

IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields From AC Power Lines

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IEEE Power Engineering Society**

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Abstract: Uniform procedures for the measurement of power frequency electric and magnetic fields from alternating current (ac) overhead power lines and for the calibration of the meters used in these measurements are established. The procedures apply to the measurement of electric and magnetic fields close to ground level. The procedures can also be tentatively applied (with limitations, as specified in the standard) to electric fields near an energized conductor or structure.

Keywords: ac power lines, electric field, magnetic field, measurement

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Introduction

(This introduction is not part of IEEE Std 644-1994, IEEE Standard Procedures for This Measurement of Power Frequency Electric and Magnetic Fields From AC Power Lines.)

This standard is a revision of IEEE Std 644-1987 (a revision of IEEE Std 644-1979), which establishes uniform procedures for measuring power frequency electric and magnetic fields in the vicinity of ac power lines. The following revisions have been made and are intended to improve the usefulness of the document:

- a) Text has been introduced that permits the measurement of the resultant magnetic field using three-axis (or single-axis) magnetic field meters. This change required revisions in the calibration procedure clauses and an explanation of the difference between maximum field value and resultant field value.
- b) Text (with appropriate bibliographical references) has been added to note that magnetic field calibration coil systems other than the one described in the standard may be used for calibration purposes, provided that the fields produced have comparable uniformity.
- c) Corrections in the text and improved figures.
- d) Clarification of text related to calibration uncertainty in the calibration clauses.

The working group draft was prepared by the AC Magnetic Fields Task Force of the AC Fields Working Group (**R. G. Olsen**, *Chair*) of the Corona and Field Effects Subcommittee of the Transmission and Distribution Committee. The Task Force had the following membership:

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IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields From AC Power Lines

1. Overview

The purpose of this standard is to establish uniform procedures for the measurement of power frequency electric and magnetic fields from alternating current (ac) overhead power lines and for the calibration of the meters used in these measurements. A uniform procedure is a prerequisite to comparisons of electric and magnetic fields of various ac overhead power lines. These procedures apply to the measurement of electric and magnetic fields close to ground level. They can also be tentatively applied to electric field measurements near an energized conductor or structure with the limitations outlined in 4.5.

2. References

This standard shall be used in conjunction with the following publication.

IEEE Std 100-1992 , The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).¹

3. Definitions

For additional definitions, see IEEE Std 100-1992 .²

3.1 crosstalk: The noise or extraneous signal caused by ac or pulse-type signals in adjacent circuits (measurement of power frequency magnetic fields).

¹IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

²Information on references can be found in clause 2.

3.2 electric field strength (electric field): At a given point in space, the ratio of force on a positive test charge placed at the point to the magnitude of the test charge, in the limit that the magnitude of the test charge goes to zero. The electric field strength (E -field) at a point in space is a vector defined by its space components along three orthogonal axes. For steady-state sinusoidal fields, each space component is a complex number or phasor. The magnitudes of the components, expressed by their root-mean-square (rms) values in volts per meter (V/m), and the phases need not be the same [B1].³ *See also: phasor.*

Note: The space components (phasors) are not vectors. The space components have a time dependent angle, while vectors have space angles. For example, the sinusoidal electric field E can be expressed in rectangular coordinates as

$$\vec{E} = \hat{a}_x E_x + \hat{a}_y E_y + \hat{a}_z E_z \quad (1)$$

The space component in the x -direction is

$$E_x = \operatorname{Re}(E_{x0} e^{j\phi_x} e^{j\omega t}) = E_{x0} \cos(\phi_x + \omega t)$$

The magnitude, phase angle, and time dependent angle are given by E_{x0} , ϕ_x , and $(\phi_x + \omega t)$, respectively. In this representation the space angle of the x -component is specified by the unit vector \hat{a}_x .

An alternative general representation of a steady-state sinusoidal E -field, derivable algebraically from equation (1) and perhaps more useful in characterizing power line fields, is a vector rotating in a plane where it describes an ellipse whose semimajor axis represents the magnitude and direction of the maximum value of the electric field, and whose semiminor axis represents the magnitude and direction of the field a quarter cycle later [B1], [B4]. The electric field in the direction perpendicular to the plane of the ellipse is zero. *See also: single-phase ac fields; polyphase ac fields.*

3.3 frequency: The number of complete cycles of sinusoidal variation per unit time. *Notes:* 1) Electric and magnetic field components have a fundamental frequency equal to that of the power line voltages and currents. 2) For ac power lines, the most widely used frequencies are 60 and 50 Hz.

3.4 harmonic content: Distortion of a sinusoidal waveform characterized by indication of the magnitude and order of the Fourier series terms describing the wave. *Note:* For power lines, the harmonic content is small and of little concern for the purpose of field measurements, except at points near large industrial loads (saturated power transformers, rectifiers, aluminum and chlorine plants, etc.) where certain harmonics may reach 10% of the line voltage. Laboratory installations also may have voltage or current sources with significant harmonic content.

3.5 magnetic flux density (magnetic field): The vector quantity (B -field) of divergence zero at all points, which determines the component of the Coulomb-Lorentz force, that is proportional to the velocity of the charge carrier.

Note: In a zero electric field, the force F is given by $\vec{F} = q\vec{v} \times \vec{B}$ where \vec{v} is the velocity of the electric charge q . The vector properties of the field produced by currents in power lines are the same as those given above for the electric field. The magnitudes of the field components are expressed by their rms values in tesla ($1T = 10^4 G$).

3.6 maximum value of the electric field strength: At a given point, the rms value of the semimajor axis magnitude of the electric field ellipse. *See also: electric field strength.*

3.7 maximum value of the magnetic field: At a given point, the rms value of the semimajor axis magnitude of the magnetic field ellipse.

3.8 perturbed field: A field that is changed in magnitude or direction, or both, by the introduction of an object. *Note:* The electric field at the surface of the object is, in general, strongly perturbed by the presence of the object. At power frequencies the magnetic field is not, in general, greatly perturbed by the presence of objects that are free of magnetic materials. Exceptions to this are regions near the surface of thick electric conductors where eddy currents alter time-varying magnetic fields.

³The numbers in brackets correspond to those bibliographical items listed in clause 9.

3.9 phasor: A complex number expressing the magnitude and phase of a time-varying quantity. Unless otherwise specified, it is used only within the context of steady-state alternating linear systems. In polar coordinates, it can be written as $Ae^{j\phi}$, where A is the amplitude or magnitude (usually rms, but sometimes indicated as peak value) and ϕ is the phase angle. The phase angle ϕ should not be confused with the space angle of a vector. *See also:* **electric field strength.**

3.10 polyphase ac fields: Fields whose space components may not be in phase. These fields will be produced by polyphase power lines. The field at any point can be described by the field ellipse—that is, by the magnitude and direction of the semimajor axis and the magnitude and direction of its semiminor axis. *Note:* Such fields are sometimes referred to as being elliptically polarized. Certain power line geometries can produce circularly polarized fields. For polyphase power lines, the electric field at large distances (≥ 15 m) away from the outer phases (conductors) can frequently be considered a single-phase field because the minor axis of the electric field ellipse is only a fraction ($< 10\%$) of the major axis when measured at a height of 1 m above ground level. *See also:* **electric field strength.**

3.11 resultant magnetic field: The resultant magnetic field is given by the expression

$$B_R = \sqrt{B_x^2 + B_y^2 + B_z^2} \quad (2)$$

where

B_x , B_y , and B_z are the rms values of the three orthogonal field components.

