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TECHNICAL REPORT

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Exposure assessment methods for wireless power transfer systems

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Exposure assessment methods for wireless power transfer systems

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EXPOSURE ASSESSMENT METHODS FOR WIRELESS POWER TRANSFER SYSTEMS

FOREWORD

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IEC TR 62905, which is a Technical Report, has been prepared by IEC technical committee 106: Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
106/416/DTR	106/424A/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://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- withdrawn,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.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

IEC TC 106 has the scope to prepare International Standards on measurement and calculation methods used to assess human exposure to electric, magnetic and electromagnetic fields. Wireless power transfer (WPT) systems have been developed and gradually become popular over the world. WPT basically utilize similar wireless technologies to provide power to mobile phones, tablet PCs, electric vehicles (EVs) and so on without cables; but the used frequency range, i.e., tens of kHz to tens of MHz, has not been often used and paid attention to. Both stimulation-based effects (< 10 MHz, for example) and heat-based effects (> 100 kHz, for example) should be considered in this frequency range. ITU-R published a report (ITU-R SM. 2303-1) related to WPT in June 2015 which also mentions RF exposure assessment methodologies. However, no concrete assessment method has been introduced. Only IEC TC 69 has addressed exposure assessment method of WPT for EV in IEC 61980-1:2015. There is no product standard related to WPT other than that standard. Considering that WPT products might be spread in the near future, IEC TC 106 needs to be aware of this issue and established a working group to address methods for assessment of WPT related to human exposures to electric, magnetic and electromagnetic fields.

Based on these backgrounds IEC TC 106 prepared this document consisting of an overview of WPT, basic exposure assessment methods for direct and indirect effects by WPT, case studies, and relevant research. Frequency up to 10 MHz is mainly focused on because both stimulation and heat effects need to be considered but have not been addressed so far. This document also mentions enhancement of internal fields by medical implant devices.

It is hoped that this document will be useful and helpful to develop International Standards for WPT exposure assessment.

EXPOSURE ASSESSMENT METHODS FOR
WIRELESS POWER TRANSFER SYSTEMS

1 Scope

This document describes general exposure assessment methods for wireless power transfer (WPT) at frequency up to 10 MHz considering thermal and stimulus effects. Exposure assessment procedures and experimental results are shown as examples such as electric vehicles (EVs) and mobile devices.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC 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

3.1
basic restriction
BR
restriction on exposure to time-varying electric, magnetic and electromagnetic fields that is based on established biological effects

3.2
contact current
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).

3.3
current density
current per unit cross-sectional area flowing inside the human body as a result of exposure to electromagnetic fields

3.4
device under test
DUT
device that is tested according to the procedures specified in this document

3.5
dielectric constant
real part of the complex relative permittivity of the lossy material

**3.6
direct effect**
biological effect resulting from direct interaction of electromagnetic field with biological structures

**3.7
electric field strength**
magnitude of a field vector at a point that represents the force (F) on an infinitely small charge (q) divided by the charge

**3.8
exposure**
situation that occurs wherever a person is subjected to electric, magnetic or electromagnetic fields

**3.9
incident field**
electric and magnetic fields incident upon the human body

Note 1 to entry: This document focuses on the WPT operating close to the human body at frequency below 10 MHz. Electric and magnetic fields need to be separately evaluated in this region.

**3.10
induced current**
current induced inside the body as a result of exposure to electromagnetic fields

**3.11
indirect effect**
biological effect resulting from indirect interaction of electromagnetic field with biological structure

**3.12
magnetic field strength**
magnitude of 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

**3.13
peak spatial-average SAR**
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

**3.14
phantom**
physical model similar in appearance to the human anatomy and comprised of material with electrical properties similar to the corresponding tissues

Note 1 to entry: A phantom representing the human head could be a simple spherical model or a more complex multi-tissue anthropomorphic model.

**3.15
reference level**
field level derived from the basic restrictions under worst case assumptions (e.g. exposure to homogeneous field)

**3.16
specific absorption rate
SAR**
SAR in the tissue-equivalent liquid can be determined by E-field or the rate of temperature increase, according to:

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

$$SAR = C_h \frac{dT}{dt}\bigg|_{t=0}$$

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/m^3;

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

$\dfrac{dT}{dt}\bigg|_{t=0}$ is the initial time derivative of temperature in the tissue medium in K/s.

4   Symbols and abbreviations

4.1   Physical quantities

The internationally accepted SI units are used throughout this document.

Symbol	Quantity	Unit	Dimensions
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
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 (°C) = T (K) – 273,15.

4.2   Constants

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

4.3   Abbreviations

BR   basic restriction

DUT   device under test

RF   radio frequency

rms   root mean square

RSS   root sum square

CW   continuous wave

SAR   specific absorption rate

psSAR   peak spatial-average SAR

WPT   wireless power transfer

EV   electric vehicle

5 Overview of WPT systems

5.1 General

Clause 5 describes an overview of WPT systems, which include WPT technologies, applications and frequency ranges reported by ITU-R [1][1]. WPT systems using frequency range over 10 MHz are described in Annex A.

5.2 WPT systems whose frequency range is less than 100 kHz

a) Magnetic induction WPT systems for home appliances

Inductive power sources (transmitters) may stand alone or be integrated into the kitchen counter tops or dining tables. These transmitters could combine the WPT to an appliance with conventional inductive heating.

For the home appliance application, the power level is usually up to several kilowatts, and the load may be motor-driven or heating type (Figure 1). Future products will support more than 2 kW power and some new design proposal for cordless kitchen appliances is being investigated.

Considering the high power usage in the home, frequencies in the order of tens of kHz are preferred to restrict electromagnetic exposure to human bodies. And high reliable devices such as Insulated Gate Bipolar Transistors (IGBTs) are usually used and these devices are working in the 10 kHz to 100 kHz frequency range.

The product applied in the kitchen needs to meet the safety and electromagnetic field (EMF) requirements and it is a key issue that transmitter should be the light and small size to fit the kitchen in addition to being low cost. The distance between the transmitter and the receiver is intended to be less than 10 cm.

The following pictures show examples of wireless power kitchen appliances that will come to the market soon.

Tightly coupled mixer   Tightly coupled rice cooker

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Figure 1 – Wireless power kitchen appliances [1]

WPT systems have already integrated into the product lines of semiconductor and LCD panel; the following pictures show examples (Figure 2).

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[1] Numbers in square brackets refer to the Bibliography.

(WPT overhead shutter of
LCD product line)

(WPT overhead transmission
of Semiconductor product line)

Concept of wireless hybrid kitchen

(WPT kitchen island of apartment)

IEC

**Figure 2 – Use cases of the LCD and semiconductor product lines and
kitchen WPT systems [1]**

b) Magnetic induction WPT systems for electric vehicles

Magnetic field wireless power transmission (MF-WPT) is one of the focus points in standardization discussion such as IEC PT 61980 and SAE J2954TF regarding WPT for EV including plug-in hybrid EV (PHEV) though there are several types of WPT methods. MF-WPT for EV and PHEV contains both inductive type and magnetic resonance type. Electric power can be transmitted from the primary coil to the secondary coil efficiently via magnetic field by using resonance between the coil and the capacitor.

Expected passenger vehicle applications assume the following aspects:

1) WPT application: Electric power transmission from electric outlet at a residence and/or public electric service to EVs and PHEVs.

2) WPT usage scene: at residential, apartment, public parking, etc.

3) Electricity use in vehicles: All electric systems such as charging batteries, computers, air conditioners, etc.

4) Examples of WPT usage scene. An example for passenger vehicles is shown in Figure 3.

5) WPT method: A WPT system for EV/PHEV has at least two coils (Figure 3). One is in the primary device and the other is in the secondary device. The electric power will be transmitted from primary device to secondary device through magnetic flux/field.

6) Device location (Coil location):

   i)   primary device: on ground or/and in ground;

   ii) secondary device: lower surface of vehicle.

7) Air gap between primary and secondary coils: less than 30 cm.

8) Transmission power class example: 3 kW, 6 kW, and 20 kW.

9) Safety: primary device can start power transmission only if secondary device is located in the proper area for WPT. Primary device needs to stop transmission if it is difficult to maintain safe transmission.
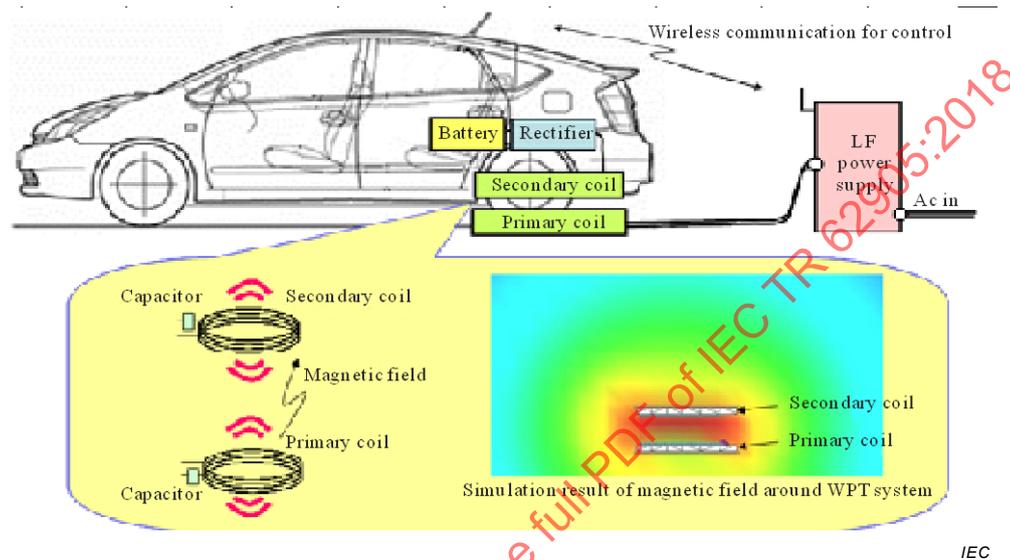
Figure 3 – Example of a WPT system for EV/PHEV [1]

In order to run heavy duty vehicles such as an electrical bus, the infrastructure of the system is to embed electric strips in roadbeds that magnetically transmit energy to battery-powered vehicles above. The bus can move along the electrical strips without any stopping for charging its power, known as on-line electric vehicle (OLEV) (Figure 4). Furthermore, the bus can be charged at stopping condition in bus stop or bus garage. The online bus at an amusement park or at the city is the first system operated in the form of EV for heavy duty vehicles in the world.

IEC

Figure 4 – Example of an online electric vehicle [1]

The design of magnetic field from transmitting coil to receiving coil is the key in WPT system design for maximum power and efficiency.

First, the magnetic field should be in resonance by using resonant transmitting and receiving coils to have high power and efficiency.

Second, the magnetic field shape should be controlled, by using magnetic material such as ferrite core, to have minimum magnetic resistance in the path of the magnetic field, for lower leakage magnetic field and higher transmission power.

It is called shaped magnetic field in resonance (SMFIR) (Figure 5).
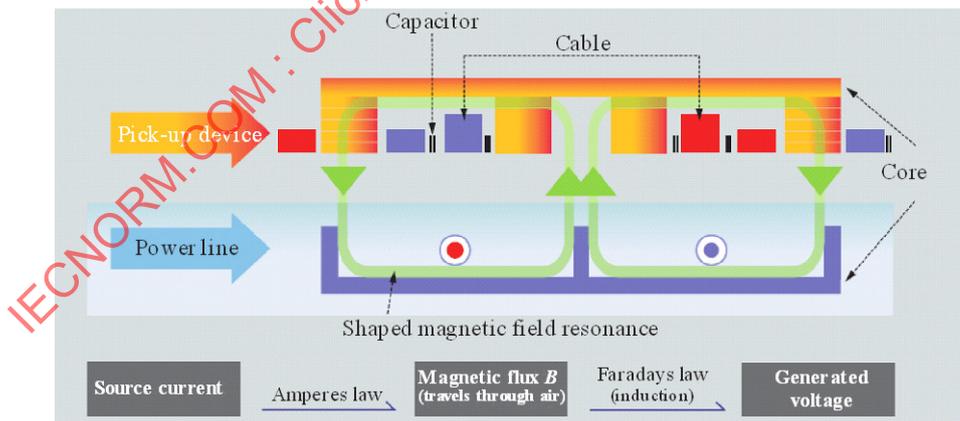
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Figure 5 – Technical characteristics of an online electric vehicle [1]

Table 1 summarizes application, technology, and specification of WPT systems at frequency less than 100 kHz.

**Table 1 – Summary of application, technology and specification
of WPT systems whose frequency range is less than 100 kHz.**

Parameter/Category	Magnetic induction for home appliances	Magnetic resonance and/or induction for electric passenger vehicles	Magnetic induction for heavy duty vehicles
Application types	Home appliances, office equipment (incl. higher power applications)	EV charging in parking (Static)	On-line electric vehicle (OLEV) (EV charging while in motion including stopping/parking) EV charging in parking for bus
Technology principle	Magnetic induction	Magnetic resonance and/or induction	Magnetic induction
Frequency ranges under consideration	Japan: 20,05 kHz to 38 kHz, 42 kHz to 58 kHz, 62 kHz to 100 kHz	Global: 84,5 kHz to 85,5 kHz, or 81,38 kHz to 90,00 kHz 81,38 kHz to 90 kHz (SAE J2954 TIR)	
Frequency ranges assigned nationally		Japan: 79 kHz to 90 kHz Europe: 81,38 kHz to 90,00 kHz	Korea: 19 kHz to 21 kHz, 59 kHz to 61 kHz Sweden: 19 kHz to 21 kHz
Power range	Japan: Several watts to 1,5 kW	Japan: 3,3 kW and 7,7 kW; Classes are assumed for passenger vehicle Worldwide: 3,3kW (WPT1), 7,7kW (WPT2) and 11 kW (WPT3)	Korea: – Minimum power: 75 kW – Maximum power: 80 kW – Air gap: 20 cm – Time and cost saving Sweden: – Minimum power: 100 kW – Maximum power: 200 kW – Air gap: 3 cm to 5 cm
Power transfer distance	0 to 10 cm	10 cm to 25 cm	20 cm (typical)
Advantage	– Increased power – Flexibility for placement and distance of receiving end – Transmitter can supply power for several receivers within a wide range simultaneously.	Higher power transmission efficiency	– Increased power transmission efficiency – Maximized air gap – Reduced audible noise – Effective shield design – Time and cost saving

5.3   WPT systems whose frequency range is from 100 kHz to 10 MHz

a) Magnetic induction WPT systems for portable and mobile devices

The WPT by magnetic inductance is a well-known technology, applied for a very long time in transformers where primary and secondary coils are inductively coupled, e.g. by the use of a shared magnetic permeable core (Figure 6). Inductive power transmission through the air with primary and secondary coils physically separated is also a known technology for more than a century, also known as Tightly Coupled WPT. A feature of this technology is that the efficiency of the power transmission drops if the distance through the air is larger than the coil diameter and if the coils are not aligned within the offset distance. The

efficiency of the power transmission depends on the coupling factor (k) between the inductors and their quality (Q). This technology can achieve higher efficiency than magnetic resonance method. This technology has been commercialized for charging of smart phones. With a coil array, this technology also offers flexibility in the receiver coil location of the transmitter.
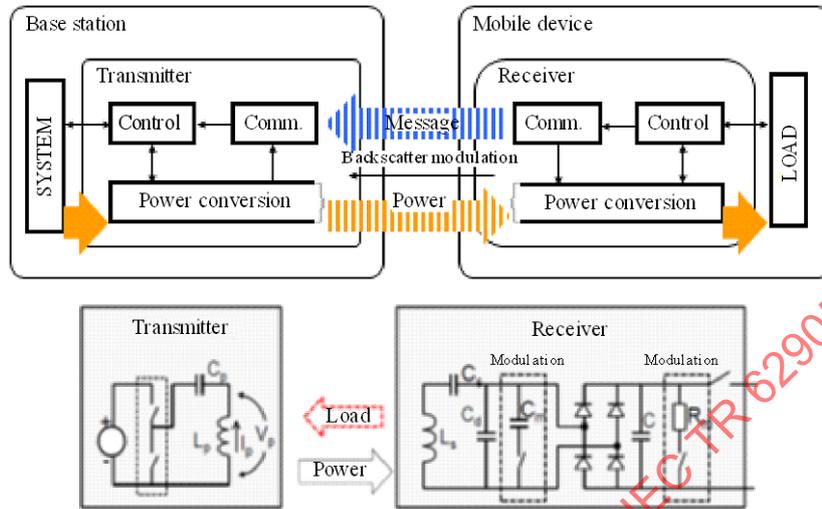
IEC

Figure 6 – Example magnetic induction WPT system block diagram [1]

b) Magnetic resonance WPT systems for portable and mobile devices

The WPT by magnetic resonance is also known as loosely coupled WPT (Figure 7). The theoretical basis of this magnetic resonance method was first developed in 2005 by Massachusetts Institute of Technology, and their theories were validated experimentally in 2007 [2]. The method uses a coil and capacitor as a resonator, transmitting electric power through the electromagnetic resonance between transmitter coil and receiver coil (magnetic resonant coupling). By matching the resonance frequency of both coils with high Q factor, electric power can be transmitted over a long distance where magnetic coupling between two coils is low. The magnetic resonance WPT can transmit electric power over a range of up to several metres.

This technology also offers flexibility in the receiver coil location of the transmission coil. Practical technical details can be found in many technical papers, for example, those in [2] and [3].
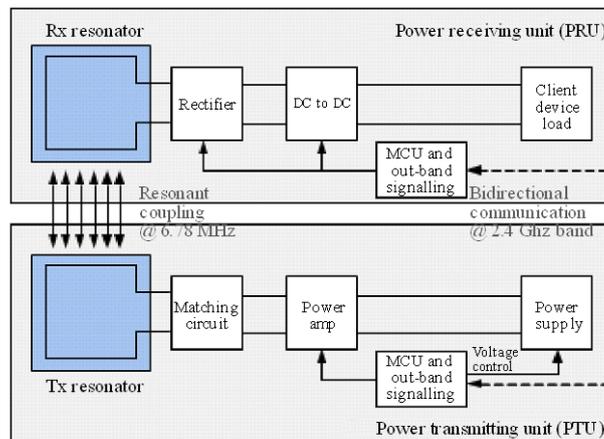
IEC

Figure 7 – Example magnetic resonance WPT system block diagram [1]

c) Capacitive coupling WPT systems for portable and mobile devices

The capacitive coupling WPT system has two sets of electrodes, and does not use coils as magnetic type of WPT systems. Power is transmitted via an induction field generated by coupling the two sets of electrodes. The capacitive coupling system has some merits as follows. Figures 8 and 9 show system block diagram and typical structure, respectively.

1) Capacitive coupling system provides horizontal position freedom with an easy-to-use charging system for end customers.

2) Very thin (less than 0,2 mm) electrode can be used between transmitter and receiver in the system, and hence suitable for integration into slim mobile devices.

3) No heat generation in the wireless power transmission area. This means the temperature does not rise in the wireless power transmission area, which protects the battery from heating even when the unit is placed nearby.

4) The emission level of the electric field is low because of the structure of its coupling system. The electric field is emitted from electrodes for power transmission.

Table 2 summarizes application, technology and specification of WPT systems whose frequency range is from 100 kHz to 10 MHz.
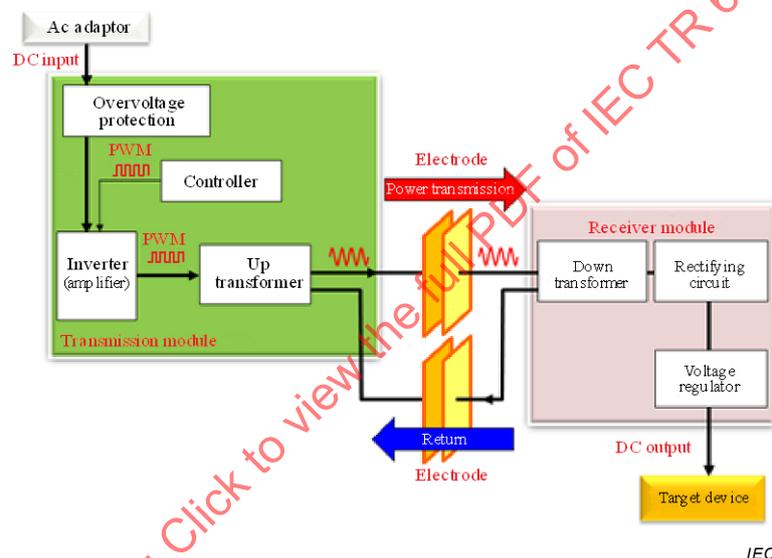
Figure 8 – Capacitive coupling WPT system block diagram [1]
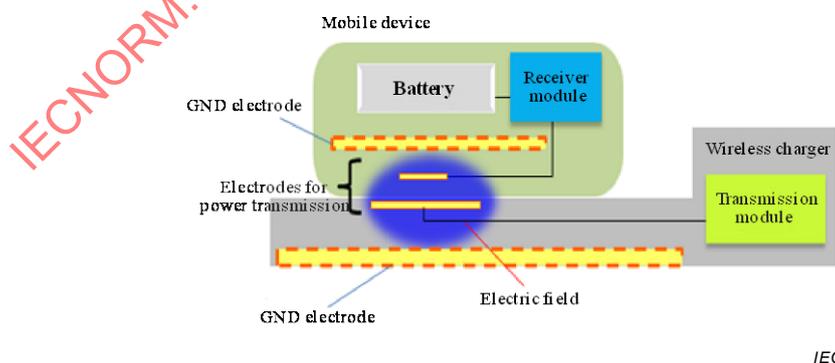
Figure 9 – Typical structure of the capacitive coupling system [1]

Table 2 – WPT systems whose frequency range is from 100 kHz to 10 MHz

Parameter/Category	Magnetic induction for portable and mobile devices	Magnetic resonance for portable and mobile devices	Capacitive coupling for portable and mobile devices
Application types	Mobile devices, tablets, note-PCs	Mobile devices, tablets, note-PCs, IT devices	Portable devices, tablets, note-PCs
Technology principle	Resonant magnetic induction	High magnetic resonance	WPT via electric field
Frequency ranges under consideration	Global: 110 kHz to 205 kHz	Global: 6 765 kHz to 6 795 kHz	
Frequency ranges assigned nationally	Korea: 100 kHz to 205 kHz	Japan, Korea: 6 765 kHz to 6 795 kHz	Japan: 425 kHz to 524 kHz
Power range under consideration	5 W to 15 W	Japan: Several watts to 100 W	Japan: Up to 100 W
Power transfer distance	0 to 1 cm	0 to 30 cm	0 to 1 cm
Advantage	Global harmonized spectrum Higher power transmission efficiency	– Global spectrum availability possible – Flexibility for placement and distance of receiving end – Transmitter can supply power for several receivers within a wide range simultaneously.	High efficiency (70 % to 85 %) – No heat generation at the electrode – Low emission level – Horizontal position freedom

6 Basic assessment methods

6.1 General

Clause 6 provides basic assessment methods considering both direct (6.2) and indirect (6.3) effects of electromagnetic fields for WPT systems. The direct effect deals with induced electric field and/or SAR and the indirect effect deals with contact current. International exposure guidelines are described in Annex B. Assessment methods for those quantities are different. More detailed explanation of the methods and case studies are described in Annex C and Annex D, respectively. Numerical and experimental studies with respect to exposure assessment of WPT are presented in Annex E.

6.2 Basic assessment methods considering direct effect

6.2.1 General

Subclause 6.2 provides basic assessment methods considering direct effect of electromagnetic fields [4-7]. Evaluations are made either against basic restrictions or against derived reference levels. In the international guidelines, different limits of basic restrictions and reference levels are defined for thermal and stimulus effects. There are four steps as described in 6.2.2 to 6.2.5 to assess the WPT exposure and demonstrate compliance with the basic restrictions and/or reference levels. Any of the four steps suitable for the exposure situation can be used. The evaluation based on transmit power or current (6.2.2) is the easiest way to confirm compliance and the compliance against reference levels by evaluating incident fields (6.2.3) is the next; however those methods are rather more conservative than the compliance against basic restrictions. The compliance against basic restrictions by evaluating induced E-field and/or SAR (6.2.5) represents practical exposure without additional evaluations. There is another method for the compliance directly against basic restrictions by evaluation of incident fields (6.2.4).

There is an important issue with respect to medical implants. It was reported that electromagnetic fields in the body might be enhanced around medical implants when expose to electromagnetic field emitted by a source. According to [8] electromagnetic fields used for WPT generate a 1 °C temperature increase in the tissue around medical implants at levels even when the field is below the exposure limits at frequencies below 10 MHz. The factor considered in enhancement by medical implant is proposed in Annex F. IEC TC 106 invited ICNIRP and IEEE/ICES to provide their opinions and IEC TC 106 had conference call with IEC TC 62, ISO/TC 105, and Association for the advancement of Medical Instrumentation (AAMI) to discuss the issues. As a result the liaisons with IEC TC 62/SC 62A, SC 62C, SC 62D, ISO/TC 150/SC 6, and IEC TC 77 are important for IEC TC 106 to exchange information [9].

