

INTERNATIONAL STANDARD



BASIC EMC PUBLICATION

**Electromagnetic compatibility (EMC) –
Part 4-36: Testing and measurement techniques – IEMI immunity test methods
for equipment and systems**

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IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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for equipment and systems**

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ELECTROTECHNICAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC) –**Part 4-36: Testing and measurement techniques –
IEMI immunity test methods for equipment and systems**

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International Standard IEC 61000-4-36 has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility.

It forms part 4-36 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107.

This second edition cancels and replaces the first edition published in 2014. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) addition of a hyperband and mesoband radiated transients immunity test method in Annex H;
- b) addition of a calibration method of sensors for radiated hyperband and mesoband transient fields and measurement uncertainty in Annex I.

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

FDIS	Report on voting
77C/295/FDIS	77C/299/RVD

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

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

A list of all parts in the IEC 61000 series, published under the general title *Electromagnetic compatibility (EMC)*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
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INTRODUCTION

IEC 61000 is published in separate parts according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as international standards or as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: IEC 61000-6-1).

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 4-36: Testing and measurement techniques – IEMI immunity test methods for equipment and systems

1 Scope

This part of IEC 61000 provides methods to determine test levels for the assessment of the immunity of equipment and systems to intentional electromagnetic interference (IEMI) sources. It introduces the general IEMI problem, IEMI source parameters, derivation of test limits and summarises practical test methods.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

For the purposes of this document, the following terms, definitions and abbreviated terms 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 Terms and definitions

3.1.1

attenuation

reduction in magnitude (as a result of absorption and/or scattering) of an electric or magnetic field or a current or voltage, usually expressed in decibels

[SOURCE: IEC 61000-2-13:2005 [3]¹, 3.1]

3.1.2

bandratio

ratio of the high and low frequencies between which there is 90 % of the energy

Note 1 to entry: If the spectrum has a large DC content, the lower limit is nominally defined as 1 Hz (see IEC 61000-2-13 [3] for further details).

[SOURCE: IEC 61000-2-13:2005 [3], 3.2, modified – The second part of the definition has been made into a note.]

3.1.3

bandratio decades

bandratio expressed in decades as: bandratio decades = $\log_{10}(\text{bandratio})$

¹ Numbers in square brackets refer to the Bibliography.

[SOURCE: IEC 61000-2-13:2005 [3], 3.3]

**3.1.4
burst**

sequence of a limited number of distinct pulses or oscillations of limited duration

Note 1 to entry: When multiple bursts occur, the time between bursts is usually defined.

SOURCE: [IEC 60050-161:1990 [19], 161-02-07, modified – The note has been added.]

**3.1.5
conducted HPEM environment**

high-power electromagnetic currents and voltages that are either coupled or directly injected to cables and wires with voltage levels that typically exceed 1 kV

[SOURCE: IEC 61000-2-13:2005 [3], 3.5]

**3.1.6
continuous wave
CW**

time waveform that has a fixed frequency and is continuous

[SOURCE: IEC 61000-2-13:2005 [3], 3.6]

**3.1.7
electromagnetic compatibility
EMC**

ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

[SOURCE: IEC 60050-161:2018, 161-01-07.]

**3.1.8
electromagnetic disturbance**

any electromagnetic phenomenon which can degrade the performance of a device, equipment or system

[SOURCE: IEC 60050-161:2018, [19] 161-01-05, modified – The last part of the definition, "or adversely affect living or inert matter", has been removed.]

**3.1.9
electromagnetic interference
EMI**

degradation of the performance of a device, transmission channel or system caused by an electromagnetic disturbance

Note 1 to entry: Disturbance and interference are respectively cause and effect.

[SOURCE: IEC 60050-161:2018 [19], 161-01-06, modified – Notes 1 and 2 have been removed and a new Note 1 has been added.]

**3.1.10
shield**

<electromagnetic> electrically continuous housing for a facility, area, or component used to attenuate incident electric and magnetic fields by both absorption and reflection

**3.1.11
(electromagnetic) susceptibility**

possibility of degradation to the performance of a device, equipment or system in the presence of an electromagnetic field

Note 1 to entry: Susceptibility is a lack of immunity.

**3.1.12
high-altitude electromagnetic pulse
HEMP**

electromagnetic pulse produced by a nuclear explosion outside the earth's atmosphere

Note 1 to entry: Typically above an altitude of 30 km.

[SOURCE: IEC 61000-2-13:2005 [3], 3.12]

**3.1.13
high-power microwave
HPM**

narrowband signals, nominally with peak power in a pulse, in excess of 100 MW at the source

Note 1 to entry: This is a historical definition that depended on the strength of the source. The interest in this document is mainly on the EM field incident on an electronic system.

[SOURCE: IEC 61000-2-13:2005 [3], 3.13]

**3.1.14
hyperband signal**

signal or waveform with a pbw (see 3.1.19) value between 163,4 % and 200 % or a bandratio > 10

[SOURCE: IEC 61000-2-13:2005 [3], 3.14]

**3.1.15
hypoband signal**

narrowband signal or waveform with a pbw (see 3.1.19) of < 1 % or a bandratio < 1,01

[SOURCE: IEC 61000-2-13:2005 [3], 3.15, modified – The second term "narrowband signal" has been removed.]

**3.1.16
intentional electromagnetic interference
IEMI**

intentional malicious generation of electromagnetic energy introducing noise or signals into electric and electronic systems, thus disrupting, confusing or damaging these systems for terrorist or criminal purposes

[SOURCE: IEC 61000-2-13:2005 [3], 3.16]

**3.1.17
L band**

radar frequency band between 1 GHz and 2 GHz

[SOURCE: IEC 61000-2-13:2005 [3], 3.17]

**3.1.18
mesoband signal**

signal or waveform with a pbw (see 3.1.19) value between 1 % and 100 % or a bandratio between 1,01 and 3

[SOURCE: IEC 61000-2-13:2005 [3], 3.18]

3.1.19

percentage bandwidth

pbw

bandwidth of a waveform expressed as a percentage of the centre frequency of that waveform

Note 1 to entry: The pbw has a maximum value of 200 % when the centre frequency is the mean of the high and low frequencies. The pbw does not apply to signals with a large DC content (e.g., HEMP) for which the bandratio decades is used.

[SOURCE: IEC 61000-2-13:2005 [3], 3.19]

3.1.20

port-of-entry

PoE

physical location (point) on an electromagnetic barrier, where EM energy may enter or exit a topological volume, unless an adequate PoE protective device is provided

Note 1 to entry: A PoE is not limited to a geometrical point.

Note 2 to entry: PoEs are classified as aperture PoEs or conductive PoEs according to the type of penetration. They are also classified as architectural, mechanical, structural or electrical PoEs according to the functions they serve.

[SOURCE: IEC 61000-2-13:2005 [3], 3.20, modified – The second term "point-of-entry" has been removed.]

3.1.21

pulse

transient waveform that usually rises to a peak value and then decays, or a similar waveform that is an envelope of an oscillating waveform

[SOURCE: IEC 61000-2-13:2005 [3], 3.21]

3.1.22

pulse repetition frequency

prf

number of pulses per unit time, measured in Hz

3.1.23

radiated HPEM environment

high-power electromagnetic fields with peak electric field levels that typically exceed 100 V/m

[SOURCE: IEC 61000-2-13:2005 [3], 3.22]

3.1.24

rE_{far}

measured or known electric field multiplied by the distance at which it was measured to give an equivalent voltage at a distance of 1 m from the antenna

3.1.25

sub-hyperband signal

signal or a waveform with a pbw value between 100 % and 163,4 % or a bandratio between 3 and 10

[SOURCE: IEC 61000-2-13:2005 [3], 3.23]

**3.1.26
transient**

pertaining to or designating a phenomenon or quantity which varies between two consecutive steady states during a time interval which is short compared with the time-scale of interest

Note 1 to entry: A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity.

[SOURCE: IEC 60050-702:2019 [20], 702-07-781, modified – The words "pertaining to or designating a" and the note have been added.]

**3.1.27
ultrawideband
UWB**

signal that has a percent bandwidth greater than 25 %

[SOURCE: IEC 61000-2-13:2005 [3], 3.25]

3.2 Abbreviated terms

AC	Anechoic chamber
BCI	Bulk current injection
CWI	Complex waveform injection
DEW	Directed energy weapon
DS	Damped sinusoid
DSI	Damped sinusoid injection
EFT	Electrically fast transient
EM	Electromagnetic
EME	Electromagnetic environment
EMI	Electromagnetic interference
EMP	Electromagnetic pulse
ERTMS	European rail traffic management system
ESD	Electrostatic discharge
EUT	Equipment under test
FO	Fibre optic
FOL	Fibre optic link
FT	Fourier transform
GNSS	Global navigation satellite system
GPS	Global positioning system
GSM-R	Global system for mobile – railways
GTEM	Gigahertz transverse electromagnetic
HEMP	High-altitude electromagnetic pulse
HIRA	Half impulse radiating antenna
HIRF	High-intensity radiated field
HPD	Horizontally polarized dipole
HPEM	High-power electromagnetic
HPM	High-power microwave
IC	Integrated circuit
IEMI	Intentional electromagnetic interference

IFT	Inverse Fourier transform
IRA	Impulse radiating antenna
LEMP	Lightning electromagnetic pulse
LISN	Line impedance stabilization network
LLSC	Low level swept current
LLSF	Low level swept field
LNA	Low noise amplifier
MPA	Minimum phase algorithm
NEMP	Nuclear electromagnetic pulse
NLTL	Non linear transmission line
OATS	Open area test site
prf	Pulse repetition frequency
SAC	Semi-anechoic chamber
SE	Shielding effectiveness
TEM	Transverse electromagnetic mode
TMR	Triple modular redundancy
UAV	Unmanned aerial vehicle
UFA	Uniform field area
URSI	International radio scientific union
UWB	Ultra wideband
VPD	Vertically polarized dipole

4 General

The use of electromagnetic sources to generate intentional electromagnetic interference (IEMI) is of increasing concern as the reliance of society on technology increases significantly. Many technical papers have been published that show the effects of IEMI are cause for concern; they are summarised in [1]. A summary of failure mechanisms at equipment level is provided in Annex A.

IEMI can be included within the set of HPEM environments, which also include high-intensity radiated fields (HIRFs) generated by radio and radar systems, lightning electromagnetic pulse (LEMP) and electrostatic discharge (ESD).

The IEC defines IEMI (see 3.1.16) as "intentional malicious generation of electromagnetic energy introducing noise or signals into electric and electronic systems, thus disrupting, confusing or damaging these systems for terrorist or criminal purposes".

Within this definition it is possible to also include jammers, which are designed to overload antenna receiver circuits (front doors) by operating at or close to the victim receiver frequency of operation. Jammers typically require low power to operate due to the fact that receivers are designed to operate at very low power levels (nW or less). More information on the issue of jammers can be found in Annex G.

This document complements IEC 61000-4-25 [2], which deals with high-altitude electromagnetic pulse (HEMP) immunity test methods for equipment and systems.

5 IEMI environments and interaction

5.1 General

There are many types of sources which are capable of generating electromagnetic environments potentially causing intentional electromagnetic interference (IEMI). IEC 61000-2-13 [3] discusses the various environments that can be generated and categorises them in terms of time characteristics, frequency range and bandwidth. Further details and actual examples are included within Annex B.

A key requirement of developing IEMI test methods and test levels is to achieve a good understanding of the environment in which the victim equipment or system will be required to operate. Within this document specific focus is provided for victim equipment that is integrated within a site or other fixed installation and it is generally assumed that such equipment is housed within a building.

IEMI phenomena are unlike other EMC standardised phenomena where assumptions can be made about the general or average disturbance level arriving at victim equipment ports. Important parameters related to the IEMI interaction with victim systems which will affect the test level include:

- a) IEMI source parameters
 - 1) frequency range of the source,
 - 2) peak and average power of the source
 - 3) pulse width, pulse repetition frequency, burst length of the source,
 - 4) source mobility,
 - 5) technical complexity of the source,
 - 6) antenna characteristics and/or conducted injection method characteristics
- b) the protection level of the equipment, system or installation
 - 1) the range or distance between the IEMI source and the victim electronics,
 - 2) the propagation channel loss including the properties of the intervening barriers (attenuation and absorption).

Once these characteristics of the IEMI source and environment are well understood, then appropriate test methods and test levels for ports on the victim equipment can be determined.

One approach would be to take all of the IEMI source parameters of interest and combine them such that one set of test levels is derived. The disadvantage of this approach is that, should effects be observed, it would be difficult to assign them to any single IEMI parameter set. In addition the combination of widely varying waveform characteristics would likely result in an extreme set of test levels.

Some IEMI sources generate waveforms/environments that are similar to other electromagnetic (EM) environments, for example electrostatic discharge (ESD) or lightning electromagnetic pulse (LEMP). Analytical methods can be used to determine the amount of similarity between IEMI environments and other EM environments, in particular through the use of waveform norms (see IEC 61000-4-33 [4]). Any deficiencies in the test evidence could be made up through increasing the distance between the IEMI source and the electronic systems of interest or by undertaking testing focussed on specific frequencies.

5.2 IEMI environments

5.2.1 Technical capability groups

IEMI sources vary in complexity. It is therefore important to understand the relationship between this complexity and the technical capability of the perpetrator. This document defines three levels:

- a) Novice – Individuals or small groups with minimal technical or financial support.
- b) Skilled – Moderately well-funded adversaries with training and expertise in relevant technology.
- c) Specialist – Well-funded adversaries with post-graduate level training and access to substantial research capabilities, resources and funding.

When considering the IEMI sources of interest it is important to consider the deployment scenario.

5.2.2 IEMI deployment scenarios

IEMI sources can be packaged and deployed in different ways, although this generally depends on the technical capability of the designer and the available resources. A set of potential scenarios for deployment of IEMI generators is given in Table 1.

Table 1 – Possible IEMI deployment scenarios

Deployment scenarios	Example use	Victim interaction	Technical capability group
Man portable	Carried to the victim and used while in possession of the adversary. Could be assembled in place.	Direct Radiated Conducted	Novice Skilled
Hand delivered	Carried to the victim and concealed, perhaps remotely activated. Could be assembled in place.	Direct Radiated Conducted	Novice Skilled
Fixed installation	Set-up in a space adjacent to the victim, i.e. an adjoining room or building.	Radiated Conducted	Novice Skilled Specialist
Automotive / marine delivered	Mounted inside a pick-up truck or on the after deck of a marine vessel.	Radiated Conducted	Skilled Specialist
Air delivered	Installed inside an aircraft bay, carried as a pod, or dropped (i.e., E-bomb).	Radiated	Specialist

5.2.3 Radiated IEMI environment summary

Table 2 provides a summary of threat source environments defined by capability group.

Table 2 – Summary of high power radiated IEMI source output (rE_{far}) by capability group

Category	IEMI source type	IEMI source name or technology type	rE_{far} (V)	Far field boundary (approx.)
Novice	Hyperband	ESD gun	5 000	1 m
	Hypoband	Microwave oven magnetron	2 000	1 m
Skilled	Hyperband	Commercially available solid state pulser (e.g. pockels cell driver)	60 000	1 m
	Mesoband	Commercially available pulser	120 000	2 m
	Hypoband	Radar	450 000	5 m
Specialist	Hyperband	Military demonstrator (e.g. jolt)	5 300 000	50 m
	Mesoband	Military mesoband demonstrator	500 000	5 m
	Hypoband	Military hypoband demonstrator	30 000 000	50 m

NOTE Table 2 does not include jammers. These are discussed in Annex G.

5.2.4 Published conducted IEMI environments

Unlike the situation with radiated IEMI sources, examples of conducted IEMI sources are less common. However, it has been shown that many conducted EMC tests exist within published civilian EMC documents such as IEC 61000-4-18 [5], IEC 61000-4-4 [6] and IEC 61000-4-25 [2] and that the sources that generate these test waveforms can be uprated or applied to equipment ports in a different way or otherwise used for malicious effect. There are also various military standards that contain relevant conducted tests.

5.3 Interaction with victim equipment, systems and installations

5.3.1 General

The magnitude of the IEMI environment impinging on a victim system is primarily dependent upon two factors:

- 1) the range or distance between the IEMI source and the victim electronics;
- 2) the propagation loss, including the attenuation properties of intervening barriers.

It is important to note that radiated IEMI interacts not only with apertures and structures, but also cables. The total EM disturbance presented to the victim electronics inside is therefore a function of the direct radiated IEMI and the coupling of this IEMI to EM conductors such as cables, pipe-work and ducting. When determining an appropriate test level for a particular radiated IEMI environment of concern, an assessment of the transfer of the IEMI to the victim electronics inside the building is required and this should include any attenuation afforded by the building material, propagation loss and any other aspects that can affect the resulting currents or voltages presented to the equipment.

Figure 1 shows a typical radiated and conducted IEMI scenario with a vehicle-mounted IEMI source illuminating a building and separately injecting into a power cable. The fields generated by the radiating source penetrate through apertures and separately couple to conductors (both outside and inside the building), generating induced currents and voltages that can affect the victim electronic equipment. The current/voltage generated by the conducted source is coupled to the conductor, allowing it to propagate inside the building and potentially affect electronic equipment.

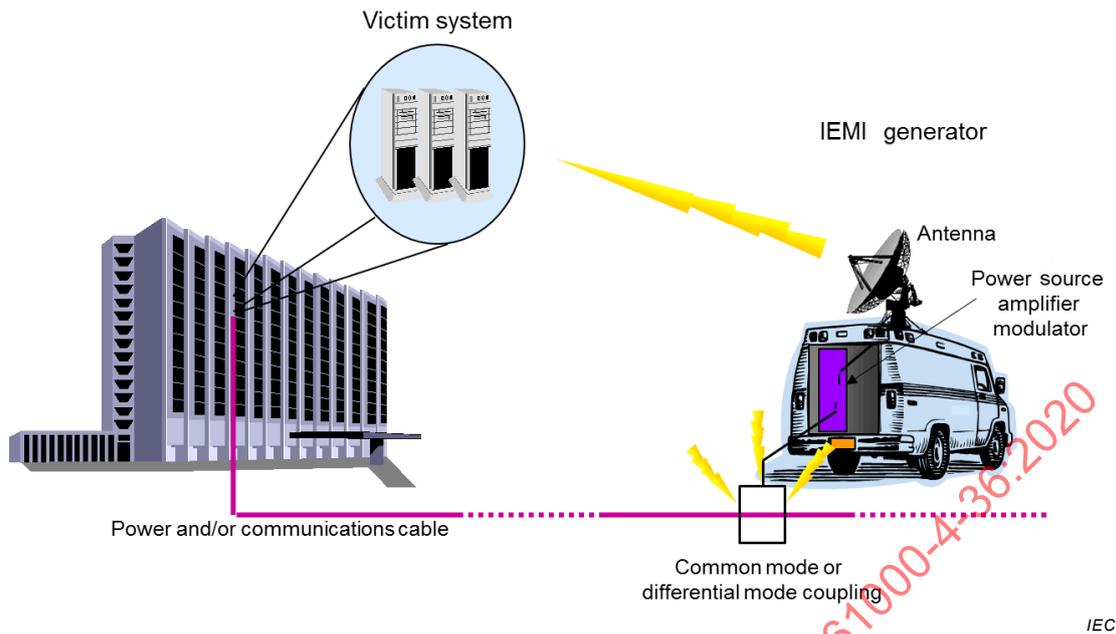


Figure 1 – Example of radiated and conducted IEMI interaction with a building

It should be noted that cable attenuation and attenuation afforded by lumped components (such as transformers) should be considered when determining the currents and voltages presented at the electronic equipment. It should also be noted that different coupling modes (i.e. common mode or differential mode) can result in very different path losses during the propagation.

5.3.2 Protection level

Given the discussion above it can be implied that victim electronics located inside equipment, systems or installations will have an "inherent protection level" which is a function of the physical distance between the IEMI source and the victim electronics and the loss in the propagation channel. A discussion on the radiated and conducted interaction of IEMI sources within buildings is provided in Annex C.

Examples of protection levels are indicated in Table 3. These levels have been identified using the information in Annex C. However, it is highly important that the actual protection level is quantified through measurements, possibly as part of a site survey. Test methods which can be used to assess the barrier attenuation/propagation loss are discussed in Clause 6.

Table 3 – Examples of protection levels

Example of protection level (EPL) rating	Assumed range to victim (m)	Path loss (dB)	Assumed barrier attenuation (dB)	Total EPL (dB)
EPL0	2	6	0	6
EPL1	10	20	0	20
EPL2	12	22	4	26
EPL3	18	25	7	32
EPL4	30	29,5	11	40,5
EPL5	30	29,5	18	47,5
EPL6	35	31	29	60

NOTE The path loss equates to the assumed threat to the victim range expressed in dB relative to 1 m.

The EPL should be considered when deriving the applicable IEMI immunity test parameters discussed in Clause 7. In the absence of actual data the generic EPLs in Table 3 can be used.

6 Test methods

6.1 Derivation of applicable test methods

A detailed discussion on test methods is included in IEC TS 61000-5-9 [7]. The test methods summarised below encompass the evaluation of the "example protection level" and the immunity test level for potential victim equipment.

As IEMI falls into two main categories, namely radiated and conducted, the methods for testing against IEMI fall broadly into the same categories.

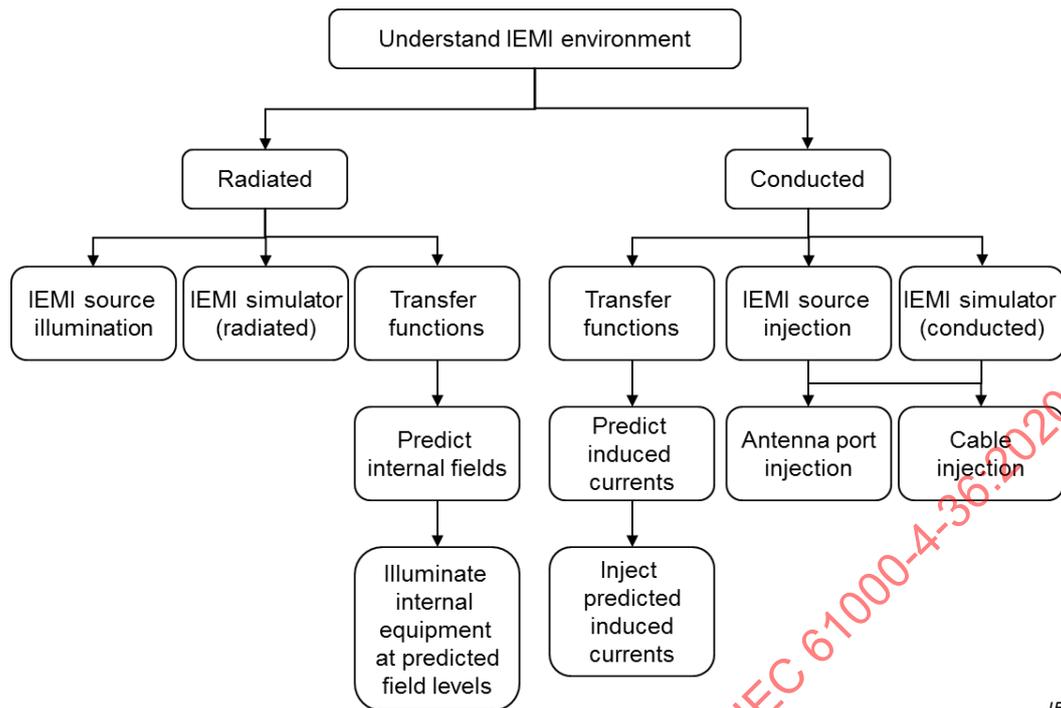
Testing against radiated IEMI can be undertaken with the IEMI source of interest, a simulated environment such as that shown in IEC TR 61000-4-35 [8], or by injecting the signal expected to be induced into conductors by exposure to the IEMI radiated environment. The latter relies on knowledge of the transfer function² of each conductor of concern (typically these conductors are cable bundles that carry power and/or data that is vital to the continuing function of the equipment or system).

