J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

POWER SYSTEM MEASUREMENT

Alternating current (*ac*) electric power systems present some unusual and interesting measurement challenges. The basic parameters—voltage and current—are almost always at dangerous levels. Often, measurements require one to mathematically combine several different physical parameters. Many measurements are integrated or accumulated over time, others discard large amounts of data while waiting for a triggering event. Many power system measurements are made in dirty, noisy, hot, or cold environments. There are difficult grounding issues. But by understanding all of the parameters that can affect measurement, and by understanding how and why an instrument works, reliable, useful, and accurate power system measurements can be made.

Measuring Power System Voltage and Current

All electric power system measurements begin by measuring voltages and currents. All other power system parameters are obtained by combining or otherwise processing these measurements. Like any other physical measurement, we must choose a location for our measurement; it may be at the point in the power system where an electric utility delivers power to a consumer, or at the point in the power system where the electric power leaves a generator, or at any other point; but we must choose a single location.

Connection of Voltage and Current Measurements. At any given location, electric power systems consist of N conductors (common values for N include 2 for single-phase systems with no earth conductor; 3 for single-phase systems with an earth conductor, split-single-phase systems with no earth conductor, and three-phase-delta systems with no earth conductor; 4 for three-phase-delta systems with an earth conductor; and 5 for three-phase-wye systems with an earth conductor). In some precision measurements, the earth itself may sometimes be considered as an additional conductor, adding 1 to N. Voltage measurements always determine the potential difference between two conductors, so there are always $N - 1$ instantaneous voltage measurements available. Often, the voltage between power system conductors is determined indirectly by measuring the instantaneous voltage between each conductor and the earth, and then arithmetically determining the difference between those two readings.

Current measurements always determine the current flowing in one conductor, so there are always N instantaneous current measurements available. An assumption is often made that, due to Kirchhoff's law, any individual current measurement is equal to the negative sum of all the other current measurements. This assumption is valid as long as there are no other current paths in the system, such as an earth current path, and leads to the common practice of making $N - 1$ instantaneous current measurements.

Voltage and Current Transducers. It is impractical to design instruments to connect directly to many power system voltages and currents. Voltages may require insulators that are more than a meter long, and currents may require conductors that are many centimeters in diameter, making it impossible to construct a conveniently sized instrument. With high voltages, there are obvious safety hazards. Often we want to examine the voltages and currents at a location that is tens of meters away from the conductors—at the base of a wooden power pole, for example.

For all of these reasons, it is common to use voltage transducers and current transducers to convert the original voltage or current to a much smaller voltage or current, usually at a fixed ratio to the original voltage or current.

There are two common forms of voltage transducers: potential transformers (*PT*s) and resistive voltage dividers. They are commonly used on power systems at potentials above 600 V; below this level, instrumentation is often connected directly to the power system.

Potential transformers may be constructed with two insulated primary connectors, so that they can be connected between two power system conductors; more commonly, they are constructed with a single insulated primary connector and are connected between one power system conductor and local earth. The secondary of a potential transformer provides a voltage that is proportional to primary voltage. Typical nominal secondary voltages are in the range of 50 V to 250 V. Potential transformers are inexpensive and fairly accurate near the nominal power system frequencies; however, like all transformers, they do not transform direct current (*dc*) signals, and they introduce both amplitude and phase errors at higher harmonic frequencies. In general, potential transformers are not useful for making high-frequency transient measurements.

Resistive voltage dividers, on the other hand, are commonly used for measuring dc and higher frequency measurements on ac power systems. There are almost always constructed with a single insulated primary connector and are connected between one power system conductor and local earth. The very high resistance of the input section of the divider—typically in the tens to hundreds of megaohms—can introduce a frequency roll-off with the stray capacitance of any cable attached to the output of the divider. For this reason, most resistive dividers incorporate a capacitive divider as well, which is placed in parallel with the resistive divider. Resistive voltage dividers are more expensive and less common than potential transformers and are generally used only for investigations of transients and dc on the power system.