6.2.2 Evaluation based on transmit power or current

The maximum permissible transmit power or current of WPT can be defined as not to exceed basic restrictions. The concept of evaluation procedure is described in detail in Clause C.1.

6.2.3 Evaluation of incident fields against reference levels

Both incident electric and magnetic field strengths are measured or calculated at a certain distance including the closest distance and in all directions where DUT may operate near persons. For the uniform field, the measured or calculated values of electric and magnetic fields are simply compared to the reference level. In the case of non-uniform field such as from the WPT systems, the measured or calculated field values may be spatially averaged over the exposed regions of the body, with the important proviso that the basic restrictions for local SAR and internal electric field are not exceeded. The spatial averaging may not be practical if only a very small portion of a body region is exposed to the DUT. Under such circumstances, maximum peak field needs to be considered. Usage of the spatial averaging and its precise method needs to be defined for each product standard. Either the peak or spatially averaged field strength is compared to the applicable reference levels to determine compliance.

The assessment method is described in detail in Clause C.2.

6.2.4 Evaluation of incident fields against basic restrictions

6.2.4.1 General

The reference levels of electromagnetic field are established based on the maximum induced quantities in the human body exposed to the uniform electromagnetic fields. Therefore, the evaluated results considering reference levels may be too conservative for localized exposure from an EMF source such as WPT systems.

6.2.4.2 Coupling factor method

IEC 62311 [10] and IEC 62233 [11] introduce a coupling factor for magnetic field evaluation so as to consider non-uniformity of the field close to the EMF source. From the definition of the coupling factor, it is possible to evaluate the value of the coupling factor by numerical simulation with the ratio of induced quantities and incident magnetic field [12-13].

For a specific condition of frequency, field distribution, distance to human body, etc., a conservative value of the coupling factor can be derived numerically.

Using the coupling factor value determined for a certain kind of WPT systems, the incident magnetic field strength can be multiplied by the coupling factor and compared to the reference levels directly. The assessment method is described in detail in Clause C.3.

The following criteria need to be considered in order to apply coupling factor.

– Induced quantities such as internal electric field or SAR caused by incident electric field are negligible compared to those by incident magnetic field.

– The whole-body average SAR is negligible compared to respective limits and contribution of the localized average SAR or the internal electric field is dominant.

– Evaluation conditions such as frequency, field distribution, distance to human body, etc., need to be comparable to those used in derivation of the coupling factor.

6.2.4.3   Generic gradient source model

The generic gradient source model (GGSM) [14] is a method 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 based on the following quantities of the incident magnetic field:

– frequency;

– B-field amplitude (B_{xyz}) and the local max B-field gradient per metre $(B_{x,y,z-\Delta} - B_{x,y,z+\Delta})/2\Delta \times B_{x,y,z})$ of the field at any point in free space.

Based on the above parameter [14] provides transformation matrices to conservatively estimate the induced electric field, current density and the absorbed power, allowing to test against basic restrictions for all international guidelines.

– ICNIRP 1998:

  • 10 g peak spatial-average SAR;

  • current density averaged over 1 cm^2.

– ICNIRP 2010:

  • E-field in a $2 \times 2 \times 2$ mm^3 cube.

– IEEE C95.1-2005:

  • 10 g peak spatial average SAR;

  • E-field along a straight-line of 5 mm.

The assessment method is described in detail in Clause C.4.

6.2.5   Evaluation of induced E-field and SAR against basic restrictions

6.2.5.1   Measurement

SAR can be measured using a small probe in a liquid-filled phantom model of the human body, which is exposed to electromagnetic fields created by the DUT. Measured values can be directly compared with basic restrictions. The evaluation and validation procedure is described in IEC 62209-2:2010, whose frequency range is 30 MHz to 6 GHz [15]. IEC TC 106 is expanding the lower frequency limit to 4 MHz. The assessment method is described in detail in C.5.1.

6.2.5.2   Calculation

Induced electric field or SAR can be calculated by numerical simulation using anatomical human model, analytical method and so forth to be compared with basic restrictions. Validity of the simulation model and methodology need to be validated prior to evaluation. The assessment method by numerical simulation is only described in detail in C.5.2.

6.2.6   Assessment procedure

Figure 10 is a flowchart of assessment procedure. There are four steps including (6.2.2) to (6.2.5) in case of the direct effect exposed to WPT products. The step which is the most suitable for products and the exposure situation can be used.

IEC
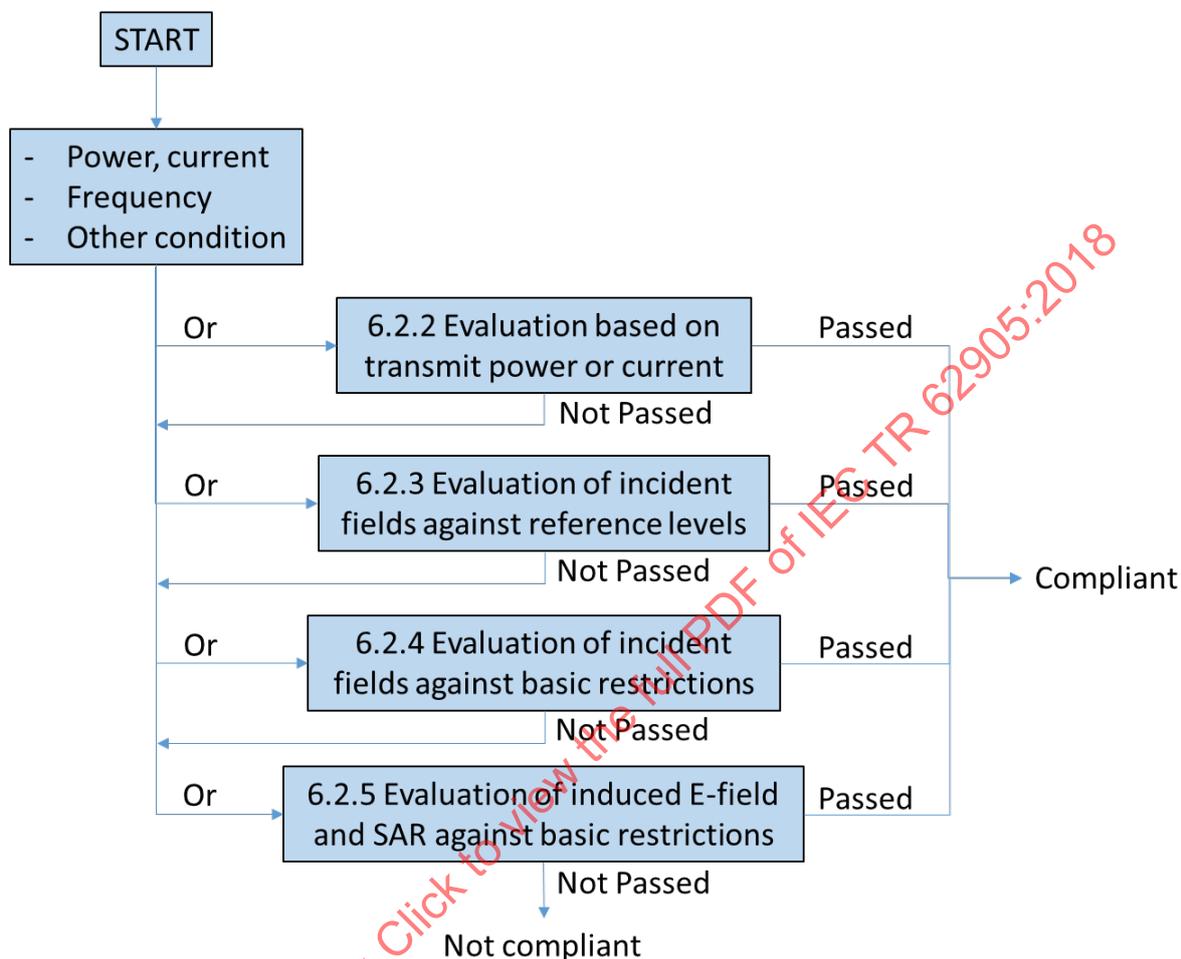
Figure 10 – Flowchart of assessment procedure considering the direct effect

6.3   Basic assessment method considering indirect effect

Subclause 6.3 provides basic assessment methods considering indirect effect of electromagnetic fields. Contact current is the only indirect effect considered in this document and international guidelines. Contact current flows into a biological body via a contacting electrode or other source of current.

Evaluation of contact current can be assessed either by incident electromagnetic fields or direct measurement.

In regard to compliance by incident electromagnetic fields, the following considerations both need to be applied.

–   Incident electric field level to prevent adverse indirect effects of contact current (shocks and burns) is shown in guidelines [5].

–   Incident magnetic field level to prevent adverse indirect effects of contact current can be calculated by current induced in the loop formed with grounded metal and human body with Formula (1).

$$H = \frac{Z}{2\pi f \mu_0 S} I_c \tag{1}$$

where

I_c is contact current (A);

Z is impedance of human body (Ω) (see Clause C.6);

S is area of loop such as 1,5 m $\times$ 0,5 m.

Contact currents can also be directly measured by a contact current meter with ungrounded or grounded metal object placed in the vicinity of the WPT systems. Figure 11 shows exposure situations for ungrounded and grounded metal objects.

Figure 12 is a flowchart of assessment procedure. Details of measurement conditions, measurement setup, etc., for contact current are under investigation within IEC TC 106. The assessment method is described in detail in Clause C.6.

Currents by touching to ungrounded metal   Currents by touching to grounded metal
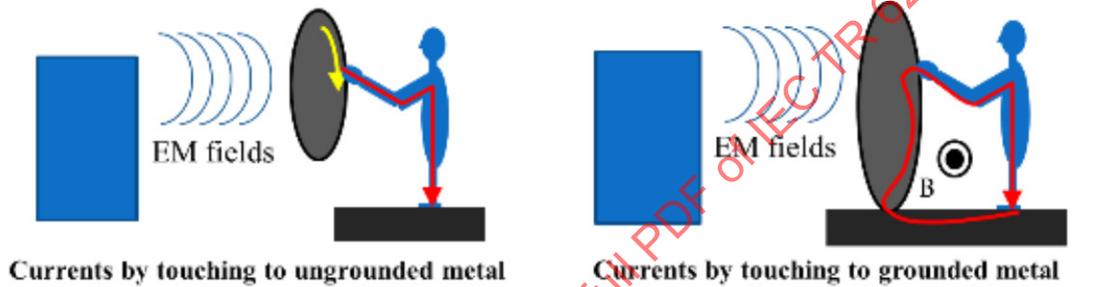
IEC

Figure 11 – Two exposure situations for ungrounded and grounded metal objects

ungrounded condition (incident E)   grounded condition (incident H)
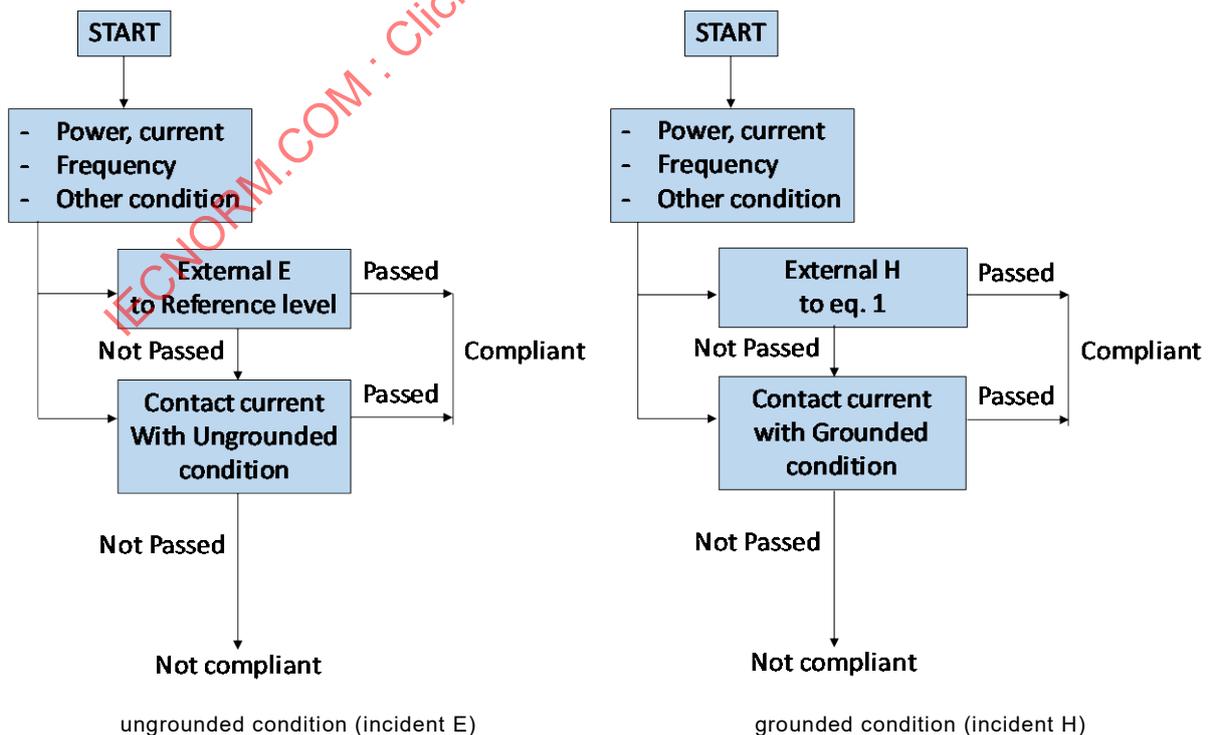
Figure 12 – Flowchart of assessment procedures for indirect effects

Annex A
(informative)

WPT systems whose frequency range is over 10 MHz

WPT system operating at the frequency over 10 MHz is also under development, although the method for exposure assessment is not discussed in this document.

WPT system operating at the frequency over 10 MHz is classified as a non-coupled WPT whose energy is radiated from the transmitter and in which there is no effect from change of parameters of the transmitter/receiver to those of the receiver/transmitter. It is also named as WPT via radio frequency. Typical electromagnetically coupled WPT is an inductive coupling WPT, a capacitive coupling WPT, and a resonance coupling WPT and its frequency is generally lower than 10 MHz. Number of transmitters and receivers in the non-coupled WPT system are free from circuit parameters of the transmitters and the receivers. Main theory of the WPT via radio frequency in free space is based on Friis' transmission formula. The radiated power of the electromagnetic wave is propagated not only in space but also in two-dimensional waveguide (called 'sheet') and in waveguide (called 'pipe'). Microwave and millimetre wave are often used for the non-coupled WPT system [16]. But frequency itself is not important in the classification of coupled and non-coupled WPT. There is a research and development of the coupled WPT at microwave frequency in which dielectric resonators at 2,45 GHz are used as a transmitter and a receiver [17]. The non-coupled WPT is historically called a MPT (Microwave Power Transfer/Transmission), a WPT via radio frequency, and 'beam-type' WPT whose word is mainly used in ITU (International Telecommunication Union).

The present development of the WPT via radio frequency beam owes to William Brown in 1960s in US using microwave technology developed during the World War II [18]. He transmitted the microwave power from a transmitter to a receiver (point-to-point) with the overall (DC-microwave-DC) efficiency of 54 % in his laboratory [19]. In the 1960s, the main stream of R&D of the WPT via radio frequency was beam-type WPT whose radiated power from the transmitter was concentrated to one receiver. In 1980s, Hiroshi Matsumoto's group at Kyoto University in Japan advanced the MPT toward a Solar Power Satellite (SPS) application and also toward the other commercial application of the MPT to battery-less sensors, to a mobile phone, to an electrical vehicle, and in pipe in building [20][21]. After a revolution of the resonance WPT by MIT in 2006, not only the coupled WPT but also the WPT via radio frequency arises again to produce various commercial WPT applications. In the twenty-first century, the R&D of the WPT via radio frequency is not only beam-type WPT but also a WPT to multi-users with distributed weak electromagnetic wave like RF-ID, WPT in sheet and in pipe, and an energy harvesting from broadcasting waves.

Applications of the WPT via radio frequency beam are classified in the WPT systems as follows (Table A.1):

a) wide beam to multi-users at short range;

b) WPT in closed area;

c) narrow beam to single user at short/long range.

In Japan, the two-dimensional (2D) WPT system, which is one of WPT application in closed area, has been standardized in ARIB (Association of Radio Industries and Business) as ARIB STD-T113 [22]. Frequency is 2,498 GHz ± 1 MHz and its power is below 30 W.

Table A.1 – Classification of WPT applications

ID	Application	a) Wide beam to multi-users at short range	b) WPT in closed area	c) Narrow beam to single user at short/long range
a1	Wireless powered sensor network	○		
a2	Wireless charger of mobile devices	○		
b1	Wireless power transfer sheet		○	
b2	Wireless power provided in a pipe		○	
b3	Wireless power buildings Supported by MPT		○	
c1	WPT to moving/flying target			○
c2	Point-to-point WPT			○
c3	Wireless charging for electric vehicles			○
c4	Solar power satellite			○

The frequency bands for the WPT via radio frequency, which have already been used in field WPT experiments and in R&D of the WPT, are shown in Table A.2. These frequency bands are in ISM band (Industrial, Scientific and Medical band) in the world. Only 900 MHz band is in ISM band in Region 2 which covers the Americas including Greenland, and some of the eastern Pacific Islands.

Table A.2 – Characteristics of beam WPT applications

Type	ID	Applications	Frequency band	Condition	Distance	Power
a	a1	Wireless powered sensor network	915 MHz band, 2,45 GHz band, 5,8 GHz band	Indoor, Outdoor	Several metres to dozens of metres	< 50 W
	a2	Wireless charger of mobile devices	2,45 GHz band	Indoor	Several metres to dozens of metres	< 50 W
b	b1	Wireless power transfer sheet	2,498 GHz ± 1 MHz	In shielded sheet	Several metres (in sheet)	< 30 W
	b2	Wireless power provided in a pipe	2,45 GHz band, 5,8 GHz band	In shielded pipe	1 m to 100 m (in pipe)	< 50 W
	b3	Wireless power buildings Supported by MPT	2,45 GHz band, 5,8 GHz band	In shielded pipe underfloor	1 m to 100 m (in pipe)	50 W to 5 kW
c	c1	WPT to moving flying target	2,45 GHz band, 5,8 GHz band	Outdoor	100 m to 20 km	50 W to 1 MW
	c2	Point-to-point WPT	2,45 GHz band, 5,8 GHz band	Outdoor	1 m to 20 km	100 W to 1 MW
	c3	Wireless charging for electric vehicle	2,45 GHz band, 5,8 GHz band	Parking place	0,1 m to 1 m	100 kW to 500 kW
	c4	Solar power satellite	TBD	Space to ground	36 000 km	1,3 GW

Annex B
(informative)

International exposure guidelines

B.1   ICNIRP guidelines

ICNIRP (International Commission on Non-Ionizing Radiation Protection) guidelines are one of the most widely accepted protection guidelines for human body exposure to electromagnetic fields. The guideline was first published in 1998 (ICNIRP1998) [4], and partially revised for low frequency region in 2010 (ICNIRP2010) [5] considering nervous system effect. In the frequency range from 100 kHz to 10 MHz, both guidelines need to be considered depending on exposure conditions.

In ICNIRP guidelines, basic restriction is defined based on the established health effects. ICNIRP1998 employs induced current density, specific absorption rate and power density as the metric for basic restrictions. On the other hand, ICNIRP2010 replaces the induced current density with an internal electric field (in situ electric field) as a metric of the basic restriction. Table B.1 and Table B.2 show the basic restrictions of ICNIRP1998 and ICNIRP2010.

Table B.1 – Basic restrictions up to 10 GHz of ICNIRP1998

Type of exposure	Frequency range	Current density for head and trunk (mA/m^2) (rms)	Whole-body average SAR (W/kg)	Localized SAR for head and trunk (W/kg)	Localized SAR for limbs (W/kg)
Occupational exposure	Up to 1 Hz	40	-	-	-
	1 Hz to 4 Hz	$40/f$	-	-	-
	4 Hz to 1 kHz	10	-	-	-
	1 kHz to 100 kHz	$f/100$	-	-	-
	100 kHz to 10 MHz	$f/100$	0,4	10	20
	10 MHz to 10 GHz		0,4		
General public exposure	Up to 1 Hz	8	-	-	-
	1 Hz to 4 Hz	8/f	-	-	-
	4 Hz to 1 kHz	2	-	-	-
	1 kHz to 100 kHz	$f/500$	-	-	-
	100 kHz to 10 MHz	$f/500$	0,08	2	4
	10 MHz to 10 GHz		0,08	2	4
f is the frequency in Hz.					
Current density is averaged over a cross-section of 1 cm^2.					
Localized SAR averaging mass is any 10 g of contiguous tissues.					

Table B.2 – Basic restrictions of ICNIRP2010

Type of exposure	Target parts	Frequency range	Internal electric field (V/m)
Occupational exposure	CNS tissue of the head	1 Hz to 10Hz	$0,5/f$
		10 Hz to 25 Hz	0,05
		25 Hz to 400 Hz	$2 \times 10^{-3} f$
		400 Hz to 3 kHz	0,8
		3 kHz to 10 MHz	$2,7 \times 10^{-4} f$
	All tissues of head and body	1 Hz to 3 kHz	0,8
		3 kHz to 10 MHz	$2,7 \times 10^{-4} f$
General public exposure	CNS tissue of the head	1 Hz to 10 Hz	$0,1/f$
		10 Hz to 25 Hz	0,01
		25 Hz to 1 000 Hz	$0,4 \times 10^{-3} f$
		1 000 Hz to 3 kHz	0,4
		3 kHz to 10 MHz	$1,35 \times 10^{-4} f$
	All tissues of head and body	1 Hz to 3 kHz	0,4
		3 kHz to 10 MHz	$1,35 \times 10^{-4} f$
f is the frequency in Hz.			
All values are rms.			

Reference levels are provided for comparison with measured value of physical quantities such as incident electromagnetic fields. They are given for the condition of maximum coupling of the field to the exposed individual. Table B.3 and Table B.4 show the reference level of ICNIRP1998 and ICNIRP2010, respectively.

**Table B.3 – Reference levels for electric and magnetic
fields (unperturbed rms values) of ICNIRP1998**

Type of exposure	Frequency range	Electric field strength (V/m)	Magnetic flux density (µT)
Occupational exposure	Up to 1 Hz		2×10^5
	1 Hz to 8 Hz	20 000	$2 \times 10^5/f^2$
	8 Hz to 25 Hz	20 000	$2,5 \times 10^4/f$
	0,025 kHz to 0,82 kHz	$500/f$	$25/f$
	0,82 kHz to 65 kHz	610	30,7
	0,065 MHz to 1 MHz	610	$2,0/f$
	1 MHz to 10 MHz	$610/f$	$2,0/f$
	10 MHz to 400 MHz	61	0,2
	400 MHz to 2 000 MHz	$3f^{1/2}$	$0,01f^{1/2}$
	2 GHz to 300 GHz	137	0,45
General public exposure	Up to 1 Hz		4×10^4
	1 Hz to 8 Hz	10 000	$4 \times 10^4/f^2$
	8 Hz to 25 Hz	10 000	$5 000/f$
	0,025 kHz to 0,8 kHz	$250/f$	$5/f$
	0,8 kHz to 3 kHz	$250/f$	6,25
	3 kHz to 150 kHz	87	6,25
	0,15 MHz to 1 MHz	87	$0,92/f$
	1 MHz to 10 MHz	$84/f^{1/2}$	$0,92/f$
	10 MHz to 400 MHz	28	0,092
	400 MHz to 2 000 MHz	$1,375f^{1/2}$	$0,004\,6f^{1/2}$
	2 GHz to 300 GHz	61	0,20
f as indicated in the frequency range column.			

**Table B.4 – Reference levels for electric and magnetic
fields (unperturbed rms values) of ICNIRP2010**

Type of exposure	Frequency range	Electric field strength (kV/m)	Magnetic flux density (T)
Occupational exposure	1 Hz to 8 Hz	20	$0,2/f^2$
	8 Hz to 25 Hz	20	$2,5 \times 10^{-2}/f$
	25 Hz to 300 Hz	$5 \times 10^2/f$	0,001
	300 Hz to 3 kHz	$5 \times 10^2/f$	$0,3/f$
	3 kHz to 10 MHz	0,17	0,000 1
General public exposure	1 Hz to 8 Hz	5	$4 \times 10^{-2}/f^2$
	8 Hz to 25 Hz	5	$5 \times 10^{-3}/f$
	25 Hz to 50 Hz	5	0,000 2
	50 Hz to 400 Hz	$2,5 \times 10^2/f$	0,000 2
	400 Hz to 3 kHz	$2,5 \times 10^2/f$	$0,08/f$
	3 kHz to 10 MHz	0,083	0,000 027
f is the frequency in Hz.			

