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Power Factor Measurement

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Electricity can be thought of as a means of delivering power from one place to another to do work. The laws and relationships for delivering power were originally developed for direct current (dc). Power delivered, expressed in watts, was calculated by multiplying the voltage and current as shown in Equation 23.1:

\[ P_{dc} = EI \]  
(23.1)

The situation becomes more complex when alternating current (ac) is used to deliver power. Figure 23.1 shows a sine wave representing either ac or voltage. Since the instantaneous value of the wave is continually changing, a numerical quantity is needed to represent an average property of this wave. This is quantity, the root-mean-square, or \( rms \) value, calculated by squaring the instantaneous value, integrating it during one cycle, dividing by the period, and taking the square root of the result, is equal to the peak value of the ac wave divided by the square root of 2, or, for ac current, \( I_{rms} = i_{peak}/\sqrt{2} \). In the physical world, a sine wave ac having an rms value of 1 A (\( A = \) ampere), passed through a resistive load, produces the same heating effect as 1 A of dc. Thus, one might expect delivered ac power to be easily calculated in watts using Equation 23.1 and inserting rms values for current and voltage. While this simple relationship holds true for the instantaneous voltage and current values as shown in Equation 23.1a in general,
FIGURE 23.1 Sine wave characteristics. One cycle of a continuous wave is shown. The wave begins at a zero-crossing, reaches a positive peak, and continues through zero to a negative peak and back to zero. The wave repeats every 360°. The wave angle can also be expressed as a function of frequency $f$ and time $t$. For a given frequency, the wave angle is related to the expression, $2\pi ft$.

It is not true for the rms quantities except for the special case when the ac current and voltage are restricted to perfect sine waves and the load is a pure resistance:

$$p_{\text{rms}} = EI \tag{23.1a}$$

In real-world situations where current and/or voltage waveforms are not perfectly sinusoidal and/or the loads are other than resistive, the relationships are no longer simple, and the power delivered, or active power, is usually less than the product of rms voltage and current, as shown in Equation 23.2:

$$p_{\text{ac}} \leq E_{\text{rms}}I_{\text{rms}} \tag{23.2}$$

The product of rms voltage and rms current does, however, define a quantity termed apparent power, $U$, as shown in Equation 23.3:

$$U = E_{\text{rms}}I_{\text{rms}} \tag{23.3}$$

A derived term, the power factor, $F_p$, used to express the relationship between delivered or active power, $P$, and apparent power, $U$, is defined by Equation 23.4:

$$F_p = \frac{P}{U} \tag{23.4}$$

From Equations 23.2 through 23.4, it is clear that the value of $F_p$ must lie in a range between zero and one. This chapter focuses on (1) ac power relationships and the calculation of power factor, (2) the physical meaning of these relationships, and (3) measurement techniques and instrumentation for determining these relationships and calculating power factor.
23.1 Reasons for Interest in Power Factor

Power factor is a single number that relates the active power, $P$, to the apparent power, $U$. Electric components of a utility distribution system are designed on a kVA basis; that is, they are designed to operate at a given voltage and carry a rated current without undue temperature rise. Transformer and conductor sizes are chosen on this basis. While active power does useful work, reactive and harmonic powers do no useful work, absorb system capacity, and increase system losses, but reactive and harmonic powers are needed to provide magnetic fields or nonlinear currents. The capacity of electric systems is limited by apparent power, not active power. Power factor expresses, with a single value, the extent to which an electric distribution system is efficiently and effectively utilized. A low value for the power factor means that much of the system capacity is not available for useful work. From a utility viewpoint, this means reduced ability to deliver revenue-producing active power; from a user viewpoint, a low-power factor reduces the available active power or requires increased system size to deliver needed power.

23.2 AC Electric Loads

23.2.1 Linear Loads

Electric loads in ac power systems with sinusoidal voltages are categorized by the way they draw current from the system. Loads that draw sinusoidal currents, that is, the current waveshape is the same as the voltage waveshapes, are defined as linear loads. Historically, a high percentage of electric loads have been linear. Linear loads include (1) induction motors, (2) incandescent lighting, and (3) heaters and heating elements. Linear loads use ac electric power directly to accomplish their functions.

23.2.2 Nonlinear Loads

Electric loads that draw nonsinusoidal currents, that is, the current waveshape differs from the voltage waveshape, are defined as nonlinear loads. As energy savings and efficient use of electricity are emphasized, an increased percentage of nonlinear electric devices, both new and replacement, are being installed. Nonlinear loads include (1) adjustable-speed motor drives, (2) fluorescent and arc-discharge lighting, (3) computers and computerized controls, and (4) temperature-controlled furnaces and heating elements. Nonlinear loads, rather than using ac electric power directly, often convert ac power into dc before it is used to accomplish their functions. A common element in nonlinear loads is some kind of rectifier to accomplish this ac to dc conversion. Rectifiers do not draw sinusoidal currents.