NOTES:

1 — The resultant magnetic field is also given by the expression

$$B_R = \sqrt{B_{\max}^2 + B_{\min}^2} \quad (3)$$

where B_{\max} and B_{\min} are the rms values of the semimajor and semiminor axes of the magnetic field ellipse, respectively. The resultant B_R is always $\geq B_{\max}$. If the magnetic field is linearly polarized, $B_{\min} = 0$ and $B_R = B_{\max}$. If the magnetic field is circularly polarized, $B_{\max} = B_{\min}$ and $B_R = 1.41B_{\max}$.

2 — A three-axis magnetic field meter simultaneously measures the rms values of the three orthogonal field components and combines them according to equation (2) to indicate the resultant magnetic field. Although power line magnetic fields are typically two dimensional in nature, i.e., elliptically polarized, unless two axes of a three-axis probe are in the plane of the ellipse, each of the three probes will sense a component of the rotating magnetic field vector.

3.12 single-phase ac fields: Fields whose space components are in phase. These fields will be produced by single-phase power lines. The field at any point can be described in terms of a single direction in space and its time-varying magnitude. *Note:* Such fields are sometimes referred to as being linearly polarized.

3.13 uniform field: A field whose magnitude and direction are uniform at each instant in time at all points within a defined region.

3.14 vertical component of the electric field strength: The rms value of the component of the electric field along the vertical line passing through the point of measurement. This quantity is often used to characterize electric field induction effects in objects close to ground level.

3.15 weakly perturbed field: At a given point, a field whose magnitude does not change by more than 5% or whose direction does not vary by more than 5 degrees when an object is introduced into the region.

4. Electric field strength meters

4.1 General characteristics

Two types of meters used to measure the electric field strength from ac power lines are described in technical literature.

- Free-Body meter: Measures the steady-state induced current or charge oscillating between two halves of an isolated conductive body in an electric field [B2], [B23].
- Ground-Reference-Type meter: Measures the current-to-ground from a flat probe introduced into an electric field [B16].

The free-body meter is suitable for survey-type measurements because it is portable, allows measurements above the ground plane, and does not require a known ground reference. Therefore, this type of meter is recommended for outdoor measurements near power lines.

This standard presents measurement techniques for only the free-body type meter. Flat ground-reference-type meters can be used only under special conditions described in 6.2. Electric field strength meters intended for characterization of radio-frequency electric fields should not be used to measure the electric field strength from ac power lines.

Basically, an electric field strength meter consists of two parts, the probe and the detector. For commercially available free-body meters, the detector is usually contained in, or is an integral part of, the probe. The probe and detector are introduced into an electric field on an insulating handle. The detector measures the steady-state induced current or charge oscillating between the conducting halves (electrodes) of the probe. The observer is sufficiently removed from the probe to avoid significant perturbation of the electric field at the probe (see 5.1). The size of the probe should be such that charge distributions on the boundary surfaces generating the electric field (energized and ground surfaces) are, at most, weakly perturbed when the probe is introduced for measurement. The electric field should be approximately uniform in the region where the probe will be introduced. Probes can be of any shape; however, meters commercially available in the U.S. are generally in the shape of rectangular boxes, with side dimensions ranging from ~7 to ~20 cm. The meters are calibrated to read the rms value of the power frequency electric field component along the electrical axis (the axis of greatest electric field strength sensitivity).

There also exist free-body meters designed for remote display of the electric field strength. In this case, a portion of the signal processing circuit is contained in the probe and the remainder of the detector is in a separate enclosure with an analog or digital display. A fiber-optic link connects the probe to the display unit. This type of probe is also introduced into an electric field on an insulating handle.

In order to characterize the instrumentation adequately, the manufacturer should provide a detailed description of the electronics, as well as other relevant information, as indicated in figure 1, section G. For example, if the field meter reading has a temperature dependence, the temperature coefficient should be provided. This permits the operator to correct E -field readings made outdoors using an instrument calibrated at room temperature. If the electrical axis of the field strength meter is not coincident with the geometric axis, the departure in degrees and direction shall be specified.

A. Line Voltage, kV/ Line Current, A	_____
(1) Nominal	_____
(2) Actual	_____
B. Line Conductors and Overhead Ground Wires	
(1) Type	_____
(2) Diameter, cm	_____
(3) Height, m	_____
(4) Phase relation of conductors	_____
(5) Sketch of line configuration (for example, figure 7)	_____
C. Atmospheric Conditions	
(1) Temperature, °C	_____
(2) Relative humidity	_____
(3) Barometric pressure, pascal (Pa)	_____
(4) Wind velocity, m/s	_____
(5) Fair, rain, snow, etc.	_____
D. Towers	
(1) Metal	_____
(2) Wood	_____
(3) Others	_____
(4) Sketch with dimensions	_____
E. Harmonics	
(1) Content, percent	_____
(2) Nature of source, for example, industrial load	_____
(3) Distance to source, m	_____
F. Number of Measurements	
G. Instruments	
(1) Meter type	
(a) Manufacturer	_____
(b) Model	_____
(2) Probe and signal conditioning circuit	
(a) Description (shape)	_____
(b) Dimensions	_____
(c) Equivalent circuit	_____
(d) Frequency response	_____
(e) Directional characteristics	_____
(f) Corona onset field strength	_____
(g) Effects of	
(1) Electric or magnetic field	_____
(2) Temperature	_____
(3) Humidity	_____
(h) Reading characteristics (rms, etc.)	_____
(i) Accuracy and sensitivity	_____
(3) Holding devices	
(a) Length	_____
(b) Electrical characteristics	_____
(4) Connecting cable (if signal conditioning circuit is separate from probe)	
(a) Length	_____
(b) Type	_____
(5) Calibration information (brief description)	_____

Figure 1— Typical background data sheet

4.2 Theory and operational characteristics

Briefly, the theory of operation of free-body meters can be understood by considering an uncharged conducting free body with two separate halves introduced into a uniform field E . The charge induced on one of the halves is

$$Q = \int_{S/2} \vec{D} \cdot d\vec{A} \quad (4)$$

where

\vec{D} is the electric displacement and $d\vec{A}$ is an area element on half of the body with total surface area S . The case of spherical geometry [figure 2]) yields the result

$$Q = 3\pi a^2 \epsilon_0 E \quad (5)$$

where

a is the radius of the sphere
 ϵ_0 is the permittivity of free space [B20]

NOTE — The surface charge density is given by $3\epsilon_0 E \cos \theta$. Integration over the hemisphere gives equation (5) (see [B20]).

For less symmetric geometries, the result can be expressed as

$$Q = k\epsilon_0 E \quad (6)$$

where

k is a constant dependent on geometry. Sensing electrodes resembling cubes and parallel plates [figure 2] have been employed. If the electric field strength has a sinusoidal dependence, for example, $E_0 \sin \omega t$, the charge oscillates between the two halves and the current is given by

$$I = \frac{dQ}{dt} = k\omega\epsilon_0 E_0 \cos \omega t \quad (7)$$

It should be noted that the uniform E -field direction serves as an alignment axis for the field probe and that during field measurements this axis should be aligned with the field component of interest. The constant k can be thought of as a field strength meter constant and is determined by calibration. For more exact results, a second term not shown should be added to the right-hand side of equation (7) because of the presence of the dielectric handle held by the observer. The influence of the handle, representing a leakage impedance, and the perturbation introduced by the observer are taken to be negligible in the above discussion.

The detector, although calibrated to indicate the rms value of the power frequency field, may, depending on the detector circuit design, measure

- a) A quantity that is proportional to the average value of the rectified power frequency signal from the probe
- b) The true rms value of the signal

The response of the detector to harmonic components in the E -field also depends on the design of the detector circuit. For example, in case a), because of the signal-averaging feature, an analog display will not necessarily indicate the rms value of the composite E -field waveform (fundamental plus harmonics) [B14]. For case b), the true rms value of the electric field strength with harmonics could be observed if the detector circuit contained a stage of integration [B17].

The frequency response of the free-body meter can be determined experimentally by injecting a known alternating current at various frequencies and observing the response.

