



IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz

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Sponsored by the
IEEE International Committee on Electromagnetic Safety

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IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz

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IEEE International Committee on Electromagnetic Safety

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Abstract: Techniques and instrumentation for the measurement and computation of electric, magnetic, and electromagnetic (EM) fields in the near field of an EM field source are presented in this recommended practice. Descriptions of the concepts, techniques, and instruments that can be applied to the measurement of the electric and magnetic fields and the currents induced in the human body by these fields are provided. Techniques for determining the current density and the electric field strength within the human body are discussed. This recommended practice is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic EM field theory and practice, and the potential hazards associated with EM fields. It will be most useful to bioeffects researchers, instrumentation developers and manufacturers, those developing calibration systems and standards, and persons involved in critical hazard assessments or hazard surveys.

Keywords: contact current measurement, electric field computation, electric field measurement, electromagnetic field computation, electromagnetic field measurement, ELF/VLF/RF survey instruments, exposure assessment, induced current measurement, magnetic field computation, magnetic field measurement, nonionizing radiation, RF/ELF/VLF hazard assessment

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Introduction

This introduction is not part of IEEE Std C95.3.1-2010, IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz.

In 1960, the American Standards Association approved the initiation of the Radiation Hazards Standards project under the co-sponsorship of the Department of the Navy and the Institute of Electrical and Electronics Engineers, Inc. (IEEE). Prior to 1988, C95 standards were developed by Accredited Standards Committee C95, and submitted to the American National Standards Institute (ANSI) for approval and issuance as ANSI C95 standards. Between 1988 and 1990, the committee was converted to Standards Coordinating Committee 28 (SCC 28) under the sponsorship of the IEEE Standards Board. In 2001, the IEEE Standards Association Standards Board approved the name “International Committee on Electromagnetic Safety (ICES)” for SCC 28 to better reflect the scope of the committee and its international membership. In accordance with policies of the IEEE, C95 standards are issued and developed as IEEE standards, as well as submitted to ANSI for recognition.

In 2005, SCC 28 and SCC 34 became Technical Committees 95 and 34, respectively, under a new IEEE Standards Coordinating Committee (SCC), SCC 39, which is now called ICES.^a

The present scope of IEEE ICES is as follows:

“Development of standards for the safe use of electromagnetic energy in the range of 0 Hz to 300 GHz relative to the potential hazards of exposure of man, volatile materials, and explosive devices to such energy. It is not intended to include infrared, visible, ultraviolet, or ionizing radiation. The committee will coordinate with other committees whose scopes are contiguous with ICES.”

There are five TC95 subcommittees, each of whose area of responsibility is described as follows in correspondence with its designated subcommittee number:

- I Techniques, Procedures, Instrumentation and Computation
- II Terminology, Units of Measurements and Hazard Communication
- III Safety Levels with Respect to Human Exposure, 0 Hz–3 kHz
- IV Safety Levels with Respect to Human Exposure, 3 kHz–300 GHz
- V Safety Levels with Respect to Electro-Explosive Devices

Subcommittee I of ICES Technical Committee 95 (TC95) is responsible for this recommended practice. Three standards, four recommended practices, and one guide have been issued. Present versions are as follows:

- IEEE Std C95.1TM-2005 [B55]^b
- IEEE Std C95.2TM-1999 [B56]
- IEEE Std C95.3TM-2002^c
- IEEE Std C95.3.1TM-2010
- IEEE Std C95.4TM-2002 [B57]
- IEEE Std C95.6TM-2002 [B58]
- IEEE Std C95.7TM-2005 [B59]
- IEEE Std 1460TM-1996 [B54]

^a Standards Coordinating Committees are established by the IEEE-SA Standards Board, and provide a mechanism to oversee the development of standards that are beyond the scopes of individual technical committees within IEEE's societies.

^b The numbers in brackets correspond to those of the bibliography in Annex D.

^c Information on references can be found in Clause 2.

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1. Overview

1.1 Scope

This recommended practice describes 1) methods for measuring external electric and magnetic fields and contact currents to which persons may be exposed, 2) instrument characteristics and the methods for calibrating such instruments, and 3) methods for computation and the measurement of the resulting fields and currents that are induced in bodies of humans exposed to these fields. This recommended practice is applicable over the frequency range of 0 Hz to 100 kHz.

1.2 Purpose

The purpose of this recommended practice is to describe preferred measurement techniques and computational methods that can be used to ascertain compliance with contemporary standards for human exposure to electric and magnetic fields in the frequency range of 0 Hz to 100 kHz such as

IEEE Std C95.1™-2005 [B55], IEEE Std C95.6™-2002 [B58], and similar standards.¹ This document is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic electromagnetic (EM) field theory and practice, and the potential hazards associated with exposure to EM fields. It will also be useful to bioeffects researchers, instrument developers and manufacturers, those developing calibration systems and standards, and individuals involved in critical hazard assessments or surveys.

1.3 Application

This recommended practice is not intended to replace any recommended practice or standard intended for a particular product or product family, but should be useful to regulatory agencies, manufacturers and operators of systems such as high-voltage transmission and distribution lines, underground power distribution vaults, induction motors, MRI devices, electric transportation, etc., and may also be useful in assessment of exposure from other equipment such as domestic appliances that generate and/or use EM energy, especially cookers, ovens, washing machines, tumble dryers, hair dryers and electric heaters, low-voltage power distribution lines, railway power distribution systems, electric welding and induction heating equipment, electronic security devices such as metal detectors, induction loop communications systems, and low-frequency radio communications and time-signaling transmitters that produce electric, magnetic, and EM fields in the workplace and general environment.

There are a number of other international and national standards that identify product-specific methods that also may be used, e.g., IEC 62369:2008 [B48], European standards EN 50357 [B33] and EN 50364 [B34] for electronic article surveillance (EAS) and RFID devices, and IEC 62233:2005 [B47] for appliances. The requirements of these or other national and international standards can take precedence over this document for the evaluation of human exposure from specific products and systems.

IEEE Std C95.1-2005 [B55], IEEE Std C95.6-2002 [B58], and other contemporary standards and guidelines (e.g., ICNIRP [B44]) for human exposure to electric, magnetic, and EM fields include provisions concerning induced and contact currents, internal current density, and internal electric field strength. Accordingly, this document contains a description of the concepts, techniques, and instruments that can be applied to the measurement and determination of these quantities.

While this recommended practice is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic EM field theory and practice and the potential hazards associated with exposure to electric, magnetic, and EM fields, it is also intended to be a general guidance document and should be most useful to bioeffects researchers, instrument developers and manufacturers, and those developing calibration systems and standards. It should also be useful to persons involved in critical hazard assessments or surveys. The material in Clause 4, Clause 5, and Clause 6 of this document that treats measurement problems, desirable instrument characteristics, and procedures for measuring external fields should be of direct interest to anyone concerned with potential EM exposure hazards.

The scope of IEEE ICES also includes potential hazards resulting from exposure of flammable materials and explosive devices to EM radiation. IEEE Std C95.4™-2002 [B57] provides an analysis of EM radiation phenomena that could present a potential hazard to the transportation, handling, or use of electric blasting caps or detonators in an EM environment; other documents, e.g., NAVSEA OP 3565, Volume 1 [B83] describe hazards associated with fuel and other flammable material in such environments. Although this recommended practice is devoted exclusively to methods used for the evaluation of human exposure to electric and magnetic fields, the measurement techniques and instruments described herein are also applicable to the measurement of fields in the vicinity of flammable materials and explosive devices.²

¹ The numbers in brackets correspond to those of the bibliography in Annex D.

² Equipment, including test and measurement equipment, operated in the vicinity of flammable materials, explosive devices, and explosive atmospheres may have additional safety requirements, not included in this recommended practice.

1.4 Frequency range

The techniques and instrumentation specified in this recommended practice are useful for field measurements over the frequency range of approximately 0 Hz to 100 kHz.³ In some cases a specific measurement technique or instrumentation arrangement will not be valid over the entire frequency range covered by this recommended practice.

1.5 Quantities and exposure metrics to be evaluated

1.5.1 Internal electric fields and currents

Electric fields and currents are induced in the human body when partial-body or whole-body exposures to electric or magnetic fields occur. IEEE Std C95.1-2005 [B55] and IEEE Std C95.6-2002 [B58] specify limits for these quantities, called *basic restrictions*, to protect against established adverse health effects. These basic restrictions include the *in situ* root-mean-square (rms) and peak electric field strength (V/m) and current (A). Derived values, called *maximum permissible exposure* (MPE) values (IEEE Std C95.1-2005 [B55] and IEEE Std C95.6-2002 [B58]), are specified in terms of the external electric and magnetic field strength and contact current levels that ensure that exposures conform to the basic restrictions. Other standards and guidelines have different names of their exposure limits on external electric and magnetic fields, e.g., *reference levels* (RL) (ICNIRP [B44]).

NOTE—Exceeding the MPE values does not necessarily mean that the exposures do not conform to the basic restrictions. In such cases a more detailed assessment is required to decide if the EMF exposures conform to the basic restrictions. Techniques in this recommended practice may be used for this purpose.

For best accuracy in predicting the magnitude of induced field strengths and current densities in humans, use of a representative model of the human body is required. The model position used in the exposure evaluation should be representative of the human body position and posture relative to the exposure source. Special measurement or computational techniques are then used to evaluate the induced fields, as described in the following clauses and subclauses.

For actual measurements of induced currents, a complication arises concerning the pathways through which these currents flow in a person's body. For example, when the exposure is such that the electric field is parallel to the axis of the body, the induced currents typically flow through the body or parts of the body, through the legs and the feet, to the ground or floor (i.e., whichever is the lowest potential surface in contact with the body). Instrumentation is available that can provide a measure of these electric-field-induced currents. In the case of magnetic field exposure, however, the currents that are induced in the body, called *eddy currents*, typically circulate around the cross sections of the anatomy, i.e., with the greater magnitudes being at the outer periphery of the body near the surface. These circulating currents typically do not exit the body in the same fashion as do electric-field-induced currents; consequently these present an important measurement challenge. However, evaluations of induced currents should consider contributions from both electric and magnetic fields.

1.5.2 Environmental electric and magnetic fields

For the purposes of this recommended practice, *environmental fields* means electric and/or magnetic fields external to the body, and measured in the absence of the body. The MPE values in IEEE Std C95.6-2002 [B58] that are applicable over the frequency range of this recommended practice are expressed in terms of the electric field strength (E), magnetic field strength (H), or magnetic flux density (B), and induced contact

³ These frequency limits should not be considered rigid or absolute, but are intended to be used as a general guide. Normally, the measurement results obtained with a particular measurement instrument do not abruptly become invalid at a specific frequency; rather the accuracy or sensitivity of the instrument, or both, deteriorate over some frequency range until eventually it becomes no longer usable. For example, some instruments designed for power frequencies (50/60 Hz) may be used for measuring fields from induction heaters up to 1 kHz. When using a particular instrument, a user should be aware of its frequency limitations.

currents. Most measurements at frequencies below 100 kHz are made in the near field of the source, where the field configuration can be relatively complex. Usually electric and magnetic fields need to be evaluated separately because their relationship is not easily predicted as it would be in the far field where the vectors are perpendicular and their magnitudes are in proportion to the free-space wave impedance (377 Ω). For well-defined EMF sources where analysis indicates that only one type of field (electric or magnetic) is sufficient to assess conformance with a particular MPE value, only that field component needs to be measured.

1.5.3 Contact currents

Contact currents flow through the body of a person touching objects that are at a different potential than that of the person. They can range from subliminal currents to life-threatening electric shocks. In addition to safety limits in the National Electrical Code® (NEC®) (NFPA 70, 2007 Edition) [B84], IEEE Std C95.6-2002 [B58] has limits for the contact currents that result from EM induction of voltage differences in the environment. Contact currents can be measured either as currents (in amperes) passing from an object to body (usually through the hand) or as a potential difference (in volts) between two extremities (hand to foot, or hand to hand).

1.6 Types of situations covered

- Static and quasi-static electric fields
- Static and quasi-static magnetic fields

This recommended practice treats non-propagating electric and magnetic fields (static, quasi-static, and reactive fields) found in the immediate vicinity of an EMF source.⁴

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std C95.3™-2002 (Reaff 2008), IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure to Such Fields, 100 kHz–300 GHz (supersedes IEEE Std C95.3-1991).^{5, 6}

3. Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.⁷

amplitude modulation: The process by which a continuous wave (carrier) is caused to vary in amplitude by the action of another wave containing information.

⁴For purposes of this recommended practice, *EMF* means *electric and magnetic fields* (see 3.1).

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⁷ *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

average power (\bar{P}): The time-averaged rate of energy transfer:

$$\bar{P} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} P(t) dt$$

averaging distance: The distance over which the internal electric field is averaged when determining conformance with basic restrictions.

averaging time: The appropriate time period over which exposure is averaged for purposes of determining conformance with a maximum permissible exposure (MPE) or reference level (RL).

axial cross section: A cross section of the body taken in a plane perpendicular to its long axis.

axial exposure: Exposure by an electric or magnetic field perpendicular to the axial cross section.

basic restrictions: Limitations on the internal electric fields, current, and current density that protect against known adverse health effects with an acceptable safety factor.

conductivity: The ratio of the conduction-current density in a medium to the electric field strength. The unit of conductivity is siemens per meter (S/m).

conform: A person's EMF exposures are within the safety limits from an applicable standard while allowing for the uncertainties of the exposure assessment method. *Syn:* **conformance assessment; conformity assessment.**

coverage factor: Factor (k) that multiplies the standard uncertainty (u) or relative standard uncertainty (u_r), giving an interval that may be expected to encompass a large fraction (usually 95%), of the distribution of values that could reasonably be attributed to the true exposure metric. *See also:* **relative standard uncertainty, standard uncertainty.**

dielectric constant: *See:* **permittivity.**

diode: A device having two terminals and exhibiting a nonlinear voltage-current characteristic; commonly, a semiconductor device that has the asymmetrical voltage-current characteristic typical of a single p-n junction.

dipole (antenna): **(A)** Any one of a class of antennas producing the radiation pattern approximating that of an elementary electric dipole. **(B)** A receiving sensor loaded in the center.

distortion factor (DF): The ratio of the rms value of the harmonic content to the root-mean-square (rms) value of the fundamental quantity, expressed as a percentage of the fundamental.

duty cycle: Deprecated. *See:* **duty factor.**

duty factor: The ratio of the pulse duration to the pulse period of a periodic pulse train.

duty ratio: The ratio of average to peak pulse power.

electric dipole: A pair of equal and opposite charges separated by an infinitesimal distance.

electric field (general): A vector field of electric field strength or of electric flux density.

NOTE—The term is also used to denote a region in which such vector fields have a significant magnitude.⁸

electric field strength (E): At a given point in space and time, E is force ΔF on a positive test charge ΔQ in the limit as the charge approaches zero, i.e.,

$$E = \lim_{\Delta Q \rightarrow 0} \frac{\Delta F}{\Delta Q}$$

Electric field strength may be measured either in newton per coulomb or in volt per meter (V/m).

NOTE—This term is sometimes called the *electric field intensity*, but such use of the word intensity is deprecated, since intensity connotes power in optics and radiation.

electric field vector: Electric field strength as a vector quantity with direction and magnitude. *See also:* **electric field strength.**

electric flux density (displacement): A vector equal to the product of the electric field strength and the permittivity of the medium. In an anisotropic medium, the permittivity is a function of direction; hence, the electric flux density is not necessarily in the same direction as the electric field strength. Electric flux density can be considered as a surface charge density and is expressed in units of coulombs per square meter (C/m²).

electromagnetic (EM) field: The mutually coupled time-varying electric and magnetic fields that transmits energy through space. This term is sometimes used incorrectly, instead of *electric and magnetic fields* or *EMF*.

NOTE—See **EMF** in 3.1.

electromagnetic (EM) radiation: The propagation of energy through space in the form of EM fields.

NOTE—Not intended to describe propagation along waveguides and other transmission lines.

environmental field: An electric or magnetic field external to the body measured in the absence of the body.

exposure metric: A single number derived from an exposure that varies over time, space, and frequency for the purposes of predicting health risks in epidemiology or other studies or for expressing exposure limits. *Syn:* **metric.**

finite difference time domain (FDTD) method: The FDTD method is a numerical algorithm for solving Maxwell's differential equations of electromagnetic (EM) field interactions in the time domain by discretizing the problem space into unit cells where the space and time derivatives of the electric and magnetic fields are directly approximated by simple, second-order accurate central-difference equations.

finite element method (FEM): A class of numerical algorithms for solving Maxwell's differential equations of electromagnetic (EM) field interactions. Discrete Differential Forms (DDF), which are finite element basis functions defined on a mesh, are utilized in the FEM.

NOTE—A *mesh* is a subdivision of the region into polyhedrons. The most common are triangles in two dimensions and tetrahedrons in three dimensions.

⁸ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

fundamental frequency: The frequency in a complex waveform with the greatest amplitude, and the principal frequency of a sinusoidal waveform. In the case of unmodulated sinusoidal waveforms, it is the lowest frequency of a harmonic series or Fourier representation of the periodic quantity. *Syn:* **primary frequency.**

NOTE—For fields associated with modern electrical power systems, the fundamental frequency is 60 Hz in most of the Americas, 50 Hz in most of the rest of world, and 400 Hz on airplanes and submarines. Other frequencies were used in the early years of electric power and still are in use, e.g., for traction systems.

grasping contact: An electrical connection with a large energized conductor made by firmly holding the conductor in the hand.

NOTE—In this recommended practice, a contact area of 15 cm² is assumed for such contact.

harmonic: A Fourier component of a signal or vector field whose frequency is an integral multiple of the fundamental frequency.

in situ electric (magnetic) field: *See:* **internal electric (magnetic) field.**

internal body current: The current that is induced in a biological subject that is exposed to low-frequency fields.

internal electric (magnetic) field: The electric (magnetic) field within biological tissue in its normal anatomical position.

ionizing radiation: Any electromagnetic (EM) or particulate radiation capable of producing ions directly or indirectly in its passage through matter. Examples are X-rays and gamma rays.

isotropic: Having the same properties in all directions.

isotropic probe: A sensing probe capable of radiating or receiving equally well in all directions, and equally responsive to all polarizations of electric and/or magnetic fields.

lower uncertainty limit (LUL): A lower bound of a measurement incorporating all sources of bias and random uncertainty so that the true value of a stated exposure metric is greater in 95% of repeat measurements. Also known as the *lower confidence limit (LCL)* when it includes only random uncertainties and omits uncorrected biases. *See also:* **upper uncertainty limit.**

loss tangent: The ratio of the imaginary component of the complex permittivity of a material to the real component of the complex permittivity.

magnetic dipole: A magnetic field moment caused by current flowing in an infinitesimally small loop. When the current is oscillating, the dipole becomes an elementary radiating magnetic dipole.

magnetic field strength (*H*): The magnitude of the magnetic field vector, expressed in units of amperes per meter (A/m).

magnetic field vector: A field vector that is equal to the ratio of the magnetic flux density to the permeability, expressed in units of amperes per meter (A/m). *See also:* **magnetic field strength.**

magnetic flux density (magnetic induction) (*B*): The vector quantity *B* producing a torque *T* (in newton meter) on a plane current loop in accordance with the relation $\mathbf{B} = IA(\hat{\mathbf{n}} \times \mathbf{B})$, where $\hat{\mathbf{n}}$ is the positive unit vector normal to the loop, *A* is its area (in units of meter squared) and *I* is the loop current (in units of ampere). Magnetic flux density is expressed in units of tesla (T), formerly weber per square meter.

maximum permissible exposure (MPE): The root-mean-square (rms) electric and magnetic field strengths, their squares, or the plane-wave equivalent power densities associated with these fields and the induced and contact currents to which a person may be exposed without harmful effect as set by incorporating an acceptable safety factor below hazardous levels. *See also: reference level.*

NOTE—Non-compliance with the MPEs does not mean that the basic restrictions have been exceeded. If an exposure is proven to be below the basic restrictions, the MPE can be exceeded. MPEs are closely comparable to *reference levels*, *derived limits*, and *investigation levels* as used in exposure standards and exposure guidelines prepared by various organizations, and can have indistinguishable meanings and applications.

maximum root-mean-square (rms) component: The rms component of an EMF vector in the direction that results in the maximum value. Mathematically, the maximum rms component is defined as follows:

$$G_{\max} = \sqrt{\frac{1}{T} \int_0^T (\hat{\mathbf{n}}_{\max} \cdot \mathbf{G}(t))^2 dt}$$

where T is the averaging time, $\mathbf{G}(t)$ is a time-dependent EMF vector, and $\hat{\mathbf{n}}_{\max}$ is a unit vector pointing in the direction that maximizes the expression. For a single-frequency, elliptically polarized field, $\hat{\mathbf{n}}_{\max}$ is aligned with the ellipse's major axis, and G_{\max} is the ellipse's semi-major axis divided by $\sqrt{2}$.

mean: The arithmetic average of a series of measurements or other data.

median: The value within a statistical distribution at which 50% of data are above and below.

modulation: Alteration of the waveform of a time-varying electric current, electric field, magnetic field, or electromagnetic (EM) field by impressing another waveform or signal in order to change the original amplitude, frequency, or phase

NOTE—For the purpose of this recommended practice, continuous wave (CW) operation is considered to be a special form of modulation, that is, zero modulation.

near-field region: For a device or object that produces electromagnetic (EM) fields, the near-field region is that region closest to the device where the following applies: 1) The electric and magnetic fields vary considerably from point to point; 2) The ratio of the electric to magnetic fields is not a constant, but varies from point to point; 3) The stored energy associated with the fields predominates over the energy that is radiated.

nonionizing radiation: Any electromagnetic (EM) radiation incapable of producing ions directly or indirectly. Microwaves and radio frequency (RF) energy are forms of nonionizing radiation.

non-uniform field: A field that is not constant in amplitude, direction, or relative phase over the dimensions of the body or body part under consideration. In the case of electric fields, the term is often applied to an environmental field disturbed by the presence of the body.

normal load current: The maximum current in an electric power transmission line under conditions that exclude outages or other emergency operating conditions.

open-circuit voltage: The potential difference between two conducting objects without a current load being applied to the objects.

passive or parasitic re-radiator: An electrically conducting structure located in the radiation field of a primary source of radio frequency (RF) electromagnetic (EM) fields that acts as a secondary radiating source because of RF currents induced in the structure. In some cases, re-radiators can produce localized EM fields significantly more intense than the co-located fields associated with the prime source. *See also: re-radiated fields.*

peak power density: The maximum instantaneous power density occurring during the interval when power is transmitted. Power density is expressed in units of watts per square meter (W/m^2).

NOTE— $1 \text{ W}/\text{m}^2 = 0.1 \text{ mW}/\text{cm}^2$.

peak power output: In a modulated carrier system, the output power averaged over a carrier cycle, at the maximum amplitude that can occur with any combination of signals to be transmitted.

peak pulse amplitude: The maximum absolute peak value of a pulse excluding spurious elements, such as spikes, provided that the spurious energy is small (5% or less) compared with the total energy in the pulse.

NOTE—Where such excursions are made, it is desirable that the amplitude chosen be illustrated pictorially.

peak vector magnitude: The greatest magnitude of a vector quantity at a single point in space over an observation time of at least one period.

permittivity (complex): The ratio of the electric flux density in a medium to the electric field strength at a point. Complex permittivity (ϵ^*) is expressed as

$$\epsilon^* = \epsilon_0(\epsilon' - j\epsilon'') = \epsilon_0 \left(\epsilon' - j \frac{\sigma}{\omega \epsilon_0} \right)$$

where ϵ_0 is the permittivity of free space (8.854×10^{-12} farads per meter), ϵ' is the dielectric constant, or real part of the complex relative permittivity, ϵ'' is the imaginary part of the relative complex permittivity, σ is the conductivity of the medium, and ω is the angular frequency in radian.

personal monitor: A portable device that can be worn on the body to measure, record, or analyze one or more components of an electric or magnetic field for purposes of exposure assessment.

polarization: That property of periodic electric or magnetic field describing the figure traced over one cycle by the extremity of the field vector at a fixed location in space.

NOTE—For a single-frequency field, the figure is in general elliptical. The commonly referenced circular and linear polarizations are obtained when the ellipse becomes a circle or a straight line, respectively. For multi-frequency fields, the polarization can have an arbitrary shape in the time domain. In the frequency domain, the field is composed of a sum of elliptically polarized components with variable phases and orientations with respect to each other.

power: A physical quantity describing the rate of delivery or transmission of energy. Power is measured in units of watt (W).

power gain: Of an amplifying device, the ratio of the radio frequency (RF) power delivered to a specified load impedance to the RF power absorbed by its input.

NOTE—Power gain is usually expressed in decibels (dB).

probe: A minimally perturbing device that contains an electrically small (in the medium) sensor (or sensors) for detecting and measuring a component of an electromagnetic (EM) field in air or a dielectric medium.

probe sensor-length: The maximum physical dimension of the sensing element, e.g., dipole or loop of an electric or magnetic field probe, respectively, or the dimension of the largest sensing element in a multiple array, i.e., the tip-to-tip dimension of a simple dipole or the diameter of a loop sensor. *Syn:* **probe-antenna length; probe length.**

pulse repetition frequency (PRF): In a pulsed or pulse-modulated system using recurrent pulses, the number of pulses per unit of time.

pulse repetition rate: *See:* **pulse repetition frequency.**

pulsed radio frequency (pulsed RF): A continuous-wave RF carrier signal that is amplitude-modulated at a known pulse repetition frequency (PRF) with a controlled duty factor.

quasi-static electric (magnetic) field: A field of interest whose wavelength is much longer than the specific distance from its source or any re-radiator that creates this field.

NOTE—Quasi-static electric and magnetic fields from any source are decoupled from each other. Therefore, eliminating the quasi-static electric field will not affect the quasi-static magnetic field.

radio frequency (RF): The frequency in the portion of the electromagnetic (EM) spectrum that is between the audio-frequency and infrared regions.

NOTE—The present practicable limits of RF are roughly 10 kHz to 300 GHz. Within this frequency range, electromagnetic (EM) radiation may be detected and amplified as an electric current at the wave frequency.

reference level (RL): The exposure field and contact current values derived or estimated from the basic restrictions, i.e., induced electric field and current density. *See also:* **maximum permissible exposure.**

relative standard uncertainty (u_r): The standard uncertainty divided by the mean. May also be expressed as a percentage (% u_r). Also known as the *relative standard deviation* or *coefficient of variation*. *See also:* **standard uncertainty.**

re-radiated fields: An electromagnetic (EM) field resulting from currents induced in an object, usually a conductor, by incident EM energy from one or more primary radiating structures. Re-radiated fields are sometimes called *reflected* or, more correctly *scattered fields*. The scattering object is sometimes called a *parasitic re-radiator* or *secondary radiator*. *See also:* **passive or parasitic re-radiator; scattering.**

response time: The time required for a field-measuring instrument to reach some specified percentage of the final value after being placed in the field to be measured.

NOTE—In this recommended practice, 90% of the final value is assumed.

resultant: A metric for an EMF vector $G(t)$ defined by

$$\sqrt{G_{x, \text{rms}}^2 + G_{y, \text{rms}}^2 + G_{z, \text{rms}}^2}$$

where $G_{x, \text{rms}}$, $G_{y, \text{rms}}$, and $G_{z, \text{rms}}$ are the root-mean-square (rms) components of the field measured simultaneously or sequentially in three orthogonal directions at a single point in space. If the field is either static or periodic over the time when the three components are measured (i.e., constant peak magnitude, frequency composition, polarization and spatial orientation), the resultant equals the rms vector magnitude. *See:* **rms vector magnitude.** *See also:* **maximum root-mean-square (rms) component; rms (EMF) vector magnitude.**

rms (EMF) vector magnitude: The root-mean-square (rms) of the magnitude of an EMF vector.

root-mean-square (rms): The measure of average effect determined from the function:

$$\sqrt{\frac{1}{T} \int_0^T v(t)^2 dt}$$

where a signal $v(t)$ is measured over an averaging time T .

scattering: The process that causes waves incident on discontinuities or boundaries of media to be changed in direction, frequency, phase, or polarization.

screening method: A simple method for measuring EMF exposures in order to determine whether more accurate methods are needed to achieve conformity with the applicable safety limits. *Syn:* **screening measurements.**

separation distance: As applied to the measurement of electric and magnetic fields, separation distance means the distance between a source and the nearest point on the probe sensing elements.

spatial average: As applied to the measurement of electric or magnetic fields for the assessment of whole-body exposure means the root-mean-square (rms) value, i.e., rms value of the field over an area equivalent to the vertical cross section of the adult human body. The spatial average can be measured by scanning (with a suitable measurement probe) a planar area equivalent to the area occupied by a standing adult human (projected area). In most instances, a simple vertical, linear scan of the fields over a 2 m height will be sufficient. Averages can also be taken over the effective volume occupied by the person.

standard uncertainty (u): The standard deviation associated with a measurement that characterizes the dispersion of values that occurs upon making repeated measurements under nearly identical conditions.

touch contact: A contact of small area made between the human body and an energized conductor.

