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BSI Group Headquarters

389 Chiswick High Road London W4 4AL

Tel: +44 (0)20 8996 9000

Fax: +44 (0)20 8996 7400

www.bsigroup.com

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Interested committees:

Title: Draft BS EN 63184 Ed.1.0 Basic standard for the assessment of the human exposure to electric and magnetic fields from wireless power transfer systems. models, instrumentation, numerical methods and procedures (Frequency range of 1 kHz to 10 MHz).

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Responsible Committee Secretary: Ms Sophie Erskine (BSI)

Direct tel: 0208 996 7254

E-mail: sophie.erskine@bsigroup.com

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Introduction

This draft standard is based on national and international discussions. Your comments on this draft are invited and will assist in the preparation of the consequent standard.

For international standards, comments will be reviewed by the relevant UK national committee before sending the consensus UK vote and comments to the international committee, which will then decide appropriate action. If the international standard is approved, it is usual for the text to be published as a British Standard.

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Template for comments and secretariat observations

Date: xx/xx/20xx	Document: ISO/DIS xxxx
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1	2	(3)	4	5	(6)	7
MB	Clause No./ Subclause No./Annex (e.g. 3.1)	Paragraph/ Figure/Table/Note	Type of comment	Comment (justification for change) by the MB	Proposed change by the MB	Secretariat observations on each comment submitted
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	



106/586/CD

COMMITTEE DRAFT (CD)

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DATE OF CIRCULATION:

2022-09-02

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2022-10-28

SUPERSEDES DOCUMENTS:

106/432/NP, 106/440/RVN

IEC TC 106 : METHODS FOR THE ASSESSMENT OF ELECTRIC, MAGNETIC AND ELECTROMAGNETIC FIELDS ASSOCIATED WITH HUMAN EXPOSURE

SECRETARIAT:

Germany

SECRETARY:

Mr Diego Cuartielles

OF INTEREST TO THE FOLLOWING COMMITTEES:

TC 9,TC 26,TC 27,TC 34,SC 62A,SC 62B,TC 69,TC 77,TC 78,TC 96,TC 100,TC 124,TC 125,CISPR

PROPOSED HORIZONTAL STANDARD:



Other TC/SCs are requested to indicate their interest, if any, in this CD to the secretary.

FUNCTIONS CONCERNED:

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☐ ENVIRONMENT

☐ QUALITY ASSURANCE

☐ SAFETY

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TITLE:

Basic standard for the assessment of the human exposure to electric and magnetic fields from wireless power transfer systems - models, instrumentation, numerical methods and procedures (Frequency range of 1 kHz to 10 MHz)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**ASSESSMENT METHODS OF THE HUMAN EXPOSURE TO ELECTRIC AND
MAGNETIC FIELDS FROM WIRELESS POWER TRANSFER SYSTEMS –
MODELS, INSTRUMENTATION, MEASUREMENT AND
COMPUTATIONAL METHODS AND PROCEDURES
(FREQUENCY RANGE OF 1 kHz TO 30 MHz)**

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IEC/IEEE 63184 was prepared by IEC technical committee 106: Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure, in cooperation with the International Committee on Electromagnetic Safety of the IEEE Standards Association, under the IEC/IEEE Dual Logo Agreement between IEC and IEEE. It is an International Standard.

This document is published as an IEC/IEEE Dual Logo standard.

The text of this International Standard is based on the following IEC documents:

Draft	Report on voting
XX/XX/FDIS	XX/XX/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with the rules given in the ISO/IEC Directives, Part 2, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications/.

The IEC Technical Committee and IEEE Technical Committee have decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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308

INTRODUCTION

309 The scope of this document falls under the IEC/IEEE work item "development of standard for
310 measurement and calculation methods used to assess human exposure to electric, magnetic
311 and electromagnetic fields." Wireless power transfer (WPT) is the transmission of electrical
312 power from a transmitter to a receiver without current-carrying wires. This technology is
313 increasingly being implemented in a wide range of applications at different frequency ranges
314 from consumer electronics (e.g. mobile phones, tablet PCs) to automotive (electric vehicles
315 (EVs)). Human exposure is limited to avoid established adverse health effects, including
316 electrostimulation of nervous tissues (< 10 MHz) and thermal effects (> 100 kHz). An ITU-R
317 published report (ITU-R SM. 2303-1) from June 2015 on WPT systems describes RF exposure
318 assessment methodologies, yet no definitive assessment method was introduced. An
319 exposure assessment method of WPT for EV was described in IEC 61980-3:2019, however,
320 there is currently no other product standard related to WPT. As WPT systems will become
321 ubiquitous in a multitude of applications in the near future, IEC and IEEE established a joint
322 working group to address WPT assessment methods related to human exposures to electric,
323 magnetic, and electromagnetic fields.

324 In this document, IEC TC 106 and IEEE International Committee on Electromagnetic Safety
325 (ICES) TC34 describe the basic methods to assess the direct and indirect effects of exposure
326 to WPT systems, case studies, and relevant research. These methods mainly focus on
327 frequencies up to 30 MHz and consider both nerve stimulation and thermal effects. This
328 document specifies:

- 329 • general conformity assessment procedures (Clause 5);
- 330 • measurement methods (Clause 6);
- 331 • computational assessment methods (Clause 7);
- 332 • assessment combining experimental and computational methods (Clause 8).

333

334

ASSESSMENT METHODS OF THE HUMAN EXPOSURE TO ELECTRIC AND MAGNETIC FIELDS FROM WIRELESS POWER TRANSFER SYSTEMS – MODELS, INSTRUMENTATION, MEASUREMENT AND COMPUTATIONAL METHODS AND PROCEDURES (FREQUENCY RANGE OF 1 kHz TO 30 MHz)

1 Scope

The objective of this document is to specify the assessment methods to evaluate compliance of stationary and dynamic wireless power transfer (WPT) systems with electromagnetic human exposure guidelines (specific absorption rate (SAR), internal electric fields, or current density including contact currents). The frequency range covered by this document is from 1 kHz to 30 MHz. This version of the standard focuses on exposures from inductive WPT systems. Future versions will consider extended guidance for assessments of exposure from capacitive WPT systems.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC Guide 98-1:2009, *Uncertainty of measurement – Part 1: Introduction to the expression of uncertainty in measurement*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

IEC 61786-1:2013, *Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings – Part 1: Requirements for measuring instruments*

IEC 61786-2:2014, *Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings – Part 2: Basic standard for measurements*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO, IEC, and IEEE maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>
- IEEE Dictionary Online: available at <http://dictionary.ieee.org>

3.1**exposure**

<of a body> situation that occurs wherever a person is subjected to electric, magnetic or electromagnetic fields

3.2**basic restriction****BR**

maximum allowable exposure limit to time-varying electric, magnetic and electromagnetic fields that is based directly on established health effects

Note 1 to entry: Examples of basic restrictions can be found in Annex II of the Council Recommendation 1999/519/EC [1], ICNIRP Guidelines [2], [3], [4], IEEE Std C95.6 [5], and IEEE Std C95.1 [7], [8], [9].

[SOURCE: IEC 62311:2019 [10], 3.1.2]

3.3**reference level**

<of a field> field level derived from the basic restrictions under worst-case assumptions (e.g. exposure to a homogeneous field) used for the assessment of incident fields

Note 1 to entry: Examples of reference level can be found in Annex II of the Council Recommendation 1999/519/EC [1], ICNIRP Guidelines [2], [3], [4], IEEE Std C95.6 [5], and IEEE Std C95.1 [7], [8], [9].

3.4**direct effect**

biological effect resulting from direct interaction of electromagnetic field with biological structures

[SOURCE: ICNIRP Guidelines:2010 [3]]

3.5**indirect effect**

biological effect resulting from indirect interactions of electromagnetic fields with biological structures such as contact currents

3.6**incident field**

field that would exist in the absence of a person at a point where a person could be located

Note 1 to entry: In some documents, the incident field is called an unperturbed field or environmental field.

3.7**coupling factor, <in a body>**

factor which correlates the measured incident field to the induced field in the human body

3.8**electric field strength**

vector field quantity E which exerts on any charged particle at rest a force F equal to the product of E and the electric charge Q of the particle:

$$F = QE$$

[SOURCE: IEC 60050-121:1998, 121-11-18]

3.9**internal electric field**

<in a body> electric field induced inside the body as a result of exposure to electric, magnetic, or electromagnetic fields

3.10**magnetic field strength**

vector quantity obtained at a given point by subtracting the magnetization M from the magnetic flux density B divided by the magnetic constant μ_0

[SOURCE: IEC 60050-121:1998, 121-11-56]

3.11**contact current**

<for human body> current flowing into the body resulting from contact with a conductive object in an electromagnetic field

Note 1 to entry: This is the localized current flow into the body (usually the hand, for a light brushing contact).

3.12**current density**

<in a body> current density induced inside the body as a result of exposure to electromagnetic fields

3.13**specific absorption rate****SAR**

measure of the rate at which energy is absorbed by the human body when exposed to a radio frequency electromagnetic field

Note 1 to entry: The SAR in the tissue (or tissue-equivalent medium) can be determined by the rate of temperature increase or by E-field measurements, according to the following formulas:

$$SAR = \frac{\sigma E^2}{\rho}$$

$$SAR = c_h \left. \frac{\partial T}{\partial t} \right|_{t=0}$$

where

SAR is the specific absorption rate in W/kg;

E is the RMS value of the electric field strength in the tissue medium in V/m;

σ is the electrical conductivity of the tissue medium in S/m;

ρ is the mass density of the tissue medium in kg/m³;

c_h is the specific heat capacity of the tissue medium in J/(kg K);

$\left. \frac{\partial T}{\partial t} \right|_{t=0}$ is the initial time derivative of temperature in the tissue medium in K/s.