23.3 AC Power Relationships

23.3.1 Sinusoidal Voltage and Current

Power calculations for sinusoidal ac electric systems require knowledge of the rms voltage, the rms current, and the phase relationships between the two. Figure 23.2 illustrates possible phase relationships between voltage and current. If the positive-going zero-crossing of the voltage is considered the reference point, then the nearest positive-going zero-crossing of the current can occur at a wave angle either less than or greater than this reference. If the current zero-crossing occurs before the reference, the current is said to lead the voltage. If the current zero-crossing occurs after the reference, the current is lagging. If the zero-crossing for the current coincides with the reference, the two waves are said to be in phase. The wave angle, $\theta$, by which the current leads or lags the voltage is called the phase angle, in this case, $30^\circ$. 

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23.3.2 Single-Phase Circuits

23.3.2.1 Power Calculations

The power delivered to do work is easily calculated [1]. Given a sinusoidal voltage of rms magnitude \( E \) and sinusoidal current of rms magnitude \( I \), displaced by angle \( \theta \), at time \( t \),

\[
\text{Instantaneous voltage} = e^{\sqrt{2}E \sin(2\pi ft)}
\]

\[\text{Instantaneous current} = i = \sqrt{2}I \sin(2\pi ft - \theta)\text{ (note that } \theta \text{ can have a positive or negative value)}\]

\[
\text{Instantaneous power} = p = ei
\]

\[p = 2E \sin(2\pi ft) \sin(2\pi ft - \theta)\]

\[p = EI \cos(\theta) - EI \cos(4\pi ft - \theta)\]  \hspace{1cm} (23.5b)

Average power over an integral number of cycles \( p = EI \cos(\theta) \)

\[
\text{Power factor } F_p = \frac{P}{U} = \frac{EI \cos(\theta)}{EI} = \cos(\theta) \]  \hspace{1cm} (23.5c)

Equation 23.5 is the fundamental equation that defines power for systems in which the current and voltage are sinusoidal. The application of this equation is illustrated for three cases: (1) the current and voltage are in phase, (2) the current and voltage are out of phase by an angle less than 90°, and (3) the current and voltage are out of phase by exactly 90°.
23.3.2.2 AC Power Examples

Figure 23.3 shows voltage current and power when the voltage and current are in phase and the current displacement angle is zero (0°). (An example would be a resistance space heater.) The power curve is obtained by multiplying together the instantaneous values of voltage and current as the wave angle is varied from 0° to 360°. Instantaneous power, the product of two sine waves, is also a sine wave. There are two zero-crossings per cycle, dividing the cycle into two regions. In region (1), both the voltage and current are positive, and the resultant product, the power, is positive. In region (2), both the voltage and current are negative, and the power is again positive. The average power in watts, given by Equation 23.5, \( EI \cos(0°) = EI \), is the maximum power that can be delivered to do work. When sinusoidal voltage and current are in phase, the delivered power in watts is the same as for dc and is the maximum that can be delivered. The power factor \( F_p = \cos(0°) = 1 \) or unity.

Figure 23.4 shows voltage, current, and power when the current lags the voltage by 60°. (An example might be a lightly loaded induction motor.) The power sine wave again is obtained by multiplying together the instantaneous values of voltage and current. There are now four zero-crossings per cycle, dividing the cycle into four regions. In regions (2) and (4), voltage and current have the same sign, and the power is positive. In regions (1) and (3), voltage and current have opposite signs, resulting in a negative value for the power. The average power in watts, given by Equation 23.5, \( EI \cos(60°) = EI(0.5) \), is less than the maximum that could be delivered for the particular values of voltage and current. When voltage and current are out of phase, the delivered power in watts is always less than the maximum. In this example, \( F_p = \cos(60°) = 0.5 \).

Figure 23.5 shows voltage, current, and power when the current lags the voltage by 90°. (This situation is not attainable in the real world.) The power sine wave again is obtained by multiplying together the instantaneous values of voltage and current. Again, four zero-crossings divide the cycle into four regions. In regions (2) and (4), the power is positive, while in regions (1) and (3), the power is negative.

![Figure 23.3](https://example.com/image.png)

**Figure 23.3** Voltage, current, and power for sine waves in phase. The vertical scales for voltage and current are equal. The scale for power is relative and is selected to permit the display of all three waves on a single graph. The voltage and current are in phase and both are sinusoidal. The power is positive everywhere, and average power delivered to do work is the maximum power.
FIGURE 23.4 Voltage, current, and power for sine waves 60° out of phase. The vertical scales for voltage and current amplitudes are the same as those for Figure 23.3. Current lags voltage by 60° and both are sinusoidal. The power is positive in regions (2) and (4) and negative in regions (1) and (3). Average power delivered to do work is less than the maximum power.