NOTE—In this recommended practice, a contact area of 1 cm² is the assumed touch contact area.

uncertainty factor: A factor incorporating all sources of bias and random uncertainty that multiplies a measurement in order to enclose the true value of the specified measurement for 95% of repeat measurements.

uniform field: A field that is constant in amplitude, direction, and relative phase over the dimensions of the body or body part under consideration. In the case of electric fields, the definition applies to an environmental field undisturbed by the presence of the body.

upper uncertainty limit (UUL): An upper bound of a measurement incorporating all sources of bias and random uncertainty so that the true value of a stated measurement is less in 95% of repeat measurements. Also known as the *upper confidence limit* (UCL) when it includes only random uncertainties and omits uncorrected biases. *See also:* **lower uncertainty limit.**

vector magnitude: The length of an EMF vector. In Cartesian coordinates, the magnitude of a vector \mathbf{G} equals

$$\sqrt{G_x^2 + G_y^2 + G_z^2}$$

where G_x , G_y , G_z are the components of the vector. *See also:* **rms (EMF) vector magnitude.**

3.1 Special terms

EMF: For the purposes of this recommended practice, EMF means electric and magnetic fields [although it also may mean a propagating electromagnetic (EM) field in other contexts]. As used here, it means low-frequency fields (<100 kHz) where the relationship between electric and magnetic fields is not mutually determined and the impedance that relates propagation fields is not defined.

4. Basic issues in measuring electric and magnetic fields for use in exposure assessments (0 Hz to 100 kHz)

4.1 Introduction

In the frequency range up to 100 kHz, the common basis for protection is to limit the effects of electrostimulation of cells and/or tissues of human nervous systems, the cardiac system, and other biological systems, caused by induced electric fields, currents, or current densities within tissues and/or organs of the human body. In addition, for environmental electric fields, protection against indirect effects resulting from spark discharges, and touch and/or contact currents is necessary.

The MPE values and other EMF exposure limits found in contemporary standards and guidelines are derived from the basic restrictions, e.g., the internal electric field (E_i). The basic restrictions provide a more fundamental evaluation of exposure but are difficult or impossible to measure directly, so calculation and numerical modeling methods are required. The basic restrictions (E_i) may be calculated with induction models, including computer modeling methods when external field characteristics and the electrical properties of the relevant tissue are known (see Clause 7).

In practice, measurement or computation of the external environmental fields is often used for purposes of exposure assessment because measurement of the internal fields (basic restrictions) is impossible and their computation difficult. For exposure assessment purposes, these external environmental fields are compared with the MPE values in standards such as IEEE Std C95.1-2005 [B55] and IEEE Std C95.6-2002 [B58], or the corresponding quantities of other standards and guidelines that have been derived from the basic restrictions. Conformance with the MPEs ensures conformance to the basic restrictions. In contrast, exceeding the MPEs does not necessarily mean that the basic restrictions have been infringed.

This clause discusses the concepts and issues associated with measurements of the environmental fields for use in assessments of human exposure, or other purposes. For EMF exposure levels close to the MPEs, an accurate evaluation may require of the operator a thorough understanding of electromagnetism, specialized instruments, and/or software. Subclause 4.2 discusses the issues that EMF specialists need to consider for accurate measurements for any EMF environment. However, simple methods and basic instrumentation can be adequate for assessing exposure to the fields associated with common EMF sources. Subclause 4.3 describes simple screening measurements that occupational and environmental health generalists can use to determine whether a specialist is needed. These measurement methods can also be used to assess exposures to electric and magnetic fields at levels far below the MPEs, e.g., for the evaluation of control measures, epidemiology studies, investigations of reported health hazards, and other research.

4.2 Considerations for exposure assessments of electric and magnetic fields

4.2.1 Characteristics of environmental EMF (0 Hz to 100 kHz)

The characteristics of electric fields (E) and magnetic fields (either H or B) that are important for the purposes of comparison with the MPEs found in contemporary standards and guidelines are as follows:

- Continuous wave (CW), pulsed or pulsed-modulated fields
- Frequency spectrum (single frequency, harmonics, rectified sine waves, complex waveforms)
- Polarization (linear, elliptical, circular, or multi-frequency—see Figure 1)
- Variability over a person’s body and over time
- Intensity (rms or peak, vector component or magnitude)

In cases where environmental fields are spatially, temporally, and spectrally uniform, measurements can be carried out with simple methods and basic instrumentation. However, when dealing with sources that produce fields with atypical or non-uniform characteristics, care must be taken when comparisons are made with the MPEs. Such characteristics include the following:

- Nonlinear polarization
- Multiple-frequency sources
- Spatially and temporally non-uniform fields
- Non-sinusoidal or fields with high-harmonic content

Because electric and magnetic fields are multi-dimensional quantities, safety standards define *exposure metrics*, which are functions for converting the time-varying EMF vectors into a single number for comparison with the MPEs. In the 0 Hz to 100 kHz range, important metrics are the *rms vector magnitude* and the *peak vector magnitude*, which are measured over the averaging time specified by the standard. For the elliptically polarized, sinusoidal fields produced by three-phase transmission lines and similar EMF sources, another metric related to the exposure guidelines is the *maximum rms component*, which lies along the major axis of the elliptical trace of the field vector (see Figure 1).

For multi-frequency and pulsed fields, the exposure guidelines establish limits based on a sum rule for the Fourier components, as shown in Equation (1):

$$\sum_i \frac{A_i}{MPE_i} \leq 1 \quad (1)$$

where A_i is the rms vector magnitude or maximum rms component of the i -th Fourier component, and MPE_i is the MPE value for frequency f_i . IEEE Std C95.6-2002 [B58] offers two other metrics for multi-frequency fields: the *peak vector magnitudes* of the internal electric field (E_i) and the time derivative of the magnetic field (dB/dt).

Two statistics are recommended in IEEE Std C95.6-2002 [B58] for combining multiple measurements taken over the area equivalent to that of a person’s body. For electric fields, the average of the chosen metric is used for comparison with the MPE; for magnetic fields, the maximum is used, which implies that a single measurement would suffice if the field is spatially uniform, but measurements at multiple locations are clearly needed to demonstrate uniformity.

Finally, the temporal variability of the field affects the sampling strategy used for measurements for assessing exposure. A single time point can be adequate if it represents the maximum power of the EMF source and the person’s closest proximity. If these maximal conditions are not reliably known, multiple measurements over time, and possibly personal monitoring, will be needed to determine the maximum exposure.

Strategies for selecting exposure metrics are discussed further in 4.2.4, measurement considerations are discussed in 4.2.2, and the role of measurement uncertainty in EMF conformity decisions is described in 4.2.3.

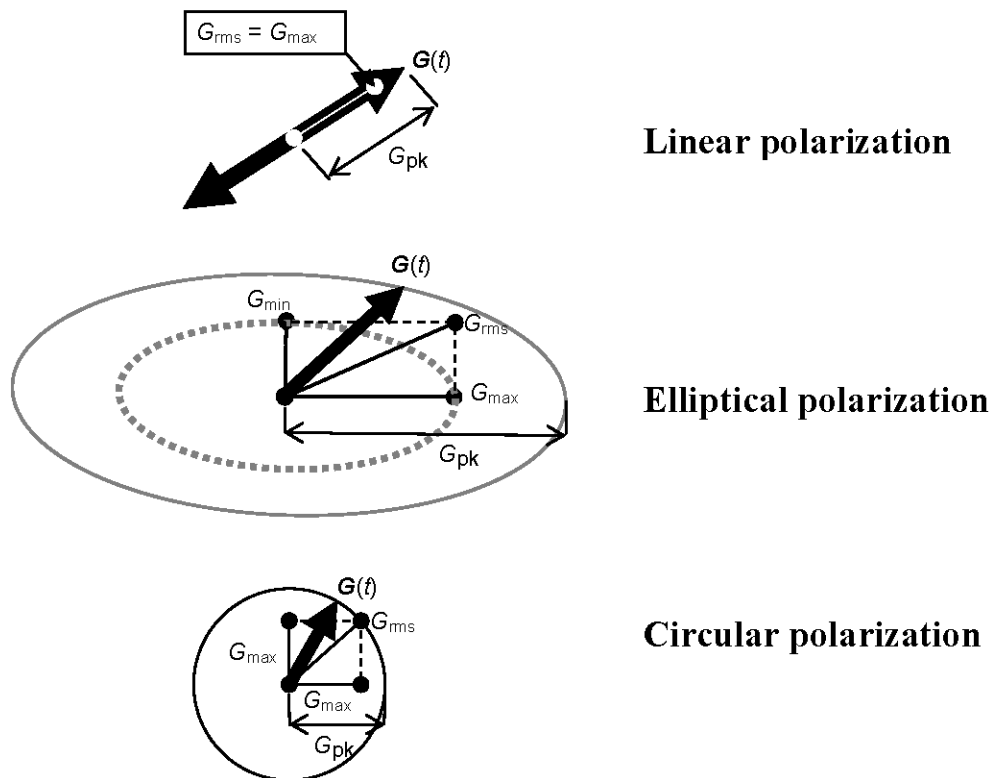


Figure 1—Vector traces of the polarizations with single-frequency electric or magnetic field $G(t)$, showing the rms vector magnitude (G_{rms}), the maximum (G_{max}) and minimum (G_{min}) rms components, and the peak magnitude (G_{pk})

4.2.2 Measurement considerations for purposes of comparisons with the MPEs

The MPE values depend on the frequency and/or waveform of the field because they are fundamental variables in the coupling mechanisms with body tissues. Therefore, the frequency of the field must be determined, preferably by measurement but at least from reliable specifications of the EMF source. A frequency meter with the correct bandwidth is often adequate, but care should be taken that the correct phenomena are being measured when simple equipment is used.

At frequencies below 100 kHz, exposures are usually in the near field (i.e., non-radiating) where electric and magnetic fields are independent and need to be measured separately. For well-defined sources, where analysis indicates that one field is much closer to the applicable MPE, only that field needs to be measured for purposes of conformity assessment.

Although, for measurements of environmental electric and magnetic fields, it is unlikely that a single instrument will cover the entire frequency of this recommended practice [0 Hz (dc) to 100 kHz], the instrumentation must cover the frequency range of the fields produced by a source under test. In the event that broadband instruments are used, the bandwidth of the instrumentation must cover the range of frequencies produced by the source.

Some measuring instrumentation may have a frequency dependent response that correlates with the MPEs. In order to fully characterize the exposure conditions, it may be necessary to use several instruments including a broadband meter, oscilloscope, or spectrum analyzer. If more than one instrument is used, care

must be taken to ensure that the ranges of the instruments do not overlap, resulting in an over-evaluation of the levels.

For single-frequency fields, the polarization helps determine the most accurate metric for use when assessing conformance with the MPEs and, therefore, the most practical instrument and measurement procedure. EMF sources powered by single-phase electricity usually generate linearly polarized fields. With a three-phase power line, linear polarization is also encountered by a person who is much closer to one phase than the other two, as in bare-hands work on high-voltage transmission lines. EMF sources with three-phase electric power generally create nonlinear polarization, as do multi-frequency sources.

For magnetic fields, the polarization can be confirmed with a three-axis digital waveform capture (DWC) instrument, or a single-axis gaussmeter. DWC instruments measure the polarization exactly as the axial ratio = B_{\min} / B_{\max} (see Figure 1). With a single-axis gaussmeter, the probe must be rotated to determine if $B_{\min} = 0$ (i.e., linear polarization). First, study the geometry of the source to determine the plane of polarization of the magnetic field, using the principle that magnetic fields are always perpendicular to a conductor. For a power line, the plane of polarization is therefore perpendicular to the line. For a solenoid, the plane of polarization lies along the radius of the coil. If the field is zero at probe orientations perpendicular to the maximum direction, the field is linearly polarized.

When spectral information is required, e.g., for comparing measurements with frequency dependent MPEs, the measurements shall be performed using instrumentation capable of measuring relevant frequency domain and time domain characteristics of the signal. In the case of time domain measurements, it may also be necessary to determine the frequency content for comparisons with the MPEs. It may also be necessary to sum the field strength at each frequency in accordance with the appropriate MPE [see Equation (1)].⁹ In cases of multi-frequency evaluations, it is not necessary to include all the low-level spectral components, such as those of low-energy spikes and minor modulation components representing less than 5% of the total energy or spectral size relative to the fundamental or carrier frequency.

For screening measurements where less accuracy is needed (see 4.3), an rms meter with a three-axis (isotropic) probe can be used instead of measuring the frequency spectrum and the polarization. If the frequency of the field is known from the specifications of the source, an accurate measurement of the rms vector magnitude is reasonably accurate for purposes of comparisons with the MPEs for single-frequency fields. Depending on the method of signal processing (see 5.2.2), the resultant reported by these isotropic rms meters can equal the rms vector magnitude of the field being measured. In addition, the rms vector magnitude can be easily measured for multi-frequency and pulsed fields, but is only an approximate measure of the multi-frequency metrics specified in IEEE Std C95.6-2002 [B58] and other relevant standards and guidelines. It also is necessary to consider the frequency range of the fields, e.g., when time averaging of exposure is allowed, and it may be necessary to calculate the instantaneous maximum field strength for comparison with MPEs for pulsed sources.

Electric field measurements of the unperturbed field strengths are necessary because the presence of the human body can significantly affect the results. In this case, the instrumentation should be mounted on a non-conductive support. It may also be appropriate to use a fiber-optic coupled remote readout unit (or similar means of distancing the body of the operator) for some electric field measurements. Because people do not perturb magnetic fields, they are preferably measured during common exposure conditions.

If control of the source under test is possible, the power should be set to maximum or adjusted according to the manufacturer's set-up instructions. The unit under test should be located at sufficient distance from nearby objects, so that the electric field is not disturbed.

In addition, considerations need be given to the following:

- Measurement requirements: both electric and magnetic fields

⁹ In cases where the exposure standards or guidelines contain their own summation formulae or requirements, these take precedence over those in 4.2.2.

- Frequency bandwidth of instrumentation, probes, and sensors
- Overall measurement uncertainty
- Separate instrument for static or dc electric and magnetic fields

4.2.3 Measurement uncertainty and conformity decisions

Measurement uncertainty as well as uncertainties in calculations of such exposures may need to be considered in deciding whether exposures conform to the applicable safety standards, for example when a regulatory or accreditation agency has such requirements. General methods for handling uncertainty are given in ISO/IEC Guide 98-3:2008 [B62].¹⁰ This subclause provides an alternative method that focuses on the large asymmetric biases that can result from the choice of an EMF exposure metric.

Uncertainty in EMF measurement consists of random errors and systematic biases of an instrument, plus the bias of the metric relative to the definition of the basic restriction and MPE. Bias is particularly an issue in cases where measurements use approximate metrics, such as the rms vector magnitude for magnetic fields with harmonics. Calculations may also contain errors due to uncertainties in input parameters (such as current levels) and approximations in the mathematical techniques. Practitioners should first determine the bias in their EMF evaluations relative to the metric specified in the standard (the “true” value).¹¹ The percent bias $\% \Delta_m$ in an evaluation of a metric X is defined as shown in Equation (2):

$$\% \Delta_m = 100 \% \frac{X_{\text{metric}} - X_{\text{true}}}{X_{\text{true}}} \quad (2)$$

The bias due to an inexact metric, X_{metric} , is usually a range of values that depends on the environmental parameters, like the polarization or the frequency spectrum.

As an example, Annex C derives the possible biases in measurements of the rms vector magnitude of magnetic fields (B_{rms}) for fields with harmonics. In this situation, a “true” metric for comparison with the MPE (IEEE Std C95.6-2002 [B58] or other guidelines) is the harmonic sum rule [Equation (1)]. For the MPE, the rms vector magnitude can have percent biases ranging from -1% to -20% for the harmonic distortion commonly found in homes and workplaces, while other extremely low frequency (ELF) standards have biases from -4% to -49% (Annex C). With this negative bias, measurements of the rms vector magnitude can be less than the MPE while the harmonic sum rule (the true metric) exceeds it.

The next step in the treatment of measurement uncertainty is to determine the accuracy of the meter from the manufacturer’s specifications, calibration data, and/or independent tests. The random errors can be expressed as the standard uncertainty $u(X)$, or the relative standard uncertainty, i.e., $\%u_r(X) = 100\% u(X) / \text{Mean}(X)$. Any uncorrected bias in the instrument relative to its specified metric $\% \Delta_i$ is expressed as shown in Equation (3):

$$\% \Delta_i = 100 \% \frac{X_{\text{measurement}} - X_{\text{metric}}}{X_{\text{metric}}} \quad (3)$$

With ELF magnetic fields, the largest and most important instrument bias occurs with three-axis gaussmeters that calculate the resultant from serial measurements of the magnetic field components with a multiplexing rate slower than changes in the environmental fields (see 5.2.2). In the only field trial of a serial-measuring gaussmeter side-by-side with a DWC monitor, the reported instrumental biases in the

¹⁰ Further details on measurement uncertainty and conformance decisions are provided by numerous documents, including UKAS LAB34 [B107], UKAS M3003 [B106], CISPR 16-4-1:2003 [B21], and Bartley and Lidén [B8]

¹¹ When estimating uncertainty for EMF measurements using the GUM approach, additional efforts may be needed concerning how to handle the bias component; see e.g., O’Donnell and Hibbert [B88], ASME PTC 19.1:2005 [B6].

resultant versus the rms vector magnitude in personal monitoring were as much as –68% in rapidly varying fields (McDevitt et al. [B72]).

Such uncorrected instrumental bias $\% \Delta_i$ should be combined with the bias of the metric $\% \Delta_m$ to give the total bias, as shown in Equation (4):

$$\begin{aligned} \% \Delta &\equiv 100\% \frac{X_{\text{measurement}} - X_{\text{true}}}{X_{\text{true}}} \\ &= \% \Delta_i + \% \Delta_m + (\% \Delta_i \% \Delta_m) / (100\%) \end{aligned} \quad (4)$$

Because both the instrumental and metric biases vary with environmental factors such as the frequency spectrum, bounds to their variability should be determined, resulting in minimum and maximum values for the total bias. When serial-measuring gaussmeters are used in fields with harmonics, the total biases in the resultant versus the sum rule method for the MPE ranges from $\% \Delta_{\text{min}} = -74\%$ to $\% \Delta_{\text{max}} = -1\%$.

The large asymmetric range of biases possible in EMF measurements should be considered in deciding whether exposure measurements conform to the MPE. Following the methods of NIOSH Publication No. 77-173 [B85], one-sided uncertainty limits may be used in conformance decisions with large biases for which upper and lower bounds can be estimated. For the most conservative determination that an exposure conforms to the MPEs, the upper uncertainty limit (UUL) on the measurement results should be used, as given by Equation (5):

$$\text{UUL} = X \left(\frac{100\% + k \% u_r(X)}{100\% + \% \Delta_{\text{max}}} \right) \quad (5)$$

where k is the coverage factor for a stated probability of assurance in the decision (usually 95%). A common value for the coverage factor in one-tailed hypothesis tests is 1.645, the 95th percentile of the standard normal distribution. If repeat measurements are not normally distributed, other error distributions will result in different values for the coverage factor (ISO/IEC Guide 98:2008 [B62]).

To evaluate whether the exposure truly exceeds the MPEs, the lower uncertainty limit (LUL) should be used, as given by Equation (6):¹²

$$\text{LUL} = X \left(\frac{100\% - k \% u_r(X)}{100\% + \% \Delta_{\text{max}}} \right) \quad (6)$$

If more than one measurement has been taken of the site, consult an occupational health statistics text, e.g., NIOSH Publication No. 77-173 [B85] or ISO/IEC Guide 98:2008 [B62], for methods to calculate the uncertainty limits.

For the approach described in the preceding paragraphs, the hypothesis tests that follow from these confidence limits are:

- UUL < MPE: Implies that potential exposures are below the MPEs. If this is not the case, more accurate measurements should be made or the internal electric fields should be calculated in order to determine conformity with the basic restrictions in an applicable standard.
- LUL > MPE: Implies that potential exposures are above the MPEs and some action should be taken to achieve conformity.

¹² Different regulatory domains, guidelines, and/or standards may have different ways of accounting for uncertainty when determining compliance with a limit, for example, a shared-risk approach as described in ITU-R Recommendation M.1545 [B64].

- $LUL < MPE < UUL$: Implies the measurements are not accurate enough to decide whether or not the MPEs are exceeded. In this case, more accurate measurements and/or metrics are needed when a conformity decision is needed.

Since these conformity decisions depend on the exposure metric, the next subclause develops strategies for selecting optimal metrics based on these concepts.

Other strategies to account for measurement uncertainty include assuming generous uncertainty limits when doing screening measurements (see 4.3). To ensure the rms vector magnitude is truly less than the exposure limit, the upper uncertainty factor [i.e., the quantity in parentheses in Equation (5)] should accommodate the most extreme values for all sources of uncertainty. For magnetic fields in underground distribution vaults, as analyzed in Annex C, an uncertainty factor of 3 should be adequate for demonstrating conformance with the relevant standards by using meters with no instrumental bias. For instruments with bias in measuring the rms vector magnitude, an uncertainty factor of 10 should be sufficient with underground vaults and similar ac sources. For EMF sources with greater distortion, e.g., dc welders, larger uncertainty factors are probably required to minimize erroneous decisions based on screening measurements, but more research is needed to determine their values.

4.2.4 Selecting an EMF exposure metric by its uncertainty and practicality

Selecting an exposure metric from among the many specified by safety standards and guidelines may be challenging. The metrics vary both in their ease of measurement and their accuracy when used in predicting conformity with the basic restrictions on the internal electric fields or current densities.

This subclause discusses efficient strategies for selecting metrics. The basic approach is to start with screening measurements of the more convenient metrics with methods that seek the maximum exposure (see 4.3). If the initial results suggest that the applicable exposure limit may be exceeded (using uncertainty limits as discussed in 4.2.3), then more accurate metrics and/or dosimetry calculations (see Clause 7) can be used to support a conformity decision.

A full implementation of this strategy requires accurate estimates of metric bias relative to the basic restriction for all the field characteristics discussed in 4.2.1. Subclause 4.2.3 and Annex C describe an example of a bias calculation for two metrics and a single EMF source. However, the comprehensive bias determinations needed to guide practitioners for dealing with all EMF sources clearly requires more research. Nonetheless, the assumptions required to predict the maximum internal electric field in the brain or other organ (as specified by the basic restrictions) from a measurement of a metric allows for their ranking in order of increasing bias, as shown in Table 1.

Table 1—Metrics for measuring EMFs to compare with the IEEE MPE, ranked in order of the assumptions used to derive the maximum internal electric field in an organ (the basic restriction specified in IEEE Std C95.6-2002 [B58]) from a measurement of the metric

Metric	Assumptions
Peak internal E_i calculated from dB/dt and a spheroidal model of the organ (Annex B of IEEE Std C95.6-2002)	Constant fields over the body; averaging over a 0.5 cm length
Peak dB/dt	Above assumptions + optimal orientation of the peak dB/dt vector to the organ
Sum rule with maximum rms components of the harmonics	Above + equal phases and orientation for all harmonics
Maximum rms component	Above + neglect of harmonic frequencies ^a
Sum rule with rms vector magnitudes of the harmonics	Above + linear polarization of all harmonics
RMS vector magnitude	Above + neglect of the harmonic frequencies ^a

^a When present, harmonic frequencies produce negative bias.

In deriving the MPE for a given metric, IEEE Std C95.6-2002 [B58] uses the worst case for the polarization of the field, phases, and orientation to the organ, where “worst” means it produces the largest internal electric field averaged over a 0.5 cm length. For magnetic fields, the worst case has all Fourier components (the fundamental frequency and all harmonics) with linear polarization and equal phases aligned with the organ’s longest axis. Another EMF exposure with the same rms vector magnitude but other harmonic distortion, polarization, or spatial orientation therefore has internal electric fields less than or equal to the worst case, so the bias of the metric relative to the basic restriction is positive. Where a metric requires more assumptions to be converted into the maximum internal electric field, its bias versus the worst case exposure becomes larger.

An efficient measurement strategy therefore starts with a metric towards the bottom of Table 1. (e.g., the rms vector magnitude) for reasons that: 1) it is less expensive to measure, and 2) its positive bias (in the absence of harmonics) guarantees that a measurement less than the MPE truly does not exceed the basic restriction. If the measurement exceeds the MPE, a metric with less bias further up the table (e.g., the maximum rms component or peak dB/dt) can be sought for demonstrating conformity, even though this may require more expensive instruments and training. If the more accurate metric still exceeds the MPE, a dosimetry calculation may be used to determine exposure relative to the basic restriction (see Clause 7). Conversely, if a metric near the bottom of Table 1 is used and an exposure is found to be below the MPE within the measurement uncertainty, no further measurements are needed to assure conformity with the basic restriction.

The only exception to this rule is using the maximum rms component or the rms vector magnitude to measure fields with harmonics, which produces a negative bias (see 4.2.3). This negative bias from harmonic distortion can raise doubts whether a measurement result below the exposure limit truly complies with the standard. Unless the possibility of harmonics can be eliminated by measurements (see 4.2.2), when doing conformity testing the uncertainty limits described in 4.2.3 should be applied to measurements of the rms metrics in order to facilitate accurate decisions regarding conformance with the MPEs. For rms exposure measurement results falling between the upper and lower uncertainty limits, measurements taken with the more complex metrics at the top of Table 1 should be considered.

As the considerations in this subclause indicate, specialized skills and knowledge are generally needed to make accurate measurements that can be used to assess conformance with MPEs for EMF sources with multiple frequencies, nonlinear polarization, spatial variability, and rapid changes over time. However, for many common EMF sources, reliable field-strength evaluations and conformity assessments are possible using the simpler methods described in 4.3.

4.3 Screening methods

Measuring field strengths, e.g., for occupational and environmental exposure assessments for comparisons with the applicable MPEs and RLs, can be simplified in practice based on the following two facts. First, the MPEs are most likely to be exceeded by sources such as underground vaults, overhead transmission lines, and metal induction heaters, whose fields have linear polarization and a simple frequency spectrum. For these examples of simple fields, knowing the frequencies and using an instrument that accurately measures the rms vector magnitude can be sufficient for comparisons with the MPEs. Second, complex EMF fields that require specialized measurement techniques are typically far below the MPEs. (Exceptions include rectified dc welders and other devices with large harmonic content, which require more demanding methods, at least for accurate site conformity assessment purposes.) Although the rms vector magnitude can have large biases under these conditions, the UULs are generally below the MPEs, so the same simple screening techniques can be used to determine field strength levels relative to the limits, or whether more accurate measurements are required.

These screening methods are based on a few simple principles as follows:

- *Determine the primary frequencies of the EMF source.* Usually this is 50 Hz or 60 Hz, or a specialized frequency listed on the manufacturer's specifications. Remember that devices with specialized frequencies usually have an ac power supply whose EMF emissions may also reach personnel access areas. Measuring the primary EMF frequencies and any distortion with the methods in 4.2.2 makes EMF measurements more reliable. In many cases, however, the primary frequency from the manufacturer's specifications is adequate to determine the applicable field-strength exposure limits from IEEE Std C95.1-2005 [B55], IEEE Std C95.6-2002 [B58], or other relevant standards and guidelines.
- *Use an rms instrument with an isotropic (i.e., three-axis) probe and a bandwidth encompassing the frequency spectrum of the EMF source.* For VLF sources with ac power supplies, several instruments may be required to encompass the frequency spectrum. To eliminate instrumental bias and narrow the uncertainty limits, use an instrument with a true rms response and simultaneous measurements of the vector components.
- *Search for the maximum EMF magnitudes over time and space, particularly where people are exposed.* Measurements should be taken where people normally spend time, but within those constraints, the highest reading should be used for the conformance test. For screening measurements, the maximum value will give an indication of the worst-case possible exposures. If this is below the MPE then there is no need to undertake further investigations.

The preceding recommended procedures are based on conservative conditions, therefore supporting that a finding of conformity should be reliable.

