase (customary in industrial installations), and it displays on a register of dials the energy that has passed, to date, to the system beyond the meter. The customer frequently pays for energy consumed per the reading of such a meter. See also: Electrical energy measurement; Watt-hour meter

Power is measured on a wattmeter. Since power is the rate of consumption of energy, the reading of the wattmeter is proportional to the rate of increase of the reading of a watt-hour meter. The same relation is expressed by saying that the reading of the watt-hour meter, which measures energy, is the integral (through time) of the reading of the wattmeter, which measures power. A wattmeter usually measures power in a single-phase circuit, although three-phase wattmeters are sometimes used. See also: Electric power measurement; Wattmeter

Current is measured by an ammeter. Power absorbed by an element is the product of current through the element, voltage across it, and the power factor between the current and the voltage, as shown in Eq. (5). With unidirectional (direct) current, the amount of current is the rate of flow of electricity; it is proportional to the number of electrons passing a specified cross section of a wire per second. This is likewise the definition of current at each instant of an alternating-current cycle, as current varies from a maximum in one direction to zero and then to a maximum in the other direction (Fig. 1). An oscilloscope will indicate instantaneous current, but the value of instantaneous current is not often useful for analysis purposes. A dc (d'Arsonval-type) ammeter will measure average current, but this is useless in an ac circuit, for the average of sinusoidal current is zero. A useful measure of alternating current is found in the ability of the current to do work, and the amount of current is correspondingly defined as the square root of the average of the square of instantaneous current, the average being taken over an integer number of cycles. This value is known as the root-mean-square (rms) or effective current. It is measured in amperes. It is a useful measure for current of any frequency. The rms value of direct current is identical to its dc value. The rms value of sinusoidally alternating current is $I_m/2$, where I_m is the maximum instantaneous current. [See Fig. 1 and Eq. (1).] See also: Ammeter; Current measurement; Oscilloscope

Voltage is measured by a voltmeter. Voltage is the electrical pressure. It is measured between one point and another in an electric circuit, often between the two wires of the circuit. As with current, instantaneous voltage in an ac circuit reverses each half cycle and the average of sinusoidal voltage is zero. Therefore the rms or effective value of voltage is used in ac systems. The rms value of sinusoidally alternating voltage is $V_m/2$, where V_m is the maximum instantaneous voltage. This rms voltage, together with rms current and the circuit power factor, is used to compute electric power, as in Eqs. (4) and (5). See also: Voltage measurement

The ordinary voltmeter is connected by wires to the two points between which voltage is to be measured, and voltage is proportional to the current that results through a very high electrical resistance within the voltmeter itself. The voltmeter, actuated by this current, is calibrated in volts.

Phase difference

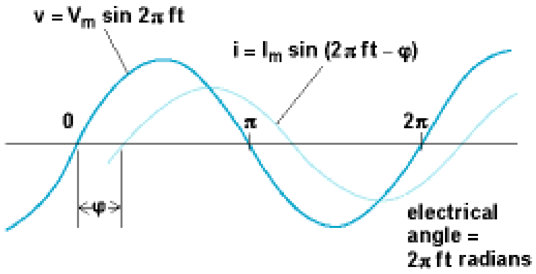
Phase difference is a measure of the fraction of a cycle by which one sinusoidally alternating quantity leads or lags another. **Figure 2** shows a voltage waveform *v* which is described in Eq. (2) and a current *i* which is described in Eq. (3).

$$v = V_m \sin 2\pi f t \tag{2}$$

$$i = I_m \sin(2\pi f t - \varphi) \tag{3}$$

The angle φ is called the phase difference between the voltage and the current; this current is said to lag (behind this voltage) by the angle φ. It would be equally correct to say that the voltage leads the current by the phase angle φ. Phase difference can be expressed as a fraction of a cycle, as an angle in degrees, or as an angle in radians, as shown in Eq. (3). If there is no phase difference, and φ = 0, voltage and current are in phase. If the phase difference is a quarter cycle, and φ = ±90°, the quantities are said to be in quadrature.

Fig. 2 Phase angle φ.



Add to 'My Saved Images'

Power factor

Power factor is defined in terms of the phase angle. If the rms value of sinusoidal current from a power source to a load is *I* and the rms value of sinusoidal voltage between the two wires connecting the power source to the load is *V*, the average power *P* passing from the source to the load is shown as Eq. (4).

$$P = VI\cos\varphi \tag{4}$$

The cosine of the phase angle, cos φ, is called the power factor. Thus the rms voltage, the rms current, and the power factor are the components of power.

