



IEEE Master Test Guide for Electrical Measurements in Power Circuits

STANDARDS

IEEE Power and Energy Society

Developed by the
Power System Instrumentation and Measurements Committee

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Power System Instrumentation and Measurements Committee
of the
IEEE Power and Energy Society

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Abstract: The material submitted for the 2020 reinstatement of Working Group 120 is the basis for this updated version. 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 is the basic approach for the new organization. The contributors strived to maintain the relevant and important knowledge that was previously carefully collected and update this as appropriate.

Keywords: calibration, current measurement, driven shield, grounding, IEEE 120™, instrument transformer, measurement, power factor measurement, power measurement, reactive power measurement, resistance measurement, shielding, voltage measurement

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Participants

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Harold Kirkham, *Chair*
Dani Strickland, *Vice Chair*

Andrew Berrisford
Matthew Bihler
Jeffrey Britton
Gustavo Brunello
Patrick Chavez

Branislav Djokic
Shannon Edwards
Trevor Gaunt
Martin Greschner
Aaron Liu

Ronald Pate
Artis Riepnicks
Vivek Siddharth
Thomas Sizemore
Xiao-Ping Zhang

The following members of the individual Standards Association balloting group voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

Saif Aldeen Saad Obayes Al-Kadhim
Mihaela Albu
Matthew Bihler
Jeffrey Britton
Bill Brown
Koti Reddy Butukuri
William Byrd
Ritwik Chowdhury
Neal Dowling
Jorge Fernandez Daher
Carl Fredericks
Shubhanker Garg
George Gela
Jean Hernandez-Mejia
Michael Higginson

Thang Hochanh
Werner Hoelzl
John Kay
Harold Kirkham
Jan-Philipp Kitzig
Mikhail Lagoda
Wang Lei
Lei Liu
Lawrenc Long
James McBride
Jeffrey McElray
Arthur Neubauer
Lorraine Padden
Ronald Pate
Bansi Patel

Howard Penrose
Johannes Rickmann
Artis Riepnicks
Zoltan Roman
Daniel Sabin
Thomas Sizemore
Gary Smullin
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Dani Strickland
David Tepen
John Vergis
Quintin Verzosa
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Gui Lin
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Andrew Myles

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Robby Robson
Lei Wang
F. Keith Waters
Karl Weber
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Don Wright

*Member Emeritus

Introduction

This introduction is not part of IEEE Std 120-2023, IEEE Master Test Guide for Electrical Measurements in Power Circuits.

Much has changed since the previous edition of this standard. When that was issued, in 1989, digital technology was new to the fields of measurements and instrumentation. Thirty years later, analog technology is the exception rather than the rule.

In the view of some observers of the fields of engineering and science, digital methods have amounted to a quiet revolution in both instrumentation and measurement. The change in instrumentation is evident to all: the user of an instrument need no longer be concerned with parallax in reading an instrument or with friction and dust impeding the movement of a pointer. The reporting and collecting of results is now easily automated.

The change in measurement has been more subtle but is in some ways more important. It has become clearer than ever that the result of a measurement is critically dependent on the way the signals are treated and that the quality of those signals plays a major part in adding uncertainty to the result. Measurement processes, built into the instrumentation, are based on assumptions about the nature of the signals being measured. The power system voltages and currents are usually assumed to be well represented by mathematical sinusoids, for example. If a particular signal is distorted, a good instrument will measure the rms value quite accurately, but the ratio of the peak value to the rms may not be root-two and its effect in the power system may not be what is expected.

Because of the electronic technology used, the processing in an instrument can be “adjusted” far more than it could in the days of analog instruments. Smoothing of results can be used to reduce the effect of noise, filtering can be used to reduce the effect of distortion, and so on. In the analog part of the instrument, guarding can be used to preserve the quality of an analog signal in a challenging environment.

While the user may be aware of the capabilities of modern instrumentation, he or she should also be careful to understand the limitations. Digital instruments have made it more important to distinguish resolution from accuracy. There may be four or five digits on the display, but there may be so much distortion on the signal that there is no meaning to any beyond the first or second.

And it has become more evident that the result of a measurement does not tell the user what anything in the physical world “is.” It never did, though that was harder to see when measurement involved such physical things as magnetic fields. A digital instrument can measure all sorts of things that have no physical existence. Some are obvious: frequency, for example, or power factor. In the electric power system, only voltage and current are observable quantities. All other electrical quantities are indirect measurements, based on these two. What seem to be “measured” values of something real are only reports of a value whose calculation is based on a number of unverified assumptions, and possibly based on a modified version of the signal being measured. The user is advised that just because the instrument is a good one, the result may not be.

The goal of measurement is, usually, to obtain a high-quality value for some quantity or quality of interest. Despite the caveats, the working group is aware that modern measurement theory and instrumentation allow that goal to be more nearly obtained than ever before. The goal of this guide is to serve as a useful source of assistance for the engineer and technician working in any of the increasing number of fields in which electrical measurements are used, with the aim of getting better data.

Contents

1. Overview	11
1.1 Scope	11
1.2 Purpose	11
1.3 Word usage	11
2. Normative references	11
3. Definitions, acronyms, and abbreviations	12
3.1 Definitions	12
3.2 Terms in general use in measurement	12
3.3 Measurement system	17
3.4 Instrument transformer ratio, phase angle, and correction	18
3.5 International System of Units (SI)	19
3.6 Acronyms and abbreviations	19
4. Safety	20
5. Ground and magnetic coupling	21
5.1 Grounding	21
5.2 Electric and magnetic coupling	26
6. Voltage and current measurements	33
6.1 Introduction	33
6.2 . Voltage measurements	36
6.3 Current measurements	42
6.4 Instrument transformers	46
7. Power, energy, and power factor	56
7.1 Power measurement	56
7.2 Energy measurements	62
7.3 Power factor and phase-angle measurement	64
8. Frequency measurements	65
8.1 Theoretical background	65
8.2 Possible problems in measurement	66
8.3 The phasor measurement unit	67
9. Impedance measurements	70
9.1 Description	70
9.2 Determination of impedance	71
9.3 Effective resistance	71
9.4 Effective reactance	72
9.5 General measurement problems and techniques	72
9.6 Standard resistors	84
9.7 Instrumentation	86
9.8 Ohmmeters	94
9.9 Applications	94
10. Calibration	96
10.1 General	96
10.2 Standardization of apparatus	96
10.3 Calibration of watthour meters	96
10.4 Polyphase meter calibration	96

10.5 Maintenance of measuring instruments	97
11. Big data.....	97
Annex A (informative) Bibliography	98
Annex B (informative) Frequency response of instrument transformers.....	102
B.1 Voltage measurement.....	102
B.2 Current measurement	108
B.3 Frequency response compensation.....	110
B.4 Summary.....	111
Annex C (informative) Operating principles of measuring instrument	112
C.1 General.....	112
C.2 Waveform digitizing	112
C.3 Measurement of average voltage and current.....	112
C.4 Measurement of average absolute value	112
C.5 Measurement of peak value and quasi-peak value	113
C.6 Phase-sensitive detector	113
C.7 Square law devices and signal multipliers	113

IEEE Master Test Guide for Electrical Measurements in Power Circuits

1. Overview

1.1 Scope

This guide relates to measurements of power, energy, voltage, and current in dc or ac power systems. The guide does not deal with measurements of resistance or temperature that may be of use in determining the performance characteristics of electric machinery.

1.2 Purpose

The purpose of this guide is to give guidance for the measurement of electric quantities whose values are commonly needed in determining the performance of electric power systems. The choice of the measurement method and instruments to be used depends on the nature of the circuit and the purpose of the measurement.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

There are no normative references in this guide.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁸

If there is no definition, please refer to the authoritative dictionary of IEEE standard terms (IEEE Std 100™).⁹

To ensure clarity of meaning, this guide defines many of the terms it uses. Some of the terms are in general use (e.g., “uncertainty”) and some are specific to parts of the systems used in the power system (e.g., “frequency”). Definitions that are based on definitions in the *International vocabulary of metrology* (VIM; Joint Committee for Guides in Metrology (JCGM), WG 2, *International vocabulary of metrology—Basic and general concepts and associated terms*, 2008 [B46]) are identified.¹⁰ Remarks in this guide that are associated with such definitions are not extracted from the VIM. The latest version of the VIM should be consulted as appropriate; the definitions here are for the convenience of the user of the guide.

