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An American National Standard

IEEE Master Test Guide for Electrical Measurements in Power Circuits

Sponsor

**Power Systems Instrumentation and Measurements Committee
of the
IEEE Power Engineering Society**

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Foreword

(This Foreword is not a part of IEEE Std 120-1989, IEEE Master Test Guide for Electrical Measurements in Power Circuits.)

This updated version is based on the material submitted for the abandoned 1981 draft plus material submitted during the 1985–87 reinstatement of Working Group 120.

The basic approach for the new organization is to provide general guidelines intended to assist nonelectrical engineers and technicians involved in quality control, acceptance, and prototype testing where electrical instrumentation is the main tool for measuring, observing, or recording physical quantities.

The contributors strived to reflect in the new text the many improvements and novel techniques developed in modern instrumentation in the last decades.

A list of complete definitions characterizing voltage/current waves generated or injected by modern converters is provided.

Digital meters are presented in the context of all the measurements described in this standard when applicable.

Since the new instrumentation based on digital logic is most sensitive to electromagnetic noise, special sections, 1.7 and 1.8, were dedicated to grounding and shielding.

This updated edition also contains the following new material:

- Chapter 6, Measurements of Magnetic Quantities in Power Circuits
- Section 7.1, Transducers
- Section 7.2, Oscilloscopes
- Section 7.3, Analog Recorders
- Section 7.4, Power Supplies
- Section 8.1, Computer-Based Techniques
- Section 8.2, Optical Fibers in Instrumentation

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IEEE Master Test Guide for Electrical Measurements in Power Circuits

1. Chapter 1—General

1.1 Purpose

It is the purpose of this guide to give instructions for those measurements of electrical quantities that are commonly needed in determining the performance characteristics of electric machinery and equipment. The choice of the measurement method and instrument systems to be used depends on the purpose of the measurement, the accuracy required, the time and testing equipment available, and the nature of the circuit.

1.2 Scope

The methods given here relate to measurements, as made with either analog or digital indicating or integrating instruments, of power, energy, voltage, and current, in dc or ac rotating machines, transformers, induction apparatus, arc and resistance heating equipment, mercury arc, thermionic, or solid-state rectifiers and inverters. Measurements made with supplementary instruments and devices are also included. This guide does not deal with measurements of resistance or temperature that are often included in determining the performance characteristics of electric machinery. Instruments for these latter measurements will be found in the specific publications dealing with the particular measurement, such as IEEE Std 118-1978, IEEE Standard Test Code for Resistance Measurements [4]¹, and IEEE Std 119-1974, IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus [5].

1.3 Units

The measurement of any electrical quantity is the comparison of that quantity with another quantity of the same kind that has been chosen as a unit. The fundamental or basic electrical units are based on the International System of Units (SI), which is a modern version of the MKSA (meter, kilogram, second, ampere) system. For further details see ansi/ieec 268-1982, IEEE Standard for Metric Practice [3]. In magnetic measurements it is the common practice to use the cgs (centimeter-gram-second) system. The instrument readouts are frequently in the cgs units. Hence, in Chapter 6 of this guide both units are used and a conversion table is provided.

¹The numbers in brackets correspond to those of the bibliography at the end of this chapter.

1.3.1 International System of Units

The units of the electrical quantities are as follows:

Quantity	Name of SI Unit	Symbol
Electric potential, potential difference, tension, electromotive force	volt	V
Electric current	ampere	A
Electric charge (quantity)	coulomb	C
Power	watt	W
Energy	joule (watt-second)	J
Capacitance	farad	F
Inductance	henry	H
Frequency	hertz	Hz
Resistance	ohm	Ω

1.4 Definitions

1.4.1 RMS Value:

$$y_{\text{rms}} = \left[\frac{1}{T} \int_a^{a+T} y^2 dt \right]^{1/2}$$

where y_{rms} is the root-mean-square (rms) value of y , y is an instantaneous value of a period function, a is any instant of time, and T is the period.

The rms value of a periodic waveform may also be expressed as the square root of the sum of the squares of the Fourier components of y .

$$y_{\text{rms}} = [A_1^2 + A_2^2 + \dots + A_n^2]^{1/2}$$

where A_1 , A_2 , A_n are the rms values of the fundamental component, second harmonic, and n th harmonic, respectively.

1.4.2 Average Absolute Value:

$$y_{\text{AAV}} = \frac{1}{T} \int_a^{a+T} |y| dt$$

where y_{AAV} is the average absolute value (often called simply the average) of y , a is any instant of time, and T is the period.

1.4.3 Peak Value: The peak value y_p is the largest absolute value of y .

1.4.4 Form Factor: The form factor (ff) of a periodic function is the ratio of the rms value to the average absolute value

$$ff = y_{\text{rms}}/y_{\text{AAV}}$$

1.4.5 Crest Factor: The crest factor (cf) of a periodic function is the ratio of the peak value to the rms value

$$cf = y_p/y_{\text{rms}}$$

1.4.6 Distortion Factor: The distortion factor df is defined as

$$df = \left[\sum_{k=2}^n \frac{A_k^2}{A_1^2} \right]^{1/2}$$

where A_1 is the rms value of the fundamental component and A_2 to A_n are the rms values of the harmonic components.

1.4.7 Deviation Factor: The deviation factor is the ratio of the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave to the maximum ordinate of the equivalent sine wave when the waves are superposed in such a way as to make this maximum difference as small as possible. The equivalent sine wave is defined as having the same frequency and the same rms value as the wave being tested.

1.4.8 Apparent (Phasor) Power: $S = VI$

where S is the apparent power, V is the rms value of the voltage, and I is the rms value of the current.

1.4.9 Average Active Power:

$$P = \frac{1}{T} \int_{t_0 - T/2}^{t_0 + T/2} p \, dt$$

where P is the average active power at any time t_0 , $p = vi$ is the instantaneous power, v and i are the instantaneous values of voltage and current, and T is the period.

If both the voltage and current are sinusoidal and of the same period, P is given by

$$P = VI \cos \theta$$

where V and I are the rms values of voltage and current respectively and θ is the phase angle separating V and I .

The general expression for polyphase active power in a system with m phases and n harmonics involves a summation over all harmonics in accordance with the above equation and a summation over all phases.

1.4.10 Reactive Power: The reactive power Q is defined as the square root of the square of the apparent power S minus the square of the active power P .

$$Q = (S^2 - P^2)^{1/2}$$

Reactive power is developed when there are inductive, capacitive, or nonlinear elements in the system. It does not represent useful energy that can be extracted from the system but it can cause increased losses and excessive voltage peaks.

1.5 Waveform Parameters (see Table 1-1)

1.5.1 Sine Wave

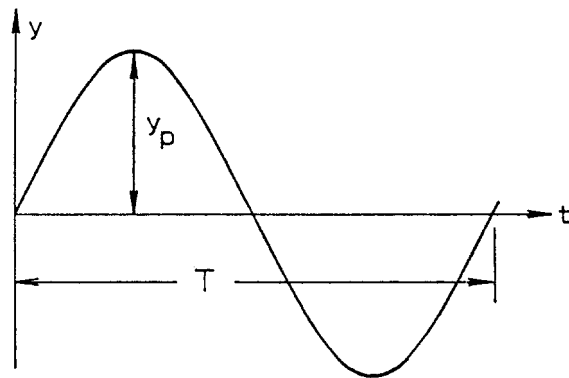
$$y_{\text{rms}} = \left[\frac{1}{T} \int_0^T (y_p \sin \omega t)^2 dt \right]^{1/2} = \frac{y_p}{\sqrt{2}} = 0.7071 y_p$$

where $\omega\tau = 2\pi$

$$y_{\text{AAV}} = \left[\frac{1}{T} \int_0^T y_p |\sin \omega t| dt \right] = \frac{2y_p}{\pi} = 0.6366 y_p$$

$$ff = \frac{y_p}{\sqrt{2}} / \frac{2y_p}{\pi} = \frac{\pi}{2\sqrt{2}} = 1.1107$$