Reference levels for contact current are also given in ICNIRP guidelines to avoid shock and burn hazards. The point contact reference levels are presented in Table B.5.

Table B.5 – Reference levels for contact currents of ICNIRP1998 and ICNIRP2010

Type of exposure	Frequency range	Maximum contact current (mA)
General public exposure	Up to 2,5 kHz	0,5
	2,5 kHz to 100 kHz	$0,2f$
	100 kHz to 110 MHz	20
Occupational exposure	Up to 2,5 kHz	1,0
	2,5 kHz to 100 kHz	$0,4f$
	100 kHz to 110 MHz	40
f is the frequency in kHz.		

B.2   IEEE standards

IEEE (Institute of Electrical and Electronics Engineers) International Committee on Electromagnetic Safety has two standards, in which their border frequency is 3 kHz; the standard for low frequency is C95.6 "IEEE Standard for Safety Levels With Respect to Human Exposure to Electromagnetic Fields, 0-3 kHz" issued in 2002 [6] and the standard for high frequency is C95.1 "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz" revised in 2005 [7].

In IEEE standards, similar to ICNIRP guidelines, basic restrictions are defined based on the established health effects. Maximum permissible exposure (MPE) is also defined for electric fields, magnetic fields, derived from the basic restrictions. Table B.6 and Table B.7 show the basic restrictions of IEEE C95.6 and IEEE C95.1. MPEs for electric and magnetic fields are summarized in Tables B.8 to B.10.

Table B.6 – Basic restrictions up to 5 MHz of IEEE C95.6 and IEEE C95.1

Exposed parts	f_e (Hz)	E_0 (V/m-rms)	
		General public	Controlled environment
Brain	20	$5,89 \times 10^{-3}$	$1,77 \times 10^{-2}$
Heart	167	0,943	0,943
Hands, wrists, legs, ankles	3 350	2,10	2,10
Other tissue	3 350	0,701	2,10

From Table B.6, internal electric field is calculated as follows:

If frequency $f \leq f_e$ then $E_i = E_0$; if frequency $f \geq f_e$ then $E_i = E_0 (f / f_e)$.

The magnetic field 10 Hz or less is limited to 167 mT and 500 mT for general public and controlled environment, respectively.

Table B.7 – Basic restrictions between 100 kHz and 3 GHz of IEEE C95.1

Type of exposure	Exposed parts	SAR (W/kg)	
		Action level	Controlled environment
Whole-body exposure	Whole-body average	0,08	0,4
Localized exposure	Localized (peak spatial-average)	2	10
Localized exposure	Extremities and pinnae	4	20

Table B.8 – Magnetic field MPE up to 5 MHz of IEEE C95.1 and IEEE C95.6

Exposed parts	Frequency (Hz)	B (mT-rms)	
		General public	Controlled environment
Head and body	< 0,153	118	353
	0,153 to 20	$18,1/f$	$54,3/f$
	20 to 759	0,904	2,71
	759 to 3 350	$687/f$	$2061/f$
	3 350 to 5 × 10^6	0,205	0,615
Arms or legs	< 10,7	353	353
	10,7 to 3 350	$3790/f$	$3790/f$
	3 350 to 5 × 10^6	1,13	1,13
f is expressed in kHz.			

Table B.9 – Electric field MPE for whole-body exposure up to 100 kHz of IEEE C95.1 and IEEE C95.6

General public		Controlled environment	
Frequency (Hz)	E (V/m-rms)	Frequency (Hz)	E (V/m-rms)
1 to 368	5 000	1 to 272	20 000
368 to 3 000	$1,84 × 10^6/f$	272 to 3 000	$5,44 × 10^6/f$
3 000 to 100 000	614	3 000 to 100 000	1842
f is expressed in Hz.			

Table B.10 – MPE for electric and magnetic field over 100 kHz
for whole-body exposure of IEEE C95.1 and IEEE C95.6

Type of exposure	Frequency range (MHz)	Electric field strength (V/m)	Magnetic field strength (A/m)
Controlled environment	0,1 to 1,0	1842	16,3/f
	1,0 to 30	1842/f	16,3/f
	30 to 100	61,4	16,3/f
	100 to 300	61,4	0,163
General public	0,1 to 1,34	614	16,3/f
	1,34 to 3	823,8/f	16,3/f
	3 to 30	823,8/f	16,3/f
	30 to 100	27,5	158,3/$f^{1,668}$
	100 to 400	27,5	0,0729
f is expressed in MHz.			

MPE for contact current are also shown in Table B.11.

Table B.11 – Contact current MPE of IEEE C95.1 and IEEE C95.6

Condition	Frequency range	Contact current (mA)	
		General public	**Controlled environment**
grasp	Up to 2,5 kHz	-	6,0
	3 kHz to 100 kHz	-	1,00f
	100 kHz to 110 MHz	-	100
touch	Up to 2,5 kHz	0,50	1,5
	3 kHz to 100 kHz	0,167f	0,5f
	100 kHz to 110 MHz	16,7	50
f is the frequency in kHz.			

Annex C
(informative)

Assessment methods

C.1 Exclusion based on transmit power or current

In case that the thermal effect is dominant or the restriction by internal electric field is relatively small compared to that by SAR, maximum transmit power P_{max} of the equipment can be calculated to determine compliance with the basic restriction for SAR as follows:

$$P_{max} = SAR_{max} \times m \qquad (C.1)$$

where

SAR_{max} is basic restriction of local SAR;

m is average mass.

The P_{max} is called "possible exclusion power level". Table C.1 shows examples of exposure standards and their basic restrictions of SAR. Table C.2 shows the calculated possible exclusion power level regarding local SAR.

Table C.1 – Basic restrictions regarding SAR (unit is W/kg)

Exposure standard	Exposure environment	Frequency	Whole-body average SAR	Local SAR [a] (head/body)	Local SAR [a] (extremities)
ICNIRP guideline (1998 version) [4]	Occupational exposure	100 kHz to 10 GHz	0,4	10	20
	Public exposure		0,08	2	4
IEEE C95.1 (1999 version) [23]	Controlled environment	100 kHz to 6 GHz	0,4	4	20
	Uncontrolled environment		0,08	1,6	4
IEEE C95.1 (2005 version) [7]	Controlled environment	100 kHz to 3 GHz	0,4	10	20
	Action Level		0,08	2	4
[a] The values are 10 g average SAR, except under the uncontrolled environment for head/body of IEEE 95.1(1999 version) that is based on 1 g average SAR.					

Table C.2 – Possible exclusion power level regarding local SAR

Basic limits of SAR (basic restrictions)		Possible exclusion power level [mW]	Note
SAR value [W/kg]	Mass of tissue to average [g]		
1,6	1	1,6	IEEE95.1(1999 version) Head/Body
2	10	20	ICNIRP/IEEE(2005 version) Head/Body
4		40	
10		100	Occupational exposure Head/Body
20		200	Occupational exposure Extremities

In the case of frequency lower than 10 MHz, it is also possible to define maximum transmit power or current considering internal electric fields and SAR. For a known geometry and loop currents, the induced field levels and SAR can be calculated analytically [24].

C.2   Measurement of incident electromagnetic fields

C.2.1   Equipment for electric field measurement

The electric field strength can be measured by an antenna that has sensitivity to electric fields exclusively (e.g. small dipoles) connected to the calibrated measurement equipment. In general, measurement equipment used for the electric field is divided into broadband and narrowband measurement systems. In both cases, the equipment consists of antenna (including power feeding section), measurement part, and data recording and processing unit. Following is the system characteristics and selection method.

a) The broadband system uses dipole antennas. The size is small enough to ensure uniform sensitivity at each frequency. To ensure isotropy, generally three antennas are set perpendicular to one another and each signal or combined signal is extracted. This type of antenna is suitable to near field electromagnetic field of complicated distribution. A typical measurement equipment is a broadband isotropic electric field strength meter designed for radio wave protection. The other systems may consist of waveform observation equipment such as diode detector and oscilloscope.

b) The narrow band system is tuned to each target frequency. The measurement system generally has broad measurement frequencies, high receiving sensitivity and quite short response. It is thus suitable even for pulsed waves or multiple sources. However, for the pulsed wave measurement, it is valid measuring in the frequency domain where the target frequency range is broader than the passband width of the measurement system. A biconical antenna is often used, which has broadband characteristic. However, it is thus suitable for far field region only because the size of the antenna is not electrically small. A three-axis orthogonal small dipole is suitable for near field measurement.

c) For electromagnetic environmental assessment, a broadband isotropic electric field strength meter is preferentially used unless the equipment cannot measure properly and is replaced by another method.

When selecting measurement system, the required performance, measurable frequencies, and electromagnetic field strength range need to be considered.

C.2.2   Equipment for magnetic field measurement

With magnetic field measurement sensor system for low frequency range of several 100 kHz and less, search coil systems are often used: hall element, flux gate type, magnetic

resistance method, magnetic oscillation method, quantum interference method (SQUID) and so forth. In general, the search coil system is used for measuring environmental magnetic field. Magnetic field measurement principle based on the search coil system measures induced voltage associated with time change variation of the magnitude of magnetic flux interlinked to search coil. Induced voltage is calculated according to Formula (C.2). All the quantities are in phasor forms.

$$V = -j\omega NBS \tag{C.2}$$

where

V is induced voltage;

ω is angular frequency (= $2\pi f$);

N is number of turns;

B is magnetic flux density (vertical to the coil surface);

S is cross-section area of interlinkage magnetic flux;

To gain sufficient sensitivity, the area and winding number is increased as well as enhancing magnetic flux density by using ferromagnetic material to the core of coil. The signal is processed to gain flat frequency characteristics by integrator in subsequent stage as the output is proportional to the frequency.

Magnetic field measurement equipment is divided into one- and three-axis-sensor types in which three antennas are set perpendicular to one another. IEC 61786-1 [25] recommends using the three-axis type. The magnetic field of three-axis component given in Formula (C.3) applies.

$$B_R = \sqrt{B_x^2 + B_y^2 + B_z^2} \tag{C.3}$$

where

B_x, B_y, and B_z are effective magnetic flux density for three-orthogonal axis.

Three-axis magnetic field measurement equipment has an advantage that can exhibit the B_R in spite of the direction of measuring equipment. However, the equipment with one sensor that has waveform output function can be used for identifying the frequency component of magnetic field, arrival direction, and so forth.

C.2.3   Measurement method

In principle, the measurement is conducted in the space without human. In general, the human existing position against the WPT cannot be determined completely. In that case, typical measurement position needs to be selected.

When the measurement antenna comes close to source, metallic and/or highly insulated objects, capacitive couplings with them may occur, resulting in the impedance change. In addition, large antennas may cause electromagnetic field disturbance and averaging of the field over the antenna area. These measurement errors cannot be ignored. The measured value is based on time average or maximum instantaneous value based on the circumstance of the target electromagnetic field. Thus, the measured value needs to be properly processed to compare with the guidelines.

Following are additional things to be considered.

a) Time average: Squared effective value of electric or magnetic field strength over time is evaluated for time average value.

b) Multiple frequency evaluation: If incident wave consists of multiple frequency components of non-negligible level for guideline, the electromagnetic field strength of each component is measured to calculate the ratio against guideline. The sum of squares of the ratio against guidelines for incident electric and magnetic fields needs to be less than or equal to 1 for thermal effects. For stimulus effects, the sum of the ratio against guidelines for incident electric and magnetic fields needs to be less than or equal to 1.

IEC 61786-1:2013 [25] and IEC 61786-2:2014 [26] describe electromagnetic field basics, measurement method and requirements of the measurement equipment. Also IEC 62233 [11] and IEC 62311 [10] define electromagnetic field measurement based on guideline conformity assessment.

These International Standards define measurement position based on the size and regular usage of equipment. IEC 62311 [10] defines it as "user's usual position". IEC 62233 [11] defines the measurement position in detail for household appliances and similar apparatus including inductive battery chargers.

C.3   Coupling factor

Reference levels are determined based on the condition of maximum coupling of electromagnetic fields to an exposed individual, as in the case of uniform exposure of a standing human body. In many situations of localized exposure such as at the vicinity of WPT systems, the evaluations are too conservative when the maximum or spatial average value is compared to the reference levels of EMF. In such case, a coupling factor can be applied to evaluation as a corrective method for the non-uniformity of fields.

The coupling factor was originally introduced for exposure assessment in low frequencies in IEC 62311 [10] and IEC 62233 [11]. In IEC 62311, coupling factor k_c is defined as the ratio of maximum values of induced current density (J_{max}) to incident magnetic flux density (B_{max}).

$$k_c = J_{max} / B_{max} \tag{C.4}$$

IEC 62311 introduced the procedure to estimate the factor k_c from the measured gradient of magnetic field and the equivalent source (coil) size. The measured magnetic field strength multiplied by the factor k_c can be compared to the basic restriction directly.

In IEC 62233, the coupling factor a_c is defined by product of the factor k_c and ratio of incident magnetic flux density (reference level) to induced current density (basic restriction) in guidelines.

$$a_c = k_c \times \frac{B_{lim}}{J_{lim}} = \frac{J_{max}/B_{max}}{J_{lim}/B_{lim}} \tag{C.5}$$

where B_{lim} and J_{lim} is the basic limit for magnetic flux density and induced current, respectively. The measured magnetic field strength, multiplied by the coupling factor a_c, can be compared to the reference level directly.

Instead of estimating the coupling factor k_c or a_c by the measured gradient of magnetic field, the coupling factor can be numerically derived by incident magnetic field and induced current density from Formula (C.5). If the typical value of the coupling factor is defined for certain kind of the WPT product, the compliance assessment can be done by comparing the multiplied value of measured magnetic field strength and coupling factor a_c to the reference level of magnetic field strength.

The concept of the compliance using coupling factor a_c is expanded to internal electric field and local SAR [12,13].

$$a_{c1} = \frac{E_{\text{max\_sim}} / H_{\text{max\_sim}}}{E_{\text{lim}} / H_{\text{lim}}} \tag{C.6}$$

$$a_{c2} = \frac{\sqrt{SAR_{\text{max\_sim}}} / H_{\text{max\_sim}}}{\sqrt{SAR_{\text{lim}}} / H_{\text{lim}}} \tag{C.7}$$

where

E_{lim} is the basic limit for internal electric field strength;

SAR_{lim} is the basic limit for local SAR;

H_{lim} is the basic limit for the magnetic field strength.

E_{lim} and H_{lim} depend on frequency. The coupling factor a_c is multiplied by the measured magnetic fields to consider the effects of field non-uniformity. In other words, compliance to basic restrictions (internal electric field strength or local SAR) are then assessed by comparing the multiplied value to the reference level of magnetic fields only.

Following criteria need to be considered in order to use coupling factor.

– Induced quantities such as internal electric field or SAR caused by incident electric field are negligible compared to those by incident magnetic field.

– The whole-body average SAR is negligible compared to respective limits and contribution of the local average SAR or the internal electric field is dominant.

– Evaluation condition such as frequency, field distribution, distance to human body, etc., need to be considered equivalent to the condition used in derivation of the coupling factor.

C.4   Generic gradient source model

The generic gradient source model (GGSM) [14] is a method to mitigate over-estimation by incident field assessment in strong field gradients that are common in the vicinity of WPT systems.

The method is based on the following quantities of the incident field:

– frequency

– B-field amplitude (B_{inc}) at x,y,z and the local max B-field gradient G_n per metre ($(B_{\text{x,y,z-}\Delta} - B_{\text{x,y,z+}\Delta}) / 2\Delta \times B_{\text{x,y,z}}$) of the field at any point in free space

An equivalent source model, consisting in a two-line magnetic field source, is built based on the above parameters [14] and is used to mimic a whole-body gradient B-field exposure. This analysis provides transformation matrices to conservatively estimate the induced field quantities, allowing to test against basic restrictions for all international safety guidelines. The transformation matrices for representative frequencies field gradients have been pre-computed and are summarized in Tables C.3 to C.6 below. Each element of the transformation matrix $k_{\text{GGSM}}(G_{\text{ni}}, f_{\text{i}})$ represents the maximum induced quantity for an exposure to an incident B-field of amplitude of 1 T (tesla) and gradient G_{ni} at the human body surface at the frequency f_{i}.

To test compliance with basic restriction, the local peak magnetic field amplitude and local gradient generated by the WPT system are measured by a gradient field probe, which simultaneously measures the generated magnetic field amplitude (B_{measured}) and gradient ($G_{\text{n,measured}}$) at any closest accessible location around the source. The induced electric field, current density and SAR can then be determined by the specific transformation matrix (Tables C.3 to C.6) through Formulas (C.8) to (C.10):

$$E_{peak} = k_{GGSM,E}(G_{n,measured}, f_i) \times B_{measured} \tag{C.8}$$

$$J_{peak} = k_{GGSM,J}(G_{n,measured}, f_i) \times B_{measured} \tag{C.9}$$

$$SAR = k_{GGSM,SAR}(G_{n,measured}, f_i) \times B_{measured}^2 \tag{C.10}$$

where

$k_{GGSM}(G_{n,measured}, f_i)$ is the element of the matrix $k(G_n, f)$ for the induced electric field E (V/m/T), current density (A/cm^2/T) or SAR (W/kg/T^2) estimation, for the measured gradient G and the working frequency of the WPT source;

$B_{measured}$ is the local magnetic field measured by the field gradient probe;

E_{peak} is the estimated peak induced electric field;

J_{peak} is the estimated peak induced current density;

$G_{n,measured}$ is the local, normalized field gradient in T/m/T measured by the field gradient probe.

Table C.3 – Coupling transformation matrix to estimate induced E-field for compliance with ICNIRP 2010

Source frequency	ICNIRP 2010 $k_{GGSM,E}$ (V/m/T)				
	G_n (T/m/T)				
	0	6	13	80	235
10 kHz	$1,1 \times 10^5$	$4,8 \times 10^4$	3×10^4	$5,2 \times 10^3$	7×10^2
100 kHz	$1,1 \times 10^6$	$4,8 \times 10^5$	3×10^5	4×10^4	$8,1 \times 10^3$
1 MHz	$1,2 \times 10^7$	$4,9 \times 10^6$	$2,2 \times 10^6$	$4,4 \times 10^5$	$9,4 \times 10^4$
4 MHz	$4,7 \times 10^7$	2×10^7	$1,2 \times 10^7$	2×10^6	$3,9 \times 10^5$

Table C.4 – Coupling transformation matrix to estimate induced current density for compliance with ICNIRP 1998

Source frequency	ICNIRP 1998 $k_{GGSM,J}$ (A/m/T)				
	G_n (T/m/T)				
	0	6	13	80	235
10 kHz	$1,07 \times 10^3$	$7,20 \times 10^2$	$4,96 \times 10^2$	$1,23 \times 10^2$	$3,31 \times 10^1$
100 kHz	$1,16 \times 10^4$	$7,73 \times 10^3$	$5,44 \times 10^3$	$1,38 \times 10^3$	$3,68 \times 10^2$
1 MHz	$1,26 \times 10^5$	$9,14 \times 10^4$	$6,47 \times 10^4$	$1,85 \times 10^4$	$4,57 \times 10^3$
4 MHz	$6,54 \times 10^5$	$4,50 \times 10^5$	$3,27 \times 10^5$	$9,00 \times 10^4$	$2,22 \times 10^4$

**Table C.5 – Coupling transformation matrix to estimate
induced E-field for compliance with IEEE 2005**

Source frequency	IEEE 2005 $k_{GGSM,E}$ (V/m/T) G_n (T/m/T)				
	0	**6**	**13**	**80**	**235**
10 kHz	$9,5 \times 10^4$	$4,1 \times 10^4$	$2,6 \times 10^4$	$5,2 \times 10^3$	$1,1 \times 10^3$
100 kHz	$9,5 \times 10^5$	$4,1 \times 10^5$	$2,6 \times 10^5$	$3,6 \times 10^4$	$1,1 \times 10^4$
1 MHz	$9,7 \times 10^6$	$4,2 \times 10^6$	$2,6 \times 10^6$	$4,7 \times 10^5$	$1,2 \times 10^5$
4 MHz	4×10^7	$1,7 \times 10^7$	$1,1 \times 10^7$	$2,2 \times 10^6$	$4,9 \times 10^5$

**Table C.6 – Coupling transformation matrix to estimate SAR (pSAR$_{10g}$ and wbSAR)
for compliance with ICNIRP 1998 and IEEE 2005**

Source frequency	$k_{GGSM,SAR}$ (W/kg/T²): psSAR$_{10g}$ G_n (T/m/T)				
	0	**6**	**13**	**80**	**235**
100 kHz	$4,39 \times 10^6$	$7,64 \times 10^5$	$2,96 \times 10^5$	$2,06 \times 10^4$	$1,21 \times 10^3$
1 MHz	$6,23 \times 10^8$	$1,04 \times 10^8$	$4,00 \times 10^7$	$2,74 \times 10^6$	$1,58 \times 10^5$
4 MHz	$1,18 \times 10^{10}$	$1,96 \times 10^9$	$7,58 \times 10^8$	$5,32 \times 10^7$	$2,99 \times 10^6$

Source frequency	$k_{GGSM,SAR}$ (W/kg/T²): wbSAR G_n (T/m/T)				
	0	**6**	**13**	**80**	**235**
100 kHz	$2,74 \times 10^5$	$6,53 \times 10^4$	$3,03 \times 10^4$	$1,24 \times 10^3$	$5,99 \times 10^1$
1 MHz	$3,54 \times 10^7$	$8,32 \times 10^6$	$4,00 \times 10^6$	$2,06 \times 10^5$	$7,47 \times 10^3$
4 MHz	$6,47 \times 10^8$	$1,25 \times 10^8$	$7,30 \times 10^7$	$3,77 \times 10^6$	$1,33 \times 10^5$

As an example of application of the GGSM, a gradient field probe is used to determine the compliance of a WPT system at 100 kHz. During the test the probe has been swept over all accessible locations. The measured peak E-field was found of 30 V/m, the measured peak B field of 70 µT and the peak measured gradient $G_{measured}$ was found of 80 T/m/T. Therefore, considering the reference levels established by ICNIRP 1998, $E_{measured}$ is well within the limits (i.e. 87 V/m at 100 kHz), while $B_{measured}$ is more than ten times larger than reference levels (i.e. 6,25 µT at 100 kHz). According to Formula (C.9) and Table C.4 the estimated $J_{peak} = k_{GGSM,J}$(80 T/m/T, 100 kHz) $\times B_{measured} = (1,38 \times 10^3) \times (70 \times 10^{-6}) = 97$ mA/m². Therefore, although the measured B-field exceeds the reference levels, J_{peak} is significantly lower than ICNIRP 1998 basic restrictions for general public at 100 kHz, i.e. of 200 mA/m².

C.5   Induced E-field or SAR

C.5.1   Measurement

Clause 5 describes the procedure for measurement of induced E-field or peak spatial-average SAR for 1 g or 10 g in phantom model that simulates a human body exposed to electromagnetic field generated by the WPT systems. Using an isotropic electric field probe, the local SAR inside an irradiated body model can be determined. By moving the probe in a part of the body phantom, the SAR distribution and partial-body averaged SAR values can be determined. A measurement system for SAR is composed of a phantom, electric field probe and a scanning system.

The physical characteristics of the phantom model (size, shape, electrical properties, etc.) need to simulate the human exposed condition by the WPT system. Phantom models such as the elliptic phantom defined in IEC 62209-2 [15] or a rectangular phantom is used. Materials of the phantom model have dielectric property similar to human. At a frequency lower than 10 MHz, electrical properties of the material are dominantly affected by conductivity of the material [27]. For the materials, the liquid defined in IEC 62209-2 may be used (Table C.7). The NaCl solution having an appropriate conductivity may also be used (Table C.8). The relationship between conductivity and concentration of the NaCl solution can be found in the reference [28].

Dielectric properties resulting conservative value needs to be investigated in the future.

Table C.7 – Dielectric properties of the tissue equivalent liquid defined in IEC 62209-2

Frequency (MHz)	Real part of the complex relative permittivity, ε_r'	Conductivity, σ (S/m)
4	56	0,75
6	56	0,75
30	55	0,75
NOTE Dielectric properties at 4 MHz and 6 MHz are under investigation within IEC TC 106.		

Table C.8 – Dielectric properties of the tissue equivalent NaCl solution

Frequency (MHz)	Real part of the complex relative permittivity, ε_r'	Conductivity, σ (S/m)
NaCl concentration = 0,04 mol/l		
4	78	0,41
6	78	0,41
30	78	0,41
NaCl concentration = 0,074 mol/l		
4	77	0,75
6	77	0,75
30	77	0,75
NaCl concentration = 0,154 mol/l (physiological saline)		
4	76	1,54
6	76	1,54
30	76	1,54

The measurement equipment is calibrated as a complete system in each tissue-equivalent liquid at the appropriate operating frequency and temperature.

