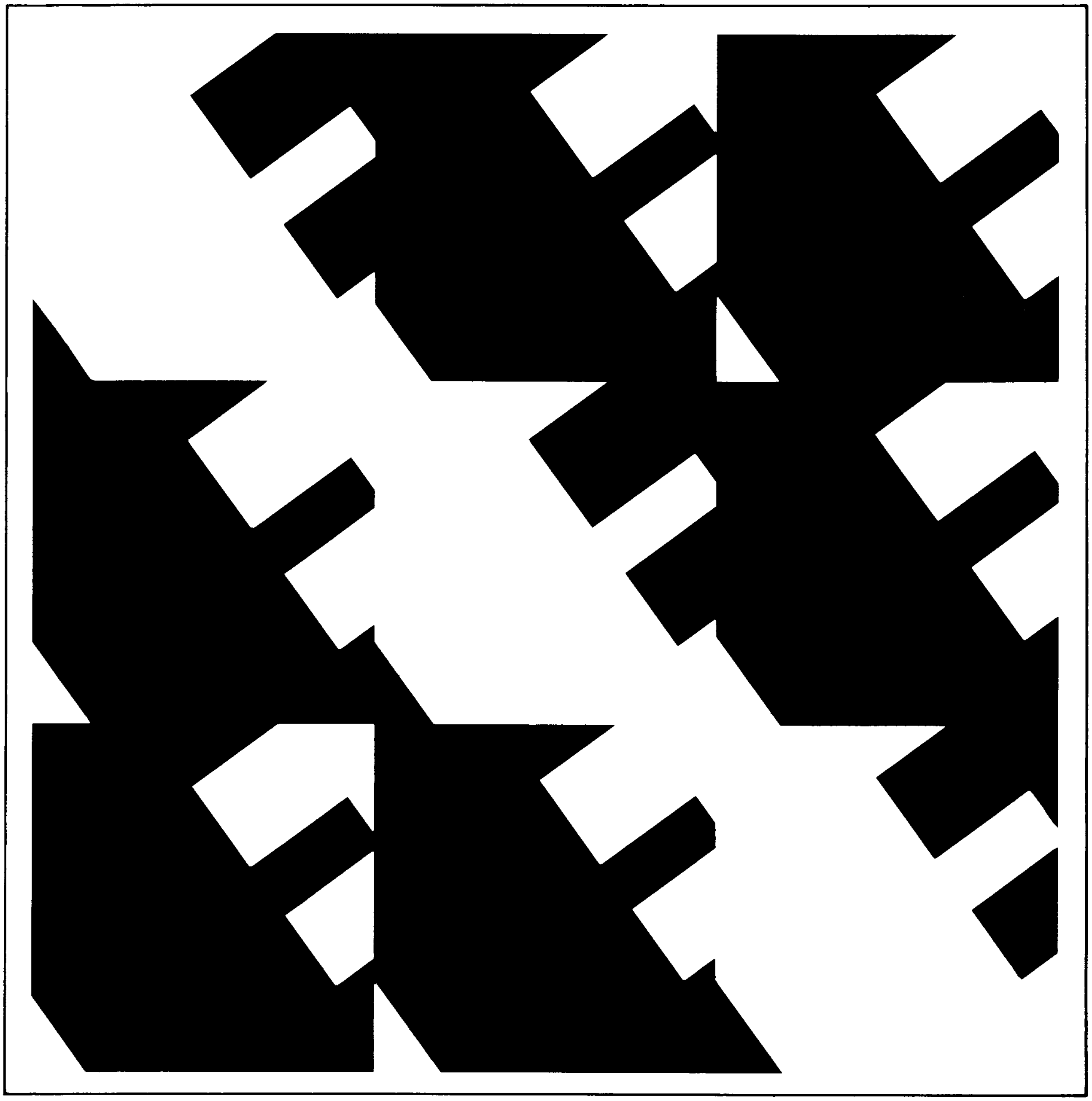
AMERICAN NATIONAL STANDARD

ANSI/IEEE Std 644-1987
(Revision of IEEE Std 644-1979)

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



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An American National Standard

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

Sponsor

Corona and Field Effects Subcommittee
of the
Transmission and Distribution Committee
of the
IEEE Power Engineering Society

Approved June 19, 1986
IEEE Standards Board

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Foreword

(This Foreword is not a part of ANSI/IEEE Std 644-1987, IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines.)