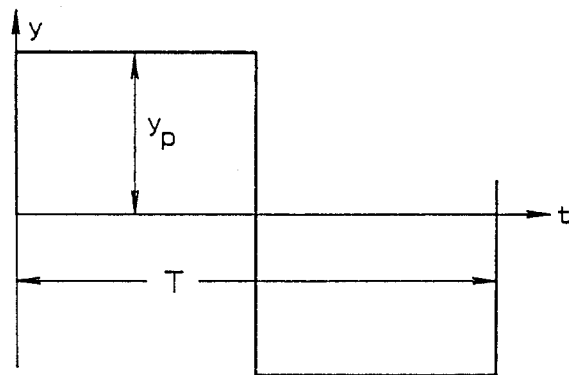
$$cf = y_p / \frac{y_p}{\sqrt{2}} = 1.4142$$



1.5.2 Square Wave

$$y_{\text{rms}} = y_{\text{AAV}} = y_p$$

$$ff = cf = 1$$



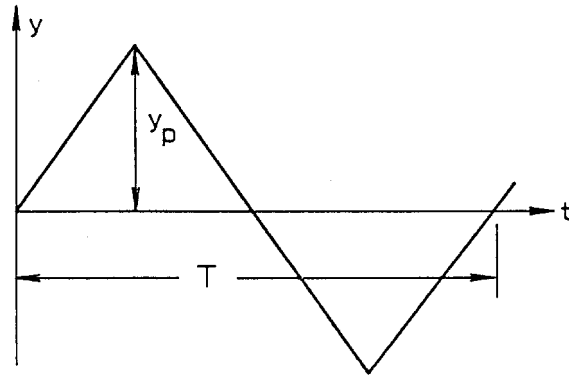
1.5.3 Triangular Wave

$$y_{\text{rms}} = \left[y_p^2 \int_0^{T/4} \left(\frac{4}{T} t \right)^2 dt \right]^{1/2} = \frac{y_p}{\sqrt{3}} = 0.5774 y_p$$

$$y_{\text{AAV}} = y_p \int_0^{T/4} \frac{4}{T} t dt = 0.5 y_p$$

$$ff = \frac{0.5774 y_p}{0.5 y_p} = 1.1548$$

$$cf = \frac{y_p}{0.5774 y_p} = 1.7319$$



1.5.4 Sine Wave Distorted with 30% Third Harmonic Shifted by θ

(This is the waveform influence test specified in the ANSIC39 series [2].)

$$y_{\text{rms}} = \left[\left(\frac{y_p^2}{\sqrt{2}} \right) + \left(\frac{0.3y_p}{\sqrt{2}} \right)^2 \right]^{1/2} = 0.7382y_p$$

$$y_{\text{AAV}} = \frac{y_p}{T} \int_0^T |\sin \omega t + 0.3 \sin(3\omega t + \theta)| dt$$

$$= \frac{y_p}{\pi} [2 + 0.2 \cos \theta]$$

$$= \frac{2.2y_p}{\pi} = 0.7003y_p$$

(for $\theta = 0^\circ$, maximum AAV)

$$= \frac{1.8y_p}{\pi} = 0.573y_p$$

(for $\theta = 180^\circ$, minimum AAV)

where $\omega T = 2\pi$ and y_p is the peak value of the fundamental component,

$$ff(\theta = 0^\circ) = \frac{0.7382}{0.7003} = 1.0541$$

$$cf(\theta = 0^\circ) = 1.2460$$

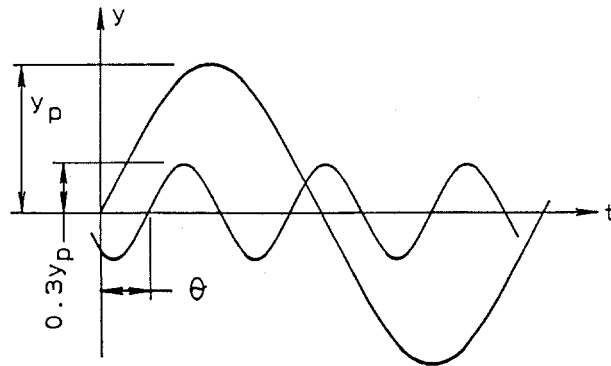
$$ff(\theta = 180^\circ) = 1.2883$$

$$cf(\theta = 180^\circ) = 1.7610$$

Table 1-1—Waveform Parameters

Waveform	rms	AAV	Peak	ff	cf
Sine wave	$0.707 y_p$	$0.637 y_p$	y_p	1.111	1.414
Square wave	y_p	y_p	y_p	1	1
Sine wave + 30% 3rd Harmonic (in phase— 0°)	$0.738 y_p^*$	$0.700 y_p^*$	$0.920 y_p^*$	1.054	1.246
Sine wave + 30% 3rd Harmonic (180°)	$0.738 y_p^*$	$0.573 y_p^*$	$1.300 y_p^*$	1.288	1.762
Triangular wave	$0.577 y_p$	$0.500 y_p$	y_p	1.155	1.732
SCR (90° firing angle)	$0.354 y_p$	$0.318 y_p$	y_p	1.111	2.828

* y_p is the peak value of the fundamental component of the measured signal.



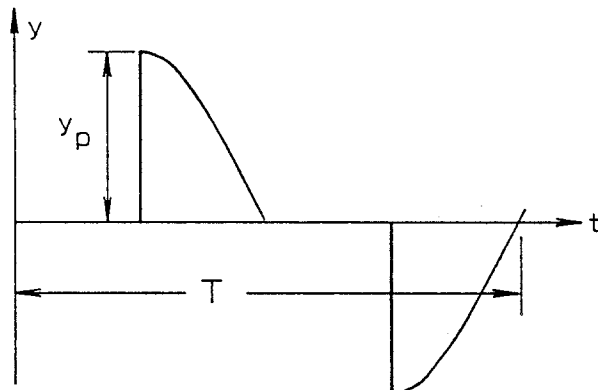
1.5.5 SCR Switched Sine Wave (90% Firing Angle)

$$y_{\text{rms}} = 0.3536 y_p$$

$$y_{\text{AAV}} = 0.3183 y_p$$

$$ff = 1.1109$$

$$cf = 2.8281$$



1.6 Operating Principles of Measuring Instrument

In this section, the operating principles of numerous types of measuring instruments are briefly described. More complete descriptions are provided where appropriate in other sections of this guide.

1.6.1 Measurement of Average Voltage and Current

The average value of a periodic signal is obtained by integrating the instantaneous value y over k periods (where k is an integer 1, 2, ...).

$$y_{AVE} = \frac{1}{kT} \int_0^{kT} y \, dt$$

This is normally done using a capacitor-type integrator. A wide variety of both passive and active circuits is in use. Since the integral of a symmetrical alternating signal (over one period) is zero, the averaging circuit gives only the dc component of the waveform.

1.6.2 Measurement of Average Absolute Value

The average absolute value (AAV) is a more useful parameter that is obtained by rectifying the signal before integration. Circuits ranging from simple diode bridges to operational-amplifier-aided rectifiers and integrators are commonly used in analog and digital indicating instruments.

The scales of such instruments can be, and are, usually marked to indicate the rms value of a sinusoidal signal. With sinusoidal waveforms, accuracies of about 0.1–1.0% can be achieved in the measurement of the rms values. With nonsinusoidal waveforms, the errors can be large.