Potential transformers can tolerate higher burdens than resistive voltage dividers. Indeed, it is common practice to take instrumentation power from the secondary of a potential transformer. You must be careful, however, that the instrumentation power does not detract from the accuracy of the measurement by affecting the transformer secondary voltage. Harmonic currents in the instrument's power supply deserve special attention in this case.

Power system current transducers, in general, measure the magnetic field created by the flow of current in a conductor. For two reasons, the technique, common in other engineering disciplines, of measuring the voltage across a series resistor is rarely used in power system measurements: (1) Current is rarely flowing to earth, so a differential measurement is required across the series resistor. (2) Both terminals of the resistor are at voltages that are between 4 and 10 orders of magnitude higher than the signal of interest, making this an extremely challenging measurement.

The most common form of current transducer is the current transformer (CT). CTs and PTs are sometimes referred to collectively as instrument transformers. In a CT, the current-carrying power conductor works as a single-turn primary when the CT is installed around the conductor. The secondary of a CT typically provides a current that is proportional to the primary current, but two to five orders of magnitude smaller. Current transformers may be constructed as spring-loaded, clamp-on devices for temporary installation or may be constructed as pass-through devices for permanent installation; sometimes CTs and PTs are combined in a single construction. There are even CTs with flexible, snakelike cores for physically challenging installations. You should be aware of two safety concerns with CTs: First, the CT insulation must be properly rated for the voltage of the power system conductor; and second, the CT secondary terminals must always be connected with a low impedance—otherwise, the voltage across the secondary terminals can rise to a destructive and possible dangerous level.

Hall-effect current transducers are sometimes used on ac power systems and can be configured to measure dc currents as well as ac currents. However, they are more complicated than CTs, more sensitive to noise, more expensive, and require both temperature compensation and power. Recent interesting developments using the effect of magnetic fields on the polarization of laser beams to measure current in ac power could be useful on very high-voltage systems.

Analog and Sampling Techniques. Most power system instruments (with one important exception, the electromechanical revenue meter) first process the voltage and current signals through an analog circuit, then convert them to a series of discrete time domain values. Typical analog processing includes level conversion—often reducing voltage signals to a range of ±1 V to ±15 V, and amplifying current signals to a similar level—differential measurement, and low-pass frequency filtering. In certain applications, subsequent analog processing is employed, such as time-division multiplication to multiply two analog signals or analog true root mean square (*rms*) techniques.

This analog processing is typically followed by conversion of each signal to digital values, typically between four digital values and a few thousand digital values per power system cycle. The time between individual conversions may be fixed, or it may be programmable, or, in a technique called phase-locked sampling, it may automatically track the power system frequency to generate a controlled number of samples per power system cycle, regardless of small variations in power system frequency. Each digital value typically contains between 6 and 18 bits.

We will refer to these digital values, with multiple samples per cycle equally spaced in time, in the following equations as E_i and I_i. In some high-accuracy systems, the initial digital values represent the voltages between a power system conductor and ground; the differential voltage between power system conductors is determined by the difference between two digital values. This approach eliminates the need to balance differential analog voltage dividers and makes digital calibration easier and more accurate.

Measuring Basic Power System Parameters

RMS Measurements. The instantaneous power available into a resistive load is proportional to the square of the voltage, but the instantaneous voltage on an ac power system varies regularly with time. So it is useful to take the average, or mean, of the square of the voltage. However, this measure has the somewhat distressing units of volts-squared; it is convenient to take its square root prior to using the measure, to get us back to a unit of volts. This gives us the root of the mean of the square of the voltage, or the rms voltage. It is a representation of the power available into a resistive load averaged over time.

$$E_{\mathrm{rms}} = \sqrt{\frac{\sum_{i=1}^{N} E_i}{N}} \tag{1}$$

Note that the rms value is defined over a specific period of time, the period that elapses over the course of N samples. In high-accuracy measurements, this period is always chosen to be an integer multiple of the half-period of the fundamental ac power system frequency; however, its duration is less critical if its duration is large with respect to the period of the fundamental frequency.