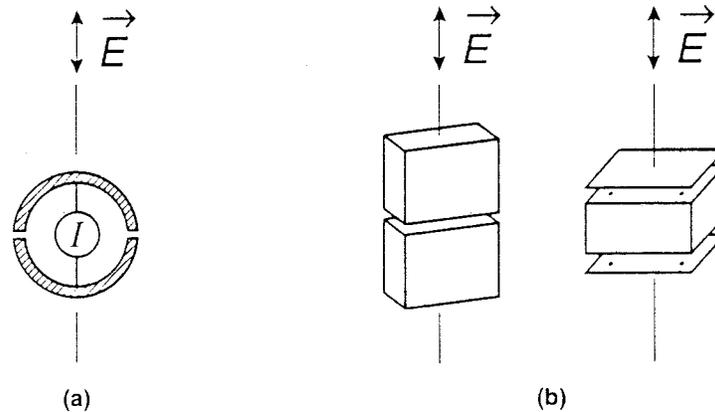


Figure 2— Geometries of E -field probes: (a) spherical probe (b) commercial U.S. probes

The rated accuracy of the detector at power frequency is a function of the stability of its components at a given temperature and humidity and is generally high (<0.5% uncertainty) compared with the reading accuracy when the analog display is read at a distance of 1 or 2 m.

4.3 Calibration of electric field strength meters

4.3.1 Description of calibration apparatus

Parallel plate structures, single ground plates with guard rings, and current injection circuits have all been used for calibration purposes. Each is now briefly described.

4.3.1.1 Parallel plates

Uniform field regions of known magnitude and direction can be created for calibration purposes with parallel plates, provided that the spacing of the plates, relative to the plate dimensions, is sufficiently small. The uniform field value E_0 is given by V/t , where V is the applied potential difference and t is the plate spacing. As a guide for determining plate spacing, the magnitudes of the electric field strength E , normalized by the uniform field, that is E/E_0 , at the plate surface and midway between semi-infinite parallel plates are plotted [B22] as a function of normalized distance x/t from the plate edge in figure 3.

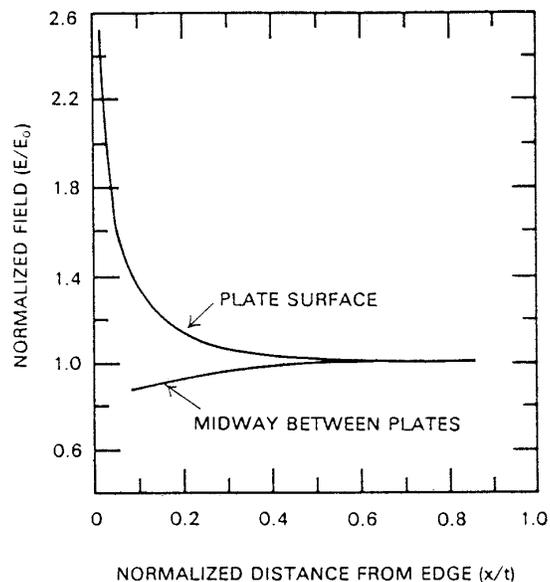
NOTE — For field distributions between finite size parallel plates in the absence of nearby ground planes, see also [B21].

Numerical values are presented in table 1. In the absence of nearby objects or surfaces, these results can be used to design a finite-size parallel plate structure if the edge effects (field nonuniformities) due to all four edges of the plate become less than ~0.5% at the center; superposition of the nonuniformities can then be made. Compatibility with the probe size, noted previously in 4.1, should also be considered.

Table 1— Normalized E -field values midway between plates and at plate surfaces

Midway between plates	
x/t	E/E_0
0.0698	0.837
0.1621	0.894
0.2965	0.949
0.4177	0.975
0.6821	0.995
0.7934	0.997
Plate surface	
0.7954	1.002
0.6861	1.005
0.4376	1.025
0.2431	1.095
0.1624	1.183
0.1230	1.265
0.0991	1.342
0.0829	1.414
0.0452	1.732
0.0307	2.000
0.0185	2.449

Because nearby ground surfaces are always present, grading rings have been employed to grade the field at the perimeter of the structure and to provide isolation from surrounding perturbations. No exact theoretical treatment of the problem is available for rectangular geometries, but analytical solutions do exist for structures of cylindrical symmetry [B3].

**Figure 3— Normalized E -field at plate surface and midway between plates**

Parallel plate structures can be energized with one plate at zero potential or both plates can be energized using a center tapped transformer, as shown in figure 4. For example, stretched metal screens on 3 m × 3 m frames with a 1 m separation and four grading rings have been used to form a parallel plate structure.⁴ Potentials are applied to the grading rings using a resistive divider. Resistors that effectively “short out” stray capacitance between the grading rings and nearby surfaces are used [B14]. Theoretical considerations and experimental measurements [B14] indicate that energization of the plates using a center tapped transformer provides a field that is more immune from nearby sources of perturbation than other energization schemes.

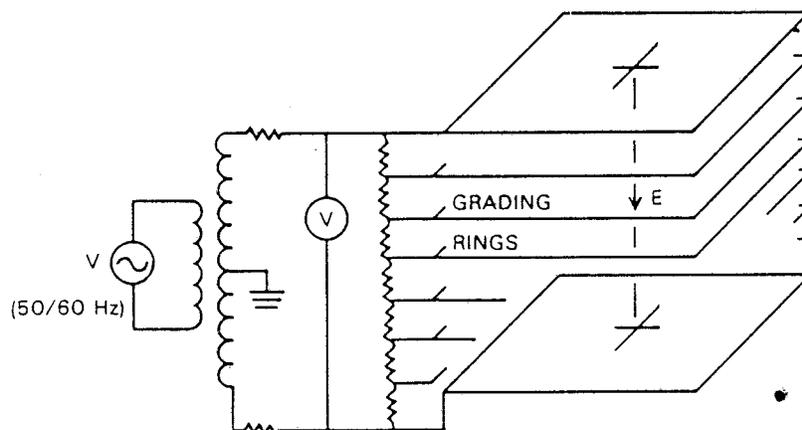


Figure 4— Large parallel plates used for calibration *E*-field meter

4.3.1.2 Plate at ground under a high-voltage line

A second method for generating an electric field for calibration purposes employs a conducting plate. The conducting plate of surface area A surrounded by a flat guard ring is placed at ground level in an ac field generated by an overhead line. The induced rms current I is measured and the electric field strength at the surface of the plate E is calculated from the relation

$$E = I/(\epsilon_0 \omega A) \quad (8)$$

where

ω is the angular frequency of the line voltage [B23].

The electric field strength meter to be calibrated is supported 1 m above the plate. The field is assumed to be approximately uniform from the plate surface to the point where the field meter is introduced. It is also assumed that the actual ground plane is coincident with that of the metal plate and guard ring surface. The plate at ground is itself a device to measure the field at ground level, and various meters have been built on this principle [B16], [B23]. These meters, however, are not adequate for measuring electric field strengths above the ground plane because the induced current is dependent, in part, on the height of the plate above the ground plane.

4.3.1.3 Current injection

A circuit such as that shown schematically in figure 5 can be used to inject a known current I onto the probe sensing plates of the electric field strength meter to be calibrated. V is a precision voltmeter and Z is a known impedance at least two orders of magnitude greater than the input impedance of the electric field strength meter. The injected current

⁴Project Ultra-High Voltage, Pittsfield, Mass.

can thus be calculated from Ohm's law, with an uncertainty of less than 0.5%. Although resistors or capacitors may be used as the impedances shown in figure 5, the use of resistors is recommended. Resistors are preferred because the admittance of capacitors increases with frequency. Therefore, the presence of harmonics in the source waveform can lead to greater errors than if resistors were used (see 4.2).