FIGURE 23.5 Voltage, current, and power for sine waves 90° out of phase. The vertical scales for voltage and current amplitudes are the same as those for Figure 23.3. Current lags voltage by 90° and both are sinusoidal. The power is positive in regions (2) and (4) and negative in regions (1) and (3) and is of equal absolute magnitude in all four regions. Average power delivered to do work is zero.
The average power in watts is given by Equation 23.5, \( EI \cos(90^\circ) = 0 \). No matter what the values of voltage and current, when voltage and current are exactly 90\(^\circ\) out of phase, the delivered power in watts is always zero. The power factor \( F_p = \cos(90^\circ) = 0 \).

### 23.3.2.3 Power Factor

Resolving the current into orthogonal components on a phasor diagram illustrates how delivered power can vary from a maximum to zero, depending on the phase angle between the voltage and the current sine waves. Figure 23.6 shows the voltage vector along with the current resolved into orthogonal components [1]. The current \( I \) at an angle \( \theta \) relative to the voltage can be resolved into two vectors: \( I \cos(\theta) \) and \( I \sin(\theta) \). The in-phase component \( I \cos(\theta) \) multiplied by the voltage gives average power in watts. The current component that is 90\(^\circ\) out of phase with the voltage, \( I \sin(\theta) \), is not associated with delivered power and does not contribute to work. For want of a better name, this was originally termed the *wattless component* of the current. Since this wattless current could be associated with magnetic fields, it was sometimes termed *magnetizing current* because, while doing no work, this current interacts through the inductive reactance of an ac motor winding to provide the magnetic field required for such a motor to operate.

Three types of power have been defined for systems in which both the voltage and current are sinusoidal. Throughout the years, a number of different names have been given to the three power types. The names in present usage will be emphasized.

**Active power** is given the symbol \( P \) and is defined by Equation 23.5:

\[
P = EI \cos(\theta)
\]  

(23.5d)

Other names for active power include (1) real power and (2) delivered power. Active power is the power that does the work. Note that while all power quantities are volt-ampere products, only active power is expressed in watts.

**Reactive power** is given the symbol \( Q \) and is defined by the equation:

\[
Q = EI \sin(\theta)
\]  

(23.6)

Other names for reactive power include (1) imaginary power, (2) wattless power, and (3) magnetizing power. Reactive power is expressed in volt-amperes\(_\text{reactive} \) or vars. If the load is predominantly inductive, current lags the voltage, and the reactive power is given a positive sign. If the load is predominantly capacitive, current leads the voltage, and the reactive power is given a negative sign.

---

**FIGURE 23.6** Phasor diagram for current and voltage. Voltage is the reference phasor. The current \( I \) has been resolved into orthogonal components \( I \cos(\theta) \) and \( I \sin(\theta) \). (From Bullock, O.F., Methods of measuring apparent power, GE Meter, Missouri Valley Electrical Association Annual Engineering Conference, Kansas City, MO, 1996.)
FIGURE 23.7  Power triangle showing the geometric relationships between active, reactive, and phasor power. Power factor is defined geometrically as \( \cos \theta \).

**Phasor power** is given the symbol \( S \) and is defined by the equation:

\[
S = \sqrt{P^2 + Q^2}
\]  
(23.7)

Phasor power was called apparent power for many years, and it will be seen in a later section that phasor power \( S \), for sinusoidal voltages and currents, is identical to what is now called apparent power \( U \). Phasor power is expressed in voltamperes or VA.

Figure 23.7 is a phasor diagram, often called a **power triangle**, which illustrates the relationships among the three types of power defined earlier. Reactive power is orthogonal to active power and is shown as positive for lagging current. It is clear that the definition of phasor power, Equation 23.7, is geometrically derived from active and reactive power.

**Power factor** is given the symbol \( F_p \) and for sinusoidal quantities is defined by the equation:

\[
F_p = \frac{\text{Active power}}{\text{Phasor power}} = \frac{P}{S} = \frac{\text{Watts}}{\text{Voltamperes}} = \cos \theta
\]  
(23.8)

Since the power factor can be expressed in reference to the displacement angle between voltage and current, power factor so defined should be termed **displacement power factor**, and the symbol is often written as \( F_p \text{ displacement} \). Values for displacement power factor range from one (unity) to zero as the current displacement angle varies from 0° (current and voltage in phase) to 90°. Since the cosine function is positive in both the first and fourth quadrants, the power factor is positive for both leading and lagging currents. To completely specify the voltage–current phase relationship, the words **leading** or **lagging** must be used in conjunction with power factor. Power factor can be expressed as a decimal fraction or as percent. For example, the power factor of the case shown in Figure 23.4 is expressed as either 0.5% lagging or 50% lagging.