[SOURCE: IEC/IEEE 62209-1528 [11]]

3.14**peak spatial-average SAR****psSAR**

maximum average SAR within a local region based on a specific averaging volume or mass, e.g. any 1 g or 10 g of tissue in the shape of a cube

3.15**magnitude <of a vector>**

for any vector U , non-negative scalar, usually denoted by $|U|$, equal to the non-negative square root of the scalar product or, in the case of a complex vector, of the Hermitian product of the vector by itself

[SOURCE: IEC 60050-121:1998, 102-03-23]

3.16**gradient**

vector ∇f associated at each point of a given space region with a scalar f , having a direction normal to the surface on which the scalar field has a constant value, in the sense of increasing value of f , and a magnitude equal to the absolute value of the derivative of f with respect to distance in this normal direction

Note 1 to entry: The scalar f may refer to a component of a vector field.

[SOURCE: IEC 60050-121:1998, 102-03-23, Note added.]

3.17**phantom**

physical model with an equivalent human anatomy and comprised of a tissue-equivalent medium with dielectric properties specified in this document

[SOURCE: IEC/IEEE 62209-1528 [11]]

3.18**complex relative permittivity**

under sinusoidal conditions in a medium where the phasors $\underline{D}$ and $\underline{E}$ representing respectively the electric flux density and the electric field strength are linearly related, complex quantity $\underline{\varepsilon}_r$ defined by the relation

$$\underline{D} = \varepsilon_0 \underline{\varepsilon}_r \underline{E}$$

where ε_0 is the electric constant

Note 1 to entry: The complex relative permittivity is generally frequency dependent. For an isotropic medium the complex relative permittivity is a scalar; for an anisotropic medium it is a tensor.

Note 2 to entry: Generally $\underline{\varepsilon}_r$ is expressed as $\underline{\varepsilon}_r = \varepsilon'_r - j\varepsilon''_r$ where ε'_r is the real relative permittivity and ε''_r is the dielectric loss index. In the context of this document it represents the conductivity the free charges in of the exposed tissue or tissue-equivalent medium $\sigma = \omega \varepsilon_0 \varepsilon''_r$.

[SOURCE: IEC 60050-121:2019, 121-12-14]

3.19**device under test****DUT**

device that is tested according to the procedures specified in this document

3.20**wireless power transfer****WPT**

transmission of electrical energy by electric, magnetic or electromagnetic fields without wire or cable connection between the energy source and the load

3.20.1**wireless power transfer**

<dynamic> wireless power transfer by means of a load that moves intentionally whereas the source or a track of multiple power sources remains stationary

3.20.2**wireless power transfer**

<stationary> wireless power transfer by means of devices that do not intentionally change their relative position and orientation, throughout the duration of the power transfer

4 Symbols and abbreviated terms**4.1 Physical quantities**

The internationally accepted SI units are used throughout this document.

Symbol	Quantity	Unit	Dimensions
B	Magnetic flux density	tesla	T
c_h	Specific heat capacity	joule per kilogram per kelvin	J/(kg K)
E	Electric field strength	volt per metre	V/m
f	Frequency	hertz	Hz
H	Magnetic field strength	ampere per metre	A/m
J	Current density	ampere per square metre	A/m ²
P	Average (temporal) absorbed power	watt	W
T	Temperature	kelvin	K
ε	Permittivity	farad per metre	F/m
λ	Wavelength	metre	m
σ	Electric conductivity	siemens per metre	S/m

NOTE In this document temperature is quantified in degrees Celsius, as defined by: $T(^{\circ}\text{C}) = T(\text{K}) - 273,15$.

4.2 Constants

Symbol	Physical constant	Magnitude
η_0	Intrinsic impedance of free space	$120\pi \Omega$ or 377Ω
ε_0	Permittivity of free space	$8,854 \times 10^{-12} \text{ F/m}$
μ_0	Permeability of free space	$4\pi \times 10^{-7} \text{ H/m}$

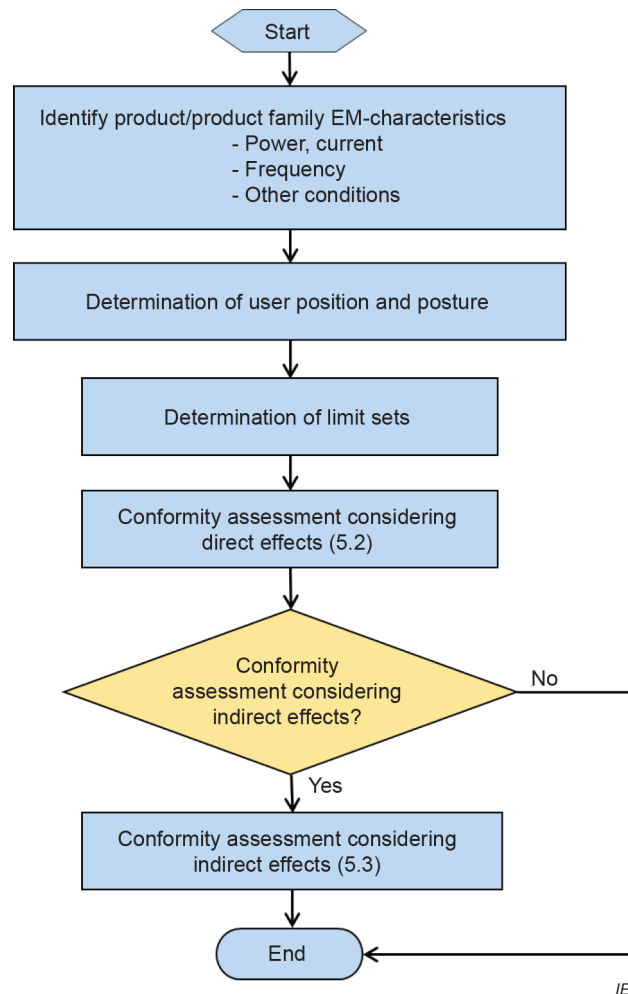
4.3 Abbreviated terms

BEM	boundary element method
B-field	magnetic flux density
BR	basic restriction
DUT	device under test
DWPT	dynamic wireless power transfer
E-field	electric field strength
EV	electric vehicle
FDFD	finite difference frequency domain
FDTD	finite difference time domain
FEM	finite element method
FIT	finite integration technique
GGSM	generic gradient source model
H-field	magnetic field strength
IM	impedance method
MoM	method of moments
psSAR	peak spatial-average SAR
RF	radio frequency
RL	reference level
RMS	root mean square
RSS	root sum square
SAR	specific absorption rate
SWPT	stationary wireless power transfer
SPFD	scalar potential finite difference
WPT	wireless power transfer

5 Assessment procedures

5.1 General

Figure 1 presents a flowchart for the assessment procedure for evaluating both the direct effects (internal electric field, current density, and/or SAR) and indirect effects (contact current) of electromagnetic fields generated by WPT systems. The assessment methods for these quantities are different.



IEC

Figure 1 – Flowchart for the assessment procedure

5.2 Conformity assessment considering direct effects

5.2.1 General

This clause provides basic assessment methods considering the direct effects of electromagnetic fields [2], [3], [4], [5], [7], [8], [9]. Evaluations are made either against basic restrictions or against derived reference levels. In the international guidelines, different limits on basic restrictions and reference levels are established for thermal and stimulation effects. The following list and Figure 2 describe four methods to assess exposure from WPT and demonstrate conformity with the basic restrictions or reference levels. Any of the four methods may be selected. The tiers require increasing technical effort and yield decreasing levels of conservativeness.

- The evaluation of the exposure based on coil current is straightforward, but is the most conservative one (5.2.2).
- Assessment of the incident fields and comparison against reference levels is described in 5.2.3.
- The incident magnetic fields can be applied to conservatively evaluate the induced fields for comparison with reference levels or basic restrictions using the gradient-source-based method described in 5.2.4.
- Direct evaluation of the fields induced in the body or in a body phantom using experimental or computational methods is described in 5.2.5.

NOTE A similar scheme with multiple methods of increasing complexity is used for example in ISO/TS 10974 [12], where the methods are deemed as “Tiers.” In that scheme the lowest numbered tier (Tier 1, analogous to method a) in the preceding list) represents the least complex method, produces the least accurate result, but is conservative. As the tier number increases, the method becomes more complex and is more difficult to implement, but provides a more accurate result. The use of the higher tiers reduces the need for excess compliance margin because the result is closer to the actual physical configuration.

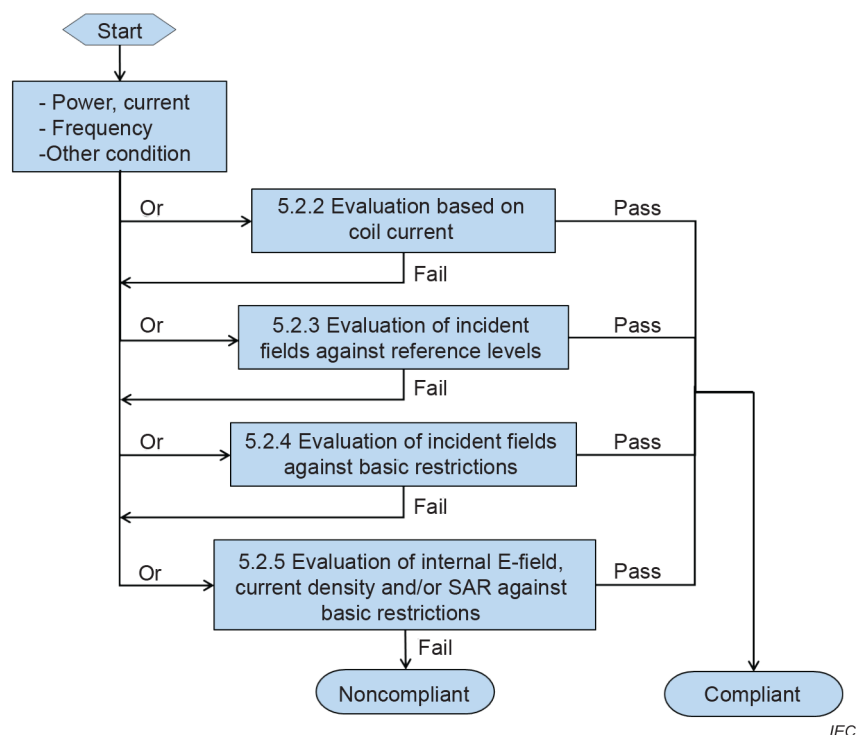


Figure 2 – Flowchart for the assessment procedure considering the direct effect

5.2.2 Evaluation based on coil current

According to Clause A.1, the maximum permissible coil current I_{mp} can be approximated by evaluating the magnetic flux density of a circular coil at a fixed distance of 10 mm and comparing it against the reference level B_{RL} . For a circular coil with radius r , I_{mp} can be estimated using Formula (1):

$$I_{mp}(r) = \frac{2\pi d_0 B_{RL}}{\mu_0 n} e^{\frac{r_0}{r}} \quad (1)$$

where

- r is the maximum coil radius (or half of the largest dimensions of non-circular coils);
- d_0 is the fixed distance of 10 mm at which the magnetic flux density is compared to B_{RL} ;
- B_{RL} is the reference level of magnetic flux density;
- μ_0 is the free space permeability;
- n is the number of turns of the coil;
- r_0 is a constant of 21,5 mm.