1.6.3 Measurement of Peak Value and Quasi-Peak Value

Peak reading instruments indicate the maximum value of a waveform during a given measurement period. The peak value is obtained by rectifying the signal and storing its maximum value on a capacitor. This value is sensed, without appreciably discharging the capacitor, with a high-impedance averaging voltmeter.

If the capacitor is coupled with a charging resistor and a discharging resistor, a type of quasi-peak-sensing circuit is obtained. If both the charging and discharging time constants are long in relation to the period of the signal to be measured, the response of the quasi-peak circuit is independent of the signal frequency. By adjusting the ratio of the two resistors, any value of rectified periodic signal can be sensed—from its peak value to a value that approaches zero.

1.6.4 Phase-Sensitive Detector

In the diode-switched phase-sensitive detector, a reference voltage, V_r , biases a pair of diodes in such a way that the signal voltage, V_s , is gated during a half cycle of V_r . The average value of the gated signal is given by

$$kV_s \cos\theta$$

where θ is the phase angle separating V_r and V_s and k is a proportionality constant.

The use of active elements to idealize the diodes has greatly improved the performance of this circuit, yielding accuracies of the order of 0.1–1.0% under sinusoidal conditions.

If the voltages are nonsinusoidal, large errors are possible. With a nonsinusoidal signal voltage and a sinusoidal reference voltage, the errors are similar to those of the AAV-sensing, rms-indicating meter mentioned in 1.6.2. Distortion in the reference voltage can be proportional to a current yielding a phase-sensitive ammeter or current transducer.

1.6.5 Square Law Devices and Signal Multipliers

From definition 1.4.1, the rms value of a periodic function is the square root of the square of the instantaneous value averaged over one period. In order to implement this definition in an electrical measuring instrument, a circuit element that responds to the square of the input waveform is required. Similarly, average power is obtained by averaging the instantaneous product of voltage and current over an integral number of cycles, according to 1.4.9. A circuit element that responds to the product of two inputs is required. Multiplication and square law response may be achieved in a number of ways as described in the following sections.

1.6.5.1 Electrostatic Instruments

These instruments consist of a set of fixed and moving electrodes (plates or disks) that are insulated from each other forming a capacitor capable of storing charge. The instantaneous stored energy (w) is given by

$$w = \frac{1}{2}v^2C$$

where v is the instantaneous voltage between the plates and C is the capacitance. The torque due to the attraction between the electrodes is

$$\tau = \frac{dw}{d\theta}$$

and the restoring torque (supplied by the spring) is proportional to the angular displacement θ . If the time constant of the mechanical system is long compared with the period of the applied torque, the deflection of the indicator is a function of the rms voltage:

$$k\theta = \frac{1}{2}V^2\frac{dC}{d\theta}$$

where V is the rms value of voltage, and k is a constant. If $dC/d\theta$ is constant, the deflection of the indicator (θ) is a quadratic function of V . The scales on the instruments are marked to indicate V , thus in effect computing the square root. In the allowable frequency band, the indication is not affected by the waveform. By combining the electrostatic voltmeter with a shunt, an ammeter can be realized. With a more complex instrument, power can be measured. Electrostatic instruments, although capable of 0.25–1.0% accuracy, are rarely used in modern measurement applications, except those at high voltages.

1.6.5.2 Electrodynamic Instruments

Such devices consist of a set of fixed and moving coils that carry currents that are proportional to the quantities to be measured. The energy stored in the magnetic field of the coils is given by

$$w = \frac{i_1^2 L_1}{2} + \frac{i_2^2 L_2}{2} + i_1 i_2 M$$

where i and L are the currents and inductances associated with each coil, and M is the mutual inductance between coils. The torque between the coils may be written as

$$\tau = \frac{dw}{d\theta} = i_1 i_2 \frac{dM}{d\theta}$$

since L_1 and L_2 are not functions of θ . Electro-dynamic instruments, when calibrated with dc, are capable of accuracies better than 0.1% under laboratory condition and better than 1.0% in the field. They are still in use, particularly in the power industry. The general considerations are analogous to those of the electrostatic meter. In the allowable

frequency band, the indication is not affected by the waveform. With appropriate resistors and shunts, electrodynamic instruments can be configured to measure rms currents, voltage, and average power.

1.6.5.3 Thermal Instruments

Thermal instruments operate by measuring the temperature rise, τ , of a heater wire carrying the current, i . The instantaneous power, p , dissipated in the heater resistance, R , is

$$p = i^2 R$$

If the thermal time constant is long in relation to the time constant of the electrical signal, if R is constant, and if the heat loss is proportional to the temperature rise,

$$\Delta(\text{temp}) = kI^2$$

where I is the rms current and k is a proportionality constant. Within the allowable frequency band, the heater temperature rise is a function of the rms value of the current and is not affected by the waveform.

The temperature is normally measured by a thermocouple that has its hot junction in thermal contact with the heater and its cold junction near room temperature. Vacuum thermoelements (having the heater and thermocouple enclosed in an evacuated tube) are capable of accuracies exceeding 0.01% when used as transfer devices in standards laboratory environments. In this mode the thermocouple output is brought to the same voltage on ac and dc. The dc value corresponds to the rms value of the ac signal, eliminating the need for precise square law response. More recently, monolithic devices using thin film heaters, temperature sensing transistors, and amplifiers have been developed and built into digital voltmeters. The accuracies are in the 0.01–0.1% range.

Average active power may be sensed with a pair of thermoelements using a quarter-square technique. A small current proportional to the voltage is combined with a portion of the test current, i , in the following manner:

$$P_{\text{AVG}} = \frac{k}{T} \int_0^T [(v+i)^2 - (v-i)^2] dt = \frac{4k}{T} \int_0^T vi dt$$

The passive implementation of the thermal wattmeter is capable of accuracies exceeding 0.5%. Higher accuracies, to 0.01%, and faster response times are possible when the thermoelements are combined with operational amplifiers and used as ac/dc transfer devices.

1.6.5.4 Transconductance Multipliers

In the variable-transconductance multiplier, one input controls the gain of an active device such as a silicon junction transistor that amplifies the other input. The relationship between the collector current, I_c , and the base-emitter voltage V_{be} is given by

$$\Delta I_c = k I_{c0} \cdot \Delta V_{be}$$

where k is a proportionality constant.

Transconductance multipliers can achieve accuracies of 0.1–1.0% over the audio frequency range. If I_c and V_{be} are derived from the same input, transconductance multipliers can be used as accurate square law circuit elements in rms voltmeters and ammeters. Wattmeters are implemented by deriving I_c and V_{be} , from the test current and test voltage, respectively.

1.6.5.5 Time-Division Multipliers

Time-division multipliers or pulse modulation multipliers generate pulses that are controlled in amplitude by one input and in width by the other. The average area under these rectangular pulses is proportional to the product of the two inputs. As with transconductance multipliers, time division multipliers can be configured as rms voltmeters and ammeters or as wattmeters. Errors of 0.01-0.1% can be achieved over the multiplier bandwidth. Since these devices effectively sample the waveform, they are limited to the measurement of frequency components that are less than the Nyquist frequency (one half the pulse or sampling frequency).

1.6.5.6 Waveform Digitizing

Waveform digitizing combined with digital calculation is one of the newest techniques currently finding application in commercial instrumentation. In this approach the voltage and current waveforms are simultaneously sampled and digitized with an analog-to-digital converter. RMS values (voltage or current) are obtained by averaging the squares of the instantaneous value of either waveform over an integral number of periods and then extracting the square root of the average

$$y_{\text{rms}} = \left[\frac{1}{n} \sum_{k=1}^n y_k^2 \right]^{1/2}$$

The average power can be calculated in a similar manner by averaging the product of the instantaneous voltage and current

$$P = \frac{1}{n} \sum_{k=1}^n v_k i_k$$

1.6.5.7 Logarithmic Amplifier

Logarithmic amplifier circuit elements use a grounded base transistor as a feedback element in a standard inverting operational amplifier circuit. With the transistor emitter connected to the output of the amplifier and the collector to the summing node, the output, v_o is related to the input, V_{in} , by the following relationship

$$v_o = k \ln \frac{v_{in}}{R}$$

where R is the input resistance and k is a proportionality constant. The antilog operation is obtained by interchanging the positions of the input resistor and the log element (transistor).