Measurement **accuracy** is defined in the VIM as the closeness of agreement between a measured quantity value and a true quantity value. The VIM cautions that the concept of measurement accuracy is not well defined (likely because the true value is something that cannot be known) and “accuracy” is not given a numerical value. The VIM defines **resolution** as the smallest change of a quantity being measured that causes a perceptible change in the corresponding indication. It may depend on noise and on the value of the quantity being measured. **Sensitivity** is defined in the VIM as the ratio of the change in indication to the corresponding change in quantity value. To evaluate sensitivity, the change in the value being measured should be large compared to the resolution.

Annex D in the *Guide to the expression of uncertainty in measurement* (GUM) [B22] is recommended for understanding uncertainty.

Safety requirements for voltage tests, insulation tests, and various other tests are listed in National Electrical Safety Code® (NESC®) (Accredited Standards Committee C2) [B1]. Please refer to manufacturer’s documentation for additional information.

3.2 Terms in general use in measurement

apparent power: This term is formally defined in IEEE Std 1459™. *See also:* **power; reactive power.**

NOTE—See IEEE Std 1459™ [B33].¹¹

⁸ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

⁹ IEEE Std 100 has been withdrawn; however, copies can be obtained from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹⁰ The numbers in brackets correspond to those of the bibliography in Annex A.

¹¹ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

average rectified value: The average value of a periodic time signal $y(t)$ is defined as

$$Y_{\text{ave}} = \frac{1}{T} \int_a^{a+T} y(t) dt, \quad (1)$$

where

T is the period
 a is any instant of time

Since all harmonics are sinusoids, the average value of a nonsinusoidal periodic time signal is equal to its dc value

$$Y_{\text{ave}} = Y_{\text{dc}}. \quad (2)$$

By contrast the average *rectified* value is defined as

$$Y_{\text{arv}} = \frac{1}{T} \int_a^{a+T} |y(t)| dt, \quad (3)$$

where

T is the period
 a is any instant of time

calibration: An experimental process by which the relation between the input to a measuring system and its output (the result) is established. Typically, a known quantity is used as a reference for comparison. The calibration process allows for adjustments to be made to the system being calibrated, or “correction” data to be obtained.

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.

crest factor: The crest factor (cf) of a periodic time signal $y(t)$ is the ratio of the peak value to the rms value

$$\text{cf} = \frac{Y_{\text{p}}}{Y_{\text{rms}}}. \quad (4)$$

direct: Direct measurements are those that are based on directly observable quantities. In the electric power system, the only directly observable electrical quantities are the voltage and the current. *Contrast:* **indirect.**

discrimination threshold: The largest change in a value that causes no detectable change in the corresponding indication. It may depend on such things as friction, noise, and the way that the change is effected.

error: Broadly, the difference between two instrument readings, both of which may be considered “known.” (For example, during an instrument calibration, the value given by the instrument being tested is certainly known, and the value of the reference quantity is treated as if it were a “true value” that is known.) This use contrasts with “uncertainty,” the difference between two quantities, one of which cannot be considered known. Any measurement associated with an unknown quantity therefore gives a result that has some uncertainty.

NOTE 1—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.

The accuracy of an 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; 1 ppm = 0.000 1%).

NOTE 2—This guide recognizes that error is an idealized concept and errors cannot be known exactly (GUM [B45]).

form factor: The form factor (ff) of a periodic time signal $y(t)$ is the ratio of the rms value to the average rectified value

$$\text{ff} = \frac{Y_{\text{rms}}}{Y_{\text{av}}} . \quad (5)$$

four-terminal impedance measurements: A measurement in which two wires are used to deliver current to the unknown impedance and two different wires are used to sense the voltage drop across the impedance.

frequency: Frequency is a parameter in the mathematical representation of a periodic function.

If the periodic function can be represented as a sinusoid, such as $v(t) = V \cos(\omega t + \phi)$, the angular frequency in [rad/s] is given by $\omega = 2\pi f$ where f is the frequency in cycle/s. The frequency can be thought of as the rate of change of the phase. The phase is the entire argument of the cosine, that is, it is $(\omega t + \phi)$ and not ϕ . (The use by some power engineers of the name “phase” for the term ϕ is misleading.)

If the periodic function is more complicated than the sinusoid, it can be expressed as a series of harmonics, and while the harmonics have different frequencies, they are all multiples of one ω , known as the *fundamental frequency*.

NOTE—The term applies only to periodic functions, and the parameters of such functions are stationary over the range $-\infty < t < \infty$. That definition rules out anything in the real world, since real things have a finite start time. Nevertheless, the term is often loosely used in the power system as the name for the result of a measurement that is expected to be related to the rotation speed of generators. There is no standardized way to measure “frequency” for a nonperiodic function. Accordingly, caution should be used in interpreting the results of “frequency” measurements.

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.

indirect: Indirect measurements combine the results of direct measurements to produce a new value.
Contrast: **direct.**

influence quantity or influence factor: A quantity or factor (other than the measured quantity) that can cause unwanted variation in the output of a transducer and the result of a measurement.

input impedance: The shunt resistance and reactance as measured at the input terminals.

input span: The arithmetic difference between the upper and lower values of the input range.

limiting value of the output current (voltage): The upper limit of output current (voltage) which must not, by design, be exceeded under rated or specified overload conditions.

linearity: The linearity of a measurement system or instrument is a description of the constancy of the sensitivity over the range of operation of the measurement system. That is 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.

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. This is caused by changes in analog components resulting in digital error.

maximum permissible values of input current and voltage: Values of input current and voltage (over voltage/overcurrent rating) assigned by the manufacturer as those which the device will withstand temporarily as the device limiting value.

measurand: A generic term for whatever is being measured. Voltage, current, reactive power, and so forth can each be treated as a measurand.

measurement: An experimental process to obtain a value that can reasonably be attributed to a quantity being measured. *See also:* **direct; indirect.**

NOTE—The use of the word “measurement” to indicate the *result* of a measurement is deprecated.

measurement model: The mathematical relationship between the quantities involved in a measurement. This is known as a *representational measurement*. The model is a definition of the quantity being measured.

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

operational: A class of measurement in which the measurement procedure is specified, rather than the quantity being measured. An operational measurement is not based on a measurement model. Also called a “pragmatic” measurement.

output span: The algebraic difference between the upper and lower values of the output range. (In *International vocabulary of metrology (VIM)*, JCGM 200:2008 [B46], this is referred to as the “nominal interval.”) The set of quantity values, bounded by rounded or approximate extreme indications, obtainable with a particular setting of the controls of a measuring instrument or measuring system and used to designate that setting.

NOTE—See VIM [B46].

peak value: The peak value

$$Y_p = \max |y(t)| \quad (6)$$

is the largest absolute value of $y(t)$.

power: This term is formally defined in IEEE Std 1459. *See also:* **apparent power; reactive power.**

NOTE—See IEEE Std 1459™ [B33].

range: The absolute value of the difference between the extreme quantity values of a nominal indication interval.

NOTE—See VIM [B46].

rated values of input current and voltage: Values of input current and voltage assigned by the manufacturer as those which the device will withstand indefinitely without damage.

reactive power: This term is formally defined in IEEE Std 1459. *See also:* **apparent power; power.**

NOTE—See IEEE Std 1459™ [B33].

rms value: The root-mean-square (rms) value of a periodic time signal $y(t)$ is defined as

$$Y_{\text{rms}} = \sqrt{\frac{1}{T} \int_a^{a+T} y^2(t) dt}, \quad (7)$$

where

T is the period
 a is any instant of time

The rms value of a periodic time signal $y(t)$ can also be expressed as

$$Y_{\text{rms}} = \sqrt{\sum_{k=1}^n Y_k^2}, \quad (8)$$

where Y_k denotes the rms value of the k -th harmonic that is contained in the Fourier series of $y(t)$.

rms responding: A measurement in which the result is equal to the rms of the input signal, for all input waveforms having components within the specified frequency range and crest factor limit.

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.

two-terminal impedance measurement: A measurement in which the same current flows through the unknown impedance and the test leads. Note that by the use of this technique, the lead impedance is measured along with the unknown.

3.3 Measurement system

Figure 1 shows a generic measurement system, measuring the electrical conditions on a power line. There is a current transformer and a potential transformer that serve to isolate the rest of the system from the high power levels of the power line. These deliver signals that bear a known ratio to the levels on the system.