On the other hand, a finding of EMF levels above the limits with these screening methods need not be the final decision because of the inherently conservative assumptions (similarly to a situation of exceeding the MPE whereas the basic restriction may not be exceeded). Especially in linearly polarized, sinusoidal fields, a few simple enhancements of the measurement methods may demonstrate conformity with the MPE. A portable oscilloscope plugged into the analog output of the meter can show that the waveform appears sinusoidal, allowing use of narrower uncertainty limits. Because the maximum rms component is usually less than the rms vector magnitude, measurements are more likely to support results below the MPE limits if a single-axis probe is used to locate the maximum component. (See Clause 6 for more details on measuring the maximum rms component.) If these additional tests still indicate high-field levels or apparent non-conformity with the MPEs, a specialist will likely then be needed for any further improvement in the exposure assessment.

5. Instrumentation

5.1 Introduction

Instrumentation for the measurement of low-frequency electric and magnetic fields is divided into the following categories: static (dc) magnetic fields, time-varying (ac) magnetic fields, static (dc) electric fields, time-varying (ac) electric fields, induced currents, and contact currents.

5.2 Magnetic field meters

General characterization of low-frequency magnetic fields is typically accomplished with instruments having probes with single-axis and three-axis coils or sensors. Single- and three-axis Hall-effect sensors and fluxgate magnetometers are available for measuring alternating and static fields. Miniature three-axis field meters with onboard memory for periodically recording field levels have been developed for determining human exposure (personal monitors) and can also be used as survey meters. Three-axis DWC systems are available that simultaneously record the field waveform in three orthogonal directions and provide field-strength values (rms, peak, average, etc.), phase, polarization information, and frequency content. Because the MPEs and RLs found in most standards and guidelines for human exposure are given in terms of rms values, true-rms-responding instruments are preferred in order to minimize errors associated with current and field waveform distortion (deviation from that of a sinusoid).

Under normal conditions, the probes of magnetic field meters may be handheld without proximity effects due to the observer. A simple example of a single-axis survey meter consisting of an electrically shielded coil probe and detector unit is shown in Figure 2. Historically, single-axis magnetic field meters have been used to measure the maximum rms component of the magnetic field at a point by rotating the probe until a maximum reading is observed. For temporally stable magnetic fields (i.e., stable rms values), the single-axis magnetic field meter can also be used to measure the resultant magnetic field by taking a series of three orthogonal measurements.

5.2.1 Magnetic field sensing

5.2.1.1 Induction coil sensors

Time-varying magnetic fields are most typically measured using an inductive loop coupled to the magnetic field being investigated. The output from the loop is calibrated to indicate the magnetic field strength (H in A/m) or magnetic flux density (B in μT). It is essential that inductive loop probes are electrically shielded.

A conducting loop placed in a time-varying magnetic field will have a current induced in the loop that is proportional to the time derivative of the magnetic field flux density, i.e., proportional to both the magnitude and the frequency of the magnetic field. Compensating the output of the loop through integration of the signal, or through other means, yields an output proportional to the average spatial value of the magnitude of the magnetic field through the loop. The electrical characteristics of the loop and its associated circuitry determine the useable frequency range of the loop for such measurements.

The output current from the loop is displayed on a suitable readout device that is calibrated to display the desired units. Because the output of the loop is proportional to the time derivative of the magnetic flux density, i.e., proportional to the frequency of the field being measured, this type of sensor cannot be used to measure static magnetic fields.

In the simplest configuration, a single loop is used to couple to the magnetic field. As these fields are vector quantities with both magnitude and direction, the orientation of the coil with respect to the field direction

will affect the coil output. The output signal will be a maximum when the axis of the coil is aligned with the direction of the magnetic field.

As the coil is rotated (the angle between the coil axis and the field varied from 0° to 90°), the coil output will vary with the cosine of this angle.

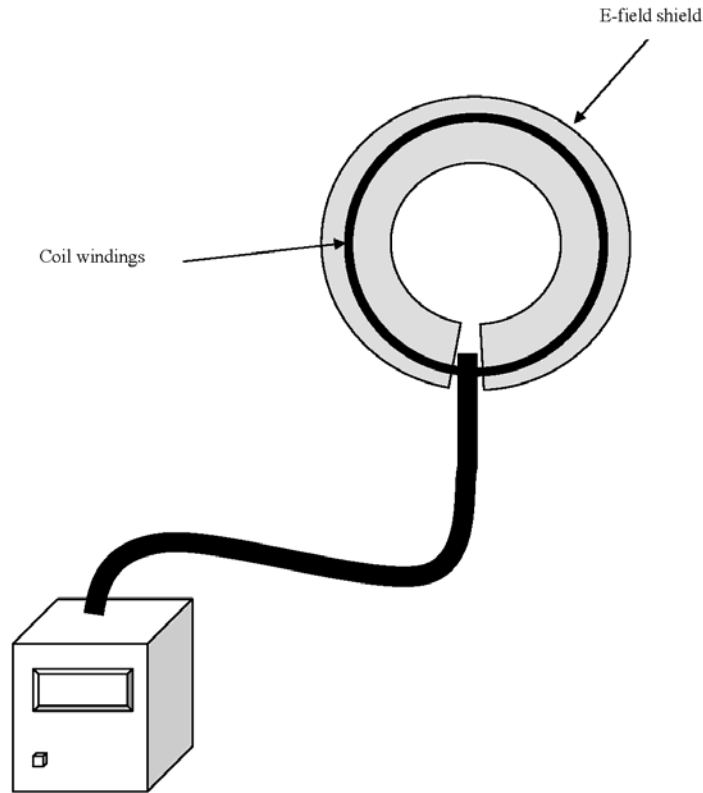


Figure 2—A simple example of a single-axis survey meter consisting of an electrically shielded coil probe and detector/readout device

When using a single-axis sensing coil, it is necessary to either align the coil with the field (obtaining a maximum reading) or to obtain three orthogonal readings, i.e., each reading is taken with the coil axis normal to the other two orientations. The three field components may then be combined in a vector sum to obtain a resultant field value (i.e., square root of the sum of the squares of the three field magnitudes).

Alternately, some designs have three sensing coils arrayed in a single sensor with the coils arranged in a concentric, orthogonal manner. The individual outputs are then internally combined to provide the resultant vector sum or isotropic measurement.

While air-core loops are typically used for low-frequency magnetic field measurements, it is possible to use a ferrous or ferrite core to increase the sensitivity of the measurement. It should be noted, however, that such sensing coils will interact more with the field and, depending on the local variations in the field, affect the reading. With the use of ferrite cores, the coils are often eccentric, which will also affect the response of the meter, especially to non-uniform fields.

Sometimes it may be necessary to calibrate an instrument for measuring magnetic flux densities that are less than $0.1 \mu\text{T}$. This requirement poses a practical problem because the ambient field in the laboratory where the calibration takes place could be higher than this value. If a very low-field environment is not available, a small ferromagnetic box larger than the meter sensor can be used to check the performance of the meter for very low or practically zero-field operation.

5.2.1.2 Hall-effect magnetic field sensors

Hall-effect magnetic field sensors have the ability to measure static magnetic fields and low-frequency time-varying fields. When an electrical conductor carrying a known current is placed in a magnetic field, and the magnetic field vector is orthogonal to the current flow, a voltage is developed in the conductor. This current is orthogonal to both the field vector and the current flow vector and is proportional to both the magnitude of the magnetic field and the magnitude of the current flow. This phenomenon is known as the *Hall effect*. In common conductors, such as copper, the effect is very small and virtually undetectable. Practical Hall-effect sensors consist of a small bar of semiconducting material to which four electrical contacts are made. An electrical current is passed through the length of the semiconductor and the voltage across the width of the sensor is measured. This Hall voltage, V_H , is directly proportional to the number of flux lines passing through the sensor, the cosine of the angle at which they pass through it (i.e., the output is polarization dependent), and the magnitude of the current passing through the device. With the current held constant, the output voltage is proportional to the net magnetic field through the sensing element (see Figure 3).

Hall-effect instruments are somewhat limited in sensitivity but can generally measure flux density from $100 \mu\text{T}$ to up to 100 T. Some meters measure only dc fields while others are capable of both dc and ac measurements.

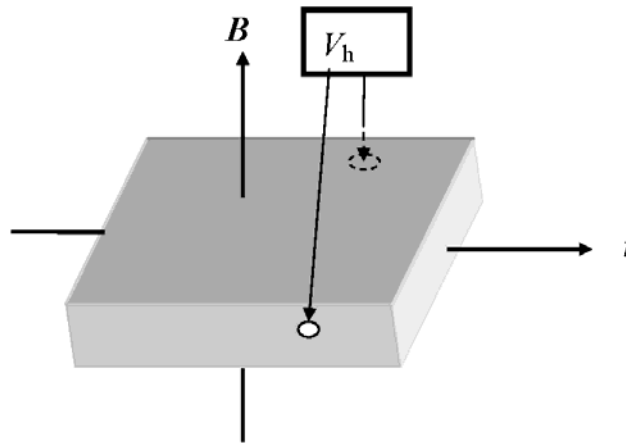


Figure 3—Hall-effect sensor—conceptual diagram

5.2.1.3 Fluxgate sensors

The fluxgate magnetometer is a sensitive device based on the magnetic saturation effect in ferromagnetic materials. Changes in the induced magnetic field in the ferromagnetic material are sensed and correlated with the ambient magnetic field.

Fluxgate magnetometers are capable of measuring magnetic flux density from 1.0 nT or less, to 0.01 T over a range of frequencies from 0 Hz (dc) to over 1000 Hz. These magnetometers show no appreciable instrument drift with time. With fluxgate sensors, it is possible to subtract the constant value of the terrestrial (Earth's) static field so that fields weaker than the terrestrial field can be measured in its

presence. Fluxgate magnetometers are used mostly for low-intensity magnetic field measurements and are not commonly used for measurements to assess human exposure. However, they are useful when oscillating and dc magnetic fields are created by the same EMF source.

5.2.2 Signal processing

The sensor output from modern magnetic field survey instruments (gaussmeters) is either digitized in waveform capture instruments or fed into an rms voltmeter. With single-axis gaussmeters, the rms output is calibrated to display either the magnetic field strength in amperes per meter (A/m) or the magnetic flux density in either microtesla (μT) or milligauss (mG).

With three-axis meters, the signals from the probes are multiplexed into a single detector at a rate dependent on the design of the instrument. With DWC capture instruments, the multiplexing is an order of magnitude faster than the analog-to-digital (A/D) conversion rate (generally 5 kHz to 7 kHz) so that the digitized data from the three probes are approximately equal to the Cartesian coordinates of the “instantaneous” magnetic field vector $\mathbf{B}(t)$, in theory the most accurate measurement method. With gaussmeters, the multiplexing among the three sensors is spread out over the meter’s total response time. Because the response time of an rms voltmeter is typically 100 ms, the shortest sampling period that will allow for multiplexing between the three signals is a half-second. Longer sampling periods (up to 1 min) can be chosen to allow for monitoring as long as a week.

The data from three-axis meters need additional calculations to display the exposure metrics of interest. The readout of the gaussmeter is the resultant of the three rms components, as shown in Equation (7):

$$B_r = \sqrt{B_x^2 + B_y^2 + B_z^2} \quad (7)$$

When the rms components are measured simultaneously, the resultant equals the rms vector magnitude as shown in Equation (8):

$$\begin{aligned} B_r &= \sqrt{\frac{1}{T} \left(\int_0^T B_x(t)^2 dt + \int_0^T B_y(t)^2 dt + \int_0^T B_z(t)^2 dt \right)} \\ &= \sqrt{\frac{1}{T} \int_0^T (B_x(t)^2 + B_y(t)^2 + B_z(t)^2) dt} \\ &= \sqrt{\frac{1}{T} \int_0^T |\mathbf{B}(t)|^2 dt} = B_{\text{rms}} \end{aligned} \quad (8)$$

However, gaussmeters multiplex the signals from its three probes sequentially, so the resultant only approximates the rms vector magnitude. These errors in the resultant are substantial when the average magnitude of the field is changing more rapidly than the multiplex rate (see 4.2.3).

Because DWC instruments record the instantaneous magnetic field vector $\mathbf{B}(t)$, they calculate the rms vector magnitude exactly [see Equation (8)], and can display many more metrics including the Fourier components, total harmonic distortion, and measures of polarization. These additional capabilities can be used to determine conformity with the exposure limits for multi-frequency magnetic fields (see 6.6.4).

Another approach to measuring to evaluate conformity of multi-frequency magnetic fields is the use of instruments whose signal processing mimics the harmonic sum rule for the Fourier components of the field [see Equation (9)] (Héroux [B43]). The readout of these devices is simply the right-hand side of this

equation, i.e., the sum of the ratio of each field component to its respective MPE, expressed as a percentage of the MPE.

$$\sum_i \frac{A_i}{MPE_i} \leq 1 \tag{9}$$

5.3 Electric field sensing

Low-frequency electric field meters are typically divided into time-varying (ac) field strength meters and static (dc) field strength meters.

5.3.1 Time-varying (quasi-static, ac) electric field meters

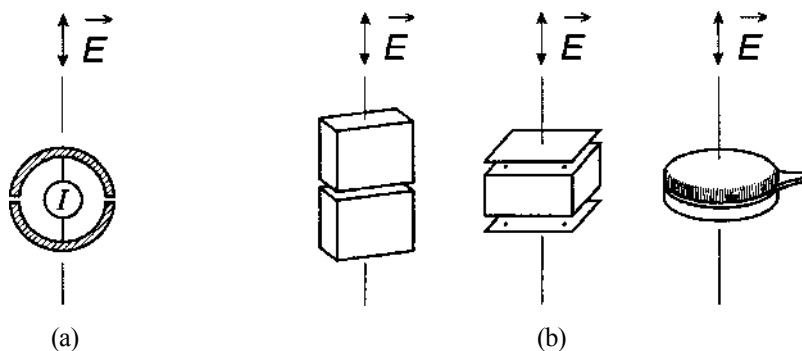
AC electric field meters are of three types: free-body meters, ground-reference meters, and electro-optic meters. Electric field meters used to measure quasi-static fields are typically single-axis devices, although three-axis meters are available. Free-body meters are normally battery-operated, electrically isolated from ground potential, supported in the field by an insulating support, and may be used to measure fields at most locations. Free-body meters using the displacement current principle are most commonly used in low-frequency measurement applications.

5.3.1.1 Free-body meters

This type of electric field meter operates on the displacement current principle. Two parallel conductive electrodes, when immersed in a time-varying (ac) electric field and electrically connected together, will exhibit a displacement current flowing between the two plates. The time-varying external field causes a redistribution of electric charge on the two electrodes with each half-cycle, and this redistribution, or displacement, of charge causes a current to flow between the two plates. The measured displacement current flowing between the plates can be correlated to the magnitude of the applied electric field.

A circular sensing plate, surrounded by a *guard ring*, is often used and the displacement current developed between the disks is sensed and converted to an equivalent electric field strength. For accurate measurements of electric fields, the sensor must be oriented perpendicular to the incident field lines for maximum readings.

Possible sensor geometries of single-axis, free-body electric field meters are shown in Figure 4.



**Figure 4—(a) Spherical free-body electric field meter;
 (b) geometries of typical electric field meters**

5.3.1.2 Ground-reference electric field meters

Ground-reference electric field meters are normally used to measure the electric field strength on grounded conducting surfaces (including the surface of the Earth). Such meters are normally used to measure the electric field at ground level or on flat conducting surfaces that are at ground potential. One notable exception is the use of ground-reference electric field meters to measure perturbed electric fields near video display terminals (VDTs), as described in IEEE Std 1140™-1994 [B52].

5.3.1.3 Electro-optic electric field meters

Although the principle of operation of electro-optic field meters differs from free-body meters, they are used in a similar fashion to measure the field at most locations above the ground plane; such meters are not commonly used for measurements to assess human exposure. Refer to IEEE Std 1308™-1994 [B53] for a discussion of these meters.

5.3.2 Static (dc) electric field meters

Several types of electric-field-strength sensors are commercially available for measuring static electric fields with respect to a reference object (usually electrical ground). However, this type of instrument is not commonly used for measurements to assess human exposure. One type of sensor is the so-called *field mill*; the second type uses a vibrating plate or probe. Each of these sensors can determine the static electric field strength by measuring modulated, capacitively induced charges sensed by metal electrodes. The most common field mill (Figure 5) uses a shutter assembly with a sensing electrode that is periodically exposed and shielded from the electric field by a grounded rotating shutter. The shutter is very close to a ground plane, or in the case of high-voltage dc power lines, the Earth itself. The induced charge at any instant, as well as the induced current, is measured between ground and the sensing electrode. The time-varying charge and the current are proportional to the electric field strength (E). Sensitivity of the field mill sensor is of the order of a few hundred volts per meter with a maximum measurement capability of up to 100 kV/m or more.

The vibrating-plate and vibrating-probe sensors consist of a faceplate with an aperture and a central vibrating plate or probe. The faceplate is placed in parallel to, and in contact with the ground plane. A mechanical driver moves the vibrating plate or probe in the direction normal to the faceplate. The mechanical motion adds a known modulation to the applied dc electric field providing an output proportional to the dc field. Sensitivity of the vibrating plate sensor is of the order of a few hundred volts per meter.

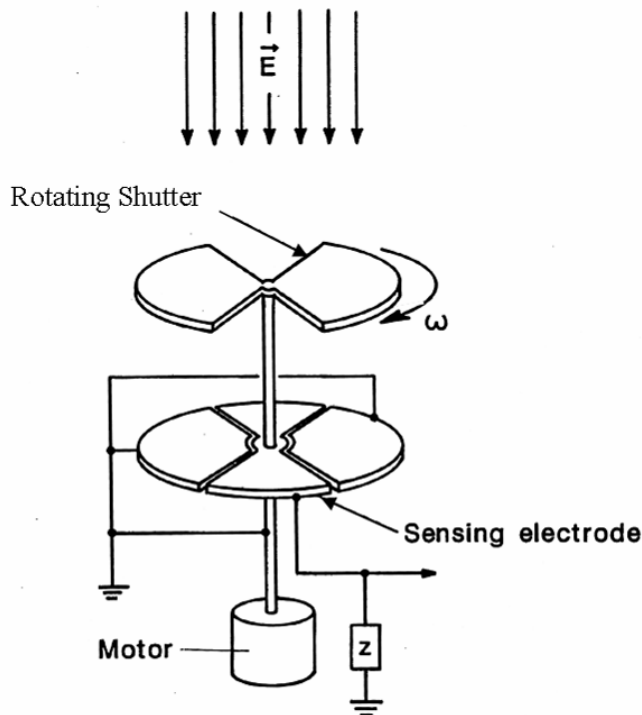


Figure 5—Diagram of a field mill type device for measuring static electric fields

5.3.3 Perturbation effects on electric field meters

Unlike magnetic field measurements, electric field measurements are easily perturbed by the surveyor, nearby dielectric objects, and by the measuring instrument itself. Metal structures and vegetation such as trees and tall weeds may also affect electric field measurements. The use of optical isolation between electric field sensor and the observer/readout location is recommended for electric field measurements.

All of the noted electric field meters are susceptible to proximity effects. The observer is a major source of proximity error as discussed in IEEE Std 1308-1994 [B53].

5.4 Induced current meters

Several common techniques are used for measuring induced currents, including clamp-on “loop” type current transformers for measuring current through the ankle or calf, and parallel plate “stand-on meters” for measuring currents that flow to ground through the feet when in the presence of an electric field source.

While some work has been done with “human equivalent” devices for simulating personnel, most induced current measurements are performed using a human subject. Preliminary free-field measurements are recommended to evaluate the fields present and to indicate locations clearly in excess of MPEs and comparable limits in other standards. The induced currents flowing in the subject are affected by the subject’s height, footwear, and the floor material present. Mats or insulating floor materials serve to reduce induced currents. Note that using a human subject can be extremely dangerous if these safety precautions are not followed. (See 6.5.)

5.4.1 Clamp-on current transformer sensors

For practical purposes, measurements of induced body currents are limited to those produced by external electric fields. In such cases the subject would not be in direct contact with objects in the field other than the ground upon which the subject may be standing. In many cases, the measurement of induced body current is used for purposes of comparison with the induced current MPEs found in contemporary guidelines, e.g., IEEE Std C95.1-2005 [B55]. Induced current meters can also be used for determining specific absorption rate (SAR) in the ankles or wrists at frequencies where SAR is relevant (above 100 kHz).

Lightweight clamp-on current transformer instruments may be worn about the subject's lower leg (ankle) or arm. A readout module, either mounted directly on the transformer or connected through an optical link for remote reading, provides a display of the current flowing through the aperture (primary circuit) of the transformer.

True-rms current detection is usually achieved with thermal sensors that respond accurately to the simultaneous flow of currents at different frequencies and to low duty cycle pulsed currents. Current transformer-type instruments (depending on the core material used) may have sharp changes in response above their specified operating frequency. Care must be used since operation at frequencies above the specified high-frequency limit can result in erroneous measurement results.

Air-core transformers, though commonly used measuring induced current, have been used to help extend the upper frequency response of induced current sensing. The lower weight of the air-core sensors makes them useful for long-term measurements. Air-core instruments, however, tend to be significantly less sensitive than ferrite-core devices.

5.4.2 Stand-on induced current meter

An alternative to the clamp-on device is the parallel plate stand-on meter. In this instrument, the body current flows through the foot (feet) to a conductive top plate, through some form of current sensor to the bottom plate, and then to ground. The current flowing between the top and bottom plates may be determined by calculation from the measured voltage drop across a known resistance.

Alternatively, a small aperture current transformer may be placed around a conductor that is placed between the two plates, and with appropriate circuitry (which includes narrowband instruments such as field strength meters and spectrum analyzers), the current can be determined. Another alternative is a direct reading thermocouple ammeter placed in series between the plates. This method is entirely passive since power supplies or other associated circuitry is not required. Two factors that may reduce the effectiveness of the thermocouple ammeter are its physical size and sensitivity to burnout.

An issue associated with the use of stand-on type body current meters relates to the existence of displacement currents that tend to flow from the top plate directly to ground and fringing currents that flow from the body to ground, escaping the current sensing path between the top and bottom plates. This displacement current is produced by the charge distribution on the top plate including charge accumulated by the body of the person standing on the plate as well as electric fields directly incident on the top surface of the plate. While the body tends to shield the top plate from such field capture, there is always some charge caused by these fields. The charge on the top plate results in a radio frequency (RF) potential on the top plate relative to ground and, hence, fringing electric fields at the periphery of the top plate that drive displacement currents to ground. Because any current that bypasses the current sensor because of this phenomenon will not be sensed, body currents measured with stand-on type meters generally indicate values less than the actual current flowing in the body.

5.4.3 Calibration of induced current meters

Calibration of induced current meters can be carried out using current injection and power measurement techniques in a terminated RF circuit. The clamp-on induced current meter is calibrated in a manner similar to that used for common RF current transformers. A special fixture is used that connects to a 50 Ω coaxial line and expands the outer shield to allow access to the inner center conductor [similar in principle to a transverse electromagnetic (TEM) cell] (see Figure 6). The size of the fixture must accommodate the larger dimension of the clamp-on induced current meter when it is connected around the center conductor of the test fixture. An insulating spacer is often used to center the conductor within the aperture of the induced current meter. EM energy from a suitable source is transmitted through the fixture to a termination, with a means for measuring total transmitted power (e.g., a feed-through termination), then the current flowing in the coaxial line (i.e., through the aperture of the induced current meter) is calculated using Ohm's law.

5.4.4 Limitations of induced current meters

A current transformer may be viewed as a form of inductive loop measurement antenna. It is useful when measuring induced currents in a body that is in the presence of an electric field source. However, if one is trying to measure the induced currents caused by an electric field generated by an inductive loop source, the inductive loop source will likely overwhelm the desired induced current reading.

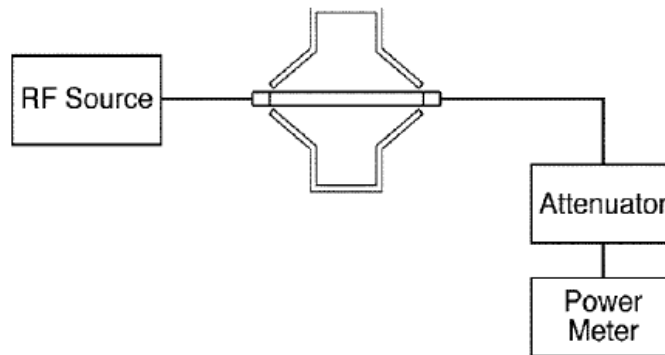


Figure 6—Method used for calibrating clamp-on induced current meters

5.5 Contact current meters

To assess possible contact currents in a specific area, the short-circuit voltage between various objects that a person might touch with their hands or feet can be measured with a multi-meter. The voltage measurements are then converted to current by selecting a conservative value for the body's impedance through the applicable contact points (hands or shoes, wet or dry).

The area of interest may also contain grounded conductive objects while the subject is illuminated by a localized field source. A current can flow from the illuminated subject (person) to a grounded object when that object is touched, or from an illuminated object through a grounded person. The current-reading mode of the multi-meter can be used to measure the current. The body appears as a circuit consisting of a voltage source with some source impedance, primarily the impedance of skin. The contact current can be measured with a multi-meter connected to the conductive object and the other lead grasped by the person. When the most sensitive ranges are used (which may be necessary when measuring relatively small contact currents), the input impedance of the meter may be significant and may affect the indicated values. The input impedance of these instruments on their most sensitive ranges may also vary significantly depending on the range selected. Due to the low frequency, the reading will be consistent for small as well as large contact

areas for the person being measured. There may be a dependence on the skin resistance of each subject being measured, and some compensating mechanism or technique may need to be developed.

A simulated body impedance (standard load) that can be inserted in the measurement circuit can also be used when measuring contact current. Information on a *standard load* is described in ANSI/AAMI ES60601-1:2005 [B2]; the impedance network is shown in Figure 7.

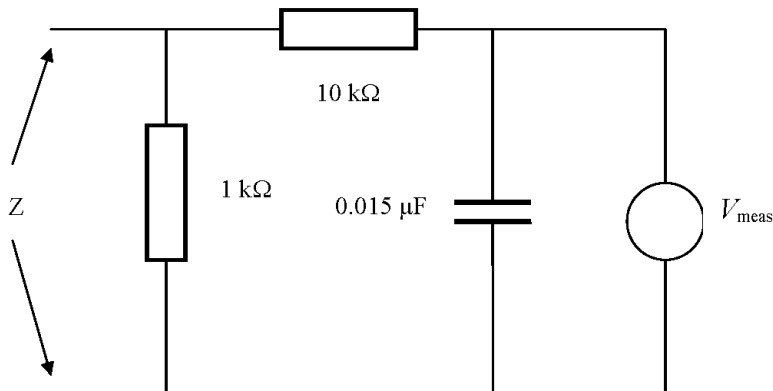


Figure 7—Simulated body impedance for contact current measurements

For more definitive measurements, a contact current meter has recently been developed by Niple et al. [B86]. This personal monitor uses medical electrodes on the wrists and ankles to record voltage differences resulting from contact currents. Computer software then filters out voltages that result from electrostatic spark discharges, and for the remaining 60 Hz voltages, calculates the currents passing through the body. This new instrument has been used to assess contact currents associated with sewing machines (Niple et al. [B87]) and some electric utility occupations (Bowman, Niple, Kavet [B13]). However, further studies (Bracken [B14], Bowman and Kavet [B9]) reported substantial problems with the accuracy of this meter in high electric fields. Moreover, the wires running from the data collection unit to electrodes on either side of the heart raise safety issues for electric line-workers, whose likelihood of encountering contact currents is very high (Bowman, Niple, Kavet [B13]).

5.6 Instrument measurement uncertainty

An instrument should be provided with calibration data that permit the user to estimate the maximum uncertainty in determining EMF levels when using the instrument in various types of fields of different frequencies. Calibration data should also include the sensitivity of the instrument to frequencies beyond the intended useful range (out-of-band response). A meter sensitive to out-of-band fields should not be used in an environment where such fields may be present at other than negligible levels. Absolute field strength calibration uncertainties (accuracy) of no greater than ± 1 dB are desirable but difficult to achieve. Uncertainties of ± 2 dB or even greater may be acceptable if the levels are well below the MPE, but as the MPE is approached, measurement uncertainty becomes of greater importance. In any event, the uncertainty factor should be known and included in the measurement report. The instrument readout should permit resolution (precision) of the measured field strength to within 5% of the full-scale value or less.