Multiplication is obtained by summing the output of two log stages driven from different sources, while powers and roots can be generated by adjusting the gain of the log and antilog stages. The square-root capability of the log circuit element is particularly important in rms measurements for extracting the root of the mean-squared signal, thus allowing the use of linear scale displays.

1.6.5.8 Diode-Type Function Generators

Square-law approximation using multiple diodes is achieved by altering the voltage to current relationship in segments (e.g., as the voltage crosses preselected thresholds, diodes switch in different resistances which change the current slope). The rms error in the approximation is inversely proportional to the square of the number of equally spaced segments, N , produced by $N-1$ diodes

$$\varepsilon = \frac{0.38}{N^2}$$

By optimizing segment length (i.e., using shorter segments in the areas of greatest curvature), fewer segments may be needed to achieve a given accuracy. Between four and five diodes are required to approximate quadratic response to within 1%. Square root response can also be approximated which, when combined with an averaging filter, provides linear scale rms indication.

As with the thermal wattmeter, quarter-square techniques can be used to convert the square-law diode array to a multiplier for measuring active power.

1.6.5.9 Hall Effect Multiplier

In Hall effect multipliers a magnetic field, B , proportional to the test voltage, v , is applied at right angles to the test current, i , in a semiconductor. A voltage v_H , which is perpendicular to both B and i , is developed across the semiconductor

$$v_H = k Bi$$

where k is a proportionality constant.

Hall multipliers are generally configured as wattmeters and power transducers in the 0.5-1% accuracy class.

1.7 Grounding

Many instruments have three input terminals, marked high, low, and ground or +, −, and $\perp$. Others have four terminals, +, − common, and ground. The terminal marked ground, or $\perp$, is the safety ground; all external metal parts of the instrument are connected to this point, which in turn is connected to the ground lead of the ac utility power line. In proper installations the ground connection will prevent hazardous potentials from developing between adjacent metallic enclosures and between enclosures and building ground. This assures that none of the conducting parts of the instrument that the user could touch can rise in potential above the safe margin (42 V) with respect to ground. A metal link is often provided between the common terminal (sometimes the low terminal) and the ground. The common point is then grounded. Measuring errors may occur where other instruments or devices under test in the same system have also a connection to ground. (See ground loops.) In such situations the common terminal and the ground terminal must be disconnected. Nevertheless, the instrument's cabinet chassis or ground terminal must remain connected to ground.

Clear distinction should be made between the common and ground; under normal operating conditions, a common is intended to carry current, while a ground is not. Grounds must be designed to carry fault current under abnormal conditions.

Minimum ground wire size and general safety practices should comply with ANSI C2-1990, American National Standard National Electrical Safety Code [1].

1.7.1 Ground Loops

When two points in a measuring system are connected to the ground, a ground loop is formed. Ground loops should be considered in the layout of the measurement circuit as they can cause erroneous measurement results.

An example of a ground loop formed between a grounded transducer and a measuring instrument grounded at a different location is shown in Fig 1-1. The impedance Z_1 represents the transducer impedance, Z_2 and Z_2^1 are the impedances of the conductors that connect the two devices, and Z_{1n} is the instrument impedance. The transducer might be an ac-power-to-dc-voltage transducer, a thermocouple, an accelerometer, or any electrical-to-electrical or

mechanical-to-electrical transducer. V_s is the transducer output voltage. The instrument can be a digital or analog indicating meter, an oscilloscope, an impedance bridge, or any type of data acquisition device.

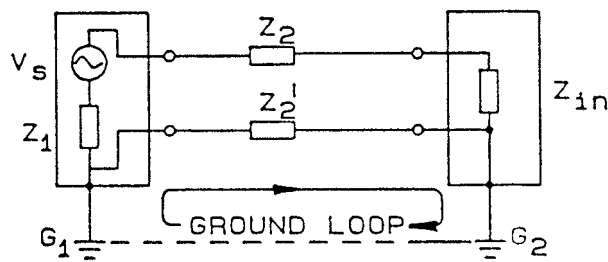


Figure 1-1—Ground Loop

1.7.2 Common-Mode and Series-Mode Voltages

A common-mode voltage is the voltage between a common point, usually the point at which the instrument is grounded, and both conductors connected to the input terminals of the instrument. A series-mode or normal-mode voltage is the voltage in series with the two input terminals of the instrument. In the presence of ground loops, a common-mode voltage can couple into the measurement circuit so as to appear as a series-mode voltage.

A common-mode voltage, V_{cm} , is shown in Fig 1-2. A voltage between two physical grounding points, G_1 and G_2 , may exist as a result of currents in the ground or grounded conductors. Such ground currents could be caused by unbalanced load currents in the 3-phase system and by unbalanced line-to-ground capacitive currents. The common-mode voltage in turn introduces currents in the measuring circuit and an erroneous series-mode voltage, V_{sm} , that is added to the output voltage of the transducer.

With $V_s = 0$, the voltage across Z_{in} becomes

$$V_{sm} = V_{cm} \left[\frac{Z_1 + Z_2}{Z_1 + Z_2 + Z_{in}} - 1 \right]$$

For $Z_2 \ll Z_1$, $Z_2 < Z_{in}$, and $Z_1 \ll Z_{in}$

$$V_{sm} = -V_{cm}$$

In the above example, the common-mode voltage effectively becomes the series-mode voltage and is measured by the instrument. V_{cm} is a noise in the presence of the signal, V_s , that is being measured.

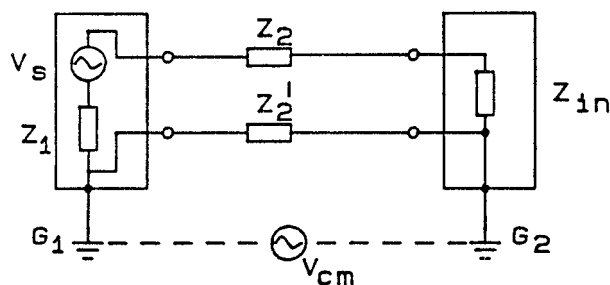


Figure 1-2—Common-Mode Voltage

To avoid the generation of series-mode voltage, the system should be grounded only at one point, e.g., (1) by connecting the ground terminals of the instrument and the transducer to one physical ground point, (2) by grounding the entire instrument and the enclosure of the transducer as shown in Fig 1-2, but by disconnecting the grounded end of the transducer proper from its enclosure. The transducer itself is then grounded at the measuring instrument and through the lead impedance Z_1^2 . In any grounding modification, the safety aspects should not be compromised.

1.7.3 Remedial Methods

In many measurement systems multiple grounding and the resulting common-mode voltages cannot be avoided and remedial techniques should be used. Popular remedial methods are shown in Fig 1-3, and they involve isolation transformers, bifilar or coaxial inductors (chokes), instrumentation amplifiers, and optocouplers.

1.8 Magnetic and Capacitive Interferences and Their Reduction

Even if the ground current and associated common-mode voltages, as discussed in 1.7.2, are eliminated by grounding the system at a single point, erroneous signals can still be introduced in the measuring circuit from the nearby power system and other sources by magnetic and capacitive couplings. The elements of such coupling and the methods for their reduction are discussed.