Current rms measurements are defined and made in a similar way (the square of the instantaneous current is proportional to the power in a resistor).

$$I_{\mathrm{rms}} = \sqrt{\frac{\sum_{i=1}^{N} I_i}{N}} \qquad (2)$$

The choice of rms as a fundamental measurement parameter is conventional but somewhat arbitrary. Other averaging techniques may make more sense in specific applications: Switch-mode power supplies, for example, respond to the peak voltage, not the rms voltage, and even resistive heaters have an exponential temperature time constant that is better addressed with a definition of rms that incorporates an exponential averaging interval, a modified form of Eq. (1). True rms current measurements, on the other hand, are almost always useful, because they accurately correspond to heat in conductors.

Note that the definition of rms voltage applies to a single voltage. It is sometimes useful to speak of the voltage or the current in a three-phase system, when in fact there are at least three voltages and currents. Several different techniques are used to combine these individual voltages or currents into a single value, which is intended to be representative of the complete three-phase system at that point. These techniques include arithmetic averaging, geometric averaging, and a form of vector averaging.

Watt, Watt–Hour, Volt-Amp, and VAR Measurements. The whole point of an ac power system is to produce and deliver power, typically measured in watts, and energy, typically measured in watt–hours. Instantaneous power, *P*, can be defined by the product of the instantaneous voltage and the instantaneous current; for most applications, power is averaged over a period of time that is an integer multiple of the ac power system fundamental period.

$$P = \sum_{i=1}^{N} \frac{E_i I_i}{N} \qquad (3)$$

Energy is simply the integration of power over time. Note that power is a parameter that is defined (in this form of the equation) for a single voltage-current pair. In three-phase systems, power is simply the arithmetic sum of the power in each phase. However, choosing the voltage and current pair must be done carefully, especially in three-phase delta systems.

Volt-amps (*VA*) is simply defined as

$$\mathrm{VA} = E_{\mathrm{rms}} I_{\mathrm{rms}} \qquad (4)$$

Three-phase volt-amps are calculated using the same voltage and current pairs selected for the corresponding power and energy calculations.

Volt-amps-reactive, or VAR, is more complicated. VARs are only defined at a single frequency: the fundamental frequency of the power system, typically with the "power triangle" equation:

$$\mathrm{VA}^2_{\mathrm{fundamental}} = P^2_{\mathrm{fundamental}} + \mathrm{VAR}^2_{\mathrm{fundamental}} \qquad (5)$$

$$\mathrm{VA}^2 \overset{?}{\underset{?}{=}} P^2 + \mathrm{VAR}^2 \qquad (6)$$

Note that Eq. (6) is true only if all voltages and currents are at the fundamental frequency of the power system; otherwise it is incorrect. Modern power systems often have substantial currents at nonfundamental frequencies (although the nonfundamental voltages are usually small). As a result, frequencies other than the fundamental must be removed before measuring and calculating VARs. VARs are rarely measured directly; instead, they are derived from filtered measurements of VA and watts.

Electromechanical Watt–Hour and VAR–Hour Meters. For nearly 100 years, electric power flow has been measured with electromechanical revenue meters. These meters are essentially electric motors, with a two-part stator: One part is energized by the line voltage, and the other by the line current. The line voltage portion of the stator is wound so that it is highly reactive, and the current portion of the stator is not. Consequently, the two stators are displaced in phase from each other, and they are displaced in position as well. These displacements cause a simple rotor disk to turn at a speed that is proportional to the product of the instantaneous voltage and the instantaneous current. Consequently, the total number of rotor revolutions is proportional to watt-hours. A simple set of geared dials is sufficient to accumulate and indicate this total. These meters are inexpensive, rugged, and accurate over a wide range of conditions.

When these meters are used with potential transformers and current transformers, it is common to multiply their readings by a scale factor, which is (in most cases) simply the primary-to-secondary ratio of the instrument transformers.

As a simple interface to other recording and control systems, electromechanical revenue meters may be equipped with electric contacts that close and reopen one time for each revolution of the stator. To help with switch debouncing, these contacts are often configured with a common terminal (referred to as K), and one normally open terminal and one normally closed terminal (often referred to as Y and Z), so the complete set of contacts are referred to as KYZ contacts.