Testing against conducted IEMI is typically undertaken with either the IEMI source directly or with a conducted simulator. Although it is possible to use a radiated method to assess against the effects of conducted IEMI, it is not commonplace.

Once the preferred test methodology has been agreed, it is possible to determine the required test levels.

Figure 2 shows the options available when undertaking an assessment of the effects of IEMI on equipment or systems.

² A measure of internally induced current or electromagnetic field as a result of an externally illuminating electromagnetic environment.



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Figure 2 – Assessment options

It is essential that testing is conducted in a representative configuration and that careful consideration is given to those aspects of the test set-up that can have a significant impact on test results, for example cable layout. If the requirement is for equipment to be immune to IEMI when in a power-off configuration, then testing with the equipment powered off is applicable. For all other cases, testing with the equipment powered and functioning is essential. Research has shown that transient effects can be significantly enhanced when the equipment is being operated functionally, for example with computer equipment that is constantly conducting hard drive operations or memory intensive functions.

A summary of test methods that can be used for the assessment of equipment or systems to the effects of IEMI is provided below.

6.2 Derivation of transfer functions

Transfer functions are essential for any equipment or system that is to be tested against the effects of a radiated IEMI source using conducted methods and can also be used to evaluate the protection level of a victim installation.

Transfer functions can either be measured (using techniques such as those discussed in IEC TS 61000-5-9 [7]) or generated analytically using some understanding of relevant geometry.

Transfer functions provide the means of estimating induced currents or voltages on conductors as a result of an EM field illuminating the conductor or from an EM source injected onto external cabling. Transfer functions are generally measured over a broad frequency range (e.g. ~1 MHz to ~1 GHz) and enable predictions to be computed for any IEMI environment with similar frequency content. Transfer functions can be extended to tens of GHz by measuring internally induced EM fields and reflecting the change in dominance of the interaction mechanism from cable coupling to aperture coupling.

For applicable test methods and test set-up see IEC TS 61000-5-9 [7].

6.3 Radiated tests using IEMI simulator

IEMI simulators are becoming increasingly available as the threat of IEMI is understood and accepted to pose real risk to the continuing operation of electronic equipment. IEC TR 61000-4-35 [8] contains details on IEMI simulators and their respective parameters. The equipment under test (EUT) shall be set-up in a representative condition of its intended use for the results to be indicative of the EUT response when fielded. The use of IEMI simulators to assess the protection level of an operational installation is not recommended since it can present a significant interference risk.

For applicable test methods and test set-up of IEMI sources see IEC TR 61000-4-35 [8].

6.4 Radiated tests using a reverberation chamber

IEC TR 61000-4-35 [8] also provides some examples of reverberation chambers. Reverberation chambers can be used to produce the high field levels for equipment level testing and are useful for testing of a material's shielding effectiveness in accordance with IEC 61000-4-21 [9].

Care should be taken to understand how the results of measurements made within a reverberation chamber compare with the realistic case of IEMI interaction which is closer to a plane wave phenomenon. This difference is discussed in Annex D.

For applicable test methods and test set-up see IEC 61000-4-21 [9].

6.5 Complex waveform injection (CWI)

This method takes the predicted currents from transfer functions and injects them onto conductors one-by-one whilst monitoring for effects. The injected waveforms are a function of the resonances measured by the transfer function and the environment itself and are complex in nature, i.e. they contain many frequencies. Further details on this method can be found in Annex E.

6.6 Damped sinusoidal injection (DSI)

This method uses single frequency damped sinusoidal waveforms and is generally required to be repeated across many frequencies to give an indication of how an EUT can respond to an IEMI environment. For applicable test methods and test set-up see IEC 61000-4-12 [10] and IEC 61000-4-18 [5].

6.7 Electrostatic discharge (ESD)

Testing to IEC 61000-4-2 [11] provides confidence of the continuing operation of the EUT as a result of ESD. ESD is a complex event generally characterised by a fast transient with a rise-time of the order of hundreds of picoseconds and a pulse-width of tens of nanoseconds. This information may be used to infer likely susceptibility to certain IEMI environments via the generation of radiated fields.

For applicable test methods and test set-up see IEC 61000-4-2 [11].

6.8 Electrically fast transient (EFT)

The EFT test has parameters that compare favourably with certain IEMI conducted environments, and data from the test defined in IEC 61000-4-4 [6] may be used to indicate the response of an EUT to IEMI.

For applicable test methods and test set-up see IEC 61000-4-4 [6].

6.9 Antenna port injection

This type of test provides valuable information on the response of transceiver systems to the effects of IEMI including jammers which are discussed in Annex G. The IEMI environment of interest shall either be used directly to inject signals into the antenna port or to determine (through the use of transfer functions) those signals that would exist at the associated electronics. Figure 3 shows a typical EUT with various ports including an antenna port.

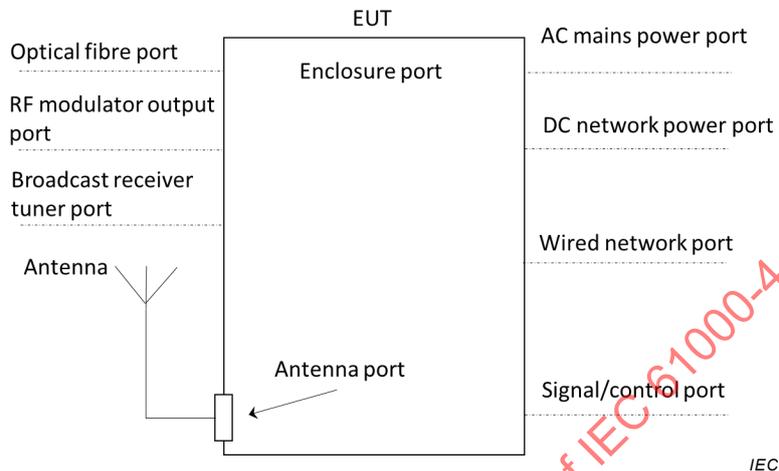


Figure 3 – Examples of ports

In general, antenna ports are commonly subjected to an ESD test. Also covered under 6.7, this is likely to provide useful information concerning the response of antenna ports to IEMI environments.

7 Test parameters

7.1 Derivation of immunity test parameters

The key to deriving immunity test levels lies in understanding the IEMI source of interest, the immunity requirement of the equipment or system that is to be assessed and the protection level for a given scenario.

For example, if the equipment or system is to be located within a secure facility (assuming 20 dB of attenuation for physical barriers) and such that an IEMI source cannot be any closer than 50 m (distance) away, this provides a useful bound on the test level. It can be prudent to consider some margin to deal with issues such as measurement uncertainty or measurement limitation to ensure that the test results carry a high level of confidence. This gives a solid foundation for developing the required test level. Once this is understood, the test levels can be derived using a radiated IEMI source or simulator or with the use of transfer functions as discussed in 6.2.

Subclause 7.2 indicates generic test parameters based on the skilled category using the environment levels derived in Table 2 and the examples of protection levels indicated in Table 3.

7.2 Radiated test parameters

7.2.1 Generic hyperband test parameters (skilled capability group)

Table 4 defines the immunity test levels for hyperband IEMI environments (i.e. those with a bandratio ≥ 10).

Table 4 – Generic hyperband test parameters (skilled capability group)

EPL	Amplitude (V/m)	Rise time (ps)	Pulse width (ns)	prf (Hz)	Burst duration (s)
EPL0	30 000	100 to 500	0,2 to 5	1 to 1 000	1 to 10
EPL1	6 000				
EPL2	3 000				
EPL3	1 500				
EPL4	565				
EPL5	252				
EPL6	60				

NOTE Any combination of waveform parameters in Table 4 will result in a different frequency spectrum of the waveform applied during the test. In some cases, this will result in a test that is less severe when considering the overall content or the associated maximum derivative of the applied waveform.

All combinations of the parameter ranges given in Table 4 are not simultaneously achievable with existing IEMI test sources. Once a test level is selected, some parameter variation is recommended within the stated parameter ranges, if possible.

Table 5 shows a description of the radiated hyperband test waveform and other important test parameters.

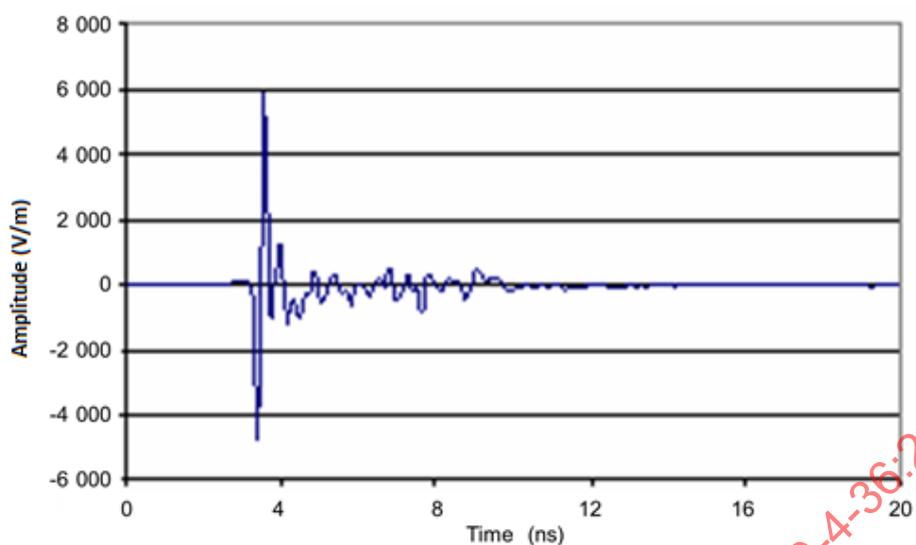
Table 5 – Radiated hyperband test waveform and other pulse parameters

Bandratio	≥ 10 ^a
Pulse to pulse amplitude reproducibility	amplitude (E-field) ± 10 % ^b
Rise time	100 ps to 500 ps ± 20 %
Pulse width	0,2 ns to 5 ns ± 20 %
Pulse repetition frequency	1 Hz to 1 000 Hz ± 10 % ^b
Burst duration	1 s to 10 s ± 10 % ^b
Minimum number of bursts	1
Minimum burst interval (period)	2 s ± 20 %
Radiated E-field exposure test level	selectable according to Table 4 ± 20 %
Field polarization	selectable, horizontal or vertical, or both

^a The 3 dB bandratio of the hyperband waveform is measured and confirmed that it is greater than or equal to 10.

^b The mean amplitude of the pulses in a burst is used. The reproducibility of the pulse amplitude (the flatness of the burst envelope) is important to control in order to accurately describe the test level used during exposure.

An example of a hyperband waveform is given in Figure 4.



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Figure 4 – Example of hyperband waveform

7.2.2 Generic mesoband test parameters (skilled capability group)

These types of IEMI environment are characterised by a damped sinusoidal waveform. Table 6 contains the test levels and associated parameters. It should be noted that any combination of waveform parameters in Table 6 will result in a different frequency spectrum of the waveform applied during the test. In some cases, this will result in a test that is less strenuous when considering the overall content or the associated maximum time derivative of the applied waveform.

Table 6 – Generic mesoband test parameters (skilled capability group)

EPL	Amplitude E_{pk} (V/m)	Dominant frequency, f_d (MHz)	Damping factor, Q	Pulse repetition frequency (prf) (Hz)	Burst duration (s)
EPL0	60 000	80 to 500	5 to 20	1 to 1 000	1 to 10
EPL1	12 000				
EPL2	6000				
EPL3	3 000				
EPL4	1 130				
EPL5	504				
EPL6	120				

It should be noted that not all combinations of the parameter ranges given in Table 6 are simultaneously achievable with existing IEMI sources. Once a test level is selected, some parameter variation is recommended within the stated parameter ranges if possible.

The waveform shape is well described by damped sine waves as shown in Formula (1).

$$E(t) = kE_{pk} e^{-\pi f_d t / Q} \sin(2\pi f_d t) \quad (1)$$

where, k is a normalising factor, f_d is the dominant frequency of the oscillation and t is time. The mesoband bandratio values of 1,01 to 3 can be shown by Formula (1) to correspond to Q -factor values of ~5 to 100, as shown in Table 7, however Q -factor values of between ~5 to 20 are more typically observed from IEMI generators and through IEMI and HEMP coupling to cables. Further information can be found in IEC 61000 2-13 [3].

Table 7 – Comparison of quality factor (Q) with bandratio

Quality factor Q	Normalising factor k	Bandratio
4,8	1,171	3,00
5,0	1,164	2,87
10,0	1,080	1,81
15,0	1,053	1,51
20,0	1,040	1,36
100,0	1,008	1,01

Table 8 shows a description of the radiated mesoband test waveform and other important test parameters. For more detail information, see Annex B.

Table 8 – Radiated mesoband waveform and other pulse parameters

Dominant oscillation frequencies ^a	80 MHz to 500 MHz \pm 10 % ^b
Bandratio	shall be within the range 1,01 to 3 ^c
Pulse to pulse amplitude reproducibility	amplitude (E-field) \pm 10 % ^d
Pulse repetition frequency	1 Hz to 1 000 Hz ^b
Burst duration	1s to 10s \pm 20 % ^b
Minimum number of bursts	1
Minimum burst interval (period)	2 s \pm 20 %
Radiated E-field exposure test level	selectable according to Table 6 \pm 20 %
Field polarization	selectable, horizontal and vertical or circular
^a Dominant oscillation frequency is defined as the dominant frequency (the frequency with the highest spectral magnitude contribution) identified from a Fourier transformation of the measured time domain waveform. ^b These are ranges of recommended values. The user selects values appropriate to the situation. A minimum number of three frequencies is recommended to cover the frequency range of mesoband sources. ^c The 3 dB bandratio of the mesoband waveform is measured and it is confirmed that it lies within the range 1,01 to 3. ^d The mean amplitude of the pulses in a burst is used. The reproducibility of the pulse amplitude (the flatness of the burst envelope) is important to control in order to accurately describe the test level used during exposure.	

An example of a mesoband waveform is given in Figure 5.

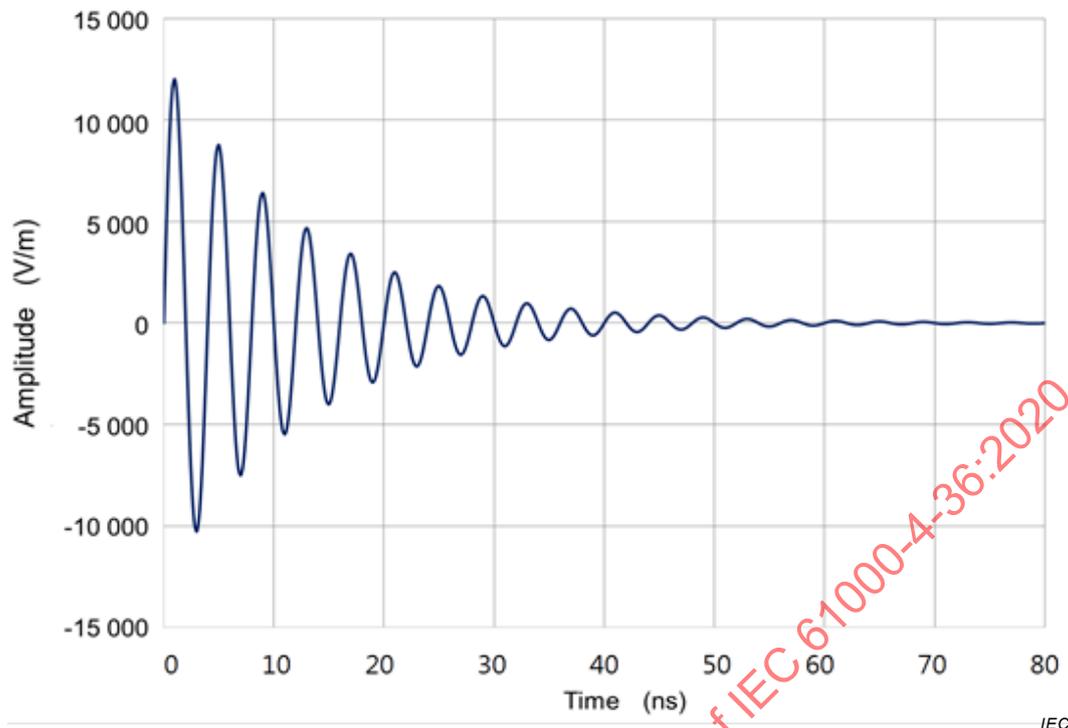


Figure 5 – Example of mesoband waveform

7.2.3 Generic hypoband test parameters (skilled capability group)

Table 9 gives the test levels for hypoband/narrowband IEMI which are characterised by low relative bandwidth, centre frequencies of \geq GHz and an associated pulse repetition frequency of \leq 1000 Hz.

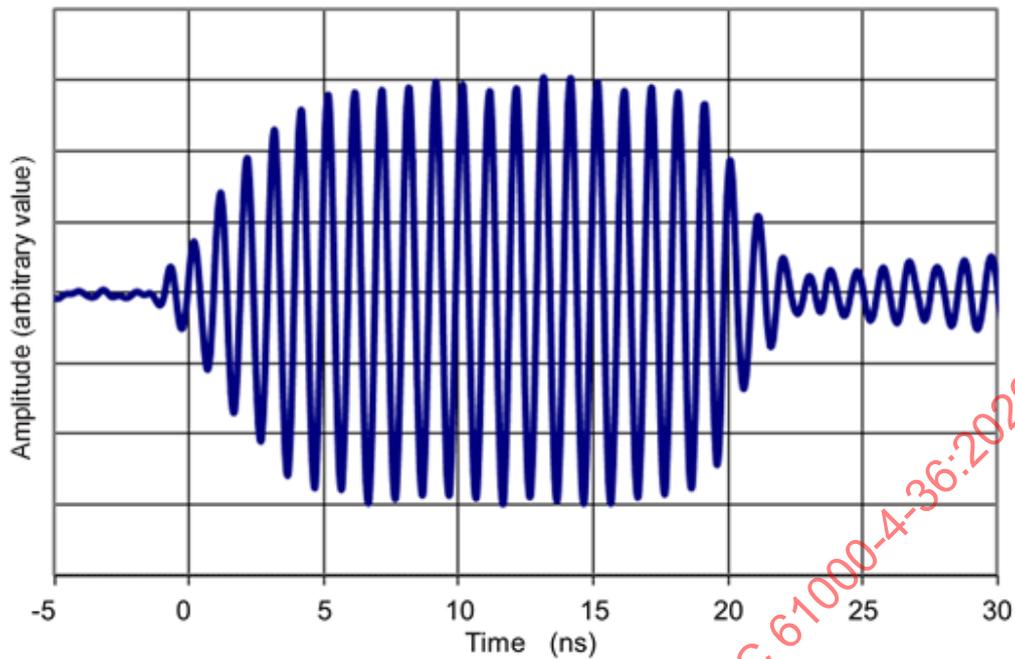
Table 9 – Generic hypoband/narrowband test parameters (skilled capability group)

EPL	Amplitude (V/m)	Pulse width (μ s)	Pulse repetition frequency (Hz)	Burst duration (s)
EPL0	225 500	0,01 to 10	1 to 1 000	1 to 10
EPL1	45 000			
EPL2	22 550			
EPL3	11 300			
EPL4	4 240			
EPL5	1 890			
EPL6	450			

NOTE Any combination of waveform parameters in Table 9 will result in a different frequency spectrum of the waveform applied during the test. In some cases, this will result in a test that is less severe when considering the overall content or the associated maximum derivative of the applied waveform.

All combinations of the parameter ranges given in Table 9 are simultaneously achievable with existing IEMI test sources. Once a test level is selected, some parameter variation is recommended within the stated parameter ranges, if possible.

An example of a hypoband/narrowband waveform is shown in Figure 6.



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NOTE The y-axis is amplitude (scale intentionally removed).

Figure 6 – Typical hypoband/narrowband waveform

7.3 Generic conducted IEMI test parameters

7.3.1 General

This document defines conducted IEMI test levels in Table 10. The user shall define specific test levels relevant to a specific IEMI environment by following the process in Clause 6.

Table 10 – Conducted IEMI test levels

V_{oc} V	I_{sc} A	Waveform	Basic document
100	2	Damped sinusoids ^a	IEC 61000-4-18 [5]
250	5	Damped sinusoids ^a	IEC 61000-4-18 [5]
500	10	Damped sinusoids ^a	IEC 61000-4-18 [5]
1 000	20	Damped sinusoids ^a	IEC 61000-4-18 [5]
2 000	40	Damped sinusoids ^a	IEC 61000-4-18 [5]
4 000	80	Damped sinusoids ^a	IEC 61000-4-18 [5]
4 000	80	5/50 ns	IEC 61000-4-4 [6]
8 000	160	5/50 ns	IEC 61000-4-4 [6]
16 000	320	5/50 ns	IEC 61000-4-4 [6]

NOTE 1 Voltage and current levels shown in the table are for common mode values.

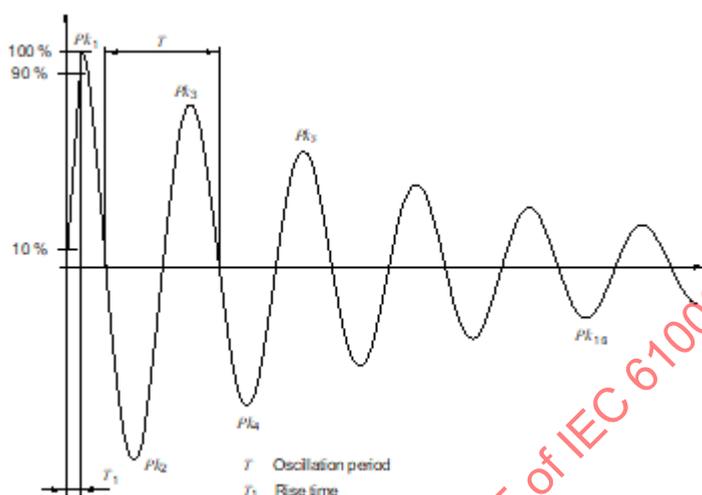
NOTE 2 For the two highest immunity test levels, it is sufficient to test with a single pulse.