### 23.3.3 Polyphase Circuits

#### 23.3.3.1 Power Calculations

The power concepts developed for single-phase circuits with sinusoidal voltages and currents can be extended to polyphase circuits. Such circuits can be considered to be divided into a group of two-wire sets, with the neutral conductor (or a resistively derived neutral for the case of a delta-connected, three-wire circuit) paired with each other conductor. Equations 23.3 and 23.5 can be rewritten to define power terms equivalent to the single-phase terms. In these equations,
$k$ represents a phase number, $m$ is the total number of phases, and $\alpha$ and $\beta$ are, respectively, the voltage and current phase angles with respect to a common reference frame:

$$p = \sum_{k=1}^{m} E_k I_k \cos(\alpha - \beta)$$  \hspace{1cm} (23.9)

$$Q = \sum_{k=1}^{m} E_k I_k \sin(\alpha - \beta)$$  \hspace{1cm} (23.10)

and, restating Equation 23.7,

$$S = \sqrt{P^2 + Q^2}$$

For example, a three-phase sinusoidal power distribution service, with phases a, b, and c

$$p = E_a I_a \cos(\alpha_a - \beta_a) + E_b I_b \cos(\alpha_b - \beta_b) + E_c I_c \cos(\alpha_c - \beta_c)$$

$$Q = E_a I_a \sin(\alpha_a - \beta_a) + E_b I_b \sin(\alpha_b - \beta_b) + E_c I_c \sin(\alpha_c - \beta_c)$$

$$S = \sqrt{p^2 + Q^2}$$

### 23.3.3.2 Power Factor

Power factor is defined by Equation 23.11. Note that it is no longer always true to say that power factor is equal to the cosine of the phase angle. In many three-phase balanced systems, the phase angles of all three phases are equal and the cosine relationship holds. In unbalanced systems, such as that represented by the phasor diagram Figure 23.8, each phase has a different phase angle, the phase voltages and currents are not equal, and the cosine relationship fails [3]:

$$F_p = \frac{\text{Total active power}}{\text{Phasor power}} = \frac{P_{\text{Equation 23.9}}}{S} = \frac{\text{Watts}}{\text{Voltamps}} \text{ often } \neq \cos \theta$$  \hspace{1cm} (23.11)

![FIGURE 23.8 Phasor diagram for a sample polyphase sinusoidal service in which each phase has a different phase angle. Power factor cannot be defined as the cosine of the phase angle in this case. (From Bullock, D. F., Phase Angle Relationships, Part 1: Theory, GE Meter, Arkansas Electric Meter School, Fayetteville, AR, 1995.)](image)
23.3.4 Nonsinusoidal Voltage and Current

23.3.4.1 Fourier Analysis

Figure 23.9 shows voltage, current, and power for a typical single-phase nonlinear load, a computer switch-mode power supply. Due to the nature of the bridge rectifier circuit in this power supply, current is drawn from the line in sharp spikes. The current peak is only slightly displaced from the voltage peak, and the power is everywhere positive. However, power is delivered to the load during only part of the cycle, and the average power is much lower than if the current had been sinusoidal. The current waveform required by the load presents a problem to the ac power system, which is designed to deliver only sine wave current. The solution to this problem is based on mathematical concepts developed in 1807 for describing heat flow by Jean Baptiste Joseph Fourier, a French mathematician [4]. Fourier’s theorem states that any periodic function, however complex, can be broken up into a series of simple sinusoids, the sum of which will be the original complex periodic variation. Applied to the present electric problem, Fourier’s theorem can be stated: any periodic nonsinusoidal electric waveform can be broken up into a series of sinusoidal waveforms, each a harmonic of the fundamental, the sum of which will be the original nonsinusoidal waveform.

23.3.4.2 Harmonics

Harmonics are defined as continuous integral multiples of the fundamental waveform. Figure 23.10 shows a fundamental sine wave and two harmonic waves—the third and fifth harmonics. The harmonic numbers 3 and 5 express the number of complete cycles for each harmonic wave per cycle of the fundamental (or first harmonic). Each harmonic wave is defined by its harmonic number, its amplitude, and its phase relationship to the fundamental. Note that the fundamental frequency can have any value without changing the harmonic relationships, as shown in Table 23.1.

**FIGURE 23.9** Voltage, current, and power for a single-phase, switch-mode computer power supply, a typical nonlinear load. The current is no longer sinusoidal.
Power Factor Measurement

23.3.4.3 Power Calculations

Calculating power delivered to do work for a nonlinear load is somewhat more complicated than if the current were sinusoidal. If the fundamental component of the voltage at frequency \( f \) is taken as a reference (the a-phase fundamental for a polyphase system), the subscript “1” means the fundamental, and \( E \) denotes the peak value of the voltage; then, the voltage can be expressed as

\[ v_{a1(t)} = E_{a1} \sin(2\pi ft + 0\degree) \]

The voltage fundamental will then have an amplitude \( E_{a1} \) and pass through zero in the positive-going direction at time \( t = 0 \). If \( h \) = harmonic number, and \( E_h \) and \( I_h \) are peak amplitudes of the harmonic voltage and current, respectively, then general expressions for any harmonic will be

\[ v_{h(t)} = E_h \sin(2\pi f h t + \alpha_h) \]

\[ i_{h(t)} = I_h \sin(2\pi f h t + \beta_h) \]