The working group is indebted to Martin Misakian for leading and coordinating the effort to update and expand IEEE Standard 644-1979, IEEE Recommended Practices for Measurement of Electric and Magnetic Fields from AC Power Lines, into the present document.

Dr. Misakian and his task force of Luciano Zaffanella, Rod Baishiki, and Bruce Whitney were responsible for preparing the original version of this document, which was presented as a working group report at the 1977 IEEE Power Engineering Society Summer Meeting in Mexico City. The working group members acknowledge the contribution of the many participants to the field trips at the Bonneville Power Administration (BPA) and at the Electric Power Research Institute (EPRI) Project Ultra-High Voltage (UHV), particularly Dr. Dan Bracken, formerly of BPA, Dr. Don Deno of Project UHV, members of the Energy Research and Development Administration (ERDA) sponsored *E*-Field Project[1] at the National Bureau of Standards (NBS), and the contribution of the participants to a special Field Strength Measurement Workshop organized by W. Johnson of EPRI. Contributions of working group members during the preparation of the original document and the present version are also gratefully acknowledged.

This standard was prepared by the AC Fields Working Group of the Corona and Field Effects Subcommittee of the Transmission and Distribution Committee of the IEEE Power Engineering Society. At the time it approved this standard, the working group had the following membership:

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[1] See [B8] on p 21.

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

1. Purpose

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 of this standard.

2. Definitions

For additional definitions, see ANSI/IEEE Std 100-1984 [1].[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 (see **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]. *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 $\vec{E}$ can be expressed in rectangular coordinates as

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

The space component in the x-direction is

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

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 Eq 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 **single-phase** and **polyphase ac fields.**

frequency. The number of complete cycles of sinusoidal variation per unit time. *Note:* (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.

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

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[2] The numbers in brackets correspond to those of the references listed in Section 3; when preceded by B, they correspond to the bibliography in Section 9.

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 may also have voltage or current sources with significant harmonic content.

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 carrier. *Note:* In a zero electric field, the force $\vec{F}$ 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 ($1\ \mathrm{T} = 10^4\ \mathrm{G}$).

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 **electric field strength.**

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

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.

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 **electric field strength.**

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. See **electric field strength.** *Note:* For polyphase power lines, the electric field at large distances ($\geq$ 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 (less than 10%) of the major axis when measured at a height of 1 m above ground level. Similar remarks apply to the magnetic field.

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.

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

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.

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.

3. References

[1] ANSI/IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms.[3]

4. Electric Field Strength Meters

4.1 General Characteristics of Electric Field Strength Meters. Two types of meters used to measure the electric field strength from ac

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[3] ANSI/IEEE publications can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018, or from the Institute of Electrical and Electronics Engineers, Service Center, Piscataway, NJ 08854.

power lines are described in technical literature: (1) the free-body meters, which measure the steady-state induced current or charge oscillating between two halves of an isolated conductive body in an electric field [B2], [B15]; and (2) the ground-reference-type meter, which measures the current-to-ground from a flat probe introduced into an electric field [B10]. 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 4.3.1.2. 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 US 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 Table 1, Section G. For example, if the field meter

Table 1
Typical Background Data Sheet

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, Fig 6) ______
C. Atmospheric Conditions
  (1) Temperature, °C ______
  (2) Relative humidity ______
  (3) Barometric pressure, mm of Hg ______
  (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) ______

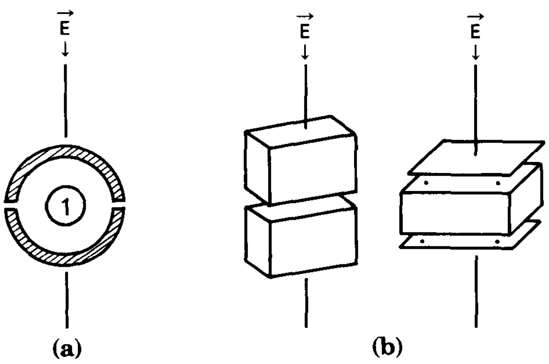

Fig 1
(a) Spherical *E*-Field Probe; (b) Geometries of Commercial US *E*-Field Meters

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.