With proper preparation and execution of an EMF measurement according to the protocols in this recommended practice, the target expanded measurement uncertainty should be less than $\pm 30\%$ (+1.14 dB, -1.55 dB). If the uncertainty is higher, the test lab should evaluate which measurement uncertainty

component(s) need to be reduced to achieve the $\pm 30\%$ target uncertainty, and then take actions to implement improvements. When the expanded uncertainty is greater than 30%, the measured results may need to take into account the percentage difference between the actual uncertainty and the 30% target value. In all cases the measurement uncertainty must accompany the measured EMF results in the test report. See IEEE Std 1308-1994 [B53] (5.4, 5.6, etc.) for various discussions about uncertainty.

6. Measurement of electric and magnetic fields (0 Hz to 100 kHz) for use in exposure assessments

6.1 Introduction

This clause discusses measurement of the exposure metrics for environmental electric and magnetic fields defined in Clause 4 and how they relate to the evaluation of human exposure, with respect to relevant IEEE and other standards that prescribe safety levels with respect to human exposure. These parameters can be determined by measurement or computation (discussed in Clause 7). The selection of appropriate instruments—defined as devices that can measure fields accurately for the exposure metrics that are being evaluated—is most important. The various instruments that can be used are discussed in Clause 5; considerations for choosing the proper instruments are presented as follows, along with other considerations. Before using the comprehensive methods described, use of the simpler screening measurements described in 4.3 should be considered and/or attempted. When a screening measurement result or its UUL (see 4.2.3) exceeds the applicable MPEs, the methods described in this clause are necessary.

6.2 Preliminary considerations

It is important at the outset to clearly define the preliminary considerations and goals of any measurement program. A clear definition of the goals is important in order to determine the appropriate instrumentation performance and calibration requirements. In addition to providing information for assessing human exposure, these measurements might also be used for other purposes, e.g., medical surveillance, evaluation of control measures.

Once the goals have been identified and appropriate instrumentation has been acquired, a pilot study in the measurement environment of interest is often desirable before decisions on final measurement methods and associated measurement protocol are made.¹³ The protocol should describe the step-by-step procedure to be followed, using the possible methods indicated, to accomplish the measurement goals. The protocol may explicitly indicate such things as instrument requirements (e.g., passband, probe size, magnitude range), location of measurements, and duration of measurements. The measuring instrumentation may have a frequency-dependent response that correlates with the limits. In order to fully characterize the exposure conditions, it may be necessary to use several instruments including broadband meters, oscilloscopes, or spectrum analyzers. If more than one instrument is used, care must be taken so that the ranges of the instruments do not overlap, resulting in an over-evaluation of the levels.

Spectral information may be required to fully assess conformance with frequency-dependent MPEs and RLs. Measurements should be performed using instrumentation capable of measuring relevant frequency-domain and time-domain characteristics of the signal. In the case of time-domain measurements, it also may be necessary to determine the frequency content in order to compare the results with the MPEs and RLs.

¹³ A pilot study is a “scaled down” version of a major effort conducted before a larger study to test feasibility, suitability of the instrumentation, hone the methodology, etc.

6.2.1 Preliminary considerations for magnetic field measurements.

When measurements are made of low-level magnetic fields from power lines or other complex, partially hidden sources, electrical diagrams of the sources may be helpful. These diagrams can identify sources of fields in buildings or inside large equipment cabinets. However, excessive reliance on such documentation should be avoided because of unrecorded changes in the electrical system. While many sources of magnetic fields are visible, and thus known, e.g., overhead lighting or electrical appliances, others are not, e.g., electrical equipment in adjacent rooms or on upper or lower floors. During pilot studies, decisions may be made regarding spacing between measurements, measurement locations, sample size, datasheet format, questionnaires for job/task classification, etc. For some systems, e.g., metal detectors and anti-theft systems, there may be several coils, each operating at a slightly different frequency, but not necessarily simultaneously. In such systems, the principles in IEC 62369:2008 [B48] should be followed.

In certain applications the selection and use of a magnetic field instrument is simple and straight forward. However, in applications where the measured fields are highly localized and distorted, care must be exercised to reduce measurement uncertainties (Misakian [B76], Misakian and Fenimore [B78], [B79], [B80], Olsen et al. [B91]). Some of the major measurement issues are discussed as follows.

- *Harmonic content of the EMF source and frequency response of the instrument:* Depending on design, there are considerable variations in the frequency response of different commercially available instruments. This will strongly influence the measurement results in environments where harmonic content of the field source is high. Care must be taken in selecting the appropriate instrument and interpreting the measurement results.
- *Residential field sources:* In the ELF region, residential ambient fields differ in several respects from fields produced near transmission lines and power system installations, which requires additional consideration in the measurement procedures used when performing residential-site measurements. Depending on the instrument and operator, it can be difficult to obtain consistent measurement results due to the non-uniformity and harmonic content of fields near appliances.
- *Background electric and magnetic fields:* The ambient or background electric and magnetic fields in a location where no localized sources exist (e.g., electrical appliances or equipment, power-system installations, motors) are much lower than those produced in the vicinity of these sources. The spatial variations of these field strengths can reach a few orders of magnitude. Therefore, instrument errors, limitation in operating ranges, and the inherent random variations of sources of these fields can produce large uncertainties.
- *Residential fields:* The fields produced by appliances and ground currents can contain large percentages of harmonics.
- *Magnetic fields produced by three-phase balanced systems:* These systems will produce elliptically polarized fields, while single-phase sources will produce linearly polarized fields (see Figure 1).
- *Residential wiring geometry:* Residential wiring is usually complex, producing fields that are more localized and linearly polarized.
- *Low-field applications:* Early magnetic field survey instruments could exhibit significant differences in performance at low-field levels (Olsen et al. [B91]). Improvements in currently available instruments enable low-field measurements in the range of 20 nT (0.2 mG) or below. Careful selection and calibration of the instruments can provide accurate measurements in low-field environments. The noise threshold of the instrument and its linearity specification are the major factors in determining low-field performance.

6.2.2 Preliminary considerations for electric field measurements

Measurements for assessing human exposure to electric fields are often more difficult than for magnetic field exposure because the human body perturbs the electric field significantly. It is noteworthy that limits for human exposure to electric fields are given in terms of the unperturbed electric field (ACGIH [B1],

ICNIRP [B44], IEEE C95.1-2005 [B55], IEEE C95.6-2002 [B58]). Characterization of the unperturbed electric field is the focus of this subclause.

Established measurement procedures for power-frequency applications recommend a meter-to-operator distance of 2 m or more. Other influencing factors on measurement accuracy and uncertainty include the following:

- Conductivity of the probe handle
- Position of the electrical axis of the sensor along the direction of the measured field
- Harmonic content of the measured field
- Ambient temperature and humidity

Electric field meters are generally designed and calibrated to measure unperturbed fields for outdoor measurements applications. Consequently, large variations in measurement results exist when these meters are used in environments where electric fields are highly distorted. As an alternative, measurement of body-induced currents can be considered, e.g., for verification of conformance with MPEs and RLs.

6.3 Measurement checklists

Before performing a survey of potentially hazardous electric and magnetic fields, it is important to identify as many of the known characteristics of the sources of these fields as possible, and estimate the characteristic of the fields they produce. This knowledge will permit a better estimate of the expected field strength, and consequently a more appropriate selection of test instruments and test procedures. Therefore a checklist of sources and field distributions should be made before performing any measurements. In addition, the instruments to be used should be identified and tabulated.

6.3.1 Preliminary checklist

A preliminary checklist should be created to enable measurements at the site of interest to be performed with a minimum number of errors and to eliminate return trips. The checklist should include the following:

- a) Location and number of EMF sources, type of field source(s).
- b) If the measurements will be made in the workplace, the number of workers exposed, occupations, and work locations.
- c) Estimate of expected field strengths: Calculations or comparison with published data can be used to obtain estimated field strengths before any measurements are performed. For some sources (e.g., power lines), much of this information is available. For other sources (e.g., industrial heaters, domestic appliances), estimation is very difficult because the field-generating components in these sources are complex or unknown. Information on walk-through metal detectors, anti-theft, and other such devices may be available from the manufacturer or from product specific standards, e.g., IEC 62369:2008 [B48] (article surveillance systems).
- d) Orientation, physical size of each source, and its size with respect of the distance from the source to the measurement instrument's sensors.
- e) Frequencies associated with each source.
- f) Modulation characteristics for each source, e.g., amplitude or frequency modulation, peak and average values, waveform.
- g) Time-domain characteristics of each source, e.g., continuous or intermittent operation, waveform of the fields. For intermittent fields, time domain characteristics (pulse duration, pulse-repetition frequency, etc.) need to be identified.

- h) Expected polarization of the electric and magnetic fields (linear, elliptical, etc.), based on the source characteristics.
- i) Presence of conducting objects likely to influence the field distribution at the test site (e.g., conducting ground, tall protruding grounded objects).
- j) Suitability of measurement instrumentation (see 6.4).
- k) Effects of EM interference on the survey instrument, if it was not designed for operation in the presence of the fields being measured (e.g., strong electric fields may significantly affect magnetic field measuring instruments and cause significant measurement errors).

6.3.2 Review of checklist

A review of such a checklist is a necessity if the surveyor is to avoid some simple, but often surprising, situations. For example, it is necessary to know the location of the source(s) during surveys with handheld probes. Only then can an appropriate evaluation of the effect of the presence of the surveyor's body be determined. An estimation of the field strengths should be made before operating the source (when possible) and conducting the survey. The presence of secondary structures such as towers, guy wires, fences, reflecting surfaces, etc., can enhance the fields and produce EMF *hot spots*. If the information in the checklist is adequate, then the surveyor may proceed with the survey. However, this can be done only after making estimates of expected field strengths and selecting appropriate instruments. The surveyor should begin using the least sensitive probe with the range switch set on the most sensitive scale. The surveyor then can gradually proceed to move progressively closer to the regions of higher field strength. A survey for potentially hazardous fields of unknown frequency, modulation, distribution within an area, etc., may require use of several instruments. Examples of such instruments are spectrum analyzers or field-strength meters that display frequency-domain information with a means to analyze amplitude modulation characteristics. These instruments also have a wide dynamic range, e.g., 60 dB (a factor of 1000 in field strength). After this preliminary procedure is performed, it may be possible to continue a more meaningful survey with isotropic hazard survey instruments.

6.4 Determination of type of instruments required

6.4.1 Instrumentation checklist

Instrument selection should be based on the ability of an instrument to perform accurate measurements of the specific fields of interest. Every field will have a unique combination of the following parameters. Appropriate instruments that can measure fields accurately for the parameters of interest are discussed in Clause 5. When selecting an instrument(s), the flowchart of Figure 8 and its associated Table 2, and the following items, should be considered:

- a) Dominant field type—magnetic, electric, or both: The type of field should be estimated; both E and B may need to be measured, but the one that dominates should be measured in much more detail (e.g., magnetic field near a coil or electric field near ac power lines).
- b) Exposure metric: Exposure standards and guidelines specify several exposure metrics for measuring conformity with different types of fields (see 4.2.1). With single-frequency fields, either the rms vector magnitude or the maximum rms component can be used, depending on the required accuracy, e.g., for verification of conformance with MPEs and RLs (see 4.2.4). With multi-frequency or pulsed fields, IEEE Std C95.6-2002 [B58] provides a choice between using Fourier components, the peak magnitude of the vector $d\mathbf{B}/dt$, or the peak magnitude of the internal (*in situ*) electric field. For accurate measurements, these three options all require DWC instruments, and the Fourier components require an instrument or software with Fast Fourier Transform (FFT) capability. Another option for multi-frequency fields is use of a new type of meter whose frequency response is shaped to reproduce the harmonic sum rule [Equation (9)]. If exact measurements of the metrics

specified by the standards are not feasible, the rms vector magnitude or the maximum rms components can be used for screening measurements (see 4.3).

- c) Frequency response of the instrument: The frequency spectrum of the field should be measured (preferable) or estimated so that an instrument can be selected with a bandwidth encompassing the frequency content of the field. If the field has harmonics or a pulsed waveform, an accurate evaluation for purposes of comparison with MPEs and RLs will require measurements of either the three-axis Fourier components or the trace of the field vector in the time domain (three-axis waveform capture).
- d) Single-axis versus three-axis instruments: If a field is linearly polarized, and the direction of the field vectors (\mathbf{E} and \mathbf{B}) are known or can be determined, a surveyor may be able to use a single-axis (non-isotropic) probe for surveys. In the absence of such knowledge, a three-axis (isotropic) probe is highly desirable, both for accuracy and ease of performance of the survey in a reasonable period of time. The probe choice is also influenced by the metric to be measured and the frequency content of the field (see Figure 8).
- e) Time domain response: For amplitude- and pulse-modulated fields, the frequency and transient response of the instruments used must be sufficient to enable accurate measurements. If the waveshape, field values, and frequencies are known (or can be measured), it may be possible to calculate the rms values. Otherwise, true-rms responding instruments are required. For slowly changing fields it is necessary to use an instrument with an appropriate response time. For example, measuring the fields from ac power lines may require only a response time of one second, if the source signal is continuous. In contrast, measuring a 50 kHz magnetic field from a system that pulses on and off 10 times per second will require an instrument with a response time that is sufficient to measure and record the peak field at least 20 times per second. The detection of intermittent fields requires a response time of less than one millisecond, and a peak hold capability.

Alternatively a single-axis instrument can send its output to a digital oscilloscope while a three-axis meter requires DWC systems that are specifically designed for use in EM field measurements. DWC instruments with three-axis coils sample the motion of the vector at a rate several orders of magnitude faster than its fastest frequency, so the accompanying software therefore can calculate any desired metrics, including the polarization and frequency spectrum of the field. DWC instruments are essential to the accurate calculation of the metrics of the standards for multi-frequency and pulsed fields (see Figure 8).

- f) Measurement method: The use of some instrument types requires more effort and training than others to measure a metric accurately. When using a single-axis sensing coil, it is necessary to either align the coil with the field (obtaining a maximum reading), or to obtain three orthogonal readings (each reading orthogonal, i.e., normal) to the other two. The three field components may then be combined in the resultant function [Equation (7)] to obtain an approximation to the rms vector magnitude [Equation (8)]. Alternately, a three-axis sensor needs no manipulation, and the resultant is calculated automatically.

To measure the maximum rms component of an elliptically polarized field, a single-axis sensor must be rotated until the readout reaches its maximum. This method can also be used with a three-axis instrument with an rms detector if it will display the individual components. No manipulation is needed with a three-axis instrument with DWC. However, these instruments must either be programmed to read out the maximum rms component, or the user must do the calculation from the metrics in the output.

- g) Dynamic range: The maximum anticipated field strengths should be estimated before measuring emissions from an EM source. A survey instrument should be capable of withstanding continuous exposure to both electric and magnetic field strengths that are at least ten times the estimated maximum value to be encountered. Also, adequate sensitivity is required to achieve a reasonable signal-to-noise ratio when the minimum expected field strengths are being measured. Knowledge of the peak field-strength limitations of the instruments is necessary to protect probes from damage and to measure the peak field strength accurately when pulsed fields with very short on-to-off ratios exist.

- h) Area monitoring versus personal monitoring: In areas where people live or work, a wide range of instruments can be used to make accurate measurement of the metrics specified by the standards and guidelines. However, the electric and magnetic fields often change with time in such areas making it difficult for practitioners with limited time to measure all exposure conditions, especially in dangerous environments. Therefore, miniaturized magnetic field personal monitors have been developed that people can wear or keep near them for hours or even days. When a personal monitor can be worn close to the organ of interest, they often give the most accurate picture of exposure variability over time. Factors in the choice between area and personal monitors are:
- 1) Specifications of the available instrument,
 - 2) Accuracy of the instrument,
 - 3) People’s willingness to wear a personal monitor,
 - 4) Any safety hazard created by the monitor, and
 - 5) Practitioner’s ability to take measurements when and where the peak exposure occurs.

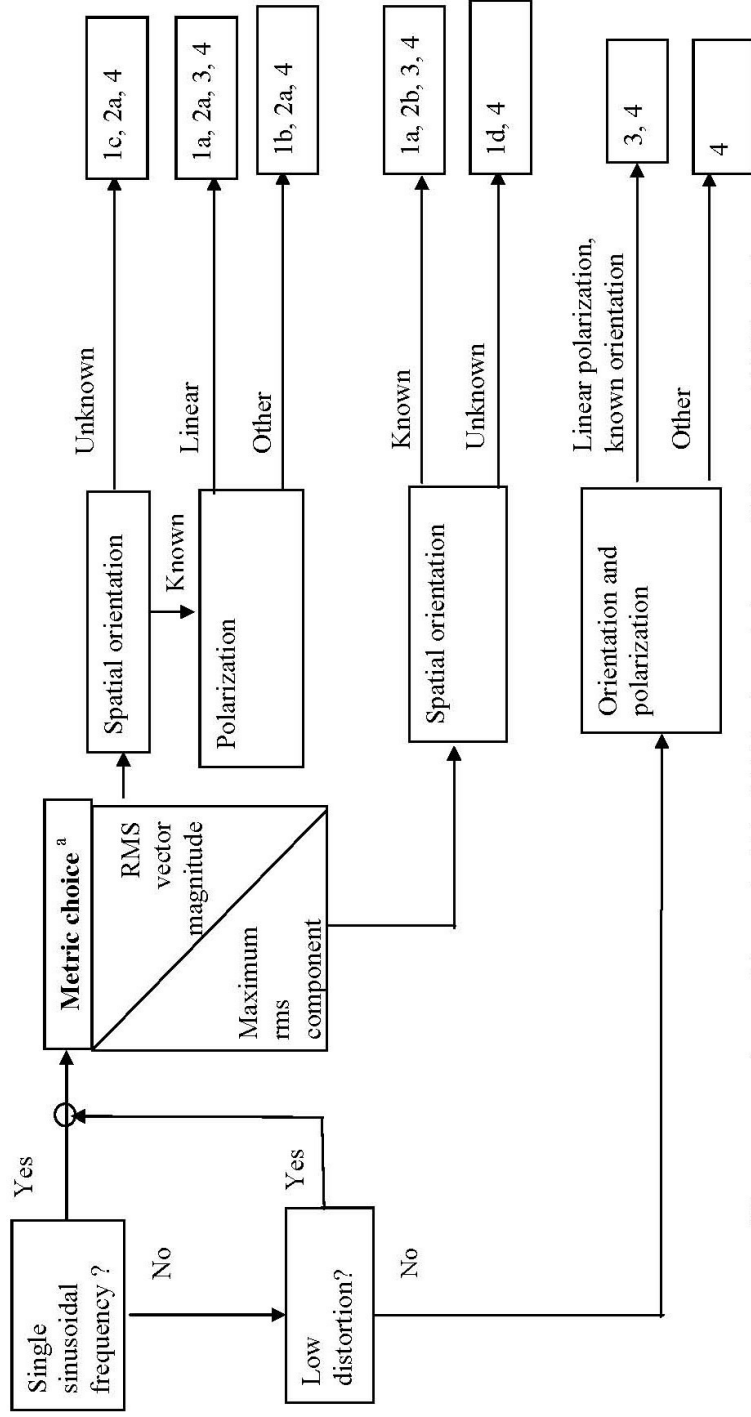
To capture peak exposures with area measurements, one option is to set the source at its peak capacity for the sampling. On the other hand, peak exposures are sometimes created by the person’s activity and can be captured most accurately and efficiently by personal monitoring.

Table 2—Options for EMF instruments and measurement methods in Figure 8

1. Single-axis rms-sensing meters
a. One measurement per location and/or time ^a
b. Two orthogonal measurements in plane of polarization
c. Three orthogonal measurements
d. Probe rotated to locate maximum rms component
2. Three-axis (isotropic) rms meters
a. One measurement per location and/or time
b. Align meter with plane of polarization and read out 3 components ^b (one measurement per location and/or time)
3. Single-axis probe with DWC analyzer (one measurement per location and/or time)
4. Three-axis DWC meter (one measurement per location and/or time)

^a The number of locations and times measured to make a conformity decision depends on the field’s homogeneity in space and time.

^b Requires an isotropic meter that records the components



^a These exposure metrics are used the most. See 4.2.4 and 6.6.4 for other metrics that are useful for non-sinusoidal fields, pulsed fields and multi-frequency fields with higher distortion.

Figure 8—Flow chart for choosing an instrument and measurement procedure (Table 2) to measure the most common metrics in the EMF exposure standards and guidelines

6.4.2 Field sensor size

An important consideration for instrument selection is the sensor size of a field measuring probe. This sensor size is evaluated with respect to the size of the source of the fields and the distance from the sensor (probe) to the source. Large spatial gradients exist near many sources. A spatial gradient can be defined as the change in field strength per unit distance along a linear axis. Usually the steepest gradient is along an axis that proceeds radially away from the source. For situations where large spatial gradients exist, measurements must be made with an instrument having sensors (usually dipoles and/or loops) that are physically small compared with the gradient existing from one end to the other of the sensor. This is necessary to provide reasonably accurate measurements of the fields. If a probe is used that is too large, spatial averaging of the field occurs, resulting in a lower value than actually exists at a point.¹⁷ In addition, use of a small probe sensor produces minimal perturbation of the field and the characteristics of the source are not modified by the presence of the probe (i.e., no alteration occurs of reactive near fields). To accommodate the degradation of accuracy by spatial gradients and spatial averaging, all probe sensors must be located a distance of at least three probe lengths away from a source of fields.

The accuracy of measured data can be affected when using a near-field probe with sensing elements of finite dimensions to map large spatial gradients, e.g., very close to an EM source. These gradients cause the amplitude of the field to vary significantly over the volume of space that is occupied by the probe sensors. This can introduce measurement errors due to spatial averaging over the volume of the sensors. As the separation distance between the probe and the source increases, the field throughout the entire volume occupied by the probe sensors becomes more uniform and the measurement errors decrease. The minimum distance between a near-field probe and an active source that will avoid significant measurement errors due to spatial averaging can be estimated. For example, for an infinitesimal electric dipole antenna located at the origin, the electric and magnetic field strengths at a point r can be expressed mathematically by Equation (10) where spherical coordinates are used (Ramo, Whinnery, Van Duzer [B94]).

$$\begin{aligned}
 E_r &= \frac{I_0 h}{4\pi} e^{-jkr} \left(\frac{2\eta_0}{r^2} + \frac{2}{j\omega\epsilon r^3} \right) \cos\theta \\
 E_\theta &= \frac{I_0 h}{4\pi} e^{-jkr} \left(\frac{j\omega\mu}{r} + \frac{1}{j\omega r^3} + \frac{\eta_0}{r^2} \right) \sin\theta \\
 H_\phi &= \frac{I_0 h}{4\pi} e^{-jkr} \left(\frac{jk}{r} + \frac{1}{r^2} \right) \sin\theta
 \end{aligned} \tag{10}$$

where

$$k = \frac{2\pi}{\lambda} \text{ m}^{-1}$$

η_0 = impedance of free space = $120\pi \Omega$ ($\approx 377 \Omega$)

ϵ = permittivity of free space = 8.84×10^{-12} F/m

μ = permeability of free space = $4\pi \times 10^{-7}$ H/m

h = length of the dipole (m)

I_0 = antenna current (A)

ω = angular frequency (radians/second)

λ = wavelength (m)

r = distance from the center of the dipole to the location of interest (m)

¹⁷ If the spatial average over a human body is being assessed, it is not critical if the probe is averaging over an area or volume that is significantly smaller than the body itself.

θ = angle between the axis of the dipole and the unit direction vector from the center of the dipole to the point r

$$j = \sqrt{-1}$$

Examination of Equation (10) shows that the radial component of the electric field strength (E_r) decreases inversely with the cube of the separation distance r between the source and the point of measurement. At distances very close to this source, the radial component dominates and thus the terms with inverse cube relationships dominate. Further examination of Equation (10) provides data that define the range of separation distance over which E_r varies less than a factor of ± 3 dB. With this as a criterion, Equation (10) can be used to provide a worst-case, simplified analysis using the single term for E_r in Equation (10). The results indicate that the minimum separation distance necessary for less than 3 dB variation is five sensor “probe-lengths.” A probe length is equal to the tip-to-tip dimension of a simple dipole or the diameter of a loop sensor. A worst-case estimate of the “probe-antenna length” can be readily obtained following the procedure described in 6.4.3. It should be noted that the preceding worst-case analysis can yield errors that are significantly larger than the actual errors encountered for many types of sources.

6.4.3 Estimation of the physical size of field probe sensors (antennas)—probe length

Usually the size of the array of sensors of a probe is not obvious (length of the electric field sensor or diameter of the loops). However, the maximum size of sensors encased within a probe can be estimated. A survey probe has sensors that are physically smaller than the non-conducting outer housing that is often used to surround them. The size of the housing can then be used to approximate the maximum size of the sensors within. Thus, the diameter of the spherical ball or the maximum dimensions of the cube or cone that surrounds the sensors of most survey instruments can serve as a worst-case estimate of the size of the enclosed loop or electric field sensors. This, in turn, can aid in determining the minimum separation distance that should be used between the survey probe and any surrounding object.

6.5 Safety precautions

Personnel should take appropriate safety precautions while conducting surveys, and the degree of care exercised should increase in proportion to the field strengths being surveyed. Potential hazards not directly associated with the survey should be considered in addition to EMF exposures. These additional hazards include the following:

Electrical and electronic equipment with high voltages present can present potentially lethal shock hazards. Ordinary precautions, such as not defeating interlock protection systems, exercising care around necessarily exposed high-voltage leads and terminals, and avoiding working alone near high-voltage systems, should be employed. Appropriate precautions should be exercised to minimize the risk of coming in contact with improperly grounded objects in strong EM fields. In addition, discharging of high voltages on capacitors must be performed with shorting/grounding hooks or bars. Additional caution is advised when performing measurements in the vicinity of electrically conductive structures, such as tall cranes or long vertically suspended cables when near high-power, low-frequency EMF sources. In such circumstances, high voltages can be induced on these large conducting objects when exposed to ambient electric and magnetic fields. Serious hazards are associated with electro-explosive devices (EEDs), combustible gas, or flammable materials exposed to EM fields. Relevant safety standards should be followed, such as IME 20-2001 [B60] or IEEE Std C95.4-2002 [B57] about safe exposure distances for EEDs relative to various transmitters. EM field hazards associated with fuel and other flammable material are described in NAVSEA OP 3565, Volume 1 [B83].

The survey process should be planned to limit exposures of all personnel to EMF levels below the MPEs found in the applicable exposure standards, e.g., IEEE Std C95.1-2005 [B55], IEEE Std C95.6-2002 [B58], or MPEs and RLs of other relevant standards and guidelines. In situations where the fields may exceed the applicable MPEs, and the person performing the field measurements has control of the EMF source,

consideration should be given to operating the source at a reduced power level (if possible) and using power scaling to compute the corresponding field levels that would exist during full-power operation. If measurements are to be performed while scanning an area with steep gradients in the electric or magnetic fields, one must be aware of the damage or “burnout” characteristics of measurement probes. Therefore, when performing a survey one should begin by approaching the source or any unintended radiating/leaking structures from an appropriate distance to minimize safety risks. The possibility of shocks and RF burns may exist, so contact should be avoided with any metallic structure on or near a point where high-field strengths or high induced voltages could exist.

6.6 Measurement procedures for electric and magnetic fields

6.6.1 Measurement of fields from a single source

Measurement of a linearly polarized field whose source location and frequency are known may be performed with a single-axis magnetic or electric field sensor such as a loop or dipole calibrated for the frequencies to be measured. The sensor should be rotated to find the maximum response to the field and this will identify the direction of polarization. The exposure metric determined by this type of measurement is the maximum rms component of the field (exposure metrics are discussed in 4.2.1). For the case of linear polarization, the result is the same as a measurement of the rms vector magnitude. Caution must be exercised, because the polarization direction can vary with position in the vicinity of any near-field source.

To avoid varying polarization issues, measurement may be made with an isotropic probe containing three orthogonal sensors calibrated for the frequencies that are to be measured. This will accommodate a field whose polarization is changing direction with location, as well as fields with nonlinear polarizations. The output of an isotropic probe can be displayed as the resultant of the three field components, i.e., the rms vector magnitude of the field (by using an rms detector), or as the instantaneous rms vector magnitude of each of the field components (by using a DWC system). The former method (usually called the *resultant*) is far more common, but with meters that measure the three field components sequentially, large errors in the rms vector magnitude can result in rapidly changing fields (see 5.2.1.). The three-axis DWC instruments that measure the rms vector magnitude exactly are more expensive, but also have the capacity to determine the polarization and frequency spectrum of the magnetic field. Except for linearly polarized fields, the rms vector magnitude will be greater than the maximum rms component.