1.8.1 Magnetic Coupling

Magnetic coupling is illustrated in Fig 1-4(a). An error voltage, V_{sm} , equivalent to the series-mode voltage of 1.7.2 is introduced in the measurement circuit by the current I in the power conductor above the measuring circuit. The current in this conductor produces a magnetic field. A portion of the resulting magnetic flux links the measuring circuit and introduces an error voltage

$$V_{sm} = 2\pi f\Phi$$

where Φ is the magnetic flux that links the measuring circuit, and f is the frequency of the magnetic field. This error voltage can be represented by an equivalent generator as in Fig 1-4(b). The size of the loop, the proximity and orientation of the power conductor relative to the measuring circuit, and the magnitude of I determine the magnitude of V_{sm} .

1.8.2 Capacitive Coupling

Capacitive or electrostatic coupling is illustrated in Fig 1-5(a). The capacitive current, I_{c1} and I_{c2} , from the power conductor, could introduce an erroneous "series-mode" voltage. This voltage can be calculated from the circuit of Fig 1-5(a) leading to a somewhat complicated expression. The calculation can be simplified by removing the negligible terms, such as products of capacitive current and lead impedances. Under those assumptions I_{c2} has no effect. Usually Z_1 , is much smaller than Z_{in} and thus nearly all of I_{c1} passes through Z_1 . The resultant series-mode voltage is given by

$$V_{sm} = V_2\pi C_1 Z_1$$

The equivalent circuit showing V_{sm} is given in Fig 1-5(b).

1.8.3 Coaxial and Twisted Leads

The problems of magnetic and capacitive couplings as illustrated in Figs 1-4 and 1-5 can be eliminated by the use of a coaxial connecting cable. Such a cable has no net loop to capture extraneous magnetic flux such as Φ in Fig 1-4. The outer conductor of a coaxial cable is connected to the ground. It shields electrostatically the inner conductor and thus eliminated I_{c1} in Fig 1-5.

If the connecting cable is a twisted pair of conductors, the net loop to capture the flux Φ is reduced by creating a large number of small loops in which alternatively positive and negative voltages are induced thus nearly eliminating any net erroneous voltage. The twisted pair does not eliminate capacitive coupling but may reduce it.

1.8.4 Shielding Techniques

Cables discussed in 1.8.3 may not suffice for eliminating undesirable magnetic and capacitive couplings, and additional shielding of the measuring circuit might be necessary. For example, exposed components in the transducer or the instrument could become the points of pickup of undesirable signals. At high frequencies, including fast surges, the cables that suffice at dc or low frequencies may become inadequate. While the shielding over a wide frequency band is an involved subject beyond the scope of this guide, several guidelines are of particular importance in the power system.

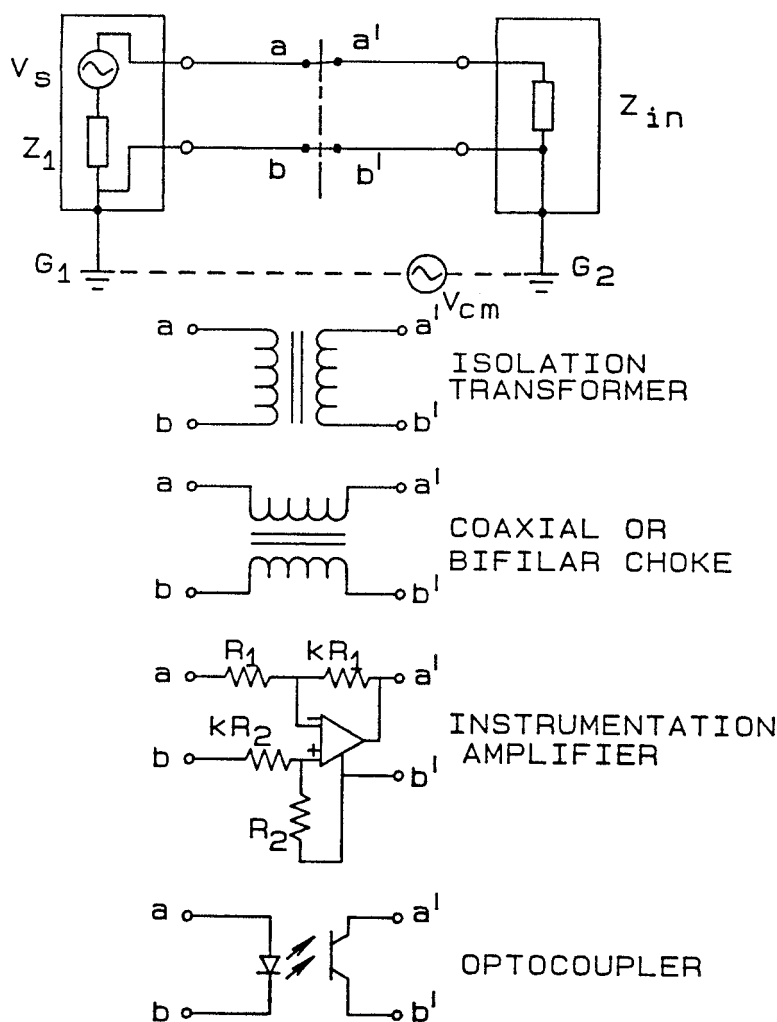


Figure 1-3—Methods for Elimination of Adverse Effects of Group Loops

Electrostatic fields produce not only interference in the measurement but may also permanently damage solid-state electronic components. A properly grounded metal housing provides the most effective means of shielding against such fields. For low frequency investigations, such a housing can be made of sheet metal, foil, or braid. Near perfect electrostatic shielding can be achieved for fully enclosed parts.

Nonmagnetic metal enclosures with thin walls, such as those made of sheet metal, are ineffective as low-frequency magnetic shields. In order to become effective, the wall thickness of the enclosure must be of the same order as or larger than the penetration depth of the electromagnetic field for the particular shielding material. Effective low-frequency magnetic shields made of conductive material must be constructed so as not to impede the paths for the eddy currents.

High-permeability ferromagnetic materials are the best shielding materials against dc and low-frequency magnetic fields. An effective magnetic shield should have low reluctance/high permeability material, large cross-sectional area material, and a short path for the flux that is to be shielded against. Shields having simple geometries, such as spheres and long cylinders, have simple expressions for the shielding ratios at dc and at low frequencies. For cylindrical enclosures (magnetic field perpendicular to the axis of the cylinder)

$$\frac{B_I}{B_0} = \frac{2r}{d\mu}$$

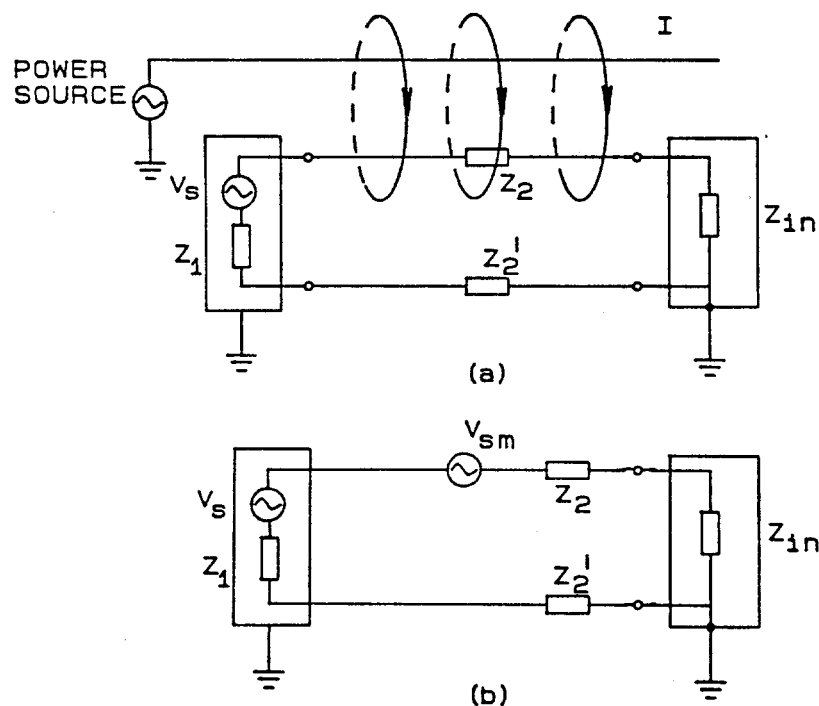


Figure 1-4—(a) Magnetic Coupling (b) Equivalent Circuit Showing Series-Mode Voltage