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

$$Q = \int_{S/2} \vec{D} \cdot \mathrm{d}\vec{A} \qquad \text{(Eq 2)}$$

where $\vec{D}$ is the electric displacement and $\mathrm{d}\vec{A}$ is an area element on half of the body with total surface area S. The case of spherical geometry [Fig 1(a)] yields the result

$$Q = 3\pi a^2 \epsilon_0 E \qquad \text{(Eq 3)}$$

where a is the radius of the sphere and ϵ_0 is the permittivity of free space [B12].

NOTE: The surface charge density is given by $3\epsilon_0 E \cos\theta$. Integration over the hemisphere gives Eq 3 (see [B12]).

For less symmetric geometries, the result can be expressed as

$$Q = k\epsilon_0 E \qquad \text{(Eq 4)}$$

where k is a constant dependent on geometry. Sensing electrodes resembling cubes and parallel plates [Fig 1(b)] 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

$$I = \frac{\mathrm{d}Q}{\mathrm{d}t} = k\omega\epsilon_0 E_0 \cos \omega t \qquad \text{(Eq 5)}$$

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 Eq 5 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 normally calibrated to read the rms value of the power frequency field, measures a quantity that is proportional to the average value of the rectified power frequency signal. The response of the detector to harmonic components in the *E*-field depends on the specific design of the measuring electronics. In any case, because of the signal-averaging feature, the analog output will not necessarily be the rms value of the composite *E*-field waveform (fundamental plus harmonics) [B8].

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.

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

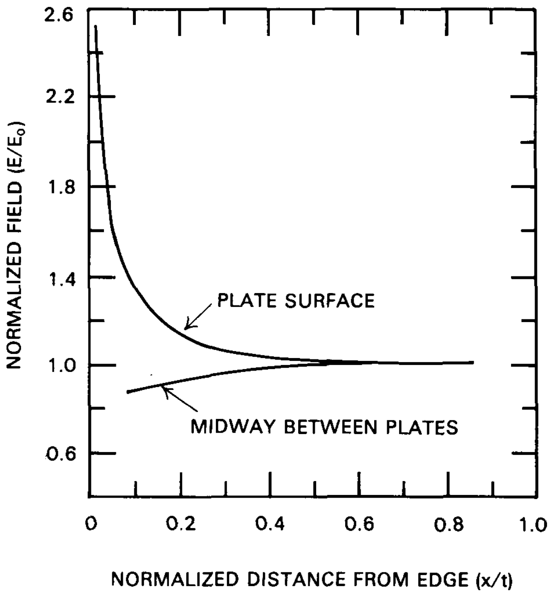

Fig 2
Normalized *E*-Field at Plate Surface and Midway Between Plates

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 [B14] as a function of normalized distance x/t from the plate edge in Fig 2.

NOTE: For field distributions between finite size parallel plates in the absence of nearby ground planes, see also [B13].

Numerical values are presented in Table 2. 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.

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].

Table 2
Normalized *E*-Field Values Midway Between Plates and at Plate Surfaces

x/t	E/E_0
Midway Between Plates	
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

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 Fig 3. 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 [B8]. Theoretical considerations and experimental measurements [B8] 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.

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

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[4] Project Ultra-High Voltage, Pittsfield, MA.