Three-axis probes with either an rms sensor or DWC can be used to measure the rms vector magnitude for any type of field. With sinusoidal fields, such measurements are sufficient for determining conformance with exposure standards. For fields with harmonics or non-sinusoidal waveforms, the rms vector magnitude is an approximate metric to use for evaluation at the principle frequency of the field. This metric can also be measured approximately with single-axis probes by taking sequential measurements in three orthogonal planes. When the plane of polarization of a single-frequency sinusoidal source is unknown, sometimes the polarization of the field can be deduced from the geometry of the source.

Evaluations of the fields for purposes of exposure assessment should always include a determination of the frequency spectrum. If the operating frequencies cannot be readily identified from the equipment label or user information, then use of a single-axis sensor or an antenna and spectrum analyzer, field strength meter or a digital oscilloscope, or a three-axis sensor with DWC should be used to determine the frequency of the field and possible significant harmonics. If harmonics are significant (e.g., 10% of the fundamental frequency) then the survey instrument to be used should be capable of measuring these as well (see also 6.6.4 for more details about measuring multi-frequency or pulsed fields).

To assess the level of exposure at any general location, a series of measurements should be made at numerous points within a volume whose size is appropriate for the purpose, e.g., conformance with the MPEs and RLs in safety standards and guidelines. For such conformity assessments, it may be desirable to measure the spatial distribution over a volume that encompasses all points in the region of the source that would be occupied by personnel, e.g., the area around a metal detector where a guard may be continuously

stationed. In contrast, exposures to fields from a power line may need to be mapped for tens of square meters. Alternatively, personal monitoring can be performed on a sample of personnel who are spending substantial time near the source. Personal monitors use isotropic probes, sample the fields at rapid intervals (e.g., 1 s to 10 s), and record the results in a data logger for later download onto a computer for graphing and detailed analyses.

Measurements near EMF sources should be made with the probe of a survey instrument placed at least three “probe lengths” away from the source (see 6.4.2). Variations in measured field strengths should be considered when interpreting measurements used to demonstrate conformance with MPEs and RLs. Field strengths usually fall off with increasing distance from the source, unless unusual arrangements of multiple sources exist near the source under consideration.

While mounting or holding the measuring probe for electric fields, care should be taken to avoid perturbations of the fields, by cables connecting the probe to the readout or by the surveyor’s body. It is highly recommended that survey instruments with fiber optic cables connecting the sensor to the readout be used. If this is not possible, metallic interconnect cables should be oriented orthogonal to the electric field or routed in contact with the ground.

6.6.2 Measurement of fields from multiple sources¹⁸

Simultaneous measurement of fields from multiple sources, including fields at the same or different frequencies and/or polarizations, requires other considerations besides those in 6.6.1. These measurements require the use of a field-measuring device with an isotropic response and constant sensitivity over the entire frequency range of the signals and their significant harmonics. In some cases, more than one instrument may be needed to cover the entire frequency range and range of magnitudes. If the operating frequencies cannot be readily determined, e.g., from the equipment label or user information, then use of a broadband sensor feeding a spectrum analyzer, or a digital oscilloscope with frequency transform capabilities, should be used to determine all significant frequencies of the fields. If the fields associated with multiple sources have widely different amplitudes and frequencies, the source that produces the strongest field should be turned off (if possible) so that the contributions of the different frequency components can be accurately determined. Also, when there are multiple sources, it can be useful to perform an evaluation of each source independently with the others turned off.

6.6.3 Field mapping procedures for specific emitters

Specific emitters, such as anti-theft devices or power lines, may have particular field measuring and spatial mapping techniques already specified in source-specific standards. For example, fields near power lines can be measured using procedures in IEEE Std 1460™-1996 [B54] and IEEE Std 644™-1994 [B51]. Fields near electronic article surveillance devices and metal detectors may use measurement procedures described in European standard EN 50357-2001 [B33] and IEC 62369:2008 [B48].

6.6.4 Measuring multi-frequency and pulsed fields

IEEE Std C95.6-2002 [B58] and other standards and guidelines specify that fields with harmonic frequencies, pulsed fields, or non-sinusoidal fields whose spectrum has multiple frequencies should have their Fourier components measured in order to determine conformance with the standard (see 4.2). In addition, IEEE Std C95.6-2002 offers two alternative metrics as follows:

- a) Measuring the peak magnitude of the magnetic field’s time derivative vector $\dot{\mathbf{B}}(t)$
- b) Calculating the peak vector magnitude of the internal (*in situ*) electric field

¹⁸ In many exposure situations where there are multiple sources in an area, one of these is closest to the assessment point and may dominate the exposure. The other sources often may be relatively insignificant because of the relative distances. If this situation can be easily determined, the exposure evaluation can often be simplified.

Measuring all of these metrics requires DWC. With linearly polarized fields, this can be provided by an oscilloscope or signal analyzer. Otherwise, a three-axis DWC meter is needed for accurate measurements.

In measuring the Fourier components, precautions must be taken to avoid artifacts in the spectrum. The analog-to-digital (A/D) sampling rate $f_{A/D}$ and the number of samples N in a measurement should be chosen so that the field's fundamental frequency is an integer multiple of the spectrum's base frequency, i.e., $f_f = f_{A/D} / N$, and the sampling rate is greater than twice the frequency of the highest spectral component to be captured. Otherwise, the spectrum will not have sharp lines for each harmonic but bands whose exact frequency is difficult to determine. To avoid "aliases" (high-frequency fields appearing with a lower frequency), the instrument must have a low-pass anti-aliasing filter with a cutoff frequency less than $1/2 f_{A/D}$. In magnetic field spectra, artifacts arise when the probe moves through spatial gradient of the field and can be avoided by keeping the probe stationary during the measurement. Finally, a spectrum of the instrument noise response should be taken so that signals can be distinguished from noise.

With these precautions, the FFT algorithm of the instrument then provides the rms magnitude for each frequency in the spectrum (or the rms vector magnitude with three-axis instruments). Those Fourier components greater than the noise level of the instrument are then substituted into the Equation (11):

$$\sum_i \frac{A_i}{MPE_i} \leq 1 \quad (11)$$

Determining if the peak vector magnitude $\dot{\mathbf{B}}(t)$ conforms to the frequency-dependent MPE also requires the determination of the field's maximum frequency, which is defined by the *phase duration* t_p between the zero crossings of the waveform. To calculate t_p , calculate the instantaneous vector magnitude over time from the three component waveforms, identify the peak value, subtract the mean vector magnitude from the time plot, locate the zero crossings on either side of the peak, and measure the time duration t_p between those two points (Figure 9). For the magnetic field derivative, the measurement of the peak $\dot{\mathbf{B}}_{pk}$ can then be compared with the MPE for the rms B-field with frequency $1/2 t_p$ by using the relationship in Equation (12):

$$t_p \dot{\mathbf{B}}_{pk} / \pi\sqrt{2} \leq MPE \quad (12)$$

This procedure gives the maximum frequency present in the waveform, which is the most conservative approach because the MPE is inversely proportional to the frequency.

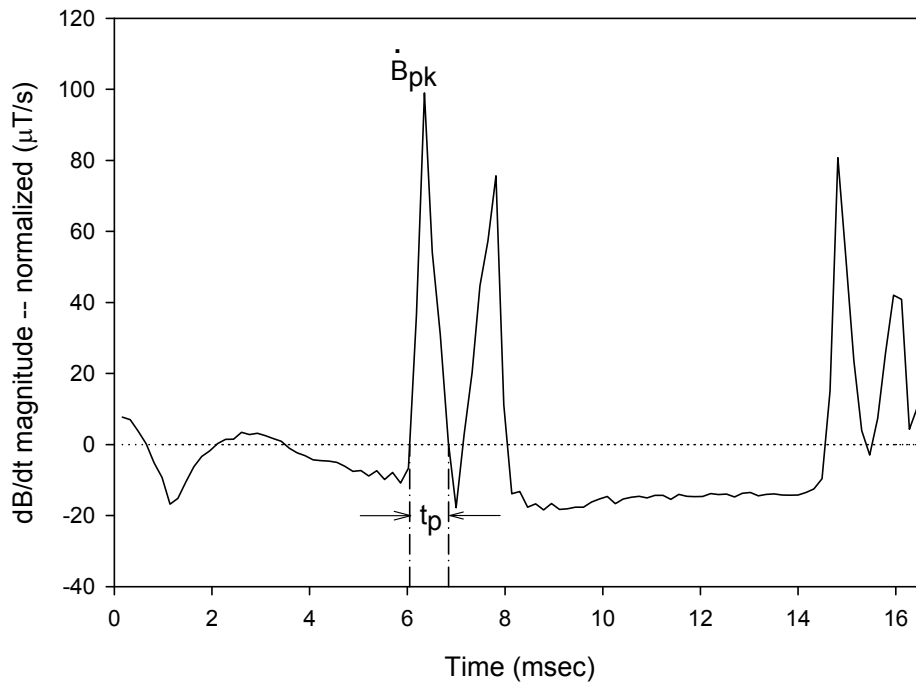


Figure 9—Measurement of the phase duration t_p for the magnetic field derivative

6.7 Measurements of induced body current

There are several issues that should be considered when selecting an instrument and measuring induced body currents. Procedures for making measurements and selecting an instrument using stand-on and clamp-on meters are discussed as follows.

Induced and contact currents result from a subject (exposed individual) in proximity to, or touching, a conductive object having an induced voltage resulting from the low-frequency electric fields present. These currents can be caused by either voltages induced on a conducting object, insulated from ground, such as a vehicle near a grounded subject or by voltages induced on a subject insulated from ground and touching a grounded, conducting object, such as a fence post.

These induced and contact currents should not be confused with safety issues due to touch potentials or stray voltage (leakage currents) due to fault conditions in electrical distribution systems.

Note the safety precautions in 6.5 and the contact current discussion in 1.5.3. In high-field conditions, consider first monitoring the induced voltages present using a high-impedance voltmeter or making preliminary measurements using an instrument that measures the induced or contact current flow through a simulated body impedance as described in 6.7.4. Using a human subject can be extremely dangerous if these safety precautions are not followed.

6.7.1 Measurements using clamp-on current meters

A clamp-on induced current meter functions in the same manner as a typical current transformer, with the subject's arm or ankle as the current-carrying conductor. Induced currents measured with a clamp-on instrument are generally considered the most representative of actual limb currents. Because the body is interacting with the field over its entire height, the currents flowing through the parts of the body are not

the same. For this and other reasons, the measured values of the current do not necessarily agree with those obtained using a stand-on instrument.

While some work has been done with “human equivalent” devices for simulating an exposed subject, most induced current measurements are performed using a human subject. Preliminary free-field measurements are recommended to evaluate the fields present and indicate locations clearly in excess of MPE values. The induced currents flowing in the subject are affected by the subject’s height, footwear, and the floor material present. Mats or insulating floor materials serve to reduce induced currents.

Clamp-on meters may be optically coupled to a readout device, to minimize possible perturbation effects due to surveyor proximity, or may be direct reading that requires the subject to record the data.

6.7.2 Measurements using stand-on induced current meters

Stand-on induced current meters consist of two parallel plates wherein the current flowing from the top plate to the bottom plate is sensed, typically through some known impedance (see 5.4.2). The device is placed on a standing surface and the person stands on the top plate. However, these devices are subject to the influence of displacement currents flowing from the top plate to ground, via fringing fields caused by the charge distribution on the top plate. The charge on the top plate is produced by both the current flowing from the exposed body to the plate, as well as electric fields that are directly incident on the plate. This means that such meters may produce some indication of current when subjected to strong electric fields, even without a subject standing on the meter. When a subject stands on the meter, however, the electric fields are generally partially shielded from significant interaction with the top plate, because they preferentially terminate on the surface of the subject. The degree of shielding is influenced by body size and geometry. Generally, however, when using parallel-plate type meters, the displacement current indicated without the subject in place can be ignored. That is, the induced current reading with the subject in place should be taken as the most accurate indication of the induced body current (i.e., the initial background displacement current should not be subtracted).

While the current passing through the ankle, just above the foot, may be slightly greater than that passing through the bottom surface of the foot due to displacement current leakage off of the foot, this current is not likely to be significant (IEEE Std C95.3-2002¹⁹). For example, differing ground conductivity conditions and ground surface textures, such as grass, gravel, concrete, steel decking, wood floors, etc., can result in different indicated body currents, for the same electric field strength, when measured with a stand-on meter (IEEE Std C95.3-2002). This effect is due to the differing degree of electrical contact between the bottom metal plate and the actual ground surface, i.e., the flat surface of the bottom plate does not necessarily make uniform contact with many surfaces on which it is placed. Also, the degree of contact can vary according to the weight of the subject. The inherent variability introduced by the stand-on meter suggests that a direct measurement of ankle current using a clamp-on current meter will be subject to less variability due to contact conditions, and will yield a more meaningful measure of the current flowing in the ankle under realistic conditions of shoe contact with differing ground surfaces.

6.7.3 Measurements of contact current

At frequencies nearer to the low end of the 0 Hz to 100 kHz frequency range, internal body currents may be more influenced by actual contact, as opposed to the capacitive coupling effects present at higher frequencies. Typically, these currents are measured using an instrument substituting for the subject exposed to the field effects. These instruments indicate the current flow through some arbitrary impedance simulating the body of the subject. The most common simulated impedance is 1500 Ω shunted by 0.15 μF .

Measurement of contact currents is problematic primarily due to the variables involved. Skin conductivity, contact surface area, current path through the body, the shape of the contacted surface, the type of contact

¹⁹ Information on references can be found in Clause 2.

(brushing, grasping, etc.) all affect the magnitude of the current. The arcing effect is further complicated by the velocity of the “contact objects” as they approach each other.

At present, contact currents through the hand are often estimated by the induced current flowing in the wrist using a clamp-on induced current meter when contact is made (Tell [B104]). This is complicated by the induced current that flows when the body part is close to, but not touching, the energized object.

As a surrogate for actual contact measurements, the electric potential of the energized object is sometimes measured. IEEE Std C95.1-2005 [B55] describes a maximum open-circuit voltage to assist in protecting against arcing.

Contact-current measurements at lower frequencies can be characterized using a voltage measurement across some specified impedance simulating the response of a human body. These measurements take into account the current-limiting effect of a high-impedance source. These measurement electrodes are typically low-resistance electrical contacts that do not simulate the contact impedance of the exposure situation. Instruments for such contact- or leakage-current measurements have operating characteristics specified for frequencies up to 1 MHz.

It is important to note that when performing measurements of contact currents, the ambient RF field may produce spurious readings due to cable pick-up. It is recommended that the indicated contact current provided by the measurement equipment be observed without touching the probe to any object. If an elevated contact-current reading is observed, try coiling the cables into a small coil to determine if this provides a noticeably reduced reading before proceeding with the measurement.

7. Theoretical calculations of induced currents (0 Hz to 100 kHz)

7.1 General considerations for calculations of low-frequency internal fields

The problem of evaluating low-frequency EM fields for use in human exposure assessments has been the subject of many theoretical studies and numerical simulations. Recent advances in computer technology, especially the recent generation of personal computers with 64-bit architecture allowing memory larger than 4 GB (gigabyte), have provided new opportunities in computational EM dosimetry. Faster computers with much larger memory storage space have allowed millimeter-resolution simulations of low-frequency dosimetry in realistic human models exposed to various low-frequency EMF sources. Various numerical methods have been used for such simulations, including finite element methods (FEM), integral equation (IE) methods, finite difference (FD) techniques, the impedance method, finite difference time domain (FDTD) methods, and inverse admittance methods (Armitage, LeVeen, Pethig [B4]). In all cases, these methods take advantage of the quasi-static nature of the low-frequency EM fields. Analytical methods have been mostly limited to simple configurations, but usually are not applicable to most final conformity assessment exposure situations. Nevertheless, many already established results are very useful for validating the computational methods.

This recommended practice focuses on three well-established methods for low-frequency dosimetry: the FDTD frequency-scaling method, the finite element method, and the impedance method. For quasi-static problems, the dimensions of the simulation model are small in comparison with the wavelength.

The exponential growth of computer performance in the last decade or more, as well as various enhancements in the technique, has made FDTD a popular and widely applied approach for various low-frequency EMF problems. In its original form, the FDTD method is not really a very attractive method for low-frequency problems. The required simulation times may be too long for anatomical models, even with moderate spatial resolution. For instance, for a model of an EMF source at 1 kHz with a spatial discretization of $\Delta x = \Delta y = \Delta z = 1$ cm, from the Courant stability criterion, the duration of one time step

would be 19 ps. Allowing for six periods of the source signal, the number of time steps required for the simulation would be $N = 3 \times 10^8$. Even on a supercomputer, the simulation time for this problem would be several years. To overcome this problem the frequency-scaling FDTD method was suggested and used in various publications, and compared with analytic solutions (e.g., De Moerloose and Stuchly [B26], DeFord and Gandhi [B25], Gandhi [B38], Kainz et al. [B66]). This method overcomes excessive simulation times, and has been successfully applied for low-frequency dosimetry simulations.

For low frequencies, where the dimensions of the biological body are small compared with the wavelength, the impedance method has been found to be highly efficient as a numerical procedure for calculations of induced electric fields and internal current densities. As described in Gandhi [B38], the impedance method has been used for a number of bioelectromagnetics problems, including for example operator exposure to spatially variable magnetic fields of induction heaters (DeFord and Gandhi [B25]), and linear or circularly polarized magnetic fields of magnetic resonance imagers (Nadeem et al. [B82]). Other similar methods have also been used, such as the inverse admittance method (Armitage, LeVeen, Pethig [B4]), but are not discussed in this document. (See Annex B for details on each of the numerical techniques described in this clause.)

7.2 FDTD frequency-scaling method

The frequency-scaling method uses the quasi-static nature of the EM field. For quasi-static EM fields the imaginary part of the complex conductivity of biological tissue ($= \sigma / (\omega \varepsilon)$) is small in comparison with the real part ($\varepsilon' \varepsilon_0$) where σ and ε are the relative permittivity, respectively, and ε_0 is the permittivity of free space. For dielectric properties of biological tissue for use in the numerical computations, see e.g., Gabriel, Lau, Gabriel [B37].

The actual FDTD simulation is performed at an artificially scaled higher frequency f' . This higher frequency has to be again one where the signal has quasi-static characteristics. After the FDTD computations are performed at frequency f' , the induced electric field E' at this simulation frequency (f') has to be scaled to the frequency of interest (f) using Equation (13).

$$E(f) = \frac{f}{f'} E'(f') \quad (13)$$

Equation (13) specifies $E(f)$ as the electric field (E-field) at the frequency of interest, $E'(f')$ as the E-field at the higher (scaled) frequency, f as the frequency of interest and f' as the higher (scaled) frequency.

7.3 Impedance method

In this method, the biological body or the exposed part thereof is represented by a 3-D network of impedances whose individual values are obtained from the complex conductivities $\sigma + j\omega\varepsilon$ for the various locations in the body. The impedances for various directions for the 3-D network can be written as shown in Equation (14):

$$Z_m^{i,j,k} = \frac{\delta_m}{\delta_n \delta_p (\sigma_m^{i,j,k} + j\omega \varepsilon_m^{i,j,k})} \quad (14)$$

where i, j, k indicate the cell index; m is the direction, which can be x, y or z , for which the impedance is calculated; $\sigma_m^{i,j,k}$ and $\varepsilon_m^{i,j,k}$ are the conductivities and the electrical permittivities for the cell i, j, k ; δ_m is the thickness of the cell in the m^{th} direction, and δ_n and δ_p are the widths of the cell in directions at right angles to the m^{th} direction.

7.4 Finite element method

7.4.1 Introduction

The finite element method (FEM) is a numerical technique for finding approximate solutions of partial differential equations (PDE). The goal of developing an FEM solver is to create an equation that approximates the equation to be studied, but is numerically stable, meaning that errors in the input data and intermediate calculations do not accumulate and cause the resulting output to be meaningless.

7.4.2 Field equations

7.4.2.1 Maxwell's equations

EM phenomena are described by a set of partial differential equations (Jin [B65]) known as Maxwell's equations. These are given by Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t} + \text{curl } \mathbf{E} = 0$$

and (in the absence of magnetic monopoles) as

$$\text{div } \mathbf{B} = 0$$

by Ampere's law

$$\text{curl } \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

and by Gauss' law

$$\text{div } \mathbf{D} = \rho$$

where \mathbf{E} is the electric field strength, \mathbf{D} is the electric displacement, \mathbf{J} is the current density, \mathbf{H} is the magnetic field strength and \mathbf{B} is the magnetic flux density.

These equations are joined by the material relations

$$\mathbf{B} = \mu(\mathbf{H} + \mathbf{M}), \quad \mathbf{J} = \sigma\mathbf{M} + \mathbf{J}_s, \quad \mathbf{D} = \varepsilon\mathbf{E},$$

where \mathbf{M} is the magnetization, μ is the magnetic permeability, σ is the electric conductivity, ε is the electric permittivity, and \mathbf{J}_s is the induced current density.

7.4.2.2 Magnetic fields

The eddy current equation [Equation (15)] arises from Maxwell's equations as the magneto-quasi-static approximation by neglecting the displacement current, $\partial \mathbf{D} / \partial t$, which is reasonable for low-frequency, high-conductivity applications.

$$\sigma \frac{\partial \mathbf{A}}{\partial t} + \text{curl} \left(\frac{1}{\mu} \text{curl } \mathbf{A} \right) = \mathbf{J}_s + \text{curl } \mathbf{M} \quad (15)$$

Equation (15) is solved for the vector potential, \mathbf{A} , which does not have physical meaning. The excitations are the current density \mathbf{J}_s and the magnetization, \mathbf{M} . In order to solve a problem, appropriate boundary conditions have to be defined.

Figure 10 shows a model of a motor with stator, rotor, and two excitation coils. The coils are driven by a constant current that creates a static magnetic field. Additional coils (not shown in the figure) are set up by wires across the rotor. If these coils are driven by a current, a torque is created that causes the rotor to spin. If no source current is present, Equation (15) can be simplified to a Poisson equation for the scalar magnetic potential. Figure 11 shows an example of a permanent magnet with a magnetization \mathbf{M} . The isolines of the magnetic scalar potential are shown. The magnetic field lines, which are not shown in the figure, are perpendicular to the isolines.

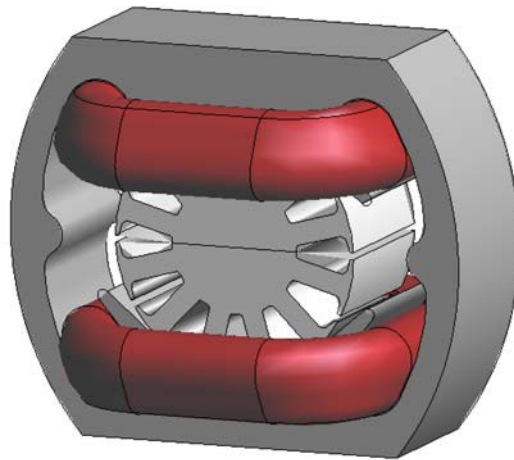


Figure 10—Motor model with stator, rotor, and coils

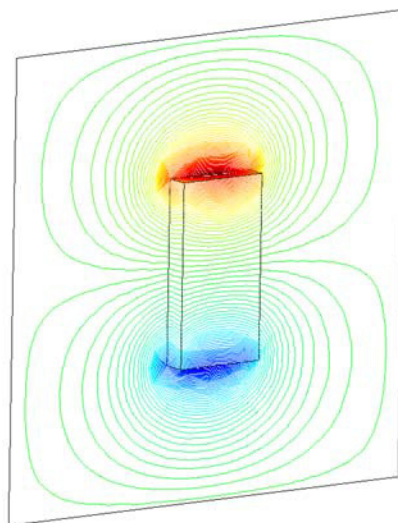


Figure 11—Permanent magnet with contours of the magnetic scalar potential

7.4.2.3 Electric fields

The electrostatic approximation of Maxwell's equations neglects EM wave propagation as well as inductive phenomena, while capacitive and resistive phenomena are taken into account (Steinmetz et al. [B99]). EM wave propagation can be neglected if the device under consideration is much smaller than the wavelength of the EM wave. The transient equation can be stated as follows:

$$-\operatorname{div}(\epsilon \operatorname{grad} \frac{\partial \phi}{\partial t}) - \operatorname{div}(\sigma \operatorname{grad} \phi) = 0$$

The sources are applied voltages at boundaries or inner surfaces. The electrostatic equation, which considers only the electric charge density ρ as source, can be written as follows:

$$-\operatorname{div}(\epsilon \operatorname{grad} \phi) = \rho$$

Figure 12 shows a plate with a constant boundary excitation of 30 V. The charge density is zero over the plate. In the middle of the plate, a peak voltage of 324 V is calculated.

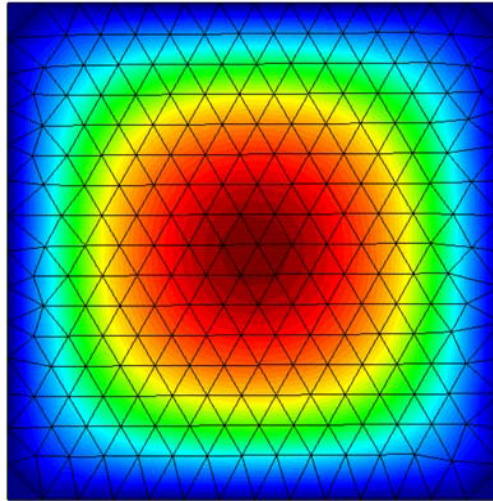


Figure 12—Plate with voltage excitation at the boundary

7.4.3 Finite elements

Because EM quantities, such as electric field or magnetic flux density, possess different mathematical properties, e.g., continuity, differentiability, adjusted basis functions have to be used. Therefore, Discrete Differential Forms (DDFs), which are finite element basis functions defined on a mesh, have been devised. DDF exist for 2-D elements and 3-D elements such as triangle, quadrilateral, tetrahedron, hexahedron, and prisms. In the C++ library FEMSTER (Castillo et al. [B17]) higher-order DDF basis functions for 2-D and 3-D elements are implemented. Classic nodal basis functions are used for continuous scalar quantities such as magnetic scalar potentials (0-form field), H (curl) basis functions for quantities that are tangentially continuous across different elements for the magnetic vector potential (1-form), H (div) basis functions for quantities that have a continuous normal component such as the magnetic flux density (2-form), and piecewise constant functions that are used for the charge density (3-form). Table 3 shows different EM quantities (field), the corresponding degree of form (form), the topological quantity to which the form is associated (integral), the continuity property of the form (continuity), and the derivative operator that can be applied to the form (derivative).

The magnetic flux density \mathbf{B} , for example, can be integrated over a surface providing the value of flux flowing through this surface; the normal component of \mathbf{B} is continuous across elements if the divergence of \mathbf{B} is well defined. In order to obtain a discretization of 0-forms, Lagrangian nodal finite elements $N_i(x, y)$ are introduced with a triangulation of the computational domain Ω_h , which is generally an approximation of Ω (see Figure 13). The solution is approximated as a linear combination $\sum_{i=1}^N a_i N_i$ of this basis function and a system of linear equations is set up for the unknown a_i . Small systems can be solved by direct methods that rely on matrix factorizations, but large systems can only be solved by iterative methods because of limited memory. If a series of linear systems is to be solved, more sophisticated methods based on subspace recycling can be used to accelerate the solution process (Wimmer et al. [B110]).

Table 3—Different EM quantities and the properties of the associated form, form field, integral, continuity property of the field, and the derivative operator that can be applied

Form	Form field	Integral	Continuity	Derivative operator
0-form	Scalar magnetic or electric potential	Point	Total	Gradient
1-form	Electric field E , magnetic field H , magnetization M	Edge	Tangential	Curl
2-form	Magnetic flux density B , electric displacement D , current density, J	Surface	Normal	Div
3-form	Charge density	Volume	—	None

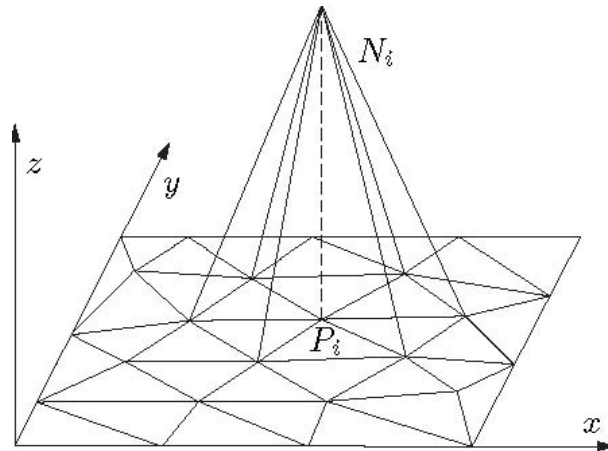


Figure 13—Linear basis function N with $N_i(P_i) = 1$

7.4.4 Application of electromagnetic software

7.4.4.1 Sequence of steps

When using simulation software for the solution of EM field problems, typically the following steps are applicable:

- a) Set up the geometry: Is it a 2-D or a 3-D problem? In some cases 3-D problems can be reduced to 2-D problems if the model has axial or translatory symmetry.
- b) Set up the right problem type—transient (frequency), static electric, or magnetic solver.