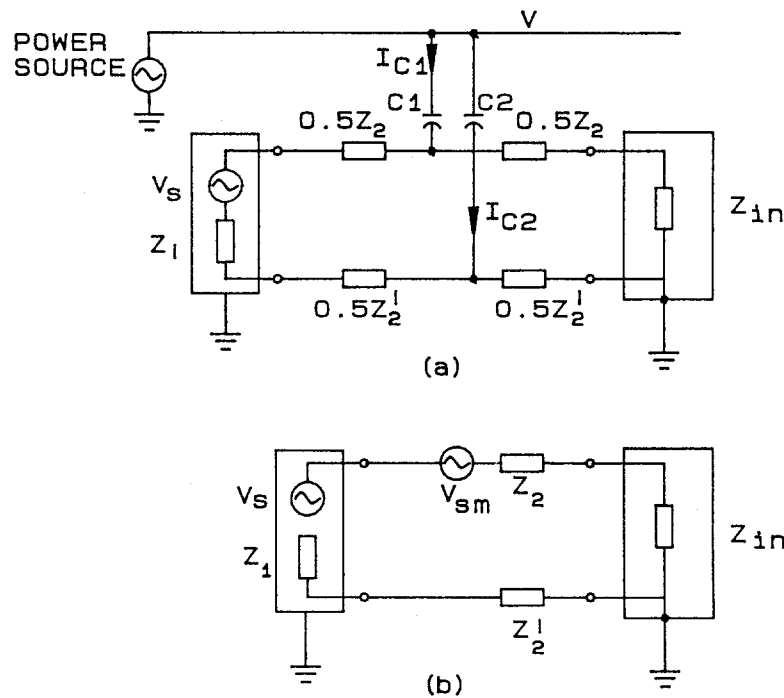


Figure 1-5—(a) Capacitive Coupling (b) Equivalent Coupling

For spherical enclosures

$$\frac{B_I}{B_0} = \frac{3r}{2d\mu}$$

where

- B_I = the magnetic flux density inside the enclosure
- B_0 = the unperturbed uniform flux density without the shield
- d = the wall thickness of the enclosure
- r = the radius of the enclosure
- μ = the permeability of the shielding material relative to air

Care should be exercised in constructing the high-permeability magnetic shields in order to avoid discontinuities and increased reluctances in critical paths for the magnetic flux. To achieve the highest permeabilities, the materials may have to be annealed after constructing the enclosure. High level of magnetic shielding is much more difficult to achieve than of electrostatic shielding. A high permeability magnetic shielding enclosure made of metal sheet has sufficient conductivity and thus will serve adequately also as an electrostatic shield.

In high-frequency electromagnetic waves, both electric and magnetic field components must be considered. Near perfect shielding as in the low-frequency electrostatic case cannot be readily achieved in practical enclosures because of limited thickness of the shielding material and because of discontinuities such as joints, openings, and power supply leads, all of which facilitate penetration by electromagnetic fields.

A cylindrical shield is illustrated in Fig 1-6.

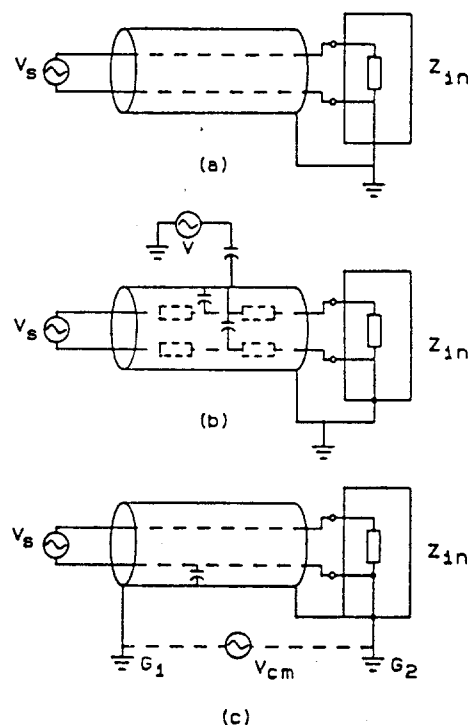


Figure 1-6—(a) Shielding of Conductors (b) imperfect Shielding Caused by Finite Lead and Shield Impedances (c) Incorrect Grounding of Shield

In 1-6(a) a shield, e.g., braid, surrounds a pair of conductors. If magnetic shielding is also required, a high-permeability tube can be used at dc or at low frequencies.

In Fig 1-6(b) a condition is illustrated where a finite shield and lead impedances and shield-to-conductor capacitances cause noise to be coupled to the signal leads. Figure 1-6(c) illustrates multiple grounding of a shielded circuit whereby the ground current in the shield and the shield-to-conductor capacitance could introduce error in the measuring circuit. A single ground, if permissible under safety considerations, is preferable.

For more detailed information on grounding, shielding, and noise reduction, refer to the following literature:

IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources [6].

R. Morrison. *Grounding and Shielding Techniques in Instrumentation*, (3rd edition). New York: John Wiley & Sons, 1986 [7].

H.W. Ott. *Noise Reduction Techniques in Electronic Systems*. New York: John Wiley & Sons, 1976 [8].

1.9 Terms and Definitions for Performance Evaluation of a Measurement Process or Instrument

The process of measurement is to determine the true value of a quantity by measurement. In practice this goal is never achieved, only approached. No measurement, however carefully made, can be completely free of uncertainties. To evaluate the performance of a measurement process or instrument requires the understanding and definition of such terms as error, correction, uncertainty, accuracy, precision, resolution, threshold, sensitivity, linearity, and offset.

1.9.1 Error and Correction: Error is the quantity difference between the value obtained from the measurement process or indicated by the instrument employed in the measurement process and the true value. Since the actual magnitude of the error is unknown and cannot be known, the measured value minus the estimated error is only an approximation to the true value.

The performance of the measurement process or instrument is quite often defined in terms of the limits of error. The limits of error implies that the measured value lies within the bounds prescribed by the limits of error and is usually expressed as percentage of full scale value or percentage of reading.

Several kinds of errors exist. Some are readily evaluated, others may only be estimated. The errors are generally classified as systematic and random.

Systematic errors cause the measured value to be displaced or biased a fixed amount. If these errors are known through a calibration process, their effect can be eliminated by correction factors. However quite often their magnitude and direction are not known, or are known only partly, and, therefore, only estimated limits of systematic error can be made.

Random errors have random causes that will force several independent measurements of a quantity to be distributed randomly about their average value. The average or arithmetic mean is usually assumed to be the “most probable value” or “best estimate value” of the measured quantity. For n observations $x_1, x_2, \dots, x_n$ it may be expressed as

$$\bar{x} = \frac{x_1 + x_2 + \dots + x_n}{n} = \frac{\sum x_n}{n}$$

Standard deviation is a measure of the dispersion from the mean. It is defined as the rms of the deviations of a set of observations from the arithmetic mean of the set and is expressed as

$$s_x = \sqrt{\frac{\sum d_n^2}{n-1}}$$

where s_x is the standard deviation, d_n is the deviation of any individual observation from the mean of the set, that is $(x_n - \bar{x})$ and n is the number of observations in the set.