If it cannot be demonstrated that approximation of Formula (1) is conservative for the DUT or the evaluation distance is different from d_0 , then results per 5.2.2 are not valid regardless that the coil current is lower than the I_{mp} .

Annex A provides additional information regarding exposure evaluations using approximations.

5.2.3 Evaluation of incident fields against reference levels

Both incident electric and magnetic field strengths are measured or calculated at different distances including the closest distance and in all directions where the DUT can operate near people. If the field is uniform over the area of interest, the measured or calculated values of electric and magnetic fields shall be compared to the reference level. In the case of non-uniform fields, the measured or calculated field values may be spatially averaged over the exposed regions of the body under some conditions (Annex I, Annex J).

NOTE For example, Annex I and Annex J introduce an averaging method for WPT EV systems for persons standing vertically next to the EV on a non-conductive ground. These are demonstrated to be conservative for measurement distances beyond 20 cm and frequencies up to 100 kHz.

5.2.4 Evaluation of incident magnetic fields using coupling factor

5.2.4.1 General

The reference levels of electromagnetic fields are derived from the maximum coupling conditions between the fields and the human body, i.e. the maximum induced quantities in the human body exposed to the uniform electromagnetic fields. In many situations of localized exposure, such as in the vicinity of WPT systems, the evaluations can be overly conservative when the maximum or spatial average value is compared to the reference levels of EMF exposure guidelines.

Coupling factors for magnetic field exposure can be applied for the incident field to mitigate the over-estimation and still warrant conservativeness with respect to the basic restrictions, based on Formula (2).

$$QoI = k \times F \quad (2)$$

where

QoI is the quantity of interest to be compared to the limits (exposure metric);

k is a generic coupling factor that shall be derived according to 5.2.4.2 for specific coil configurations and evaluation distances, or according to 5.2.4.3 for the generic gradient source model (GGSM);

F is the measured incident field at the location of the evaluation.

Two methods are specified in this document:

- the coupling factor k_L is estimated from localized exposure scenarios based on the concept described in IEC 62233 [13] (5.2.4.2)
- the generally applicable coupling factor k_G is characterized with respect to the incident field gradient at the location of the exposure evaluation by applying the GGSM method [14] (5.2.4.3).

NOTE The method described in 5.2.4.2 specifies coupling factors for the maximum induced current density, electric field, and SAR. The GGSM method described in 5.2.4.3 specifies coupling factors for all basic restrictions of [2], [3], and [8].

The methods of 5.2.4.2 and 5.2.4.3 can be applied only under the following conditions.

- a) The induced quantities such as internal electric field, current density, or SAR caused by incident electric fields are negligible compared to those induced by the incident magnetic fields.
- b) The whole-body average SAR is negligible compared to respective limits, and the contribution of the psSAR or the internal electric field is dominant.
- c) Evaluation conditions such as frequency, field distribution, distance to human body, etc., are identical to those used in the derivation of the coupling factor. Otherwise the uncertainty due to the deviation shall be determined following the methodology of [15], [16] for 5.2.4.2, and of [14] for 5.2.4.3.
- d) Quasi-static conditions (7.2) apply for the incident magnetic field.

5.2.4.2 Coupling factor k_L based on the analysis of localized exposure scenarios

The coupling factor was originally introduced for exposure assessments in low frequencies in IEC 62226-2-1 [17] and IEC 62311:2007 [18], then amended in IEC 62233 [13]. The coupling factor for the current density $k_{L,J}$ is determined using Formula (3).

$$k_{L,J} = \frac{J_{\max}/B_{\max}}{J_{BR}/B_{RL}} \quad (3)$$

where

- $J_{\max}$ is the maximum current density induced in the human body;
- $B_{\max}$ is the maximum magnetic flux density in the absence of a person at a point where a person could be located;
- J_{BR} is the basic restriction of current density;
- B_{RL} is the reference level of magnetic flux density.

Using this coupling factor, the measured magnetic field strength, multiplied by the coupling factor, can be compared to the reference level directly.

The concept of compliance using coupling factor is expanded to the internal electric field and SAR per Formula (4) and Formula (5) ([15], [16]).

$$k_{L,E} = \frac{E_{\max}/B_{\max}}{E_{BR}/B_{RL}} \quad (4)$$

$$k_{L,SAR} = \frac{\sqrt{SAR_{\max}}/B_{\max}}{\sqrt{SAR_{BR}}/B_{RL}} \quad (5)$$

where

- $E_{\max}$ is the maximum internal electric field induced in human body;
- E_{BR} is the basic restriction of internal electric field strength;
- $SAR_{\max}$ is the maximum SAR induced in human body;
- SAR_{BR} is the basic restriction for psSAR.

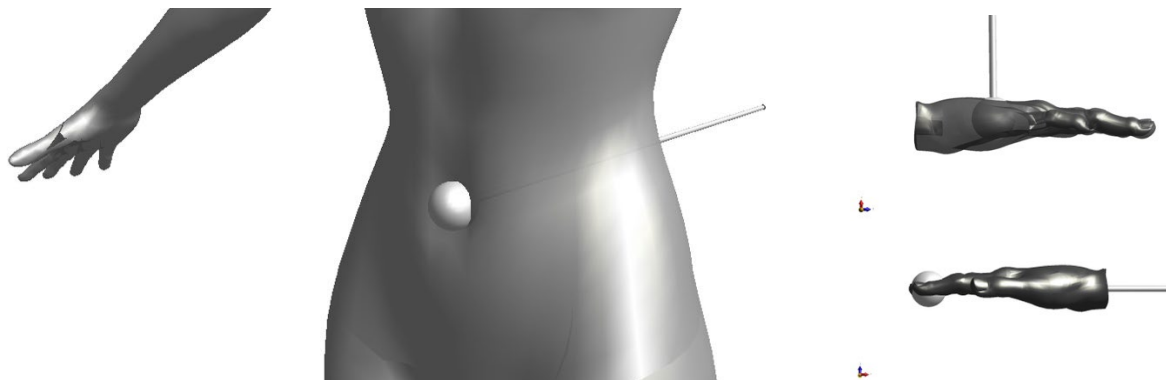
E_{BR} and B_{RL} depend on frequency. The coupling factor k_L is multiplied by the measured magnetic fields to consider the effects of field non-uniformity. Conservative coupling factors k_L are typically determined by simulation with the ratio of the induced quantities to the incident magnetic field ([15], [16]), e.g. for a specific frequency, field distribution, distance to human body and for different anatomies. Based on such an evaluation, conservative values of the coupling factors can be derived, the uncertainty of which must be estimated and documented following the methodology applied in [15], [16]. Appropriate methods for the computational modelling of the coil and the exposed person are described in Clause 7,

NOTE See also Annex F and Annex G. Annex H describes procedures for validation of the computational results.

Compliance with basic restrictions (internal electric field strength, current density, or psSAR) is then assessed by comparing the multiplied value to the reference level of the magnetic fields only.

5.2.4.3 Coupling factor k_G based on the GGSM method

A generally applicable coupling factor $k_G(G_n)$ is proposed using the GGSM in [14] to mitigate over-estimation by incident magnetic field assessment in strong field gradients that are common in the vicinity of WPT systems. The method is conservative for real sources because the coupling factors are derived from a 2D gradient model, whereas real sources have gradients in 3D. However, it requires evaluation of both the local field amplitude and the local gradient in the normal direction with respect to the exposed body, as indicated in Figure 3.



NOTE The sphere symbolizes the location of the field probe that measures the field amplitude and gradient at the reference location (body surface).

Figure 3 – The gradient is determined at the surface and normal to the surface, i.e. in the direction of the axis shown

The method applies the following quantities of the incident magnetic field at the location of the exposed body:

- frequency;
- B-field amplitude (B_{xyz}) at the skin surface of the exposed body;
- local B-field gradient G_n (T/m/T) normal to the skin surface of the exposed body.

The GGSM source consists of a generic magnetic field source with two parallel line currents with independent amplitudes. This source is described in [14] and generates a 2D gradient field (i.e. uniform in one direction) with arbitrary magnetic flux density B and gradient G_n . The fields induced in the exposed body are normalized to the maximum B-field amplitude and gradient at the skin surface. Based on a large-scale computational study including human body models of different ages, heights, and weights [14], worst-case exposure conditions (i.e. the highest induced field quantities) were determined for each gradient and frequency analysed. The coupling factors $k_G(G_n)$ are determined per Formula (6):

$$k_{G,QoI} = \frac{QoI_{\max}(G_n)/B_{\max}(G_n)}{QoI_{BR}/B_{RL}} \quad (6)$$

675 where

$QoI_{\max}(G_n)$ represents the maximum of the induced quantity of interest (electric field, current density, or SAR) in the body when the field gradient is G_n ;

$B_{\max}(G_n)$ is the maximum measured B-field at the human body surface;

QoI_{BR} is the basic restriction of the induced metric QoI;

B_{RL} is the reference level of the magnetic flux density B or a fixed normalization value, e.g. B_0 .