DUT is placed close to the liquid phantom considering the typical usage position.

To assess the localized SAR in certain volume such as 1 g or 10 g for mobile handset, IEC 62209-2 defines procedure as follows.

a) Measure the SAR distribution within the phantom along the inside surface of the phantom (area scan procedure) [29].

b) From the scanned SAR distribution identify the position of maximum SAR value, as well as the positions of any local maxima with SAR value within 2 dB of the maximum value.

c) Measure SAR with a grid step of 8 mm or less in a volume with a minimum size of 30 mm cube (zoom scan procedure).

Similar measurement procedure can be used for the WPT system.

Reference loop antenna is proposed to IEC TC 106 to validate SAR measurement system.

A simple and stable source that can be easily tuned to operate at specific frequency between 4 MHz and 40 MHz is a magnetic loop antenna represented by three turns of wire that resonate with series capacitor at the required frequency. The 90 mm diameter three-turn loop antenna is supported by a hollow cylindrical dielectric core support that allows positioning of the loop parallel to the flat phantom at a distance of a few millimetres from its surface. In such position the loop wire leads are extended 60 mm away and normal to the phantom surface and via series capacitor can be fed directly with coaxial cable. The design of those lead extensions and the dielectric support core are such that they allow an RF current sensor to clamp around one of the leads to provide real time current monitoring and control during the system check SAR measurements. The capacitor value is adjusted for the reference antenna to resonate at the specified frequency. It is recommended to use a tunable capacitor to fine tune the resonant frequency and to maximize the current in the loop while reducing the maximum power rating of the RF source feeding this antenna. It is also recommended to connect the RF source through a high power 6 dB or more attenuator to decouple the loop antenna from the power amplifier.

Positioning such source at the bottom of the phantom is convenient and SAR induced in the phantom is stable and easily reproducible. The numerically derived SAR target values for this reference antenna are provided scaled to the specific RF current level. The power delivered to the antenna is adjusted until this required reference current is established in the loop as measured by the RF current sensor as described above [30].

C.5.2   Calculation

In general, numerical simulation can be used to evaluate the induced quantities in a human body.

Table C.9 shows the human body models and source models. Table C.10 shows the computational methods for exposure evaluation in IEC 62311:2007, Annex C [10]

Table C.9 – Human models and source models

Classification	Model/ name of projects	Note
Anatomical model (realistic model)	The Visible Human Project	United States National Library of Medicine
	MEET Man	Karlsruher Institut für Technologie, Germany
	Hugo	Viewtec, Switzerland
	Norman	National Radiological Protection Board, U.K.
	University of Utah	University of Utah
	University of Victoria	University of Victoria, Canada
	Brooks Air Force Base	Brooks Air Force Base, U.S.A.
	Average Japanese male and female human models	National Institute of Information and Communications Technology, Japan
	Korean human model	Electronics and Telecommunications Research Institute, Republic of Korea
Simplified model	Spheroids (spherical model)	Model size Body : 600 mm × 300 mm Head : 300 mm × 200 mm
	Cuboids (cuboid model)	Model size 0,4 m × 0,4 m × 1,8 m (x × y × z)
	Homogeneous and simple-shaped human body model (Uniform human body model)	 *IEC*
Source model	Straight Wire	Applied to a simple exposure amount evaluation
	Circular/Rectangular coil	
	Equivalent source model Measure the magnetic flux density around the equipment and convert that to the equivalent combination of magnetic dipoles arranged on the surface of equipment	Applied to a detailed and non-uniform exposure calculation
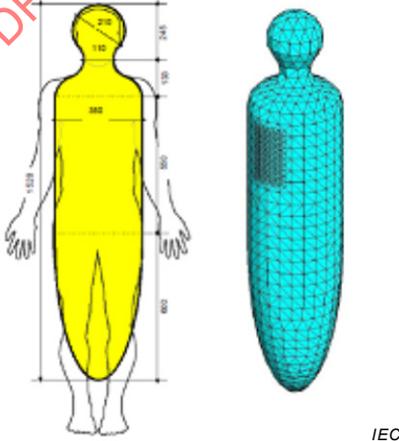
Table C.10 – Computational methods

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 computation
FIT (Finite Integration Technique)	Full-wave computation
MoM (Method of Moments)	Full-wave computation
SPFD (Scalar Potential Finite Difference)	Quasi-static approximation computation
IP (Impedance Method)	Quasi-static approximation computation

The induced electric field or SAR in a human body can be calculated by using above mentioned models and calculation methods.

Currently, there are standardizations on numerical simulation of SAR using anatomical human models. IEC and IEEE are in the process of establishing international standardization for numerical simulation methods (Table C.11).

Table C.11 – SAR evaluation method based on numerical simulation

IEC/IEEE standard	Contents		Current status
	Scope	Calculation method	
62704-1 [31]	Requirement for numerical code	FDTD (Finite Difference Time Domain)	IS
62704-2 [32]	Car mount antenna	FDTD	IS
62704-3 [33]	Mobile phone	FDTD	IS
62704-4 [34]	Requirement for numerical code	FEM (Finite-Element Method)	First CD

C.6 Contact current

C.6.1 Equipment

An impedance circuit equivalent to human body, which has frequency dependency, is used for the measurement of contact current. Figure C.1 shows the frequency characteristics of human body impedance of an adult male [35]. An equivalent circuit of IEC 60990 (Figure C.2) that simulates a human body is also shown [36].
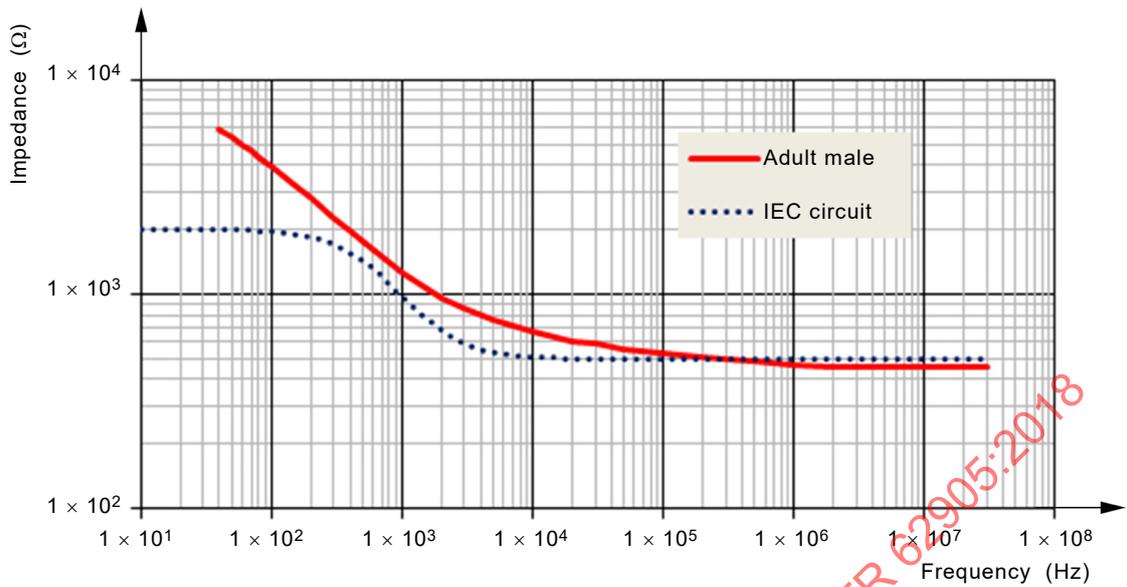
**Figure C.1 – Frequency characteristics of impedance
of adult male and IEC equivalent circuit**
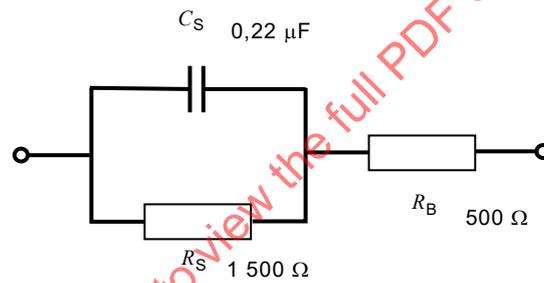
Figure C.2 – IEC equivalent circuit

Figure C.3 shows configuration of contact current meter. The contact terminal is made of metal. If the target point of contact part is painted, attach 10 cm × 20 cm metal foil to it according to IEC 60990 [36] to simulate a hand palm contact. Metal board with the equivalent size of foot is used as the ground electrode. The contact current is measured from the current flowing through the equivalent circuit of human inside the meter.
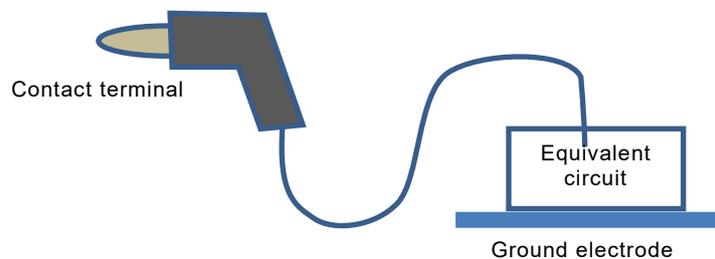
Figure C.3 – Example of contact current measurement equipment

C.6.2   Measurements

It is important to secure measurer's safety. Also bear in mind following.

- Select measurement system properly.

- Avoid electromagnetic field disturbances caused by the measurer and measurement systems as much as possible.

- Environmental condition (temperature, humidity, vibration, electromagnetic field, etc.) may affect measurement equipment.

Use calibrated measurement system. Regular calibration based on the aging and frequency of use and so forth is recommended.

a) Measurement methods using ungrounded metal board

   1) Place a ground electrode where human may stand.

   2) Place an ungrounded metal board larger than 1,2 m × 1,2 m at the location where metal objects may exist in the actual usage condition. Choose the closest position in the actual usage since the contact current tends to become higher as metal objects come closer to the WPT system. Find the maximum condition of contact current because the metal board position (height) and direction may change the contact current strength.

   3) Touch the contact terminal to the metal board where human may touch. Find a stable indicated value. Find the maximum value if there is a dependency to the touch position.

b) Measurement methods using grounded metal board

   1) Place ground electrode where human may stand.

   2) Place a grounded metal board at the location where metal objects may exist in the actual usage condition. Choose the closest position in the actual usage since the contact current tends to become higher as metal objects come closer to the WPT system. Find the maximum position of contact current because the metal board position (height) and direction may change the contact current strength.

   3) Touch the contact terminal on the metal board where human may touch. The contact current becomes larger according to the magnitude of the interlinkage magnetic flux to a loop created by grounded metal board and human body. The size of rectangular loop approximately 1,5 m (height) × 0,5 m (width) can be used to evaluate the contact current. Find arrangement of the loop which gives maximum contact current value.

Annex D
(informative)

Case studies

D.1 WPT system for EV

D.1.1 General

Clause D.1 shows the case study for WPT system for EV at frequency less than 100 kHz. This case study refers to IEC 61980-1:2015 [37], Annex C, "EMF, protection from electromagnetic field" that defines the measurement area and points. The results of assessment are also provided.

The case studies shown here consider only ICNIRP 2010 [5], which is referred in Annex B.

An assessment method of WPT system for EV applied the procedure which is described in main body of this document and Annex C. The assessment procedure of Clause D.1 is described with measurements as an example and exposure assessment can be done with numerical simulation with the similar manner. There are four steps as described in 6.2.1 through 6.2.4 to assess the WPT exposure and demonstrate compliance with the basic restrictions and/or reference levels and any of the four steps can be selected for the most suitable exposure situation.

The compliance to the guideline for both the electric field and the magnetic field need to be confirmed as the system is under near-field exposure condition where wave impedance is not 120π (= 377 Ω). However, for the WPT system for EV using frequency less than 100 kHz, the human safety for direct effect can be confirmed by solely using the magnetic field strength since the induced quantities caused by incident electric field is negligible compared with that by incident magnetic field [38]. For the compliance of the WPT system for EV, incident magnetic field may be compared to the reference level of magnetic field. According to the ICNIRP guidelines, spatial average value of magnetic field occupied by human body may be used for compliance [5].

For exposure scenario, the WPT system transmits power from a transmitting coil installed in the parking area to a receiving coil installed in a parked vehicle. This case study applied the following situation and scenario as a public exposure case. A human stands in the vicinity of the vehicle body where the misaligned WPT with a maximum power.

In the literature [39], exposures of many human postures were also discussed and simulated, but Clause D.1 covers only the standing posture human as a public exposure case scenario to harmonize with another existing standard such as AC power systems [40].

For the standing posture case, a good correlation between the spatial average value of the magnetic field strength over a volume where a human model exists and the induced electric field is observed [41]. If the averaged value of magnetic field is below the reference level of magnetic field, induced electric field complies to the basic restriction with enough margins. Three points of magnetic field spatially averaged at heights of 0,5 m, 1,0 m, 1,5 m above ground at the distance 20 cm far from vehicle are higher than spatially averaged value over a human volume [41].

There are possibilities of existence of metal objects such as adjacent automobiles in the parking area where the charging place is. In such situations, reference level of contact current is applied in order to consider indirect effects. Compliance against the contact currents can be assessed either by incident electromagnetic fields or by direct measurement of contact currents.

For the contact current caused by the electric field, the reference level of electric field for general public exposure prevents the effect of contact current for more than 90 % of exposed individuals [5]. The direct assessment of contact current with ungrounded metal can be omitted if the incident electric field does not exceed the reference level.

For the contact current caused by the magnetic field, the magnetic field not to exceed reference level of contact current can be calculated by Faraday's law assuming the human impedance and size of the current loop with Formula (1). The direct assessment of contact current with grounded metal can be omitted if the incident magnetic field does not exceed the calculated magnetic field.

NOTE   If the WPT system and/or its installed vehicle has the electrically conductive surface which can be directly touched by passengers or general public during charging, other standards such as IEC 60990 [36] for touch current need to be considered. This document does not include measurement procedure for such cases.

D.1.2   Assessment procedures for WPT system for EV

The guidelines for stimulus effects are applicable to the WPT system for EV at frequency less than 100 kHz.

IEC 61980-1 [37] defines four areas of protection shown in Figure D.1.

- Area 1: Area of operation. The space formed by the outline of the primary and the secondary coils. The area reserved for operation of the device and unexposed to the user under normal operating conditions.
- Area 2: Transition area. The section between Area 1 (area of operation) and Area 3.
- Area 3: Area surrounding the vehicle. Public area is the side, front and rear of the vehicle. Area around the chassis silhouette of the vehicle.
- Area 4: Vehicle interior (vehicle cabin).

Areas 3 and 4 are both accessible to public and vehicle passengers. Therefore, this assessment procedure covers only Areas 3 and 4 to assess compliance to public exposure guidelines of ICNIRP 2010 [5].

In order to confirm compliance of WPT systems for EV, three-part evaluation is introduced.

Part 1: Assessment of incident H-fields around the vehicle (Area 3)

Part 2: Assessment of incident H-fields inside the vehicle (Area 4)

Part 3: Assessment of incident E-fields and contact current around the vehicle (Area 3)

Key

Area 1: Area of operation

Area 2: Transition area

Area 3: Area surrounding the vehicle

Area 4: Vehicle interior
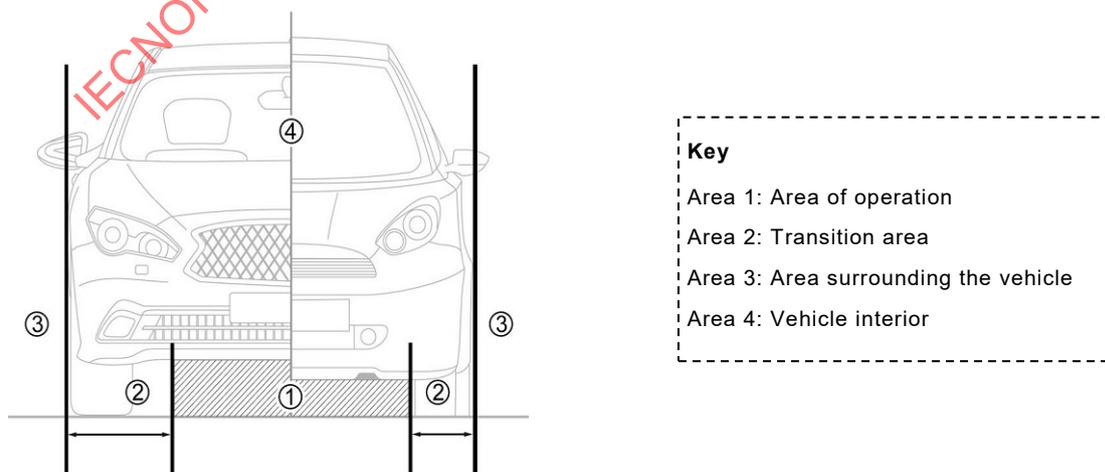
Figure D.1 – Example for areas of protection, for ground mounted systems [37]

Key

1. Primary device
2. Secondary device
3. EV
4. Virtual area for scanning the worst case position
5. Probe (P)
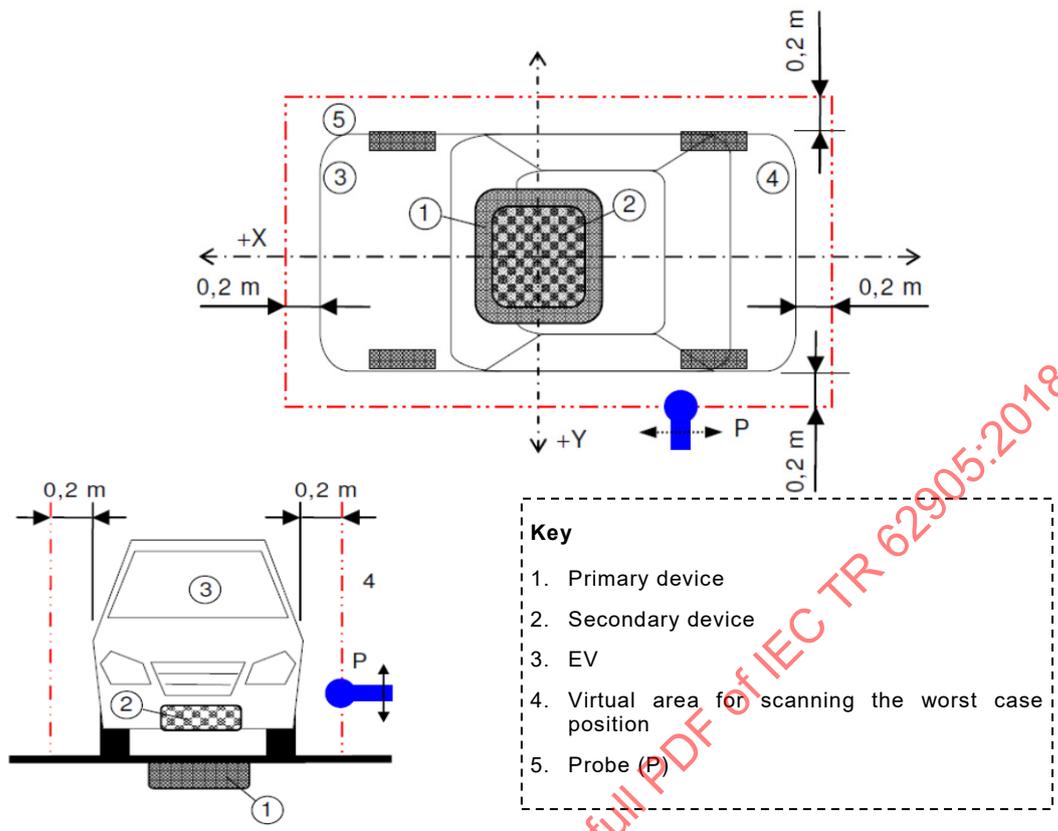
Figure D.2 – Area 3 measurement position [37]

Key
a. Travel range forward/backward, centre position
b. Travel range in height, centre position

Key
a. Centre position of headrest
b. Centre position of backrest
c. Centre position of seat
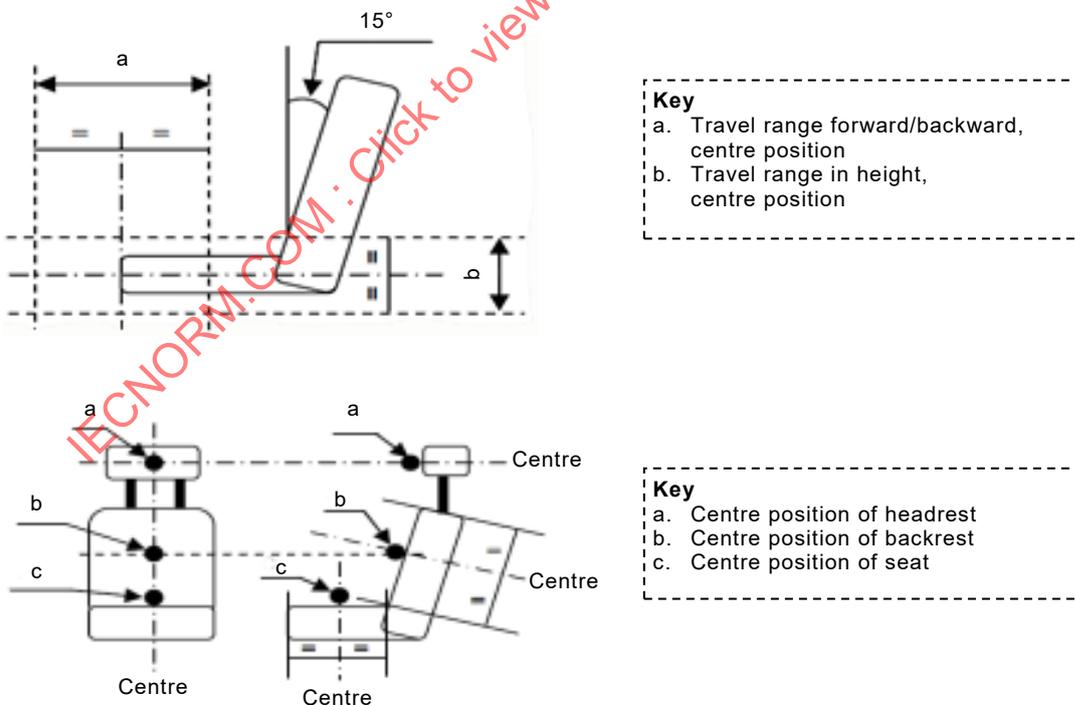
Figure D.3 – Area 4 measurement position [37]

a) Part 1 assessment of incident H-fields of Area 3

The assessment procedure is summarized in Figure D.4. The maximum magnetic field strength in the Area 3 is measured at 20 cm from the charging automobile using the WPT system and compared to the reference level. If it exceeds the reference level, it is possible

to use spatially averaged value in the area occupied by human body or the averaged magnetic field strength measured at the height of 0,5 m, 1 m and 1,5 m above the ground. If the averaged magnetic field strength exceeds the reference level, proceed to the next evaluation using coupling factor if it is applicable.

Following criteria need to be considered in order to use coupling factor.

– Induced quantities such as internal electric field caused by incident electric field is negligible compared to that by incident magnetic field.

– Evaluation condition such as frequency, field distribution, distance to human body, etc., need to be considered equivalent to the condition used in derivation of the coupling factor.

The maximum magnetic field strength is multiplied with the coupling factor and compared to the reference level of magnetic field. For example, the coupling factor of 0,15 may be used to consider the condition of human body standing in the vicinity of vehicle according to the analysis results in [13]. If it exceeds the reference level, proceed to the next evaluation against basic restrictions.

The uncertainty of the measurement needs to be evaluated. Table D.1 summarizes the possible factors of uncertainty [42-44]. c_i is the sensitivity coefficient and k is the coverage factor.

A list of possible parameters of variation caused by the exposure systems are:

– variation of incident field (i.e. gradient);

– variation of frequency;

– variation of geometry of WPT source (size of the coils, shape, alignment);

– variation of position of WPT system below the EV;

– variation of size of EV;

– variation of the H-field over shape of human body due to the size and posture.

If the induced electric field or current density is acquired by numerical dosimetry, the uncertainty in numerical dosimetry should also be evaluated. Table D.2 summarizes the possible factors of uncertainty.

Possible parameters of variation caused by anatomical human models are:

– differences in size/weight as a function of age within the exposure population;

– differences of anatomy (age, weight, sex);

– differences of posture.

b) Part 2 assessment of incident H-fields of Area 4

The assessment procedure is summarized in Figure D.5. The maximum magnetic field strength in Area 4 is measured during charging. The magnetic fields at driver's seat and the closest seat to primary coil are measured and compared to the reference level. The probe centre is positioned at 10 cm above the surface of the seat and headrest. It is possible to use spatially averaged value. In that case, the spatial averaged magnetic field strength can be calculated based on the average of three values measured at a, b and c in Figure D.3.