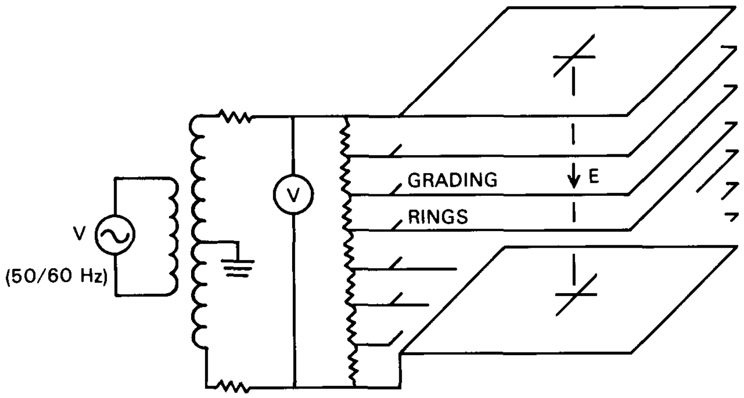


Fig 3
Large Parallel Plates Used for Calibration of E-Field Meter

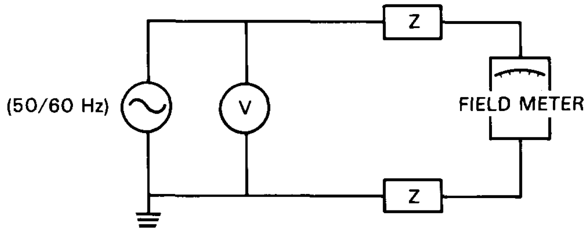


Fig 4
Current Injection Calibration Check

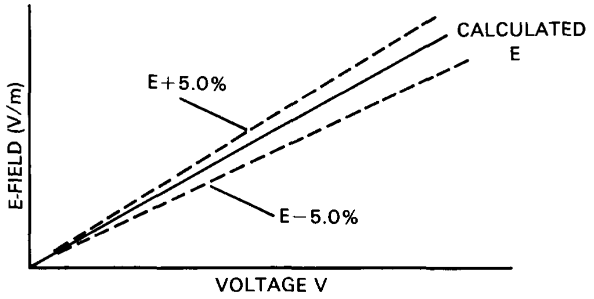
$$E = I/(\epsilon_0 \omega A) \quad \text{(Eq 6)}$$

where ω is the angular frequency of the line voltage [B15].

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 [B15], [B10]. 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 Fig 4 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 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 Fig 4, 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.



NOTE: Uncertainty in the voltage should be indicated with a representative horizontal line.

Fig 5
Known *E*-Field for Large Parallel Plates and Tolerance Levels

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 [B8].

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 Fig 3, with the insulating handle normally used during measurements. The dimensions of the structure should be 1.5 m × 1.5 m × 0.75 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 [B8]. 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 [B8]. 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 [B11]. For example, 10 MΩ resistors are satisfactory for applied voltages up to 10 kV (that is, $E \sim 13$ kV/m).

A plot of calculated *E*-field magnitude versus applied voltage shall be made as shown in Fig 5, where a region of ±5.0% error is indicated. The measurement uncertainty of the applied voltage shall be indicated with a representative horizontal error bar. The maximum measured *E*-field value shall occur when the meter axis is rotated to within ±10 degrees relative to the vertical (Fig 3) and this maximum value shall be within ±5.0% of the calculated magnitude. Measured values of the maximum *E*-field obtained in this manner shall also be plotted. At least three calibration points shall be obtained for each range of the electric field strength meter that will be used. Meters with readings that fail to satisfy both of the above criteria (that is, data points lie outside the ±5.0% region) will be considered inaccurate.

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 Table 1, Section G2).

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 Section 5 on field measurement procedures.

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 (Fig 1) in a nonuniform single-phase ac field generated by a point charge (in the absence of nearby ground planes) is given by

$$I = 3\pi a^2 \omega \epsilon_0 E \left[1 - \frac{7}{12}\left(\frac{a}{d}\right)^2 + \frac{11}{24}\left(\frac{a}{d}\right)^4 \ldots\right] \qquad \text{(Eq 7)}$$

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 [B9]. 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 Eq 3 and Eq 5 reveals that the induced current is the same as that produced by a uniform field of magnitude $Q/4\pi\epsilon_0 d^2$ 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

$$\Delta E/E \cong 4\ a/d = 0.4$$

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 Eq 7, 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 balance of an analog display can also 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 degrees (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 meter's inclination, 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 Procedures[5]

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 ~1.5% and ~3% [B5], [B8]. 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], [B8].