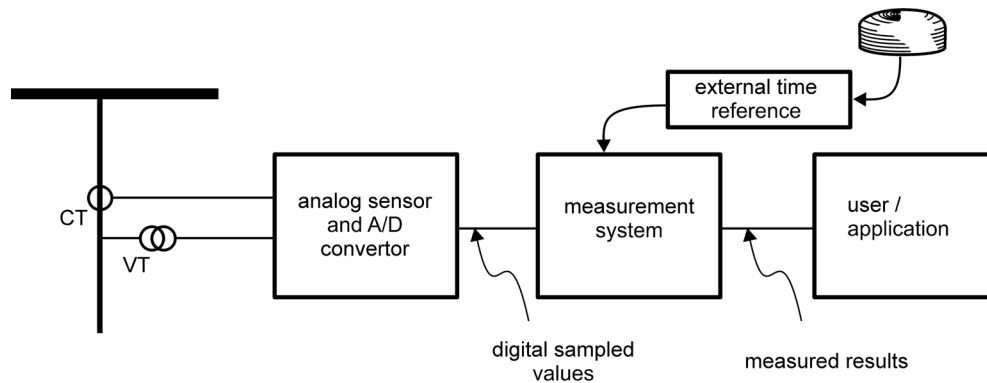


Figure 1—Generic measurement system

The measurement system converts the input current and voltage to a digital representation, which is passed to the measurement system. The analog-to-digital (A/D) conversion and the measurement system may be located at the same place as the current transformer (CT) or voltage transformer (VT), or it may be in a control house. The output of the measurement system is the *result* of the measurement, and it is passed to the user, which may be an individual or a software application.

Nonelectrical quantities can be measured if the interface to the power system includes the appropriate sensor. For example, a thermocouple could be used to measure line temperature, and a strain gauge or a Bourdon tube could be used to measure the pressure in a tank of sulfur hexafluoride (SF₆).

It is increasingly likely that an external timing signal will be available to the measuring system so that the results of measurements can be delivered time-stamped to Universal Time Coordinated (UTC) time.

burden: The load imposed on a system by the equipment connected to it.

electrical measuring transducer: A device, used in measurement, that provides an output quantity having a specified relation to the input quantity.

NOTE—See VIM [B46].

fiducial (reference) value: A value to which reference is made in order to specify the accuracy of a transducer. The fiducial value is the span except for transducers having a symmetrical reversible input and output. In this case, the fiducial value is half the span.

nominal: An arbitrary reference value selected to establish equipment ratings.

nominal input of an instrument or transducer: The value of an input quantity expected by the instrument/transducer designer or specified by the manufacturer.

nominal input of VT or CT: The value of the input quantity for which an instrument or transducer is expected to operate satisfactorily.

nominal value: Rounded or approximate value of a characterizing quantity of a measuring instrument or measuring system that provides guidance for its appropriate use.

NOTE—See VIM [B46].

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.

reference conditions: A set of values assigned to the influence quantities used for determining the intrinsic accuracy of the transducer.

response time: The time from the instant of application of an input step until the output reaches and remains within a specified percentage of the final value.

transducer output current (voltage): The current (voltage) produced by the transducer which is a defined function of the measured quantity.

transducer output power: The power available at the transducer output terminals.

3.4 Instrument transformer ratio, phase angle, and correction

The terms in this standard are consistent with the formally defined terms in IEEE Std C57.13™, IEEE Standard Requirements for Instrument Transformers [B41].

marked ratio: IEEE Std C57.12.80™-2010, IEEE Standard Terminology for Power and Distribution Transformers defines it as the ratio of the rated primary value to the rated secondary value as stated on the nameplate.

NOTE—See [B39]

nominal ratio: Industry practice is to refer to the nominal ratio as the marked ratio scaled to unity; for example, a marked ratio of 1000:5 would be referred to as a nominal ratio of 200:1. Please be aware that this gives no indication of the rating and it is preferable to use marked ratio.

phase angle: IEEE Std C57.12.80-2010, IEEE Standard Terminology for Power and Distribution Transformers defines it as the phase displacement, in minutes, between the primary and secondary values.

NOTE—See [B39].

ratio correction: IEEE Std C57.12.80-2010, IEEE Standard Terminology for Power and Distribution Transformers defines it as the difference between the ratio correction factor and unity, expressed in percent $[(RCF - 1) \times 100]$.

NOTE 1—See [B39].

NOTE 2—The percent ratio correction is positive if the ratio correction factor is greater than unity. If the percent ratio correction is positive, the measured secondary current or voltage will be less than the primary value divided by the marked ratio.

ratio correction factor (RCF): IEEE Std C57.12.80-2010, IEEE Standard Terminology for Power and Distribution Transformers defines it as the ratio of the true ratio to the marked ratio. The primary current or voltage is equal to the secondary current or voltage multiplied by the marked ratio times the ratio correction factor.

NOTE—See [B39].

3.5 International System of Units (SI)

For the authoritative view for the International System of Units (SI) see the International Bureau of Weights and Measures (BIPM) website [B14]. 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 SI, which is a modern version of the MKSA (meter, kilogram, second, ampere) system. For further details see IEEE/ASTM SI 10™, American National Standard for Metric Practice [B24].

The units of the electrical quantities are shown in Table 1.

Table 1—International System of Units (SI) electrical quantities

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

3.6 Acronyms and abbreviations

CCVT	coupling capacitor voltage transformers
CT	current transformer
EHV	extra-high voltage
GPS	Global Positioning System
OCVD	optical capacitive voltage divider
OCVT	optical capacitive voltage transformer
PLL	phase locked loop
PMU	phasor measurement unit
PT	potential transformer

NOTE—This is more commonly referred to in this standard as a voltage transformer (VT).

ROCOF	rate of change of frequency
TN-C-S	This is a type of earthing arrangement. The T stands for Terra which is Latin for Earth. The N is the Neutral. The C stands for Combined, and the S stands for Separate. A TN-C-S system has the neutral and earth combined in the supply cable(s), and separate within an installation.
TN-S	This is a type of earthing arrangement where the protective ground conductor is separate from the neutral.

TT	This is a type of earthing arrangement where the system is unearthed.
UTC	Universal Time Coordinated (also Coordinated Universal Time)
VIM	<i>International vocabulary of metrology</i>
VT	voltage transformer

4. Safety

Care should be taken in any measurement to avoid coming into contact with dangerous and possibly lethal voltages and also to help avoid damage to the installation. Dangerous voltages include many commonly used voltages such as 400 V or 480 V as well as higher voltages. 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. Current transformers (CT) may be installed with shorting terminal blocks to provide a means for shorting of CT leads when reconfiguring the instrumentation connected to the CT. Please refer to 6.4.11. Likewise, a short circuit on the secondary winding of a voltage transformer **cannot** be tolerated.

Voltage instrument transformers may be supplied with primary side fuses, secondary side fuses, or both, depending on specific application requirements.

Primary side fuses may provide protection to the instrument transformer and, more importantly, provide protection to the surrounding equipment and personnel in the event of instrument transformer damage. Primary side fuses can operate to separate the unit from the system voltage when the transformer's primary side current reaches excessive levels. These current levels may be due to a secondary side short circuit or in the case of an overvoltage high enough to force the magnetic core into saturation. Primary side fuses provide significant protection to personnel and other equipment from an instrument transformer with a damaged primary winding. If a primary winding suffers an insulation failure, a primary side fuse can operate to remove the failed unit from the circuit before damage becomes so severe that it causes the unit to rupture, which could potentially result in an arc flash event.

Secondary side fuses remove the load from the instrument transformer in the case of an excessive current draw on the secondary of the transformer. When devices connected to the secondary of the instrument transformer fail or wiring shorts to ground occur on the secondary side, the load current will rise dramatically and secondary side fuses can operate to prevent damage to the instrument transformer. The fuse removes the load from the transformer before it is damaged, reducing the risk of endangering other equipment or personnel.

The requirements for voltage tests, insulation tests, and other safety requirements are listed in IEEE Std C57.13™ [B41]. Please refer to manufacturer's documentation for additional requirements (see IEEE Std C57.13 [B41]).

5. Ground and magnetic coupling

5.1 Grounding

There is a general guideline in electrical systems that no metal should be allowed to be “floating.” That means its potential must be established by connecting it to some part of the system whose potential is well established (a process called *bonding*). For safety reasons, ground potential is commonly used. Bonding to ground is called *grounding*.

Apart from safety, ground connections influence the level of induced noise pick-up on measurement systems, and the amount of common-mode signal at the input of a system. Electrical measuring instruments and systems may be fundamentally divided into two categories:

- a) Grounded measurement systems
- b) Ungrounded measurement systems

For the purposes of this discussion, it should be clarified that *grounded measurement systems* are those in which the measuring circuit is electrically (galvanically) connected to the signal source and incorporates a reference to instrument chassis ground, either through direct connection or through an impedance of less than 1 M Ω . For safety reasons, instrument chassis ground is normally connected to the ac utility ground, often informally referred to as “safety ground,” or formally referred to as “protective earth.” Using this broad definition, the majority of measuring instruments and systems are considered to be grounded systems.