If the ratio I/E for a given electric field strength meter is known, a current injecting circuit can be used for calibrating the electric field strength meter. The above ratio, however, is normally determined by using a parallel plate structure or ground plate under a high-voltage line. Thus, the current injection procedure serves as a convenient calibration check.

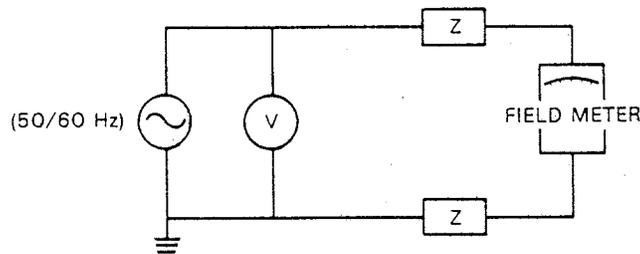


Figure 5— Current injection calibration check

If current injection is used, adequate shielding should be employed to eliminate signal contributions from such ambient sources as interior lighting, power cords, or nearby power supplies. If sufficient shielding cannot readily be achieved because of field meter design, an indication of the magnitude of interfering ambient fields may be obtained by changing the phase relationship between the calibrating and interfering signals. This magnitude may be determined by interchanging the lead connections to the sensing plates of the meter being calibrated, or by reversing connections to the power supply. If the calibrating voltage required for a given meter reading is the same for the two configurations, the interfering signal may be regarded as negligibly small. If a small difference exists, the average of the two voltages is that which would be required for the same meter reading in the absence of interference [B14].

The validity of the calibration check described rests on the assumption that the geometry of the field meter probe has not been altered by use.

4.3.2 Calibration procedures

The electric field strength meter shall be calibrated periodically, with the frequency of calibrations depending in part on the stability of the meter. The meter shall be placed in the center of a parallel plate structure similar to that shown in figure 4, with the insulating handle normally used during measurements. The dimensions of the structure should be $1.5 \text{ m} \times 1.5 \text{ m} \times 0.75 \text{ m}$ spacing. With these dimensions, no grading rings (or resistor dividers) are necessary to obtain a calibration field that is within 1% of the uniform field value V/t [B14]. It is assumed that the largest diagonal dimension of the electric field strength meter to be calibrated is no larger than 23 cm. The distance to nearby ground planes (walls, floors, etc.) shall be at least 0.5 m [B14]. The dimensions of the calibration apparatus may be scaled upward or downward for calibration of larger or smaller electric field strength meters.

Adequate current-limiting resistors shall be used in the transformer output leads as a safety measure [B19]. For example, $10 \text{ M}\Omega$ resistors are satisfactory for applied voltages up to 10 kV (that is, $E \sim 13 \text{ kV/m}$).

A plot of the calculated uniform electric field, E_0 , vs. the voltage applied to the parallel plates shall be made as shown in figure 6. The uncertainty in the calculated electric field should be indicated at a representative point with a vertical error bar. This error bar represents the combined uncertainties (i.e., the square root of the sum-of-the-squares) in the voltage measurement, the parallel plate spacing, and the field nonuniformity (<1%), and shall be $<\pm 3\%$.

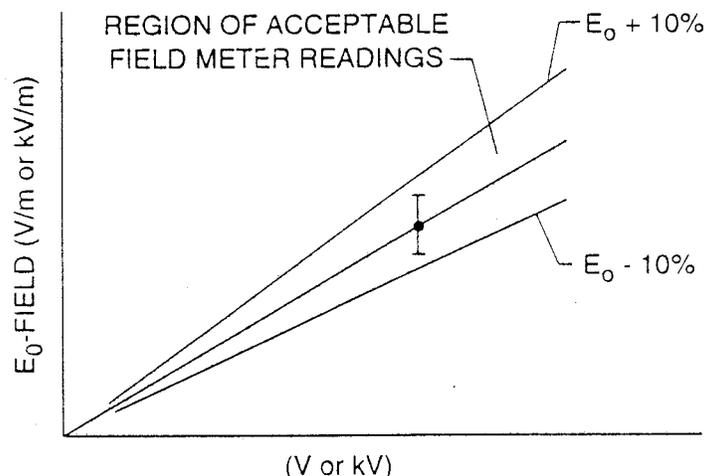


Figure 6— Known *E*-field for large parallel plates and tolerance levels

NOTE — For example, if the uncertainties in the voltage measurement and parallel plate spacing are $\pm 1\%$ and $\pm 2\%$, respectively, the combined uncertainty in the value of the calibration field is

$$\pm [(1.0)^2 + (2.0)^2 + (1.0)^2]^{1/2} \text{ or } \pm 2.4\%$$

A region of acceptable field meter readings, given by $E_0 \pm 10\%$, also shall be indicated on the plot as shown in figure 6. Measured values obtained with the field meter that is being calibrated shall be plotted. At least three electric field levels for each range of the field meter, sufficient to span 30–90% of full scale, shall be recorded for meters with analog displays. At least four electric field levels, sufficient to span 10–90% of full scale, shall be recorded for meters with digital displays. Field meters with autoranging capabilities shall be calibrated on each range at no less than three representative points that span most of the range. On the most sensitive range, one of the calibration points shall be 10% of the maximum value *for that range*. On the least sensitive range, one of the calibration points shall be 90% of the maximum value *for that range*. The maximum measured field shall occur when the meter axis is rotated to within $\pm 10^\circ$ of the vertical direction, and the maximum value shall lie within the region of acceptable readings (figure 6). Field meters with readings that fail to satisfy the above criteria (i.e., data points lie outside the $\pm 10\%$ region) shall be considered inaccurate.

The recorded field values permit the determination of correction factors that should be applied to field meter readings when measurements are performed in the vicinity of power lines. The uncertainty associated with the above calibration process is equal to $\pm 3\%$ once the correction factors have been applied to the field meter readings.

Calibration checks (see 4.3.1.3) shall be made prior to and after any extended period of electric field strength meter use.

Energizing power supplies used for calibrations and calibration checks described in 4.3 should be nearly free ($< 1\%$) of harmonic content (see 4.2).

The temperature and humidity shall be recorded at the time of calibration and calibration checks to permit corrections for these parameters, if necessary, when measurements are performed under power lines.

4.4 Immunity from interference

Perturbation of E -field strength meter operation due to anticipated levels of ambient magnetic fields under transmission lines should be quantified by the manufacturer and supplied to the user. Such perturbations, expressed as percentages, should be included in reports of measurements if significant [see figure 1, G(2)].

4.5 Parameters affecting accuracy of electric field strength measurements

The measurement uncertainty during practical outdoor measurements using commercially available free-body meters is typically near 10%, although this figure can be reduced under more controlled conditions. The most likely sources of major errors are difficulty in positioning the meter, reading errors, handle leakage in some cases, temperature effects, and observer proximity effects. Several of these parameters will be considered further in clause 5.

Nonuniformities in the E -field can also reduce the accuracy of the measurements because the calibration procedure is only valid for measuring uniform fields. Separate calibration procedures using nonuniform fields could be devised, but it is noteworthy that the current induced in a spherical E -field probe (figure 2) in a nonuniform single-phase ac field generated by a point charge (in the absence of nearby ground planes) is given by

$$I = 3\pi a^2 \omega \epsilon_0 E \left[1 - \frac{7}{12} \left(\frac{a}{d} \right)^2 + \frac{11}{12} \left(\frac{a}{d} \right)^4 \dots \right] \quad (9)$$

where

$$E = \frac{1}{4\pi\epsilon_0} \frac{Q}{d^2}$$

Here, a is the radius of the spherical probe and d is the distance between the point charge Q and the probe center. The axis of the probe is aligned with the field direction.