^a IEC 61000-4-18 [5] defines the following test frequencies: 3 MHz, 10 MHz and 30 MHz. Depending on the characteristics of the incident IEMI electric field, tests can be recommended for damped sinusoids with frequencies of 100 MHz or 300 MHz using the waveshape defined in IEC 61000-4-18 [5].

7.3.2 Characteristics and performance of the fast damped oscillatory wave generator

Subclause 7.3.2 details the characteristics and performance requirements of the fast damped oscillatory wave generator required to undertake the testing referred to in Table 10, footnote a.

The waveform of the fast damped oscillatory wave is given in Figure 7.



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Figure 7 – Waveform of the damped oscillatory wave (open circuit voltage)

Open circuit specifications associated with Figure 7 are given in Table 11:

Table 11 – Open circuit specifications

Voltage rise time (T_1 in Figure 7)	5 ns \pm 30 %
Voltage oscillation frequencies ^a	3 MHz, 10 MHz and 30 MHz \pm 10 %
Pulse repetition frequency	5 000 Hz \pm 10 %
Decaying (see Figure 7)	Pk_5 shall be > 50 % of the Pk_1 value and Pk_{10} shall be < 50 % of the Pk_1 value
Burst duration	3 MHz: 50 ms \pm 20 %
Burst period	300 ms \pm 20 %
Output impedance	50 Ω \pm 20 %
Open circuit voltage	Pk_1 value, 100 V to 4 kV \pm 10 % (see Figure 7)
Phase relationship with the power frequency	No requirement
Polarity of the first half-period	Positive and negative
^a Oscillation frequency is defined as the reciprocal of the period between the first and third zero crossings after the initial peak. This period is shown as T in Figure 7.	

Short circuit specifications associated with Figure 7 are given in Table 12:

Table 12 – Short circuit specifications

Current rise time (T_1 in Figure 7):	3 MHz: < 330 ns 10 MHz: < 100 ns 30 MHz: < 33 ns
Current oscillation frequencies ^a	3 MHz, 10 MHz and 30 MHz \pm 30 %
Decaying (see Figure 7)	Pk_5 shall be > 25 % of the Pk_1 value and Pk_{10} shall be < 25 % of the Pk_1 value
Short circuit current (Pk_1 value)	5 A to 80 A \pm 20 %
^a Oscillation frequency is defined as the reciprocal of the period between the first and third zero crossings after the initial peak. This period is shown as T in Figure 7.	

7.4 Tailored test level derivation

The test levels defined within 7.2 and 7.3 are provided to allow the reader to apply generic IEMI test levels to equipment and systems where prior knowledge of a particular IEMI environment is not available.

For situations where one or more specific IEMI environments are the subjects of the assessment, tailored test levels shall be derived by considering the source-to-victim path using the following steps:

- a) understand the IEMI threat environment of particular interest
- b) measure the protection level by obtaining transfer function (coupling) data
 - 1) develop analytically
 - 2) measure
- c) predict induced currents/voltages/fields/power at the location of the equipment/systems
- d) create an envelope predictions
- e) assess immunity of equipment/systems
 - 1) inject predicted induced waveforms into equipment/systems
 - 2) compare injected results with existing immunity data (if available)

7.5 Relevance of EMC immunity data

Immunity data from general EMC testing can be useful in determining whether testing to the levels presented within this document is necessary to declare immunity to IEMI environments. A rigorous mathematical approach utilising waveform norms should be used as the basis for such assessments. Further information on the application of waveform norms can be found in IEC 61000-4-33 [4].

Measurement uncertainties, whose quantitative calculations are possible, for example, intensity of projected electric field, discharge voltage of static electric test facilities, current induced in cables, etc., shall be included in any test report. It can be necessary to consider the use of additional test margins to take account of limitations in test methods; further details on this subject can be found in Annex F. Additionally, any test reports shall include the statement that test results are dependent on the test conditions and configuration of the tested equipment, and the note that the test results are, therefore, only valid for the cases specifically under identical test conditions, test methods and equipment configuration.

Information and determination of measurement uncertainty for EMC testing can be found in CISPR TR 16-4-1 [12], CISPR 16-4-2 [13], CISPR 16 4-3 [14], CISPR16-4-4 [15] and IEC TR 61000-1-6 [16] and are equally applicable to the determination of measurement uncertainty for IEMI test results.

Annex A (informative)

Failure mechanisms and performance criteria

A.1 General

Electronic components and subsystems are essential parts of modern systems like airplanes, communication, IT infrastructure, traffic management, industrial controls or safety systems. Since these electronic components have begun to control safety critical functions, concern is growing over the vulnerability of electronic systems. Therefore the susceptibility of critical systems is of vital interest since an upset or failure in these systems could cause major accidents or economic disasters. As a consequence, the investigation of the susceptibility of electronic systems as well as their protection and hardening against IEMI threats is of great interest [A.1]³, [A.2], [A.3], [A.4] and [A.5].

There have been several documented cases, where high-power electromagnetic (HPEM) environments caused unwanted action or failure. In addition the last decade has witnessed worldwide numerous IEMI susceptibility investigations. Published reports of such investigations document a variety of observed effects such as:

- disturbed screens (flickering of screens, distorted displays, black screens),
- display of wrong data,
- corruption of signals and data (signal drifts, corruption of signals, lost data),
- false response of sensors and systems,
- unintentional response or action of systems (movement of actuator, change of course),
- decreased performance (reduction of computational performance, data transfer),
- hang up of software,
- reboot of digital devices (computer, controller, processor),
- destruction of components.

Due to the large range of observed effects, the systematic assessment (fail/pass) as well as the development of sufficient protection measures require a classification of the effects and the failure mechanisms, which summarise the essential information.

A.2 Failure mechanisms

A.2.1 General

If the observed effects are analysed with regard to the underlying failure mechanism, five main categories can be extracted:

- 1) noise
- 2) parameter offset and drifts
- 3) corruption of information
- 4) system upset or breakdown
- 5) component destruction

³ Numbers in square brackets refer to the references in Clause A.5.

Any of these mechanisms can occur on a system as a result of an incident EM environment, sometimes with disastrous consequences. Further details are given for each of the categories below.

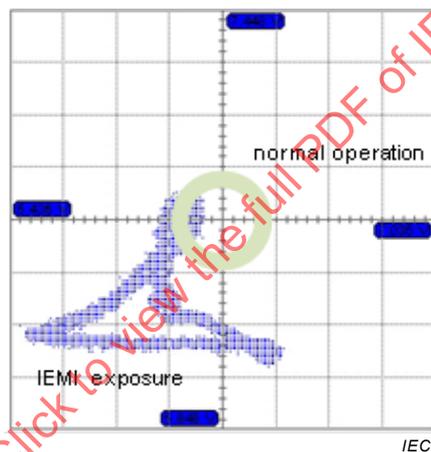
A.2.2 Noise

Electromagnetic disturbances can raise the noise level on signal and power lines, which results in flashing of displays or reduced data rates.

In a particular case of jamming the IEMI source (jammer) operates at or close to the frequency of operation and the induced noise level overloads the receiver circuits. Due to the fact that receivers are designed to operate at very low signal levels, jamming typically requires less radiated power.

A.2.3 Parameter offset and drifts

Parameters of analogue circuits are subject to changes (e.g. offset, drift) caused by induced signals. According to the application, these parameter changes can result in distortions of signals and/or false control signals and affect control circuits as well as the system status. This is shown in Figure A.1:



[Source: Bundeswehr Research Institute for Protective Technologies and NBC-Protection, WIS.]

Figure A.1 – IEMI induced offset of sensor output – Corruption of information

Injected signals are capable of changing bits of a data stream and of corrupting transferred information. In the worst case the receiving subsystem interprets the injected signal or the corrupted data stream as valid information or instructions. Typical effects of this class are the activation of a pop up menu, the opening and closing of programs, device failure messages, wrong sensor readings, and movements of actuators. This is shown in Figure A.2:

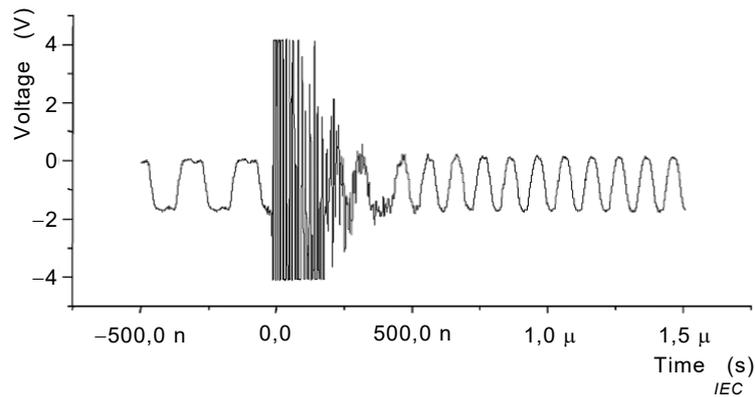


Figure A.2 – Collision of an induced disturbance with data bits [A.1]

A.2.4 System upset or breakdown

A system upset or breakdown is the inability of a physically undamaged system to perform its desired function. Upsets and breakdowns are caused by electromagnetic disturbances that are capable of affecting the logic state of an electronic system (e.g. by triggering digital devices, by changing counters or altering the state of logic circuits). After a reset (self, external, or power reset), the system will return to its usual capabilities.

A.2.5 Component destruction

Insulating layers of printed circuit boards or components (e.g. integrated circuits) can be sensitive to interfering disturbances. If the dielectric insulation is too thin, induced voltage signals can cause an electrical breakdown. The resulting component destructions range from flashover effects over melted lines to bond wire destruction (see Figure A.3).

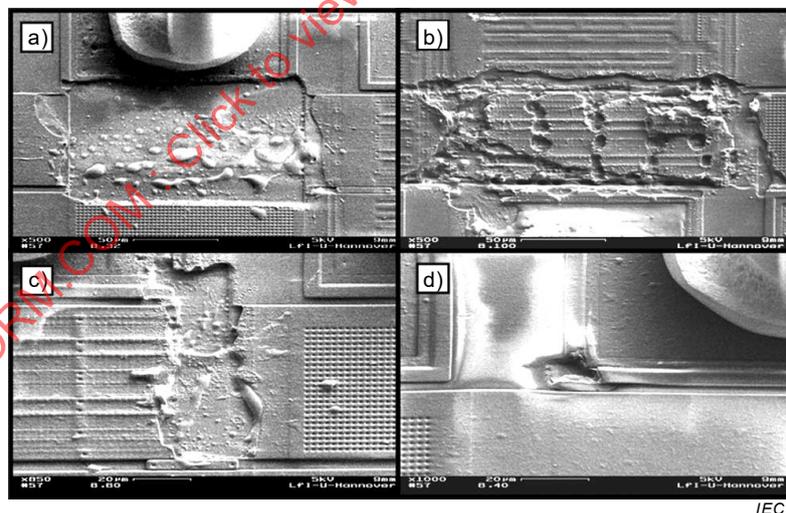


Figure A.3 – Examples of destruction on a chip [A.2]

The identification of which destruction mechanism occurs requires additional detailed examinations of the system (e.g. opening of integrated circuits (ICs) and detailed on-chip investigation). As the destructive effects are of a permanent nature, usually the time consumption of such additional examination is not a problem. In contrast, the temporary nature of interferences requires a real-time measurement of signals and additional measurements, which enable observation, storage and analysis of the internal stages of the system under investigation.

A.3 Effect of pulse width

Electronic equipment generally responds to either the peak power or the average power of the incident IEMI environment. Much data has been collected to determine the relationship between peak and average effects [A.6], [A.7], [A.8], [A.9], [A.10], [A.11], and the trend from this data is summarised in Figure A.4.

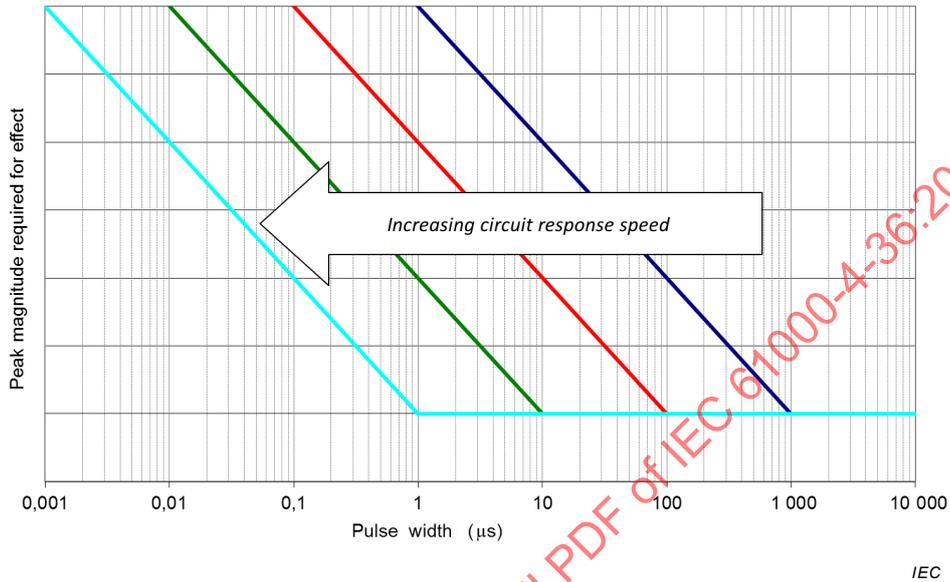


Figure A.4 – Generic failure trend as a function of pulse width

Figure A.4 shows how the peak power for failure for a typical circuit will decrease as the pulse width increases, corresponding to the average power failure mode. At the transition point the circuit no longer reacts to the increasing average power and appears to depend only on the peak power corresponding to the peak power mode.

A comparison between the failure modes of typical older analogue equipment and newer digital equipment is given in several of the references. Most modern equipment cannot be defined as wholly analogue or wholly digital in nature, and the assumption that a single mechanism is responsible for the equipment susceptibility is a simplification. However, it is clear from the references that for many systems there is a dependency on pulse width and the peak power required. Additionally, as indicated by the arrow in Figure A.4, faster circuits are generally more susceptible to shorter pulse widths.

A.4 Performance criteria

Determination of a system under test either passing or failing a test requires classification of the test results in terms of the loss of function or the degradation of performance of the system under test, relative to a performance level defined by its manufacturer or specified in the test plan.

Recommended performance criteria are shown in Table A.1.

Table A.1 – Recommended performance criteria

Performance	Description
Normal	Normal performance within specified limits.
Tolerable interference	Appearing disturbances can be tolerated or do not influence the main function.
Performance degradation	The appearing disturbance reduces the efficiency and capability of the system.
Temporary loss of function	Temporary loss of function or degradation of performance which ceases after the disturbance ceases, and from which the equipment under test recovers its normal performance, without operator intervention.
Persistent loss of function	Temporary loss of function or degradation of performance, the correction of which requires operator intervention.
Permanent loss of main function	Loss of function or degradation of performance which is not recoverable, owing to damage to hardware or software, or loss of data.

The manufacturer shall define the performance criteria of the system under test in accordance with Table A.1.

A.5 References

- [A.1] Nitsch, D.; Camp, M.; Sabath, F.; ter Haseborg, J.L.; Garbe, H.; "Susceptibility of some electronic equipment to HPEM threats", IEEE Transactions on Electromagnetic Compatibility, vol.46, no.3, pp. 380- 389, Aug. 2004
- [A.2] Camp, M.; Garbe, H.; "Susceptibility of Personal Computer Systems to Fast Transient Electromagnetic Pulses", IEEE Transactions on Electromagnetic Compatibility, vol.48, no.4, pp.829-833, Nov. 2006
- [A.3] Sabath, F.; "Classification of Electromagnetic Effects at System Level", Ultra-Wideband, Short Pulse electromagnetics 9, Springer Science+Business Media, pp. 325- 334, 2010, ISBN 978-0-387-77844-0
- [A.4] IEC TR 61000-1-5, *Electromagnetic compatibility (EMC) – Part 1-5: General – High power electromagnetic (HPEM) effects on civil systems*
- [A.5] Hoad, R.; Carter, N.J.; Herke, D.; Watkins, S.P.; Trends in EM susceptibility of IT equipment, IEEE Transactions on Electromagnetic Compatibility, vol.46, no.3, pp. 390-395, Aug. 2004
- [A.6] Unified Electromagnetic Environmental Protection: A Design Guide, Part A: Introduction and the Philosophy of Hardening', by Dr NJ Carter, QinetiQ
- [A.7] 'A time-domain view of the choice of transient excitation waveforms for enhanced response of electronic systems', Interaction Note 560, by C. E. Baum September 2000
- [A.8] 'Measuring the upset of CMOS and TTL due to HPM-Signals', by Norbert Esser and Bernd Smailus, ABB AG Corporate Research Center
- [A.9] 'Pulse Length and Power Dependency of the failure threshold of a Low Noise Amplifier', by Rolf Jonsson, Magnus Hoijer, Swedish Defence Research Agency
- [A.10] 'HPM Effects on Electronic Components and the Importance of this knowledge in Evaluation of System Susceptibility', by Gunnar Goransson, FOA Defence Research Establishment

- [A.11] 'Comparative Susceptibility Study of Pulse and Constant Illumination of Wires over Ground Planes', by KP Slattery, CKC Laboratories, Inc.

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Annex B (informative)

Developments in IEMI source environments

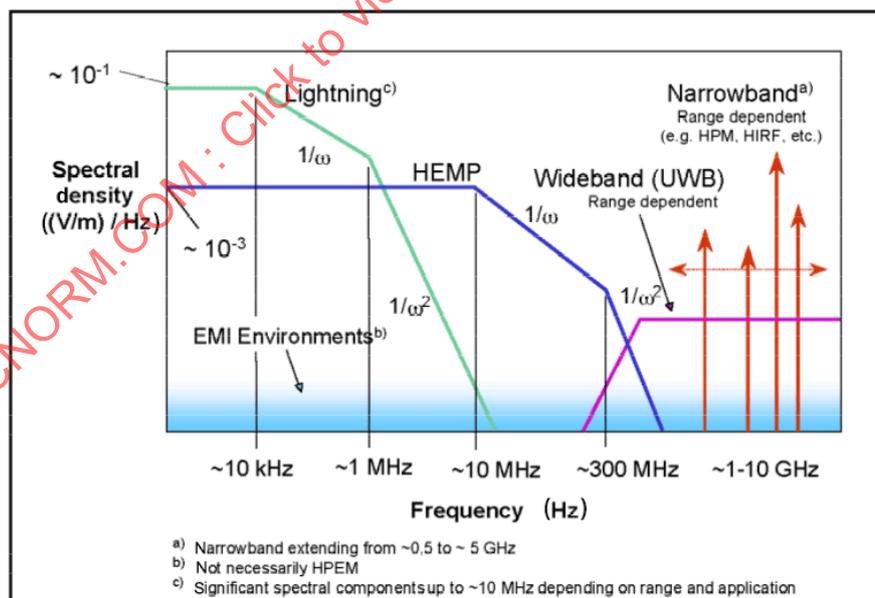
B.1 General

The use of electromagnetic sources [B.1]⁴ to generate intentional electromagnetic interference (IEMI) is becoming an increasing concern as the reliance of society on technology increases significantly. Many technical papers have been published that show the effects of IEMI are cause for concern [B.2], [B.3].

The effects of IEMI on equipment can be similar to the effects caused by high-power electromagnetic (HPEM) environments. HPEM environments include high-intensity radiated fields (HIRFs) generated by radio and radar systems, lightning electromagnetic pulse (LEMP) fields and electrostatic discharge (ESD). Some of these HPEM environments have similar characteristics to those sources used to cause IEMI but are unintentional IEMI sources, i.e. they are not used for malicious use. However, it is possible to use information regarding qualification of equipment and systems to these environments to inform the likely response to IEMI.

The scientific community has decided to accept the more generic term IEMI [B.4], which includes EM terrorism [B.5]. In February 1999 at a workshop held at the Zurich EMC Symposium, a widely accepted definition for IEMI was suggested: “Intentional malicious generation of electromagnetic energy introducing noise or signals into electric and electronic systems, thus disrupting, confusing or damaging these systems for terrorist or criminal purposes”.

Figure B.1 qualitatively presents several of these electromagnetic environments, along with the narrowband and wideband IEMI threats that are the subject of this document [B.6].



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Figure B.1 – A comparison of HPEM and IEMI spectra [B.6]

⁴ Numbers in square brackets refer to the references in Clause B.6.

In August 1999 the problem of IEMI was recognized by the International Radio Scientific Union (URSI) during a special session that resulted in an URSI resolution. The URSI “Resolution of Criminal Activities using Electromagnetic Tools” [B.7] was intended to make people aware of the following:

- The existence of criminal activities using electromagnetic tools and associated phenomena.
- The fact that criminal activities using electromagnetic tools can be undertaken covertly and anonymously and that physical boundaries such as fences and walls can be penetrated by electromagnetic fields.
- The potentially serious nature of the effects of criminal activities using electromagnetic tools on the infrastructure and important functions in society such as transportation, communication, security, and medicine.
- That the possible disruptions of the health and economic activities of nations could have major consequences.

The URSI Council recommended to the scientific community in general, and the EMC community in particular, to take account of this threat and to undertake the following actions:

- Perform additional research pertaining to criminal activities using electromagnetic tools in order to establish appropriate levels of vulnerability.
- Investigate techniques for appropriate protection against criminal activities using electromagnetic tools and to provide methods that can be used to protect the public from the damage that can be done to the infrastructure by terrorists.
- Develop high-quality testing and assessment methods to evaluate system performance in these special electromagnetic environments.
- Provide data regarding the formulation of standards of protection and support standardization work.

It should be noted that the International Electrotechnical Commission (IEC) added the IEMI threat to its previous standardization work dealing with HEMP in 1999.

B.2 IEMI environment

In order to understand the nature of IEMI threats it is necessary to understand the different types of electromagnetic environments that can be produced and that can affect exposed equipment. This document focuses mainly on radiated threats, although injected threats will be summarised.

In terms of system vulnerabilities, the narrowband threat is usually one of very high power and high energy, since the electrical energy is delivered in a narrow frequency band. It is fairly easy to deliver fields in the order of many kV/m at a single frequency. Of course each system under test can have a vulnerable frequency that is different from others. Often the malfunctions observed in testing equipment with narrowband waveforms are those of permanent damage. Available test facilities using the narrowband or hypoband waveforms can be found in an article by Sabath *et al.* in [B.8].