Ungrounded measurement systems are those in which the measuring circuit does not incorporate a direct connection to instrument chassis ground. In such systems, the impedance measured from any point in the measuring circuit to the chassis of the instrument is typically > 1 M Ω , up to the maximum input frequency of the measurement system.

Measurement systems that are fully optically isolated from the signal source are not addressed in this guide, as the measurement circuit is not affected by ground potential differences appearing between the signal source and the measurement instrument.

5.1.1 Grounded systems

There are a number of types of grounded systems, including those on the distribution network such as TT, TN-C-S, or TN-S—see BS 7671 [B13] and National Electrical Code® (NEC®) (NFPA 70®, Edition) [B57]—which relate to how and where grounding is provided at a customer site.

The grounding requirements of a measurement system may be shown on a single line diagram. Typical symbols used for showing grounding are shown in Figure 2 adapted from IEC 60417 [B42].

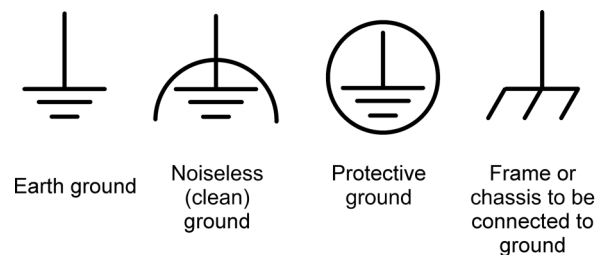


Figure 2—Grounding symbols from IEC 60417 [B42]

CAUTION

Understand in advance how and where the system you are testing is grounded.

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 reduce hazardous potentials 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 (to limit current to < 30 mA) 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. 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 NEC [B57].

Measuring circuits are subjected to working voltages and transient stresses from the circuit to which they are connected during measurement or test. When the measuring circuit is used to measure electrical signals, the transient stresses must be considered by the user to see that they do not exceed the capabilities of the measuring equipment. Measurement categories are defined by CE and UL safety standard IEC 61010-1 [B23] and are used to indicate the ability of an instrument to withstand voltage spikes without posing a shock hazard to the operator. A measurement device should only be used at or below its rated measurement category and voltage. Regular impulse testing to check insulation resistances are required on all such devices.

5.1.2 Ungrounded systems

Ungrounded systems, where the impedance measured from any point in the measuring circuit to the chassis of the instrument is typically $> 1\text{ M}\Omega$, are not common but they do exist. Examples include some railway signalling power supplies (UK), some ac power systems, and the dc bus of transformerless grid-connected inverters, for example, as part of an energy storage system. Although they are classified as ungrounded (in the UK this is called an *IT system*), it is fairly common for these to be high impedance grounded through capacitors and/or resistors or earth leakage monitoring devices.

In circuits of these various types, particular care is needed when using an oscilloscope because standard voltage probes are grounded at the chassis. Where multiple measurements are needed on a circuit (e.g., looking at voltages across different batteries connected in series) or where a ground signal is not part of the measurement, it is recommended to use differential measurement techniques, for example, differential voltage probes which have inbuilt isolation and are typically separately powered for isolation purposes.

5.1.3 Issues with grounding

Measurement errors may arise in systems where there are multiple low impedance ground paths through different pieces of equipment that are connected electrically in parallel with the power ground conductor. When two points in a measuring system are connected to the ground, a parallel ground path or ground loop is formed. This can lead both to measurement errors (such as noise, hum, or inference), instrument damage, and even personal shocks. During transient conditions especially (insulation flashovers), large potential

differences often appear between components, which can cause destructively large current flows over the measurement system ground paths.

Parallel ground paths should be considered in the layout of the measurement circuit as they can cause erroneous measurement results. Wiring practices should be employed to protect against parallel ground paths and include ensuring that all vulnerable signal circuits are referenced to one point as a ground. An example of a parallel ground path formed between a grounded transducer and a measuring instrument grounded at a different location is shown in Figure 3. The impedance Z_s represents the transducer output impedance, Z_1 and Z_2 are the impedances of the conductors that connect the two devices, and Z_{in} is the instrument input 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 meter, an oscilloscope, signal conditioner, or any type of data acquisition device.

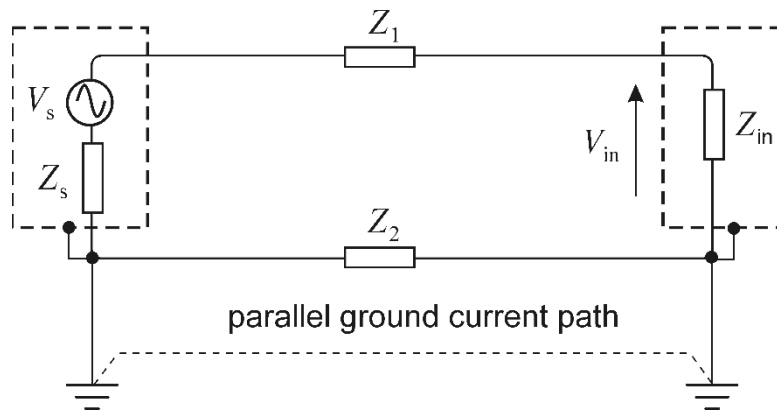


Figure 3—Parallel ground current path example

A ground differential between the transmitting and receiving locations can result in a common-mode voltage as shown in Figure 4. A common-mode voltage is the voltage between a common point and both conductors connected to the input terminals of the instrument. This ground differential 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 three-phase system and by unbalanced line-to-ground capacitive currents.

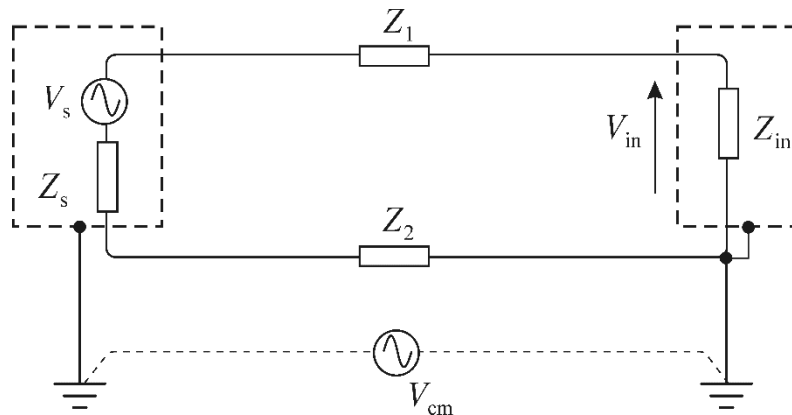


Figure 4—Parallel ground current path example showing common-mode voltage

If the transducer output voltage $V_s = 0$, then the voltage across Z_{in} becomes

$$V = V_{cm} \left[\frac{Z_s + Z_1}{Z_s + Z_1 + Z_{in}} - 1 \right]. \quad (9)$$

It is normal for $Z_1 \ll Z_s$, $Z_2 \ll Z_{in}$, and $Z_s \ll Z_{in}$, resulting in $V = -V_{cm}$.

The common-mode voltage is a noise and in the presence of a signal introduces currents into the measuring circuit and an erroneous voltage, V , that is added to the output voltage, V_s of the transducer that is being measured. This has previously been referred to as a *series voltage* and can also be thought of as an *offset voltage* due to bias currents in the two connecting conductors.

Sometimes “ground loops” or “parallel ground current paths” only exist at higher frequencies, due to capacitive coupling. In this case, a path may measure “open circuit” using a dc ohmmeter, but at higher frequencies, there is sufficient coupling to cause significant steady-state measurement errors and/or instrument damage during transient conditions. This is covered in 5.2.2.

5.1.4 Solving grounding problems

To help avoid the issue of parallel ground current paths, the system could be grounded only at one point, for example, a) by connecting the ground terminals of the instrument and the transducer to one physical ground point or b) by grounding the entire instrument and the enclosure of the transducer as shown in Figure 5, 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. It is necessary to eliminate parallel paths. Grounding secondary circuits in only one place contributes to greater safety. Consistent policy to achieve safety and eliminate ground points may be to adopt grounding only at the sensor. Spark gaps or protective clamping devices can be used to reduce impacts caused by the loss of the single ground.

In any grounding modification, the safety aspects should not be compromised and possible touch potentials due to this configuration should be considered.