If a second set of n measurements were recorded, the second value of the mean would in general differ from the first value. But the difference between the two means would be expected to be less than the standard deviation in either set. The best measure of the uncertainty of the final answer $x_{\text{best}} = \bar{x}$ is the standard deviation s_x divided by $\sqrt{n}$. This quantity is called the standard deviation of the mean, and is denoted $s_{\bar{x}}$:

$$s_{\bar{x}} = \frac{s_x}{\sqrt{n}}$$

Other common names for this are standard error and standard error of the mean. A multiplying factor or a t -factor, that is $t s_{\bar{x}}$ where t is any positive number, may be used to modify the standard deviation of the mean to increase the limits or error, and the probability that the new mean will be within the increased limits. This multiplying factor or t -factor is usually associated with a confidence level that is a measure of the probability that the new mean will be within the increased limits. For example, for a normal distribution, the probability that a measurement, x_{best} , will fall inside $3 s_{\bar{x}}$ is 99.7%.

If the data from a finite number of measurements were plotted on a graph of value versus frequency of occurrence of each value, a profile could be faired through the plotted points. As the number of measurements approaches infinity, their distribution approaches some definite, continuous curve. If the data stems from completely random effects, the curve will be a symmetrical bell-shaped curve with the mean value as the center of the curve. This curve is known as the normal or Gaussian distribution curve. The confidence level or percentage probability of occurrence is calculated from the distribution function or can be obtained from a table in a book on statistics.

Correction is the quantity that must be added algebraically to the measured value to obtain the true value. It is opposite in sign to error.

1.9.2 Uncertainty: The uncertainty of a measurement is the interval about the quoted value in which the actual or true value of the unknown is believed to lie. An uncertainty is associated with the result because one can never exactly determine the measurement error. The uncertainty is thus the interval of a probable range of the error in the measurement.

Total uncertainty and limits of error are both used to give an indication of measurement accuracy. These terms are occasionally used in the technical literature interchangeably. Limits of error implies an absoluteness; total uncertainty does not. The total uncertainty of a measurement is a function of both systematic and random errors. The standard deviation of the mean can be regarded as the random component of the total uncertainty. For example, the total uncertainty of a measurement can be stated as the estimated limits of the systematic error, plus t times the standard deviation of the mean for random errors. The multiplying factor depends on the chosen level of confidence. Depending on the conditions and end use of the results, the total uncertainty can also be expressed in terms of the root-sum-square of the two error components.

1.9.3 Accuracy: Accuracy is the degree of closeness that the measured value approaches the true value, the deviation of the measured value from the true value being an accuracy index.

1.9.4 Precision: Precision is a measure of consistency or repeatability. It is related to the random error and expresses the variation between individual measurements of the same quantity. The index of precision is stated in terms of deviation of a single observation or a group of observations from a mean value. Precision, however, does not consider systematic errors and thus does not guarantee accuracy.

1.9.5 Resolution: Resolution is the degree to which a measurement system or instrument can detect the smallest change of a quantity starting from a non-zero value of the quantity. Resolution is not constant but is dependent on test conditions.

1.9.6 Threshold: Threshold is the largest repeatable absolute value of the minimum input change to which can be assigned a unique value of the change of expected output whenever the measurement system or instrument is used in a prescribed, repeatable measurement situation.

1.9.7 Sensitivity: Sensitivity is a measure of instrument effectiveness and is usually defined as the ratio of the output change to input change, that is, the unit output corresponding to the unit input under static conditions. In instruments with strong nonlinearities, no single number can be given as the “sensitivity” of the instrument.

1.9.8 Linearity: The linearity of a measurement system or instrument is a property expressing the condition wherein the change in the value of one quantity or input is directly proportional to the change in the value of another quantity or output. It describes a constant ratio of incremental cause and effect.

1.9.9 Offset: Zero offset is the output of a measurement system or indication of an instrument for an input equal to zero.

1.9.10 Practices in Denoting Measurement Accuracies: The practices in specifying measurement and instrument accuracy are not uniform and, if not adequately specified or understood, may lead to erroneous interpretation. Different authors may use the terms “accuracy” “error,” and “uncertainty” to denote the estimated difference between the true and measured values, or the limits of error as defined in 1.9.1.

The accuracy of the instrument can be expressed as a percentage of the full scale, or of the reading, or of the combination of both. For instruments measuring quantities with several variables, the expression of accuracy can be more involved. For ac wattmeters, in addition to the frequency, the variables include the magnitudes of voltage and current and the phase angle between the two. The accuracy can be expressed as a percentage of the measured combined voltage and current range.

In most engineering applications the measurement and instrument accuracies are expressed as percentages. The calibration laboratories frequently express accuracies in parts per million (ppm). (One ppm equals 0.0001%.)

1.10 Transportation

The modern electronic instrument, provided that it is surrounded by shock absorbing material, is usually sufficiently robust to withstand the rigors of normal transport. Older instruments, however, particularly those with bearing or taut-band supported meter movements, require more care. If possible, the movement should be clamped to prevent uncontrolled vibrations and relieve the pressure on the bearings. Bearing type meters should be packed face down so as to remove the pressure on the lower bearing, which supports the movement when in use. In car or truck transport, the instrumentation package should be firmly tied down to the vehicle frame to prevent uncontrolled motion and consequent severe shock.

1.11 Safety

Care should be taken in any measurement to avoid coming into contact with dangerous and possible lethal voltages, and also to avoid damage to the installation. Small, hand-held, instruments capable of measuring voltages up to 1 kV or higher are becoming quite common, and it is preferable to place these on some convenient surface when such voltages are applied rather than hold them in one's hand. Leads should be kept clean and in good condition, be insulated to withstand the voltages being accessed, and should be replaced immediately if worn or damaged.

When using current transformers, the possibility of an open circuit across the secondary winding MUST be avoided. Likewise, a short circuit on the secondary winding of a voltage transformer CANNOT be tolerated.

1.12 Bibliography

[1] ANSI C2, American National Standard National Electrical Safety Code.²

[2] ANSI C39 series:

C39.1-1981, American National Standard Requirements for Electric Analog Indicating Instruments.

C39.2-1964 (R1969), American National Standard Direct-Acting Electrical Recording Instruments (Switchboard and Portable Types).

C39.4-1966 (R1972) American National Standard Specifications for Automatic Null-Balancing Electrical Measuring Instruments.

ANSI C39.6-1983, American National Standard for Electrical Instrumentation-Digital Measuring Instruments.

ANSI C39.7-1975, American National Standard Requirements for Electronic Analog Voltmeters.

[3] ANSI/IEEE Std 268-1982, IEEE Standard for Metric Practice.³

[4] IEEE Std 118-1978, IEEE Standard Test Code for Resistance Measurements.

[5] IEEE Std 119-1974, IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus.

[6] IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources.

²ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

³ANSI/IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, Piscataway, NJ 08855-1331, or from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

- [7] Morrison, R. *Grounding and Shielding Techniques in Instrumentation*. New York: John Wiley & Sons, 1986 (Third Edition).
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2. Chapter 2—Voltage and Current Measurements

2.1 Introduction

2.1.1 Digital Instruments

Modern technology has provided digital instruments that can measure voltages and currents over a wide range, and that are accurate, convenient, and rugged. Such instruments are available as dedicated panel meters, portable hand-held multimeters (measuring voltage and current, both dc and ac, and resistance), and portable bench-top meters. For measurements considered in this guide, the latter two types should normally be used.

The basic component of a digital meter is a dc digital voltmeter (DVM). Several operating principles are available. To measure other quantities, a transducer is used at the input of the meter to convert the measured quantity to dc voltage. For example, an internal shunt is used to measure current, and an ac-dc converter to measure ac quantities. The digital meters, in relation to their analog counterparts, have dynamic range and bandwidth and greater accuracy.