NOTE — This result is given without derivation in [B15]. It can readily be derived by considering an uncharged conducting sphere in the field of a point charge and using the method of images.

Reference to equations (5) and (7) reveals that the induced current is the same as that produced by a uniform field of magnitude

$$\frac{Q}{4\pi\epsilon_0 d^2}$$

if the terms in (a/d) are ignored. Thus, the induced current between the two halves of a spherical dipole that is located at a point in a highly nonuniform field produced by a point charge is nearly the same as that produced by a uniform field of equal magnitude if d is sufficiently large. For example, if $a/d = 0.1$, the difference in induced current (E -field measurement) produced by a uniform field and a highly nonuniform field is less than 1%. The change in E -field magnitude over the dimensions of the sphere is

$$\frac{\Delta E}{E} \cong \frac{4a}{d} = 0.4$$

It can be shown that the measurement error remains small even when the probe is not aligned with the field direction. Consequently, the error caused by nonuniformity of the field under transmission lines is negligible for all practical cases. For comparisons with equation (9), it should be noted that the effective or equivalent radius of commercially available electric field strength meters, which have rectangular geometries, can conservatively be estimated as half of the largest diagonal dimension.

Mechanical imbalance of an analog display also can be a source of error. If it is not sufficiently well-balanced, the meter should be used in the same orientation with respect to the vertical as existed during calibration. An estimate of the magnitude of this type of error can be made by rotating the meter in the absence of an E -field and observing the displacement of the needle. The measurement error due to mechanical imbalance can be reduced by repeating a measurement after rotating the electric field strength meter 180° (about an axis normal to the face of the meter) and taking the average of the two measurements. This procedure can be used if the electrical and geometrical axes of the electric field strength meter coincide. Replacement of an analog display with a digital display will eliminate errors due to poor mechanical balance.

The response of an electric field strength meter with an analog display to the same induced current may depend on the inclination of the meter, even if mechanically balanced. This effect can be a source of measurement error if the electric field strength meter is used in an orientation that differs from that during calibration in a uniform field. The magnitude of this possible source of error can be determined using the current injection technique (see 4.3.1.3) while rotating the electric field strength meter in the absence of an electric field.

5. Electric field strength measurement procedures⁵

5.1 Procedure for measuring electric field strength near power lines

The electric field strength under power lines should be measured at a height of 1 m above ground level. Measurements at other heights of interest shall be explicitly indicated. The probe should be oriented to read the vertical E -field, because this quantity is often used to characterize induction effects in objects close to ground level. The distance between the electric field strength meter and operator should be at least 2.5 m (8 ft). This distance will reduce the proximity effect (shading E -field) of a grounded 1.8 m (6 ft) tall observer to between $\sim 1.5\%$ and $\sim 3\%$ [B5], [B14]. In instances where larger proximity effects are considered acceptable, the observer distance may be reduced. In such cases, the distance shall be explicitly noted. Five percent proximity effects occur when the observer distance is between ~ 1.8 m (5.9 ft) and 2.1 m (6.9 ft) away from the meter. The actual value will depend on the geometry of the observer-meter-power line combination. Because observers are normally near ground potential, the proximity effects indicated previously can be regarded as typical. The observer will introduce less perturbation when standing in the region of lowest electric field strength while performing the measurement [B5], [B14].

Asymmetries in the design of an electric field strength meter probe can change the direction of the electrical axis with respect to the apparent vertical axis. Measurements performed with such an instrument may be more or less immune to the observer's proximity [B14]. In such a case, the observer proximity effects shall be quantified before the electric field strength meter is employed for measurement. Proximity effects in excess of those just noted shall be reported.

To provide for a more complete description of the E -field strength at a point of interest, measurements of the maximum field with its orientation and the minimum field with its orientation, both in the plane of the field ellipse (see electric field strength, 3.2), can be made. Under the idealized conditions of horizontal power lines and a flat ground surface below, the plane of the ellipse is perpendicular to the direction of the conductors. This is approximately the case under actual power lines in the absence of nearby objects and very rough terrain. To perform measurements in the plane of the ellipse, the observer-field meter line should be parallel to the conductors. Rotation of the meter about this line, which coincides with the handle, will permit the determination of the maximum and minimum field components and

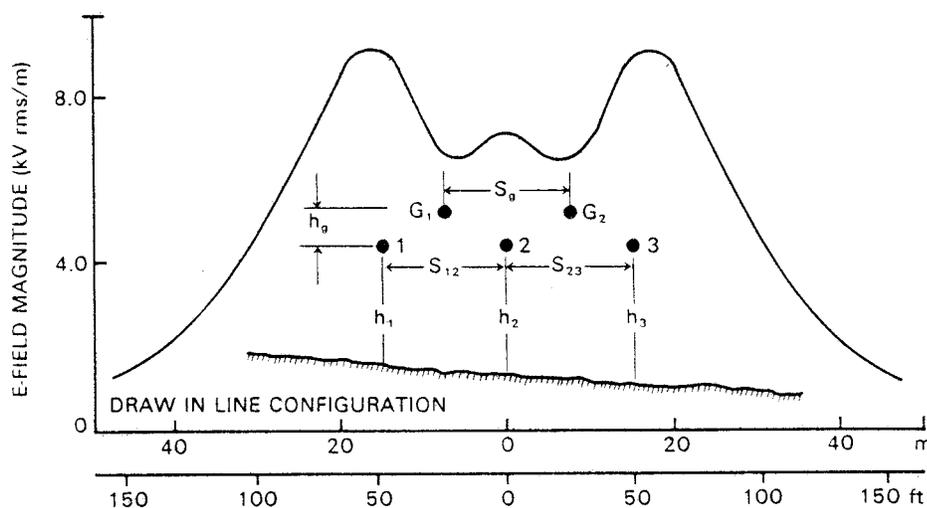
⁵See also clause 8.

their directions. Care during alignment should be exercised during this measurement if the electrical axis of the probe does not coincide with the apparent geometric axis.

The distance between the meter and nonpermanent objects shall be at least three times the height of the object in order to measure the unperturbed field value. The distance between the meter and permanent objects should be ~ 1 m or more to ensure sufficient measurement accuracy of the ambient perturbed field (see 4.5).

5.2 Lateral profile

The lateral profile (see figures 7 and 8) of the electric field strength at points of interest along a span should be measured at selected intervals in a direction normal to the line at 1 m above the ground level. Measurements of the lateral (half) profiles should begin from the center line in the area of interest and be made to a lateral distance of at least 30 m (100 ft) beyond the outside conductor. At least five equally spaced measurements should be performed while under the conductors. It is recommended that profiles be plotted in the field to determine if adequate detail has been obtained. Complete profile measurements should commence in the region of interest beyond the outer conductor and progress successively to the opposite side of the right-of-way. Several final measurements repeated at some intermediate points will provide some indication of possible change in line height, load, or voltage during the course of measurements. Local time should be recorded on the data sheet periodically during the measurements to facilitate later review of the data together with the recorded substation line voltage and load data.



NOTE—The symbols (h_1 , S_{12} , etc.) represent conductor heights and spacings.

Figure 7— Example of lateral profile of vertical *E*-field strength at midspan

5.3 Longitudinal profile

The longitudinal (see figure 8) profile of the field strength should be measured where the field is greatest at midspan or other points of interest, as determined from the lateral profile, parallel with the line and 1 m above the ground level. Measurements of the longitudinal profile should be made at least at five nearly equal consecutive increments from a point at midspan in both directions for a total distance equal to one span.