An electromechanical watt–hour meter can be configured as a var-hour meter by shifting one of its signals—typically the voltage signal—by 90°. This shift is normally accomplished with a simple passive-component network. Once watt-hours and VAR-hours are known, it is a simple matter to use the power triangle method to determine VA-hours and the integrated displacement power factor.

In most applications of electromechanical revenue meters, there is an implicit assumption that the signals—especially the voltage signals—are sinusoidal. In some applications, such as the $2\frac{1}{2}$ element configuration, there is a further assumption that three-phase voltage signals are balanced. Deviations from these assumptions can cause substantial errors in electromechanical meters, although the watt–hour measurements tend to remain reasonably accurate.

Peak Demand and Power Factor Measurements. Electric power requires two kinds of economic investment: fuel to generate the power, and capital to construct the generation and distribution system. Watt-hours are roughly proportional to the amount of fuel consumed; peak VA demand is roughly proportional to the investment required to service a particular load. In concept, peak VA demand is measured with an instantaneous VA meter that ratchets to the highest value of VA ever recorded; in practice, peak VA demand is averaged over a period of time called a demand interval (typically 15 min), and the ratchet is periodically reset (typically once per year). The demand intervals may be sequential, or they may overlap each other. Overlapping demand intervals are called sliding demand intervals and are useful for preventing peak splitting, a process in which peak demand loads are timed so that they fall partially in one demand interval and partially in another.

It is simpler to construct an electromechanical peak watt-demand meter than a peak VA-demand meter, so demand is often measured in watts rather than VA. In this case, a power factor penalty may be employed to correct the economic charges.

The power factor, PF, is not the cosine of the angle between the voltage and current waveforms; it is the ratio of watts to volt-amps. If both waveforms are sinusoidal (an assumption that was generally valid prior to the 1970s), the ratio of watts to volt-amps happens to be equal to the cosine of the displacement angle. Measurements made by examining this angle are referred to as displacement PF and are inaccurate if either voltage or current is distorted. Power factor measurements based on the power triangle method are, in fact, measuring displacement PF. To measure accurately the true power factor, one must measure true VA, which generally requires a digital meter rather than an electromechanical one. However, not all digital meters measure true power factor; some are designed to mimic the response of electromechanical meters.

Power System Parameters Vary Over Time. Unlike the weight of a sample or the length of a piece of rope, power system parameters cannot be measured once with the expectation that they will have the same value in the future. It is in the nature of an electric power system with varying loads, generator impedances, and connections that parameters will vary over time. There are also varying definitions of power parameters and interpretations of those definitions. For these reasons, careful measurements made with accurate instruments can disagree with each other. Thorough understanding of the instrumentation, the definitions, and the state of the power system is necessary to resolve these disagreements.

Measuring Power Quality Events

According to IEEE-1159, power quality is “the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.” This is an interesting definition, because its meaning can and does vary with the equipment being discussed. However, there are several standard power quality phenomena that are conducted by the ac power system: voltage fluctuations, voltage dips (sags) and interruptions, voltage imbalance, power frequency variations, induced low-frequency voltages, dc in ac networks, and unidirectional and oscillatory transients.

Connecting Power Quality Instruments. Portable power quality instruments are generally connected to the ac power system as close to the sensitive equipment’s connection as possible, to ensure that the instrument sees the same events that affect the sensitive equipment. Proper safety precautions must be taken during the installation; however, power quality instruments are usually left in place for at least one business cycle (typically a week), so proper safety precautions must be considered for unattended operation as well. Most power quality instruments have both measuring ground and safety ground terminals. Care must be taken to avoid creating inadvertent ground loops during installation.

Special Requirements for Power Quality Instruments. Many standard ac power instruments are designed with assumptions that can become invalid during power quality events. For example, electromechanical VAR–hour meters often assume that the power system frequency is constant, and precision power meters with phase-locked sampling assume that a signal will exist for phase lock. Power quality instrumentation usually must be designed without any of the standard assumptions; at the very least, the assumptions must be made explicit to the user.