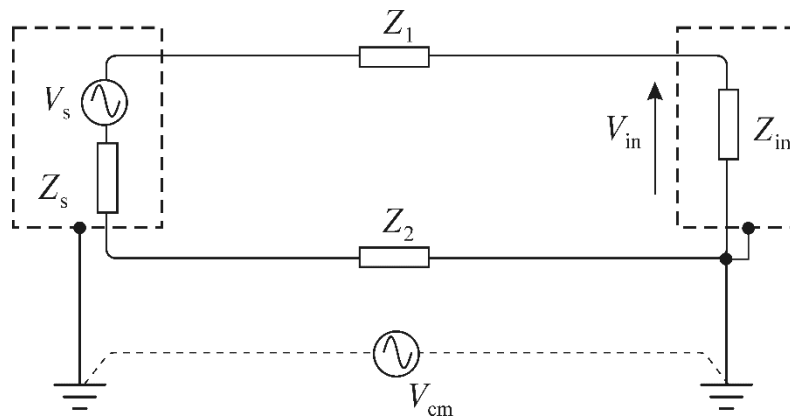


Figure 5— Alternative signal connection

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 dependent on transducer signal type (e.g., ac versus dc) and are shown in Figure 6. These methods include isolation transformers, filtering methods such as bifilar or coaxial inductors (chokes), differential measurement techniques, and isolating devices such as wireless or opto-couplers.

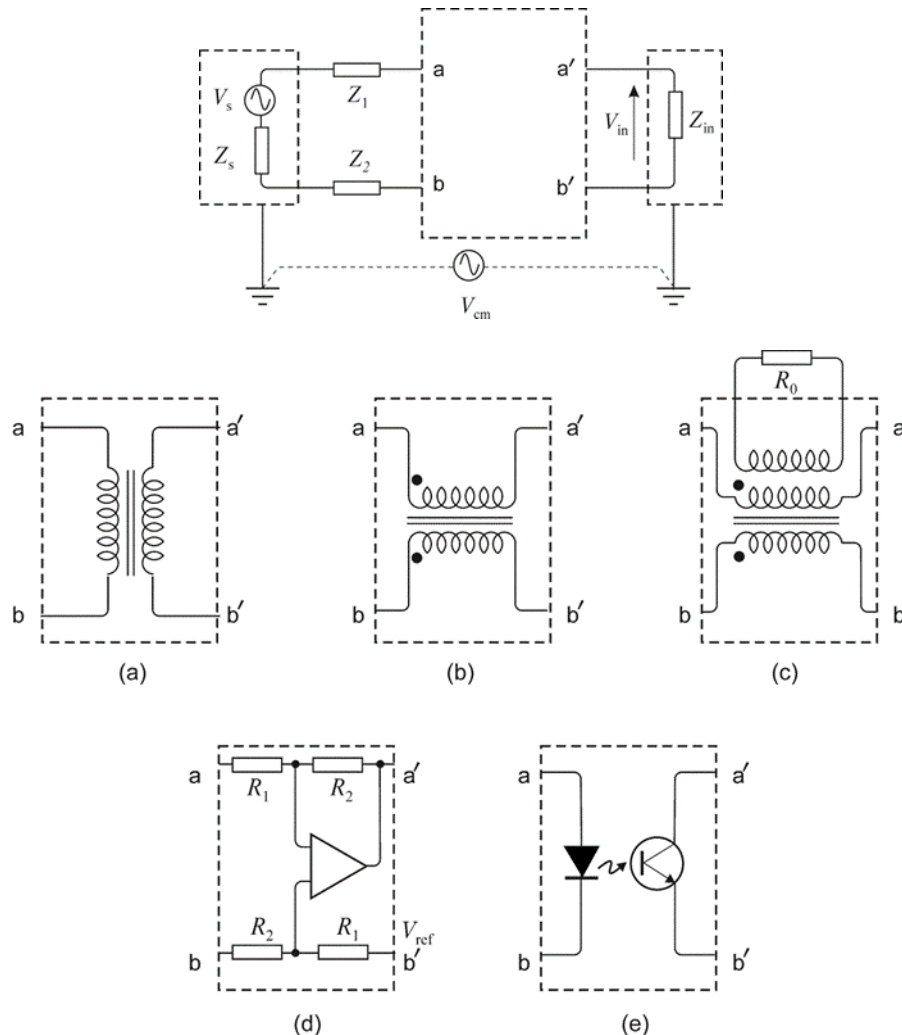


Figure 6—Methods of eliminating ground loops and reducing common-mode effects

If the transformer shown in Figure 6(a) is used, the common-mode voltage is not passed by the transformer except via some stray capacitance between the input and output windings of the transformer. A grounded shield between the winding may be a solution to such coupling. A grounded center-tap on the output side of the transformer may also be useful.

Method Figure 6(b) shows a choke inserted in series with the signal path. For the common-mode current passing through the choke, the fields add, and essentially insert, an impedance in series. The method shown in Figure 6(c) uses the flux to induce a common-mode voltage in a tertiary winding. The winding can effectively place the appropriate terminating resistance R_0 across the connection for the common mode. A trifilar winding is effective in this arrangement.

In Figure 6(d), an operational amplifier is shown. The performance of this system is dependent on the Common Mode Rejection Ratio (CMRR) of the amplifier and the matching of the resistors. If noise is the only common-mode signal, it is reduced by the product of the CMRR and the loop gain. An amplifier with a CMRR of over 86 dB (about 20 000) is not difficult to find, and for a gain of 100 ($R_2/R_1 = 100$) the common-mode signal is reduced to 46 dB, a factor of 200. However, the circuit suffers problems of matching the resistors. If the intent of the circuit is to remove a common-mode direct-voltage at the input, it does not work well, even for reasonably well-matched resistors. Fortunately, there are very good amplifiers available in which the resistors are laser-trimmed.

The method shown in Figure 6(e) should be regarded as just a reminder that optical isolation is extremely effective at removing common-mode noise. It is not intended to suggest that a simple circuit such as this should be implemented in practice.

5.1.4.1 Parallel grounded systems

There are many examples of parallel ground paths in electricity delivery networks, including the North American four-wire (3p+n) medium-voltage and the European four-wire (3p+n) low-voltage systems, where multiple grounding of the neutral wire is installed for safety reasons. In such systems, it is difficult to measure the resistance of a part of the system without intentionally breaking some connections.

An unintentional break of the neutral in the system can have curious effects because a portion of the system has an unexpectedly high conducting path for unbalanced current. One effect of this is that when a single-phase load is increased (resistance reduced, such as turning on a heating element), the voltages (to neutral) in the other phases will rise because the neutral conductor voltage is displaced towards the heavily loaded phase. Similar problems can occur in measurement systems and are sometimes difficult to identify or locate.

5.2 Electric and magnetic coupling

5.2.1 Magnetic coupling

Magnetic coupling is illustrated in Figure 7(a). An error voltage 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

$$V_{sm} = 2\pi f \Phi \quad (10)$$

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 Figure 7(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} .

WARNING

V_{sm} can introduce errors in high impedance voltmeters in portable instruments. Keeping the leads close together reduces this issue.

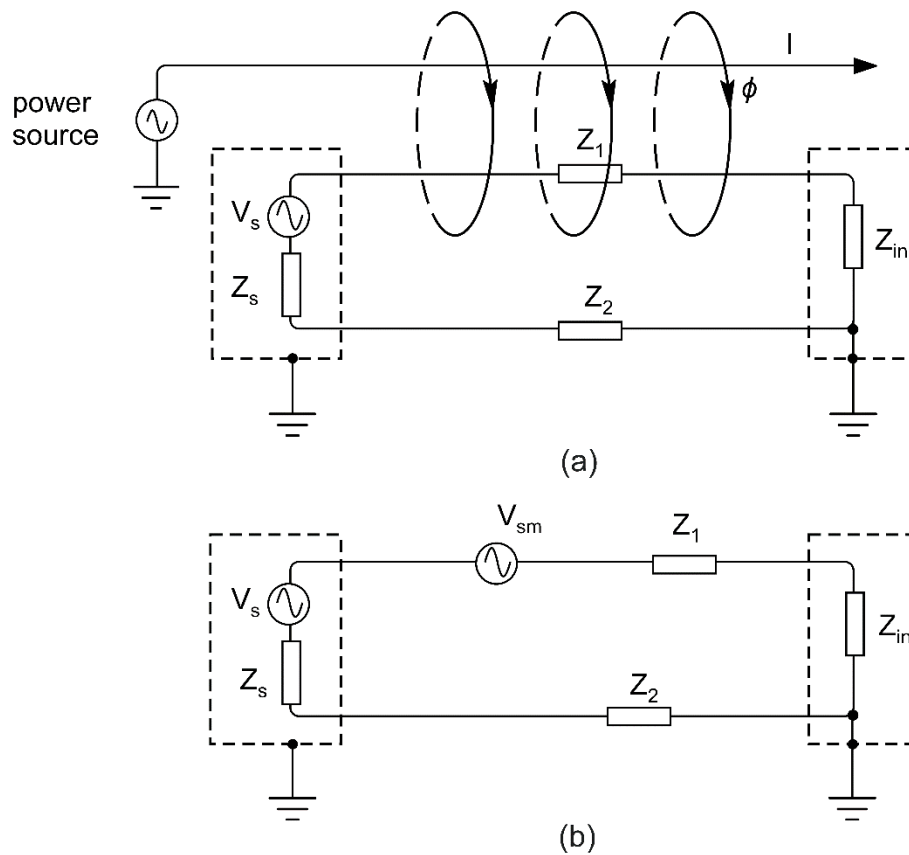


Figure 7—(a) Magnetic coupling and (b) equivalent circuit showing series-mode voltage