- c) Draw the geometry with a modeler.
- d) Assign the excitations—currents, magnetizations, charges.
- e) Assign boundaries—voltages, flux conditions.
- f) Assign material parameters—permittivity, conductivity, permeability.
- g) Generate the finite element mesh.
- h) Run the solver.
- i) Post processing—the EM field quantities are displayed.

7.4.4.2 Magnetic ring

As an example, consider an iron ring and a coil with an impressed current; the surrounding region is a vacuum. The geometry has a long extension in the z -direction; therefore the problem can be considered to be a 2-D problem. The static magnetic 2-D solver is selected, and the geometry of the ring is drawn. Then the material parameters for the coil, the ring, and the vacuum are set up and the current density in the coil is assigned. The zero vector-potential boundary condition is assigned because it is assumed that the fields go to zero at the boundary (see Figure 14).

The finite element mesh is generated and the linear system set up (see Figure 15). The user may prescribe tolerances for solution accuracy.

The last step is to run the solver and display the results. Figure 16 shows the isolines of the magnetic potential.

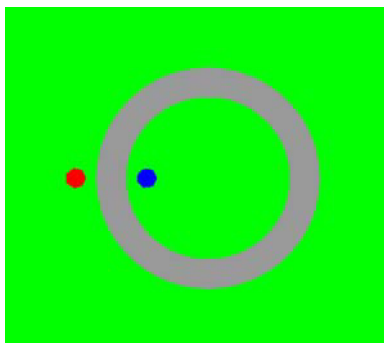


Figure 14—Geometry of an iron ring with a coil

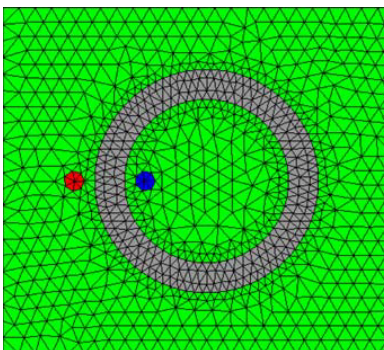


Figure 15—Geometry with finite element mesh

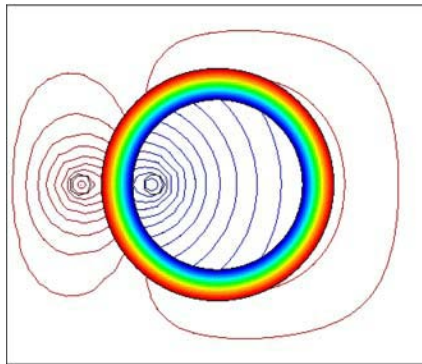


Figure 16—Geometry with isolines of the scalar magnetic potential

In order to control the spatial error, which depends on fineness of the finite element mesh and the time error in case of time-dependent problems, error estimators are introduced. While each error estimator is investigated separately and is well understood, the combination of time and space adaptivity has been addressed recently. During the magneto-quasi-static field evolution, strongly localized and layered regions of induced eddy currents may appear or vanish, depending on the external current excitation. In case of nonlinear ferromagnetic material behavior, the same holds for localized saturation effects that may arise or vanish during the considered time interval. For this type of problem, a combination of an error-controlled spatial adaptivity based on a FEM discretization, and an error-controlled time step, has been investigated in Clemens et al. [B21], [B22] and Wimmer et al. [B109].

7.5 EMF source modeling for magnetic fields

Numerical modeling of environmental EMF fields and the resulting induced fields and currents in the human body usually requires detailed electrical and mechanical specifications of a particular EM source to be provided as input to the EM modeling program. If the internal design of a source is not known, there are several ways to synthesize an equivalent source. Among the following three methods described, the first approach is the simplest but least accurate; however, it will be conservative, giving an overestimation of the induced fields and currents in an exposed person's body. The second approach is less conservative, and the third approach is the least conservative, but if done properly, is most accurate comparable to modeling the actual configuration of the source.

- a) *First approach:* Model the EMF source as two plane waves traveling in opposite directions and canceling out the electric field component. The magnetic field strength of the resulting homogeneous magnetic field is the maximum of the measured magnetic field strength. All three orientations of the magnetic field in relation to the anatomical model are to be considered for purposes of conformity assessment.
- b) *Second approach:* The source is modeled as a combination of rectangular or circular loops. The goal of the loop configuration is to model the measured field distribution as closely as possible. The loops can partially overlap to optimize the fit to the measured field distribution (Gandhi et al. [B41]).
- c) *Third approach:* The magnetic fields are measured (magnitude and phase) in several planes next to the source. These data are then used to calculate a current-source configuration (an equivalent source) that produces the same magnetic fields. This equivalent source may not correspond to the exact physical configurations of the emitter, but it can produce the same magnetic fields as does the real emitter. To determine which current source best matches the measured current distribution, the least squares method, or a similar method, can be used. Details about the equivalent current source method can be found in Wu et al. [B111].

7.6 EMF source modeling for electric fields

The EMF source is modeled according to the actual configuration of the source. If this approach is not feasible, the source shall be modeled according to the two approaches outlined as follows. Depending on the results of the first approach and the type of source, the second approach might be used to show conformity.

- a) *First approach:* Model the source as two plane waves traveling in opposite direction and canceling out the magnetic field component. The electric field strength of the resulting homogeneous electric field is the maximum of the measured electric field strength. If the source does not comply with the basic restrictions, the second approach shall be used to show conformity with the basic restrictions. All three orientations of the electric field in relation to the anatomical model shall be considered for conformity.
- b) *Second approach for line sources:* The source shall be modeled as a linear straight wire or a series of straight wires. For FDTD simulations the wire is extended into the absorbing boundary conditions (ABCs). The ABCs will fully absorb the current flowing in the wire and therefore virtually extend the linear wire indefinitely. The wire is fed by a source on one side of the wire close to the ABCs. The wire needs to be long enough to allow a sufficient reduction of the electric field close to the anatomical model due to the asymmetric source.

7.7 Anatomical models

For dosimetry using computer modeling techniques, numerous human body models are available with varying degrees of detail. The degree of detail of a model includes spatial resolution and the number of different tissue types and organs included in the model. The average²⁰ male is 172 cm tall [95% Confidence Interval (C.I.): 171 cm to 174 cm] with an average mass (weight) of 76.6 kg [95% C.I.: 74.1 kg to 79.0 kg]; the average female is 160 cm tall (95% C.I.: 159 cm to 161 cm) with an average weight of 67.1 kg (95% C.I.: 64.9 kg to 69.3 kg) (Baraton and Hutzler [B6]). Weights and sizes of children can be found in data released by the U.S. Department of Health and Human Services (Daniel [B73]) or similar publications. Topical reviews on anatomical models and computational dosimetry can be found in Caon [B16], Hand et al. [B42], and Zaidi and Xu [B113]. These or other human models are not required for assessment of conformance, unless specified in a particular exposure or equipment performance standard.

Generic anatomical CAD models for computational dosimetric evaluations were first developed by the U.S. Food and Drug Administration (Kainz et al. [B67]). Since then, the U.S. Food and Drug Administration, in cooperation with the IT'IS Foundation, developed the Virtual Family (VF) and the Virtual Family Tool (Christ et al. [B19]). This consists of four models: a 26-year-old female adult, a 34-year-old male adult, an 11-year-old female child, and a 6-year-old male child. All four VF models are based on healthy volunteers of average height and weight. High-resolution magnetic resonance (MR) imaging data were segmented to yield up to 84 different tissues and organs. The models were reconstructed as three-dimensional CAD objects with high-fidelity anatomical detail. The CAD format of the objects allows meshing of the models at arbitrary resolutions without loss of detail and small features due to multiple sampling. The models can be exported in a generic voxel-based format using the Virtual Family Tool. The models and the Virtual Family Tool can be obtained free of charge to the scientific community, for research purposes only, from the IT'IS Foundation²¹ [B63]. Figure 17 shows the four VF models, and Table 4 lists the characteristics of the VF models.

²⁰ All averages listed are worldwide averages.

²¹ More information is available at virtuallfamily@it.is.ethz.ch.

Table 4—Characteristics of the four Virtual Family models

Name	Age (years)	Sex	Height (m)	Weight (kg)	BMI ^a (kg/m ²)
Duke	34	Male	1.74	70	23.1
Ella	26	Female	1.60	58	22.7
Billie	11	Female	1.48	34	15.5
Thelonious	6	Male	1.07	17	14.8

^a BMI is body-mass index.

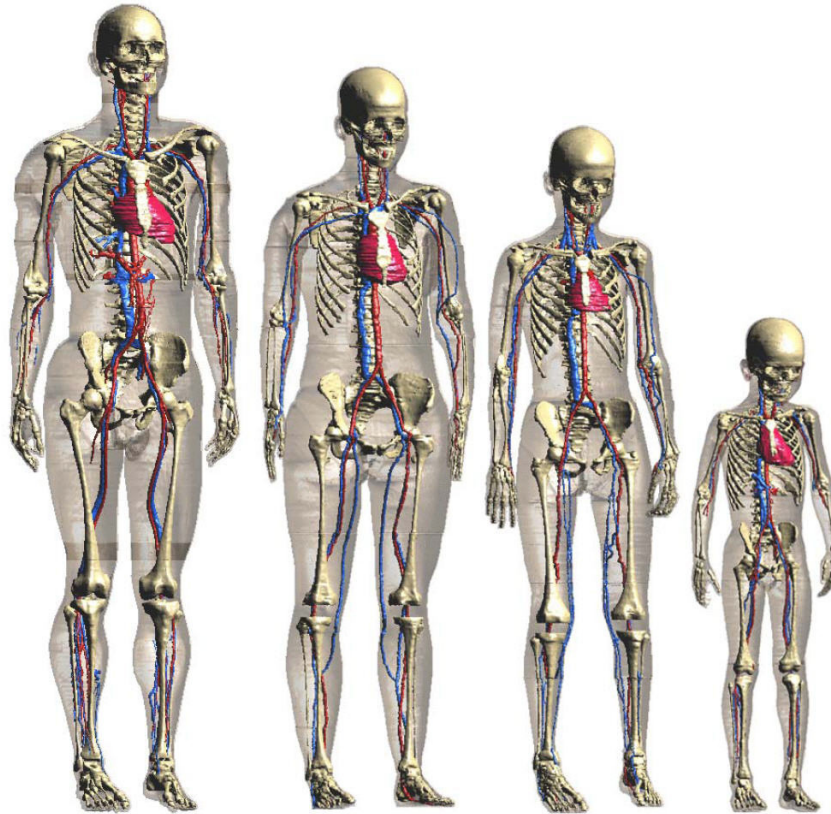


Figure 17—The Virtual Family: Duke, Ella, Billie, Thelonious (from left to right)

7.8 Averaging the induced current density

The current densities shall be averaged over a cross section perpendicular to the maximum current direction. The averaging area should not extend outside the outer boundary of the body being evaluated when the average is calculated.

7.9 Benchmark validation calculations

The simulation results should be validated with an analytical solution for the induced currents in a homogeneous model exposed to a uniform field. An example is the solution for the induced currents in an ellipsoid exposed to a homogeneous transversal magnetic field (Baraton and Hutzler [B6]). Another example using a uniform disk is used in IEC 62369:2008 [B48]. The analytical formula for the absolute value of the current density inside an ellipsoid exposed to a homogeneous magnetic field is given by

Equation (16), with the polar coordinates radius r and the elevation angle θ , β is the ratio between the semi-minor axis a and the semi-major axis b of the ellipsoid.

$$J(r, \theta) = \frac{2\pi f \sigma \mu H r}{1 + \beta^2} \sqrt{\sin^2 \theta + \beta^2 \cos^2 \theta} \quad (16)$$

The maxima of (x) that are at $(r=a, \theta = \pi)$ and $(r=b, \theta = 0)$.

For a human body approximation the following dimensions for a and b shall be used:

- Head $a = 20$ cm and $b = 30$ cm
- Body $a = 30$ cm and $b = 60$ cm

The results given by the analytical formula and the numerical model are compared to provide an indication of the validity of the numerical methods used. They are not intended to duplicate the results obtained using an anatomical model, with an often non-homogeneous field-source model.

Annex A

(informative)

Guide for the measurement of quasi-static magnetic and electric fields

(This annex includes the major portions of IEEE Std 1460-1996 [B54].)

A.1 Overview

This annex provides a listing of possible measurement goals related to characterizing quasi-static magnetic and electric fields and possible methods for their accomplishment. The annex is divided into five clauses. Clause A.1 provides an overview, and Clause A.2 describes the characteristics of quasi-static magnetic and electric fields that are candidates for measurements. The text for Clause A.3 is excerpted from IEEE Std 1308-1994. Clause A.4 briefly describes the types of available quasi-static magnetic and electric field measuring instrumentation. Clause A.5 describes specific measurement goals related to characterizing quasi-static magnetic and electric fields and possible measurement methods for their accomplishment. Throughout this annex, the terms *magnetic field* and *magnetic flux density* will be considered synonymous.

The fields of interest are typically produced by devices that operate at power frequency and that produce power frequency and power frequency harmonic fields, as well as devices that produce fields that are independent of the power frequency. The listings of possible goals and methods should not be considered as complete because there are many possible goals and methods for their accomplishment. The approach taken in this annex parallels a method described in Bowman [B8] and Bowman, Kelsh, Kaune [B12].

Descriptions of instrumentation, their principles of operation, definitions of terminology, calibration procedures, and a listing of sources of measurement error are given in IEEE 1308-1994 [B53] and should be used with this annex. Protocols for measuring magnetic and electric fields near power lines and video display terminals are given in IEEE Std 644-1994 [B51] and IEEE Std 1140-1994 [B52].

A.2 General characteristics of quasi-static magnetic and electric fields

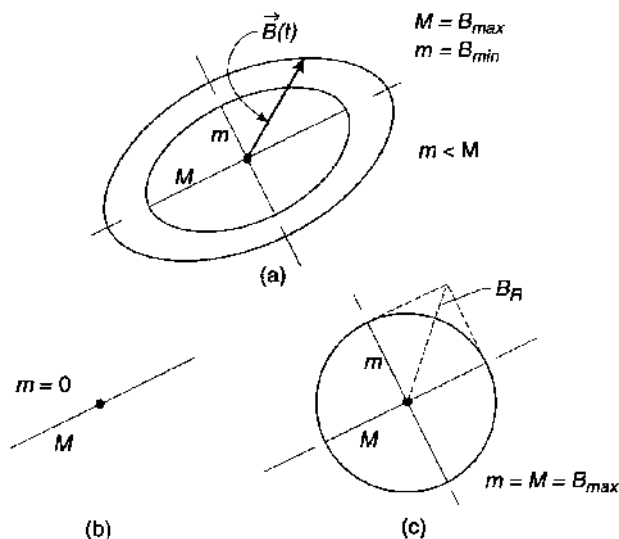
Magnetic and electric fields produced by power lines, appliances, and other electrical equipment may be characterized according to magnitude, frequency, waveform (harmonic content), degree of polarization, spatial variation, and temporal variation.²² These characteristics are described briefly because one or more of them may be selected for measurement, and because of their importance in specifying requirements for instrumentation used to measure the fields.

Several of the field parameters may be introduced by considering magnetic fields produced by currents in three-phase power lines. Some of the same parameters are also used to characterize electric fields. In general, the magnetic field at a point in space may be represented as a rotating vector that traces an ellipse for every cycle of the currents in the conductors, as shown schematically in Figure A.1(a).²³ (See Deno [B29].) The rms magnitude and direction of the semi-major axis, given by M in Figure A.1(a), indicates the

²² This annex does not consider transient temporal variations, i.e., events that are fast compared to the periods of quasi-static magnetic and electric fields under consideration.

²³ This figure shows the actual trace of the magnetic flux density vector $\vec{B}(t)$ only for elliptical polarization (a). For linear polarization (b) and circular polarization (c), only the rms maximum component M is shown, creating a false impression of path traveled by the actual magnetic field vector. With circular polarization (c), the resultant B_R shows the length of the instantaneous magnitude of the magnetic field vector $|\vec{B}(t)|$. Figure 1 presents the modern view of the EMF exposure metrics that resulted from vector waveform capture instruments.

magnitude and direction of the maximum magnetic field. Similarly, the rms magnitude and direction of the semi-minor axis, given by m in Figure A.1(a), describes the minimum magnetic field. Such fields are said to be elliptically polarized.



**Figure A.1—Oscillating and rotating magnetic field quantities for the cases of
 (a) elliptical $m < M$, (b) linear $m = 0$, and (c) circular polarization $m = M$**

NOTE—The resultant, B_R , and the maximum magnetic field, M , are equal only for the case of linear polarization. The largest difference between the resultant and maximum magnetic field occurs for circular polarization, i.e., B_R exceeds M by 41%.

An often-measured field quantity is the resultant magnetic field, B_R , given by Equation (A.1):

$$B_R = \sqrt{B_x^2 + B_y^2 + B_z^2} \tag{A.1}$$

where B_x , B_y , and B_z are the rms values of the three orthogonal field components. The differences between B_R and the maximum magnetic field, M , for different field polarizations are discussed in IEEE Std 1308-1994 [B53] and IEEE Magnetic Fields Task Force Report [B49] (see also Figure A.1).

Because magnetic fields in environments away from power lines also can be produced by multiple current sources that are not necessarily in phase, elliptically polarized magnetic fields can occur in many settings (e.g., homes and work places). Depending on the geometry and currents in the conductors, the degree of magnetic field polarization at a point can vary from linear ($m = 0$) to circular ($m = M$), as shown in Figure A.1(b) and Figure A.1(c). Linearly polarized fields are also referred to as single-phase alternating fields. This discussion of multiphase fields assumes that there are no harmonics in the field. The polarization state of fields with significant harmonic content is more complicated (Mamishv and Russell [B71], Sicree, Rauch, Dietrich [B97]).

Near ground level, the magnitude of the magnetic field from a three-phase transmission line changes slowly as a function of the height of the measurement point above ground. For example, for a typical 500 kV line, the change in the magnetic field magnitude at a height of 1 m above ground level is less than 2% for a 10% change in the measurement height for locations underneath the line. The uniformity increases at more distant points. For locations far from the line, the magnitude of the magnetic field from a single circuit three-phase line, with balanced or nearly balanced currents, decreases approximately as $1/r^2$, where r is the lateral distance from the line (r is assumed to be much greater than the conductor spacing; see Olsen, Deno, Baishiki [B90]). As the net current increases, the decrease in magnetic field magnitude changes from a $1/r^2$

to a $1/r$ dependence (Olsen, Deno, Baishiki [B90], Vinh, Jones, Shih [B108]).²⁴ The magnetic field from balanced double-circuit, three-phase lines with low reactance phasing (i.e., for identical or nearly identical load currents for both circuits) decreases nearly as $1/r^3$ where r is again much larger than conductor spacing. The temporal variations of the magnetic field are a function of load current variations, e.g., during heavy usage of electrical energy, the load currents increase and produce greater magnetic fields (the concurrent sagging of the conductors also can contribute to greater field levels at ground level).

Other commonly encountered sources of magnetic fields are straight conductors (e.g., connections to grounding systems/electrodes) and approximately circular turns of wire (e.g., found in transformers, motors, video display terminals, etc.) with single-phase currents. The magnetic field lines and vectors at representative points from such sources are shown schematically in Figure A.2(a) and Figure A.2(b). The magnetic fields are typically linearly polarized and the time-dependence of the oscillating vectors depends on the waveform of the currents. Sinusoidal currents produce sinusoidal magnetic fields free of harmonics; nonsinusoidal currents (e.g., the sawtooth waveforms from television deflection coils) produce nonsinusoidal magnetic fields that can be rich in harmonics (IEEE Magnetic Fields Task Force Report [B50]). The magnitudes of magnetic fields produced by currents in an infinitely long straight wire and a circular loop of wire decrease as $1/r$ (Halliday and Resnick [B41]) and $1/r^3$ (Stratton [B100]), respectively, where r is the distance from the field source (in the latter case it is assumed that r is much greater than the radius of the circular loop of wire).

As previously noted, some of the field parameters for magnetic fields also are used to describe quasi-static electric fields. For example, electric fields from three-phase transmission lines are, in general, elliptically polarized at points in space as shown in Figure A.3. Because normally the sum of the charges on the conductors is zero, the electric field decreases as $1/r^2$ at distances that are large compared to the conductor spacing. As for the magnetic field from a straight conductor, the electric field from an energized straight conductor also decreases as $1/r$.

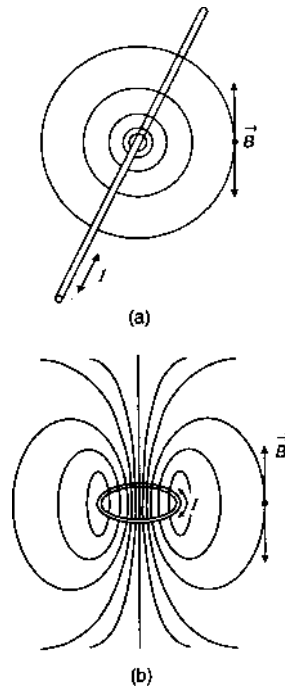


Figure A.2—Magnetic field from current in (a) straight and (b) circular conductors

²⁴ The net current is given by the summation over N conductors, $\sum i_n$, where i_n is the current in the n th conductor and is characterized by its phase with respect to current in the other conductors, and its magnitude.

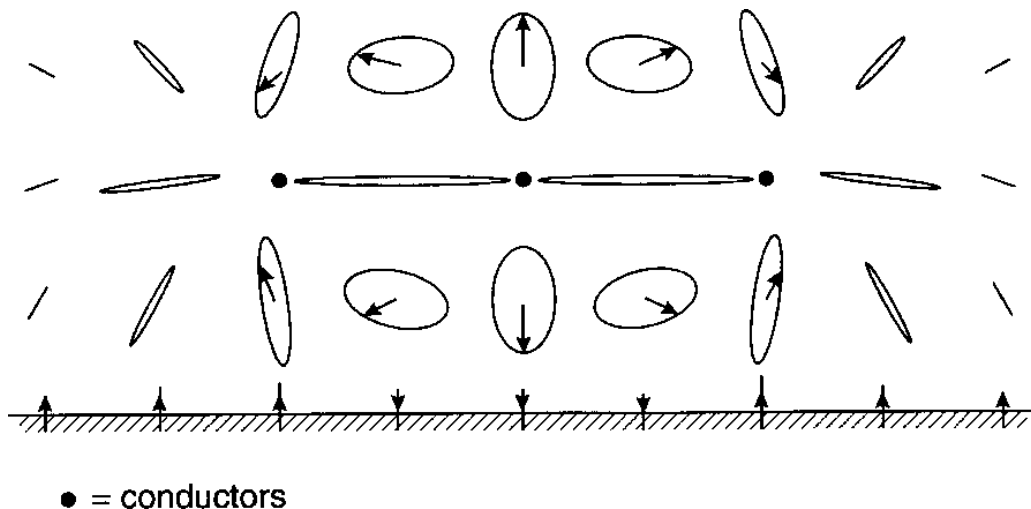


Figure A.3—Electric field ellipses at representative points in the vicinity of 3-phase transmission line (after Deno [B29]) with conductors perpendicular to page

A.3 Types of instrumentation

A range of instrumentation exists for characterizing quasi-static magnetic and electric fields. Only a brief listing is presented here. IEEE Std 1308-1994 [B53] should be consulted for further details regarding their use and principles of operation.

A.3.1 Magnetic field meters

The rms values of magnetic fields may be characterized with survey meters with different passbands and dynamic range. Magnetic field meters are available with single- and three-axis coil probes or sensors. Single- and three-axis fluxgate magnetometers are also available and are able to measure alternating and static fields. Miniature three-axis field meters with onboard memory for periodically recording field levels have been developed for determining human exposure and also have been used as survey meters. Similarly, miniature three-axis meters have been developed to record the time integral of the magnetic field for human exposure purposes (Kaune et al. [B68]). Three-axis wave capturing systems are available that simultaneously record the field waveform in three orthogonal directions and provide rms (or peak, average, etc.) field values, polarization information, and frequency content (Sicree, Rauch, Dietrich [B97]). The probes of magnetic field meters may be held by hand without proximity effects of the observer under normal conditions. A simple example of a single-axis survey meter consisting of an electrically shielded coil probe and voltmeter detector is shown Figure A.4. Historically, single-axis magnetic field meters have been used to measure the maximum magnetic field at a point by rotating the probe until a maximum reading is observed. For temporally stable magnetic fields (i.e., stable rms values), the single-axis magnetic field meter can also be used to measure the resultant magnetic field.

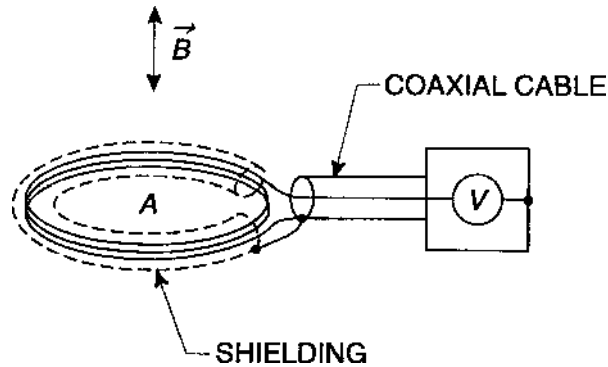
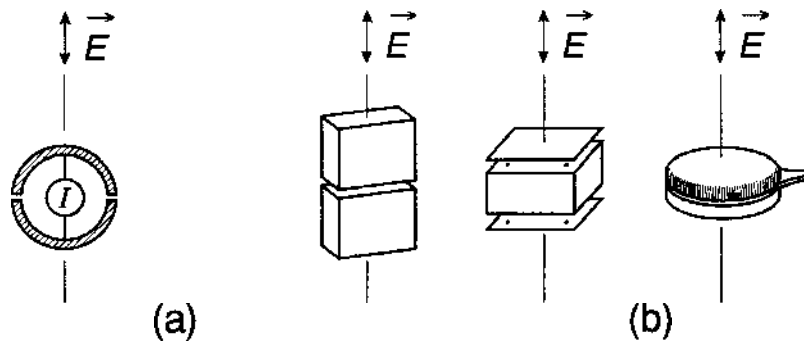


Figure A.4—Schematic view of simple magnetic field meter with coil-type probe

A.3.2 Electric field meters

Electric field meters are of three types: free-body meters, ground-reference meters, and electro-optic meters. Electric field meters used to measure quasi-static fields are typically single-axis devices, although three-axis meters are becoming available. Free-body meters are normally battery operated, electrically isolated from ground potential, supported in the field at the end of an insulating rod, and may be used to measure fields at most locations above the ground plane. Geometries of commercial single-axis, free-body electric field meters are shown in Figure A.5.



**Figure A.5—(a) Spherical free-body electric field meter;
 (b) geometries of commercial U.S. electric field meters**

Ground-reference electric field meters are normally used to measure the electric field strength on grounded conducting surfaces (including the surface of the Earth). One notable exception is the use of ground-referenced electric field meters to measure perturbed electric fields near video display terminals (VDTs), as described in IEEE Std 1140-1994 [B52] and MPR [B81].

Although the principle of operation of electro-optic field meters differs from free-body meters, it is used in a similar fashion to measure the field at most locations above the ground plane. All of the noted electric field meters are susceptible to proximity effects. The observer is a major source of proximity error as discussed in IEEE Std 1308-1994 [B53]. The proximity of other objects can also affect the field meter reading.

A.4 Magnetic field measurements

A.4.1 Goals and methods

As noted in A.3, magnetic (and electric) fields can be characterized according to a number of parameters, e.g., magnitude, frequency, polarization. Characterization of one or more of these parameters and how they might relate to human exposure may serve as possible goals of a measurement program. This clause provides a listing of such possible measurement goals and possible methods for their accomplishment. The listing should not be considered as complete since there can be a wide variety of goals and methods. While outside the scope of field parameters considered in this annex, characterization of static magnetic fields may also be of interest.