The uncertainty of the measurement needs to be evaluated. Table D.3 summarizes the possible factor of uncertainty. For probe uncertainty refer to items 1 to 15 in Table D.1.

A list of possible parameters of variation caused by the exposure systems are:

– variation of incident field (i.e. gradient);

– variation of frequency;

– variation of geometry of WPT source (size of the coils, shape, alignment);

– variation of position of WPT system below the EV;

– variation of size of EV;

– variation of size of seats (detection of points a, b, c);

–   human model, posture.

If the induced electric field or current density is acquired by numerical dosimetry, the uncertainty in numerical dosimetry also needs to be evaluated. Table D.2 summarizes the possible factors of uncertainty.

Possible parameters of variation caused by anatomical human models are:

–   differences in size/weight as a function of age within the exposure population;

–   differences of anatomy (age, weight, sex);

–   differences of posture.

c) Part 3 assessment of incident E-fields and contact current

The assessment procedure is summarized in Figure D.6. If H-field exceeds the value calculated by Formula (1) in 6.3, the contact current of the grounded metal is measured. For the measurement of contact current with grounded metal object, the metal object needs to be oriented in the direction where maximum contact current is acquired. The rectangular loop size of approximately 1,5 m (height) × 0,5 m (width) can be used to evaluate contact current.

After that, the contact current of ungrounded metal is measured. If the measured E-field does not exceed the reference level, the contact current of ungrounded metal can be omitted.

The electric field strength is measured at 20 cm from the vehicle using the WPT system and compared to the reference level. It is possible to use spatially averaged value in the area occupied by human body or the averaged electric field strength measured at the height of 0,5 m, 1 m and 1,5 m above the ground. If it exceeds the reference level, direct evaluation of contact current needs to be done with ungrounded metal object, which is installed at 20 cm from charging automobile. The contact current is compared to the reference level. The metal object needs to be oriented in the direction where maximum contact current is acquired. The area size of metal object is 1,2 m × 1,2 m or larger. Refer to Clause C.6 for the basic requirement of contact current.

If the electric field strength is not measured, direct evaluation of contact current needs to be done with ungrounded metal object, which is installed at 20 cm from charging automobile. The contact current is compared to the reference level of contact current. The metal object needs to be oriented in the direction where maximum contact current is acquired. The size of metal object is 1,2 m × 1,2 m or larger. Refer to Clause C.6 for the basic requirement of contact current.

The uncertainty of the measurement needs to be evaluated. Table D.4 summarizes the possible factor of uncertainty. For incident E-field measurements the same components as in Table D.1 apply. Parasitic H-field sensitivity needs to be evaluated instead of parasitic E-field sensitivity in element 10.

Part 1: Incident H assessment around the vehicle of WPT
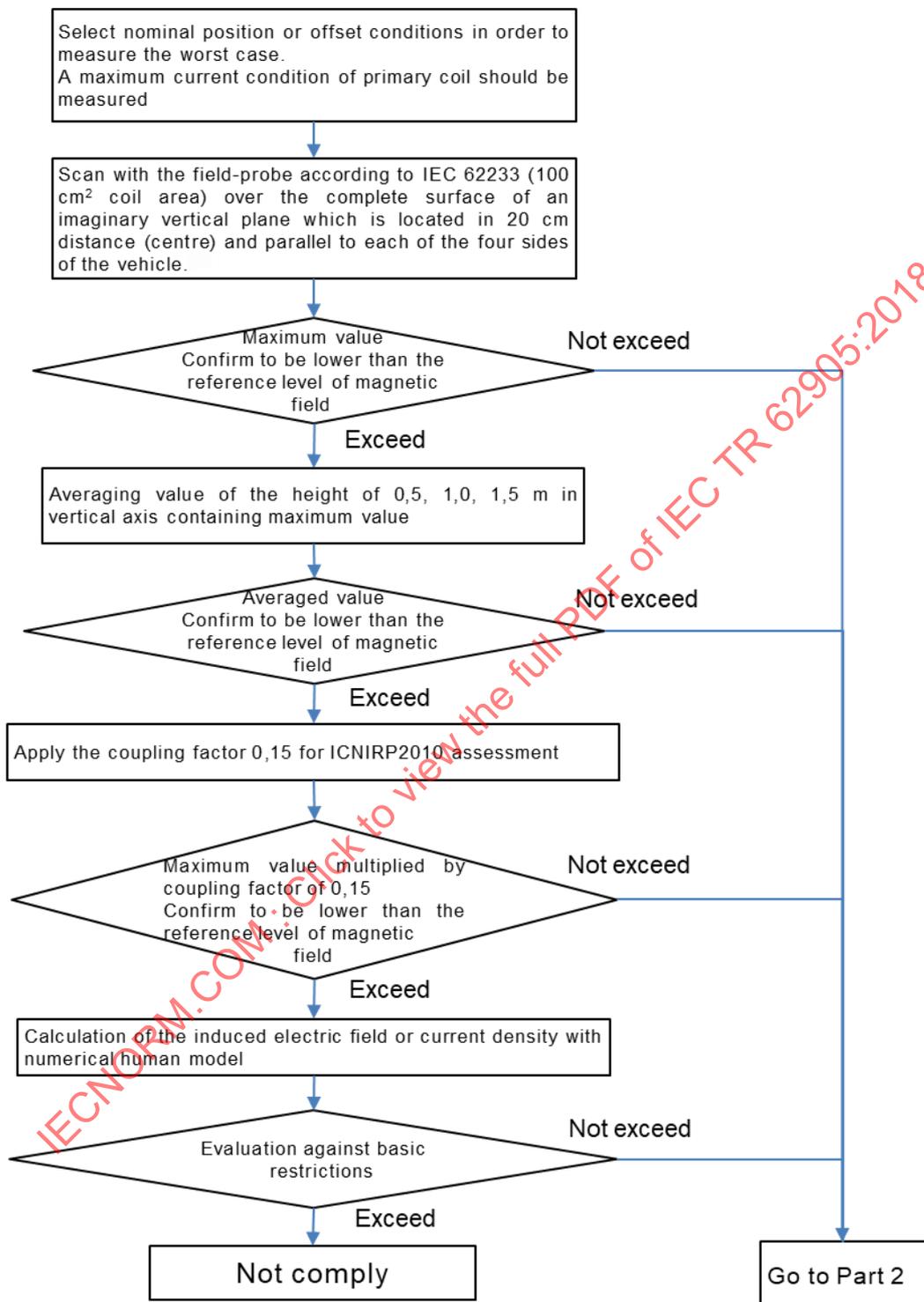
Figure D.4 – Assessment flow of Part 1

IEC

Table D.1 – Uncertainty of H-field measurements for WPT systems in Area 3

Item	Uncertainty source	Tolerance (dB)	Distribution	Divisor	c_i	Standard uncertainty (dB)
Probe uncertainty						
1	Amplitude calibration uncertainty		norm	1	1	
2	Gradient calibration uncertainty		norm	1	1	
3	Probe anisotropy		rect	√3	1	
4	Probe dynamic linearity		rect	√3	1	
5	Probe frequency domain response		rect	√3	1	
6	Modulation response		rect	√3	1	
7	Spatial averaging		rect	√3	1	
8	Gradient uncertainty		rect	√3	1	
9	Gradient detection uncertainty		rect	√3	1	
10	Parasitic E-field sensitivity		rect	√3	1	
11	Detection limit		rect	√3	1	
12	Readout electronics		norm	1	1	
13	Response time		norm	1	1	
14	Probe positioning		norm	1	1	
15	Shaping, filtering, signal conditioning		norm	1	1	
Procedure and model uncertainty (Area 3)						
16	Nominal position		rect	√3	1	
17	Repeatability		norm	1	1	
18	Compliance transfer model		rect	√3	1	
	Combined uncertainty ($k = 1$)					
	Expanded uncertainty ($k = 2$)	RSS				

NOTES

1 Uncertainty of the probe calibration system with respect to field amplitude.

2 Uncertainty of the probe calibration with respect to field gradient.

3 Probe anisotropy can be tested in incident field condition representative for WPT systems, covering normalized gradients from 0 to > 200 T/m/T.

4 Probe dynamic range needs to be evaluated covering the dynamic range from 1 % of the general public exposure limits to > 2× the exposure limit within the probes specified operating range.

5 Probe frequency domain response is evaluated for a homogenous incident field over specified operational frequency range.

6) Probe modulation response may be necessary in this case of modulated signal and can be evaluated for modulated carriers in the specified frequency range with rectangular pulse modulation.

7 Spatial averaging can be tested in incident field condition representative for WPT systems.

8 Gradient uncertainty needs be tested in incident field condition representative for WPT systems, covering normalized gradients from 0 to ≥ 200 T/m/T with the probe oriented through all spherical gradient directions.

9 Uncertainty in the accuracy of field gradient measurements.

10 Parasitic E-field sensitivity is tested with the probe in maximum hold swept through all possible spherical E-field incidences with the E-field at the occupational exposure limit.

11 Detection limit is the contribution of the readout electronic noise at 1 % of the general public exposure limits.

12 Readout electronics is the uncertainty contribution by analog to digital conversion.

13 If the probe is operated in swept mode, response time is the sampling response error for the probe swept through a gradient field of ≥ 200 T/m/T.

14 If the probe is operated in spatial sampling mode, probe positioning is the error in a gradient field of ≥ 200 T/m/T.

15 Shaping, filtering, signal conditioning is the uncertainty contribution by analog or digital signal conditioning.

16 Nominal position: positioning uncertainty with respect to which assess the worst-case exposure, i.e. the uncertainty assessing the exposure further away (20 cm) than the worst-case position.

17 Repeatability is relative to the measurements performed at 20 cm distance from EV and at height of 0,5 m, 1 m and 1,5 m above the ground, separately. It is estimated by performing 10 repeated measurements.

18 Compliance transfer model is the uncertainty of the compliance test model applied. In this case, it refers to the averaging over 100 cm^2 probe at 20 cm distance from EV and the coupling factor method used compared to the worst-case (90th percentile) exposure induced in the entire body (including legs and body parts forming loops) in a statistically representative set of human body models and postures.

Table D.2 – Numerical uncertainty of the exposure of anatomical human models to WPT systems for EV

Item	Uncertainty source	Tolerance (dB)	Distribution	Divisor	c_i	Standard uncertainty (dB)
1	Grid resolution		rect	$\sqrt{3}$	1	
2	Tissue parameters		rect	$\sqrt{3}$	1	
3	Averaging method		rect	$\sqrt{3}$	1	
4	Model and exposure location		rect	$\sqrt{3}$	1	
5	Source representation		norm	1	1	
6	Convergence		rect	$\sqrt{3}$	1	
7	Boundary conditions		rect	$\sqrt{3}$	1	
8	Post-processing, interpolation		rect	$\sqrt{3}$	1	
	Combined uncertainty ($k = 1$)					
	Expanded uncertainty ($k = 2$)	RSS				

NOTES

1 Grid resolution uncertainty is tested by increasing and decreasing the grid resolution by a factor of 2 from its nominal state.

2 Tissue parameter uncertainty is tested by varying the nominal tissue dielectric parameter.

3 The averaging method depends on the analysed metric (i.e. induced E-field, current density or SAR) and is tested analytically and numerically as a function of tissue composition and grid resolution (1).

4 Placement uncertainty of the source with respect to the human model.

5 Validation uncertainty of the source. If the source is validated in absence of the human body the loading effect of the body needs to be considered.

6 Convergence of the numerical simulation, e.g. test by time-variant stability criteria or law of energy conservation.

7 Boundary condition uncertainty can be tested by modification of the boundary condition representation.

8 Numerical uncertainties in the post-processing, e.g. interpolation and extrapolation.

Table D.3 – Uncertainty of EMF measurements for WPT systems in Area 4

Item	Uncertainty source	Tolerance (dB)	Distribution	Divisor	c_i	Standard uncertainty (dB)
Procedure and model uncertainty (Area 4)						
1	Nominal seat		rect	√3	1	
2	Repeatability		norm	1	1	
3	Compliance transfer model		rect	√3	1	
	Combined uncertainty (k = 1)					
	Expanded uncertainty (k = 2)	RSS				

NOTES

1 Selection of the seat (driver's seat and the closest seat to primary coil): evaluation of the H-field on each seat in the EV.

2 Repeatability is relative to the measurements performed at 10 cm distance over surface of the seat and head rest with 100 cm^2 probe and at points a, b and c (Figure D.3), separately. It is estimated by performing 10 measurements.

3 Compliance transfer model is the uncertainty of the compliance test model applied. In this case, it refers to the averaging over 100 cm^2 probe at 10 cm distance from surface of the seat and head rest, to the maximum found across points a, b, c (Figure D.3), compared to the worst-case (90th percentile) exposure induced in the entire body (including legs and body parts forming loops) in a statistically representative set of human body models and postures.

Part 2: Incident H assessment inside the vehicle of WPT

Select a driver's seat and worst seat in order to measure the worst case.
A closest seat to primary coil among the all passengers seat should be selected.

↓

Scan with the field-probe according to IEC 62233 (100 cm^2 coil area) over the surface of seats and it's head rest.

↓

Maximum value
Confirm to be lower than the reference level of magnetic field   — **Not exceed** →

| **Exceed**

Measure a, b and c points indicated in Figure D.3. The centre of the measurement probe is 10 cm above the surface of the seating and headrest.

↓

Maximum or average value of a, b and c
Confirm to be lower than reference level of magnetic field   — **Not exceed** →

| **Exceed**

Calculation of the induced electric field or current density with numerical human model

↓

Evaluation against basic restrictions   — **Not exceed** →

| **Exceed**

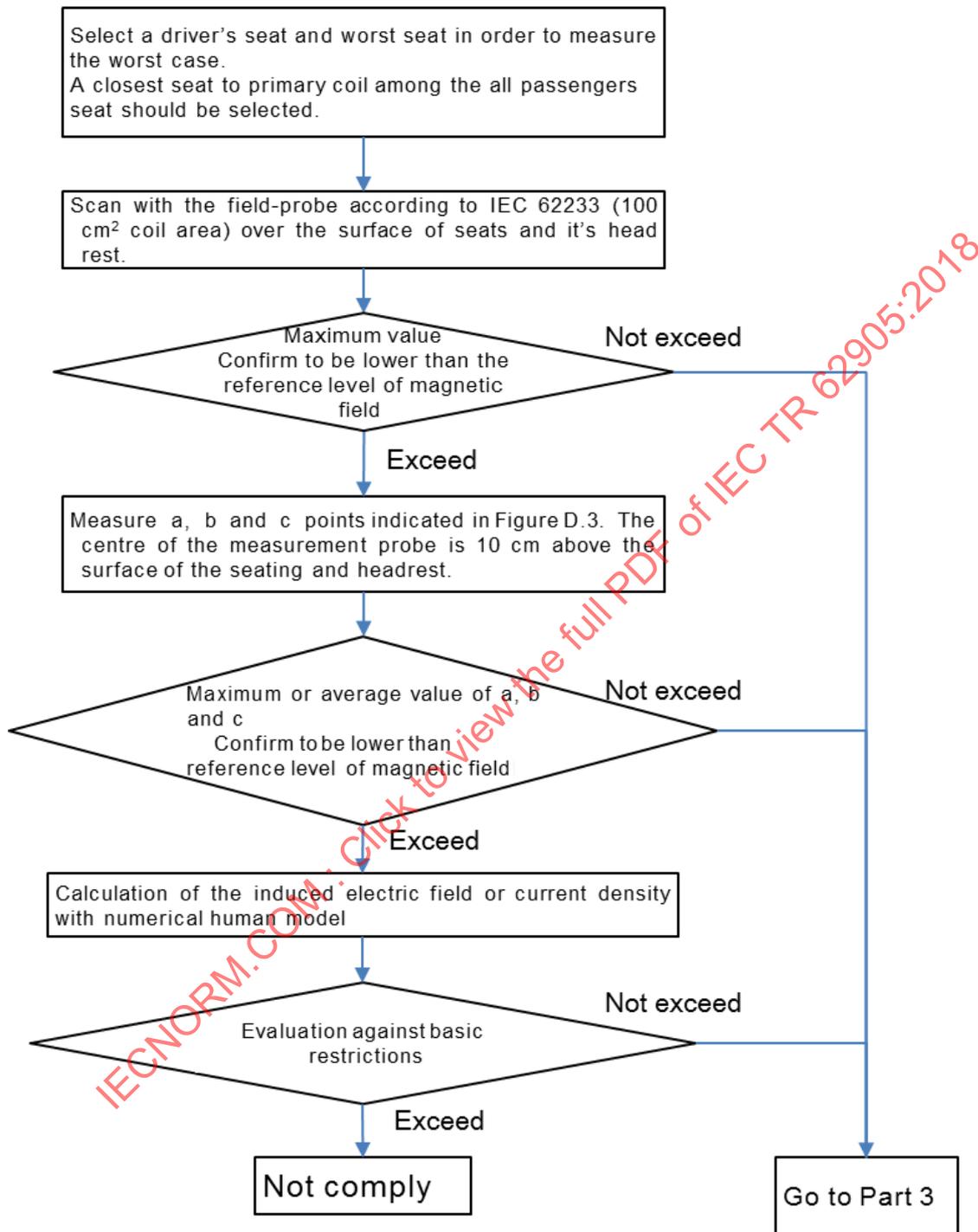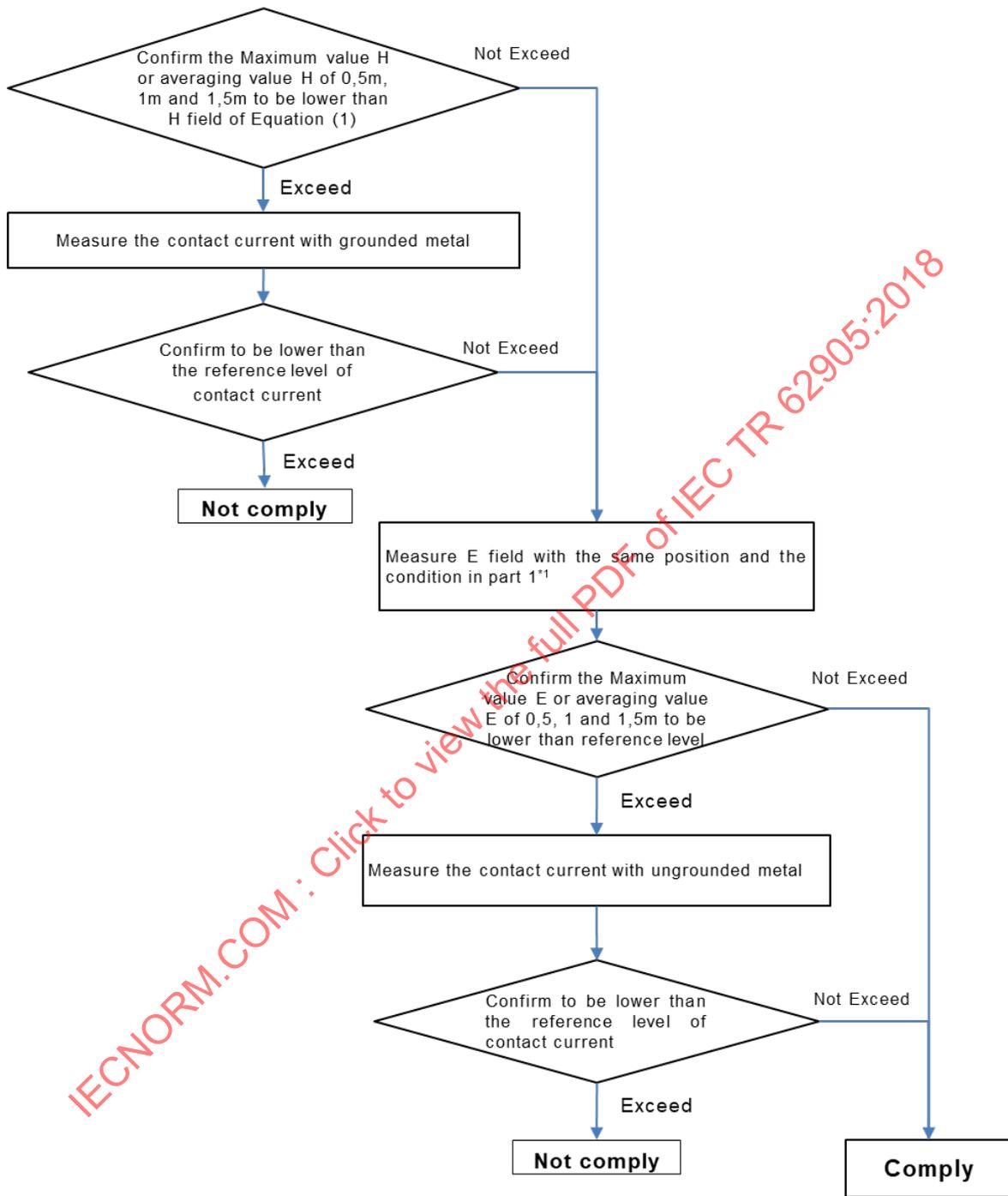**Not comply**   **Go to Part 3**

IEC

Figure D.5 – Assessment flow of Part 2

Part 3: Incident E and contact current assessment around the vehicle of WPT

Note *1 E measurement can be omitted if the measurement of contact current of ungrounded metal was complied

IEC

Figure D.6 – Assessment flow of Part 3

Table D.4 – Uncertainty of contact current measurements

Item	Uncertainty source	Tolerance (dB)	Distribution	Divisor	c_i	Standard uncertainty (dB)
Contact Current Meter uncertainty						
1	Calibration uncertainty		norm	1	1	
2	Meter dynamic linearity		rect	√3	1	
3	Meter frequency domain response		rect	√3	1	
4	Spatial averaging		rect	√3	1	
5	Detection limit		rect	√3	1	
6	Readout electronics		norm	1	1	
7	Shaping, filtering, signal conditioning		norm	1	1	
8	Temperature		rect	√3	1	
9	Equivalent circuit		rect	√3	1	
10	Anisotropy error		rect	√3	1	
Measurement uncertainty (contact current)						
11	E- and H-field measurement (refer to Table I)		rect	√3	1	
12	Repeatability		norm	1	1	
13	Metal object positioning and orientation		rect	√3	1	
	Combined uncertainty ($k = 1$)					
	Expanded uncertainty ($k = 2$)	RSS				

NOTES

1 Uncertainty of the meter calibration system.

2 Meter dynamic range needs to be evaluated covering the dynamic range within the meter specified operating range.

3 Meter frequency domain response is evaluated over specified operational frequency range.

4 Spatial averaging can be tested at the location of contact between the contact terminal of the meter and the target point.

5 Detection limit is the contribution of the readout electronic noise at 1 % of the general public exposure limits.

6 Readout electronics is the uncertainty contribution by analog to digital conversion.

7 Shaping, filtering, signal conditioning is the uncertainty contribution by analog or digital signal conditioning.

8 Deviation of measurements needs to be provided in the operating temperature range of the meter.

9 Evaluation of different impedance values to assign to the equivalent circuit considering wide range of population (child and adult).

10 Evaluation of the anisotropy of the contact current over the entire frequency range.

11 Comparison with reference levels of H-field and E-field needs be performed before conducting contact current measurements.

12 Repeatability is relative to the measurements performed in the region of contact. It is estimated by performing 10 measurements.

13 For ungrounded and grounded metal object: the position and orientation of the metal object needs to be evaluated at 20 cm distance from EV with respect to different sides of EV and heights from the ground.

D.2   Experimental assessment results for EV

D.2.1   General

Clause D.2 describes experimental assessment results of a WPT system for EV at 85 kHz. This case study refers to IEC 61980-1:2015 [37], Annex C, "EMF, protection from electromagnetic field" that defines the measurement area and points. This assessment was done for ICNIRP2010 [5] according to the proposed procedure in Clause D.1. Table D.5 shows the guideline at 85 kHz based on ICNIRP2010. E-field measurement and H-field measurement were done by electromagnetic field probe. Table D.6 shows the specification of the DUT.

Table D.5 – ICNIRP2010 guideline at 85 kHz

Basic restriction	CNS tissues of the head	11,45 V/m
	All tissues of head and body	11,45 V/m
Reference level	Electric fields	83 V/m
	Magnetic fields	21 A/m
Contact current	Contact current	17 mA

Table D.6 – Specification of DUT

WPT specification	
Operation frequency	85 kHz
Power	5 kW @ 200 V
Coil type	Circular

D.2.2   Electromagnetic field measurement results

Subclause D.2.2 shows electromagnetic field emitted from a WPT system which was installed in a passenger vehicle. Table D.7 shows the result of incident H-fields and E-fields of Area 3. Measurement location was selected according to Figure D.2. The aligned and misaligned (100 mm) conditions of WPT coils were measured. The height from 7,5 cm to 150 cm at the 20 cm distance to vehicle side metal body was scanned. Example of measurement layout at Area 3 is shown in Figure D.7. All data could meet the reference level. Magnetic field strengths of Area 3 were lower than 7 % of guideline level. Electrical field strengths were lower than 2 % of guideline levels.