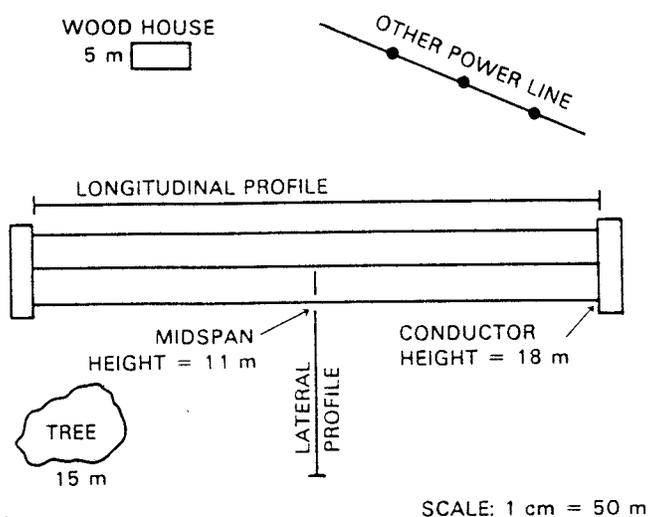


Figure 8— Typical plan view with heights of permanent nearby objects

5.4 Precautions and checks during *E*-field measurements

5.4.1 Measurement locations

In order to make electric field strength measurements representing the unperturbed field at a given location, the area should be free, as much as possible, from other power lines, towers, trees, fences, tall grass, or other irregularities. It is preferred that the location be relatively flat. It should be noted that the influence of vegetation on the electric field strength can be significant. In general, field enhancement occurs near the top of isolated vegetation and field attenuation occurs near the sides. The field perturbation can depend markedly on water content in the vegetation.

5.4.2 Check for handle leakage

To check for handle leakage, the electric field strength meter should be oriented with its axis perpendicular to the plane of the electric field ellipse (see 5.1) where, under ideal conditions, zero electric field strength should be measured. Electrical leakage through a grounded observer due to surface contamination on the handle may cause a reading by the meter. It is assumed during this leakage check that the electric axis is also perpendicular to the plane. Such a reading, expressed in percentage of the maximum field, would represent the order of magnitude of the error that could be caused by this mechanism.

5.4.3 Harmonic content

The response of certain electric field strength meters is influenced by high levels of harmonic content. Therefore, if possible, the waveform of the field or its derivative (the induced current) should be observed to obtain an estimate of the amount of harmonic content (see 4.2). A qualitative observation can be made with an oscilloscope connected to the detector output of a flat plate probe (see 4.3.1.2). Replacement of the oscilloscope with a wave analyzer would permit the measurement, in percent, of the various harmonic components.

NOTE — The magnitudes of harmonic components in the induced current (field derivative) are enhanced by the harmonic number.

5.5 Measurement uncertainty

Measurement uncertainties due to calibration (4.3.2), temperature (4.1), interference (4.4), the parameters in 4.5 and 5.4, and observer proximity (5.1) shall be combined (square root of the sum-of-the-squares) and reported as the total estimated measurement uncertainty. The total uncertainty should not exceed $\pm 10\%$.

6. Magnetic field meters

6.1 General characteristics of magnetic field meters

Magnetic field meters consist of two parts, the probe or field sensing element, and the detector, which processes the signal from the probe and indicates the rms value of the magnetic field with an analogue or digital display. Magnetic field probes, consisting of an electrically shielded coil of wire (i.e., a single-axis probe), have been used in combination with a voltmeter as the detector for survey type measurements of power frequency magnetic fields from power lines. Also available is instrumentation with three orthogonally oriented coil probes (three-axis meters) that simultaneously measures the rms values of the three spatial components and combines them to give the resultant magnetic field [equation (2)]. Magnetic field meters measure the component of the oscillating (linearly polarized) or rotating (elliptically or circularly polarized) magnetic field vector that is perpendicular to the area of the probe(s).

Hall-effect gaussmeters that can measure magnetic flux densities from dc to several hundred hertz are available. However, Hall-effect magnetic field probes respond to the total flux density. Due to their low sensitivity and saturation problems from the earth's field, they have been seldom used under power lines. Such instrumentation will not be considered here.

There are fewer mechanisms for B -field perturbations and measurement errors when compared with the E -field case. The instrumentation considered here consists of a shielded-coil probe and shielded detector with a connecting shielded cable. The probe can be held with a short dielectric handle without seriously affecting the measurement. Proximity effects of dielectrics and poor nonmagnetic conductors are, in general, negligible.

As previously noted for electric field strength meters (see 4.1), in order to adequately characterize the instrumentation, the manufacturer should provide a detailed description of the electronics, as well as the information called for in figure 1, section G.

6.2 Theory and operational characteristics

The principle of operation of a coil-type B -field probe takes advantage of Faraday's law (in differential form)

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (10)$$

Using Stokes' theorem, this can be written in the form

$$\oint \vec{E} \cdot d\vec{l} = -\frac{\partial}{\partial t} \int_A \vec{B} \cdot d\vec{A} \quad (11)$$

where the integral on the left is a line integral along a curve enclosing a surface area A [B6]. If the path of the left-hand integral is taken to be a closed loop of conductor with area A , and B is a quasi-static uniform field normal to area A , as

shown in figure 9, the line integral can be regarded as the voltage, V , developed across the ends of the loop in response to the time-rate-of-change in the magnetic flux BA . That is,

$$V = \oint \vec{E} \cdot d\vec{l} = -\frac{\partial}{\partial t}(BA) \tag{12}$$

and from figure 9

$$V = -\omega B_0 A \cos \omega t \tag{13}$$

For a coil of many turns, the voltage given by equation (13) will develop over each turn and the total voltage will increase accordingly. The induced current, I , has been assumed to be sufficiently small so that the opposing B -field generated by I can be neglected. It should be noted that the relationship between V and B_0 given by equation (13) assumes that the direction of B_0 is perpendicular to the plane of the coil. Because only the space component of B_0 perpendicular to the area of the coil induces a voltage, this is also the orientation for measuring the maximum B -field value.

Earlier remarks regarding the response of the detector to the 60 Hz and harmonic components of the E -field (see 4.2) apply in this case.

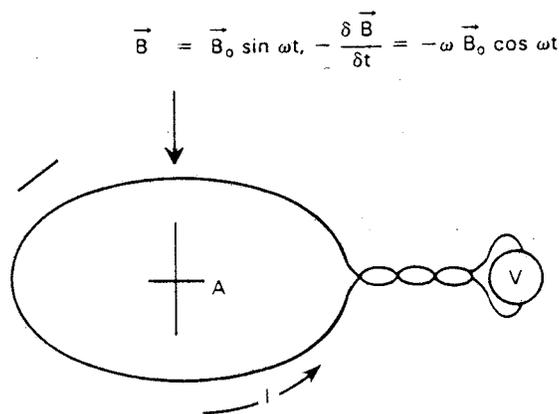


Figure 9— Conducting loop in quasi-static uniform B -field

6.3 Calibration of magnetic field meters

6.3.1 Description of calibration apparatus

Calibration of a magnetic field meter is normally done by introducing the probe into a nearly uniform magnetic field of known magnitude and direction [B8]. Known magnetic fields can be produced by coil systems with circular and rectangular geometries [B7], [B13], [B18], [B24]. For example, Helmholtz coils have frequently been employed to generate such fields. A single loop of many turns of wire with rectangular geometry for producing the field is described below because the equations for calculating the field at all points in space are in closed form [B14], [B24] and the coil system is simple to construct. The simplicity in construction is at the expense of reduced field uniformity, but sufficient uniformity for calibration purposes is readily obtained.