676 The coupling factors of each specific induced metric specified in the guidelines, i.e. [2], [3]
 677 and [8], are expressed by physics-based approximations as functions of the gradient of the
 678 magnetic flux density, i.e. Formula (7), Formula (8), Formula (9), Formula (10), and Formula
 679 (11):

$$k_{G,E;ICNIRP\ 2010}(G_n) = \frac{1}{\left[1 + 6,5 \times 10^{-6} \times (G_n/c_3)^{5,8}\right]^{(1/5,8)}} \quad (7)$$

$$k_{G,E;IEEE\ 2005}(G_n) = \frac{1}{\left[1 + 4 \times 10^{-11} \times (G_n/c_3)^{6,6}\right]^{(1/6,6)}} \quad (8)$$

$$k_{G,J;ICNIRP\ 1998}(G_n) = \frac{1}{\left[1 + 4 \times 10^{-3} \times (G_n/c_3)^{2,9}\right]^{(1/2,9)}} \quad (9)$$

$$k_{G,psSAR\ 10g}(G_n) = \left(\frac{1}{\left[1 + 2 \times 10^{-1} \times (G_n/c_3)^{1,2}\right]^{(1/1,2)}} \right)^2 \quad (10)$$

$$k_{G,psSAR\ 1g}(G_n) = \left(\frac{1}{\left[1 + 2,5 \times 10^{-1} \times (G_n/c_3)^{1,1}\right]^{(1/1,1)}} \right)^2 \quad (11)$$

680 where

c_3 constant = $1\ m^{-1}$

$k_{G,E;ICNIRP2010/20}$ coupling factor for induced E-field averaged over a cube of 2 mm

$k_{G,E;IEEE2005}$ coupling factor for induced E-field averaged over a line of 5 mm

$k_{G,J;ICNIRP1998}$ coupling factor for current density averaged over an area of $1\ cm^2$

$k_{G,psSAR10g}$ coupling factor for peak spatial SAR averaged over a cube of 10 g

$k_{G,psSAR1g}$ coupling factor for peak spatial SAR averaged over a cube of 1 g

The trend of the approximation formulas as a function of the gradient is shown in Figure 4. The method has been analytically verified (see Appendix of [14]). For any other specific induced metrics or basic restrictions, the process described in [14] needs to be repeated.

To test compliance with basic restrictions, the magnetic field amplitude (B_{meas}) and the field gradient ($G_{n,\text{meas}}$) of the WPT system are evaluated at any closest accessible location from the source using equipment that provides both values, or that measures the field using a field meter at separate locations and derives the gradient. Here the field gradient is determined at the reference location according to Figure 3. The internal electric field, current density and SAR can then be predicted by Formula (12), Formula (13), Formula (14), and Formula (15) [14]:

$$E = k_{G,E}(G_{n,\text{meas}}) \times E_{\text{BR}} \times \frac{B_{\text{inc,meas}}}{B_{\text{RL}}} \quad (12)$$

$$J = k_{G,J}(G_{n,\text{meas}}) \times J_{\text{BR}} \times \frac{B_{\text{inc,meas}}}{B_{\text{RL}}} \quad (13)$$

$$psSAR_{10g} = k_{G,psSAR10g}(G_{n,\text{meas}}) \times SAR_{\text{BR}} \times \left(\frac{B_{\text{inc,meas}}}{B_0} \right)^2 \times \left(\frac{f}{f_0} \right)^2 \times k_{B,10g} \quad (14)$$

$$psSAR_{1g} = k_{G,psSAR1g}(G_{n,\text{meas}}) \times SAR_{\text{BR}} \times \left(\frac{B_{\text{inc,meas}}}{B_1} \right)^2 \times \left(\frac{f}{f_0} \right)^2 \times k_{B,1g} \quad (15)$$

where

- B_{RL} is the reference level of the corresponding standard;
- $k(G_{n,\text{meas}})$ is the value of the coupling factor calculated for the specific gradient $G_{n,\text{meas}}$;
- $B_{\text{inc,meas}}$ is the local magnetic field measured by the field gradient probe or evaluated computationally;
- B_0 is a constant normalization magnetic flux density of 6,25 μT (ICNIRP 2010);
- B_1 is a constant normalization magnetic flux density of 2,04 μT (FCC);
- $k_{B,10g}$ is the low frequency magnetic field coupling coefficient for psSAR10g, 2×10^{-4} ;
- $k_{B,1g}$ is the low frequency magnetic field coupling coefficient for psSAR10g, $4,6 \times 10^{-5}$;
- f_0 is a constant normalization frequency of 100 kHz.

The formulas presented in this subclause, together with Figure 4, quantify the reduction of the induced field quantities in the presence of a magnetic gradient field with a coupling factor k of less than 1.

NOTE 1 An example is a case of two magnetic field sources that operate at an identical frequency and whose magnetic fields at the measurement point are equal. One of them has a uniform magnetic field distribution ($G_n = 0$), and the magnetic field gradient of the other one is different from zero (the magnetic field decreases in the direction of the human body). In both cases, E_{BR} , B_{RL} , and $B_{\text{inc,meas}}$ are the same, but $k_{G,E} = 1$ for the uniform field and $k_{G,E} < 1$ for the field with gradient. This makes the induced electric field E of the non-zero-gradient smaller than that of the no-gradient case.

The method may be applied using the following steps:

- a) determine the incident B-field at every location at which a body may be exposed to the field of the source and determine the lowest gradient that is normal to the surface of the body (see Figure 3)
- b) compute the maximum induced fields according to Formula (12), Formula (13), Formula (14), and Formula (15) for all locations
- c) if the maximum induced field is lower than the applicable basic restriction, the source is compliant.

NOTE 2 Measurement instrumentation might become available that automatically compute the maximum induced fields while sweeping the field spatial distribution.

For the application of this method the conditions listed in 5.2.4.1 shall apply. An additional condition is that the incident magnetic field is dominated by a single source. For conditions different from these, the uncertainty shall be determined following the methodology of [14].

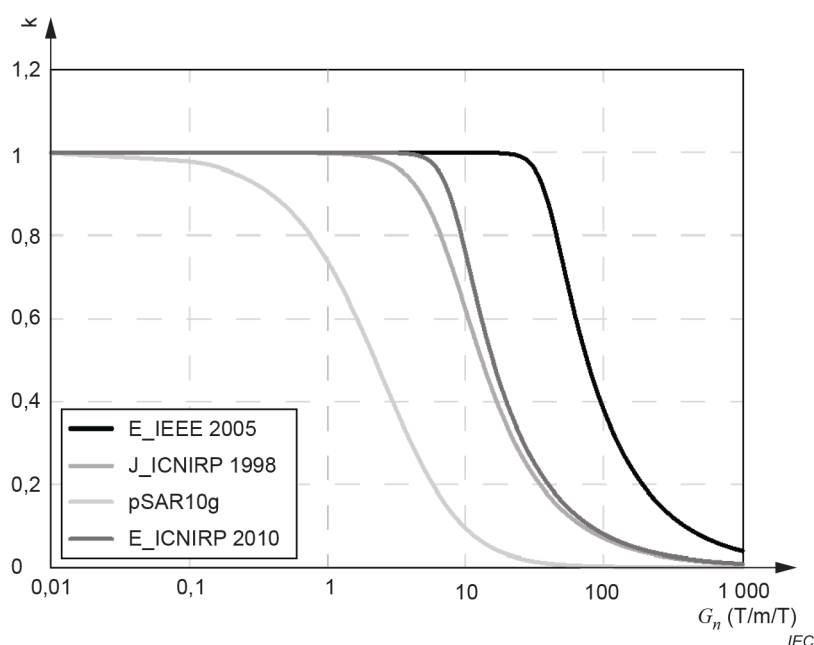


Figure 4 – Trend of the approximation formulas as a function of the gradient [14]

5.2.5 Evaluation of internal E-field, current density, and/or SAR against basic restrictions

SAR can be measured using a small probe in a liquid-filled phantom which is exposed to the electromagnetic fields of the DUT. The measured values can be directly compared with basic restrictions. The evaluation and validation procedures are described in IEC/IEEE 62209-1528 [11]. The assessment method is described in detail in 6.2.

NOTE The frequency range of IEC/IEEE 62209-1528 is from 4 MHz to 10 GHz.

Internal electric field, current density, or SAR may be evaluated analytically or by simulation using anatomical models of the human body or models of experimental phantoms for comparison with basic restrictions. The simulation model and methodology shall be validated as part of the evaluation process. The validation procedure and results shall be documented. The assessment method based on simulation is described in detail in Clause 7.

5.3 Conformity assessment considering indirect effect

This subclause describes the basic assessment methods considering the indirect effect of electromagnetic fields. Contact currents are the only indirect effects considered in this document. Contact currents flow into a biological body via a contacting electrode or other source of current.

Contact currents can be assessed either by incident electromagnetic fields or direct measurement.

The following two considerations must be applied to assess compliance by incident electromagnetic fields.

- Incident electric field levels to prevent adverse indirect effects of contact current (shocks and burns) are shown in the guidelines [2], [3], [4].
- Incident magnetic field levels to prevent adverse indirect effects of contact currents can be calculated by the current induced in the loop formed with the grounded metal and the human body with Formula (16).

$$H = \frac{Z}{2\pi f \mu_0 S} I_c \quad (16)$$

where

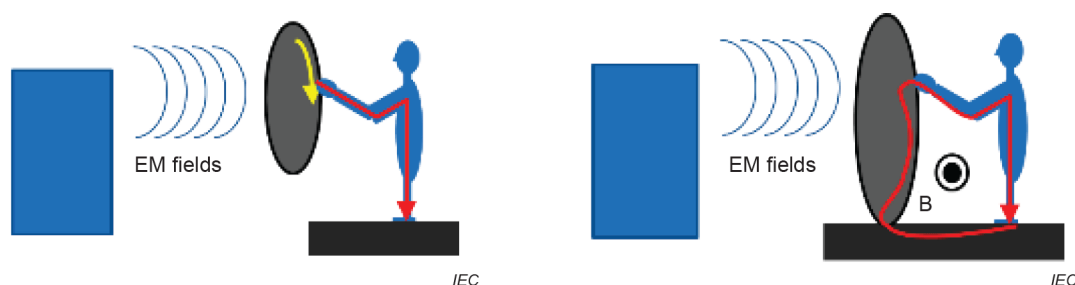
I_c is contact current (A);

Z is the impedance of the human body (Ω) (see 6.3);

S is the area of the loop such as 1,5 m × 0,5 m.