2.1.2 Analog Instruments

Prior to the development of reliable digital instruments, accurate measurements were performed by a variety of analog instruments in which a deflection by a pointer provided the measurement information. Most new meters now are of the digital type. However, analog instruments are still available and can be used in power system measurements.

2.1.3 Range Extenders

Modern instruments have a broad dynamic range for the signals that can be measured. The built-in capability of digital meters provides a voltage range that extends typically from 100 mV to 1000 V, and a current range from 100 mA to 10 A. Nevertheless, in power circuits, higher voltages and currents frequently have to be measured. Range-extending devices, such as voltage dividers, instrument transformers, shunts, transducers, and current comparators, are available. These can extend the measurements to about any value encountered in the operation of power circuits.

2.2 Voltage Measurements

2.2.1 General Considerations

2.2.1.1 Description

Voltage measurements in connection with tests under this guide shall generally be made with portable voltmeters. Modern digital voltmeters having rms-sensing capability for ac are now generally available for this purpose. However, older analog meters are acceptable if they meet the accuracy requirements for the intended use. Switchboard and panel instruments are not usually considered acceptable in the applications considered in this guide as they are generally less accurate than portable voltmeters.

2.2.1.2 Calibration

To ensure acceptable performance and accuracy, the meter should be under a regular and periodic calibration regime and adequate records should be maintained. Alternatively, it is necessary to calibrate the meter before and after each use.

2.2.1.3 Caution in Use of Instruments

Possible measurement errors due to conditions of use and environmental factors, such as position, temperature, humidity, stray fields, vibration, ripple on dc signals, waveform of ac signals, and ac frequency must be considered. The effect of the input impedance of the meter on the measured quantity must also be considered.

2.2.2 Digital Voltmeters

2.2.2.1 Introduction

Digital meters display the measured quantities as discrete numbers rather than a pointer deflection on a scale as in analog meters. Electronic circuits are employed in sensing, processing, and displaying the measured quantity. These instruments are generally available as multipurpose digital multimeters (DMMs) enabling measurement of voltage, current, and resistance. Several operating principles are available, such as dual slope conversion, ramp, staircase-ramp, and integrating. Portable meters are available as hand-held digital multimeters or benchtop meters. The higher accuracy meters are usually of the latter type. Almost any accuracy required in engineering applications is available in digital voltmeters—to 0.001% for dc, and 0.01% for ac measurements. Detailed definitions and test procedures for digital meters are available in ANSI C39.6-1983, American National Standard for Electrical Instrumentation—Digital Measuring Instruments [1].⁴

2.2.2.2 Definitions Used with Digital Instruments

The definitions listed below are for selected terms that are most appropriate for measurements in power circuits. They are applicable for both voltage and current measurements.

2.2.2.2.1 Accuracy, Rated: The limit, expressed as percentage of input plus a number of counts, that errors will not exceed when the instrument is used under specified conditions

2.2.2.2.2 Common-Mode Rejection Ratio (CMRR): The ratio in decibels (dB) of the dc or peak ac (sine-wave) common-mode voltage to the equivalent input voltage indicated as an error by the instrument

2.2.2.2.3 Common-Mode Voltage (CMV): The voltage common to both input measuring terminals and a specified reference point, such as the power-line common, the earth ground, the external power-supply common, or the output circuit common, to which the instrument is not intended to respond but which may produce an error in output indication. Unless otherwise stated, common-mode voltage rating shall be with respect to the power-line common

2.2.2.2.4 Digital Multimeter: An electronic instrument that measures voltage, current, and resistance by conversion of the analog input signal to a digital representation in decimal digits

2.2.2.2.5 Dual Slope Conversion: An analog-to-digital (A–D) conversion process in which (a) the input signal is integrated for an interval of time equal to a fixed number of clock pulses (first slope), followed by (b) integration of a reference signal in the opposite direction until the integrator output returns to its initial level (second slope), at which instant (c) the number of clock pulses in the counter, which was reset at the start of the second slope, is now the digital representation of the analog input signal.

2.2.2.2.6 Effective Range: The portion of the range in which measurements can be made to within rated accuracy

2.2.2.2.7 Four-Terminal Resistance Measurements: A measurement in which two wires are used to deliver current to the unknown resistor and two different wires are used to sense the voltage drop across the resistor

2.2.2.2.8 Guarded Input: An input circuit providing a guard electrode surrounding the measuring circuit for the purpose of reducing common-mode interfering currents or providing electrostatic shielding. The guard may be connected to the appropriate point of the complete measuring circuit

2.2.2.2.9 Input Bias Current: The current that must be supplied to the high input measuring terminal with zero input signal and offset voltage to reduce the output indication to zero.

⁴The numbers in brackets correspond to those of the bibliography at the end of this chapter.

2.2.2.2.10 Input Impedance: The shunt resistance and reactance as measured at the input terminals

2.2.2.2.11 Linearity: The ability of an instrument to follow the input signal in a proportional manner over the entire input range. Linearity shall be expressed as the maximum deviation in counts (the number displayed by the least significant digit) from a straight line connecting the ends of the range

2.2.2.2.12 Long-Term Stability: The limit, expressed as a percent of input plus a number of counts that errors will not exceed during a 90-day or other longer specified period. This does not preclude zeroing or similar adjustments that are a part of normal operating procedures and that are made from the front panel without use of external standards or equipment. The error is determined by checking change in output indication after warm-up under the same test conditions within the rated operating limits. The time period includes both operating and nonoperating time

2.2.2.2.13 Peak-Responding: An instrument in which the displayed value is equal to the peak value of the input signal for all repetitive input waveforms having harmonic components within its frequency range.

2.2.2.2.14 Range: A continuous band of input signal values that can be measured. For example: 0 to 100, 20 to 80, -20 to 60. In bipolar instruments, range includes negative as well as positive values

2.2.2.2.15 Ratio Measurement: The measurement of a signal input relative to an external reference input. The output indication is the properly scaled ratio of the signal input magnitude to a reference input magnitude

2.2.2.2.16 Resolution (as Applied to Digital Instruments): The ratio of the smallest incremental change in input signal value, throughout its range, that can be discerned and displayed by an instrument to the highest value of the range

2.2.2.2.17 RMS Responding: A measurement in which the displayed value is equal to the rms of the input signal, for all input waveforms having components within the specified frequency range and crest factor limit

2.2.2.2.18 Short-Term Stability: The limit, expressed as a percent of input plus a number of counts, that errors will not exceed during a 24-hour period of continuous operation under reference conditions following warm-up. No zeroing or adjustments of any kind are permitted

2.2.2.2.19 Two-Terminal Resistance Measurement: A measurement in which the same current flows through the unknown resistance and the test leads. Note that by the use of this technique, the lead resistance is measured along with the unknown.

2.2.2.3 DC Voltage Measurements

The following factors may affect the accuracy of dc voltage measurements made with a digital voltmeter.

2.2.2.3.1 Input Resistance

The error depends upon the resistance of the voltage source, e.g., a voltmeter with an input resistance of 1 M Ω will load a 1 k Ω source causing an error of approximately 0.1%

2.2.2.3.2 Input Bias Current

The error depends on source resistance. An error voltage of 1 mV will be produced at the input terminals of a meter with an input bias current of 1 μ A when measuring a voltage with a source resistance of 1 k Ω

2.2.2.3.3 Insufficient CMRR

An error is introduced by the signal that is common to both input terminals. For example, when measuring a 100 mV signal in presence of 10 V CMV using an instrument with CMRR of 80 dB, an error of $\pm 1\%$ may result. See 2.2.2.2.2 and 2.2.2.2.3