The wideband threat is somewhat different. Since a time domain pulse produces energy over many frequencies at the same time, the energy density at any single frequency is considerably less. Therefore damage is not as likely as in the narrowband case; however, it is easier to find a system's vulnerability since many frequencies are applied to the system simultaneously. Sources that have been built in the past typically produce repetitive pulses that can continue for many seconds, thereby increasing the probability of producing a system upset. Test facilities producing these types of waveforms are described in an article by Prather, *et al.* [B.9].

While the waveform characteristics are defined above, there are two primary ways that they can be delivered to a system. One is through the application of radiated fields, and the other is through injection along cables and wires. These two methods of delivery are consistent with the general treatment of electromagnetic disturbances in the field of electromagnetic compatibility (EMC) where nearly all environments and tests are defined in terms of radiated or injected environments [B.10].

For radiated fields, it seems clear that frequencies above 100 MHz are of primary concern in that they are able to penetrate unshielded or poorly protected buildings very well and yet couple efficiently to the equipment inside of the building. In addition, they have the advantage that antennas designed to radiate efficiently at these frequencies are small. Figure B.2 illustrates a qualitative view of how radiated fields can illuminate and couple to system electronics through apertures (e.g., windows) and through building wiring [B.3].

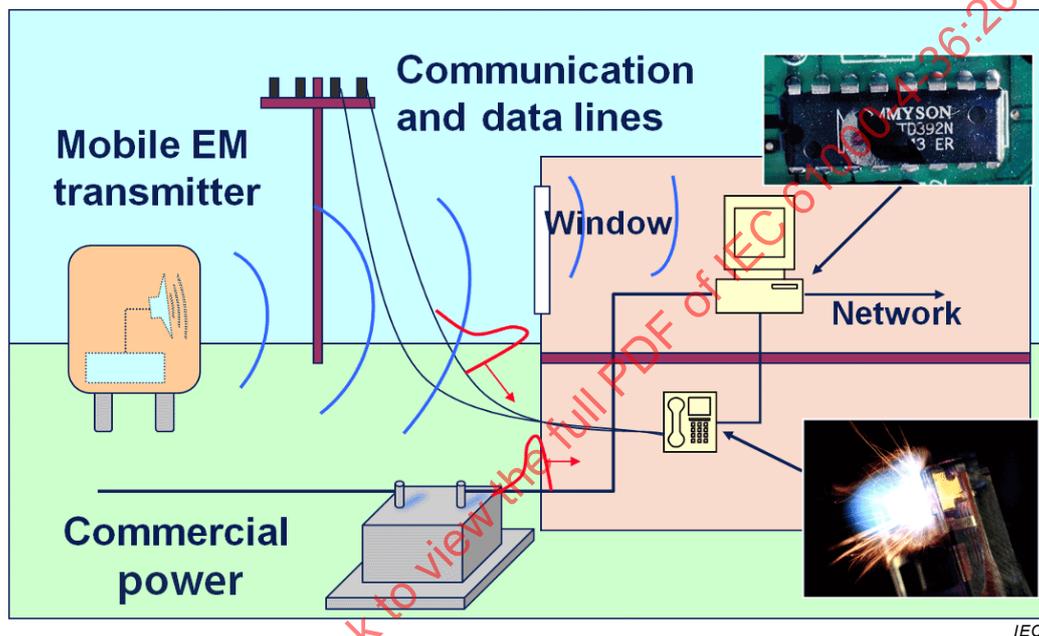


Figure B.2 – Representation of typical IEMI radiation and coupling onto systems [B.3]

For injected voltages and currents, there are some differences in terms of the frequency range of interest. It is well established that if common-mode conducted signals are injected into the power supply or telecom cables outside of a building, frequencies below 10 MHz (and pulse widths wider than 50 ns) propagate more efficiently than higher frequencies. Experiments by Parfenov *et al.* have shown that these “lower” frequencies can disrupt the operation of equipment inside a building [B.11].

B.3 IEMI sources

The nature of IEMI sources [B.1] varies from very sophisticated sources being developed in research laboratories and industry to threats hastily assembled by novices. The sophisticated sources, termed directed energy weapons (DEWs), occupy a parameter space that is illustrated in Figure B.3 [B.1]. Note that the wideband (hyperband) sources tend to be at lower frequencies and contain much less energy per pulse than the HPM (hypoband or narrowband) sources (see Figure B.4). The sophisticated IEMI sources are increasingly higher power, increasingly more compact, and can be operated repetitively. Recent advances at the Institute of High Current Electronics, Siberian Branch of the Russian Academy of Sciences have taken advantage of phase coherence to demonstrate a roughly N^2 scaling in output power when N -separate HPM sources are operated with phase coherence within 25 %. An example is shown in Figure B.7 [B.12].

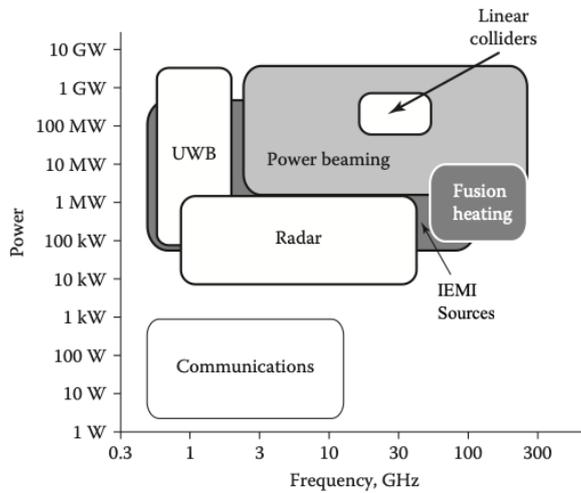


Figure B.3 – Parameter space in power/frequency occupied by sophisticated IEMI (i.e. DEW) sources in comparison to common RF systems [B.1]

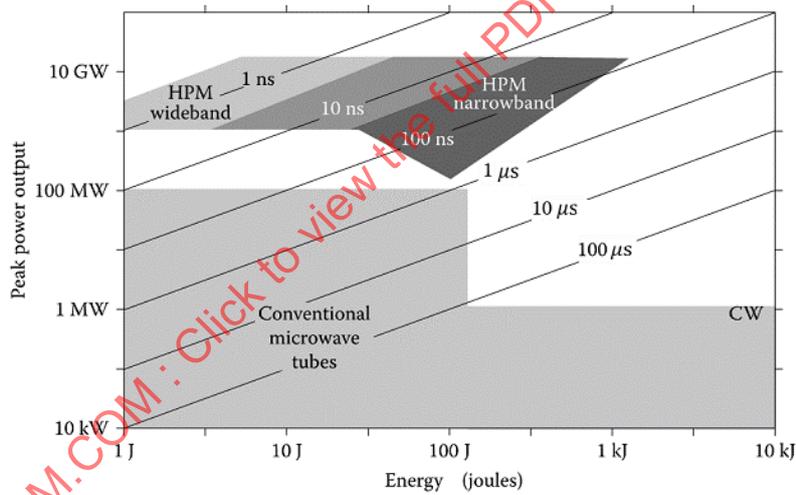
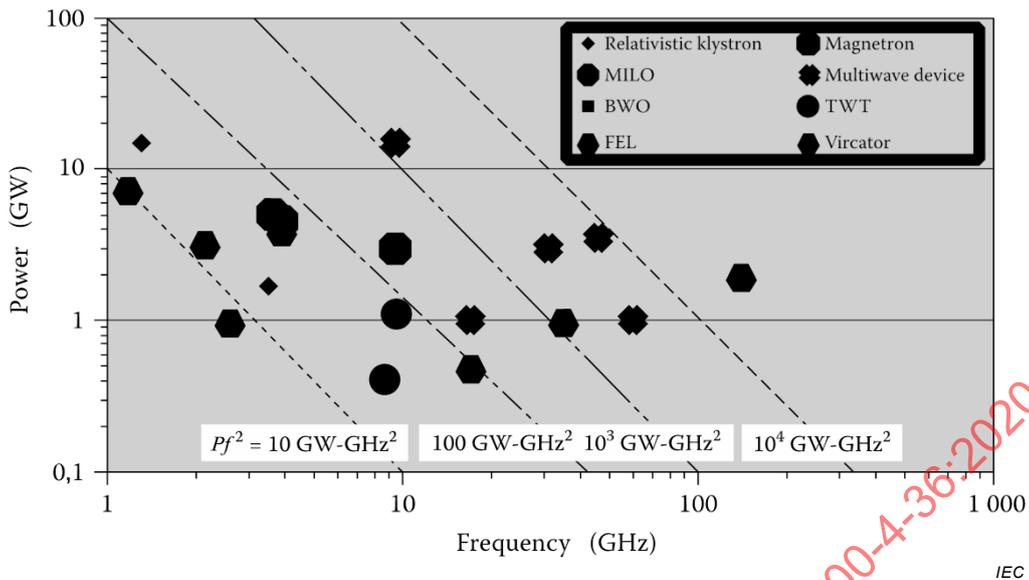


Figure B.4 – Peak power and energy from continuous and pulsed (durations shown) microwave sources, narrowband and wideband

Further, for hypoband or narrowband sources worldwide surveys of typical source power levels have been conducted, see Figure B.4 [B.17]. Figure B.5 and Figure B.6 demonstrate the achieved power levels.



NOTE The values of the quality factor Pf^2 scaling (where P is the output power and f is the frequency) vary over several orders of magnitude.

Figure B.5 – Peak powers of various types of pulsed hypoband/narrowband sources [B.1]

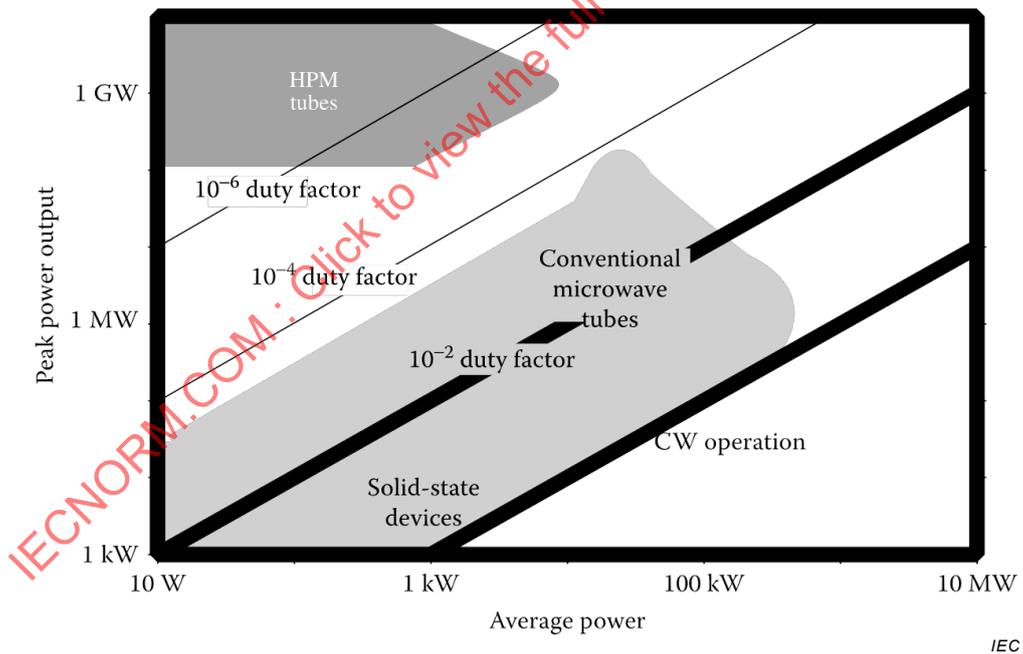
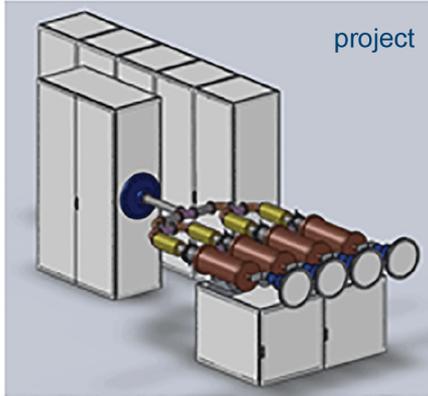


Figure B.6 – Peak versus average power for microwave sources with duty factors indicated

The duty factor for IEMI sources is the product of the pulse length and the pulse repetition rate, and is of the order of 10^{-6} (10^{-5} at most).

A prominent example of a mesoband source is the Diehl-Rheinmetall⁵ briefcase sources, shown in Figure B.8 [B.3].



Generation frequency	10 GHz
Microwave pulse duration	0,8 ns
Peak pulse power	4 × 1,5 GW
HVG type - Tesla transformer	
FL impedance	25 Ω
Max FL charging voltage	700 kV
HV pulse length	10 ns
Pulse repetition rate	up to 200 p.p.s.
Time of continuous operation	up to 1 s
Solenoids power supply stored energy	3,5 MJ

- controllable tuning of the RF phase in each channel by NLTLs with biased ferrites;
- enhancement of power density and number of channels N^2
- what about longer pulse phase synchronization?

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NOTE The system depicted is capable of radiating 6,0 GW at X-band [B.12].

Figure B.7 – Phase coherence leading to a compact HPM source with N^2 scaling of output power

- Diehl Munitions Systeme is marketing a small interference source (including antenna)
 - 350 MHz damped sine field
 - 120 kV/m at 1 m. (omni-directional antenna)
 - 30-min continuous operation (5 pulses/s or 3 hours in bursts)
 - 20 in x 16 in x 8 in and 62 lb



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Figure B.8 – Briefcase mesoband DS source sold by Diehl-Rheinmetall [B.3]

The narrowband and UWB HPM sources just described are examples of sophisticated sources that took considerable resources to design and develop. At the other extreme are sources that can be constructed by novices using microwave ovens and other readily available components (such as from radar systems). An example is shown in Figure B.9. Although such devices radiated considerably lower powers than the sophisticated devices, at close range they can have effects on exposed electronic systems.

⁵ The mesoband interference source briefcase is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

An example of a Russian industrial scale electromagnetic weapon is the RANETS-E⁶, which was advertised at an Asian air show during the last decade. RANETS-E has goals of achieving operating parameters of 0,5 GW, 10 ns to 20 ns, 500 Hz in X-band, with 45 dB to 50 dB gain antenna [B.1].



Figure B.9 – A do-it-yourself electromagnetic weapon made from an oven magnetron [B.13]

B.4 Published radiated IEMI environments

B.4.1 IEC 61000-2-13 [B.14]

IEC 61000-2-13 [B.14] presents several sources which could be considered as applicable to the IEMI threat. These are summarised in Table B.1.

Table B.1 – IEMI environments from IEC 61000-2-13

Name	Band	Typical operating frequency	Electric field	Source type
Phaser	Hypoband or narrowband	1,1 GHz	2,3 kV/m at 3 m	Magnetron
Dispatcher	Mesoband	500 MHz	100 kV/m at 1 m	Marx generator
Disrupter	Hyperband	200 MHz to 2 GHz (instantaneous bandwidth)	500 kV/m at 1 m	Impulse radiating antenna-based system

B.4.2 Mil-Std-464C

Mil-Std-464C [B.17] produced by the Department of Defense (DoD) discusses a wide range of electromagnetic environments (EMEs) and provides detailed descriptions and characteristics of the EME that military platforms/equipment could experience. It provides minimum performance and test requirements for equipment. In addition to standard electromagnetic compatibility (EMC) environments, version C includes a high power microwave (HPM) narrowband and wideband electromagnetic environment.

⁶ RANETS-E is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

Table B.2 and Table B.3 are taken from Mil-Std-464C [B.17]. Table B.2 provides field strengths that exist at 1 km for the hypoband/narrowband threat HPM environment. HPM is a military term used to describe a class of IEMI systems which can be used in military scenarios. Table B.3 and Figure B.10 provide a spectral magnitude description for wideband HPMs at a distance of 100 m. Of specific relevance here, it provides a table displaying the electric field spectral distribution for wideband threats. It should be pointed out that the levels given in Table B.2 and Table B.3 do not represent the verification requirements for a given system. For a given system a unique HPM worst-case environment has to be defined based on the operational scenarios, tactics and/or mission profiles of that system in combination with the types of HPM-weapons it can encounter.

Table B.2 – Hypoband/narrowband HPM environment from [B.17]

Frequency range (MHz)	Electric field (kV/m at 1 km)
2 000 to 2 700	18,0
3 600 to 4 000	22,0
4 000 to 5 400	35,0
8 500 to 11 000	69,0
14 000 to 18 000	12,0
28 000 to 40 000	7,5

Table B.3 – Wideband (mesoband/hyperband) HPM environment from [B.17]

Frequency range (MHz)	Electric field at 100 m engagement range (V/m/MHz)
70 to 100 (mesoband)	33
100 to 150 (mesoband)	33
150 to 200 (mesoband)	7
200 to 225 (mesoband)	7
225 to 400 (mesoband)	7
400 to 700 (hyperband)	1,33
700 to 790 (hyperband)	1,14
790 to 1 000 (hyperband)	1,05
1 000 to 2 000 (hyperband)	0,84
2 000 to 2 700 (hyperband)	0,24
2 700 to 3 000 (hyperband)	0,08

The table as published in the standard is very easy to misinterpret, however detailed scrutiny and information from other sources [B.18] identify that the data presented in Table A-5 of Mil-Std-464C:2010 [B.17] is a composite of the maxima of four wideband threat waveforms.

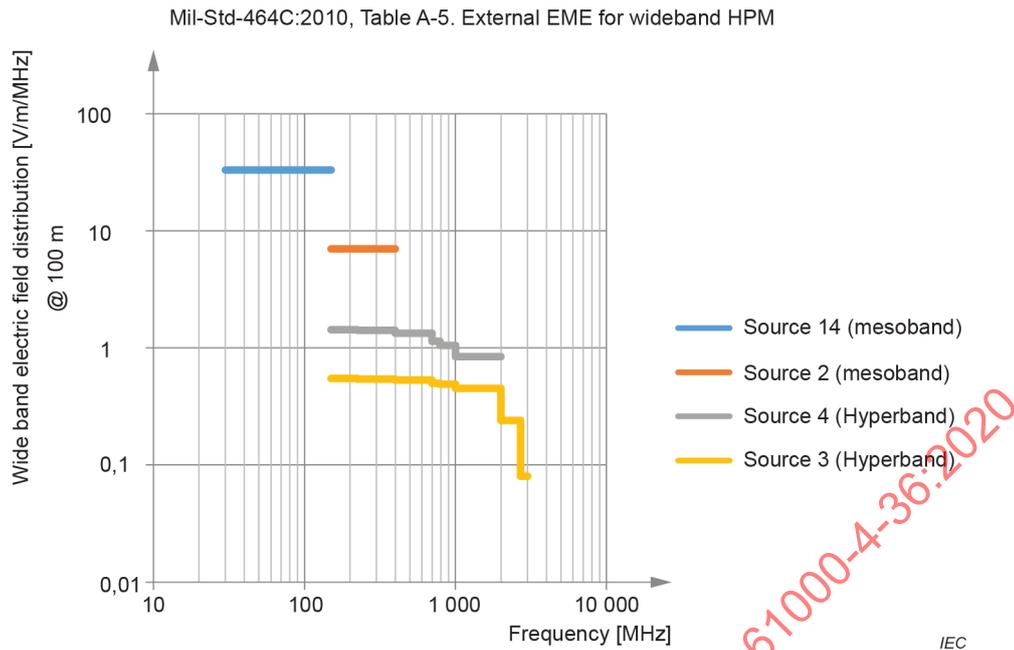


Figure B.10 – Wideband (mesoband and hyperband) EME derived from [B.17]

Within Mil-Std-464C [B.17] the mesoband and hyperband EME is defined in terms of the frequency domain's "electric field distribution" or "spectral magnitude". This information on its own is not sufficient to provide an adequate reconstruction of the equivalent time domain waveforms which are summarised by the distribution.

B.4.3 Selection of parameters for mesoband immunity test

B.4.3.1 General

Mesoband sources are typically used to produce radiated (rather than conducted) waveforms and typically employ a dipole (or a derivative thereof) as the radiating element. The dipole design strongly influences the dominant radiating frequency of the source. The dominant radiating frequency is herein defined as the frequency with the highest spectral magnitude contribution identified from a Fourier transformation of the measured time domain waveform.

Mesoband sources are tuneable, such that the dominant frequency f_d of the source waveform can be altered. However, alteration of the dominant frequency is done by changing either

- the pulsed power supply;
- the gas pressure, gas type, or gap spacing of the primary switch, if a Marx or Tesla or derivative is employed;
- the dipole antenna length/geometry; or
- any combination of the above.

Therefore tuning of mesoband sources cannot typically be achieved dynamically (during use) and requires the user to adjust key parameters in order to tune the source to a different dominant frequency. This is important in terms of the practicalities of testing with mesoband waveforms. In order to make the test practical a limited number of dominant frequencies should be selected.

The Q -factor for the mesoband pulse can be derived from Formula (1). As long as the percent bandwidth of the pulse corresponds to the 1 % to 100 % requirement to classify the waveform as mesoband, then a wide range of Q -factor values is acceptable. Values between 4,8 to 100 are considered acceptable.

Mesoband sources are pulse repetition frequency (prf) and burst duration limited. The maximum prf of the sources indicated above is 1 kHz but 100 Hz may be more typical of spark gap type switching type systems.

Mesoband sources are often burst duration limited as they are typically battery powered, whereas a mesoband immunity test simulation can be mains powered and capable of delivering mesoband pulses continuously. It is therefore important to set a burst duration limit and burst interval to be representative of the threat which is being simulated.

B.4.3.2 Dominant frequency (f_d) selection

The selection of the number of dominant frequencies to use during testing shall be selectable by the user within the range 80 MHz to 500 MHz as identified above. A minimum of three frequencies shall be selected to cover the required range. The dominant frequency selection could correspond to a known threat source or to a known susceptibility of the equipment under test. However, in terms of practicality the following can be used for guidance.

Immunity testing for mesoband sources is most likely to take place in semi-anechoic chambers where the test distance is limited to 3 m to 5 m. These chambers are generally compliant with field uniformity down to 80 MHz. Using 80 MHz as a reasonable lower bound for f_d is a compromise in terms of field uniformity, dipole dimensions and near/far field boundary conditions.

It seems reasonable and practical to use the Mil-Std-464C [B.17] frequency ranges to guide the selection of f_d .

To qualify the source as mesoband, the bandratio shall be between 1,01 and 3 (percent bandwidth between 1 % and 100 %). Assuming a bandratio of 2 for the two mesoband sources indicated in Figure B.10 and selecting the smallest number of frequencies that both cover the required frequency range, whilst also using known dominant frequencies of sources in the published literature, it is recommended that a minimum of three dominant frequencies be selected for mesoband immunity testing.