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 [B8]. 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,** Section 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 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 (Figs 6 and 7). The lateral profile 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.

5.3 Longitudinal Profile (Fig 7). The longitudinal profile of the field strength should be

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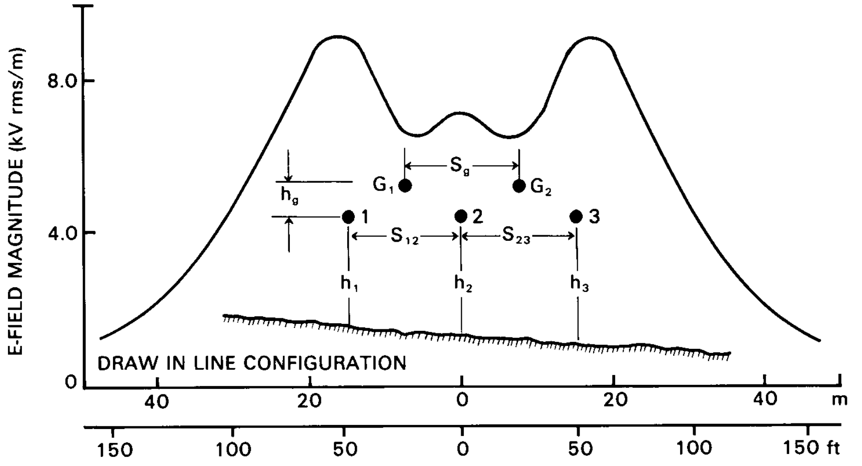
[5] See also Section 8.



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

Fig 6
Example of Lateral Profile of Vertical *E*-Field Strength at Midspan

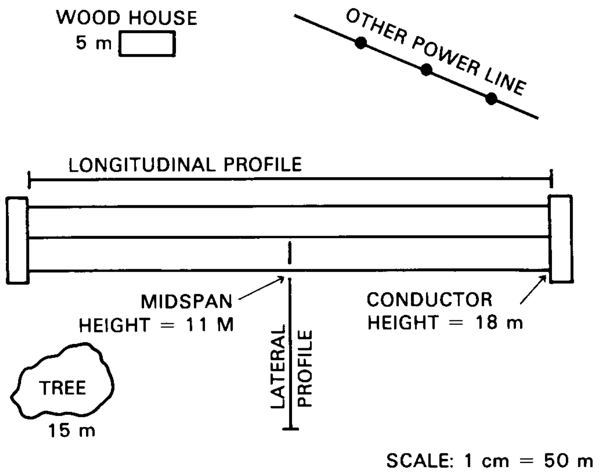


Fig 7
Typical Plan View with Heights of Permanent Nearby Objects

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.

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 ±10%.

6. Magnetic Field Meters

6.1 General Characteristics of Magnetic Field Meters. Magnetic field probes consisting of electrically shielded coils of wire have been used in conjunction with portable voltmeters to measure power frequency *B*-fields under high-voltage power lines. 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.

In contrast to *E*-field measurements, there has been less experience accumulated for measuring *B*-fields under transmission lines. This relative inexperience is offset to a degree by 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 Section G of Table 1.

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)

$$\nabla \cdot \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \text{(Eq 8)}$$

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

$$\oint \vec{E} \cdot \mathrm{d}\vec{l} = -\frac{\partial}{\partial t}\int_A \vec{B} \cdot \mathrm{d}\vec{A} \qquad \text{(Eq 9)}$$

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 $\vec{B}$ is a quasistatic uniform field normal to area A, as shown in Fig 8, the line integral can be regarded as the electromotive force (EMF) developed in the loop, and a current I will flow in response to the time-rate-of-change in magnetic flux BA. That is,

$$\text{EMF} = \oint \vec{E} \cdot d\vec{l} = -\frac{\partial}{\partial t}(BA) \qquad \text{(Eq 10)}$$

and from Fig 8

$$\text{EMF} = -\,\omega B_0 A \cos \omega t \qquad \text{(Eq 11)}$$

For a loop of many turns, the EMF given by Eq 11 will develop over each turn and the voltage V will increase accordingly. The induced current 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 the EMF and B_0 given by Eq 11 assumes that the direction of B_0 is perpendicular to the plane of the coil. Because only the space component of $\vec{B}_0$ perpendicular to the area of the loop generates an EMF, 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.