It is extremely important that the goals of a measurement program such as those considered in the following paragraphs to be clearly defined at the outset. A clear definition of goals is required for determination of instrumentation and calibration requirements, e.g., instrumentation passband, dynamic range, frequency calibration points. Once the goals have been identified and appropriate instrumentation has been acquired, a pilot study in the measurement environment of interest is often desirable before decisions on final measurement methods and associated protocols are made. The protocol will describe the step-by-step procedure that should be followed, using the possible methods indicated, to accomplish the measurement goals. The protocol may explicitly indicate such things as instrument requirements, (e.g., passband, probe size, magnitude range), location of measurements, and duration of measurements. It should be possible, using the same protocol, to compare with confidence measurement results obtained in similar electrical environments, for example, two substations.

This clause is not detailed in its descriptions of measurement methods and protocols because of their dependence on the goals and because of significant differences that will be encountered in various measurement environments. When developing a protocol, the following sources of magnetic fields and items should be considered, when applicable:

- Electrical sources serving the facility
- Types and locations of transformers
- Locations of main cables and breakers
- Magnitude of supply voltages, periods of peak power use
- Frequencies (including dc) of power supplies and electrical devices
- Location of people relative to known field sources
- Presence of any motors and generators
- Presence of small heaters
- Any electrical device with coils of wire
- Grounding systems and connections

Decisions should be made regarding permissible uncertainty during calibration of the instrumentation and total uncertainty during measurements. IEEE Std 1308-1994 [B53] describes uncertainties associated with the calibration process and uncertainties during measurements. Sketches of areas and locations where measurements will be made are often very useful. Electrical diagrams of buildings may be helpful in identifying sources of fields in office and similar buildings, although excessive reliance on such documentation should be avoided because of unrecorded changes in the building electrical system. While many sources of magnetic fields are visible, e.g., overhead lighting or electrical appliances, others are not, e.g., electrical equipment in adjacent rooms or on upper or lower floors. During pilot studies, decisions may be made regarding spacing between measurements, measurement locations, sample size, formats of data

sheets, questionnaires for job/task classification, etc. If determining human exposure is the goal of the measurements, examination of measurement procedures as described in the epidemiological studies cited as follows is strongly recommended as part of the process for developing a final measurement protocol.

While providing guidance for determining human exposure or estimates of human exposure to one or more magnetic field parameters is a major goal of this clause, other measurements goals with related applications exist. For example, “before” and “after” spatial distribution measurements of magnetic fields to check the effectiveness of power line field mitigation techniques, and spatial distributions of fields from electrical appliances are possible applications. For each goal, the frequency passband of the instrumentation is chosen for the frequency or frequencies of interest [see item g) in A.5.1].

Possible goals and methods are as follows:

- a) *Goal: Characterization of magnetic field levels.* Limits on permissible magnetic field levels as a function of frequency have been indicated in a number of documents (ACGIH [B1], ICNIRP [B44], IEEE Std C95.1-2005 [B55], IEEE Std C95.6-2002 [B58]) necessitating the determination of field levels with the greatest magnitude in specified areas.

Method: Single-axis and three-axis meters may be used to make spot measurements of the maximum and resultant magnetic fields, respectively. The difference between the resultant and maximum magnetic field values is discussed in IEEE Std 1308-1994 [B53] and can be as much as 41% (see Figure A.1).

Guidance exists for measurements near power lines (IEEE Std 644-1994 [B51]) and VDTs (IEEE Std 1140-1994 [B52]). Spot measurements near power lines may be correlated with load currents and estimates of magnetic fields for different load currents may be made. Load currents for appliances are constant or else typically cycle through a fixed range in a relatively short time, permitting the determination of the largest maximum or resultant magnetic field with relatively few spot measurements.

In environments away from power lines and appliances where correlations with magnetic field source currents are not readily made, spot measurements represent only a coarse characterization of field levels because they fail to capture the temporal variations of the field (IEEE Magnetic Fields Task Force Reports [B49], [B50]). If more definitive measurements of the magnetic field are required, magnetic field meters with recording capability may be used at locations of interest for times thought to be representative for producing the full range of field values. For example, in residences this might involve several 24 h records repeated during each season of the year [see item c) in A.5.1].

- b) *Goal: Characterization of spatial variations.* The spatial distribution of magnetic fields away from power lines or single identifiable sources is typically unknown. For example, Figure A.6 shows scatter plots of center of room measurements (vertical magnetic field, chest high) versus measurements at other locations in living rooms and kitchens during a survey of 77 residences (Silva et al. [B98], Swanson [B101]). While the field levels at different locations were not determined at the same instant, the data are indicative of possible variations in the same room of residences. Alternating magnetic fields in most environments will be non-uniform because of the spatial dependence of the fields from the source currents. It is noteworthy that static magnetic fields also show considerable spatial variability in residences (Silva et al. [B98]).

Method: Spatial variation measurements require the recording of the magnetic field components as a function of coordinate position. Standards exist for carrying out such measurements near power lines (IEEE Std 644-1994 [B51]) and VDTs (IEEE Std 1140-1994 [B52], MPR [B81]). While such measurement may be made with survey meters, instrumentation incorporating measurement wheels is available for characterizing spatial distributions of magnetic fields in environments where physical obstructions do not hinder movement of the wheel. As the wheel rotates, it periodically triggers a three-axis magnetic field meter to record the resultant magnetic field at a fixed height above the

ground or floor. Software provided with such instrumentation permits the generation of plots of magnetic field profiles, equifield contours, statistical analyses of the field levels, etc. As is the case for item a), such data will not capture the temporal variations of the field profiles without repeated measurements.

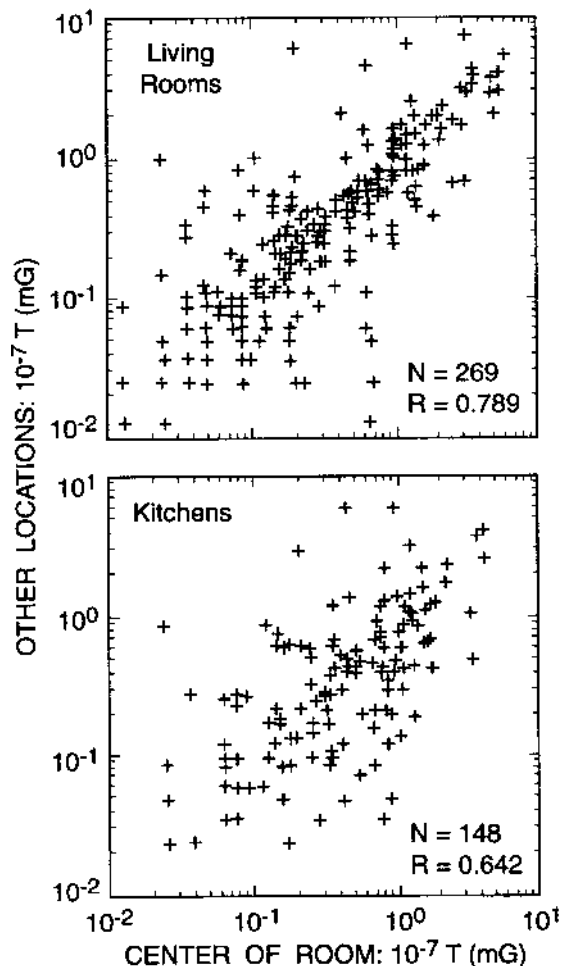


Figure A.6—Scatter plots showing magnetic field at center of room versus other points in same room for living rooms and kitchens during survey of 77 homes (Sicree, Rauch, Dietrich [B97])

NOTE—One measurement is performed at the center of the room (abscissa) and the other measurement is performed elsewhere (ordinate) with the location unspecified.

- c) *Goal: Characterization of temporal variation.* Because magnetic fields are produced by load currents and ground return currents that can vary greatly with time, the temporal variations of magnetic fields can easily exceed 100%. For example, Figure A.7 shows 24 h histories of the background resultant magnetic field at the center of a living room in a metropolitan area on two days during which load currents varied significantly because of weather conditions and the associated use of air conditioning in residences and places of business (IEEE Magnetic Fields Task Force Report [B49]). The data were recorded with an exposure meter every 15 s at a height of 1 m above the floor and the passband was adequate to characterize the fundamental and power frequency harmonics. Figure A.7(a) shows measurements during a hot, humid day when air conditioners were presumably in heavy use. Field measurements at the same location during a cool, less humid day, shown in Figure A.7(b), reveal a significantly different distribution of field values with an average field about

one-half that observed on the hot, humid day. The data, while anecdotal in the sense that measurements were performed in only one residence, is indicative of what can occur when there are significant changes in load currents. A mechanism that can produce short-term temporal variations of the magnetic field is the movement of ferromagnetic objects (e.g., automobiles and trucks), past the measurement location.

Method: Three-axis and single-axis magnetic field meters are available with output connections that may be used in combination with commercially available data loggers to record magnetic fields at one or more locations as a function of time. Three-axis exposure meters and magnetic field waveform capturing instrumentation also may be used to periodically record field levels. Because of the dependence of magnetic field levels on load currents (which can vary by day, week, or season), the challenge is to determine a time interval for recording measurements that will capture enough variations of the field to obtain a valid statistical description. Conducting an initial pilot study in the measurement environment of interest can be useful for addressing the question of measurement sampling time.

An additional consideration should be taken into account when measurements are performed in electric mass transportation systems or in other areas where there are variable speed motors. For example in subways, the magnetic field can be a function of the speed of the subway car (Dietrich, Feero, Jacobs [B32]).

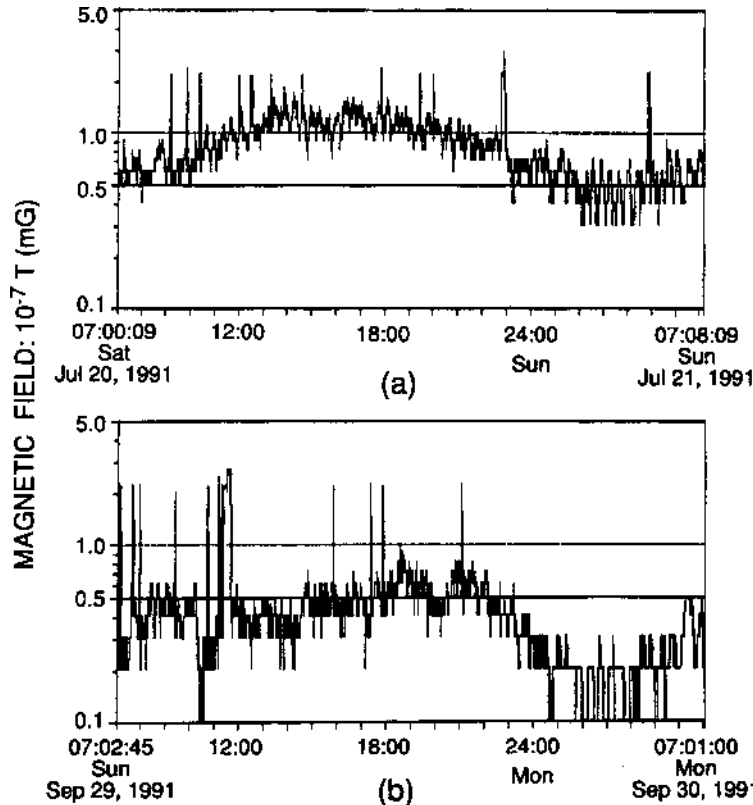


Figure A.7—Twenty-four hour measurements of magnetic field at center of living room (a) during hot, humid weather and (b) during cool, dry weather

- d) *Goal: Characterization of time-weighted-average (TWA) magnetic field.* A number of occupational and childhood cancer epidemiological studies that have examined the possibility of health effects from exposure to power frequency magnetic fields have considered the estimated TWA magnetic

field as the candidate exposure “dose” or “metric” (Feychting and Ahlbom [B35], London et al. [B70], Sahl, Kelsh, Greenland [B95], Theriault et al. [B105]). These and other studies have made determination of the TWA magnetic field a relevant measurement goal.

Method: Small three-axis exposure meters that are worn on the body and measure the time integral of the magnetic field may be used to measure the TWA magnetic field directly (Kaune et al. [B68]). Other three-axis exposure meters that record the magnetic field periodically may be used to determine the TWA magnetic field via analyses of the recorded field values. Less portable instrumentation combinations with recording capability can also be used to measure the TWA at locations of interest. Estimates of the annual TWA magnetic field have been calculated for residences from records of transmission line load currents and locations of the residences along the transmission line corridor (Feychting and Ahlbom [B35]). However, this approach does not include contributions to the field from local sources.

- e) *Goal: Characterization of magnetic field intermittency.* Reports in the literature indicate that intermittent exposure to power frequency magnetic fields may be more effective in evoking certain biological responses than steady state fields (Cook et al. [B23]). Such reports suggest that some index of the peaks and troughs (see Figure A.7) of magnetic field levels may be a characteristic of the field that should be quantified.

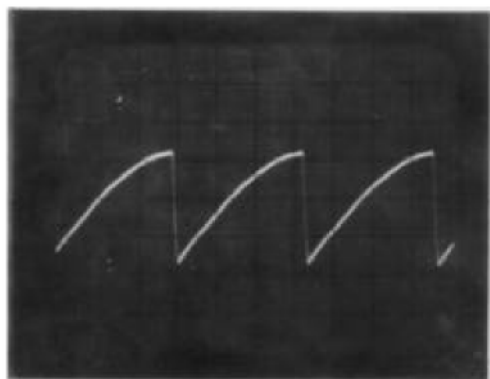
Method: Field meters that can periodically measure and record the magnetic field should be used for accomplishing this goal. What is unclear is how frequently the field values should be recorded or over what time intervals should the field values be averaged. For example, measurements recorded every 15 s (Figure A.7) will, in general, show more fluctuations than if hourly averages are used to characterize the fluctuations (Merchant, Renew, Swanson [B74]). Bioeffects researchers may be consulted for guidance on how to define an index of fluctuations. Because of the availability of the recorded data, different indices of fluctuations may be calculated and reported, e.g., the number of field increases and decreases (exceeding some percentage value) using 1 min, 2 min, etc., average field values.

- f) *Goal: Characterization of the incidence and duration of field levels exceeding a specified value.* Models that predict biological effects often assume that there is some threshold value of an agent below which, if applied, there is no effect. This model has its analogue for possible effects from exposures to magnetic fields.

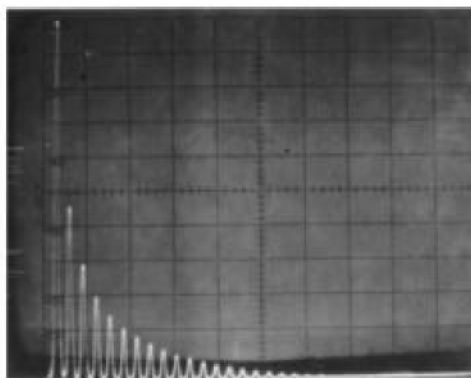
Method: Field meters that periodically record the magnetic field may be used to accomplish this goal. The choice of what field level to use as a threshold value may require consultations with bioeffects researchers. As in item e), the availability of recorded data allows the calculation and reporting of the frequency of occurrence of measured values that exceed more than one candidate threshold. Also, as for item e), the results may depend on the frequency of recording the magnetic field levels.

- g) *Goal: Characterization of frequency content in magnetic field.* Since magnetic fields from electrical equipment often contain power frequency harmonics or frequencies unrelated to the power frequency, and magnetic field limits have been set as a function of frequency (ACGIH [B1], Chartier, Bracken, Capon [B18], ICNIRP [B44], IEEE Std C95.6-2002 [B58]), characterization of frequency content may be an important goal. An example of a magnetic field that is rich in harmonics and that is produced by a common electrical appliance is shown in Figure A.8(a). Figure A.8(a) illustrates a spot measurement of the extremely low-frequency (i.e., near 60 Hz) magnetic field waveform 60 cm from the front-center of an operating 26 in cathode ray tube color television screen (Fulcomer [B36]). The harmonic components in the field are shown in Figure A.8(b), which is a spectrum analyzer display for the waveform in Figure A.8(a). Components from the second harmonic (120 Hz), which amounts to 45% of the fundamental, to the nineteenth can be discerned. It is noteworthy that measurement of the rms value of this field with a field meter that only detects the fundamental component will be too low by more than 20%.

Method: Commercially available single-axis and three-axis magnetic field meters are sometimes provided with output connections that give the integrated signal from the probe. Such instrumentation, in combination with commercially available spectrum analyzers, may be used to characterize the frequency components in the magnetic field. Alternatively, DWC instrumentation has software that allows the determination of the frequency content from the recorded data.²⁵ Three-axis instrumentation is also available that can be tuned to several harmonics of the power frequency. It should be noted that the frequency content of magnetic fields produced by variable speed electrical equipment, e.g., electric mass transportation systems, can change as a function of speed (Dietrich, Feero, Jacobs [B32]).



(a)



(b)

Figure A.8—(a) Oscilloscope display of magnetic field waveform 60 cm from operating 26 in television screen; (b) normalized spectrum analyzer display for waveform in (a)

NOTE—In (a), the rms value of the field is 0.17 μT , vertical scale = 0.2 $\mu\text{T}/\text{div}$. horizontal scale = 5 ms/div. In (b), horizontal scale = 200 Hz/div.

- h) *Goal: Characterization of magnetic field polarization* (see Figure A.1). A full characterization of the magnetic field requires a determination of its polarization for a given frequency. The magnetic field polarization may be of interest within the context of human exposure because, for example, magnetic fields with different polarizations but the same resultant value can induce in biological

²⁵ It is assumed that during such measurements, the frequency of sampling the waveform is adequate to avoid such problems as aliasing.

systems electric fields and currents that are significantly different in terms of their temporal and geometric properties (Misakian [B77]).

Method: Single-axis field meters, three-axis field meters (that provide readings of an individual axis), and three-axis DWC systems all may be used to measure the rms values of the semi-major and semi-minor axes of the magnetic field ellipse to determine its polarization at a point in space. As previously noted, this procedure assumes that only a single-frequency component of the magnetic field is being measured. With the presence of other frequencies, the rotating magnetic field vector no longer traces a simple ellipse (Mamishv and Russell [B71], Sicree, Rauch, Dietrich [B97]). Variations of the polarization as a function of time and location should be anticipated.

- i) *Goal: Characterizing human magnetic field exposure.* This important goal has been placed at the end of the listing of goals in order to first describe the magnetic field parameters that may be of interest from the viewpoint of human exposure.

Method: A clear distinction should be made between characterizing one or more magnetic field parameters and exposure to those parameters. The latter is best determined by wearing a miniature field meter that periodically records the field parameter(s) of interest at a location of interest on the body. Estimates of human exposure to a given field parameter in a specified area may be made from a combination of spatial and temporal variation measurements of the parameter and information that describes patterns of human activity in the area (see Deno and Silva [B30] for discussion of the electric field case). This approach fails to address exposures that occur outside the areas of field characterization.

Commercially available three-axis exposure meters that are worn on the body may be used to measure contemporary exposures to the field parameters identified in items a) through f) in A.5.1, for several passbands. Such instrumentation periodically records the resultant magnetic field value for times extending to several days, depending on the frequency of sampling the magnetic field, memory storage capacity, and battery life. The collected data may be downloaded to a computer and software provided with the instrumentation, or specially developed, is used to determine exposure to the parameters described in items a) through f) in A.5.1.

Past human exposures in specified areas may be estimated by having surrogates wearing exposure meters perform activities that were conducted in the past in the specified areas (Sahl, Kelsh, Greenland [B95], Savitz and Loomis [B96], Theriault et al. [B105]). This approach assumes that the magnetic field sources have not changed significantly over time.

A.4.2 Reporting magnetic field measurement results

The information that may be provided when reporting the results of measurements can vary, depending on the goals of the measurements. A clear indication of the measurement goals should be provided at the outset. The following information pertaining to the instrumentation also is desirable in all cases:

- Manufacturer
- Model/serial number
- Date
- Time
- Total measurement uncertainty
- Date of last calibration/calibration check
- Probe size/geometry (some exposure standards, e.g., IRPA/INIRC [B61], define limits in terms of a spatially averaged field through the specification of a loop surface area)

- A clear indication of what field quantity is being reported, e.g., the maximum magnetic field, the resultant magnetic field, the vertical field component, TWA. The recommended units are SI, with common units expressed in parentheses.

Other information that may be provided when appropriate includes the following:

- Magnetic field sampling frequency and descriptions of human activity when human exposure data is presented
- Drawings that describe the area and locations where measurements are performed
- Statistical information, e.g., the largest and smallest field values, median, geometric mean, standard deviation.
- Measurement height, source identification, weather conditions

A.5 Electric field measurements

A.5.1 Electric field measurement goals and methods

The reader is referred to A.4.1, as many of the points made for developing a magnetic field measurement plan are applicable for electric field measurements. For example, the requirement that measurement goals be defined early and the advisability of conducting a pilot study again applies for the reasons stated previously.

Direct measurement of human exposure to electric fields is more difficult than determining magnetic field exposure because miniature single-axis exposure meters that measure the electric field at the surface of the body (Chartier, Bracken, Capon [B18], Deadman et al. [B24], Héroux [B43]) are not readily available.²⁶ However, because of perturbations of the electric field by the body, the recorded field values are very sensitive to field meter location on the body and body orientation (Chartier, Bracken, Capon [B18], Miller et al. [B75]).²⁷ Such instrumentation has been used to determine electric field “enhancement factors,” i.e., the ratio of perturbed electric field at the surface of the body to unperturbed electric field, for different locations and orientations of the body in a vertical electric field (Chartier, Bracken, Capon [B18]). Enhancement factors for humans and animals in vertical electric fields also have been reported by other investigators (Deno [B27], Tenforde, Kaune [B103]). The enhancement factors have been used for scaling the electric field across different animal species when planning exposures for *in vivo* biological studies. Characterization of the unperturbed electric field (e.g., using a free-body meter) followed by appropriately scaled fields for *in vivo* (and *in vitro*) biological studies has been the pattern for investigating the possible effects of exposure to power frequency fields. Also, it is noteworthy that limits for human exposure to electric fields are given in terms of the unperturbed electric field (ACGIH [B1], ICNIRP [B44], IEEE Std C95.6-2002 [B58]). Thus, characterization of the unperturbed electric field is the focus of this clause.²⁸

It should be noted that the electric fields of past interest have been mainly vertical electric fields produced by power lines and related high-voltage equipment. The electric fields from such sources can be in excess of 10 kV/m (Armanini et al. [B3]) and are much larger than electric fields typically found in residences. In

²⁶ Exposure meters that simultaneously measure the electric field and resultant magnetic field at the surface of the body have also been developed (Héroux [B43]).

²⁷ An exposure measurement system that employs an electrically conducting vest as the probe to sense an average field for the upper body region is also described in the literature (Deno [B27]).

²⁸ A notable exception is described in IEEE Std 1140-1994 [B52], which requires the measurement of perturbed electric fields from VDTs using ground-reference electric field meters above the ground plane. The rationale for this approach is that the grounded probe, a flat circular plate, approximates the surface of a grounded VDT operator. The relationship between the perturbed electric field value that is measured and the electric field values at the surface of the operator is unknown.

residences, the electric fields can range in value from a few hundred V/m (e.g., near an electric blanket) to less than a few V/m away from electrical appliances (Armanini et al. [B3]).

Following is a listing of possible measurement goals and possible methods for their accomplishment. As for characterizing magnetic fields (refer to A.5.1), the listing should not be considered as complete since there can be a wide variety of goals and methods. In each case, the frequency passband of the instrumentation is chosen for the frequency or frequencies of interest [see item g) in A.5.1].

Possible goals and methods are as follows:

- a) *Goal: Characterization of electric field levels.* Limits on permissible electric field levels as a function of frequency and direction have been indicated in a number of documents (ACGIH [B1], ICNIRP [B44], [B45], IEEE Std C95.6-2002 [B58]), necessitating the determination of field levels with the greatest magnitude as well as possibly their direction in specified areas.

Method: Free-body and electro-optic meters may be used to make spot measurements of the maximum or resultant electric field. Ground-referenced meters should be used for measurements on the ground plane or on surfaces at ground potential. Guidance exists for measuring the predominantly vertical power frequency electric field near ground level in the vicinity of power lines (IEEE Std 644-1994 [B51] and IEC 833:1987 [B46]). The vertical electric field is measured because this quantity is often used to calculate induction effects in objects close to ground level (Deno [B28]). Unlike spot measurements of magnetic fields from power lines, the measured values will not change greatly because the voltages remain nearly constant (sagging of the conductors because of large current loads and thermal expansion can lead to greater field levels).

Some guidance for measuring power frequency electric fields away from power lines where the field geometry is less well-defined is given in IEC 833:1987 [B46]. Estimates of the range of electric field levels may be obtained by performing spot measurements with all electrical appliances and equipment turned on and off in the area of interest (Caola, Eno, Dymek [B15]).

- b) *Goal: Characterization of spatial variations.* The spatial distribution of electric fields away from power lines is typically unknown. Alternating electric fields will be non-uniform in most environments because the spatial dependencies from the field sources (energized conductors) are the same in some cases to that for magnetic fields.

Method: Spatial variation measurements require the recording of the electric field components as a function of coordinate position. Standards exist for carrying out such measurements near power lines (IEEE Std 644-1994 [B51] and IEC 833:1987 [B46]) and VDTs (IEEE Std 1140-1994 [B52] and MPR [B81]). While such measurements may be made with survey meters, instrumentation used in conjunction with “measurement wheels” is available for characterizing spatial distributions of electric fields in environments where physical obstructions do not hinder movement of the wheel. As the wheel rotates, it periodically triggers a single-axis free-body electric field meter that captures and transmits the waveform of the electric field (component) via a fiber optic cable to a portion of the detector circuit for storage. Software provided with such instrumentation permits the generation of plots of electric field strength profiles, equifield contours, statistical analyses of the field levels, etc., at a fixed height above the ground or floor. Such data will not capture the long-term temporal variations of the field profiles without repeated measurements. Variations of the field may occur if the probe is moved past electrically charged surfaces, e.g., plastics and synthetic clothing. It should be noted that during measurements of the electric field with a single-axis field meter and measurement wheel, the direction of the field can change.

- c) *Goal: Characterization of temporal variations.* The temporal variations of electric fields, in general, should not be as great as for magnetic fields. Electric fields are produced by conductors that are electrically energized. The electric field at a point will be the vector sum of contributions from all energized conductors in the vicinity of the measurements. Shielding effects by building materials, which can depend on weather conditions, e.g., wet structures during rainy weather, can contribute to

the variability. Short-term variations will occur if there is movement of conducting objects (e.g., automobiles and trucks) past the measurement location.

Method: Free-body instrumentation is available that periodically records the electric field waveform at a point in space for later analyses to determine the temporal variations [see Goal b)]. Ground-reference meters may be used with commercially available data loggers to record the electric field on grounded surfaces for later analyses. Similarly, optically isolated free-body electric field meters may be used with data loggers for above ground-plane measurements.

- d) *Goal: Characterization of TWA electric field.*
- e) *Goal: Characterization of electric field intermittency.*
- f) *Goal: Characterization of field levels exceeding a specified value.*

Method: These parameters may be determined for time intervals of interest by analyses of data collected with electric field meters with recording capabilities [see Goals b) and c)]. The reader is referred to A.4.1 for analogous measurements of the magnetic field.

- g) *Goal: Characterization of frequency content in electric field.* Because limits for exposure to electric fields have been set as a function of frequency (ACGIH [B1], ICNIRP [B44], [B45], IEEE Std C95.6-2002 [B58]) characterization of frequency content can be an important goal.

Method: Commercially available free-body instrumentation that can periodically record the waveform of the electric field has software that allows the determination of the frequency content from the recorded data. Signals from ground referenced electric field meters may be used with spectrum analyzers to determine the frequency content of fields characterized on grounded surfaces.

- h) *Goal: Characterization of electric field polarization.* A full characterization of the electric field requires a determination of its polarization for a given frequency.

Method: Free-body and electro-optic field meters may be used to measure the rms values of the semi-major and semi-minor axes of the electric field ellipse to determine its polarization at a point in space. As noted earlier, this procedure assumes that only a single-frequency component of the field is being measured. With the presence of other frequencies in the field, the rotating electric vector no longer traces a simple ellipse. Guidance for determining polarization near power lines is given in IEEE Std 644-1994 [B51] and IEC 833:1987 [B46].