The product of the maximum magnetic field and the coupling factor 0,15 is calculated to be 0,73 V/m, which is lower than 4 % of guideline levels.

Table D.7 – Measured incident H-fields and E-fields of Area 3

Condition	Magnetic field strength [A/m] (Guideline 21 A/m)		Electric field strength [V/m] (Guideline 83 V/m)	
	Aligned 5 kW 200 V	Misaligned 5 kW 200 V	Aligned 5 kW 200 V	Misaligned 5 kW 200 V
Maximum (7,5 cm)	3,07	4,87	2,37	3,64
50 cm	0,66	1,33	0,71	0,78
100 cm	0,25	0,65	0,31	0,23
150 cm	0,11	0,30	0,15	0,21
Average of 3 points	0,34	0,76	0,39	0,41

IEC

Figure D.7 – Example measurement layout for Area 3 surrounding area of vehicle

The electromagnetic fields in Area 4 were also measured (Figure D.8). Table D.8 shows the results of incident H-field and E-field of Area 4. According to EV body shielding effect, there is lower exposure compared to the Area 3. They were lower than 1 % of guideline levels. The electromagnetic fields in Area 4 were equivalent to background noise level of measurement probe.

Table D.8 – Measured incident H-fields and E-fields of Area 4

Measurement position according to Figure D.3	Magnetic field strength [A/m] (Guideline 21 A/m)		Electric field strength [V/m] (Guideline 83 V/m)	
	Aligned 5 kW 200 V	Misaligned 5 kW 200 V	Aligned 5 kW 200 V	Misaligned 5 kW 200 V
a　centre position of head rest	0,03	0,05	0,07	0,10
b　centre position of backrest	0,03	0,05	0,07	0,09
c　centre position of seat	0,03	0,10	0,07	0,10
Average of 3 points	0,03	0,07	0,07	0,10

IEC

Figure D.8 – Example measurement layout for Area 4 car interior

D.2.3 Contact current measurement

Subclause D.2.3 shows the results of the contact current for a same WPT installation and operating condition as in D.2.2. Three types of contact current meter were used (Figure D.9). These meters have equivalent circuit of impedance simulating human body. The equivalent impedance in the Meter A is based on adult male impedance [35]. The others consist of the IEC 60990 impedance circuit [36].

We measured the contact currents with ungrounded metal and grounded metal (Figure D.10). Measured contact currents were summarized in Table D.9. The contact currents were small compared to the reference levels of contact current. They were lower than 5 % value of contact current guideline level.
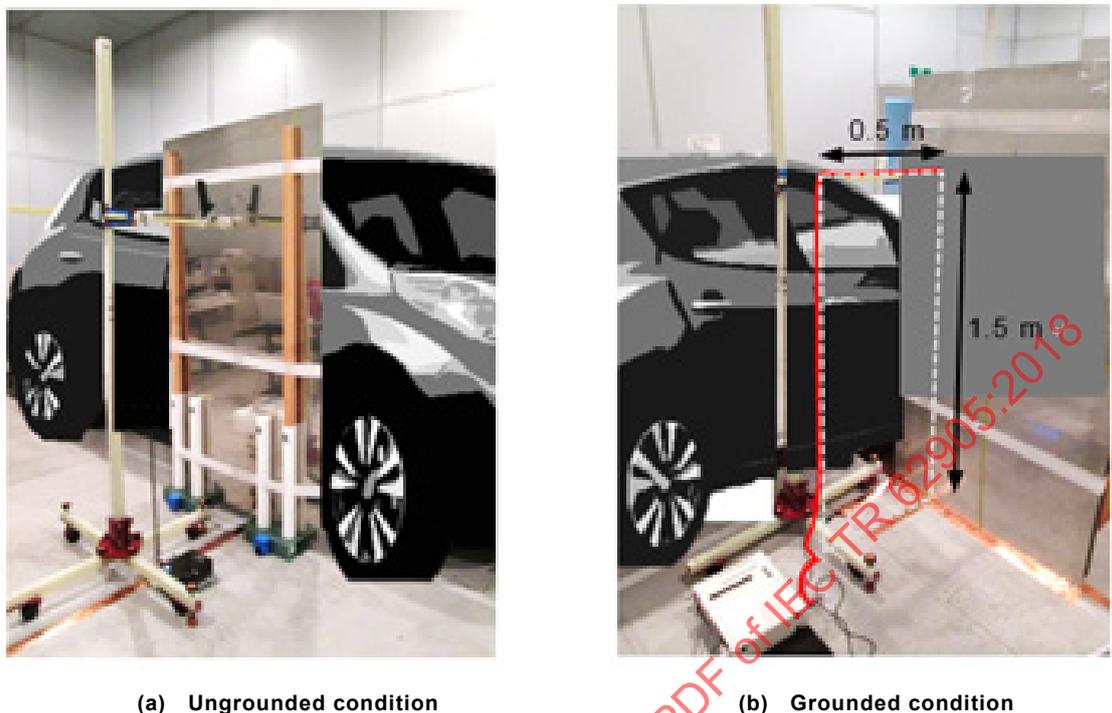

Meter A   Meter B   Meter C

IEC

Figure D.9 – Contact current meters used in the measurement

(a) **Ungrounded condition**   (b) **Grounded condition**

Figure D.10 – Measurement of contact current

Table D.9 – Measurement results of contact current [mA]

Condition		Aligned			Misaligned		
		Meter A	Meter B	Meter C	Meter A	Meter B	Meter C
Ungrounded				0,018		0,07	0,21
Grounded	20 cm distance	0,06	0,35	0,13	0,8	0,65	0,59
	40 cm distance	0,04	0,35	0,13	0,35	0,4	0,44
NOTE Reference level of contact current at 85 kHz is 17 mA.							

D.3   WPT system for mobile devices

D.3.1   General

Clause D.3 describes the applicable guideline of WPT system for mobile in the frequency range between 100 kHz and 10 MHz. Therefore, assessment for value of guideline based on both of stimulus and thermal effects needs to be conducted.

The assessment procedure shown here considers both ICNIRP1998 [4] and ICNIRP2010 [5].

The compliance to the guideline for both the electric field and the magnetic field needs to be confirmed as the system is under near-field exposure condition where wave impedance is not 120π (= 377 Ω). The WPT system is used in order to charge mobile devices indoor mainly. Depending on the case, users of mobile devices like a laptop PC may use it to charge.

In the case of mobile devices, a human body may come close to the WPT system (for example 20 cm or less from it). It is possible to measure electromagnetic field strength of the area close to 20 cm or less from the WPT system using an electromagnetic probe that is

commercially available [45]. According to the ICNIRP guidelines, spatial average value of electric field and magnetic field occupied by human body may be used when the distance from the sources to human body exceeds 20 cm [4].

For exposure scenarios, the WPT system transmits power from a transmitting coil installed in a table or a desk area to a receiving coil installed in a mobile device. This case study applied the following scenario as a public exposure case. A human body stands or sits in the vicinity of the charging device.

There are possibilities of existence of metal objects such as adjacent fixtures in the room where the charging place is. In such situations, reference level of contact current is applied in order to consider indirect effects. Compliance against the contact currents can be assessed either by incident electromagnetic fields or by direct measurement of contact currents.

For the contact current caused by the electric field, the reference level of electric field for general public exposure prevents the effect of contact current for more than 90 % of exposed individuals [5]. The direct assessment of contact current with ungrounded metal can be omitted if the incident electric field does not exceed the reference level.

For the contact current caused by the magnetic field, the magnetic field not to exceed reference level of contact current can be calculated by Faraday's law assuming the human impedance and size of the current loop with Formula (1). The direct assessment of contact current with grounded metal can be omitted if the incident magnetic field does not exceed the calculated magnetic field.

D.3.2   Assessment procedures for WPT system for mobile

The guidelines for stimulus effect and thermal effect need to be considered to the WPT system for mobile at a frequency range between 100 kHz and 10 MHz.

In order to confirm compliance of WPT systems for mobile devices, two-part evaluations are introduced.

1) Part 1: Assessment of incident electromagnetic fields around the mobile device of WPT which is measured within 20 cm

The maximum electric and magnetic field strengths are measured around the charging mobile device using the WPT system and compared to the reference level of ICNIRP1998 [4]and ICNIRP2010 [5]. Refer to Annex C for the basic requirement of the electromagnetic field measurement. It is possible to use spatially averaged value in the area occupied by human body when the distance between source and human body exceeds 20 cm [4]. If the maximum value and/or the averaged value exceed the reference level, proceed to the next evaluation using coupling factor if it is applicable.

Following criteria are needed to be considered in order to use coupling factor.

–   Induced quantities such as internal electric field or SAR caused by incident electric field is negligible compared to that by incident magnetic field.

–   The whole-body average SAR is marginal compared to respective limits and contribution of the local average SAR or the internal electric field is dominant.

–   Evaluation condition such as frequency, field distribution, distance to human body, etc., need to be considered equivalent to the condition used in derivation of the coupling factor.

The maximum magnetic field strength is multiplied with the coupling factor and compared to the reference level of magnetic field. For example, the coupling factor of 0,15 and 0,05 for reference levels considering stimulus and thermal effects, can be used to consider the condition of human body standing or sitting in the vicinity of the WPT systems installed in table or desk according to the analysis results in [13]. If the coupling factor is not applicable or assessment using the coupling factor exceeds the reference level, proceed to the next evaluation using basic restrictions.

2) Part 2: Assessment of contact current around the mobile device for WPT

If in the Part 1 measurements, H-field exceeded the value calculated by Formula (1), the contact current of the grounded metal needs to be measured. For the measurement of contact current with grounded metal object, the metal object needs to be oriented in the direction where maximum contact current is acquired. The loop size of approximately 1,5 m (height) × 0,5 m (width) can be used to evaluate contact current.

After that, the contact current of ungrounded metal is measured. If the measured E-field did not exceed the reference level, the contact current of un-grounded metal can be omitted. The evaluation of contact current needs to be done with ungrounded metal object, which is installed at nearest position from the WPT system. The contact current is compared to the reference level of contact current. The metal object needs to be oriented in the direction where maximum contact current is acquired. The size, height and contact point of metal object is 1,2 m × 1,2 m or larger. Refer to Annex C for the basic requirement of contact current.

Annex E
(informative)

Numerical and experimental studies

E.1   Exposure evaluation of WPT for EV

E.1.1   Research in Japan

Subclause E.1.1 presents numerical simulated results of induced electric field for leaked magnetic field from wireless power transfer systems in electric vehicles.

Figure E.1 illustrates an electric vehicle model considered here. The dimension of the vehicle is 4 500 mm in length × 1 700 mm in width. Ground and vehicle body are assumed to be comprised of perfect conductor while conductivity of the bumper attached to the vehicle rear is set to 0 because its conductivity is small enough to approximate the air. Three coil positions were considered; located in the front, the centre, and the rear of the vehicle as shown in Figure E.1. The distances between transmitting and receiving coil are 200 mm when placed in the front and centre, and 300 mm when placed in the rear of the vehicle. The 'centre' defined here is placed as the centre of the vehicle while the front and rear are located at 1500 mm each from the centre. The identical solenoid coils are used for receiving (vehicle) and transmitting (ground) sides. The number of coil turns is 10, and the dimension of the coil core (relative permeability, μ_r is 1 800) is width 400 mm × length 400 mm × thickness 10 mm. The frequency is 85 kHz with a transfer power of 7 kW.
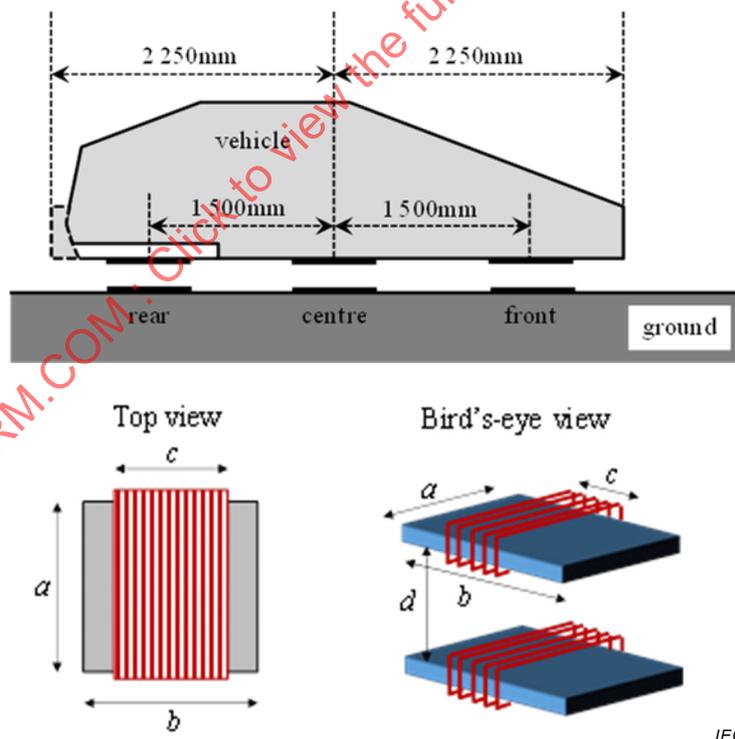

Figure E.1 – Geometry of vehicle model

When parking the vehicle, it is unlikely to align transmitting and receiving coils exactly. In addition, the magnetic field leakage from the vehicle with misaligned coils has been reported to become larger than that with aligned coils [46]. Thus, the misalignment of the coils that generates maximum magnetic field leakage is considered for a typical and worst-case scenario while the power transfer is still feasible. The primary transmitting coil is assumed to

be misaligned 20 cm in the lateral direction and 10 cm in the longitudinal direction from the secondary receiving coil.

The simulated and measured values of incident electric field are compared for confirmation. The measured value is taken from [46], in which similar vehicle model was considered and thus different from Figure E.1.
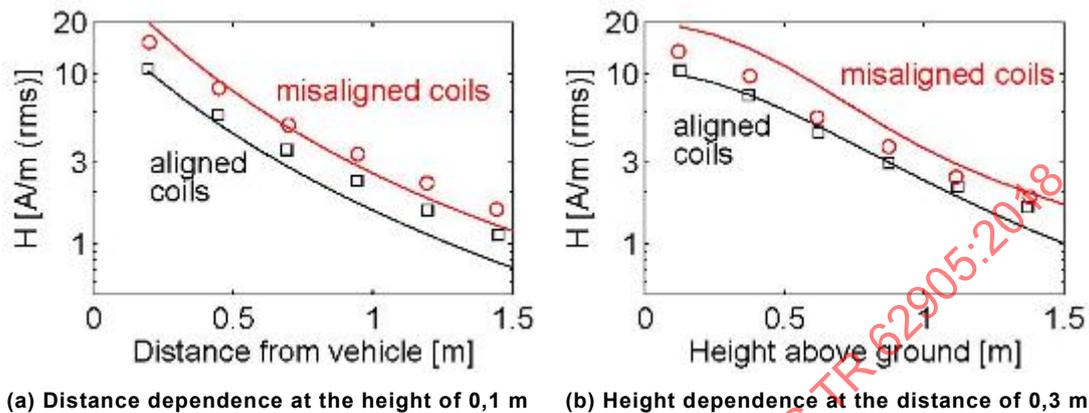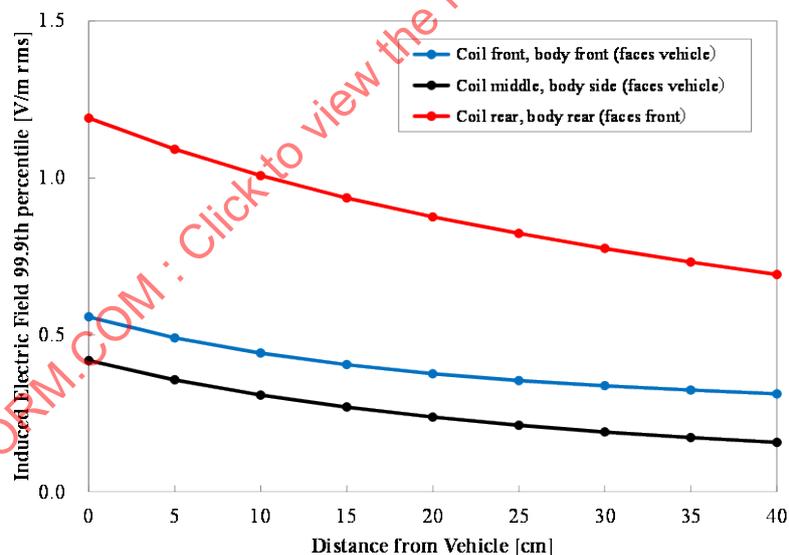

(a) Distance dependence at the height of 0,1 m   (b) Height dependence at the distance of 0,3 m

The human stands in the vicinity of the vehicle. The transmitting power is 3 kW.

Solid lines show computed results and dots show measured results.

Figure E.2 – Measured and simulated magnetic field strength leaked from wireless power system in an electric vehicle [46]


Figure E.3 – Distance dependence of peak induced electric field strength in human body model

The magnetic field distribution of the rear part of the vehicle is computed. Figure E.2 shows the comparison result, suggesting that computed and measured values are in good agreement with each other.

Figure E.3 shows the distance dependence of the maximum induced electric field strength in the human body when the WPT system is placed in the front, the centre and the rear of the vehicle. The distance is defined from tip of the human body (toe) to the vehicle. From the figure, the electric field strength induced in the human body is confirmed to be lowest when the transfer system is placed in the centre of the vehicle. This is because the human body and

coil distance in the centre is longer than that of the front and the rear, and thus the magnetic field strength to be exposed is smaller than the others. The induced electric field in the human body becomes larger when the coil is located in the rear of the vehicle. For all the conditions, the induced field strengths are smaller than the basic restrictions of 11,5 V/m at the frequency of 85 kHz.

Figure E.4 shows the induced electric field strength in the human body when the model comes closest to the human position at rear of the vehicle; a body part makes a contact with the vehicle body, and the toe is placed under the vehicle [38,47]. Three human body models were considered: TARO is as a male Japanese adult, NORMAN is as a male European adult, and Thelonious is as a child model. From Figure E.4, the induced electric field is below the basic restrictions in all the cases considered, and the child model has smaller induced electric field than that of adult models.
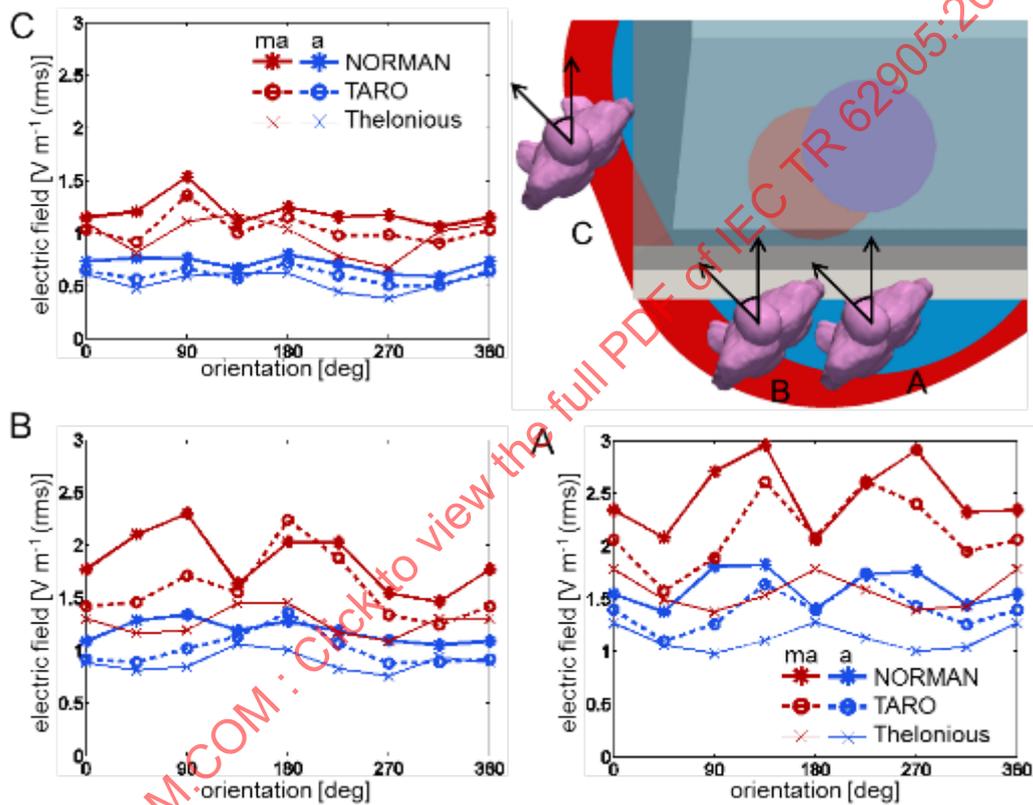
Red lines show the results for misaligned condition ("ma") and blue lines show the results for aligned condition ("a")

Figure E.4 – Analysis of induced electric field strength in the human body for different human positions relative to the vehicle [41]

(a) Averaged over the volume where human body occupies

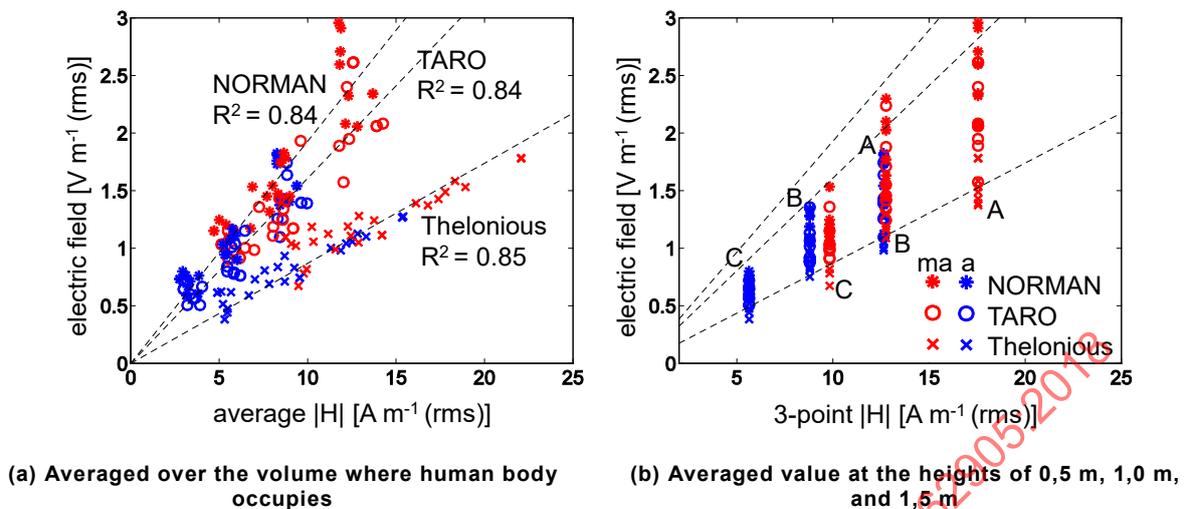(b) Averaged value at the heights of 0,5 m, 1,0 m, and 1,5 m

Figure E.5 – Relationship between the maximum induced electric field in the human body and the magnetic field strength [41]

A magnetic field strength, which is determined by averaging over the space where a human body occupies, is used as a metric. Figure E.5 shows the relationship of averaged magnetic field strength and induced electric field in the human body shown in Figure E.4. From Figure E.5 (a), good correlation is observed between induced electric field in the human body and spatially averaged magnetic field. The slopes of the regression lines differ for different models. That would be caused by the difference of magnetic flux passing through each model that has different cross-sectional area.