Contact currents can also be directly measured by a contact current meter with an ungrounded or grounded metal object placed in the vicinity of the WPT systems. Figure 5 shows exposure situations for ungrounded and grounded metal objects.

Figure 6 presents a flowchart for the assessment procedure. Details of measurement conditions, measurement setup, etc., are summarized in IEC TR 63167 [19]. The assessment method is described in detail in 6.3.



a) Currents when touching ungrounded metal

b) Currents when touching grounded metal

Figure 5 – Two exposure situations for ungrounded and grounded metal objects

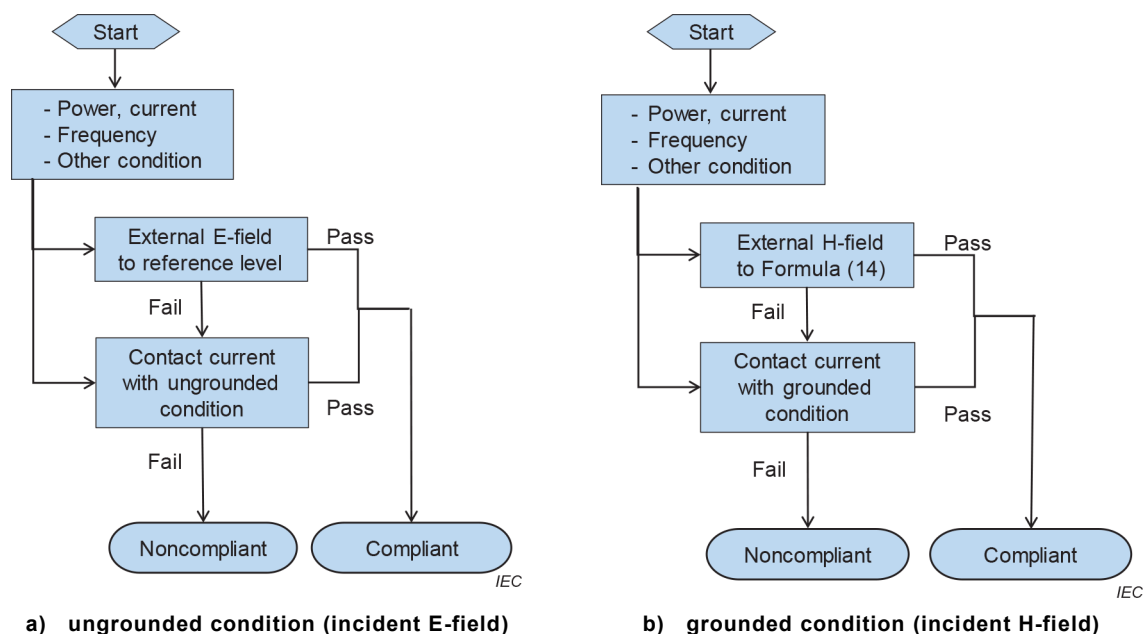


Figure 6 – Flowchart for assessment procedures for indirect effects

6 Measurement methods

6.1 Incident fields

6.1.1 General

IEC 61786-1:2013 and IEC 61786-2:2014 describe electromagnetic field basics, measurement methods, and requirements of the measurement equipment at frequencies below 100 kHz. In addition, IEC 62233 [13] and IEC 62311 [10], [18] describe electromagnetic field measurements for purposes of guidelines conformity assessments.

- a) Equipment for measuring electric fields, magnetic fields, and magnetic field gradient is described in 6.1.2.1, 6.1.2.2, and 6.1.2.3, respectively. The calibration methods are described in Annex B.
- b) The validation method is described in Annex C.
- c) Both incident electric and magnetic field vectors are measured at a specific distance, including the closest distance where the DUT may operate near people. These International Standards specify measurement positions based on the size and regular usage of equipment. IEC 62311 [10], [18] specifies it as a “user’s usual position.” IEC 62233 [13] specifies the measurement position in detail for household appliances and similar apparatuses, including inductive battery chargers.
- d) The measured value may be based on either a time-averaged or the maximum instantaneous value of the target electromagnetic field, depending on the characteristics of the source and the exposure limit being assessed.
- e) In principle, the measurement is performed in the space without the human body. In general, the existing position of the human body against the WPT cannot be determined completely. Therefore, typical measurement positions that are conservative with respect to human exposure shall be selected.
- f) When the measurement probe comes close to the source and metallic and/or highly insulated objects, electromagnetic coupling may occur and the probe sensor impedance changes. Due to the finite size of the probe, all field measurements are subject to some amount of spatial averaging. For a loop, the measurement location may be specified as the geometric centre of the loop, but the result will be a function of the average field.

passing through the loop area. The probe antenna should be sufficiently small for improved accuracy of the measurement of the spatial peak of a given field component. Larger probes are prone to larger uncertainties in strong gradient fields. The measured value and its uncertainty need to be properly evaluated with its instrumentation to determine the gradient uncertainty while rotating the probe in the gradient field (9.2.8).

NOTE If an isotropic sensor with a loop size of 1 cm² is rotated in a gradient field of 50/m the resulting error is less than 1,3 % (rectangular distribution). For a sensor of 3 cm², it is less than 5 %.

- g) In the case of non-uniform incident fields, the measured field values may be spatially averaged over the exposed regions of the body, with the important provision that the basic restrictions for psSAR and internal electric fields are not exceeded. The concept of spatial averaging may be applicable according to national regulatory requirements. If averaging is applied in the case where one or more of the measured values is above the reference levels or action levels, it is necessary to provide sound evidence that the assessment based on the averaged values does not lead to exceeding the underlying basic restrictions or exposure limit values, respectively.

National regulations can differ from the preceding conditions and might pose different requirements, e.g. on frequency range, minimum distance, or acceptability of spatial averaging as described in step g). Incident electric and magnetic field strengths shall be measured or calculated according to the applicable regulations.

Assessment procedures for SWPT, heavy duty EVs, and drones are described in Clause I.1, Clause I.2, and Clause I.3, respectively. Examples of assessment results are introduced in Annex J.

If the incident field consists of non-negligible multiple frequency components based on the guidelines, these contributions must be considered in the assessment. Summation regimes in Annex B of IEC 62311:2019 [10] may be applied to consider spectral contributions.

6.1.2 Equipment

6.1.2.1 Equipment for electric field strength measurements

Electric field strength can be measured by a calibrated antenna or probe that is sensitive to electric fields exclusively (e.g. small dipoles) and connected to the calibrated measurement equipment.

Two types of antennas or probes are used for electric field measurements: single-axis-sensor types, and three-axis-sensor types in which three sensors are arranged perpendicular to each other. IEC 61786-2 recommends using the three-axis type. Using single-axis instruments is possible in some cases, e.g. when the direction of the field is already known (IEC 61786-1). The electric field strength of the three-axis component readings given in Formula (17) applies.

$$E_R = \sqrt{E_x^2 + E_y^2 + E_z^2} \quad (17)$$

where E_x , E_y , and E_z are effective electric field strengths for the three orthogonal axes. Three-axis electric field measurement equipment has the advantage of measuring the net field E_R regardless of the probe orientation.

In general, measurement equipment for electric field strength is either broadband or narrowband. For both measurement systems, the equipment consists of an antenna or probe (including power source), measurement part, and data recording and processing unit. The following describes the system characteristics and selection method.

- a) A broadband system uses dipole antennas. It is small enough to improve the uniformity of the sensitivity at each frequency. To improve isotropy, three antennas are generally placed orthogonal to one another and each signal or the combined signal is evaluated.

This type of antenna is suitable for near-field electromagnetic fields of complicated distributions. A broadband isotropic electric field strength meter designed for radio wave protection is typically used for measurement. Other systems may include waveform observation equipment, such as diode detectors and oscilloscopes.

b) A narrowband system is tuned to each target frequency. The measurement system generally has broad measurement frequencies, high receiving sensitivity, and short responses. It is thus also suitable for pulsed waves or multiple sources. However, for the pulsed wave measurement, it is acceptable to measure in the frequency domain where the target frequency range is broader than the passband width of the measurement system. A biconical antenna with broadband characteristics is often used for far-field region because the size of the antenna is not electrically small. A three-axis orthogonal small dipole is suitable for near-field measurements.

c) For an electromagnetic environmental assessment, a broadband isotropic electric field strength meter is preferred unless the equipment cannot be measured properly with such a device, in which case it must be replaced by another measurement system.

When selecting a measurement system, the required performance, frequency response, and electromagnetic field strength range must be considered.

6.1.2.2 Equipment for magnetic field strength measurements

Search-coil sensors are often used for a low frequency range of several hundred kilohertz and below. In general, the search-coil probe is used for measuring environmental magnetic fields. The coil probe measures the induced voltage associated with the time-varying magnetic flux normal to the plane of the coil, averaged over the coil area. In a field that is uniform over the area of the coil, the induced voltage at the coil terminals is calculated according to Formula (18). All the quantities are in phasor forms.

$$V = -j\omega NBS \quad (18)$$

where

V is the induced voltage;

ω is the angular frequency ($= 2\pi f$);

N is the number of turns;

B is the magnetic flux density (normal to the plane of the coil);

S is the cross-sectional area of the coil.

To achieve better sensitivity, the area and winding number are increased, and the magnetic flux density is enhanced by using ferromagnetic material in the core of the coil. The signal is processed to obtain flat frequency characteristics by an integrator in subsequent stages because the output is proportional to the frequency. The uncertainty of the measured field at the centre of the sensor caused by the gradient shall be assessed.