B.4.3.3 Q -factor

The Q -factor is not a parameter that is simple to select and is generally a consequence of the pulse radiating equipment configuration. The Q -factor by itself is not known to be correlated with susceptibility, though a larger Q will result in a marginally longer pulse width. It is therefore considered that the Q -factor may lie anywhere within the range 4,8 to 100 as long as the bandratio remains within the range 1,01 to 3.

B.4.3.4 Pulse repetition frequency selection

The selection of the pulse repetition frequency to use during testing shall be selectable by the user within the range 1 Hz to 1 kHz as identified above. The pulse repetition frequency selection could correspond to a known threat source or to a known susceptibility of the equipment under test.

Generally speaking it is known that there is a relationship between the number of pulses in an exposure and an effect in the equipment [B.19] [B.20]. It has been observed that after some minimum number of pulses the susceptibility level, in terms of E-field, can decrease. However, the number of pulses is highly dependent on the function (clock period, data rate, cycle time, etc.) of the EUT and parameters of the test waveform.

Therefore it is recommended that the user selects the pulse repetition frequency appropriate to the test up to a maximum pulse repetition frequency of 1 kHz.

B.4.3.5 Burst duration and interval selection

The selection of the burst duration to use during testing shall be selectable by the user within the range 1 s to 10 s as identified above. The burst duration selection could correspond with a known threat source or to a known susceptibility of the equipment under test. Whilst a maximum burst duration of 10 s is possible, for practical purposes and considering the equipment under test's response time a burst duration limit of 2 s is considered adequate.

A single burst at each test level is considered adequate if the pulse repetition frequency is at the maximum. However, for guidance a minimum burst to burst interval (burst duty cycle) of one burst every 2 s with a 2-s rest period is considered practicable if it is identified that a particular threat source is capable of burst repetition.

B.4.3.6 E-field polarization

Mesoband threat sources are typically deployed with a horizontally polarised antenna. Horizontal polarization is therefore the preferred polarization for mesoband immunity testing and it is considered acceptable to use this polarization only. However, vertical or circular polarizations could be used to correspond with a known threat source if necessary.

B.4.3.7 Test environment

Free field radiated tests with the mesoband waveforms described previously can be difficult to conduct in an outdoor open air environment due to spectrum management and other interference and safety related concerns. It is considered practical to conduct mesoband immunity testing within a semi-anechoic, fully anechoic room or within a transverse electromagnetic mode (TEM) waveguide. The primary constraint for testing within a room or cell is achieving an appropriate field uniformity over the equipment under test volume at the available test distance.

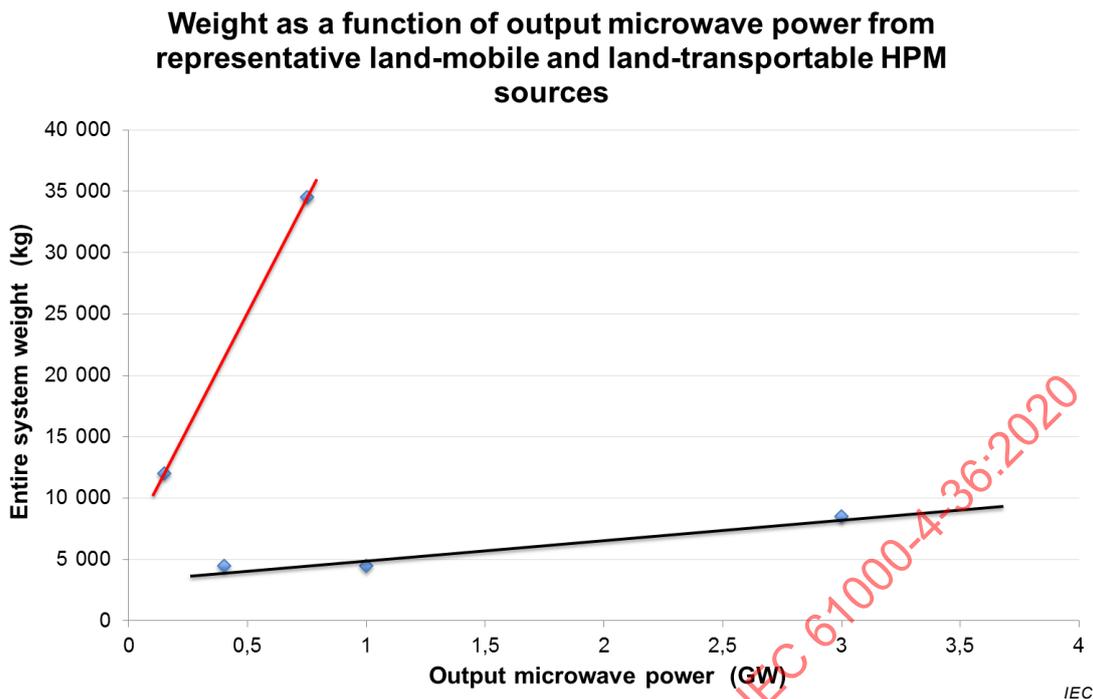
The minimum suggested dominant frequency is 80 MHz, at a typical test distance of 3 m within a semi-anechoic chamber (SAC) test chamber. At this distance it can be difficult to maintain far field conditions if the largest antenna aperture dimension is not kept to a minimum, hence field uniformity should be satisfied in accordance with Annex H.

B.4.4 International Telecommunication Union (ITU)

The International Telecommunication Union (ITU) has published a "High-power electromagnetic immunity guide for telecommunication systems" [B.21] that also contains published levels of IEMI environments.

B.5 Summary

IEMI sources are increasingly pervasive. They range from small do-it-yourself sources that can be built from directions found on the Internet to highly sophisticated narrowband (hypoband) sources that are only found in national laboratories and universities. Regarding the latter, they can also be broken up into sources that fire a single shot at a time and those that can fire repetitively in a burst. Figure B.11 presents the typical range of mass (in kg) and power (in GW) of these two types of sources.



NOTE 1 The black line (lower line) is a trend line for single shot sources and the red line (upper line) is a trend line for systems that are repetitively pulsed (tens to hundreds of hertz).

NOTE 2 This is representative data relevant for sample land-mobile or land-transportable systems and includes the weight of the entire hypoband system, from prime power to antenna. This was generated by combining data from Table 2.1 in [B.14] for the HPM sources, and models from HELMDALL [B.16] for the weight of the hypoband system components.

Figure B.11 – Plot of entire narrowband system weight as a function of output microwave power for land-mobile and land-transportable systems

Whether or not the more massive sources can find their way to be used as part of the IEMI environment remains to be seen. The lighter variants are certainly more likely to be used and can be just as effective as the higher power, more massive devices, provided they are brought closer in range to the victim.

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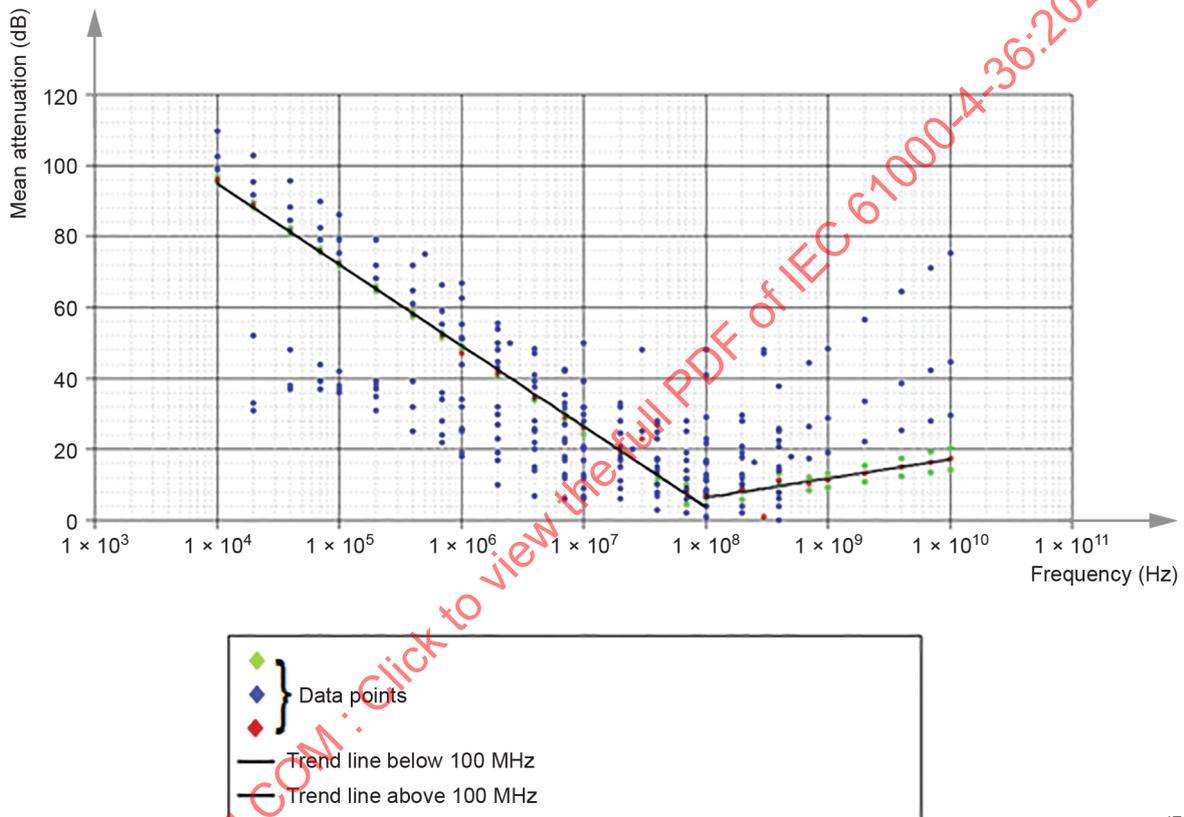
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Annex C (informative)

Interaction with buildings

C.1 Building attenuation

Buildings and structures provide a level of attenuation against IEMI environments (and other EM environments). The degree of this attenuation, referred to as shielding effectiveness, is a function of the material used in construction and the frequency range of the IEMI environment. Figure C.1 shows data collected from published sources [C.1] to [C.7]⁷.



IEC

NOTE A re-bar structure in general gives very little attenuation above 500 MHz [C.8].

Figure C.1 – Typical unprotected low-rise building plane wave E-field attenuation collected from references

The trend lines in Figure C.1 are based upon measurements made on a typical office building (building types 3, 3a and 3b relate to office buildings in suburban areas) and are supported by the data from other sources made at varying distances into the building. The general trend is that attenuation decreases linearly for frequencies from 10 kHz to 100 MHz and then increases at a much-reduced rate to 10 GHz.

In [C.7] further data derived from measurements of rooms within buildings of varying construction averaged over frequencies between 1 MHz and 3 GHz is provided. This is shown in Table C.1.

⁷ Numbers in square brackets refer to the references in Clause C.4.

Table C.1 – Shielding effectiveness measurements for various power system buildings and rooms

Description	Shielding (dB)
Wood building	2
Room under wood roof	4
Wood building, room 1	4
Concrete, no re-bar	5
Wood building, room 2	6
Concrete and re-bar, room 1	7
Concrete and re-bar, room 2	11
Concrete and re-bar, room 3	11
Concrete and re-bar, room 4	18
Metal building	26
Concrete and re-bar, well protected room	29

Figure C.1 and Table C.1 are included here to allow the reader to estimate the shielding effectiveness afforded by buildings within which electronic systems that are required to be immune to IEMI environments are located. Given the frequency of the IEMI environment of interest, a reduction to test levels can be made using the shielding effectiveness data provided. It should be noted that this type of reduction applies only to assessments of radiated IEMI. Accurate values of shielding effectiveness can only be obtained through an assessment of the specific building and installation scenario.

For narrowband (hypoband) environments, a single figure can be used with reasonable accuracy when utilising shielding effectiveness measurements to reduce the magnitude of radiated IEMI. For hyperband environments, the user should assess the significance of using a single value or if multiple frequency-point values are required to improve fidelity in the assessment process.

C.2 Coupling to cables

The extent to which IEMI is coupled to cables depends on the associated wavelength (and therefore, frequency) of the energy and the length of the cable. Cable coupling is strongest when the wavelength is equivalent, or proportional, to the cable length. This is shown simplistically in Figure C.2 [C.9].

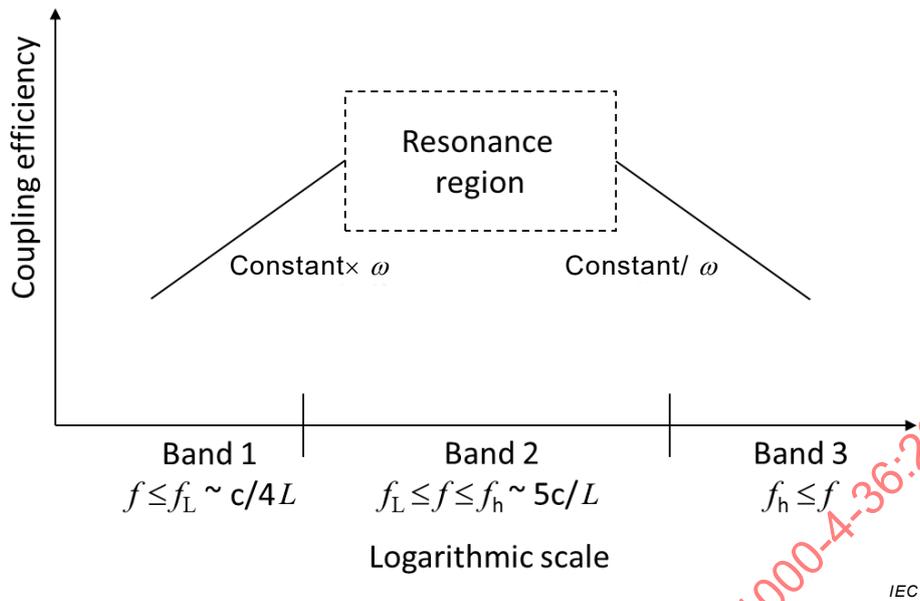


Figure C.2 – Cable coupling and resonance region

Figure C.2 shows coupling efficiency as a function of frequency where f is the frequency of interest, f_L is the lowest frequency in the incident IEMI environment, f_h is the highest frequency in the incident IEMI environment and L is the cable length; ω is angular frequency, $2\pi f$. In this example, band 2 shows the "resonance region", the region in which the maximum amount of energy is coupled to the cable from the incident IEMI environment. Coupling either below or above this region tends to follow a reduction of approximately 20 dB per decade. There are some minor adjustments to this trend for frequencies above the resonance region where "end-fire" conditions (special angles of incidence and polarization) can create a less rapid decrease in coupling.

C.3 Low voltage cable attenuation

The ability of a cable to conduct current efficiently is determined by a number of factors. One of the main factors is the material that the cable core is made of and the quality of any braid (shielding). A graph of attenuation per metre for a standard twin and earth low voltage cable is shown in Figure C.3 [C.10].

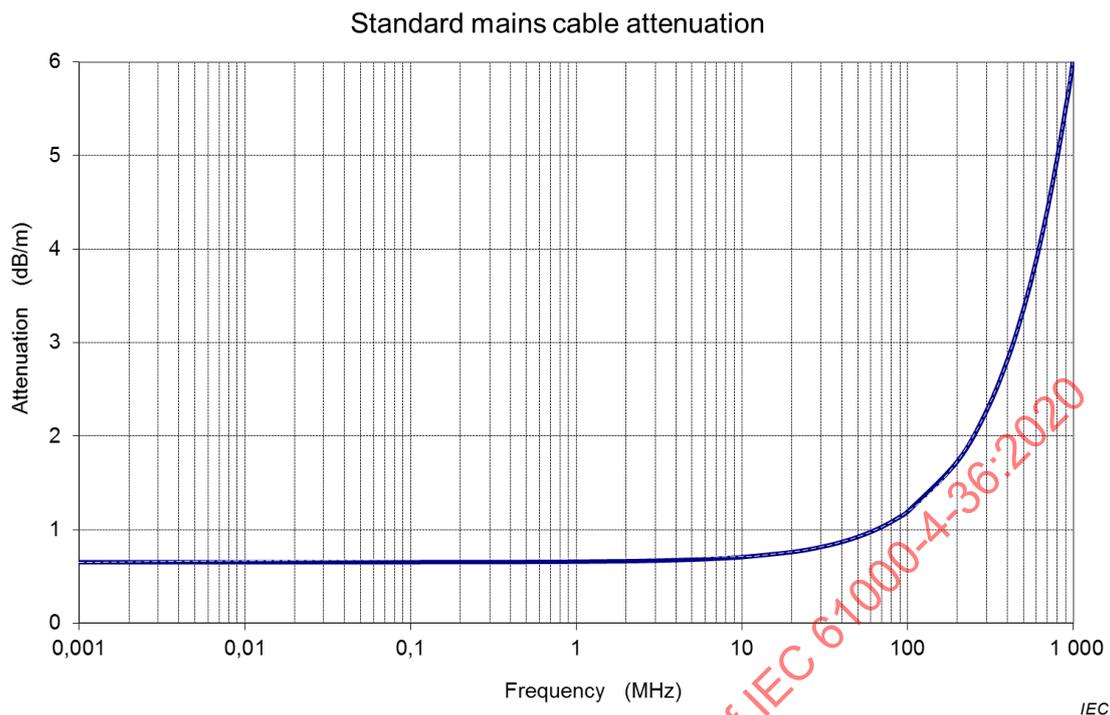


Figure C.3 – Mains cable attenuation profile

At 150 kHz the common-mode attenuation for a standard twin and earth low voltage cable is approximately 0,7 dB/m.

At frequencies around 200 MHz the common-mode attenuation of the cable approaches 2 dB/m. Given a 10-m cable length the attenuation would be 20 dB at this frequency, i.e. the injected signal would be an order of magnitude lower by the time it reached the EUT. At frequencies above 200 MHz the attenuation rises logarithmically.

C.4 References

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Annex D (informative)

Relation between plane wave immunity testing and immunity testing in a reverberation chamber

D.1 General

The problem in relating the outcome of a susceptibility test in a reverberation chamber to free-space conditions was identified and addressed early on [D.1]⁸. In a reverberation chamber the field can be regarded as illuminating the equipment under test (EUT) by plane waves coming from many directions within one stirrer rotation [D.23]. By use of a rotating stirrer located inside the chamber the boundary conditions are changed, thereby generating different field conditions. The concept of statistical isotropy, sometimes used for reverberation chambers, means that the ensemble average of the signal received by an antenna (or by a critical component inside the EUT) will be independent of the directional properties of the antenna [D.2]⁹. In an isotropic environment the ensemble average of the receiving cross-section, $\langle \sigma_p \rangle$, is, for all antennas and irrespective of their directivity properties, given by [D.3], [D.4], [D.5]:

$$\langle \sigma_p \rangle = \frac{\lambda^2}{4\pi} \cdot \langle D \rangle \cdot \eta \cdot \langle p \rangle \cdot q = \frac{\lambda^2}{8\pi} \eta \cdot q \quad (\text{D.1})$$

where λ is the wavelength, D is the directivity (sometimes denoted the directive gain), η is the antenna radiation efficiency, p is the polarization-matching factor, and q is the impedance-mismatch factor. It holds that $\langle D \rangle = 1$ and $\langle p \rangle = 1/2$ in an isotropic environment. Formula (D.1) illustrates the loss of information regarding polarization and directional properties in a reverberation chamber test.

The fact that the variations in directivity and polarization are averaged out in a reverberation chamber – illustrated by Formula (D.1) – indicates that an immunity test carried out in a reverberation chamber might be less severe than a test carried out in an anechoic chamber (AC), at least if the anechoic-chamber test comprises the worst angle of incidence and polarization. This also holds for measurements of shielding effectiveness (SE), i.e. a measurement in a reverberation chamber can yield a higher, i.e. a more favourable, value of the SE than a measurement in an anechoic chamber comprising the worst angle of incidence and polarization. Of course, the opposite can also be true, i.e. that the immunity test in an anechoic chamber might be less severe than a test in a reverberation chamber. This happens if all the test cases carried out in the anechoic chamber correspond to small values of $D \cdot p$, i.e. if the angle of incidence and/or the polarization corresponds to a weak coupling to the EUT.

The exact relation between the stresses an EUT will face in the two environments depends on the definition of the electric field used for immunity testing in a reverberation chamber (see [6]). Usually, in a measurement of shielding effectiveness (see below), the most natural choice is to use the scalar power density. This yields a value of SE measured in the reverberation chamber that is equal to the average value, with respect to all aspect angles and polarizations, of the shielding effectiveness measured in the anechoic chamber.

⁸ Numbers in square brackets refer to the references in Clause D.5.

⁹ It has been shown [D.17] that good isotropy also prevails at each position of the stirrer.

In an immunity test in a reverberation chamber the relation between the two environments becomes more complicated. One reason is that the immunity test parameter is given by, with respect to all stirrer positions used in the test, the maximum field strength and not by an average value of some more convenient parameter like the power received by the calibration antenna. Another reason is that different definitions on the test field strength, the total and a rectangular component of the electric field respectively, are used in different standards.

D.2 Relation between measurements of shielding effectiveness in the two environments

In a measurement of the shielding effectiveness (SE) of an EUT, the EUT is regarded with its internal field sensor as an antenna. The receiving cross-section, $\langle \sigma_p \rangle$, of an antenna is given by [D.7]:

$$\sigma_p = \frac{\lambda^2}{4\pi} \cdot G(\theta, \varphi) \cdot p \cdot q = \frac{\lambda^2}{4\pi} \cdot D(\theta, \varphi) \cdot \eta \cdot p \cdot q \quad (D.2)$$

where (see Formula (D.1) above) λ is the wavelength, G is the antenna gain and $D(\theta, \varphi)$ is the directivity, and where θ and φ denote the angle of incidence of the plane wave. The parameter η denotes the antenna radiation efficiency, i.e. it represents the losses of the antenna ($\eta=1$ for the lossless case), p is the polarization-matching factor, and q is the impedance-mismatch factor. In the present case, since the "antenna" consists of a shielded structure with a field sensor mounted inside, the "antenna" has a very low efficiency. In other words, the losses, represented by the parameter η , are very high, i.e. $\eta \ll 1$.

In a reverberation chamber, the scalar power density, S_{sc} , is defined by [D.3]:

$$S_{sc} = \frac{\langle |E_T|^2 \rangle}{Z_0} = \frac{8\pi}{\lambda^2} \cdot \langle P_r \rangle \quad (D.3)$$

where E_T is the total electric field strength, Z_0 is the free space wave impedance and P_r is the power received by an (lossless and impedance-matched) antenna in a reverberation chamber. The brackets indicate the average taken over all (statistically independent) stirrer positions used in the test.