5.2.2 Capacitive coupling

Capacitive or electrostatic coupling is illustrated in Figure 8(a). The capacitive current, I_{c1} and I_{c2} , from the power conductor, could introduce an erroneous “series-mode” voltage (V_{sm}). This voltage can be calculated from the circuit of Figure 8(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_s is much smaller than Z_{in} and thus nearly all of I_{c1} passes through Z_s . The resultant voltage is given by

$$V_{sm} = 2\pi V C_1 Z_s \quad (11)$$

The equivalent circuit showing V_{sm} is given in Figure 8(b).

WARNING

V_{sm} can introduce errors in high impedance voltmeters in portable instruments. Keeping the leads close together reduces this issue.

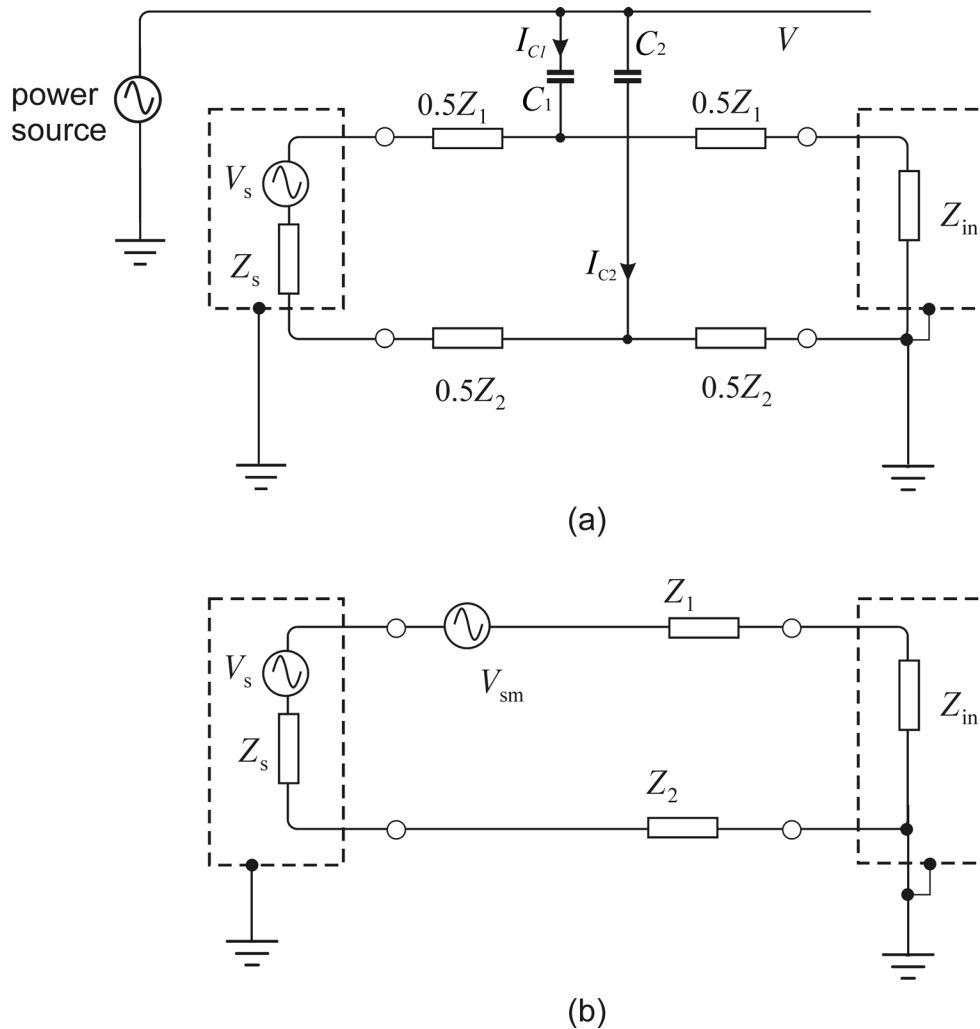


Figure 8—(a) Capacitive coupling; (b) equivalent coupling; sm stands for *series mode*

5.2.3 Coaxial and twisted leads

The problems of magnetic and capacitive couplings as illustrated in Figure 7 and Figure 8 can be reduced by the use of a coaxial connecting cable. Such a cable has no net loop to capture extraneous magnetic flux such as ϕ in Figure 9. The outer conductor of a coaxial cable is connected to the ground. It shields electrostatically the inner conductor and, thus, eliminates I_{c1} in Figure 8.

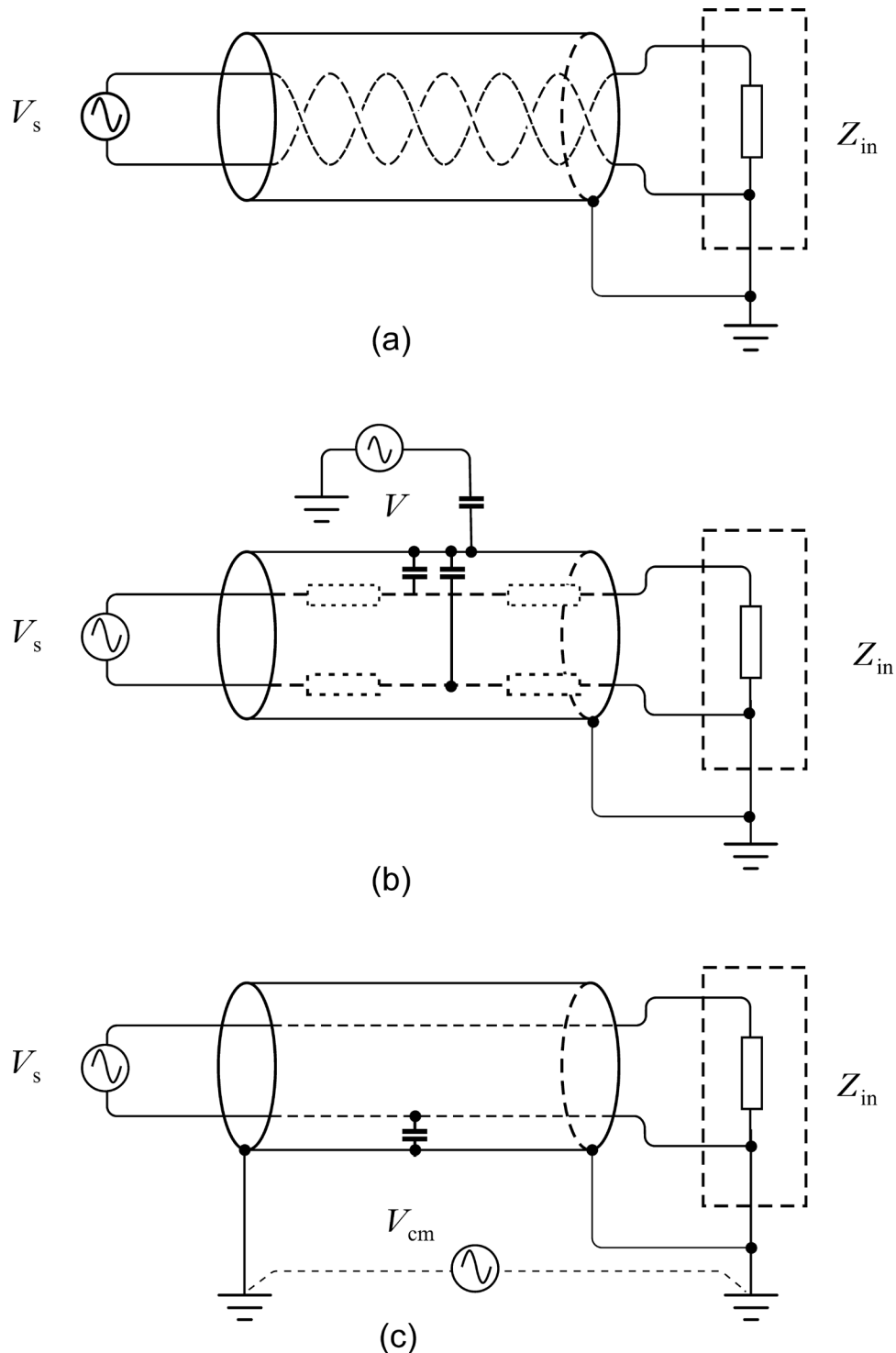


Figure 9—(a) Shielding of conductors; (b) imperfect shielding caused by finite lead and shield impedances; (c) incorrect grounding of shield

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.