Many power quality events contain frequencies that are four or even five orders of magnitude higher that the fundamental ac power system frequency, so the instruments must be designed to accommodate these frequencies.

Power quality instruments are, themselves, sensitive equipment. They must be capable of tolerating the power quality events that they are designed to measure. Indeed, they must not only survive the events, but they must function as precision measuring instruments during the events, a real challenge for the instrumentation designer.

Triggering, Parameter Extraction, and Power Quality Signatures. Power quality events are inherently transient; measuring such transient events typically requires triggering when they occur, and the triggering mechanism is closely related to the definition of the transient. Common triggering methods include level detection with hysteresis for long and short duration variations, waveshape comparison techniques for low-frequency transients, and digital- or analog-level detection for high-speed transients. Similar to a digital oscilloscope with a large number of channels, sweeping at a number of different rates, most power quality instruments continuously record a series of digital values in buffers; once a particular type of power quality event causes a trigger, the associated buffer is filled and the recording is stopped, leaving both pre- and posttrigger data in the buffer. These data are often presented graphically. However, it is also useful for the instrument to extract parameters for the user, such as rate of rise, amplitude, and duration. These extracted parameters may be particularly sensitive to cables and connections, instrument frequency response, and the definition chosen by the instrument designer. For example, consider the duration of a voltage sag on a three-phase system: Does it end when all three phase voltages are back within user's thresholds, or when the triggering phase voltage is back within the user's thresholds? Once again, careful understanding of the instrument design is necessary for proper interpretation of the readings.

Oscillographs of power quality events can be compared to libraries of similar events, called power quality signatures. This often makes it possible to determine both the cause of a power quality event and an optimal solution without further investigation.

Measuring Power System Harmonics. Unlike other power quality measurements, harmonic measurements are generally long term or steady state rather than triggered. Generally, time domain digital voltage and current samples are processed with a fast Fourier transform (*FFT*), yielding frequency domain amplitudes and phase angles. Sometimes windowing techniques are used; more commonly, phase-locked sampling or fixed-frequency sampling at a well-chosen rate are used to ensure that there are 2^n samples in an integral number of power system cycles (a requirement of FFT processing).

It is important to be aware of the frequency and phase effects introduced by all parts of the measurement system, including any current transformers and potential transformers.

Display Methods

Electric power measurements are displayed in a wide variety of ways. Traditionally, analog meters with mirrored scales (to reduce parallax effects) have been used. For voltage measurements, analog meters with expanded scales near the nominal voltage are available; and many computer screens indicate power system measurements with a picture of such a meter.

Common revenue meters may have dial indicators; when the need is between two digits, it is read as the smaller of the two digits. Adjacent dials rotate in opposite directions. Traditionally, voltages and currents have been recorded over time on circular chart recorders. A paper disk, about 20 cm in diameter, is rotated by a clockwork motor, completing one revolution in 24 h or 7 days. A pen, attached to a meter movement, indicates with axial movement the present value of the parameter. Movement of the pen is often intentionally damped so that brief power quality events may not be recorded. Digital meters are available for measuring almost any steady-state power system parameter. Advanced power analyzers often provide vector scopes (useful for seeing the phase angle and balance on three-phase systems, but only at a single frequency), oscilloscopes, spectral graphs, spectral charts that may include phase angle at each harmonic (useful for determining the direction of harmonic power flow), oscilloscopes and oscillographs (useful for analyzing power quality signatures), and various other forms of visual displays. For longer-term analysis, power analyzers can provide minimum/average/maximum charts that conveniently illustrate, in a single chart, the variation in a single power parameter over hours, days, or weeks.

Accuracy of Power System Measurements

There are a surprising range of external parameters that can affect the accuracy of power system measurements. You must decide what level of accuracy you need and then determine which of these external parameters you can control. Because certain electric power measurements often turn into financial equivalents, accurate measurements can be especially important. Ultimately, you must understand the instrument that you are using: its definitions, its limitations, its display techniques, and its sensitivities to outside parameters.