Magnetic field strength measurement equipment is divided into two classes: single-axis-sensor types and three-axis-sensor types in which three sensors are arranged perpendicular to one another. IEC 61786-2 recommends using the three-axis type. The magnetic field strength of the three-axis component reading given in Formula (19) applies.

$$B_R = \sqrt{B_x^2 + B_y^2 + B_z^2} \quad (19)$$

where B_x , B_y , and B_z are effective magnetic flux densities for the three orthogonal axes. Three-axis magnetic field measurement equipment has the advantage of measuring the net field B_R regardless of the probe orientation.

6.1.2.3 Equipment for magnetic field gradient

The evaluation method based on the coupling factor as a function of the magnetic field gradient, i.e. 5.2.4.3, requires knowledge about the local B-field amplitude and gradient.

The magnetic field amplitude and gradient can be measured by sampling the field spatially in 3D around the location of exposure. The measurement can be performed by a single field sensor or multiple isotropic magnetic field sensors. A probe with a single sensor can be moved, e.g. by a robot system, to measure the field at separate locations of known spatial placement, if the test signal is repetitive and the phase relation can be established. A probe with multiple sensors can be used to measure the gradient directly, i.e. an axial or planar gradiometer ([5], [12], [20], [21]).

6.2 SAR

SAR can be measured experimentally and directly compared with the basic restrictions. The evaluation and validation procedures of SAR measurement for wireless communication devices are described in IEC/IEEE 62209-1528 [11], whose frequency range is 4 MHz to 10 GHz. Similar measurement procedures can be used for WPT systems within the frequency range of 4 MHz to 30 MHz. In this document, only the deviations required to assess the spatial peak SAR values of WPT systems are described. Clause B.2 describes the procedure for the measurement of the peak spatial-average SAR in a phantom model that simulates a human body exposed to electromagnetic fields generated by the WPT systems. Using an isotropic electric field probe, the SAR inside an irradiated body model can be determined. A SAR measurement system consists of a suitable phantom, an electric field probe and a probe scanning system.

The physical characteristics of the phantom model (size, shape, electrical properties, etc.) shall simulate the human exposure condition by the WPT system. Phantom models such as those specified in IEC/IEEE 62209-1528 [11] may be used. The phantom model must consist of materials with dielectric properties similar to humans. At a frequency lower than 30 MHz, the electrical properties of the material are dominantly affected by the conductivity of the material. The liquid specified in IEC/IEEE 62209-1528 [11] may be used (Table 1) at frequencies between 0,1 MHz and 30 MHz. NaCl solution with an appropriate conductivity may also be used (Table 2). The relationship between conductivity and NaCl concentration is described in reference [22]. The dependency of SAR on phantom properties and size are shown in Annex D. The same media may be used for frequencies below 4 MHz provided that the uncertainty with respect to conservative estimation is determined, considered, and documented (see 9.3.3).

NOTE Reference [22] shows that the dielectric properties of saline solution differ by less than 5 % from their value at 1 GHz when the frequency tends to zero. This is why constant parameters are specified in Table 1 and Table 2 for the entire frequency range from 0,1 MHz to 30 MHz.

Table 1 – Dielectric properties of the tissue-equivalent medium liquid

Frequency (MHz)	Real part of the complex relative permittivity, ϵ'_r	Conductivity, σ (S/m)
0,1 to 30	55	0,75

**Table 2 – Dielectric properties of the tissue-equivalent medium
NaCl solution of 0,074 mol/L**

Frequency (MHz)	Real part of the complex relative permittivity, ϵ'_r	Conductivity, σ (S/m)
0,1 to 30	77	0,75



916

917 The WPT system shall be operated at the closest compliance distance to the phantom. Due to
918 the high SAR gradients of the induced field, measurements closer than 2 mm from the
919 phantom surface shall be performed. If the boundary effect, which is caused by mutual
920 interaction between the probe and the phantom surface, causes a large uncertainty in the
921 measurement, the measurement may be performed at a distance of up to 2,5 cm from the
922 phantom surface as long as it can provide a sufficient signal-to-noise ratio for the results. An
923 extrapolation method (see Annex E) of the induced field may then be used to determine the
924 SAR peak at the phantom surface. In that case, uncertainty due to the extrapolation method
925 with respect to SAR values shall be included in the uncertainty budget. Extensions of the area
926 scan or volume scan methods may be used to determine the location of maximum SAR. The
927 phantom region shall be 20 % larger than the source or as large as the phantom, whichever is
928 smaller. The grid for the zoom scan to be performed around the locations of the SAR maxima
929 (all peak SAR values within 2 dB of the global maximum), and shall be in compliance with the
930 requirements set forth in Table 4 of IEC/IEEE 62209-1528:2020 [11].

931 6.3 Contact currents

932 6.3.1 General

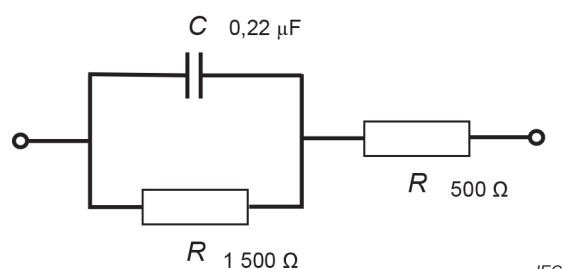
933 IEC TR 63167 [19] introduces general information on the assessment of contact current
934 related to human exposure to electric, magnetic, and electromagnetic fields including
935 assumed situations and a proposed method for measuring contact currents.

936 6.3.2 Equipment

937 An electrical equivalent circuit human body impedance model, which is frequency dependent,
938 is used to measure contact currents. Figure 7 shows an equivalent circuit, as depicted in
939 IEC 60990 [23], which simulates a human body. Several other studies have evaluated human
940 body impedance and proposed more precise equivalent circuits using arrangements of
941 resistors and capacitors [24], [25], [26], [27]. The frequency characteristics of human body
942 impedance with grasping conditions are compared in Figure 8. The impedance depends on
943 area of contact and usually the impedance for grasping contact is lower than that for point
944 contact. The assumed conditions of contact are "point contact" (area not specified) in ICNIRP
945 guidelines [2], [3], and "touch contact" with a contact area of 1 cm² and "grasping contact"
946 (applicable only for a controlled environment) with a contact area of 15 cm² for IEEE safety
947 standards [5], [7], [8], [9].

948 Figure 9 shows the configuration of a contact current meter. The contact terminal is made of
949 metal. If the target point of the contact part is painted, a 10 cm × 20 cm metal foil should be
950 attached to it to simulate a hand palm contact, according to IEC 60990 [23]. A metal board
951 equivalent to the size of a foot is used as the ground electrode. The contact current is
952 measured from the current flowing through the equivalent circuit of the human inside the
953 meter.

954



955

IEC

956 Figure 7 – Human body equivalent circuit proposed in IEC 60990 [23]

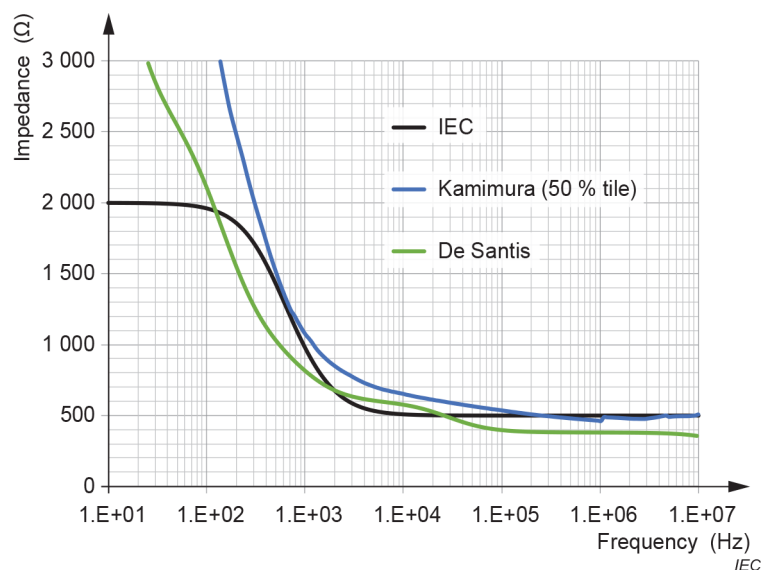


Figure 8 – Impedance frequency characteristics of adult male and equivalent circuits proposed in IEC 60990 [23] and evaluated values [24], [25], [26], [27]

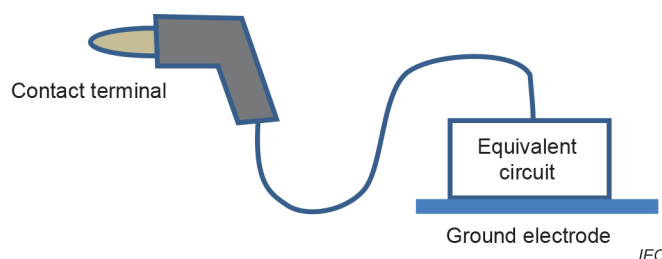


Figure 9 – Example of contact current measurement equipment

6.3.3 Measurements

The following issues must be considered for the measurement of contact currents.

- Specify requirements on measurement equipment or reference an appropriate standard.
- Avoid electromagnetic field disturbances caused by the operator and measurement systems as much as possible.
- Environmental conditions (temperature, humidity, vibration, electromagnetic fields, etc.) can affect the measurement equipment.
- Use a calibrated measurement system.

There are two types of measurements, depending on the expected exposure scenario.

a) Measurement methods using an ungrounded metal board

- 1) Place a ground electrode where a person can stand.
- 2) Place an ungrounded metal board large enough at the location where metal objects can exist in the actual usage condition. For representing an EV, a metal board larger than 1,2 m × 1,2 m may be used. Choose the closest position in the actual usage because the contact current tends to become higher as metal objects come closer to

the WPT system. Find the maximum condition of the contact current because the metal board position (height) and direction can change the contact current strength.