The z -component of the magnetic field produced by a rectangular loop of dimensions $2a \times 2b$ is given by the expression

$$B_z = \frac{\mu_0}{4\pi} IN \sum_{\alpha=1}^4 \frac{(-1)^\alpha d_\alpha}{r_\alpha [r_\alpha + (-1)^{\alpha+1} C_\alpha]} - \frac{C_\alpha}{r_\alpha (r_\alpha + d_\alpha)} \quad (14)$$

where

N = number of turns

$$C_1 = -C_4 = a+x \quad r_1 = \sqrt{(a+x)^2 + (b+y)^2 + z^2}$$

$$C_2 = -C_3 = a-x \quad r_2 = \sqrt{(a-x)^2 + (b+y)^2 + z^2}$$

$$d_1 = d_2 = b+y \quad r_3 = \sqrt{(a-x)^2 + (b-y)^2 + z^2}$$

$$d_3 = d_4 = y-b \quad r_4 = \sqrt{(a+x)^2 + (b-y)^2 + z^2}$$

I = the rms current

μ_0 = the permeability of air

and the coordinates x , y , and z are shown in figure 10 [B14], [B24]. The conductors in the current loop are assumed to be of small cross section. It is noted for purposes of reference that

$$B_z(0, 0, 0) = \mu_0 IN \sqrt{2} / \pi a$$

for a square loop of side dimension $2a$. Equation (14) has been used to calculate the field values at and near the center of a square loop of dimensions $1 \text{ m} \times 1 \text{ m}$. The percentage departure from the central magnetic field value at nearby points in the plane of the loop and 3 cm above and below the plane of the loop is plotted in figure 11. Also shown in figure 11 is a scale drawing of a magnetic field probe 10 cm in diameter.

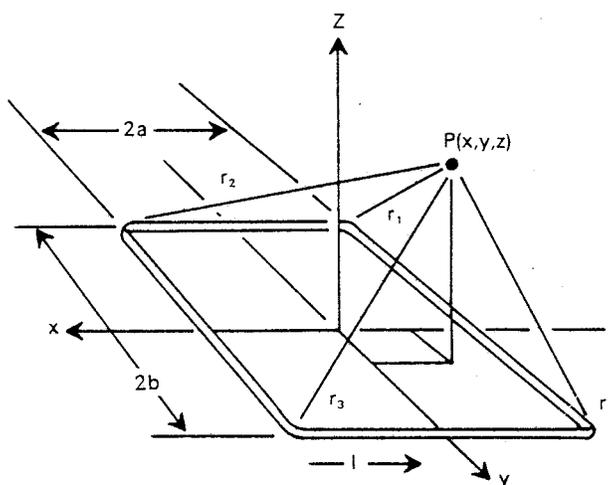


Figure 10— Coordinate system for current loop generating magnetic field B_z

It is noteworthy that a field meter with a coil probe will indicate a magnetic field value that is an average over the cross sectional area of the probe. The difference between this average and the central value [$B_z(0, 0, 0)$] will be less than the maximum percent departure from the central value. For example, while the largest departure of the magnetic field from the central value is 0.63% for the 10 cm probe (in the plane of the loop), the average field is only 0.31% more than the central (calibration field) value.

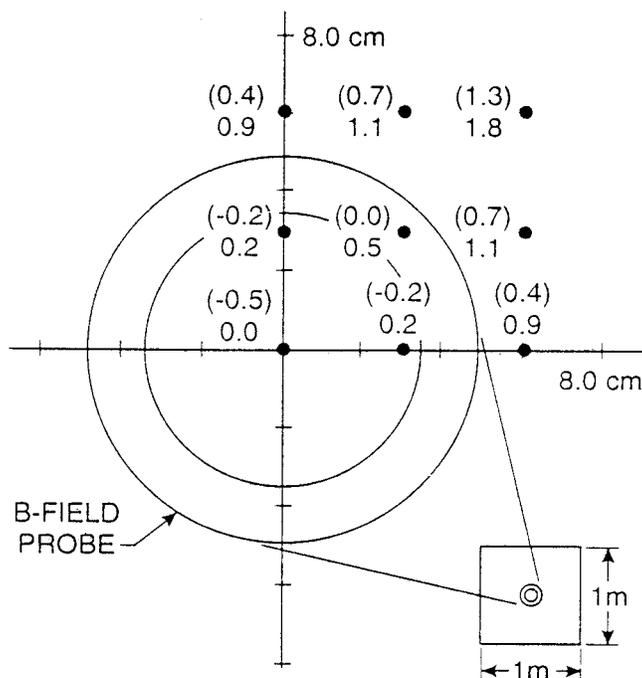


Figure 11— Percentage departure of B_z from $B_z(0, 0, 0)$ for positions in the plane of a square current loop $1\text{ m} \times 1\text{ m}$ and 3 cm above and below the plane (parentheses)

6.3.2 Calibration procedure

The magnetic field meter shall be calibrated periodically with a frequency that is dependent in part on the stability of the meter. The magnetic field probe shall be placed in the center of a single loop (of many turns) with the plane of the probe coincident with that of the loop. Figure 12 shows a schematic view of the probe, loop, and associated apparatus. The loop dimension should be at least $1\text{ m} \times 1\text{ m}$ for a probe with a 10 cm diameter. The loop may be scaled upward or downward for larger or smaller probes, respectively, to maintain a level of uniformity across the probe comparable to that shown in figure 11. It is noted with emphasis that the calibration field may be generated with other coil systems provided that comparable uniformities can be obtained. Information on fields generated by rectangular, square, and circular coil systems (including Helmholtz coils) is given in [B7], [B13], [B18], and [B24].

Calibrations should be performed for each axis of three-axis probes. Calibrations should also be accompanied by checks for crosstalk (see clause 3) between the detector circuitry for each probe. Magnetic field meters with three-axis probes should also be calibrated for one orientation where approximately the same flux passes through all the coils.

A plot of the calculated magnetic field values at the center of the loop, $B_z(0, 0, 0)$, vs. the current applied to the loop shall be made (see figure 6 for electric field case). The uncertainty in the calculated magnetic field shall be indicated at a representative point with a vertical error bar. This error bar represents the combined uncertainties (i.e., the square root of the sum-of-the-squares) in the current measurement, the side dimension of the calibration loop, and the field nonuniformity ($<0.5\%$ for 10 cm probe), and shall be less than $\pm 3\%$.

NOTE — For example, if the uncertainties in the current measurement and loop dimension are $\pm 0.2\%$ and $\pm 2\%$, respectively, the combined uncertainty in the value of the calibration field is

$$\pm[(0.2)^2 + (2.0)^2 + (0.5)^2]^{1/2} \text{ or } \pm 2.1\%$$

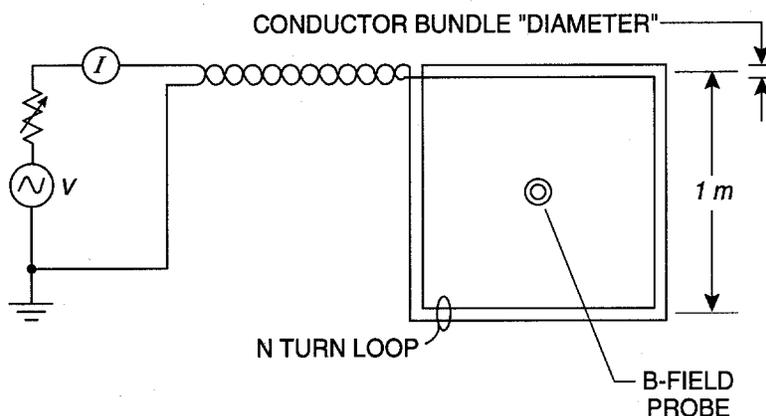


Figure 12— Schematic of circuit for calibration of magnetic field meter

A region of acceptable field meter readings, given by $B_z(0, 0, 0) \pm 10\%$, also shall be indicated on the plot and measured values obtained with the field meter that is being calibrated shall be plotted. At least three magnetic field levels for each range of the field meter, sufficient to span 30–90% of full scale, shall be recorded for meters with analog displays. At least four magnetic field levels, sufficient to span 10–90% of full scale, shall be recorded for meters with digital displays. Field meters with autoranging capabilities shall be calibrated on each range at no less than three representative points that span most of the range. On the most sensitive range, one of the calibration points shall be 10% of the maximum value *for that range*. On the least sensitive range, one of the calibration points shall be 90% of the maximum value *for that range*. The maximum measured field shall occur when the probe axis is rotated to within $\pm 10^\circ$ of the loop axis (z -axis), and the maximum value shall lie within the region of acceptable field meter readings. Field meters with readings that fail to satisfy the above criteria (i.e., data points lie outside the $\pm 10\%$ region) shall be considered inaccurate.