It is difficult and time consuming to measure a magnetic field strength averaged over the whole body in actual conformity assessments. Figure E.5 (b) shows the correlation in terms of three-point average value at height of 0,5 m, 1 m and 1,5 m from the ground as IEC defined [39]. Almost the same correlation with the whole-body average value can be obtained even for three points. Increment of measured point to six points (25 cm each) did not improve the correlation, though all the results are not shown here.
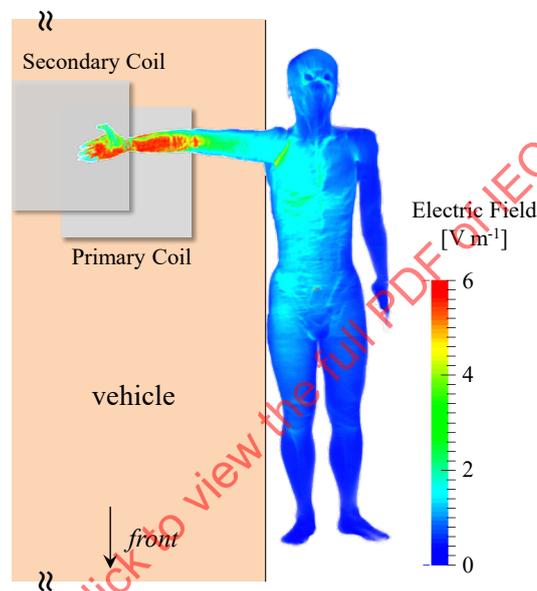
Table E.1 lists the estimated allowable input power based on the guidelines. From Table E.1, the conformity assessment based on three-point average magnetic field strength is 6 to 19 times more conservative than that of based on induction electric field in the human body 0 cm from vehicle, which is considered as the worst-case exposure. The same trend in the analysis of a simple body model is also confirmed.

The above discussion was concentrated for the solenoid coil (see Figure E.1). A similar computation has been conducted for the circular planar coil. The induced electric field in the human body model for the circular coil was smaller than that of the solenoid coil because the incident magnetic field strength is larger for the solenoid coil. In the same study, the induced electric fields in the foetus and mother were also simulated [48]. Specifically, the induced electric field strength is smaller in the foetus than in the mother, because the magnetic field is weaker than the field around the feet, even though the abdomen of the pregnant woman may come closer to the vehicle than that of a non-pregnant adult female.

The induced electric field was evaluated for the human models (i) crouching near the vehicle, (ii) lying on the ground with or without arm stretched, and (iii) sitting on the driver's seat [39]. In each scenario, the induced electric fields are smaller than the basic restriction prescribed in international guidelines, although the magnetic field strength in the human body is locally much higher than the allowable incident magnetic field strength. The highest in-situ electric field was observed when the human lies on the ground with arm extended toward the coils because of higher magnetic field strength around the arm (see Figure E.6).

Table E.1 – Estimated permissible power for WPT system for EV

| Human body position based on a vehicle body	Maximum permissible power based on three-point average magnetic field strength	Maximum permissible power based on induction current in the human body 10 cm from vehicle	Maximum permissible power based on induction current in the human body 0 cm from vehicle	The ratio of three-point average magnetic field strength to induction current in the human body
Front	210 kW	5,4 MW	4,0 MW	19 times
Side	530 kW	4,6 MW	3,3 MW	6,2 times
Rear	57 kW	673 kW	486 kW	8,5 times

Figure E.6 – The induced electric field distributions in a human body model lying on the ground with his right arm stretched [48]

E.1.2   Research in Korea

In this study, the evaluation method of magnetic fields generated by on-line electric vehicle (OLEV) using the wireless power transfer technology is considered in area accessible to the public. The electric power lines in roadbeds (first coil) and five pickup coil segments under the OLEV (second coil) is considered as a field source, in which resonance frequency is 20 kHz and output power is 75 kW.

Figure E.7 shows the EMF human exposure condition from the power lines and pickup coils of OLEV system.

(a) Outdoor Exposure condition of OLEV

(b) Indoor Exposure condition of OLEV
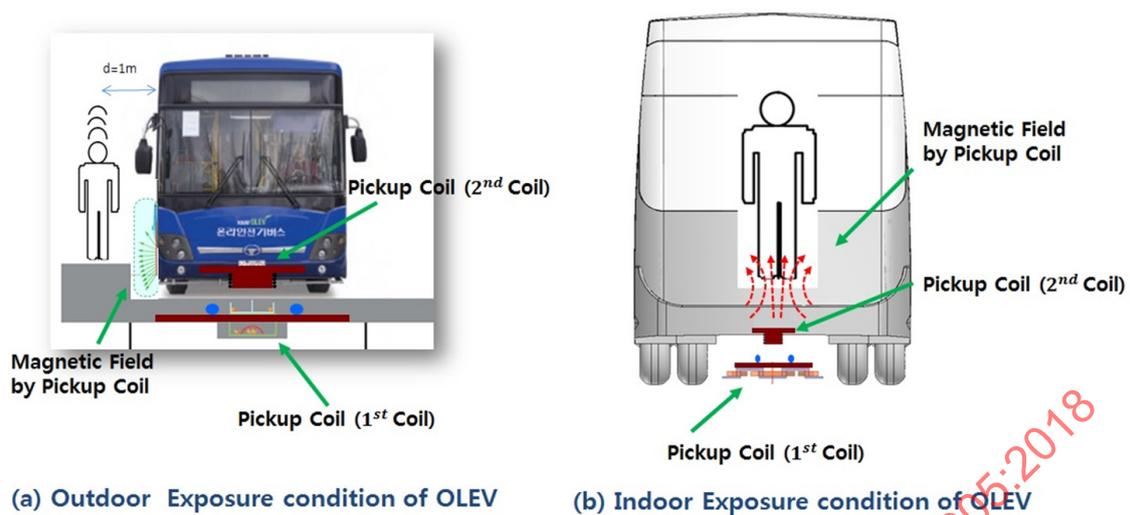
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**Figure E.7 – EMF human exposure condition from the power line
and pickup coils of OLEV system**

Where the field at exposure condition of OLEV shown in Figure E.8 is considered to be non-uniform that is similar to AC power system (IEC 62110 [40]), the field level at the position of interest is calculated and measured at the three heights 0,5 m, 1,0 m, and 1,5 m above the ground.

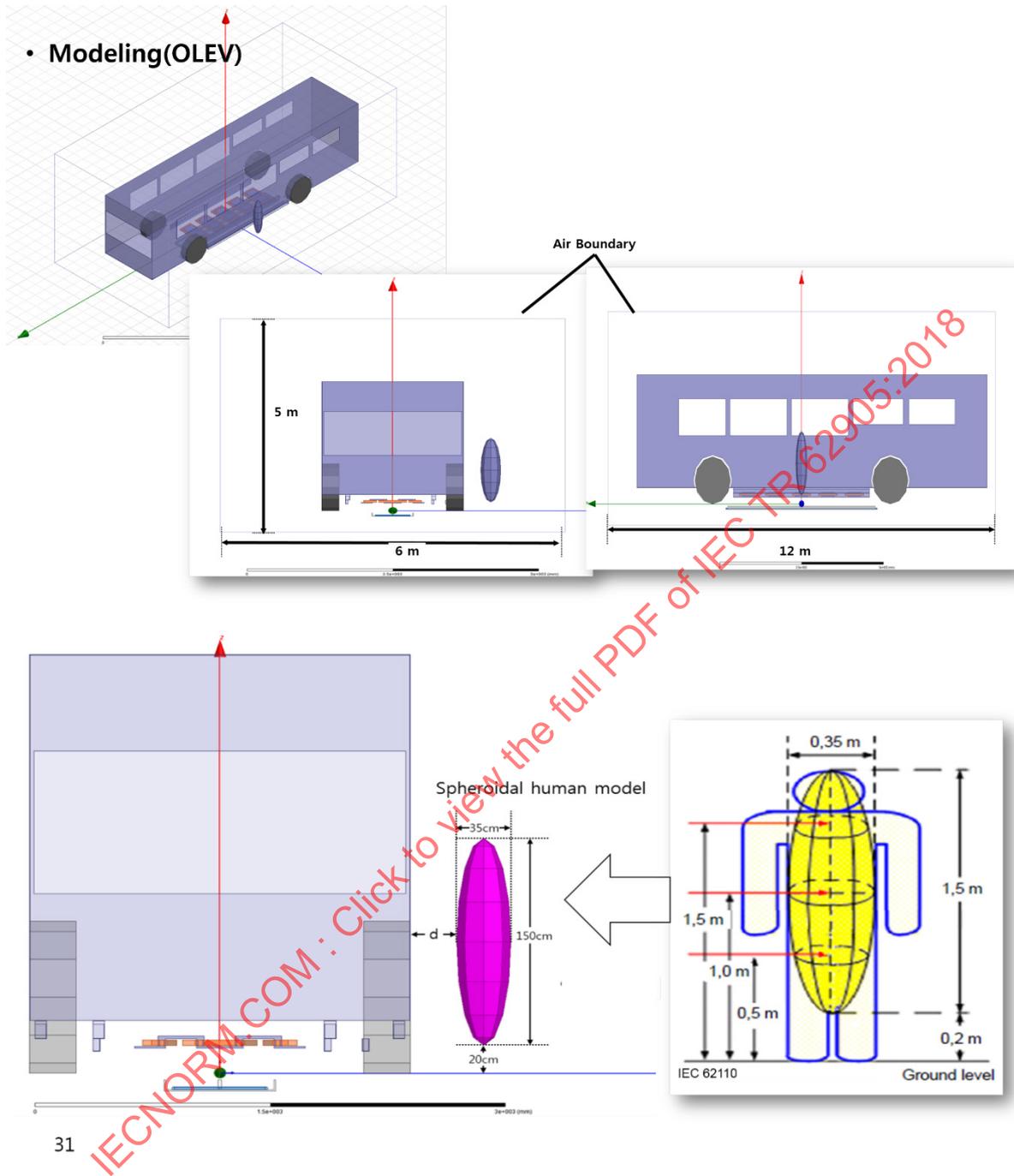*IEC*

Figure E.8 – The model in the field generated by OLEV

The deviation is 4 % at distance of 5 cm from OLEV, and −2 % at distance of 100 cm accessible to the public. Figure E.9 shows that the vertical distribution of magnetic fields is uniform. We can know that the three-point average exposure level almost corresponds to the average exposure level for the exposure condition of the OLEV.
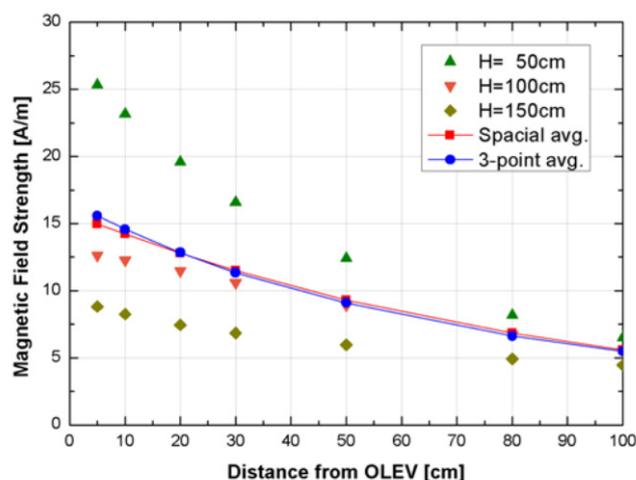
Figure E.9 – The calculated magnetic field distributions at each distance from OLEV

From the numerical analysis, the three-point (at the three heights 0,5 m, 1,0 m, and 1,5 m above the ground) average exposure level represents the average exposure level over the entire human body.

There is another study which provides experimental results on the magnetic field changes around the wireless charging system depending on the state of charge of the electric vehicle.

The wireless charging system designed for this study operates at 85 kHz, and the sizes of the transmitting and receiving pads are 745 mm × 635 mm and 485 mm × 485 mm, respectively. In order to describe the state of charge of the battery of the electric vehicle, electrical load was used. The magnetic field was measured by magnetic field probe as field strength mode for two cases, the 330 V output (describing low battery, case 1) and the 390 V output (describing full battery, case 2).

Figure E.10 shows a photograph of magnetic field measurement around the transmitting and receiving pads of the wireless charging system, and Figure E.11 shows one of the results of the measured magnetic field values for each case. As shown in the figures, the measurement probe is closely located at the transmitting pad and magnetic fields are measured at 20 mm intervals in the horizontal direction.

The experimental conditions were carried out under the assumption that the received power was always supplied at 3,3 kW. The measured magnetic field was larger when the battery was full (case 2) than when the battery was low (case 1), as shown in Figure E.11. The currents flowing in the transmitting and receiving coils were 27 A and 12,3 A in case 1, and 32 A and 10,6 A in case 2, respectively. The magnetic field generated around the wireless charging system is determined by the current flowing in the transmitting coil and the receiving coil. In this experiment, it was found that the current flowing in the transmitting coil is larger than the current flowing in the receiving coil, so that the magnetic field around the wireless charging system depends on the current flowing in the transmitting coil.

Since the charging mode and the circuit configuration of the product may be different depending on the manufacturer, the tendency of measurement in this experiment does not always occur. However, in the circuit configuration of the basic wireless charging system, as can be seen in this experiment, the higher the voltage of the battery (the more the battery is full), the greater the current flowing in the transmission coil. Accordingly, the magnetic field of the wireless charging system will also vary. Therefore, it is necessary to consider the state of charge in evaluating the magnetic field of the wireless charging system.
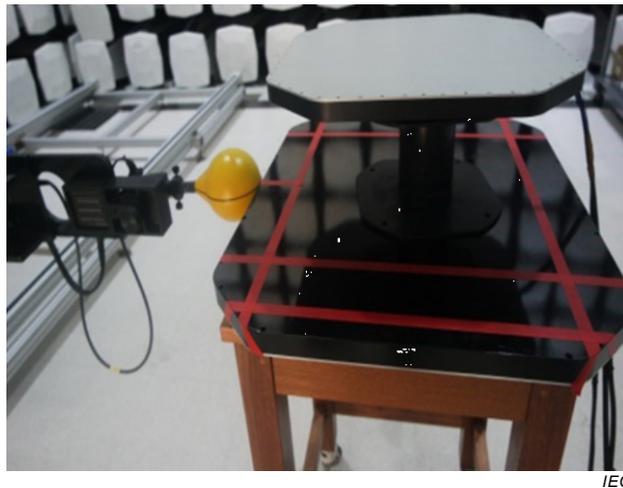
IEC

Figure E.10 – Photograph of magnetic field measurement for transmitting and receiving pads of wireless charging system

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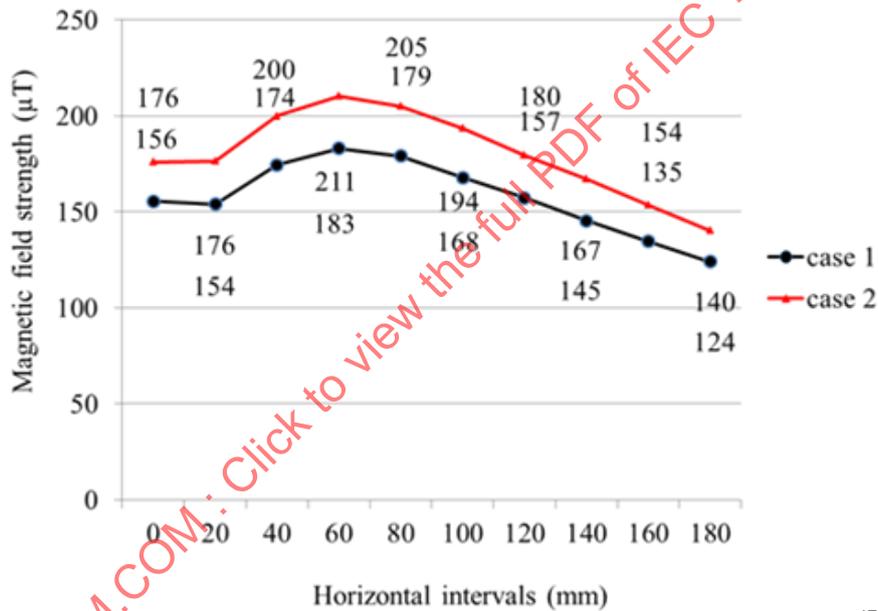
Figure E.11 – Measurement results of magnetic field value for two cases of low voltage output (case 1) and high voltage output (case 2)

E.2 Exposure evaluation of WPT for mobile device

E.2.1 WPT system in 140 kHz band

Figure E.12 (a) shows transmitting and receiving coils used for electromagnetic induction type WPT system for hand-held communication devices. Each transmitting and receiving coil consists of a spiral coil. Each coil is equipped with the matching impedance and supplies 1 W input power to the receiving side [49].

(a) Transmitting and receiving coils (R_i = 6 mm, R_o = 20 mm, D_z = 3,5 mm, 20 turns)

(b) Magnetic sheet (a = 50 mm, b = 50 mm, Thickness = 0,6 mm)
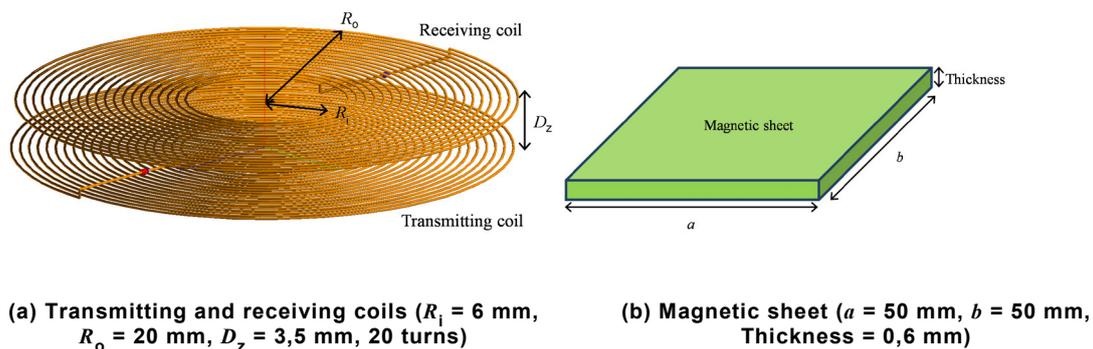
Figure E.12 – Transmitting and receiving coils, and magnetic sheet

An outline of the magnet sheet is shown in Figure E.12 (b). The magnetic sheet represents WPT system of mobile device and to be inserted above and under the transmitting coil shown as Figure E.12 (a). The relative permeability of magnetic sheet is 7 000. Two situations, charging and standby situations, are assumed as the WPT system to be analysed is a model of a mobile device. Thus, it is assumed that the lower transmitting coil represents a charger while upper receiving coil represents a mobile device, and both charging and standby situations are studied. Figure E.13 shows simulated result of both charging and standby situation [49]. The used frequency is 140 kHz. The local variations in magnetic field distribution are found when charging while symmetrical magnetic field is found in a standby situation. It is assumed this is caused by the magnetic sheet of receiving side in charging (the magnetic sheet inserted in the above of the transmitting coil). The magnetic field of standby situation is larger than that of in charging. It is assumed this is caused by the decrease of radiation (leakage) of electromagnetic field due to the power transmission to the receiving coil while in charging.
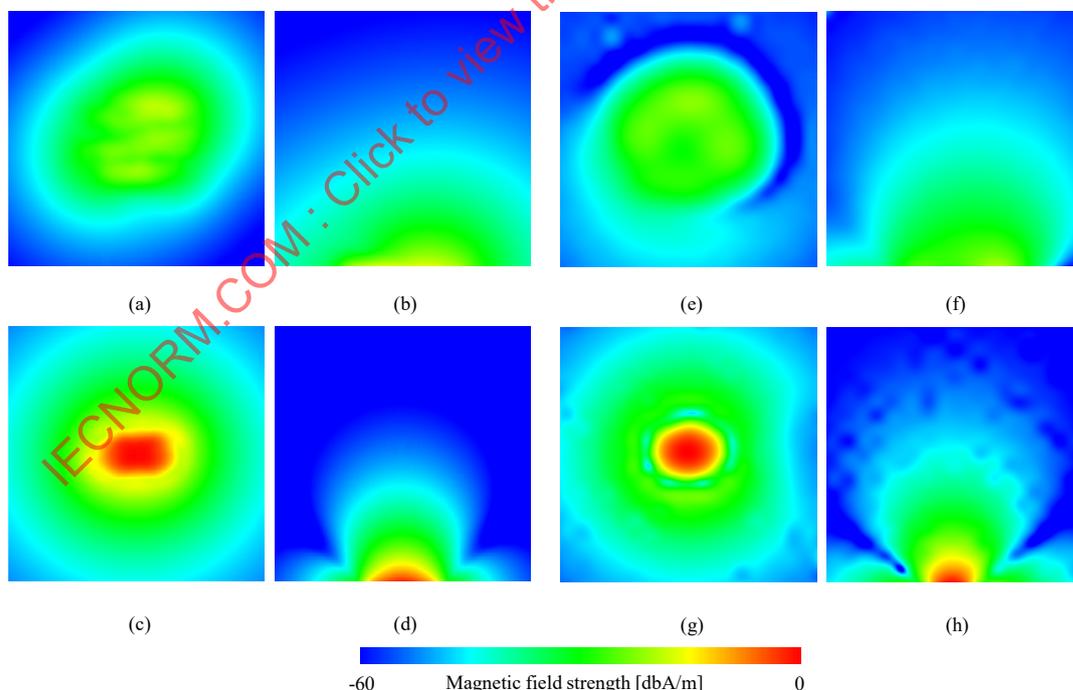
Figure E.13 – Simulated magnetic field strength distribution (Charging (a) xy plane, (b) yz plane; Standby model (c) xy plane, (d) yz plane) and measured value (Charging (e) xy plane, (f) yz plane; Standby mode (g) xy plane, (h) yz plane)

Figure E.14 shows simulated condition where a WPT system is placed next to a heterogeneous human model. The transmitting coil is placed in 10 mm from the surface of the human chest. The transmitting coil is located in front of the chest at positions labelled A to I.

The separation between the positions is 60 mm. The frequency is 140 kHz and input power is 1 W. Although it is not shown here, higher induced electric field was found in the chest than that of arms.

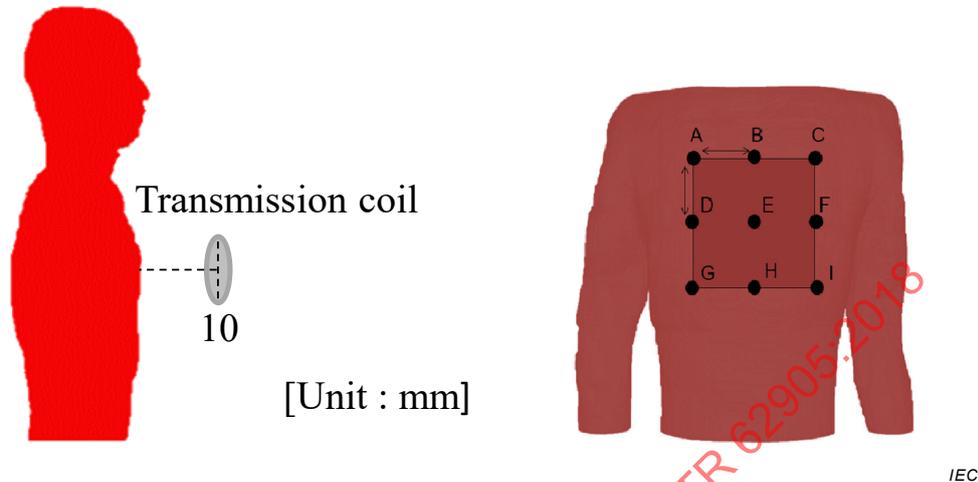Transmission coil

10

[Unit : mm]

IEC

Figure E.14 – Position of human body and coil (left), exposure point in chest (right)

Table E.2 shows induced electric field strength and SAR for both charging and standby mode at human body model respectively. The SAR values shown in Table E.2 are not averaged over time. From Table E.2, maximum value of 10 g average SAR in charging is 1,31 nW/kg. Comparing the ratio with that of basic restrictions, it is confirmed that induced electric field is dominant in this frequency range. With whole-body average SAR which is 2,89 pW/kg, $3,61 \times 10^{-11}$ times of the guideline of 0,08 W/kg. The result is less than above mentioned maximum value of 10 g average SAR that is $6,55 \times 10^{-10}$ times when compared with guideline for 2 W/kg. Thus, 10 g average SAR is more restrictive guideline than that of whole-body average SAR.

Table E.2 – Local SAR and induced electric field in in a human body on the chest surface

Exposure point	Local 10 g average SAR [nW/kg]		Maximum induced electric field in the human body [mV/m]	
	Charging	Standby	Charging	Standby
A	0,49	18,5	9,1	44,3
B	0,47	18,4	7,2	45,4
C	0,77	29,7	7,1	41,2
D	0,51	19,8	6,8	39,1
E	1,1	41,5	9,9	57,8
F	0,72	27,7	6,9	37,9
G	0,66	26,9	6,7	38,2
H	1,3	49,9	12,2	80,7
I	0,79	31,1	7,6	42,7

E.2.2   WPT systems in MHz band

Figure E.15 shows three different types of WPT systems: (a) 10 MHz solenoid type, (b) 7 MHz solenoid type, (c) 7 MHz flat spiral type. Radius of coils for 10 MHz solenoid and 7 MHz solenoid types is 30 cm. Inner and outer radii of flat spiral type are 12 cm and 24,5 cm, respectively. There are two resonant frequencies in the configuration of Figure E.15. At the

lower resonant frequency, currents in transmitting and receiving coils are in-phase (odd mode), At the higher resonant frequency, currents are out of phase (even mode). A realistic human body model of Japanese male adult (TARO) with the conductivity of 2/3 muscle is used. The distance between the system and human body is 2 cm.