6.3 Calibration of Magnetic Field Meters

6.3.1 Description of Calibration Apparatus. Calibration of magnetic field probes is typically done by introducing the probe into a nearly uniform magnetic field of known magnitude and direction [B7]. Helmholtz coils have frequently been employed to generate such fields, but the more simply constructed single loop (of many turns) with rectangular geometry has also been used. The simplicity in construction is at the expense of reduced field uniformity, but sufficient accuracy 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 [B16]

$$B_z = \frac{\mu_0}{4\pi} IN \sum_{\alpha=1}^{4} \frac{(-1)^{\alpha} d_{\alpha}}{r_{\alpha}[r_{\alpha} + (-1)^{\alpha+1} C_{\alpha}]} - \frac{C_{\alpha}}{r_{\alpha}(r_{\alpha} + d_{\alpha})} \qquad \text{(Eq 12)}$$

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 is the rms current, μ_0 is the permeability of air, and the coordinates x, y, and z are shown in Fig 9. 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 12 has been used to calculate the field values at and near the center of a square loop of dimensions 1 m × 1 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 are plotted in Fig 10. Also shown in Fig 10 is an approximate out-

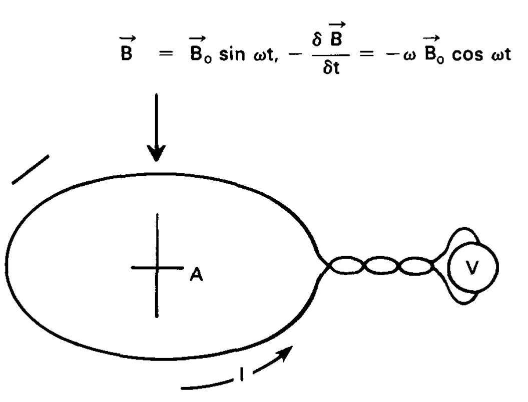


Fig 8
Conducting Loop in Quasistatic Uniform *B*-Field

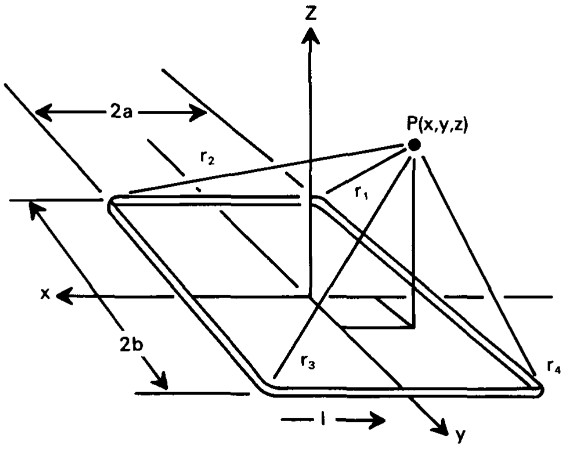


Fig 9
Coordinate System for Current Loop Generating Magnetic Field B_z

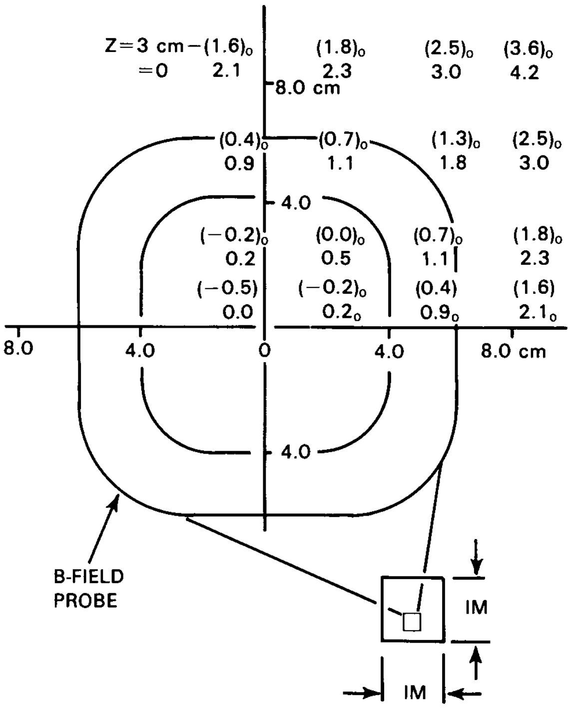


Fig 10
Percentage Departure of B_z from $B_z(0,0,0)$ for Positions in the Plane of a Square Current Loop 1 m × 1 m and 3 cm Above and Below the Plane (Parenthesis)

line (scale drawing) of a commercially available magnetic field probe. A 1.0% change in the loop dimensions changes the values over the probe by ~ 1.0%.

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 11 shows a schematic view of the probe, loop, and associated apparatus. The loop dimensions should be at least 1 m × 1 m. An indication of the *B*-field nonuniformity for a 1 m × 1 m loop is given in Fig 10; for the probe shown, the accuracy of the calibration is within 2.0% of the *B*-field value at the center.

If available, Helmholtz coils of adequate size [B12, pp 154–158] may also be used for calibrations.