In a measurement of shielding effectiveness made in a reverberation chamber the average power received by a sensor located inside the EUT, $\langle P_{r,sensor,RC-test} \rangle$, is given by (see the discussion below Formula (D.1)):

$$\langle P_{r,sensor,RC-test} \rangle = \frac{\lambda^2}{8\pi} \cdot \eta \cdot q \cdot S_{sc} \quad (D.4)$$

In a corresponding measurement of SE in an anechoic chamber, i.e. using the same sensor at the same location inside the EUT, one gets:

$$P_{r,sensor,AC-test} = \frac{\lambda^2}{4\pi} \cdot D(\theta, \varphi) \cdot p \cdot \eta \cdot q \cdot S_{AC} \quad (D.5)$$

where $S_{AC} = E_{inc}^2 / Z_0$ is the power density of the incident plane wave, with the field strength E_{inc} .

If the power densities in the two facilities are equated, i.e. $S_{sc} = S_{AC}$, the result is:

$$\frac{P_{r,sensor,AC-test}}{\langle P_{r,sensor,RC-test} \rangle} = 2D(\theta, \phi) \cdot p \quad (D.6)$$

The received power can thus differ up to $2D_{max}$ between the two environments, assuming that the power density in the anechoic chamber is equal to the scalar power density in the reverberation chamber. D_{max} denotes the maximum directivity taken over all angles of incidence.

Usually, shielding effectiveness is expressed as the ratio between field strength (electric or magnetic) or the ratio of the power densities, outside and inside the EUT. In a reverberation chamber test this can be achieved by defining an equivalent scalar power density inside the EUT in analogy with the definition in Formula (D.3) (see [D.8]). The term equivalent indicates that the field conditions inside the EUT do not necessarily fulfil the requirements for the field statistics in a reverberation chamber. The introduction of an equivalent scalar power density results in a shielding effectiveness equal to:

$$SE_{RC} = \frac{\langle P_r \rangle}{\langle P_{r,sensor,RC-test} \rangle} \quad (D.7)$$

Formula (D.7) represents a simple and fruitful way to define shielding effectiveness in a reverberation chamber (see [D.24]). By using the power received by the sensor (compensated for antenna efficiency and impedance mismatch) one does not explicitly have to derive a value of an internal field strength, which might turn out to be very difficult for narrow and complex environments. Also, it seems reasonable that the power received by a sensor is representative of the power that would be picked up by an internal cable or wire. It shall also be noted that any antenna used for the calibration of the field external to the EUT gives the same value of $\langle P_r \rangle$ (assuming that compensation has been made for differences in impedance mismatch and antenna efficiency). Thus, a measurement of SE will not depend on the type of antenna that is used for the calibration of the chamber.

For a measurement in an anechoic chamber the definition of SE is not applicable since a measurement of the power received in the calibration antenna depends on the gain of the antenna. Therefore, it is evidently a more natural choice to use the power density (or the electric or magnetic field strength) to characterise the field external to the EUT. If Formula (D.3) is used to define an equivalent scalar power density inside the EUT the result is:

$$SE_{AC} = \frac{S_{AC}}{S_{sc,eq}} = \frac{S_{AC} \cdot \lambda}{P_{r,sensor,AC-test} \cdot 8\pi} \quad (D.8)$$

Combining Formulae (D.3), (D.7) and (D.8) and assuming $S_{sc} = S_{AC}$, for the relation between SEs measured in the two chambers the following result is obtained:

$$\frac{SE_{RC}}{SE_{AC}} = \frac{P_{r,sensor,AC-test}}{\langle P_{r,sensor,RC-test} \rangle} = 2D(\theta, \phi) \cdot p \quad (D.9)$$

i.e. the same relation as given by Formula (D.6).

An alternative way, in both these environments, to avoid the difficulties associated with the concept of shielding effectiveness, for example the problem to determine field strengths or use an equivalent scalar power density in complex and narrow compartments, is to use the receiving cross-section of the sensor mounted inside the EUT, i.e.:

$$\langle \sigma_{p,RC} \rangle = \frac{\langle P_{r,sensor,RC-test} \rangle}{S_{sc}} \quad (D.10)$$

$$\sigma_{p,AC} = \frac{P_{r,sensor,AC-test}}{S_{AC}} \quad (D.11)$$

Again, compensation shall be made for the non-ideal properties of the sensor. An advantage of using the receiving cross-section instead of the shielding effectiveness is that the results of a measurement in a direct way can be related to the susceptibility of components inside the EUT that are, in one sense or the other, considered to be critical, see [D.9].

The relation between the cross-section measured in the reverberation chamber and that measured in the anechoic chamber is the same as the one given in Formulae (D.6) and (D.9). This means that the average of the receiving cross-section taken over all angles of incidence and the polarizations for a measurement in an anechoic chamber is equal to the cross-section measured in a reverberation chamber. This has been supported by measurement on several real and complex objects (see [D.10] and references in Clause D.5). These measurements have also shown a maximum directivity of the order of 10 dB to 15 dB. Useful estimates of the maximum directivity, based on the spherical wave theory and assuming that the spherical mode coefficients are independent random variables, can be found in [D.11], [D.20].

The dominant factor in the uncertainty related to a shielding effectiveness measurement is the number of stirrer positions used. The confidence interval in dB is given by [D.12]:

$$d[\text{dB}] = 10 \cdot \log_{10} \frac{1+k/\sqrt{zn}}{1-k/\sqrt{zn}} \quad (D.12)$$

where k determines the confidence level ($k=1,96$ for 95 %), z is the number of dimensions of the field data (1 or 3), and n is the number of independent stirrer positions. Assuming that the power picked up by the field probe and by the cables follows a chi-squared distribution with two degrees of freedom, it holds that $z = 1$ (see the discussion below on the choice between using the total electric field or a rectangular component of the electric field).

If Formula (D.12) is solved for n , the result is:

$$n = \frac{k^2}{z} \left(\frac{10^{\frac{d}{10}} + 1}{10^{\frac{d}{10}} - 1} \right)^2 \quad (D.13)$$

For example, if $d = 2$ dB and the desired confidence level is 95% ($k = 1,96$) then $n = 75$. Thus 75 stirrer positions yield a confidence interval equal to 2 dB, i.e. an uncertainty of roughly ± 1 dB (the confidence interval is not entirely symmetric). For $n = 100$ an uncertainty of roughly $\pm 0,9$ dB is obtained.

D.3 Relation between immunity testing in the two environments

In immunity testing in a reverberation chamber the electric field test level is expressed in terms of the maximum electric field, with respect to the (assumed statistical independent) stirrer position used in the test. Depending on the exact definition of the test level, the relation between a test in a reverberation and an anechoic chamber becomes more complicated than what was shown above for the average-based measurements of shielding effectiveness. This becomes clear when studying the expressions in [D.6] for the maximum of the total field, $|E_{T,Max}|$ and the maximum of a rectangular component of the field, $|E_{R,Max}|$. Since the relation between those two parameters depends on the number of stirrer positions there is no simple way to derive the value of one of these from the value of the other.

A "generalization" of the scalar power density (see Formula (D.3)), i.e. $S_{sc,Max} = 8\pi/\lambda^2 \cdot P_{r,Max}$ would give the same relation between the two environments as for the measurements of the shielding effectiveness and receiving cross-section shown above. However this would lead to a kind of ad-hoc definition of the maximum scalar power density leading to the relation $S_{sc} = 3 \cdot |E_{R,Max}|^2$ (see [D.13]).

For different reasons the choice of the electric field test level in a reverberation chamber has been to use either the maximum of the total field, $|E_{T,Max}|$, or the maximum of a rectangular component of the field, $|E_{R,Max}|$. Different choices have been made in different standards. In the DO-160F [D.14] standard for civil aircraft the former has been chosen while the latter has been chosen for the IEC 61000-4-21 [D.15] standard and for MIL-Std-461 [D.16]. An argument for choosing $|E_{R,Max}|$ is that the power absorbed by an antenna in a reverberation chamber follows the same statistical function (a chi-squared distribution with two degrees of freedom) as the magnitude of the square of a rectangular component of the electric field, i.e. $|E_{R,Max}|^2$, and that the same holds for the power delivered to the load, for example an electronic component, connected to a wire or a cable inside an EUT. This is of course not surprising since the wires and cables picking up the energy are expected to behave as antennas [D.17], [D.18]. The total electric field, on the other hand, can be of interest, for example in direct heating of the bulk of a component (see the discussion in [D.6]).

As was indicated above the relations between the maximum responses in the two environments become somewhat complicated when $|E_{T,Max}|$ or $|E_{R,Max}|$ are chosen as the test field strength. In both cases the relations, which in the case of determination of the shielding effectiveness equal $2 \cdot D_{Max}$, will now depend on the number of stirrer positions. The relations, which can be found in [D.19], show that the expected ratio between the maximum responses in the anechoic and reverberation chambers, respectively, varies for different choices of the number of stirrer positions, N .

If $|E_{T,Max}|$ is used to define the test field strength it follows that:

$$\frac{P_{r,AC,Max}}{P_{r,RC,Max}} = 2 \cdot D_{Max}, \text{ for } N = 1$$

$$\frac{P_{r,AC,Max}}{P_{r,RC,Max}} = 1,3 \cdot D_{Max}, \text{ for } N = 20, \text{ and}$$

$$\frac{P_{r,AC,Max}}{P_{r,RC,Max}} = 1,1 \cdot D_{Max}, \text{ for } N = 200$$

If $|E_{R,Max}|$ is used to define the test field strength (see the discussion in connection to Formula (D.8) in [D.13]), it follows that:

$$\frac{P_{r,AC,Max}}{P_{r,RC,Max}} \approx \frac{2}{3} \cdot D_{Max}, \text{ for all choices of } N.$$

Obviously, the strong dependency of N when choosing $|E_{T,Max}|$ as the test field strength can pose problems since the relation between the two environments becomes quite intricate, while this difficulty essentially does not hold for $|E_{R,Max}|$.

As noted above estimates of the maximum directivity, D_{Max} , based on the spherical wave theory can be found in [D.11], [D.20].

The relations above point out the risk for under-testing in a reverberation chamber, compared to a test in an anechoic chamber. However, apart from in-band radiated-susceptibility testing of antenna systems, it should be noted that the maximum stress level in the anechoic chamber is in practice never attained. The reason is that it would either require knowledge beforehand of the worst angle of incidence and polarization, or that a huge number of aspect angles and polarizations have to be used in the test [D.10]. In [D.22] a comparison was made, using measurements of coupling from an external field to an internal probe depicting a critical component, between a typical anechoic-chamber test – using four aspect angles and two polarizations – and a reverberation-chamber test using 12 stirrer positions. The result was expressed in terms of an error bias for each test chamber, defined as the ratio of the measured maximum response to the true maximum plane-wave response. It was shown that if the field strength in the anechoic chamber was equated to the maximum of a rectangular component in the reverberation chamber, the expected error biases became similar in the two chambers. Thus, in this case, the under-testing in each of the two chambers, with respect to the ideal worst-case plane wave test, was the same.

If a worst case test really is required, for example for safety-critical equipment, it might be better to make the test in a reverberation chamber including a margin corresponding to the relation given above, than to spend the extensive time needed to find the worst angle of incidence and polarization in an anechoic chamber. Alternatively, one can make use of the fact that the statistical distribution for the power received by a critical component inside an EUT is the same when varying the angle of incidence and polarization in an anechoic chamber as when the stirrer is rotated in a reverberation chamber, see [D.25]. By equating the average stress in the two environments and by making an appropriate choice of the number of independent stirrer positions, the maximum stress induced in the reverberation chamber test will be the same as the maximum stress that possibly can be achieved in an anechoic chamber test.

In the aforementioned standards, $|E_{T,Max}|$ and $|E_{R,Max}|$ are determined by use of a calibration procedure (see [D.14], [D.15], [D.16]). The field strengths can also be estimated from a measurement of the average (see [D.14]), or maximum (see [D.15], [D.16]) power measured by a receive antenna.

The uncertainty of an immunity test is not described by the same statistics as the one for an average measurement of for example shielding effectiveness. The test field strength is defined by the maximum field, with respect to a given number of independent stirrer positions, measured by a reference antenna. The measured value is assumed to be the maximum field seen by the EUT (however probably not at the same stirrer position). An investigation made on the uncertainty in immunity testing, based on the power received by the reference antenna, is presented in [D.17]. Figure 8 in [D.17] shows that the uncertainty in the maximum power stressing of the EUT, with respect to the maximum power measured by the reference antenna, $P_{r,Max}$, at a confidence level of 95 % is approximately ± 3 dB for $N=100$ (as for the average case above, the probability density function is not symmetric). The result can also be stated (see [D.17]) that one, for $N=100$, has to subtract a security margin of 2,3 dB from the power measured by the reference antenna to ensure that the stress on the EUT, within 95 % confidence, is equal to or larger than what is given by the reference value.

D.4 Additional aspects

The following additional aspects should be considered:

- If the EUT is to be located in an electromagnetic environment similar to that of a reverberation chamber, for example a large avionics bay, the problem of relating free field conditions to those in a reverberation chamber does have to be considered.
- The discussion above relates to the stress picked up by a critical component inside the EUT. Things become more complicated if there are several critical components and if the interference of a system is determined by a simultaneous malfunction of several critical components. The latter may be the case if the EUT employs for example triple modular redundancy (TMR) to reduce the risk of failure for critical functions.
- The term statistical isotropy is often used to point out that true isotropic conditions are only achieved in a statistical sense, for example if one in an average measurement uses a large, or infinite number of independent stirrer positions or independent spatial positions. In practice, however, it seems that, from a practical viewpoint, a sufficient isotropy is achieved also at one and the same stirrer position. This would imply that the assumption of isotropic conditions is in practice valid not only for average type measurements, for example for a measurements of shielding effectiveness, but also at radiated susceptibility testing (see [D.17]).
- If the EUT is subjected to pulse modulated waveforms, which is usually the case in susceptibility testing at microwave frequencies, it is necessary that the time constant of the chamber be shorter than the pulse length of the modulated waveform. To achieve that, the Q value of the chamber may have to be decreased, which means that the test field strength will be reduced for a given level of input power. A criterion used in several standards is that the chamber time constant shall not be greater than 0,4 times the pulse length.
- As shown above the test field strength depends on the number of independent stirrer positions. In practice this statistical independence is evaluated by checking that the stirrer positions are uncorrelated (see [D.15] and the discussion in [D.21]).

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Annex E (informative)

Complex waveform injection – Test method

E.1 General

High-power electromagnetic (HPEM) environments, including high-altitude electromagnetic pulse (HEMP) environments, interact with systems, causing currents to be induced. The frequency content and magnitude of this current is primarily a function of the geometry of the system and the impedance of the system conductors. Traditional methods assess the impact of these induced currents at equipment level with testing, using various test methods such as the injection of single frequency damped sinusoidal waveforms at various frequencies "in-band" to the threat environment. Alternatively, assessment is conducted at the system level using simulators to approximate the threat environment. The latter option is expensive with considerable time and funds being spent on planning, conducting and supporting a large-scale system test.

Equipment level testing is intended to reduce the risk of system level issues but at the present time does not consider the synergistic nature of the induced current caused by the illuminating threat environment. The synergistic nature of the induced current in this context refers to the fact that the actual induced currents from actual transient environments will be complex, consisting of many different frequencies. The determination of equipment level limits is based on historical information and one particular issue is that of the upper frequency limit. In the UK defence standard this upper limit is 50 MHz whereas the US military standard uses 100 MHz. Newer systems are adopting shielded cabling to assist in mitigating the risk when exposed to HPEM environments. These shielded cables are typically de-coupled at bay or compartment interfaces and can result in significant coupled content at frequencies greater than the present upper limit. The traditional methods rely on the defined test amplitudes, frequencies and bounds on the energy (damping factor, Q), which do not consider the synergistic nature of the transient excitation.

Given the constraints with respect to high-power transient simulators discussed above, alternative options are being sought that rely on the injection of waveforms that approximate the induced transient.

Annex E discusses a novel method for the prediction, construction and injection of complex transients that occur as a result of the exposure of a system or equipment to HPEM and HEMP environments.

E.2 Prediction

E.2.1 General

Cable bundle transfer functions can be measured using the low level swept current (LLSC) technique. This technique was developed in the 1980s by those seeking to remove the need for high-power illumination of aircraft during the process of providing aircraft clearance evidence against high-intensity radiated field (HIRF) environments [E.3]¹⁰. LLSC involves illuminating a system with a uniform low power, swept frequency, and electromagnetic field. The system under test is illuminated from four orientations in turn and completed for two polarizations of the transmit antenna. The technique is generally conducted between 500 kHz and 400 MHz and measurements are split into three bands to maximise transmit antenna efficiency and to ensure sufficient resolution in the final transfer function. The technique can be used up to 1 GHz but the validity of the transfer function at these higher frequencies is dependent on the length of

¹⁰ Numbers in square brackets refer to the references in Clause E.6.

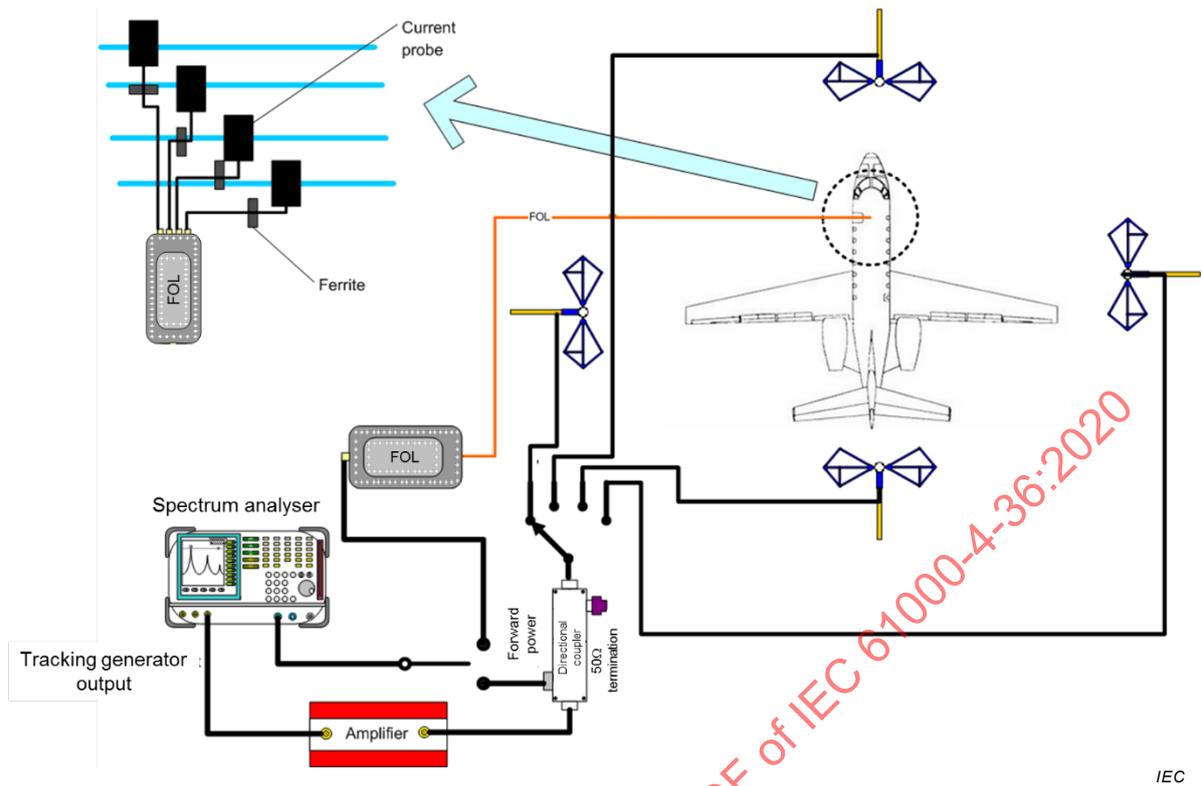


Figure E.2 – LLSC induced current measurement set-up

Each antenna is connected to the instrumentation (spectrum analyser, tracking source and amplifier) in turn such that the EUT can be illuminated from four consecutive orientations. The induced current is monitored by the spectrum analyser via a fibre optic link (FOL) to ensure electrical isolation.

A typical LLSC transfer function is shown in Figure E.3.

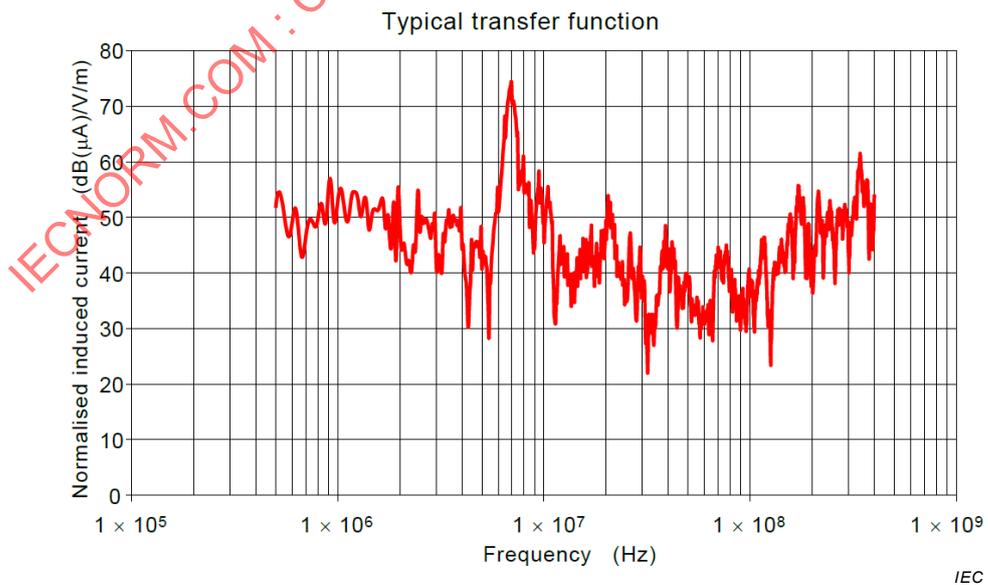


Figure E.3 – Typical LLSC magnitude-only transfer function

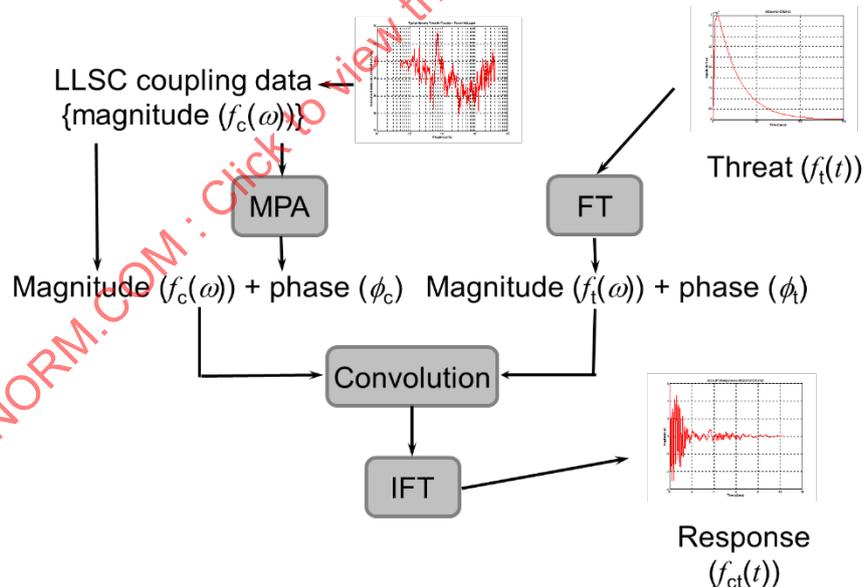
The measured transfer function can be used to predict an induced current as a result of an incident HPEM environment. In the case of frequency domain HPEM environments, the transfer function can simply be extrapolated to the frequency domain environment as it is expressed in terms of induced current normalised to the incident electric field across the relevant frequency range. However, for time domain HPEM environments, the prediction is complicated by the lack of phase information and convolution is required instead of simple extrapolation. Phase is not measured during the LLSC technique due to difficulties concerning the accuracy of phase measurements at frequencies above the dominant frequency, the effect of current probe location on the cable bundle being measured and the time burden required to carry out phase measurements. The lack of phase information is mitigated by the use of the minimum phase algorithm (MPA). This algorithm generates phase for the measured transfer function by imposing minimum phase constraints with a Hilbert Transform (Formula (E.1)):

$$\varphi(j\omega_0) = \frac{\omega}{2\pi} \int_{-\infty}^{\infty} \frac{\ln|H(j\omega)|}{\omega_0^2 - \omega^2} d\omega \quad (\text{E.1})$$

where $|H(j\omega)|$ is the magnitude component and $\phi(j\omega)$ is the phase component of the same transfer function.