5.2.4 Shielding techniques

Cables discussed in 5.2.3 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.

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 should 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 should 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):

$$\frac{B_1}{B_0} = \frac{2r}{d\mu} \quad (12)$$

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 Figure 9.

In Figure 9(a), a shield, for example, 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 Figure 9(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 9(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.

Sometimes a sensitive measuring system is enclosed in a shielded container. In the case of outdoor measurements, this container may serve primarily to give the measuring system some mechanical protection.

It has been observed in some situations that if the door or lid of the container is opened, the measuring system is susceptible to interference from RF energy from a cell phone or a walkie-talkie. This possibility should be considered when such equipment is being serviced.

5.2.5 Guarding and driven shields

It is assumed in this standard that the measuring instrument is digital. The world being measured is, however, analog, and at some place in the signal path an analog signal must be applied to an analog transducer or an A/D converter. On occasion, the analog signal path must be treated carefully so as to preserve the quality of the signal. A signal path may be susceptible to interference, and a long screened cable (used to reduce such interference effects) may act like a low-pass filter because of its capacitance. Such considerations may apply in the environment of high-voltage equipment and particularly in the case that the signal has a high source impedance.

If the instrument design is based on the assumption that such conditions might apply (perhaps the application normally demands that the signal has to be transmitted over a large distance), the designer may have incorporated a solution into the equipment. Some instrumentation is equipped with a terminal labeled “Guard.” It is the purpose of 5.2.5 this subclause to explain what guarding is, assuming that the instrument is suitably equipped. If the need arises, it may be possible for the user to add some electronics to accomplish the goal in the event the equipment is not already so equipped.

Consider the case that a sensor is generating a signal and presents a high source impedance. The connection to a resistive voltage divider may be of this nature, for example, because the source resistance is effectively the value of two high-value resistors in parallel. When the connection is made to the remotely located measuring instrument, a shielded cable is used to reduce the impact of noise in the environment. Figure 10 shows an example. Though it is customary to consider the shield to be grounded, no “ground” connection is shown in this figure. The matter of grounding is considered separately in 5.1.1.

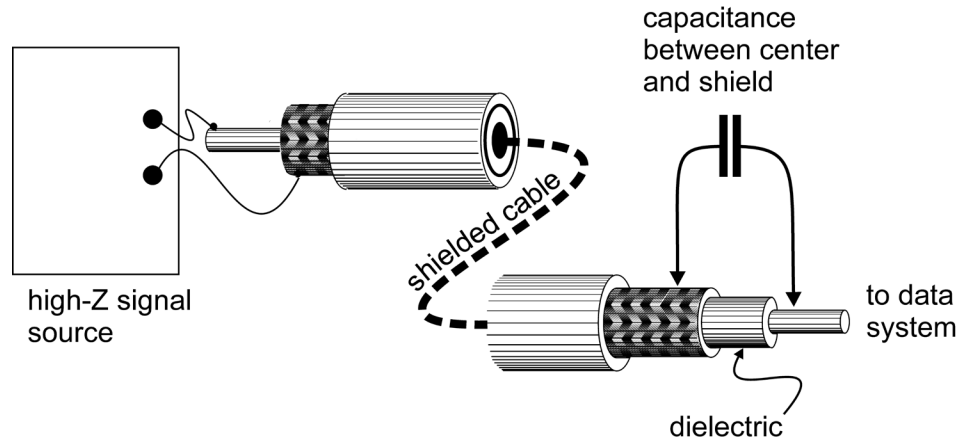


Figure 10—Remote connection to a high-impedance source

Suppose the source resistance is 100 MΩ, and the cable has a capacitance of 100 pF/m. This is a representative value for coaxial cables, and was chosen for this example simply because the number is easily remembered. A length of five meters of such a cable adds a shunt capacitance of 500 pF.

The RC time constant is thus $100 \times 10^6 \times 500 \times 10^{-12} = 5.10^{-2} \text{ s} = 50 \text{ ms}$. That would give a 3-dB frequency response of (0.35/50) kHz or 7 Hz. The amplitude and phase-shift defects at power frequency would be unacceptable for most applications.

A solution can be found by reducing the *effective* capacitance of the cable, an idea that goes back to World War II (*IEEE Spectrum*, 1990 [B28]). In this method, a copy of the signal is applied to the shield of the cable,

so it tracks the voltage on the center of the coaxial cable. Although the capacitance still exists, the voltage across it is greatly reduced. An amplifier with a high input impedance is used to generate the copy. If the amplifier driving the shield is a perfect unity-gain amplifier, the voltage across the cable is zero. The capacitance of the cable does not take any charge from the center conductor.

Interference is still “intercepted” by the cable shield, so the output impedance is required to be low, especially at the anticipated frequency of interference. The arrangement is shown in Figure 11.

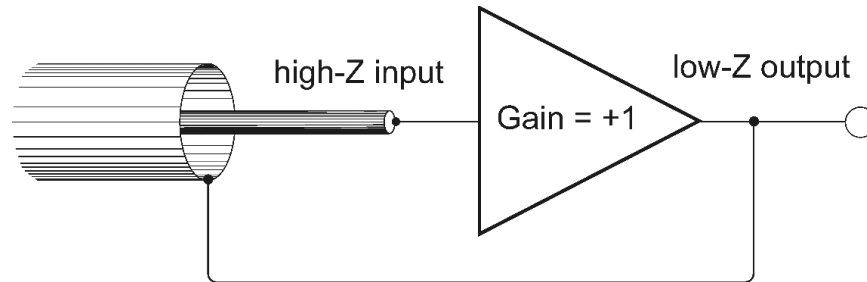


Figure 11—Driving the shield of a coaxial cable

There are two ways to apply this technique. If the cable has one signal-carrying conductor, the shield may be driven by an amplifier that produces, at low impedance, a replica of the signal, as discussed. The technique can work up to moderately high frequencies. This approach is called *driven shielding*. If the cable contains two conductors (presumably with a differential signal), the shield can be driven by the common-mode voltage. Often the common-mode voltage changes only slowly compared to the signal. This technique is called *guarding*. The difference in nomenclature is more to do with the frequency response than the single-ended or differential nature of the signals.¹²

An example of how the common-mode signal can be derived is shown in Figure 12.

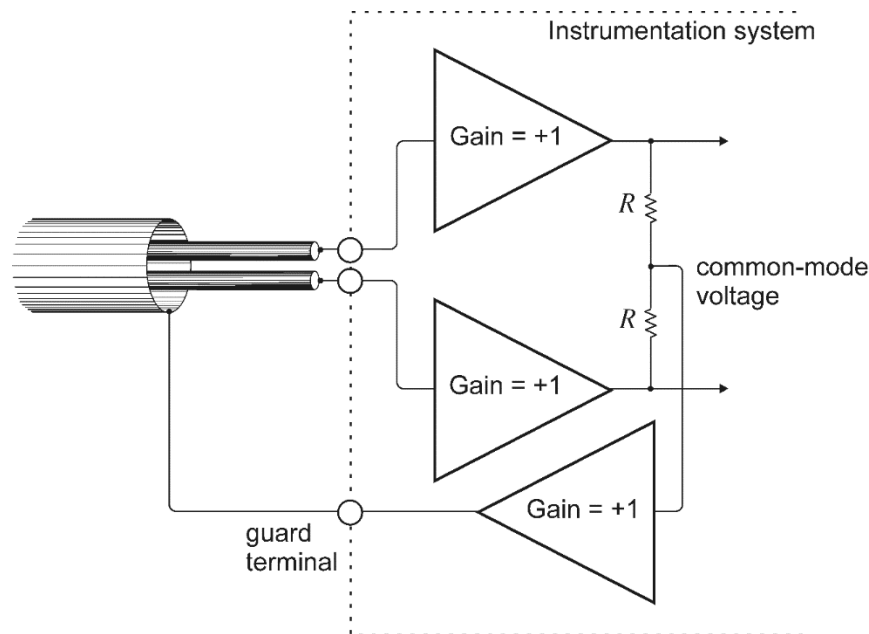


Figure 12—Common-mode guarding

¹² Guarding is quite common inside high-impedance measuring systems and has been applied to single- and multilayer circuit boards and to switching arrangements.