A plot of the calculated *B*-field values in the center of the current loop (Eq 12, $x = y = z = 0$) versus the applied current shall be made with a region of ± 5.0% error indicated (see Fig 5 for the *E*-field case). The measurement uncertainty of the applied current shall be indicated with a representative error bar. The maximum measured *B*-field value shall occur when the probe axis is rotated to within ±10% of the loop axis (z-axis) and this maximum value shall be within ±5.0% of the calculated magnitude. Measured values of the maximum *B*-field obtained in this manner shall also be plotted Meters with readings that fail to satisfy either of the above criteria (that is data points lie outside the ±5.0% region) will be considered inaccurate.

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.

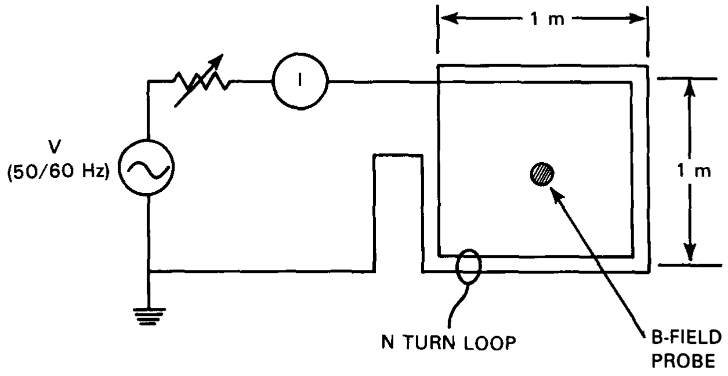


Fig 11
Schematic of Circuit for Calibration of Magnetic Field Meter

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 (Section G2 of Table 1).

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 mechanical balance of the meter movement remain possible sources of error.

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. The probe shall be oriented for the maximum reading because this quantity can be used for determining the maximum induction effects. Horizontal and vertical magnetic field components should be measured when needed for comparison with calculation, calculating induction effects in fences, etcetera.

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 ±10%.

8. Reporting Field Measurements

Background information such as environmental conditions (for example, temperature, humidity, ground cover), transmission line parameters (for example, line voltages and currents, conductor geometry, measurement locations), and instrumentation used should be recorded. Table 1 is an example of a typical background data sheet for transmission line field measurements. Table 1 should not be regarded as being appropriate for all measurement situations. Depending on the measurement objectives (for example, comparison of lateral profile with theoretical prediction versus measurement of a typical lateral profile), more or less information may be required. Plots of electric and magnetic fields as depicted in Fig 6 are recommended. A plan view similar to that shown in Fig 7 is also recommended to provide further details of environmental conditions and line parameters.