The foregoing definition of power factor has meaning only if voltage and current are sinusoidal. Whether they are sinusoidal or not, average power, rms voltage, and rms current can be measured, and a value for power factor is implicit in Eq. (5).

$$P = VI\ (\text{power factor}) \tag{5}$$

This gives a definition of power factor when *V* and *I* are not sinusoidal. If the voltage across the element and the current through it are in phase (and of the same waveform), power factor equals 1. If voltage and current are out of phase, power factor is less than 1. If voltage and current are sinusoidal and in quadrature, then the power factor is zero.

The phase angle and power factor of voltage and current in a circuit that supplies a load are determined by the load. Thus a load of pure resistance, such as an electric heater, has unity power factor. An inductive load, such as an induction motor, has a power factor less than 1 and the current lags behind the applied voltage. A capacitive load, such as a bank of capacitors, also has a power factor less than 1, but the current leads the voltage, and the phase angle φ is negative.

If a load that draws lagging current (such as an induction motor) and a load that draws leading current (such as a bank of capacitors) are both connected to a source of electric power, the power factor of the two loads together can be higher than that of either one alone, and the current to the combined loads may have a smaller phase angle from the applied voltage than would currents to either of the two loads individually. Although power to the combined loads is equal to the arithmetic sum of power to the two individual loads, the total current will be less than the arithmetic sum of the two individual currents (and may, indeed, actually be less than either of the two individual currents alone). It is often practical to reduce the total incoming current by installing a bank of capacitors near an inductive load, and thus to reduce power lost in the incoming distribution lines and transformers, thereby improving efficiency. This process is called power-factor correction.

Three-phase system

Three-phase systems are commonly used for generation, transmission, and distribution of electric power. A customer may be supplied with three-phase power, particularly if a large amount of power is needed or if the customer wishes to use three-phase loads. Small domestic customers are usually supplied with single-phase power.

A three-phase system is essentially the same as three ordinary single-phase systems with the three voltages of the three single-phase systems out of phase with each other by one-third of a cycle (120°), as shown in **Fig. 3**. The three voltages may be written as Eqs. (6), (7), and (8),

$$v_{an} = V_{an(\max)} \sin 2\pi f t \tag{6}$$

$$v_{bn} = V_{bn(\max)} \sin 2\pi (f t - {}^{1}/_{3}) \tag{7}$$

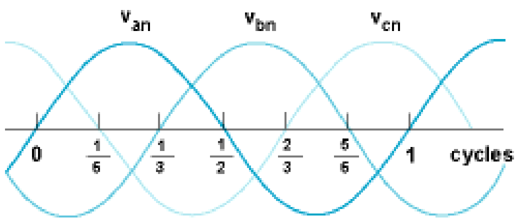
$$v_{cn} = V_{cn(\max)} \sin 2\pi (f t - {}^{2}/_{3}) \tag{8}$$

where $V_{an(\max)}$ is the maximum value of voltage in phase *an*, and so on. The three-phase system is balanced if relation (9)

$$V_{an(\max)} = V_{bn(\max)} = V_{cn(\max)} \tag{9}$$

holds, and if the three phase angles are equal, one-third cycle each as shown.

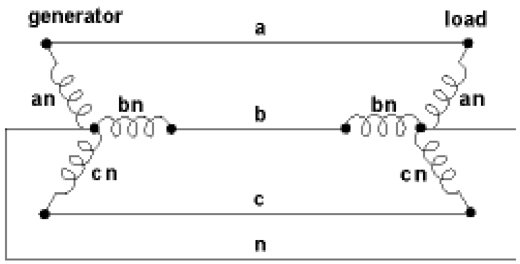
Fig. 3 Voltages of a balanced three-phase system.



Add to 'My Saved Images'

If a three-phase system were actually three separate single-phase systems, there would be two wires between the generator and the load of each system, requiring a total of six wires. In fact, however, a single wire can be common to all three systems, so that it is only necessary to have three wires for a three-phase system (**Fig. 4*a–c***) plus a fourth wire *n* serve as a common return or neutral conductor. On some systems the Earth is used as the common or neutral conductor.

Fig. 4 Connections of a simple three-phase system.



Add to 'My Saved Images'

Each phase of a three-phase system carries current and conveys power and energy. If the three loads on the three phases of the three-phase system are identical and the voltages are balanced, then the currents are balanced also. Figure 2 can then apply to any one of the three phases. It will be recognized that the three currents in a balanced system are equal in rms (or maximum) value and that they are separated one from the other by phase angles of one-third cycle and two-thirds cycle. Thus the currents (in a balanced system) are themselves symmetrical. Note, however, that the three currents will not necessarily be in phase with their respective voltages; the corresponding voltages and currents will be in phase with each other only if the load is pure resistance and the phase angle between voltage and current is zero. Otherwise some such relation as that of Fig. 2 will apply to each phase.