The recorded field values permit the determination of correction factors that should be applied to field meter readings when measurements are performed in the vicinity of power lines. The uncertainty associated with the above calibration process is equal to $\pm 3\%$ once the correction factors have been applied to the field meter readings.

Perturbations of the calibration field can occur because of ferromagnetic materials in close proximity to the calibration loop. For example, large permeability materials (such as steel in a nearby cabinet or desk, or a bracket under a table) will concentrate the magnetic flux and may perturb the value of the calculated field in the calibration loop. The influence of nearby ferromagnetic materials on the calibration field should be checked using a trial and error approach (e.g., the influence of a nearby relay rack on the magnetic field could be examined as a function of distance from the calibration coil).

The calibration loop should be no closer than two side dimensions away from any ground plane to avoid significant perturbations of the calibration field by image current loops [B9].

Calibrations shall be made prior to and after any extended period of meter use.

Energizing power supplies used for calibrations shall be nearly free ($< 1\%$) of harmonic content (see 4.2).

The temperature and humidity shall be recorded at the time of calibration to permit corrections for these parameters, if necessary, when measurements are performed under power lines.

6.4 Immunity from interference

Perturbation of B -field meter operation due to anticipated levels of ambient electric field strength under power lines should be quantified by the manufacturer and supplied to the user. Such perturbations, expressed as percentages, should be incorporated into measurement reports if significant [figure 1, G(2)].

6.5 Parameters affecting accuracy of magnetic field measurements

Many of the difficulties described in 4.5 for making E -field measurements are not serious considerations for B -field measurements. Positioning the probe, reading errors, proximity effects of the observer or nearby (nonconducting) objects, electrical leakage of probe handles, and nonuniformity of the field have much less or negligible impact. Electrical shielding of the probe, however, is essential in avoiding induced currents from the ambient electric field.

Temperature effects on the detector and poor mechanical balance of the meter movement (for meters with analog displays) remain possible sources of uncertainty.

7. Magnetic field measurement procedures

7.1 Procedure for measuring the magnetic field near power lines

The magnetic field under power lines should be measured at a height of 1 m above ground level. Measurements at other heights of interest shall be explicitly indicated. Field meters with single-axis probes shall be oriented to measure the maximum reading. Alternatively, field meters with three-axis probes may be used to measure the resultant magnetic field [equation (2)]. Horizontal and vertical field components may be measured when required for comparisons with calculations or for calculating induction effects in fences, etc. In all cases, when reporting measurement results, the quantity being reported (e.g., the maximum magnetic field or the resultant magnetic field) shall be clearly indicated.

It should be noted that during measurements of elliptically or circularly polarized fields, the resultant magnetic field will be greater than the maximum magnetic field [B10], [B11]. The largest difference occurs for the case of circular polarization when the resultant magnetic field exceeds the maximum field by 41% [equation (3)].

It also should be noted that the resultant magnetic field, B_R , is equal to the rms total magnetic flux density, independent of the phases of the orthogonal components [B12]. One consequence of the phase independence is that B_R is not unique in the sense that magnetic fields with different geometries can have the same resultant magnetic field. For example, a linearly polarized magnetic field with orthogonal components $B_0 \sin \omega t$ and $B_0 \sin \omega t$, and a circularly polarized magnetic field with orthogonal components $B_0 \sin \omega t$ and $B_0 \cos \omega t$ will have the same resultant, B_0 .

In cases where the magnetic field remains nearly constant, single-axis field meters may be used to determine the resultant field by measuring the vertical and horizontal field components and combining them according to equation (2). If signals from the individual probes of a three-axis field meter can be observed, one of the probes may be rotated to determine the maximum field.

The operator may stay close to the probe. Nonpermanent objects containing magnetic materials or nonmagnetic conductors should be at least three times the largest dimension of the object away from the point of measurement in order to measure the unperturbed field value. The distance between the probe and permanent magnetic objects should not be less than 1 m in order to accurately measure the ambient perturbed field.

Nonmagnetic metal objects will develop eddy currents due to the time variation of magnetic flux. The magnetic fields generated by these eddy currents will vary as the inverse third power of distance for large distances compared to the dimensions of the metal object.

To provide a more complete description of the B -field at a point of interest, measurement of the maximum and minimum fields with their orientations in the plane of the field ellipse can be made (see 5.1).

7.2 Lateral profile

The procedures for E -field measurements (see 5.2) shall be followed.

7.3 Longitudinal profile

The procedures for E -field measurements (see 5.3) shall be followed.

7.4 Precautions and checks during B -field measurements

7.4.1 Harmonic content

The response of certain magnetic field meters is influenced by high levels of harmonic content. Therefore, if possible, the waveform of the field or its derivative (induced voltage) should be observed to obtain an estimate of the amount of harmonic content (see 6.2). A qualitative observation can be made with an oscilloscope. Replacement of the oscilloscope with a wave analyzer would permit measurements, in percent, of the various harmonic components.

NOTE — The magnitudes of harmonic components in the induced voltage (field derivative) are enhanced by the harmonic number.

7.5 Measurement uncertainty

Measurement uncertainties due to calibration, temperature effects, etc., shall be combined (square root of the sum-of-the-squares) and reported as total estimated measurement uncertainty. The total uncertainty should not exceed $\pm 10\%$.

8. Reporting field measurements

Background information, such as environmental conditions (e.g., temperature, humidity, ground cover), transmission line parameters (e.g., line voltages and currents, conductor geometry, measurement locations), and instrumentation used should be recorded. Figure 1 is an example of a typical background data sheet for transmission line field measurements. Figure 1 should not be regarded as being appropriate for all measurement situations. Depending on the measurement objectives (e.g., comparison of lateral profile with theoretical prediction vs. measurement of a typical lateral profile), more or less information may be required. Plots of electric and magnetic fields as depicted in figure 7 are recommended. A plan view similar to that shown in figure 8 is also recommended to provide further details of environmental conditions and line parameters.

9. Bibliography

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Annex A Units and conversion factors

(Informative)

A.1 References

This annex shall be used in conjunction with the following publication.

IEEE Std 268-1992, American National Standard for Metric Practice (ANSI).⁶

A.2 Units and conversion factors

Units preferred by the IEEE are the International System of Units (Système International d’Unités, or SI units). Some commonly used units and conversion factors are listed in table A.1. For additional units and conversion factors, see IEEE Std 268-1992 .

A.3 SI units

Time:	second (s)
Electric potential:	volt (V), kilovolt (kV)
Current:	ampere (A)
Capacitance:	farad (F)
Inductance:	henry (H)
Resistance:	ohm (W)

Table A.1—Conversion from customary to SI units

To convert from (other units)	To (SI units)	Multiply by
Length		
inch (in)	meter (m)	2.540 E - 02
foot (ft)	meter (m)	3.048 E - 01
mile (mi)	meter (m)	1.609 E + 03
Magnetic induction		
gauss	tesla (T)	1.000 E - 04

A.4 Useful physical constants

Permeability constant μ_0 $4\pi \cdot 10^{-7}$ H/m

Permittivity constant ϵ_0 $8.854 \cdot 10^{-12}$ F/m

⁶IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.