In Figure 12, the two resistors labeled “R” are equal in value, but their actual value is not critical. Their midpoint establishes, by definition, the common-mode voltage of the input signal. (If the source lacks a way for common-mode current to return to ground, it is necessary to add resistors from each input terminal to ground. These resistors will usually then determine the value of system input impedance.)

The two amplifiers shown may be presumed to represent the input stages of an *instrumentation amplifier*. The two outputs would normally be passed to a differential amplifier, resulting in a single-ended output. Those details are not relevant here, but it may be noted that laser-trimmed IC instrumentation amplifiers (the trimming is used to improve CMRR in the differential stage) are inexpensively available. A system such as the one outlined here could be added externally to an instrumentation system lacking the guard feature.

For more detailed information on grounding, shielding, and noise reduction, refer to *IEEE Spectrum*, 1990 [B28], Awan et al. [B8], Morrison [B56], Ott [B59], IEEE Std 4™-2013 [B29], and *Low Level Measurements Handbook* [B51].

6. Voltage and current measurements

6.1 Introduction

6.1.1 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.

Modern technology has provided 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), portable bench-top meters, oscilloscopes, and power analyzers. For measurements considered in this guide, the latter four 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.

Oscilloscopes are instruments that graphically display electrical signals and show how these signals change with time. The oscilloscope has three main stages; the first stage attenuates or amplifies the signal voltage. Then the signal reaches the acquisition block, where the A/D converter is used to sample the signal voltage and convert it in a digital format value. A sample clock drives the A/D system and gives each voltage sample a precise time. The digital output is stored in memory. The trigger system detects a user-specified condition in the incoming signal stream. If this criterion is met, waveform data preceding or following the event may be displayed. Most oscilloscopes contain mathematical functions which allow the display of attributes such as rms and average. Many oscilloscopes have high bandwidth and are digital so are able to export captured waveforms.

Oscilloscopes are used in conjunction with voltage and current probes to provide the main signal voltage. It is necessary to degauss and auto zero current probes prior to use. It is also important to be aware of earthing issues when using voltage probes (see 5.1). Single-ended voltage probes are earthed through the connector to the mains supply of the scope, and this may place an inadvertent earth on the circuit being measured. Adequate safety precautions are needed. There are several ways of dealing with this issue. For example, isolated differential voltage probes could be used.

Power analyzers are used to measure the flow of energy in either ac or dc systems. A power analyzer should measure voltage and current as part of this process. The power analyzer aims to digitally detect the frequency to provide rms values based on whole numbers of cycles.

Power analyzers may provide more than just voltage, current, power, and energy measurements. They may also detect values of mechanical energy such as torque and speed and undertake mathematical based analysis.

6.1.1.1 Analog instruments

Broadly speaking, analog instruments have little to offer compared to their digital versions. The evident superiority of digital measurements has meant that the earlier kind is not often in evidence.

However, the “legacy” instruments sometimes exhibit performance that has no counterpart in the digital world. It is seen when the quantity being measured is changing or is not a good match for the measurement model, such as when there is some kind of distortion on the signal.

Consider that a direct current is being measured. It makes no difference *when* the dc is measured, the result is always the same. That is true even when there is ripple on the signal; the digital instrument will smooth out the ripple, and the result will be accurate: the average value of the signal.

If it should be that the digital instrument is displaying the result rapidly, the human observer finds it hard to make sense of the flickering reading caused by the ripple and is inclined to solve the problem by using a longer averaging interval. The observer of the analog instrument does not have that option, but the movement of the pointer may give information of greater use to the observer.

Consider the cutaway view in Figure 13.

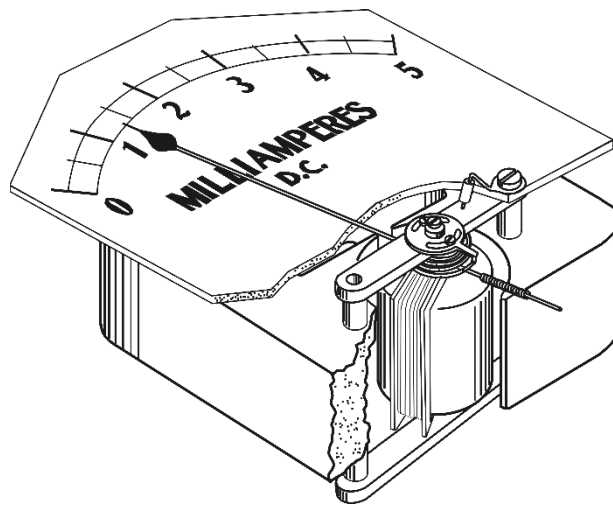


Figure 13—Cutaway view of moving-coil instrument

The measurement is made by noting the displacement of the pointer on a calibrated scale. Under steady-state conditions, the needle becomes stationary after a time that depends on the mass of the moving parts; in Figure 13, that means the pointer (and its counterweight) and the coil. Once the pointer is still, the deflection reflects a balance between the deflecting force of the current in the fixed magnetic field of the meter and the restoring force of the spring.

However, the pointer sometimes shows a noticeable vibration when there is ripple on the signal. Not all analog instruments display this feature: moving iron instruments often have greater inertia and do not vibrate.

There is a similar advantage if the quantity being measured is changing. The movement of the pointer can indicate values that are between the times that a digital instrument reports its values, and the change can be followed by the observer in a way that a digital instrument does not allow.

Sometimes it is handy to have an analog instrument. Their kind of additional information may become part of the statement of result of some future digital instrument, but it is not present at the time of writing of this standard.

6.1.2 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 almost any value encountered in the operation of power circuits.

6.1.2.1 Ammeter shunts

Shunts, either internal or external, are integral parts of all ammeters, regardless of current magnitude. Meters without external shunts or other scaling devices typically measure maximum currents from 1 A to 10 A. Above those values, external devices are used with the measuring instruments.

6.1.2.1.1 DC shunts

A shunt is constructed to have, as nearly as possible, a constant resistance under all conditions. The resistance metal has a low-temperature coefficient of resistance, and the temperature rise is kept low by improving heat dissipation with parallel strip construction. The resistance metal should have a low thermal emf against copper for two reasons: first, if one end of the shunt becomes hotter than the other because of poor contact at one current connection or to a poor connection in the cable or bus structure near that end of the shunt, a thermal emf will be produced in addition to the potential drop across the shunt; second, when current passes through the junction of two dissimilar metals which have a thermal emf with respect to each other, a Peltier effect results, that is, heat is absorbed or produced. Hence, one junction tends to become cool and the other to become hot and the resultant difference in temperature will produce an emf. Accuracies between 0.01% and 0.1% are available.

6.1.2.1.2 DC shunts for large currents

Large direct currents are measured in the same manner as small currents, that is, with millivoltmeters connected to shunts—the shunts being correspondingly larger in physical dimensions and lower in resistance. Certain precautions should be observed, however, when using large shunts. Shunts of several thousand amperes in capacity should be designed with long, multiple-leaf copper blocks to ensure that the current distribution will be uniform through the shunt and will be the same after installation as when it was calibrated. Every time a large shunt is connected to a multiple-leaf bus structure, the contact resistance distribution is changed, and if the junction is close to the resistance strips, the current will not be distributed uniformly among them.

In installing large capacity shunts in a bus structure they should preferably be placed in a horizontal bus run with the leaves mounted in a vertical plane, the shunts being so located in the bus structure as not to be immediately adjacent to right-angle turns in the bus. In addition, they should not be mounted in immediate proximity of devices that are likely to produce heat that would raise the temperature of the shunt unevenly and they should never be mounted vertically as the upper terminal would be heated by rising air currents. This latter practice would result in a thermal-gradient across the shunt. All shunt connection surfaces should be clean and the connections made tight.