Effect of Definitions and Connections. It almost goes without saying that the definition of a power parameter affects the accuracy of its measurement. This issue tends to be greatest when comparing measurements made by different instruments that employ different definitions or different parameters with the same definition, such as averaging period for rms measurements.

The location at which the instrument is connected to the power system affects its readings, especially current readings and high-frequency transient readings. In certain cases, the order in which an instrument is connected to phases on a polyphase system can affect its readings, even if the readings are polyphase values.

Power Disturbance Effects. Power quality disturbances can have surprising effects on other power system measurements. For example, a low-frequency transient near the zero crossing of a voltage phase can disrupt a frequency measuring instrument, causing it to indicate a frequency shift incorrectly. A brief interruption may cause a phase-locked sampling harmonics analyzer to indicate harmonic levels incorrectly. Or a burst of high-frequency conducted noise may be inadvertently rectified by the input circuitry of a power instrument, causing it to indicate incorrectly a dc offset in the ac voltage. It is important to be aware of how a particular instrument is affected by power quality events, especially if precision measurements are being made over a long period of time.

Phase Angle Effects. Errors in phase angles obviously lead to errors in power measurements. However, the effect of small phase angle errors on power measurements is greatly increased when the phase angle approaches quadrature. At the fundamental power system frequency, this can be an issue when measuring power dissipation in power factor correction capacitors, for example. At higher harmonic frequencies, phase angle errors, introduced by transducers, are common and can lead to incorrect conclusions about the direction of harmonic power flow if the phase angle is near quadrature.

Frequency and Harmonic Effects. Instruments that are designed for use at a single, fixed frequency—usually the power system fundamental frequency—often exhibit strange behavior at other frequencies. These other frequencies may come from an off-frequency generator (a back-up diesel generator under heavy load, for example) or from harmonic currents. This can be an especially troubling problem for two reasons: Designers who make this assumption may be unaware that they are making it and consequently fail to specify the behavior of their instrument at other frequencies; and older power system textbooks made similar assumptions (for example, any text that equates power factor with the cosine of the angle between voltage and current).

Temperature and Environmental Effects. Power measurements are often made in harsh environments. Instrument temperatures at substations can easily range from -40°C to $+60^\circ$C, and humidity can range from nearly zero to 100%. Strong radio frequency fields from arcing loads or adjacent broadcast transmitters can easily couple into measurement leads. Magnetic fields, both at power system frequencies and at other frequencies, may impinge on the instrument and its leads. Industrial ac power measurements are frequently made in environments filled with corrosives, conductive dust, or even explosive gases. In some environments, instrumentation is expected to be hosed down or exposed to storms and lightning strikes.

Instrument grounding can be an especially difficult issue. The local earth ground at the measuring point may be carrying tens or hundreds of amps of power system frequency current, or thousands of amps of transient current. Two different ground connections may be joined at the instrument: its measuring ground terminal, and its safety ground terminal. Often, a third ground reference from a telephone system or a computer network is also brought to the instrument.

Fully understanding and appreciating all of the aspects of the instrumentation chain—the location, the transducers, the definitions, the processing and the presentation—and an awareness of other parameters that can affect an instrument's readings, can lead to accurate and useful electric power system measurements.

BIBLIOGRAPHY

1. R. D. Alexander, ed. *Handbook for Electricity Metering*, 9th ed., Washington, DC: Edison Electric Institute, 1992.
2. Dranetz-BMI, *Handbook of Power Signatures*, 2nd ed., Edison, NJ: Dranetz-BMI, 1997.
3. *IEEE Recommended Practice for Monitoring Electric Power Quality*, Std. 1159–1995, New York: IEEE, 1995.
4. A. Seidman H. W. Beaty H. Mahrous *Handbook of Electric Power Calculations*, 2nd ed., New York: McGraw-Hill, 1996.

ALEX MCEACHERN
WPT: Dranetz-BMI, Electrotek, Daytronic