It is significant that, if the three currents of a three-phase system are balanced, their sum is zero at every instant. In practice, the three currents are not usually exactly balanced, and one of two situations arises. Either the common neutral wire *n* is used, in which case it carries little current (and may be of high resistance compared to the other three line wires), or else the common neutral wire *n* is not used, only three line wires being installed, and the three phase currents are thereby forced to add to zero even though this requirement results in some imbalance of phase voltages at the load.

It is also significant that the total instantaneous power from generator to load is constant (does not vary with time) in a balanced, sinusoidal, three-phase system. Power in a single-phase system that has current in phase with voltage is maximum when voltage and current are maximum, and is instantaneously zero when voltage and current are zero; if the current of the single-phase system is not in phase with the voltage, the power will reverse its direction of flow during part of each half cycle. However, in a balanced three-phase system, regardless of the phase angle, the flow of power is unvarying from instant to instant. This results in smoother operation and less vibration of motors and other ac devices.

Three-phase systems are almost universally used for large amounts of power. In addition to providing smooth flow of power, three-phase motors and generators are more economical than single-phase machines. Polyphase systems with two, four, or other numbers of phases are possible, but they are little used except when a large number of phases, such as 12, is desired for economical operation of a rectifier.

H. H. Skilling

Symmetrical (0, 1, 2) components

When three coils are equally spaced around the periphery of the stator of a generator, a properly shaped magnetic field rotating in a forward direction at uniform velocity will induce voltages in these coils. The three voltages may be written as Eqs. (6), (7), and (8). For analytical purposes it is more convenient to express the voltages as phasors, as in Eqs. (10).

$$\begin{aligned} \mathbf{V}_{a1} &= \mathbf{V}_{a1} \\ \mathbf{V}_{b1} &= \mathbf{V}_{a1}\, e^{-j2\pi/3} \\ \mathbf{V}_{c1} &= \mathbf{V}_{a1}\, e^{+j2\pi/3} \end{aligned} \tag{10}$$

For a discussion of phasor notation and complex representation. See also: Alternating-current circuit theory

In order to simplify notation, it has become accepted practice to introduce a standard set of unit three-phase phasors as in Eqs. (11),

$$1 = e^{j0} \quad \mathbf{a} = e^{j2\pi/3} \quad \mathbf{a}^2 = e^{-j2\pi/3} \tag{11}$$

so that Eqs. (10) may be written more succinctly in matrix format as in Eq. (12).

$$\begin{bmatrix} \mathbf{V}_{a1} \\ \mathbf{V}_{b1} \\ \mathbf{V}_{c1} \end{bmatrix} = (\mathbf{V}_{a1}) \begin{bmatrix} 1 \\ \mathbf{a}^2 \\ \mathbf{a} \end{bmatrix} \tag{12}$$

See also: Matrix theory

When the voltages proceed in time-phase in the order $\mathbf{V}_a$, $\mathbf{V}_b$, $\mathbf{V}_c$, as reflected in Eqs. (6), (7), and (8), the set of three-phase voltage is called a positive-sequence set of voltages and is identified by the subscript 1, as in Eqs. (10) and (12). When three coils are equally spaced around the periphery of the stator of a generator, a properly shaped magnetic field rotating in a backward direction at uniform velocity will induce voltages in these coils which proceed in time-phase in the order $\mathbf{V}_a$, $\mathbf{V}_c$, $\mathbf{V}_b$, and the set of three-phase voltages is called a negative-sequence set of voltages and identified by the subscript 2. In terms of phasor notation, the voltages are written as in Eqs. (13).

$$\begin{bmatrix} \mathbf{V}_{a2} \\ \mathbf{V}_{b2} \\ \mathbf{V}_{c2} \end{bmatrix} = (\mathbf{V}_{a2}) \begin{bmatrix} 1 \\ \mathbf{a} \\ \mathbf{a}^2 \end{bmatrix} \tag{13}$$

If coils *b* and *c* are placed in the same slot with coil *a*, then $\mathbf{V}_a = \mathbf{V}_b = \mathbf{V}_c$, and the set of three-phase voltages is called a zero-sequence set of voltages and identified by the subscript 0. In terms of phasor notation the voltages are written as in Eqs. (14).

$$\begin{bmatrix} \mathbf{V}_{a0} \\ \mathbf{V}_{b0} \\ \mathbf{V}_{c0} \end{bmatrix} = (\mathbf{V}_{a0}) \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \qquad (14)$$

The set of positive-, negative-, and zero-sequence components are collectively referred to as symmetrical components.