- 3) Touch the contact terminal to the metal board where a person can touch. Find a stable indicated value. Find the maximum value if there is a dependency on the touch position.

b) Measurement methods using a grounded metal board

- 1) Place a ground electrode where a person can stand.
- 2) Place a grounded metal board at the location where metal objects can exist in the actual usage condition. Choose the closest position in the actual usage because the contact current tends to become higher as metal objects come closer to the WPT system. Find the maximum position of the contact current because the metal board position (height) and direction can change the contact current strength.
- 3) Touch the contact terminal to the metal board where a person can touch. The contact current becomes larger according to the magnitude of the interlinkage magnetic flux to a loop created by the grounded metal board and human body. A rectangular loop with size of approximately 1,5 m (height) × 0,5 m (width) may be used to evaluate the contact current. Find the loop arrangement which gives the maximum contact current value.

7 Computational assessment methods

7.1 General

The internal electric field, psSAR, or whole-body SAR for comparison with basic restrictions shall be calculated by simulation using a representative set of anatomical human models. Calculations may be performed using full wave methods or quasi-static methods, depending on the electrical size of the problem geometry. For quasi-static problems, the effect of the induced fields in the human body on the incident field source is assumed to be negligible. The incident fields and the induced fields can be evaluated in separate simulations using separate computational methods. For the calculation of the incident fields, analytical or quasi-analytical methods may be applicable. Table 3 summarizes the computational methods for exposure evaluation. A brief description of computational methods is also given in Annex F. Annex H describes averaging algorithms, and code verification and model validation, respectively. At present, body phantoms to conservatively test for compliance of WPT systems with safety limits are not available. Hence, the relevant induced fields need to be evaluated in a representative set of anatomical body models. These models shall include the following:

- availability of larger bodies which have increased absorption rates and are therefore more susceptible to nerve stimulation effects from low frequency magnetic fields;
- availability of smaller bodies (children) which can be closer to the field source
- individual segmentation of the tissues of the central and peripheral nervous systems for evaluation with the respective basic restrictions;
- posable or movable limbs for the modelling of realistic exposure scenarios.

NOTE 1 Simulations can be also applied to assess the incident fields with respect to the reference levels.

All computational algorithms should be verified for technically correct implementation. Guidance is provided in Annex H.

NOTE 2 The experimental standard IEC/IEEE 62209-1528:2020 specifies SAR measurement methods for a frequency range from 4 MHz to 10 GHz. While a frequency range is specified for the computational standards IEC/IEEE 62704-1 [28] and IEC/IEEE 62704-4 [29], the computational methods are generally independent of the frequency. They are applicable for the frequency range of this standard provided that the uncertainty of the truncation of the computational domain is appropriately considered and its uncertainty assessed.

1029

Table 3 – Computational methods

Calculation method	Note
BEM (boundary element method)	Full-wave computation
FDFD (finite difference frequency domain)	Full-wave computation
FDTD (finite difference time domain)	Full-wave computation
FEM (finite element method)	Full-wave or quasi-static approximation computation
QS-FDTD	Quasi-static approximation computation
FIT (finite integration technique)	Full-wave or quasi-static approximation computation
MoM (method of moments)	Full-wave computation
Hybrid method (e.g. MoM + FDTD)	Full-wave computation
SPFD (scalar potential finite difference)	Quasi-static approximation computation
IM (impedance method)	Quasi-static approximation computation

1030

1031 **7.2 Quasi-static approximation**

1032 For the applicability of a computational method based on the quasi-static approximation, the
 1033 upper frequency limit is established considering the dimensions of the exposed body region or
 1034 person, the size of the field source, and the distance between them. The field source
 1035 dimensions are referred to as feature size D hereinafter. The frequency limit is then given by
 1036 the quasi-static approximation of Formula (20), Formula (21), and Formula (22):

$$|\omega^2 \varepsilon \mu D^2| \ll 1 \Leftrightarrow \left(\frac{D}{\lambda}\right)^2 \ll 1 \quad (20)$$

1037 or

$$\omega^2 \Re\{\varepsilon\} \mu D^2 \ll 1 \quad (21)$$

1038 and

$$\omega \sigma \mu D^2 \ll 1 \quad (22)$$

1039 where

- ω is the angular frequency;
- $\Re\{\varepsilon\}$ is the real part of the complex relative permittivity with the maximum absolute value within the exposed region;
- μ is the permeability;
- λ is the minimum wavelength within the exposed region;
- σ is the conductivity of the exposed tissue or the tissue-equivalent medium.

1040 Formula (20), Formula (21), and Formula (22) contain only the frequency, the dielectric and
 1041 magnetic properties, and spatial dimensions of the geometry to be analysed (field source and
 1042 exposed body). They do not refer to either electric or magnetic field exposure. The frequency
 1043 range within which electric and magnetic fields can be regarded as decoupled is identical for
 1044 electric and magnetic field exposure. Hence, the quasi-static approximation applies to both
 1045 inductive and capacitive coupling.

A rationale shall be given along with evaluation results on why the quasi-static approximation applies on the evaluated exposure scenario. Possible deviations from a full wave solution shall be discussed and may need to be considered in the uncertainty budget (9.3).

7.3 Computational assessment against the basic restrictions

7.3.1 General

Depending on the applicable safety guidelines and on the frequency range, the basic restrictions on human exposure are specified in terms of:

- peak spatial average SAR [2], [4], [7], [8], [9] (7.3.2);
- whole-body average SAR [2], [4], [7], [8], [9] (7.3.3);
- averaged current density on a surface [2] (Clause G.1);
- peak spatial average E-field in a cubical volume [3] (Clause G.2);
- peak spatial average E-field along a line [5], [7], [8], [9] (Clause G.3);
- maximum local E-field [30] (Clause G.4).

Different limits can apply for these quantities depending on the exposed body region. The computational code or the applied post-processing techniques shall implement the required averaging methods. Because the descriptions of the averaging algorithms in the exposure guidelines that establish them are generally not sufficiently detailed for an implementation as a computational algorithm, this document refers to the respective computational International Standards that specify those, or specifies its own algorithms if an appropriate definition is not available elsewhere. Details are given in 7.3.2, 7.3.3, and Annex G. The implementation of these algorithms should be validated according to the methods described in Annex H.

NOTE Peak quantities, such as the E-field or the SAR, may be read out directly from the post processor. Alternatively, the methods specified for the peak spatial average quantities may be applied (7.3.2, Clause G.2) with averaging volumes on the order of magnitude of the voxels or tetrahedra of the exposed body region. Care should be taken concerning stair-casing artefacts because these may affect the readout of the global field maximum or be dominant in small averaging volumes.

7.3.2 Peak spatial-average SAR

The peak spatial average SAR shall be evaluated according to IEC 62704-1 [28] for Cartesian meshes, and according to IEC 62704-4 [29] for unstructured meshes.

7.3.3 Whole-body average SAR

The whole-body average SAR shall be evaluated according to IEC 62704-1 [28] for Cartesian meshes, and according to IEC 62704-4 [29] for unstructured meshes.

7.3.4 Averaged current density on a surface

The electric field distribution in the exposed body shall be evaluated according to IEC 62704-1 [28] for Cartesian meshes, and according to IEC 62704-4 [29] for unstructured meshes. The averaged current density shall then be calculated according to Clause G.1.

7.3.5 Peak spatial average E-field in a cubical volume

The electric field distribution in the exposed body shall be evaluated according to IEC 62704-1 [28] for Cartesian meshes, and according to IEC 62704-4 [29] for unstructured meshes. The peak spatial average E-field in a cubical volume shall then be calculated according to Clause G.2.

7.3.6 Peak spatial average E-field along a line

The electric field distribution in the exposed body shall be evaluated according to IEC 62704-1 [28] for Cartesian meshes, and according to IEC 62704-4 [29] for unstructured meshes. The peak spatial average E-field along a line shall then be calculated according to Clause G.3.

7.3.7 Maximum local E-field

The electric field distribution in the exposed body shall be evaluated according to IEC 62704-1 [28] for Cartesian meshes, and according to IEC 62704-4 [29] for unstructured meshes. The maximum local E-field shall then be calculated according to Clause G.4. It should be noted that several simulations with different mesh resolutions according to IEC 62704-1 [28] or IEC 62704-4 [29] may be necessary to limit the impact of staircasing errors.

8 Combination of measurement and computational methods for inductive WPT systems

8.1 General

Because internal electric field, current density, or SAR are difficult to measure directly, the evaluation is often performed using computational approaches. However, it is difficult to accurately model an actual exposure situation in simulations including an electric vehicle body, ground planes, etc. In addition, it is sometimes difficult to retrieve information about the size, shape, and design of the WPT systems. It is possible to evaluate internal electric field or SAR by an approach combining both the measurement of electromagnetic fields around the system and computational analyses of induced quantities. The magnetic near-field data are first measured in the area occupied by the human body. Then, the measured magnetic fields are used as incident fields in the impedance method (IM) or the scalar-potential finite-difference (SPFD) method to derive the internal electric field strength inside the human-body model.

8.2 Measurement of magnetic field

For measurements of magnetic field distributions below 10 MHz, search-coil sensors are often used. Both amplitude and phase of the magnetic field shall be measured in the area occupied by the human body. To measure the phase of magnetic field, one magnetic sensor should be fixed at a specific position to retrieve the reference phase and the other sensor is moved over the area occupied by the human body.

8.3 Computational analyses of induced quantities

Anatomical human models or appropriate dosimetric phantoms shall be used to calculate induced field quantities. Computational methods for the calculation of the induced field quantities are summarized in Annex F. The measured magnetic field distribution is applied as the incident field in the computational method such as IM or SPFD. Measured magnetic field data may be directly applied as a source in IM. However, since SPFD uses vector potentials as a source to calculate the internal electric field, the reconstruction of vector potentials from the measured magnetic field ($\mathbf{H}$) or the magnetic flux density ($\mathbf{B}$) is required. A finite number of samples of $\mathbf{B}$ from simulations may be used for field reconstruction. Otherwise a finite number of sample measurements may be taken at monitor points. In this case the spatial coordinate of the collected measurement samples is also needed.