To compute the power associated with a voltage and current waveform, take advantage of the fact that products of harmonic voltages and currents of different frequency have a time average of zero.
Only products of voltages and currents of the same frequency are of interest, giving a general expression for harmonic power as

\[ p_{h(t)} = E_h I_h \sin \left( 2\pi f h t + \alpha_h \right) \sin \left( 2\pi f h t + \beta_h \right) \]

Simplifying with trigonometric identities, evaluating over an integral number of cycles, and replacing peak voltage and current with rms values, the average power becomes

\[ p_{h(t)} = E_h I_h \cos \left( \alpha_h - \beta_h \right) \]

For a single-phase system where \( h \) is the harmonic number and \( H \) is the highest harmonic, the total average power or active power is given by

\[ p = \sum_{h=1}^{H} E_h I_h \cos \left( \alpha_h - \beta_h \right) \] (23.12)

Total average reactive power is given by

\[ Q = \sum_{h=1}^{H} E_h I_h \sin \left( \alpha_h - \beta_h \right) \] (23.13)

It should be noted that in the real world, the actual contribution of harmonic frequencies to active and reactive power is small (usually less than 3% of the total active or reactive power). The major contribution of harmonic frequencies to the power mix comes as distortion power, which will be defined later.

For a polyphase system wherein \( r \) is the phase identification and \( N \) is the number of conductors in the system, including the neutral conductor, total average power for a polyphase system is given by

\[ p = \sum_{r=1}^{N-1} \sum_{h=1}^{H} E_{r h} I_{r h} \cos (\alpha_{r h} - \beta_{r h}) \] (23.14)

Total average reactive power is given by

\[ Q = \sum_{r=1}^{N-1} \sum_{h=1}^{H} E_{r h} I_{r h} \sin (\alpha_{r h} - \beta_{r h}) \] (23.15)

### 23.3.5 Power Factor

#### 23.3.5.1 Single-Phase Systems

For a single-phase system, phasor power is again given by Equation 23.7 and illustrated by Figure 23.7, where \( P \) is the algebraic sum of the active powers for the fundamental and all the harmonics (Equation 23.12) and \( Q \) is the algebraic sum of the reactive powers for the fundamental and all the harmonics (Equation 23.13). Therefore, phasor power is based on the fundamental and harmonic active and reactive powers. It is found, however, that phasor power \( S \) is no longer equal to apparent power \( U \) and a new power phasor must be defined to recognize the effects of waveform distortion. A phasor representing the distortion, termed distortion power and given the symbol \( D \), is defined by

\[ D = \pm \sqrt{U^2 - S^2} \] (23.16)
Without further definite information as to the sign of distortion power, its sign is selected the same as the sign of the total active power. The relationships among the various power terms are displayed in Figure 23.11, a 3D phasor diagram. Power factor, in direct parallel with sinusoidal waveforms, is defined by the equation

\[
F_p = \frac{\text{Total active power}}{\text{Apparent power}} = \frac{P}{U} = \frac{\text{Watts}}{\text{Voltamps}}
\]  

(23.17)

From Equations 23.7 and 23.16, we obtain

\[
S = \sqrt{P^2 + Q^2}
\]

(23.7)

\[
U = \sqrt{S^2 + D^2} = \sqrt{P^2 + Q^2 + D^2}
\]

(23.18)

It is clear that when waveforms are sinusoidal, that is, linear loads are drawing current, there is no distortion power and Equation 23.18 reduces to Equation 23.7. Likewise as shown in Figure 23.13, as the distortion power vector goes to zero, the figure becomes 2D and reduces to Figure 23.7, and \(U\) becomes equal to \(S\). When, however, nonlinear loads are drawing harmonic currents from the system, \(U\) will be greater than \(S\). As already noted, the contribution of the harmonics to the total power quantities is small, and one is frequently interested mainly in the fundamental quantities.

The power factor associated only with the fundamental voltage and current components was termed the displacement power factor \(F_{p\text{displacement}}\), where Equations 23.7 and 23.8 are written as [5]

\[
S_{60} = \sqrt{P_{60}^2 + Q_{60}^2}
\]

and

\[
F_{p\text{displacement}} = \frac{P_{60}}{S_{60}}
\]

When harmonics are present, \(F_p\) is always smaller than \(F_{p\text{displacement}}\).