If the voltages $\mathbf{V}_a$, $\mathbf{V}_b$, and $\mathbf{V}_c$ are written as in Eqs. (15), and, in matrix format, as in Eq. (16),

$$\begin{aligned} \mathbf{V}_a &= \mathbf{V}_{a0} + \mathbf{V}_{a1} + \mathbf{V}_{a2} = \mathbf{V}_{a0} + \mathbf{V}_{a1} + \mathbf{V}_{a2} \\ \mathbf{V}_b &= \mathbf{V}_{b0} + \mathbf{V}_{b1} + \mathbf{V}_{b2} = \mathbf{V}_{a0} + \mathbf{a}^2\mathbf{V}_{a1} + \mathbf{a}\mathbf{V}_{a2} \\ \mathbf{V}_c &= \mathbf{V}_{c0} + \mathbf{V}_{c1} + \mathbf{V}_{c2} = \mathbf{V}_{a0} + \mathbf{a}\mathbf{V}_{a1} + \mathbf{a}^2\mathbf{V}_{a2} \end{aligned} \qquad (15)$$

$$\begin{bmatrix} \mathbf{V}_a \\ \mathbf{V}_b \\ \mathbf{V}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \mathbf{a}^2 & \mathbf{a} \\ 1 & \mathbf{a} & \mathbf{a}^2 \end{bmatrix} \begin{bmatrix} \mathbf{V}_{a0} \\ \mathbf{V}_{a1} \\ \mathbf{V}_{a2} \end{bmatrix} \qquad (16)$$

then by selecting complex values for $\mathbf{V}_{a0}$, $\mathbf{V}_{a1}$, and $\mathbf{V}_{a2}$, respectively, in an arbitrary manner, it is possible to establish an infinite number of unbalanced phase voltages $\mathbf{V}_a$, $\mathbf{V}_b$, and $\mathbf{V}_c$. Conversely, and more important, since the inverse relationship given by Eq. (17) exists,

$$\begin{bmatrix} \mathbf{V}_{a0} \\ \mathbf{V}_{a1} \\ \mathbf{V}_{a2} \end{bmatrix} = (1/3) \begin{bmatrix} 1 & 1 & 1 \\ 1 & \mathbf{a} & \mathbf{a}^2 \\ 1 & \mathbf{a}^2 & \mathbf{a} \end{bmatrix} \begin{bmatrix} \mathbf{V}_a \\ \mathbf{V}_b \\ \mathbf{V}_c \end{bmatrix} \qquad (17)$$

for any given unbalanced set of three-phase voltages, it is always possible to determine a corresponding unique set of zero-, positive-, and negative-sequence voltages. Equally well, for any given unbalanced set of three-phase currents, it is always possible to determine a corresponding unique set of zero-, positive-, and negative-sequence currents.

Three-phase power system components, such as transmission lines, transformers, loads, motors, and generators, may, in many practical instances, be considered geometrically symmetrical among the three phases. In this event, it can be shown that when a zero-, positive-, or negative-sequence voltage is applied to such a component, the resultant current will be a zero-, positive-, or negative-sequence component, respectively. The associated zero-, positive-, and negative-sequence impedances can be readily identified.

Consequently, because of the symmetrical nature of each of the symmetrical-component voltages and currents, it is necessary to consider only one of the three phases of the three-phase power system in an analysis. By accepted convention, phase “*a*” is the selected phase.

Perhaps the most important virtue of symmetrical components lies in the fact that if a common type of unsymmetrical fault (single-line-to-ground fault, line-to-line fault, one open conductor, two open conductors, and so forth) occurs at one point in an otherwise symmetrical three-phase network, a relatively simple interconnection occurs between the symmetrical component networks at the fault location.

M. Harry Hesse

Power and information

Although this article has emphasized electric power, ac circuits are also used to convey information. An information circuit, such as telephone, radio, or control, employs varying voltage, current, waveform, frequency, and phase. Efficiency is often low, the chief requirement being to convey accurate information even though little of the transmitted power reaches the receiving end. For further consideration of the transmission of information. See also: Electrical communications; Radio; Telephone; Waveform

An ideal power circuit should provide the customer with electrical energy always available at unchanging voltage of constant waveform and frequency, the amount of current being determined by the customer's load. High efficiency is greatly desired. See also: Capacitance; Circuit (electricity); Electric current; Electric filter; Electrical impedance; Electrical resistance; Inductance; Joule's law; Network theory; Ohm's law; Resonance (alternating-current circuits)

H. H. Skilling

Bibliography

- J. Arrillaga and C. P. Arnold, *Computer Analysis of Power Systems*, 1990
- O. I. Elgerd, *Electric Energy Systems Theory*, 2d ed., 1982
- J. J. Grainger and W. D. Stevenson, Jr., *Power System Analysis*, 1994
- C. P. Paul, S. A. Nasar, and L. E. Unnewehr, *Introduction to Electrical Engineering*, 2d ed., 1992

How to cite this article

H. H. Skilling, M. Harry Hesse, H. H. Skilling, "Alternating current", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.025500