The constraints are that the resulting prediction is stable, causal and has a stable inverse [E.4]. Although the minimum phase response will not be the true response of the system [E.5], it provides an order of magnitude response based on the total energy content of the incident wave being concentrated towards $t = 0$. However, specific information such as the peak value, its location and maximum rise time cannot be adequately predicted.

Figure E.4 gives a flow chart of the prediction process.



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Figure E.4 – Prediction of induced current using minimum phase constraints

The first stage of the prediction process is to generate the phase to be associated with the measured magnitude-only LLSC transfer function resulting in a complex transfer function, $f_c(\omega) + \Phi_c$. In parallel to this, the HPEM environment or threat, $f_t(t)$, is converted into a complex function via the Fourier Transform (FT), $f_t(\omega) + \Phi_t$. At this stage a complex function (magnitude and phase) exists for both the measured transfer function and the incident threat. An inverse Fourier transform (IFT) is performed on the convolution output resulting in the cable bundle response, $f_{ct}(t)$.

The process can be repeated with all measured transfer functions and can be used with any HPEM environment including ultrawideband (UWB), high-power microwave (HPM), damped sinusoid (DS) and electromagnetic pulse waveforms such as nuclear EMP (NEMP), HEMP or lightning EMP (LEMP), as long as the main frequency content of the threat environment falls within the frequency range of the transfer function data.

E.2.2 Example

The magnitude-only transfer function shown in Figure E.3 has, after deriving the phase by use of the minimum phase algorithm, been convolved with the IEC 61000-2-9 [E.6] early-time EMP waveform shown in Figure E.5. The transfer function and the frequency domain EMP waveform are overlaid in the frequency domain in Figure E.6. Finally, the predicted current is shown in Figure E.7.

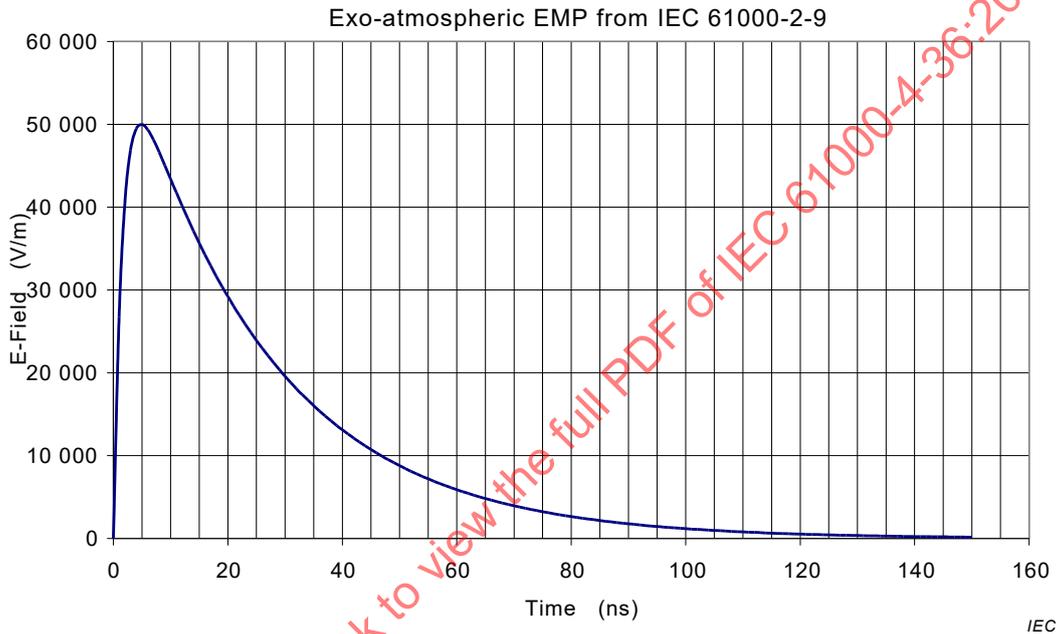


Figure E.5 – IEC 61000-2-9 early-time (E1) HEMP environment

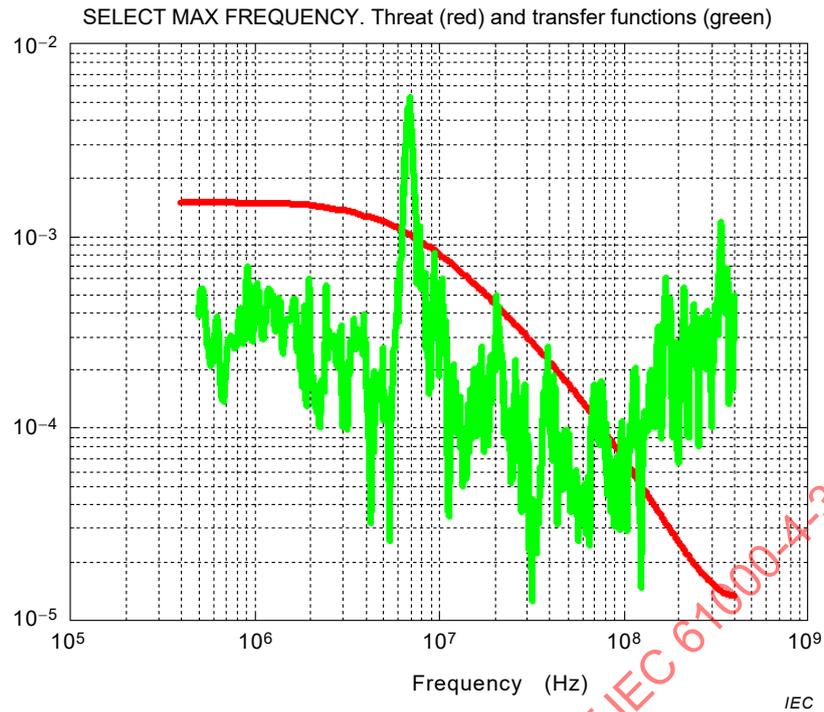


Figure E.6 – Overlay of transfer function and threat (frequency domain)

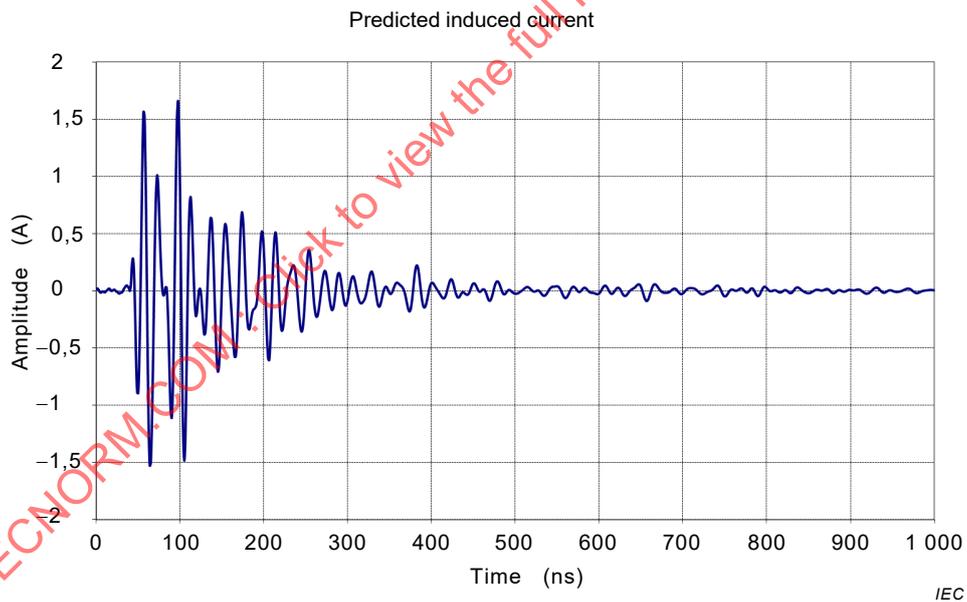


Figure E.7 – Predicted current

As part of the prediction process, the waveform norms of interest are calculated. The norms used, their mathematical definition and their physical description are given in Table E.1.

Table E.1 – Time waveform norms

Name	Type	Definition	Effect
Peak	Amplitude	$ f(t) _{\max}$	Circuit upset
Peak derivative	Variation	$\left \frac{df(t)}{dt} \right _{\max}$	Component arcing; circuit upset
Peak impulse	Content	$\left \int_0^t f(t) dt \right _{\max}$	Dielectric puncture
Rectified impulse	Content	$\int_0^{\infty} f(t) dt$	Equipment damage
Root action integral	Content	$\sqrt{\int_0^{\infty} f(t) ^2 dt}$	Component burnout

The waveform norms are used to uniquely characterise a transient and are used during the assessment of an injected waveform at the final analysis stage of this method.

E.3 Construction

In order to understand the contributions from each of the frequencies in the complex transient it is necessary to de-convolve it into its constituent damped sinusoid components such that the frequency, amplitude, relative phase and decay factors can be obtained. The de-composition algorithm used for this process is based upon a variation of the MPA that results in non-minimum phase predictions [E.7]. The Stieglitz-McBride algorithm [E.8] is used to fit poles and zeros to the complex transient. A partial fraction expansion is then used to extract the relevant parameters. The algorithm used to conduct the de-convolution allows the user to select the number of damped sinusoids to resolve (order of fit).

Typically, complex transients can be well approximated with the use of 4 to 6 damped sinusoidal components. The level of agreement between the approximation and the predicted transient is determined through an initial visual inspection followed by a mathematical analysis, which calculates the standard deviation error and the maximum error as a percentage of the peak.

Figure E.8 shows the result of de-convolving a complex transient into 10 damped sinusoids. The graph in the top-left corner shows each of the damped sinusoidal components with their respective parameters given in the table in the top-right. The graph at the bottom-left of Figure E.8 gives an overlay of the approximation and the complex transient, and the graph in the bottom-right shows the pole-zero plot of the approximation.

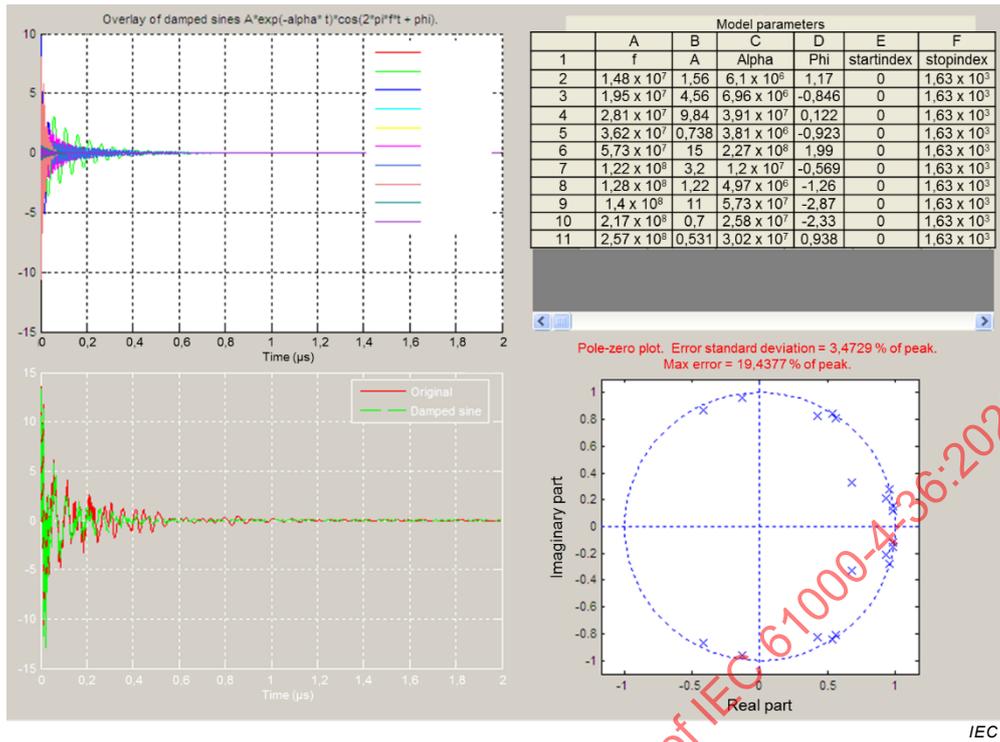


Figure E.8 – Example of de-convolution result

Figure E.9 shows the 10 individual damped sinusoidal components and Figure E.10 shows an overlay of the approximated and predicted transient.

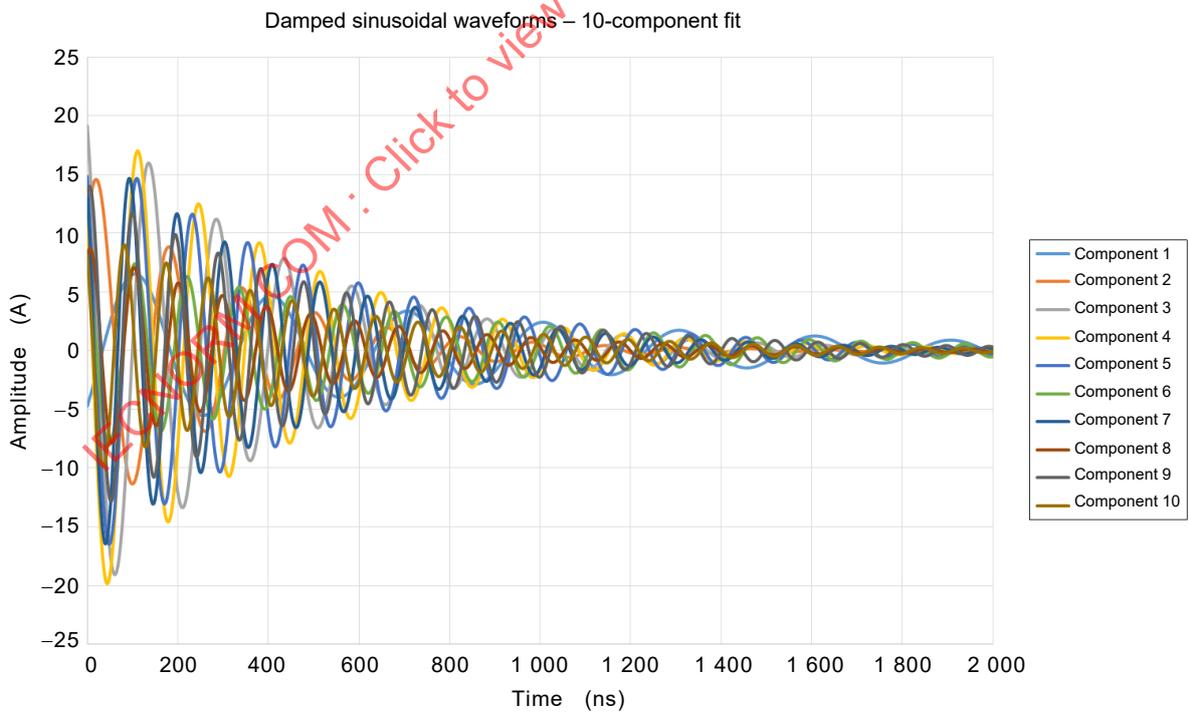
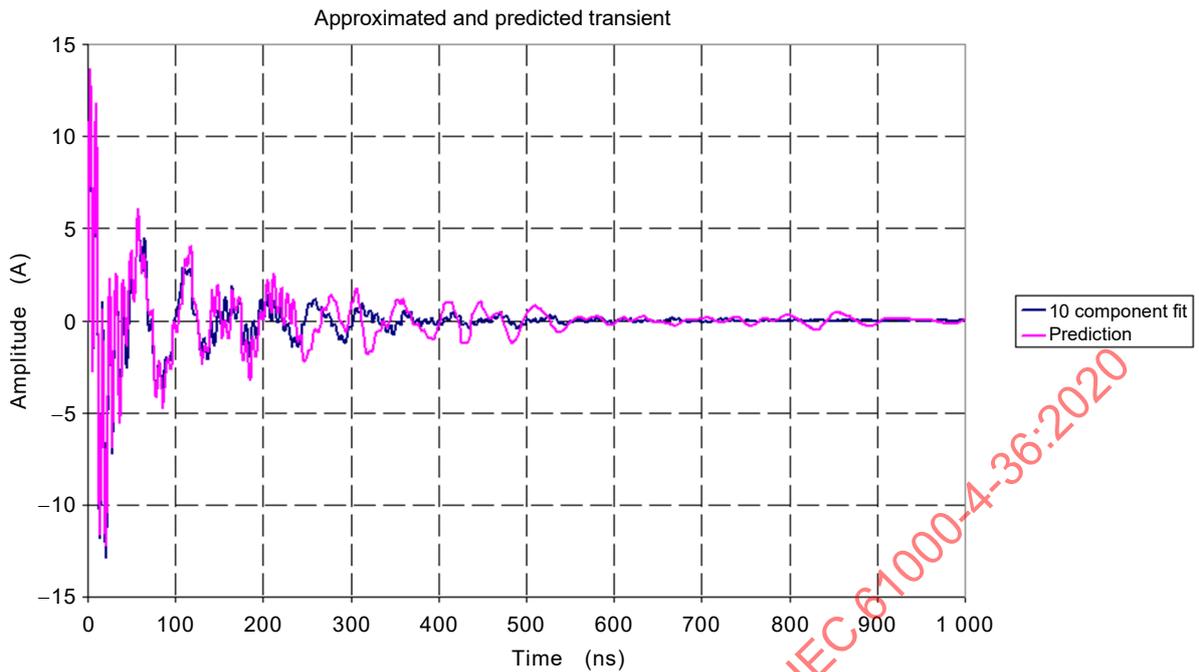


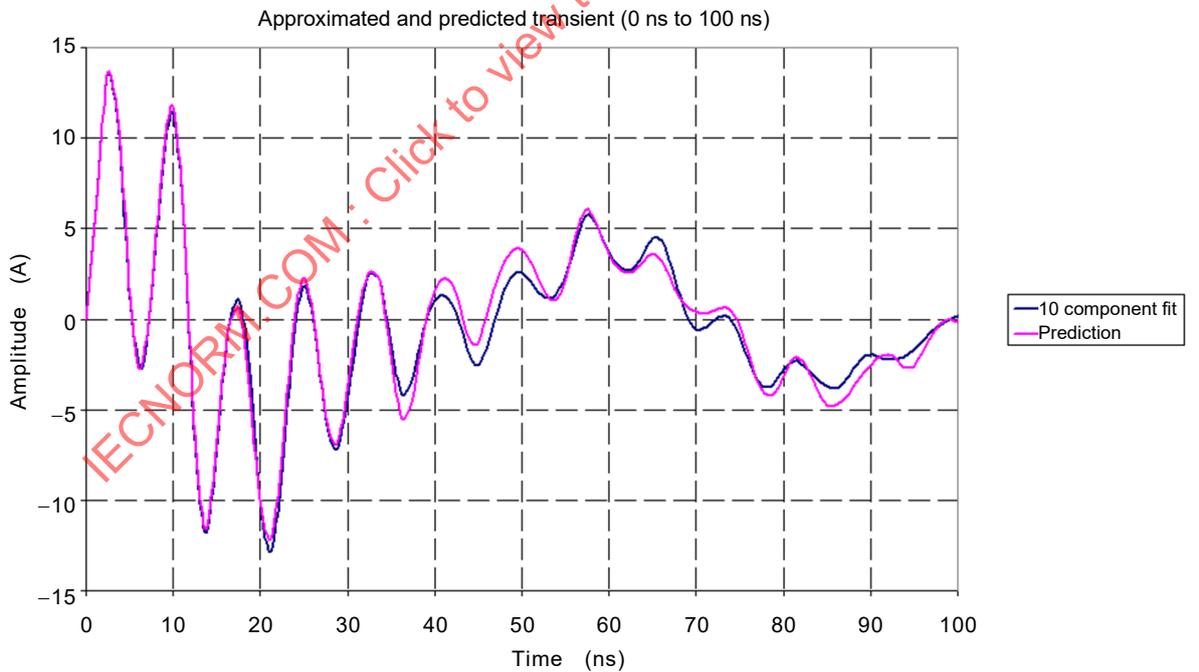
Figure E.9 – Damped sinusoidal waveforms – Ten-component fit



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Figure E.10 – Approximated and predicted transient

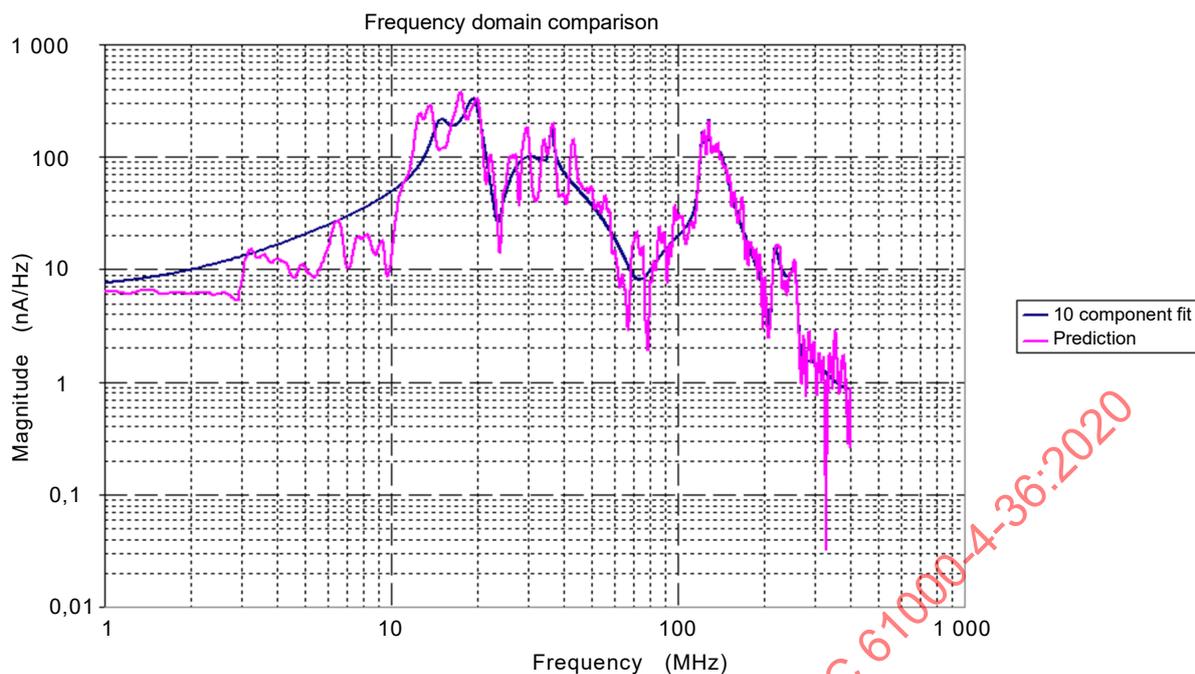
Figure E.11 shows the same overlay but expanded over the 0 ns to 100 ns range to more closely illustrate the degree of correlation between the approximation and the prediction.