**FIGURE 23.11** Phasor diagram for a single-phase, nonsinusoidal service in which the voltage and current contain harmonics. Geometric relationships are shown between active, reactive, phasor, distortion, and apparent powers.
23.3.5.2 Polyphase Systems

For a polyphase system, phasor power, $S$, is again given by Equation 23.7, but one must now use the total values for $P$ and $Q$ calculated using Equations 23.14 and 23.15. One can then define the apparent power $U$ in one of two ways:

- **Arithmetic apparent power.** The arithmetic apparent power is given the symbol $U_a$ and is defined by Equation 23.19, where $E_r$ and $I_r$ are the rms values for the respective phases and $M$ equals the number of phases. $U_a$ is a scalar quantity:

  $$U_a = \sum_{r=1}^{M-1} E_r I_r \tag{23.19}$$

- **Apparent power.** Apparent power is given the symbol $U$ and is defined by Equation 23.18 using total values for $P$ and $Q$ as defined by Equations 23.14 and 23.15 and a total value for $D$ determined using Equation 23.16 for each phase. Figure 23.12 illustrates the two alternative concepts for polyphase apparent power [6]. Note that $U_a$ uses arithmetic addition of vector magnitudes and is equal to apparent power $U$ only if the polyphase voltages and currents have equal magnitudes and equal angular spacings, a situation that often exists in balanced three-phase systems. The two alternative definitions of apparent power, $U$ and $U_a$, give rise to two possible values for power factor: (1) $F_p = P/U$, and (2) $F_{pa} = P/U_a$. Apparent power $U$ and power factor $F_p$ are the preferred definitions since using $U_a$ can give unexpected results with some nonsymmetric service arrangements such as four-wire delta, and, with extremely unbalanced resistive loads, $F_{pa}$ can exceed 1.0. Despite these shortcomings, arithmetic apparent power has become quite widely used due to the comparative simplicity of its measurement and calculation. With the advent of sophisticated digital meters, there is no longer any advantage to using arithmetic apparent power, and its use will surely decrease.

![Diagram](image_url)

**FIGURE 23.12** Phasor diagram for a three-phase, nonsinusoidal service in which the voltage and current contain harmonics. Arithmetic apparent power $U_a$ is the length of the segmented line abed and is a scalar quantity $U_a$ that can be represented by the line abc'd'. The diagonal ad, a vector quantity, is the apparent power $U$. (From Bullock, D.F. and Elmore, D.D., MIND UR PS & QS, GE Meter EEI-AEIC Meter and Service Committee Meeting, Dallas, TX, 1994.)
23.4 Power Factor “Measurement”

There are no instruments that measure power factor directly. (Power stations and large substations of en
use phase angle meters with a power factor scale representing \( \cos(\theta) \) to display power factor. Such meters
are accurate only for sinusoidal balanced polyphase systems.) One must remember that, of all the ac
power quantities discussed, the only ones that can be directly measured are voltages, currents, and their
time relationships (phase angles). All other ac power quantities are derived mathematically from these
measured quantities. The only one of these derived values that has physical reality is the active power
\( \mathbf{P} \) (the quantity that does work); the others are mathematical constructs. Therefore, correct determination
of power factor requires accurate measurement of voltage and current and proficient mathematics.

23.4.1 Metering for Linear Loads

By the early 1920s, the concepts of active, reactive, and apparent (since renamed phasor) power and
power factor were known, and metering capabilities had been developed to enable their determination.
Energy meters utilizing voltage and current coils driving an induction disk inherently measured active power
\( \mathbf{P} (EI \cos(\theta)) \), which was displayed on a mechanical register. Using the trigonometric identity
\( EI \sin(\theta) = EI \cos(90^\circ + \theta) \), with voltage delayed 90\(^\circ\), a similar energy meter displayed reactive power \( \mathbf{Q} \),
and, with these two values, displacement power factor was calculated. Voltage delay (phase shifting) was
accomplished using specially wound transformers.

Throughout the years, the method of obtaining the 90\(^\circ\) phase shift has been updated. Analog electronic
meters are available that provide the 90\(^\circ\) phase shift electronically within the meter. More recently,
digital meters have been developed that sample voltages and currents at regular intervals and digitize the
results. Voltages and currents are multiplied as they are captured to compute active power. Past voltage
samples delayed by a time equal to a quarter cycle (90\(^\circ\)) are multiplied by present current values to
obtain reactive power. Active-reactive metering of this type is a widely utilized method for determining
displacement power factor for utility billing. These meters do not accurately measure the effect of harmonic currents because the delay of the voltage samples is based on the fundamental frequency and
is incorrect for the harmonics. (The important fundamental harmonic, which is frequently the predominant
harmonic component, is accurately measured because it is delayed 450\(^\circ\) (5 \times 90\(^\circ\)), which is equivalent to
the correct 90\(^\circ\) delay).