The procedure to reconstruct the B-field distribution is described in [31]. The magnetic flux density is assumed to be $\mathbf{B} = u_x \mathbf{B}_x + u_y \mathbf{B}_y + u_z \mathbf{B}_z$, which satisfies $\nabla \cdot \mathbf{B} = 0$, where $u_{x,y,z}$ are unit vectors. Hence it can be represented using a vector potential $\mathbf{A}$, so that $\nabla \times \mathbf{A} = \mathbf{B}$. A vector potential is given by Formula (23), Formula (24), and Formula (25):

$$A_x = -\int_0^y \left[\frac{1}{3} B_z(x, y', z) + \frac{1}{6} B_z(x, y', 0) \right] dy' + \int_0^z \left[\frac{1}{3} B_y(x, y, z') + \frac{1}{6} B_y(x, 0, z') \right] dz' \quad (23)$$

$$A_y = -\int_0^z \left[\frac{1}{3} B_x(x, y, z') + \frac{1}{6} B_x(0, y, z') \right] dz' + \int_0^x \left[\frac{1}{3} B_z(x', y, z) + \frac{1}{6} B_z(x', y, 0) \right] dx' \quad (24)$$

$$A_z = -\int_0^x \left[\frac{1}{3} B_y(x', y, z) + \frac{1}{6} B_y(x', 0, z) \right] dx' + \int_0^y \left[\frac{1}{3} B_x(x, y', z) + \frac{1}{6} B_x(0, y', z) \right] dy' \quad (25)$$

Formula (23), Formula (24), and Formula (25) do not depend on electric or magnetic properties, therefore they are valid for any arbitrary inhomogeneous, anisotropic, or nonlinear medium.

8.4 Computational assessment against the basic restrictions

The basic restrictions are generally specified for induced field quantities that are averaged over a certain geometrical shape in the exposed body or phantom. For the computational assessment of the induced fields. The methods described in 8.3 shall be applied to calculate the induced fields for a representative set of anatomical models of the human body or an appropriate dosimetric phantom. Computation of the induced fields against the basic restrictions shall then be carried out according to 7.3.

9 Uncertainty assessments

9.1 General

In 9.2 through 9.4, the experimental and computational uncertainty sources are listed that shall be assessed for estimating the total evaluation uncertainty. The uncertainty budget is based on the concepts of ISO/IEC Guide 98-1, ISO/IEC 98-3, [32], and [33]. For most methods described in this standard, each source of uncertainty is considered as independent and can therefore be assessed separately from the others.

9.2 Measurement methods

9.2.1 Measurement uncertainty budget

Table 4 summarizes the main parameters related to magnetic field measurements.

Table 4 – Example of uncertainty evaluation of the exposure assessment using measurement methods

Input quantity X_i (source of uncertainty)	Ref.	Prob. Dist. ^a PDF_i	Unc. $a(x_i)$	Div. ^a q_i	$u(x_i) =$ $a(x_i) / q_i$	c_i	$u_i(y) =$ $c_i \cdot u(x_i)$	ν_i or ν_{eff}
Amplitude calibration uncertainty	9.2.2	N		1		1		
Probe anisotropy	9.2.39.2.3	R		$\sqrt{3}$		1		
Probe dynamic linearity	9.2.4	R		$\sqrt{3}$		1		
Probe frequency domain response	9.2.5	R		$\sqrt{3}$		1		
Modulation response	9.2.6	R		$\sqrt{3}$		1		
Spatial averaging (maximum gradient)	9.2.7	R		$\sqrt{3}$		1		
Gradient assessment uncertainty	9.2.8	R		$\sqrt{3}$		1		
Parasitic E-field sensitivity	9.2.9	R		$\sqrt{3}$		1		
Detection limit	9.2.10	R		$\sqrt{3}$		1		
Readout electronics	9.2.11	N		1		1		
Response time	9.2.12	N		1		1		
Probe positioning	9.2.13	N		1		1		
Shaping, filtering, signal conditioning	9.2.14	N		1		1		
Nominal position	9.2.15	R		$\sqrt{3}$		1		
Repeatability	9.2.16	N		1		1		
Combined uncertainty ($k = 1$)		RSS						
Expanded uncertainty ($k = 2$) and effective degrees of freedom							$U =$	$\nu_{\text{eff}} =$
^a Other probability distributions and divisors may be used if they better represent available knowledge of the quantities concerned.								
NOTE 1 Abbreviations: N – normal probability distribution; R – rectangular probability function								
NOTE 2 The divisor is a function of the probability distribution and degrees of freedom (ν_i and ν_{eff}).								
NOTE 3 c_i is the sensitivity coefficient that is applied to convert the variability of the uncertainty component into a variability of the exposure quantity.								

9.2.2 Amplitude calibration uncertainty

The amplitude calibration uncertainty shall be evaluated within the scope of calibration (frequency and dynamic ranges) of the calibration system, e.g. a transverse electromagnetic (TEM) cell. Details on field generation are given in B.2.1.

9.2.3 Probe anisotropy

The probe anisotropy shall be evaluated by exposure in a homogeneous magnetic field, e.g. inside a TEM cell or appropriate coil configurations. For the quantification of the uncertainty, the probe shall be tilted through angular increments of 5° along the three probe axes, and the maximum error shall be reported as uncertainty according to the definition in B.2.2.1.4.

9.2.4 Probe dynamic range linearity

Probe dynamic range shall be evaluated covering the dynamic range from 10 % (–20 dB in terms of induced E-fields or current density, or –10 dB in terms of SAR) of the general public exposure limits to greater than four times the occupational exposure limit. The probe linearity shall be evaluated in a homogeneous magnetic field, which can be generated in a TEM cell or by appropriate coil configurations. See also B.2.2.1.3.

9.2.5 Probe frequency domain response

The probe frequency domain response is evaluated for a homogenous incident field over specified operational frequency range. The uncertainty due to the probe frequency response is assessed by evaluating the flatness of the probe response across the frequency range. The frequency domain response shall be evaluated in a homogeneous magnetic field, which can be generated in a TEM cell or by appropriate coil configurations. See also B.2.2.1.2.

9.2.6 Modulation response

Probe modulation response shall be evaluated for modulated carriers in the specified frequency range with rectangular pulse modulation, 10 % duty cycle, 10 Hz, 100 Hz, 1 000 Hz pulse repetition rate (whatever is applicable at the carrier frequency). The modulation response shall be evaluated in a homogeneous magnetic field, which can be generated in a TEM cell or by appropriate coil configurations.

9.2.7 Spatial averaging (maximum gradient)

The uncertainty due to spatial averaging shall be evaluated in gradient fields that correspond to those of the incident field of the WPT system under test (DUT) with respect to amplitude and orientation within a maximum range from 0 T/m/T to ≥ 30 T/m/T. The gradient fields shall be generated using an appropriate coil configuration (B.2.1) considering the overall dimensions of the probe.

9.2.8 Gradient assessment uncertainty

The uncertainty in the accuracy of field gradient measurements shall be assessed by applying the probe positioning error (9.2.13) on the gradient uncertainty (Clause B.3) and considered as a separate uncertainty parameter. The gradient assessment uncertainty shall only be considered for Tier 3 evaluations.

9.2.9 Parasitic E-field sensitivity

Parasitic E-field sensitivity is tested with the magnetic field probe in maximum hold swept through all possible spherical incident E-fields directions with the E-field amplitude at the occupational exposure limit. Appropriate homogeneous E-fields can be generated in a TEM cell or in a parallel plate capacitor. Details on field generation are given in B.2.1.

9.2.10 Detection limit

Detection limit is the contribution of the readout electronic noise, i.e. the signal-to noise ratio, at 10 % (–20 dB in terms of induced E-fields or current density, or –10 dB in terms of SAR) of the general public exposure limits.

9.2.11 Readout electronics

Readout electronics is the uncertainty contribution by analogue-to-digital conversion.

9.2.12 Response time

If the probe is operated in swept mode, response time is the sampling response error for the probe swept through a gradient field of ≥ 20 T/m/T at a speed of 0,1 m/s.

9.2.13 Probe positioning

The uncertainty due to probe positioning shall be evaluated as the error in a gradient field of ≥ 30 T/m/T considering the mechanical tolerances, such as the positioning accuracy, of the probe positioning system (e.g. robot).

9.2.14 Shaping, filtering, signal conditioning

Shaping, filtering, and signal conditioning are the uncertainty contributions by analogue or digital signal conditioning and processing.

9.2.15 Nominal position

The nominal positioning uncertainty shall be evaluated as the positioning uncertainty (9.2.13) with respect to assessing the worst-case exposure.

9.2.16 Repeatability

The repeatability shall be evaluated by measuring the field amplitude at a specific point at the closest accessible distance to the source ten times. It then evaluated as the standard deviation of these measurements.

For incident E-field measurements the same components as in Table 4 apply. Parasitic H-field sensitivity shall be evaluated instead of parasitic E-field sensitivity in 9.2.9.

The possible variations caused by the exposure systems are:

- a) incident field distribution (i.e. gradient);
- b) frequency;
- c) geometry of WPT source (size of the coils, shape, alignment);
- d) system setup (closest accessible point, possible objects around the source not removable);
- e) calibration differences.

9.3 Computational methods**9.3.1 Computational uncertainty budget**

Table 5 summarizes the sources of uncertainty for computational methods. The methodology closely follows IEC/IEEE 62704-1 [28], IEC/IEEE 62704-4 [29], and IEC/IEEE 63195-2 [34]. These standards are referenced where necessary.

Table 5 – Example of uncertainty evaluation of computational methods

Input quantity X_i (source of uncertainty)	Ref.	Prob. Dist. ^a PDF_i	Unc. $u(x_i)$	Div. ^a q_i	$u(x_i) =$ $a(x_i) / q_i$	c_i	$u_i(y) =$ $c_i \cdot u(x_i)$	v_i or v_{eff}
Grid resolution	9.3.2	R		$\sqrt{3}$		1		
Tissue parameters	9.3.3	R		$\sqrt{3}$		1		
Exposure position	9.3.4	R		$\sqrt{3}$		1		
Source representation	9.3.5	N		1		1		
Convergence and power budget	9.3.6	R		$\sqrt{3}$		1		
Boundary conditions	9.3.7	R		$\sqrt{3}$		1		