9. Bibliography

[B1] ADLER, R.B., CHU, L.J., and FANO, R.M. *Electromagnetic Energy, Transmission, and Radiation.* New York: Wiley, 1960, p 15.

[B2] BRACKEN, T.D. Field Measurements and Calculations of Electrostatic Effects of Overhead Transmission Lines. *IEEE Transactions on Power Apparatus and Systems,* vol PAS-95, Mar/Apr 1976, pp 494–504.

[B3] BROOKS, H.B., DEFANDORF, F.D., and SILSBEE, F.B. An Absolute Electrometer for the Measurement of High Alternating Voltages. *J. Res. National Bureau of Standards,* vol 20, 1938, pp 253–316.

[B4] DENO, D.W. Transmission Line Fields. *IEEE Transactions on Power Apparatus and Systems,* vol PAS-95, Sept/Oct 1976, pp 1600–1611.

[B5] DIPLACIDO, J., SHIH, C.H., and WARE, B.J. Analysis of Proximity Effects in Electric Field Measurements. *IEEE Transactions on Power Apparatus and Systems,* vol PAS-97, Nov/Dec 1978, p 2167.

[B6] FEYNMAN, R.P., LEIGHTON, R.B., and SANDS, M. The Feynman Lectures on Physics, Vol 2. Reading, MA: Addison-Wesley, 1964, p 17-1.

[B7] GREENE, F.M. NBS Field Strength Standards and Measurements (30 Hz–1000 MHz). *Proceedings of the IEEE,* vol 55, 1967, pp 970–981.

[B8] KOTTER F.R. and MISAKIAN, M. *AC Transmission Line Field Measurements.* NBS report prepared for US Department of Energy, Report No HCP/T-6010/E1, 1977; NTIS, Springfield, VA 22161.

[B9] MIHAILEANU, C., et al. *Electrical Field Measurement in the Vicinity of HV Equipment and Assessment of its Biophysiological Perturbing Effects.* CIGRE Paper 36-08, 1976, Paris, France.

[B10] MILLER, C.J. The Measurements of Electric Fields in Live Line Working. *IEEE Transactions on Power Apparatus and Systems,* vol PAS-86, Apr 1967, pp 493–498.

[B11] REILLY, J.P., et al. Electric and Magnetic Field Coupling from High-Voltage AC Power Transmission Lines—Classification of Short-Term Effects on People. *IEEE Transactions on Power Apparatus and Systems,* vol PAS-97, Nov/Dec 1978, p 2243.

[B12] REITZ, J.R. and MILFORD, F.J. *Foundations of Electromagnetic Theory.* Reading, MA: Addison-Wesley, 1960, p 52.

[B13] SHIH, C.H., DIPLACIDO, J., and WARE, B.J. Analysis of Parallel Plate Simulation of Transmission Line Electric Field as Related to Biological Effects Laboratory Studies. *IEEE Transactions on Power Apparatus Systems,* vol PAS-96, May/June 1977, p 962.

[B14] THACHER, P.D. *Fringing Fields in Kerr Cells.* Sandia Report SLA-74-0302, 1974. See also *IEEE Transactions on Electrical Insulation,* vol EI-11, June 1976, pp 40–50.

[B15] Transmission Line Reference Book—345 kV and Above, 2nd Edition. Palo Alto, CA: Electric Power Research Institute, 1982.

[B16] WEBER, E. *Electromagnetic Theory.* New York: Dover, 1965, p 131.

Appendix
Units and Conversion Factors

(This Appendix is not a part of ANSI/IEEE Std 644-1987, IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines, but is included for information only.)

A1. 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 A1.

For additional units and conversion factors, see ANSI/IEEE Std 268-1982 [A1].

Table A1
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

A2. SI Units

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

A3. 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

A4. References

[A1] ANSI/IEEE Std 268-1982, IEEE Standard for Metric Practice.