- i) *Goal: Characterizing human electric field exposure.* It is recalled that there will be differences between perturbed electric field measurements obtained with exposure meters worn on the body, and unperturbed field measurements obtained with, for example, free-body meters. The results obtained using the two approaches will yield significantly different results, e.g., different maximum, minimum, mean values. While the focus of this Annex has been the characterization of the unperturbed electric field, a recent epidemiological study has characterized human exposure by measuring the field at the surface of the body using exposure meters (Miller et al. [B75]).

Method: A distinction should be made between characterizing one or more field parameters, e.g., Goals a) through h), and exposure to those parameters. As already noted, because electric field exposure meters are not readily available and interpretation of the recorded data can be complicated, a direct determination of exposure may not be possible. An alternative approach, as noted for the magnetic field case, is to estimate exposure to one or more parameters in a specified area from a combination of spatial and temporal variation measurements of the parameter(s) and information that describes patterns of human activity in the area. This approach has led to, in one study, the determination of “activity factors” that may be used as part of a process to estimate long-term electric field exposure in an agricultural setting (Deno and Silva [B30]).

A.5.2 Reporting electric field measurement results

The information that may be provided when reporting the results of measurements can vary, depending on the goals of the measurements. As for reporting the results of magnetic field measurements, a clear indication of the measurement goals should be provided at the outset. The following information pertaining to the instrumentation is also desirable in all cases:

- Manufacturer
- Model/serial number
- Date
- Time
- Total measurement uncertainty
- Date of last calibration/calibration verification
- Probe size/geometry
- A clear indication of what field quantity is being reported, e.g., the maximum electric field, the resultant electric field, the vertical field component, TWA, unperturbed field (free-body meter measurement), perturbed field (exposure meter measurement). The recommended units are SI units.

Other information that may be provided when appropriate includes the following:

- Descriptions of human activity when human exposure data is presented
- Drawings that describe the area and locations where measurements are performed
- Statistical information, e.g., the largest and smallest field values, median, geometric mean
- Measurement height; source identification; weather condition, etc.

Annex B

(informative)

FDTD requirements for low-frequency calculations

B.1 Basic FDTD requirements for low-frequency calculations

B.1.1 General techniques and time-step size requirements

The original algorithm, introduced by Yee [B112], forms the basis of the FDTD method where the electric and magnetic field components are positioned at the edges of a unit cell and computed at alternate half time steps. EM wave interactions in three-dimension are solved with a system of six coupled partial differential equations. The resulting system of finite-difference equations requires only the adjacent field components, around the unit cell, from its previous time step to continue, and is therefore highly adaptable to parallel processing on vector computers.

To ensure algorithm stability during time stepping, the time step chosen must satisfy the Courant condition or Courant, Frederick, and Levy (CFL) condition. For three-dimensional grids with cell edges of length Δx , Δy , Δz , and v the maximum velocity of propagation in any medium in the problem, usually the speed of light in free space, the time step size Δt is limited by the formula shown in Equation (B.1):

$$v\Delta t \leq \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \quad (\text{B.1})$$

The phase velocity of numerical modes in the FDTD lattice can vary with modal wavelength, direction of propagation, and lattice discretization causing dispersion of the simulated wave modes in the computational domain. This numerical dispersion can lead to nonphysical results such as pulse distortion, artificial anisotropy, and pseudo-refraction. The grid size (Δx , Δy , Δz) typically is selected, such that for the highest frequency at which the solution is valid, $\text{maximum}(\Delta x, \Delta y, \Delta z) \leq 0.1\lambda$, where λ is the wavelength at that frequency. This limits the numerical dispersion in most cases to an acceptable level. Under this condition, the error in the phase velocity of waves propagating in an arbitrary direction is not more than -1.3% . Thus, in this case, a sinusoidal numerical wave traveling a distance of only 2λ develops a lagging phase error of about 9.4° (Taflove [B102]). This error is linearly cumulative with the wave propagation distance. Dispersion and phase errors are negligible for quasi-static FDTD calculations.

The FDTD calculations may be excited by a variety of sources as described by Picket-May et al. [B93]), Kunz and Luebbers [B69]), and Taflove [B102], including voltage and current sources. Alternatively, a plane wave may be incident on the object as the excitation source. To have H-field or E-field exposure only, two plane waves traveling in opposite directions can be used.

Most commonly, the electric fields on one or more mesh edges are determined by an analytical function of time, such as a Gaussian pulse or sine wave. This then acts as a voltage driven source, which for example may be used to excite an antenna such as a loop generating the magnetic field of a metal detector.

The typical FDTD method is based on explicit, time-staggered, and space-staggered solution of discretized Maxwell's equations. For solutions in Cartesian coordinates, the field vectors \mathbf{E} and \mathbf{H} are dependent on the spatial variables x , y , z and the time variable t . The problem space is discretized into cells $x = i\Delta x$, $y =$

$j\Delta y$, $z = k\Delta z$, and time $t = n\Delta t$. Using the center difference approximation for each field component, six explicit finite difference equations are derived. Referring to Figure B.1, it can be noted that the electric field components are staggered half a grid with respect to the magnetic field components. For instance, the magnetic field component, H_z at time $(n + 1)$ is computed from the value H_z at time n and the values of the electric fields at time $(n+1/2)$ around the contour in the plane normal to H_z , namely $E_x^{n+1/2}(i + 1/2, j, k), E_x^{n+1/2}(i + 1/2, j + 1, k)$ and $E_y^{n+1/2}(i, j + 1/2, k), E_y^{n+1/2}(i + 1, j + 1/2, k)$. Thus, Faraday's Law is used to relate the line integral of the electric field to the normal flux component of the magnetic field in the mesh. Likewise, Ampere's Law is used to update the electric fields. The staggered space-time stepping solution of the Maxwell's curl equations is known in the iterative numerical methods as the leapfrog algorithm.

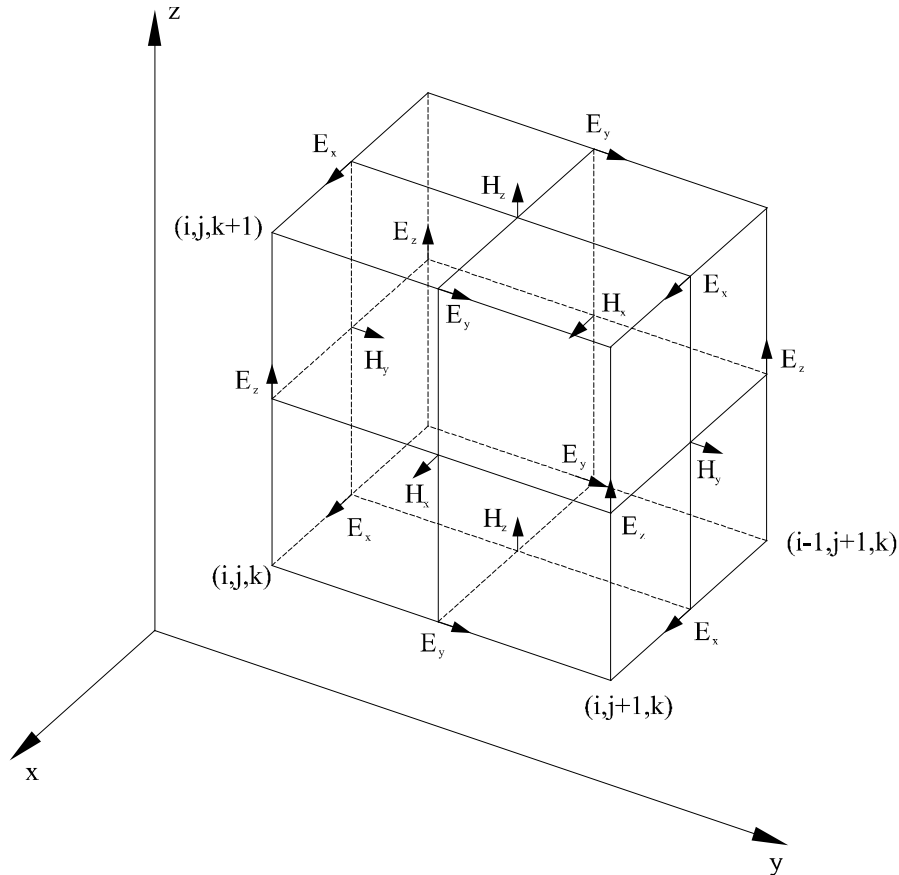


Figure B.1—FDTD method problem space discretized into cells $x = i\Delta x$, $y = j\Delta y$, $z = k\Delta z$, and time $t = n\Delta$ (electric field components are staggered half grid with respect to the magnetic field components)

In general, the time variation of the excitation may be either pulsed or sinusoidal. The advantage of using pulse is that the response for a wide frequency range can be obtained. For dosimetric exposure calculations the computational waveform depends on the waveform of the source. When the results at a single frequency or at a few frequencies are all that is desired, sine wave excitation is preferred. This is especially true if results for the entire body are needed, such as the SAR or current density distribution, since storing the transient results for the entire body mesh and applying FFT to calculate the SAR versus frequency requires extremely large amounts of computer storage.

B.1.2 Cell-size requirements

The choice of cell size is critical in applying FDTD. It must be small enough to provide accurate results at the highest frequency of interest, and yet be large enough to keep resource requirements manageable. For frequencies below 100 kHz the frequency resolution is not a problem. Cell size for low-frequency dosimetric calculations is only affected by desired resolution. Once a cell size is selected, the maximum time step is determined by the Courant stability condition. After the cell size is determined, a problem space large enough to encompass the anatomical model and the source, plus space between the objects and the outer absorbing boundary, is determined. From the number of Yee cells space (denoted as N_C) needed and the number of time steps required, resource requirements can be estimated.

B.1.3 Estimation of the computer resources

Assume that the material information for each cell edge is stored in 1 byte arrays with only dielectric materials considered. An estimate of the computer storage required in bytes (assuming single-precision variables) can be obtained from Equation (B.2):

$$storage = N_C \times \left(6 \frac{components}{cell} \times 4 \frac{bytes}{component} + 3 \frac{edges}{cell} \times 1 \frac{byte}{edge} \right) \quad (B.2)$$

where *components* indicate the vector electric and magnetic field components. If magnetic materials are included, six edges must be considered for the material arrays. The relatively small number of auxiliary variables needed for the computation process has been ignored.

The computational cost in terms of the number of floating point operations required can be estimated from Equation (B.3):

$$operations = 6 \times (components / cell) \times 15 (operations / component) \times N_C \times N \quad (B.3)$$

where 15 (*operations/component*) is the approximation based on experience and N is the total number of time steps. The total number of time steps N is determined by the frequency or the pulse length and the size of the time steps. Usually about five to eight periods are necessary to reach steady state conditions. N will be larger for resonant objects and smaller for lossy objects.

For a human body that fits into a region of 65 cm × 36 cm × 185 cm, with a 15-cell border around the body to separate it from the outer boundary, the problem space is about 160 × 110 × 400, or 7 million cells, with a cell size of 5 mm. Using Equation (B.2), the computer random access memory (RAM) necessary to do this calculation is approximately 190 Mbytes. Since this does not allow for storage of instructions and other arrays, the operating system will take some computer memory, a machine with about 256 Mbytes of RAM should be sufficient.

B.1.4 Convergence criteria

When using the FDTD method for current density calculations it is important that enough time steps are calculated so that the electric fields in the lossy tissues have reached sinusoidal steady state. When FDTD is used with pulsed excitation, determination of steady state is relatively simple, since the response dies to an essentially zero amplitude relative to the peak value. However, for sinusoidal response, determining steady state is not obvious. The number of time steps needed depends on the size of the geometry, the loss due to dissipation and radiation, and the presence of resonance. Usually for low-frequency calculations loss due to dissipation and radiation, and the presence of resonance are not a major problem.

It is possible to make an estimate of the percent error deviation from steady state while the FDTD calculation progresses. This determination uses values of the FDTD computed field or current to determine the sinusoidal complex field at different times in the calculation, then compares these results to see if they have changed. This difference over time falls to essentially zero in much the same way as does a transient FDTD calculation response.

In order to apply this approach, a method for determining the steady-state fields from two time samples can be applied. If it is assumed that steady state has been reached, then the time domain field or current response $R(t)$ must be of the form

$$R(t) = A \cos(\omega t) + B \sin(\omega t) = |R(t)| \cos(\omega t + \phi)$$

This response has two unknown values, A and B , since the radian frequency is known. If the FDTD response $R(t)$ is sampled at two different times t_1 and t_2 then the two unknown values A and B can be found by simultaneously solving the two equations. Once A and B are determined the magnitude of $R(t)$ and phase ϕ of $R(t)$ can be determined easily. Since the FDTD result may not have converged, A and B change as the calculation progresses until steady state is reached.

The time samples t_1 and t_2 cannot be chosen arbitrarily since they must provide independent samples of the sinusoidal function $R(t)$. In particular t_1 and t_2 cannot be separated in time by an even multiple of one-half of the period T of the sine function. For convenience, one might choose consecutive time steps, but the highest accuracy is achieved when the two time steps are taken at a time interval corresponding to one-fourth of the period of the sine wave. This may not be exactly possible since the FDTD time step may not allow it, but good accuracy is possible as long as the sample interval is approximately $T/4$.

Given the previously described capability to determine the magnitude of the sinusoidal response $R(t)$ as the FDTD calculation progresses, we can use this to estimate convergence. One approach is to take two samples of the FDTD output quantity to determine $R(t)$. Samples of the FDTD output might be taken at time t and at time $(t - t_s)$, where t_s is approximately $T/4$ and used to determine $R(t)$. Then two other samples at times $(t + t_p)$ and $(t + t_p - t_s)$, where t_p is approximately T , can be used to obtain $R(t + t_p)$. A necessary condition for steady state to be reached is that $R(t) = R(t + t_p)$. These two quantities can be compared as the FDTD calculation progresses (and t increases) to monitor convergence. Since steady state may be reached at different times in different parts of the geometry, samples should be taken at multiple grid points with different spatial orientations and at different locations in the mesh.

Because of the time-step restrictions given by the Courant condition, the monitoring of convergence is especially important for low-frequency applications. Most FDTD low-frequency calculations are critical for calculation time even if the frequency-scaling method is used. The monitoring of the convergence can ensure that only an absolute minimum of time steps are calculated.

B.1.5 Absorbing boundary conditions for low-frequency calculations

The reflection performance of perfectly matched layer (PML) absorbing boundary conditions (ABCs) for low frequency is analyzed in detail in De Moerloose and Stuchly [B26]. PML conditions are recommended because they are superior to most standard ABCs. For the frequency range covered by this recommended practice, the PML ABCs can produce substantial reflections. Sophisticated PML using novel PML profiles are able to improve the reflection of PML ABCs at low frequencies. However, these methods are usually not available in commercial software packages used for conformity assessments. This document recommends the use of PML ABCs with 15 or more layers for conformity simulations covered by this recommended practice.

B.2 Basic impedance method requirements for low-frequency calculations

B.2.1 General techniques

In the impedance method, an equivalent circuit network is used to represent the original biological body (De Moerloose and Stuchly [B26], Gandhi [B38]). A section of an impedance network is illustrated in Figure B.2. The values of these impedances in the network are determined by tissue electrical properties at various locations within the biology body. For example, the value for the x directional impedance can be obtained by Ogden [B89]:

$$Z_x = \frac{\Delta x}{\Delta y \Delta z (\sigma_x + j\omega \epsilon_x)}$$

where σ_x and ϵ_x are the conductivity and permittivity of the cell and $\Delta x, \Delta y, \Delta z$ are the size of the voxels in the x, y, z directions respectively.

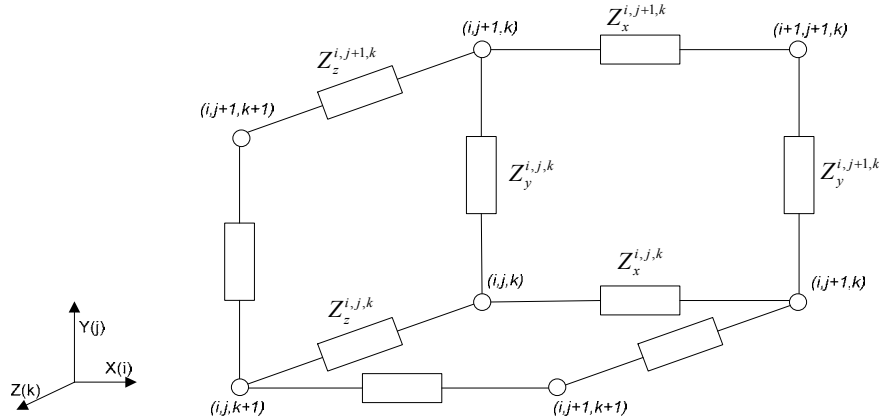


Figure B.2—A section of an equivalent circuit impedance network for the impedance method

It should be noted that this method can also model anisotropic medium and non-uniform cells, since $\epsilon_{x,y,z}$ and $\Delta_{x,y,z}$ can be direction and location dependent (Gandhi et al. [B40]).

B.2.2 Loop current versus line current

Based on the computational model defined in the previous subclause, for each node, there are six line currents $\tilde{I}_{x,y,z}$ and twelve loop currents $I_{x,y,z}$ associated with it. Figure B.3 illustrates three line currents and three loop currents associated with a node (i,j,k) (Orcutt and Gandhi [B92]).

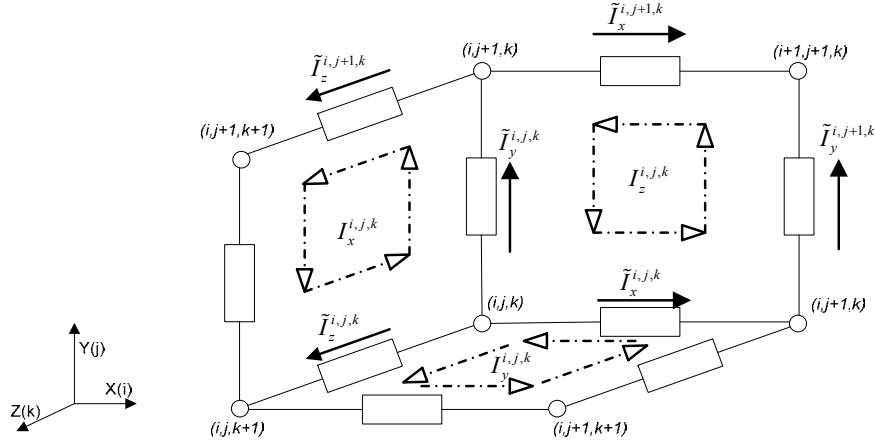


Figure B.3—Impedance network model for the impedance method showing three line currents and three loop currents associated with a node (i, j, k)

Each line current can be expressed as the summation of loop currents and vice versa. For example, the line current $\tilde{I}_{x,y,z}^{i,j,k}$, as shown in Figure B.3, can be expressed in terms of loop currents as shown in Equation (B.4):

$$\tilde{I}_z^{i,j,k} = I_x^{i,j-1,k} + I_y^{i,j,k} - I_x^{i,j,k} - I_y^{i-1,j,k} \quad (\text{B.4})$$

Similar expressions can be found for $\tilde{I}_x^{i,j,k}$ and $\tilde{I}_y^{i,j,k}$. Applying Kirchhoff's voltage equation to each loop, a linear equation for solving line current can be established. For a z-direction loop, the equation can be expressed as follows (Orcutt and Gandhi [B92]):

$$Z_x^{i,j,k} \tilde{I}_x^{i,j,k} + Z_y^{i+1,j,k} \tilde{I}_y^{i+1,j,k} - Z_x^{i,j+1,k} \tilde{I}_x^{i,j+1,k} - Z_y^{i,j,k} \tilde{I}_y^{i,j,k} = emf_z^{i,j,k}$$

where $emf_z^{i,j,k}$ is the electromotive force associated with the z-directional loop. A system equation can then be derived by combing the equation above from all loops in the network. It can be written into a matrix form as $Z\tilde{I} = V$, where Z is the impedance matrix, \tilde{I} is the line current, and V is associated with the electromotive force.

However, the resulting matrix equation is not a square matrix. One way to have a square matrix for the impedance method is to use loop current to represent the system equation above. Using this approach, a new system equation is obtained as follows (Gandhi and Kang [B39]):

$$\sum_{n=1}^3 a_{mn}^{i,j,k} I_n(i, j, k) = emf_m; 1 \leq m \leq 3$$

where $I_{1,2,3}$ stands for the loop currents along x,y,z directional loop and $a_{mn}^{i,j,k}$ are the coefficients associated with the network impedance. For most applications where the number of unknowns are relative large, it is desirable to solve the problem using iterative methods, such as the successive over relaxation (SOR) method. Once loop currents are solved, the line currents passing through the cell edges can be obtained by adding four loop currents crossing the edge. Consequently, the current density \mathbf{J} , the electric field \mathbf{E} and the normalized SAR can be calculated similar to those in the FDTD method.

B.2.3 Electromotive force

In impedance method, the electromotive force (*emf*) for each loop is generated by the temporal variation of magnetic flux across each loop. The value of this induced voltage can be expressed as follows (De Moerloose and Stuchly [B26], Ogden [B89]):

$$emf = -\frac{\partial}{\partial t} \iint \bar{B} \cdot d\bar{s}$$

where the integration area *ds* corresponds the surface where the loop current resides.

B.2.4 Computer resource requirements

To solve the system equation from impedance method, SOR algorithm is often used since this is a memory efficient technique compared to various sparse matrix solvers. Using this technique, the minimum memory required for single precision calculation is around (assuming that the biology body is discretized with total *NC* cells) (Gandhi and Kang [B39]):

$$storage = NC \times \left(3 \frac{edge\ impedance}{cell} \times 4 \frac{bytes}{edge\ impedance} + 3 \frac{loop\ current}{cell} \times 4 \frac{bytes}{loop\ current} + 3 \frac{emf}{cell} \times 4 \frac{bytes}{emf} \right)$$

If $N_{iteration}$ number of iterations is needed to solve the problem, the computational cost for solving the system equation is approximately:

$$operations = 3 \frac{loop\ current}{cell} \times 30 \frac{operations}{loop\ current} \times NC \times N_{iteration}$$

B.2.5 Convergence criteria

It is well known that relaxation factor for the SOR method affects the convergence speed. Typically, in impedance method, this factor is chosen between 1.3 and 1.8. The iteration process can be terminated when the relative error criterion satisfies (De Moerloose and Stuchly [B26]):

$$\frac{\|I^{(k+1)} - I^{(k)}\|_2}{\|I^{(k)}\|_2} \leq Error$$

where $I^{(k)}$ are values of loop current after *k* iterations. For typical simulation, *Error* should be smaller than 1×10^{-5} .

Annex C

(informative)

Measurement uncertainty and conformity decisions—an example

The concepts of measurement uncertainty are discussed in 4.2.3. By way of example, this annex describes how these concepts may be applied to deciding when the fields to which a person may be exposed are in accordance with MPE values or other exposure limits (ELs). In this example, the concepts are applied to measurements of the rms vector magnitude of the magnetic fields (B_{rms}) in an underground electrical distribution vault.

Since the 50/60 Hz magnetic fields in electrical distribution vaults have third and fifth harmonics with distortion as high as 20%, the “true” metric for comparisons with the ELs found in contemporary standards and guidelines (e.g., IEEE Std C95.6-2002 [B58]) is the harmonic sum rule [Equation (1)]. As pointed out in 4.2.2, B_{rms} (often called the *resultant*) is a convenient substitute for the sum rule. However, B_{rms} readings obtained in fields with harmonic content are biased relative to the sum rule and the uncertainty in such readings complicates comparisons with the MPE.

To estimate this bias in underground vault measurements, first write an approximate rule for B_{rms} in terms of its spectral components, shown in Equation (C.1):

$$B_{\text{rms}} = \sqrt{\sum_f B_f^2} \leq EL \quad (\text{C.1})$$

The exposure limit can be the MPE in IEEE Std C95.6-2002 [B58] or the ELs of another standard or guideline, as shown in Equation (C.2) and Equation (C.3):

$$\text{MPE}_{50/60 \text{ Hz}} = 2710 \mu\text{T} \text{ (IEEE Std C95.6-2002 [B58])} \quad (\text{C.2})$$

$$\text{EL}_{50/60 \text{ Hz}} = 25/f \text{ mT (ICNIRP [B45])} \quad (\text{C.3})$$

where f is in kHz.

NOTE—The MPE in the vault does not depend on frequency because the ac power frequency and its common harmonics lie in the 20 Hz to 759 Hz region where the MPE is constant.

Using these equations for the exposure limits, the sum rule [Equation (1)] for the first two harmonics can be rewritten as shown in Equation (C.4) and Equation (C.5):

$$(B_{50/60 \text{ Hz}} + B_3 + B_5) \leq 2710 \mu\text{T} \quad (\text{C.4})$$

$$f_{\text{pwr}} (B_{50/60 \text{ Hz}} + 3B_3 + 5B_5) \leq 25 \text{ mT-Hz} \quad (\text{C.5})$$

where $f_{\text{pwr}} = 50$ or 60 Hz

For the MPE in IEEE Std C95.6-2002 [B58], the metric bias [Equation (2)] in rms vector magnitude [Equation (C.1)] relative to the sum rule [Equation (C.4)] is:

$$\% \Delta_m = 100\% \frac{\sqrt{B_{50/60 \text{ Hz}}^2 + B_3^2 + B_5^2}}{B_{50/60 \text{ Hz}} + 3B_3 + 5B_5} - 100\%$$

or:

$$\% \Delta_m = 100\% \frac{\sqrt{1 + DF^2}}{1 + \frac{DF(1 + \alpha)}{\sqrt{1 + \alpha^2}}} - 100\% \quad (C.6)$$

where the distortion factor (DF) of the field (DF is defined in Clause 3) and the ratio between the two harmonics $\alpha = B_3 / B_5$ can be calculated from measurements in underground vaults and similar electric utility environments (Bowman and Methner [B10], Dietrich et al. [B31], Bowman et al. [B11]).

In accordance with the standard or guideline in Equation (C.3),

$$\% \Delta_m = 100\% \frac{\sqrt{B_{50/60\text{ Hz}}^2 + B_3^2 + B_5^2}}{B_{50/60\text{ Hz}} + 3B_3 + 5B_5} - 100\%$$

or:

$$\% \Delta_m = 100\% \frac{\sqrt{1 + DF^2}}{1 + \frac{DF(3 + 5\alpha)}{\sqrt{1 + \alpha^2}}} - 100\% \quad (C.7)$$

The minimum and maximum metric biases for the underground vaults are shown in Table C.1.

Table C.1—Biases in the rms vector magnitude relative to the harmonic sum rule for magnetic field characteristics measured in underground electric distribution vaults, and the resulting uncertainty factors for conformance decisions, e.g., by workplace inspectors and plant managers

Exposure limit	Metric bias		Uncertainty factors	
	Minimum	Maximum	LUL (inspector's test)	UUL (employer's test)
IEEE	-1%	-20%	0.93	1.35
Other standard	-4%	-49%	0.96	2.13
Field characteristics:				
Distortion factor (DF):	0.01	0.20		
Harmonic ratio (α):	0.39	0.55		

These large negative biases in B_{rms} can lead to “false positive” conclusions that magnetic fields in the vault conform to an exposure limit. To avoid these errors, the bias of the metric should be incorporated into the uncertainty limits [i.e., see Equation (5) and Equation (6)], which are then used to test an accordance hypothesis.

The next step in the treatment of measurement uncertainty is to incorporate the meter’s accuracy into the uncertainty limits. For measurements in an underground vault, an instrument that measures B_{rms} with 5% random error has upper and lower uncertainty factors given in Table C.1.

Finally, an appropriate hypothesis about how the measurement compares with the chosen exposure limit should be tested. In the “inspector’s test,” the null hypothesis is that the exposure is below the MPE and will be rejected only if the LUL on the measurement = 0.93 B_{rms} is greater than the MPE = 2710 μT . In other words, an inspector’s B_{rms} measurement must be greater than 2914 μT for the null hypothesis to be

rejected. In the “employer’s test,” the null hypothesis is that the exposures are greater than the MPE, so for rejection, the B_{rms} measurement must be below $2710 \mu\text{T} / 1.35 = 2007 \mu\text{T}$.

Annex D

(informative)

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⁴¹ Available from <http://www.cdc.gov/niosh/docs/77-173/>.

⁴² Available at <http://www.rsc.org/publishing/journals/AN/article.asp?doi=b414843f>.

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⁴³See Footnote 42.

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