Three computational methods are used; the method of moments (MoM), the two-step method combining MoM and FDTD method, and the two-step method combining MoM and impedance method. Analyses using MoM consider EM coupling between WPT systems and the human body while two-step method of FDTD or impedance method ignores the back-scattered field from the human body. The FDTD method considers contribution of exposures from both incident electric and magnetic fields while the impedance method considers exposure due to incident magnetic field only.

The FDTD results are compared to those obtained by the impedance method. Difference in local 10 g SAR due to ignoring the electric field is less than 30 % or so. It is confirmed that the difference in the WBA-SAR is at maximum 65 % for the solenoid-type system. For the flat-spiral system, the difference is relatively small, compared to the solenoid system; i.e., less than 14 % for local 10 g SAR, and 15 % for whole-body average SAR.

In general, the electric field is perturbed due to existence of the human body. Thus, the two-step method using the FDTD method may overestimate contribution from incident electric field. The analyses resulted by the MoM are compared with those simulated by the two-step method with the FDTD method. As a result, the differences in local 10 g SAR are approximately 53 % for the solenoid type and 33 % for the flat spiral type.
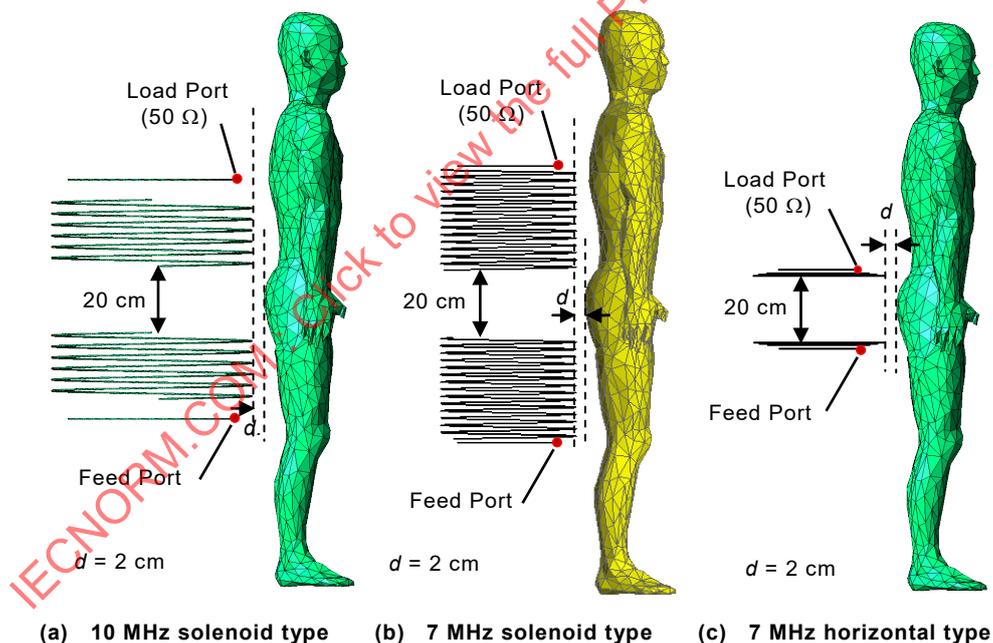

(a)   10 MHz solenoid type   (b)   7 MHz solenoid type   (c)   7 MHz horizontal type

Figure E.15 – Realistic human body model and system position

Variation in local SAR in the heterogeneous human body of Japanese adult is then simulated by using scalar-potential finite-difference method. Figure E.16 (a) shows exposure conditions where the position of the coils is varied laterally while Figure E.16 (b) shows the condition where the coil is moved in vertical direction to the human body model. Two coils are placed at the same height in the horizontal direction. The distance between the coils and the human body model is 50 mm and transfer power is 1 W.
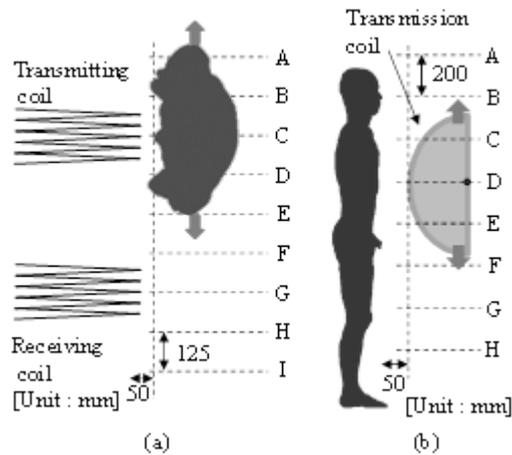
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Figure E.16 – Position of the human body model: (a) the human body is moved in the horizontal direction, (b) the coils are moved in vertical direction

Figures E.17 (a) and (b) show the peak 10 g averaged SAR for the Japanese male adult model moved in the lateral and vertical directions, respectively. Figure E.17 (a) shows that local peak SAR at the positions of C and G are larger than the other positions where transmitting and receiving coils are located in front of the chest. The SAR becomes larger due to the stronger magnetic field strength around the coil. Figure E.17 (b) shows that the local SAR at the position of D in the chest has the largest value. The local SAR for the odd mode are almost the same at the positions of D to E, corresponding to the coil location in the front chest. The magnetic flux passing through the body differs for its cross-section area of the body. Thus, the SAR induced in the body becomes largest at position D, corresponding to the highest magnetic flux. The difference of SAR for these two modes is attributable to the difference of magnetic field distribution as well as inhomogeneous electrical conductivity in the model and non-uniformity of the field. These factors result in different location of maximum local SAR.
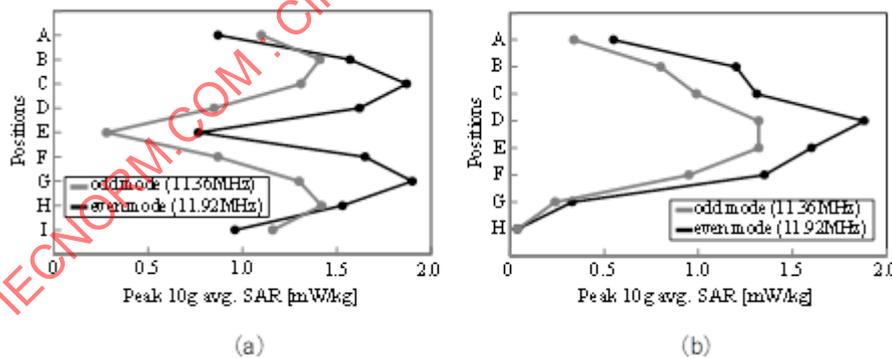
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Figure E.17 – Peak of 10 g average SAR moved in (a) horizontal direction, (b) vertical direction

Figure E.18 shows the peak SAR averaged over 10 g in different human body models where the body chest is located at 50 mm from the coil, corresponding to the worst-case exposure. The models considered are Japanese male adult TARO, female adult model HANAKO as well as an adult male Duke, a female adult Ella, a child model Thelonious developed in Switzerland, and the standard adult male and female models NORMAN and NAOMI developed in the UK. Figure E.18 shows that even modes have larger local peak SARs than those of odd modes in every human body model. The maximum difference between the two modes is found to be 72,5 %. Even mode has a stronger coupling than that of odd mode. The transmitting coil has a current flowing in the opposite direction to that of the receiving coil in

the even mode, resulting in stronger magnetic field strength. It was also confirmed that the SAR in the adult models are larger than those in a child model by 102 % in the odd mode and 72 % in the even mode. These results support the assumption that the difference in SAR is due to the difference in the cross-section area of the models.
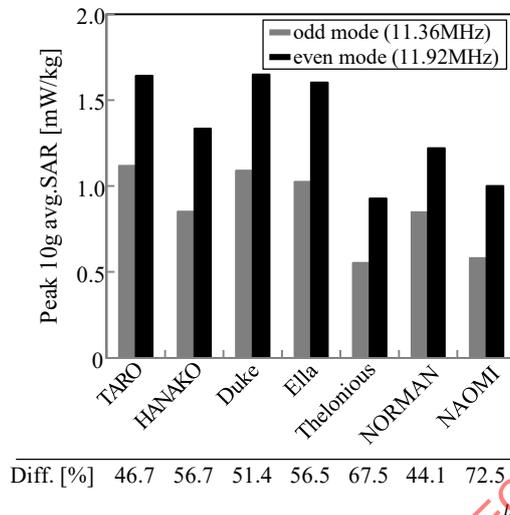

| Diff. [%] | 46.7 | 56.7 | 51.4 | 56.5 | 67.5 | 44.1 | 72.5 |

Figure E.18 – Peaks of 10 g average SAR

Numerical simulations were performed for more realistic exposure scenarios. Two types of WPT systems that transfer (a) between a single transmitting coil (500 mm × 500 mm) and a single receiving coil (200 mm × 200 mm) and (b) between a single transmitting coil (1 000 mm × 500 mm) and two receiving coils (200 mm × 200 mm) are considered, as shown in Figure E.19. The distance between the transmitting coil and receiving coil(s) is 50 mm in both cases. The internal circuit parameters of the coils are determined so that the transferred power becomes maximal at 6,78 MHz. Two research groups, NICT and Nagoya Institute of Technology (NITech) with NTT DOCOMO [50,51] performed exposure assessment for both WPT systems. For the configuration of Figure E.19 (a), the transfer efficiency computed at NICT was 59 % while it was 70 % for the result by NITech / NTT DOCOMO. The difference might be mainly due to the load difference of transmitting and receiving coils. For the configuration of Figure E.19 (b), the transfer efficiency was 94 % at NICT while 78 % at NITech / NTT DOCOMO. Figure E.20 shows the electric and magnetic field distributions for the single-to-single coil system. The electric and magnetic fields become larger around the coil.

Figure E.21 shows three exposure conditions for the WPT systems. The research group at NITech and NTT DOCOMO located the coils at (d) side, (b) upper and (e) sitting positions, while the NICT group considers the coil at (c) side and (a) upper positions.

Both FDTD method that is a full-wave computation, considering effect of both incident electric and magnetic fields, and impedance method considering only the effect of incident magnetic field were employed to evaluate the effect from incident electric field component of electromagnetic field leakage from WPT system.
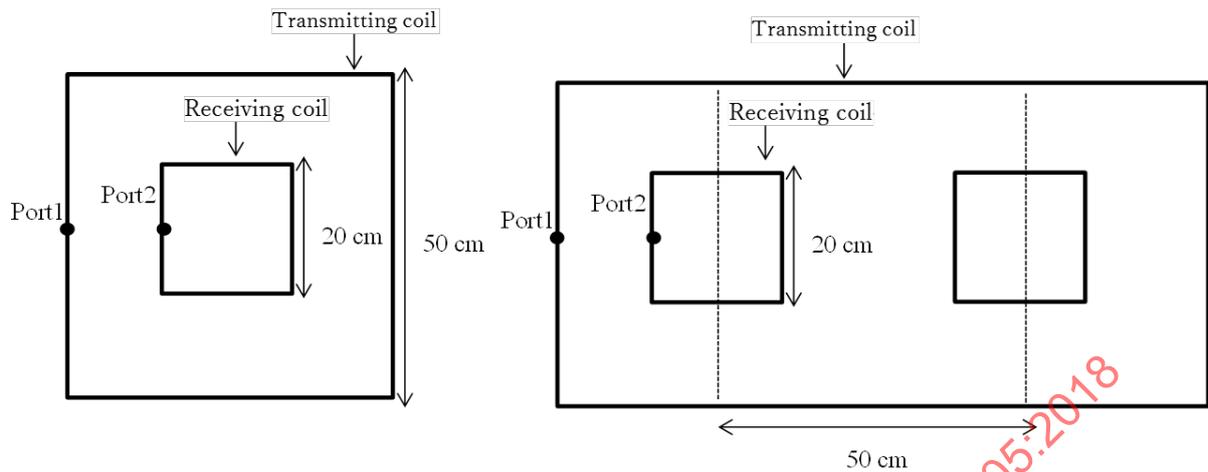
(a) A 500 mm × 500 mm transmitting coil and a 200 mm × 200 mm receiving coil

(b) A 1 000 mm × 500 mm transmitting coil and two 200 mm × 200 mm receiving coils

The distance between transmitting and receiving coils is 50 mm in both cases

Figure E.19 – Wireless power transfer system configurations
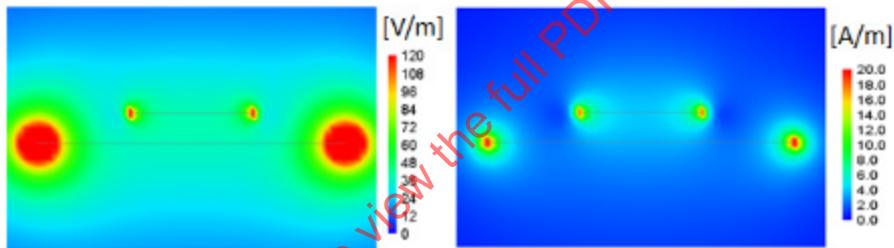
(a) Electric field

(b) Magnetic field

Figure E.20 – Electric field and magnetic field distributions around the coil when an input power is 1 W

Figure E.21 – Exposure conditions for WPT system

With the position (a) in Figure E.21, 10 g average SAR and whole-body average SAR based on FDTD methods are 1,80 W/kg and 0,049 3 W/kg, respectively. With impedance method, the results are 0,67 W/kg and 0,049 1 W/kg, respectively. The underestimation is found to be at most 7 % for the 10 g average SAR. The result shows that effect of electric field on local SAR is smaller compared to that of magnetic field.
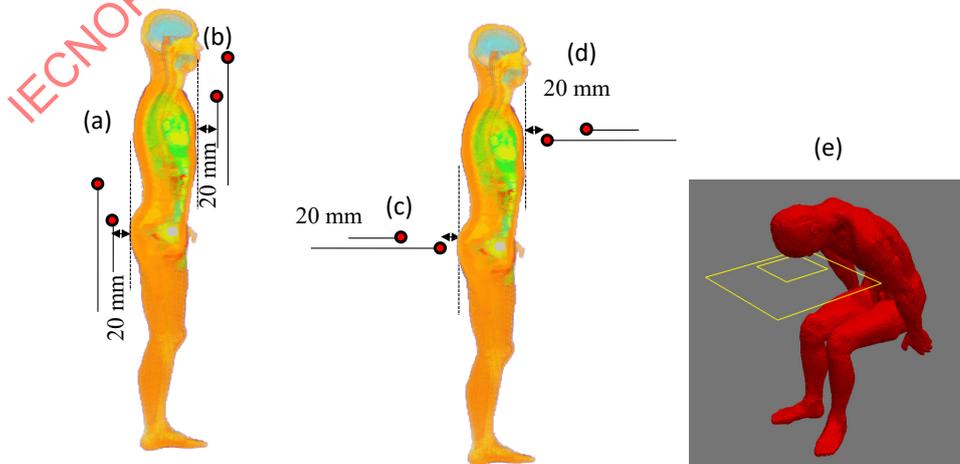
Table E.3 shows simulated results for whole-body average SAR and local SAR based on exposure condition shown in Figure E.21. From Table E.3, local SAR is dominant in both adult and child models placed aside of the WPT system. For the case in which human body is placed above the system, analysis shows that whole-body average SAR is more restrictive in some cases; however, the ratio does not exceed two times at maximum. It is an unrealistic situation where the whole human body exists above or under the system.

When the worst condition in usual usage (seated position) is considered, local SAR becomes very restrictive. The difference found in simulated results between two groups may be attributed to the difference of relative position of human body and the WPT system (NICT placed the WPT system at the rear of the human body while NITech / NTT DOCOMO placed the system in front of the human body).

For the realistic WPT system shown in Figure E.19, the whole average SAR guideline is assumed to be satisfied in most of the cases when satisfying the local SAR guideline. The effect of electric field for local SAR is more restrictive. For the realistic WPT system shown in Figure E.19, the evaluation using coupling factor to be shown later is possible if safety margin is considered and the human body placement is limited to the side of the system.

Table E.3 – Simulated result of local SAR and whole-body average SAR by Nagoya Institute of Technology (NITech) / NTT DOCOMO and NICT (input power is 40 W)

Human body model		NITech / NTT DOCOMO		NICT	
		10 g local SAR [W/kg]	Whole-body average SAR [W/kg]	10 g local SAR [W/kg]	Whole-body average SAR [W/kg]
Transmission from transmitting coil of 50 cm × 50 cm to receiving coil of 20 cm × 20 cm placed at 5 cm-distance					
Adult	Side	1,24	0,018	1,49	0,023
	Upper	3,34	0,181	5,43	0,149
	Seated	1,76	0,0516	-	-
3-year old child	Side	0,66	0,021	1,06	0,040
	Upper	2,87	0,208	7,93	0,259
Transmission from a 100 cm × 50 cm transmitting coil to two 20 cm × 20 cm receiving coils					
Adult	Side	0,459	0,007 49	0,77	0,013 7
	Upper	0,982	0,020 3	1,31	0,088
	Seated	0,342	0,008 05	-	-
3-year old child	Side	0,242	0,008 20	0,61	0,022 2
	Upper	-	-	1,33	0,071 6

E.3 Coupling factor

E.3.1 WPT system for EV

Figure E.22 illustrates the geometry of an electric vehicle with a WPT system consisting of two resonant coils. The transmitted power was 7 kW.

In the simulation conducted by NITech with Aalto University and University of L'Aquila, the vehicle body, whose dimensions shown in Figure E.22 (c) are approximately equal to those of a commercially available vehicle, is modelled with a perfect conductor. The bumper is made of plastic and does not affect the magnetic field distribution. Figure E.22 (a) and Figure E.22 (b) show WPT systems consisting of two solenoid coils or two circular-spiral coils. The transfer frequency was 85 kHz. The computational electromagnetic modelling was validated by comparing the measured and computed field distributions. Unlike other groups, coils misaligned by 200 mm in the side-to-side direction and 100 mm in the front-to-back direction were also included in the worst-case exposure scenario. A human standing in front or at the centre of the vehicle is also considered in addition to the rear of the vehicle. In addition to this, simpler exposure scenarios without a vehicle body or coils were also considered.

In the computation conducted by the NICT, only the circular spiral coils, as shown in Figure E.22 (b), were used. The vehicle body model and ferrite core were not considered. The transfer frequencies were 110 kHz and 125 kHz (equivalent to odd and even modes, respectively). The computational modelling was validated by comparing measured and computed near-field distributions [50]. Distance from the WPT system to the human body models is set as 200 mm.

The coils in the computation conducted by Tokyo Metropolitan University (TMU) are modelled with a one-turn loop having a uniform current distribution. The ferrite cores in both the solenoid and circular spiral systems are modelled as perfect magnetic conductors. The transfer frequency is 100 kHz. The distance from the WPT systems to the simplified human body model is set as 200 mm.

The parameters related to the coils considered in each group are given in Table E.4.

Table E.5 shows the calculated coupling factor based on Formula (C.6) for WPT systems for electric vehicles. The maximum value of the coupling factor from Table E.5 was 0,102. The value computed for the realistic human body model is 40 % to 50 % smaller than that of the simple human body model except in one example. One of the reasons for this is that the cross-sectional area of the leg is less than that of the simple body model. It is also expected from the comparison between the realistic and homogenized models developed by NICT that the coupling factor for the realistic body model might be larger in some cases.

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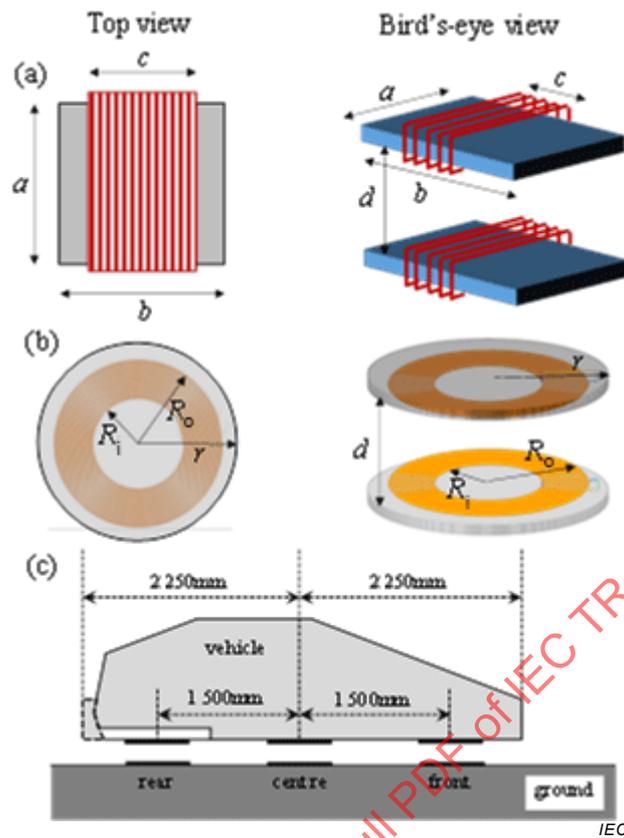
Different coil positions, i.e. front, centre, and rear of the body were considered.

**Figure E.22 – Top and bird's-eye views of (a) solenoid type and
(b) circular spiral type coupling coils, and (c) geometry of
electric vehicle with a wireless power transfer system [13]**

**Table E.4 – Dimensions of WPT systems for electric vehicles
considered by different groups [13]**

Dimension	NITech, Aalto L'Aquila	NICT	TMU	
	Coil type			
	Solenoid	Circular	Solenoid	Circular
Resonant frequency	85 kHz	110 kHz, 125 kHz	100 kHz	100 kHz
Coil dimensions	C = 15 cm	R_i = 12 cm, R_o = 22,5 cm	c = 15 cm	R_i = 4,5 cm, R_o = 19,5 cm
Separation between coils	d = 15 cm	d = 20 cm	d = 14 cm	d = 14 cm
Dimensions of ferrite core	a = 32,5 cm, b = 40,5 cm	-	a = 24 cm, b = 25 cm	r = 19,5 cm
Number of turns	14	44	1	1

Table E.5 shows the obtained coupling factors for WPT systems for electric vehicles. The maximum value of the coupling factor from Table E.5 was 0,102. The value computed for the realistic human body model is 40 % to 50 % smaller than that of simple human body model except one example. One of the reasons for this is that cross sectional area of the leg is smaller than that for the simple body model. Also expected from the comparison between the

realistic and homogenized models, the coupling factor for the realistic body model may be larger in some cases.

Table E.5 – Coupling factor for internal electric field of WPT systems for EV [13]

Group	Modelling	Coil type	Distance between coils (mm)	Human body model	Distance from coils to model (mm)	Coupling factor
NITech Aalto L'Aquila	Coil with ferrite core and vehicle body	Solenoid	120 (front)	Realistic human	200 (from vehicle) or 650 (from coils)	0,038
				Simplified human		0,053
			120 (centre)	Realistic human		0,035
				Simplified human		0,075
			150 (rear)	Realistic human		0,054
				Simplified human		0,033
NICT	Coil only	Circular spiral	200	Homogeneous human	200	0,082 (110 kHz)
				Realistic human		0,093 (110 kHz)
				Homogeneous human		0,050 (125 kHz)
				Realistic human		0,050 (125 kHz)
TMU	Coil with ferrite core	Solenoid	200	Simplified human model	300	0,093
					700	0,09
		Circular spiral			300	0,102
					700	0,087

E.3.2   WPT system for mobile device

The coupling factor of WPT system based on induction coupling for mobile at 140 kHz shown in Figures E.12 and E.14 were also evaluated. The maximum coupling factor at the fundamental frequency was 0,034. The variability of the coupling factor was approximately 30 % when the WPT system position relative to the chest was changed. The variability of coupling factor was 0,017 to 0,034 for 25 coil positions (see the 16 cases considered from [49]). This shows that if the homogenized human body model is considered for this system, a conservative internal field strength is obtained. The coupling factor varied from 0,025 to 0,036 under this assumption. This variability is attributed to the distance from the body surface to the WPT system, which may change because of body curvature.

The coupling factors for WPT system at 6,78 MHz shown in Figure E.19 and Figure E.21 were also evaluated. Table E.6 and Table E.7 show the calculation results of different coupling factors considering the thermal effect and the stimulation effect, respectively. As shown in these tables, however, the difference between the two groups is still less than 30 %. The maximum coupling factor considering the thermal effect and the stimulus effect is then determined as 0,0062 and 0,12, respectively. Note that the coupling factor is not applied when the whole-body average SAR is more dominant than the 10 g SAR or the internal electric field for the basic restrictions.