23.4.2 Metering for Nonlinear Loads

With the application of high-speed digital computing techniques to measurement of ac currents and
voltages, together with digital filtering, the quantities necessary for accurate and correct calculation
of power factor are susceptible to direct computation. In practice, the ac waveforms are sampled at a
frequency greater than twice the highest frequency to be measured, in compliance with well-known
sampling theories. Data obtained can be treated using Fourier’s equations to calculate rms values for
voltage, current, and phase angle for the fundamental and each harmonic frequency. Power quantities
can be obtained with digital filtering in strict accordance with their ANSI/IEEE STD 100 definitions.
Power quantities can be displayed for the fundamental only (displacement power factor) or for fundamental plus all harmonics (power factor for nonsinusoidal waveforms).

23.4.3 Metering Applications

Instruments with the capabilities described earlier are often called harmonic analyzers and are available
in both single-phase and polyphase versions. They can be portable, in which case they are often used for
power surveys or panel mounted for utility and industrial revenue metering. Polyphase analyzers can be
connected as shown in Figures 23.13 and 23.14. Care must be taken to connect the instrument properly.
FIGURE 23.13 Meter connections for a one-, two-, or three-phase, three-wire service. Voltage leads are connected to phases $a$, $b$, and $c$ or to $a$, $c$, and neutral as the system dictates. Care must be taken to connect the voltage lead for each phase to the input corresponding to the input for the current transformer reading that phase, and directional characteristics of the transformers must be observed. Only two current connections are required.

FIGURE 23.14 Meter connections for a three-phase, four-wire wye- or delta-connected service. Voltage leads are connected to phases $a$, $b$, and $c$ and to the neutral. Care must be taken to connect the voltage lead for each phase to the input corresponding to the input for the current transformer reading that phase, and directional characteristics of the transformers must be observed. In situations where measurement of neutral currents is desired, a fourth current transformer can be used to read the neutral. A fourth voltage connection might be used to read neutral-ground voltages.

Both voltage leads and current transformers must be connected to the proper phases, and the current transformers must also be placed with the correct polarity. Most instruments use color-coded voltage connectors. Correct polarity is indicated on the current transformers by arrows or symbols, and complete hookup and operating instructions are included. When single-phase instruments are used, the same precautions must be followed for making connections.

23.5 Instrumentation

Table 23.2 lists a sampling of harmonic and power factor measuring instruments available from major manufacturers. All instruments listed use some type of Fourier calculations and/or digital filtering to determine power values in accordance with accepted definitions. Many can be configured to measure nonharmonic-related power quality concerns. Unless otherwise noted, all instruments require the
### TABLE 23.2 Selected Instrumentation for Harmonic and Power Factor Measurement

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>V/I Inputs</th>
<th>Display Type</th>
<th>Communication</th>
<th>Special Features</th>
<th>List Price (U.S.$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handheld units</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amprobe</td>
<td>HA2000 1/1</td>
<td>Visual</td>
<td>RS232</td>
<td>Handheld, probe included,</td>
<td>21 nonvolatile memories</td>
<td>990</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>21 nonvolatile memories</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMI</td>
<td>155</td>
<td>1/1</td>
<td>Visual</td>
<td>Optional printer, RS232</td>
<td>Handheld, 1145 + 550 (printer) + 380 (probe)</td>
<td>—</td>
</tr>
<tr>
<td>Dranetz</td>
<td>4300</td>
<td>4/4</td>
<td>Panel for data and graphs RS232</td>
<td>Handheld, battery or ac power, optional PCMCIA memory card</td>
<td>5000 + 450/probe</td>
<td>—</td>
</tr>
<tr>
<td>Fluke</td>
<td>39</td>
<td>1/1</td>
<td>Visual</td>
<td>None</td>
<td>Probe included</td>
<td>895</td>
</tr>
<tr>
<td>Fluke</td>
<td>41b</td>
<td>1/1</td>
<td>Visual</td>
<td>RS232</td>
<td>Probe included, eight memories, logging with computer and supplied software</td>
<td>1995</td>
</tr>
<tr>
<td>Portable units</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMI</td>
<td>3030A</td>
<td>4/4</td>
<td>Built-in printer for data and graphs, optional internal modem</td>
<td>Portable, optional built-in disk drive for storage, long-term monitoring, optional PQ configurations</td>
<td>6000 + 600 (modem) + 1895 (disk storage) + 590/probe</td>
<td>—</td>
</tr>
<tr>
<td>Dranetz</td>
<td>PP1-R</td>
<td>4/4</td>
<td>Panel for data and graphs</td>
<td>PCMCIA card slot</td>
<td>Long-term monitoring, optional PQ configurations, remote control by software</td>
<td>12,000 + 450/probe</td>
</tr>
<tr>
<td>PC-based units</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMI</td>
<td>7100</td>
<td>4/4</td>
<td>PC-based (not included)</td>
<td>PC connection cord</td>
<td>Portable uses computer for storage, optional sof ware, long-term monitoring, optional PQ configurations</td>
<td>5294 + PC + 395 (soft ware) + 415/probe</td>
</tr>
<tr>
<td>Cooper</td>
<td>V-Monitor II</td>
<td>4/4</td>
<td>PC-based (not included)</td>
<td>Serial port</td>
<td>Portable sof ware and signal interface and data acquisition board, long-term monitoring</td>
<td>12,000 + 500/probe</td>
</tr>
<tr>
<td>RPM</td>
<td>1650</td>
<td>4/5</td>
<td>PC-based, not included</td>
<td>Ethernet long-term monitoring, optional PQ configurations, remote control by sof ware</td>
<td>6250+750 sof ware + 490/probe</td>
<td>12,000 + 500/probe</td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>V/I Inputs</th>
<th>Display Type</th>
<th>Communication</th>
<th>Special Features</th>
<th>List Price (U.S.$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel mounted</td>
<td>Cutler-Hammer/Westinghouse 4/4</td>
<td>Panel</td>
<td>Optional IMPACC</td>
<td>Panel mount to replace meters, monitoring</td>
<td>3690 + input devices</td>
<td>—</td>
</tr>
<tr>
<td>General Electric</td>
<td>kV</td>
<td>Vector electricity meter</td>
<td>Socket</td>
<td>Programmable multifunction LCD display pulse output for measured power quantities replaces industrial revenue meters and calculates and accumulates all power and revenue data</td>
<td>595 + 495 (software)</td>
<td></td>
</tr>
<tr>
<td>Square D</td>
<td>PowerLogic CM2350</td>
<td>3/3</td>
<td>Panel</td>
<td>Panel meter replacement, calculates and accumulates power data</td>
<td>1583 + probes</td>
<td></td>
</tr>
<tr>
<td>Square D</td>
<td>PowerLogic PM620</td>
<td>3/3</td>
<td>LCD panel</td>
<td>Connect to network, remote controller, monitoring</td>
<td>4290 + probes</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 23.3 Manufacturers of Power Factor Measuring Harmonic Analyzers

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Address</th>
<th>Contact Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amprobe Instruments</td>
<td>630 Merrick Road Lynbrook, New York 11563</td>
<td>Tel: (516) 593-5600, Web: <a href="http://www.amprobe.com/amprobe/user/home/">http://www.amprobe.com/amprobe/user/home/</a></td>
</tr>
<tr>
<td>Cooper Power Systems Division</td>
<td>11131 Adams Road, P.O. Box 100, Franksville, WI 53126-0100</td>
<td>Tel: (414) 835-2921, Web: <a href="http://www.cooperindustries.com/content/public/en.html">http://www.cooperindustries.com/content/public/en.html</a></td>
</tr>
<tr>
<td>Dranetz Technologies, Inc.</td>
<td>1000 New Durham Road, Edison, NJ 08818-4019</td>
<td>Tel: (800) DRANTEC, Web: <a href="http://dranetz.com/">http://dranetz.com/</a></td>
</tr>
<tr>
<td>Fluke Corporation</td>
<td>P.O. Box 9090, Everett, WA 98206</td>
<td>Tel: (800) 44FLUKE, Web: <a href="http://www.fluke.com/fluke/user/About/Contact">http://www.fluke.com/fluke/user/About/Contact</a></td>
</tr>
<tr>
<td>GE Meter</td>
<td>130 Main Street, Somersworth, NH 03878</td>
<td>Tel: (603) 749-8477</td>
</tr>
<tr>
<td>Reliable Power Meters, Inc.</td>
<td>400 Blossom Hill Road, Los Gatos, CA 95032</td>
<td>Tel: (408) 358-5100</td>
</tr>
<tr>
<td>Square D Power Logic</td>
<td>330 Weakley Road, Smyrna, TN 37167-9969</td>
<td>Tel: (615) 459-8552</td>
</tr>
<tr>
<td>Yokogawa Corp. Meter and Instrument Div.</td>
<td>Newman, GA 30655</td>
<td>Tel: (800) 888-6400 (toll free), Email: <a href="http://www.yokogawa-usa.com/">http://www.yokogawa-usa.com/</a></td>
</tr>
</tbody>
</table>

purchase of one current probe per input. Probes are available for measuring currents from 5 A to several thousand amperes. For comparison purposes, priced probes will be those with a 600 A range. Voltage leads are usually supplied as standard equipment. Table 23.3 contains addresses of these manufacturers.

Defining Terms

**Active power**: A term used to express the real power delivered to do work in an ac distribution system.

**Apparent power**: A term used to express the product of volts and amperes in an ac distribution system in which voltage and/or current is nonsinusoidal.

**Harmonic power**: A term used to express the power due to harmonic frequencies in an ac distribution system in which voltage and/or current is nonsinusoidal.

**Phasor power**: A term used to express the product of volts and amperes in an ac distribution system in which voltage and current are sinusoidal.

**Power factor**: A single number, calculated by dividing active power by either the phasor power or the apparent power, which describes the effective utilization of ac distribution system capacity.

**Reactive power**: A term used to express the imaginary power that does no work but provides magnetization to enable work in an ac distribution system.

References