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Figure E.11 – Approximated and predicted transient (0 ns to 100 ns)

Figure E.12 shows the comparison in the frequency domain.



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Figure E.12 – Approximation and prediction transient – Frequency domain comparison

As can be seen, the approximation is an excellent representation of the predicted transient.

Each individual damped sinusoid is expressed as a function of amplitude (A), time (t), frequency (f) and phase (ϕ) as shown in Formula (E.2).

$$Ae^{(-\alpha t)\cos(2\pi ft)+\phi} \quad (\text{E.2})$$

where $Q = \frac{\pi f}{\alpha}$.

The waveform approximation is the sum of each component with the phase parameter representing the relative phase between each component as shown in Formula (E.3).

$$A_1e^{(-\alpha_1 t)\cos(2\pi f_1 t)+\phi_1} + A_2e^{(-\alpha_2 t)\cos(2\pi f_2 t)+\phi_2} + \dots + A_n e^{(-\alpha_n t)\cos(2\pi f_n t)+\phi_n} \quad (\text{E.3})$$

The summation of each component and therefore the approximation is thus given mathematically by Formula (E.4).

$$\sum_n A_n e^{(-\alpha_n t)\cos(2\pi f_n t)+\phi_n} \quad (\text{E.4})$$

Figure E.13 shows the relationship between increasing the number of damped sinusoids and the associated error of fit between the approximation and the prediction.

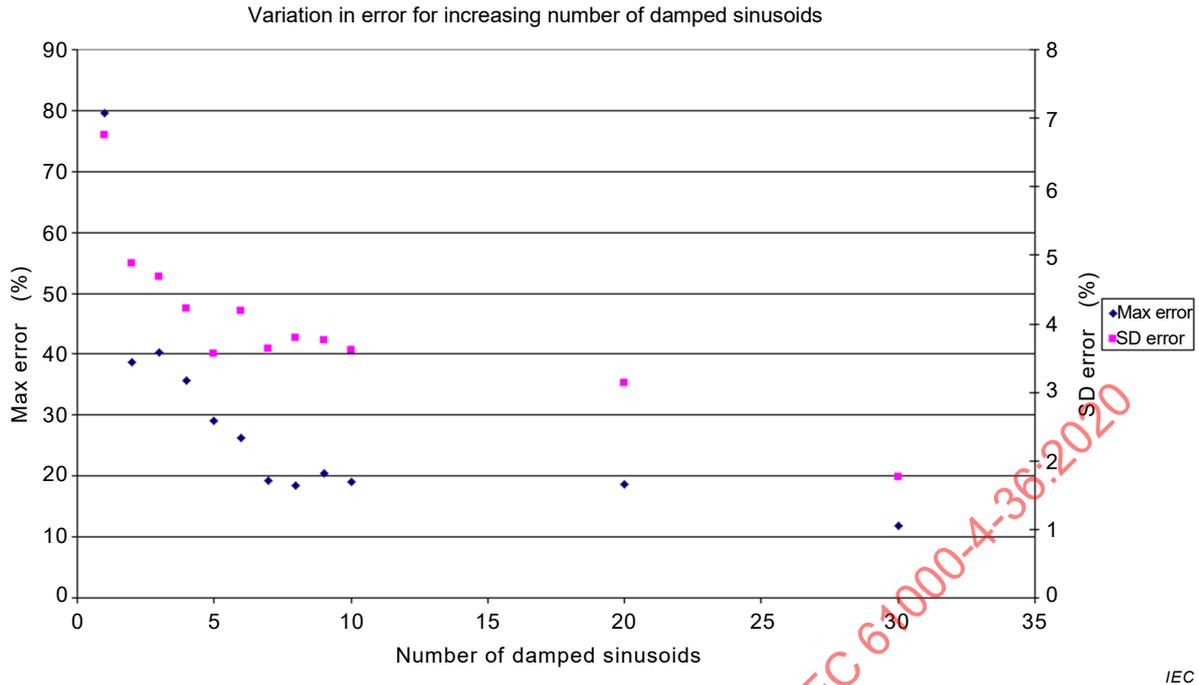


Figure E.13 – Variation in error for an increasing number of damped sinusoids

As the number of damped sinusoidal components is increased, the error decreases. After approximately 6 components are fitted, the reduction in error decreases significantly with the addition of each further component. As the number of damped sinusoids is increased the energy content of each additional component is decreasing, resulting in diminishing marginal improvements in the accuracy of the approximation.

E.4 Injection

In order to assess the response of equipment to the predicted transient, it is necessary to construct and inject the complex transient. Once the parameters of the approximating waveform are derived using the method explained in Clause E.3, a formula in the form of Formula (E.4) is programmed into a waveform synthesiser (arbitrary waveform generator). The output from the waveform synthesiser is passed through an amplifier and injected into a cable bundle using a suitable injection probe. A broadband matching transformer can be used between the amplifier output and the injection probe to improve the impedance match and maximise the injected current. This process is shown schematically in Figure E.14.

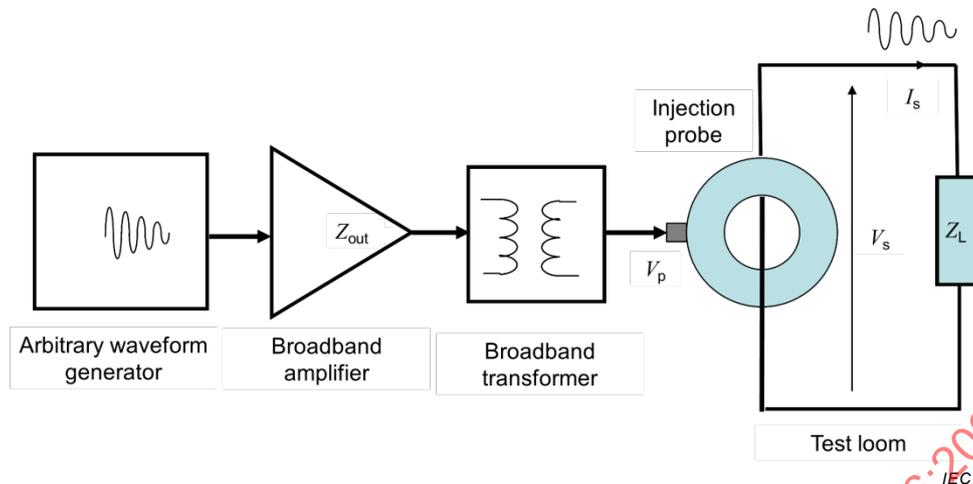


Figure E.14 – Complex injection set-up

Figure E.15 shows the results of simple calculations to estimate the amplifier power requirements needed to drive various current levels into a conductor for different impedances, assuming a broadband matching transformer is used to match the injection probe input impedance to the amplifier output impedance.

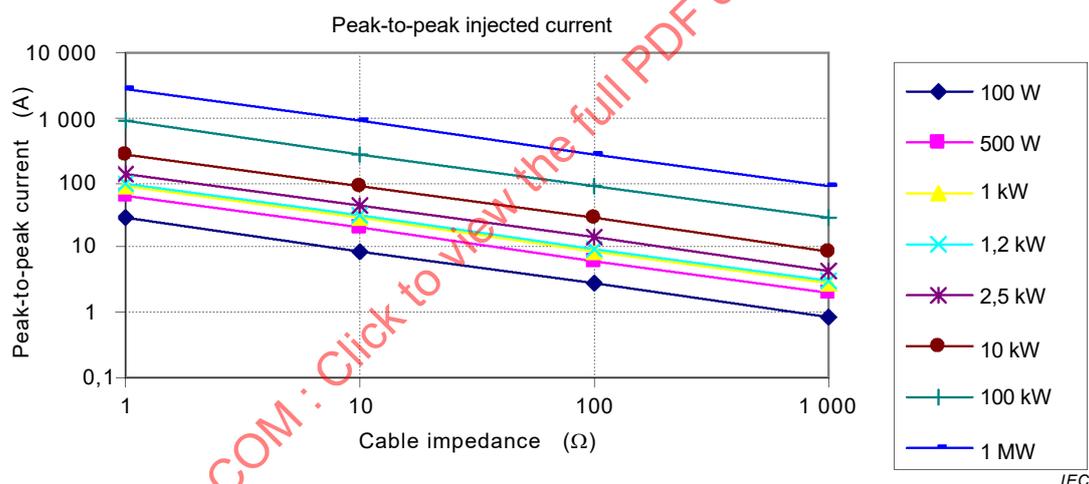


Figure E.15 – Amplifier requirements for various current levels

To achieve useful current levels (10 A to 100 A) a pulsed amplifier in excess of 10 kW is required. For example, Figure E.15 shows that the injection of current levels in the range 10 A to 100 A into a cable of 100 Ω loop impedance typically requires a 10 kW amplifier. Considerably more power would be required for situations where there is a poor match between the amplifier and its load.

One final analysis is required to assess the agreement between the predicted and injected transient as applied to a real system. An example is given in Figure E.16.

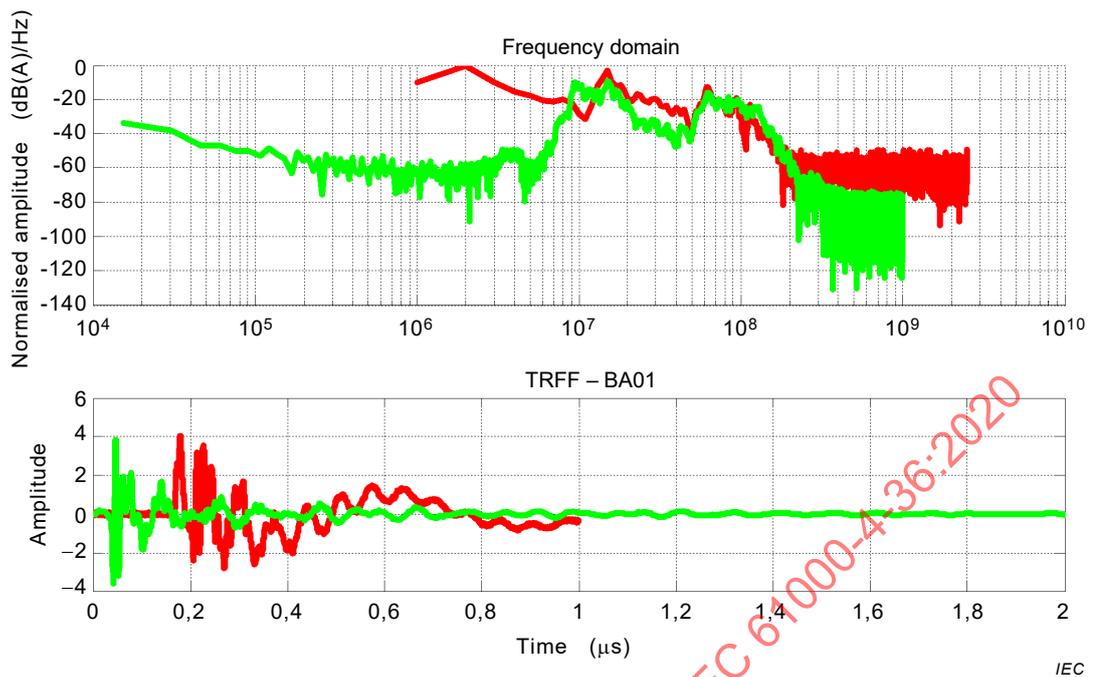


Figure E.16 – Comparison of predicted (green) and injected (red) current

As can be seen from Figure E.16, the complex injected waveform as measured on the real platform differs from the prediction. The most dominant factor affecting this variation is that the complex injected transient is injected on top of any power or data signal that the cable is already carrying. Thus, the monitor current probe will record the superposition of the injected signal and the normal operational signal.

E.5 Summary

Access and cost issues limit the availability of full threat transient simulators, and standardised damped sinusoidal waveforms are somewhat limited in their ability to reproduce realistic waveforms. The derivation and prediction of complex damped sinusoidal transients can be achieved and calculated where the system transfer function data is available.

A credible alternative method to the traditional approach of assessing the response of equipment to induced current as a result of an HPEM or HEMP environment has been presented and discussed. The new method exploits the synergistic nature of complex transients by virtue of the fact that they excite several frequencies simultaneously.

The norms of each prediction can be compared against the norms of each injected waveform to determine the level of HPEM or HEMP clearance that can be assigned.

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Annex F (informative)

Significance of test methodology margins

F.1 General

Understanding how a system responds to high-altitude electromagnetic pulse (HEMP) or high-power electromagnetic environments (HPEMs) typically requires testing of some variety. The test methods used will depend on a number of factors including the different operating configurations and functions of the system and the IEMI environment of interest. All test methods have an inherent uncertainty or error associated with them that can be readily determined by understanding the uncertainty associated with each item of test equipment, either through calibration or by referring to the manufacturer's data, and by combining them [F.1]¹¹. An example of a contributor to measurement uncertainty is the uncertainty in converting the measured voltage from a current probe to induced current. Typically, individual contributions to overall measurement uncertainty are between 1 dB and 3 dB.

Test methodology margins are another important element for understanding the overall uncertainty associated with testing and arise from limitations in the test methods. Any type of test requires a balance of time and cost against the need for evidence. Testing takes time out of any development programme and is often an unwelcome expense, therefore minimising test time is generally an overarching requirement.

Examples of contributions to the test methodology margin include [F.2]:

- Testing a single test object and applying the results to the entire production – modern quality assurance processes employed on production lines provide a high degree of confidence that all articles are built to the same design standard. However, this does not take into account any degradation of EM protection that can occur as a result of use or over time.
- Configuration/mode of system during test – due to the need to keep testing to a minimum because of the associated expense, it is common to test a number, but not all, of representative configurations. Specifically, when testing using radiated fields, general constraints include a limited number of illumination angles, polarizations and field distributions with respect to the "real" environment (hence IEMI "simulators").
- Equipment set-up – limitations such as access to cable bundles to connect probes/sensors, or limited ability to excite all ports simultaneously can generate significant uncertainty in the overall result.

Annex F includes examples of contributions to the test methodology margins based upon the limitations above.

F.2 Examples

F.2.1 General

Contributions to the test methodology margin can be either negative or positive, and Clause F.2 provides some example datasets for both types [F.2].

¹¹ Numbers in square brackets refer to the references in Clause F.3.

F.2.2 Negative contributions

F.2.2.1 Configuration

EMP testing was conducted on two aircrafts with different stores configurations, firstly "baseline" with no stores or tanks fitted and secondly "heavy" with a variety of stores and tanks fitted. Induced currents were measured across 112 test points for both horizontal and vertical polarizations. All measurements of induced current were normalised to the measured incident field to provide a direct comparison. Figure F.1 shows the induced current plotted against each configuration; the data has a range of -16,6 dB to 20,73 dB, a mean of 4,99 dB and a standard deviation of 6,38 dB.

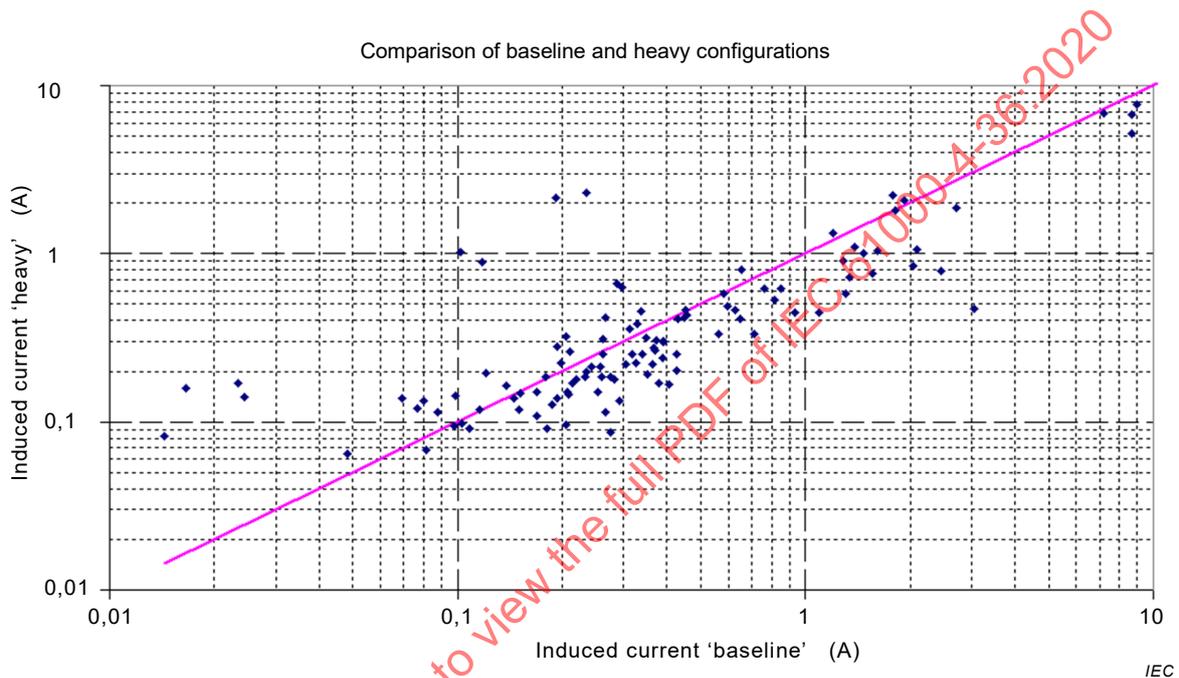


Figure F.1 – Variation in induced currents as a result of configuration

F.2.2.2 Polarization

Aircraft tests were conducted in two EMP simulators, a horizontally polarized dipole (HPD) and a vertically polarized dipole (VPD), allowing data to be obtained for both across 208 test points. In this case, the configuration was the same for all measurements. Figure F.2 shows the induced current plotted against each polarization; the data has a range of -4,4 dB to 20,96 dB, a mean of 6,46 dB and a standard deviation of 4,1 dB.

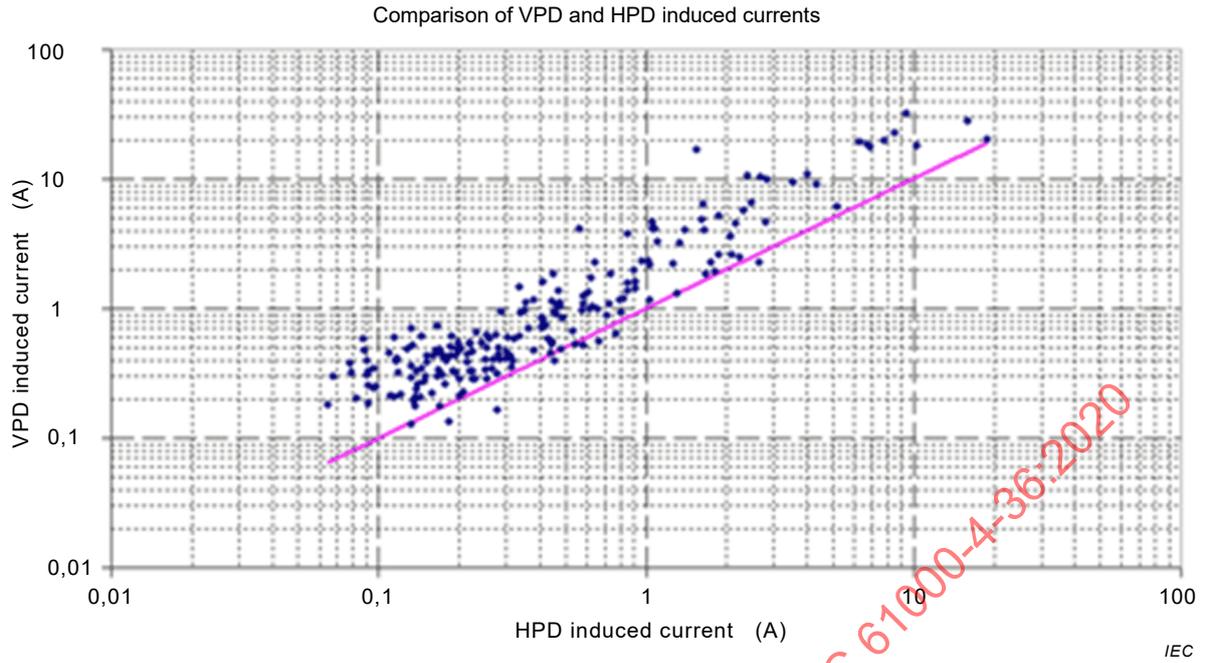


Figure F.2 – Comparison of HPD and VPD induced currents

F.2.2.3 Equipment variability

Transfer functions were measured for 12 test points across 8 aircrafts of a similar type. The variation in predicted peak current is shown in Figure F.3 with a mean difference of 18,7 dB and a standard deviation of 6 dB. This is a limited dataset and includes other areas of uncertainty such as the use of worst-case transfer functions and differences in configuration, but it is included to demonstrate the variation that can arise across systems that are nominally "similar".

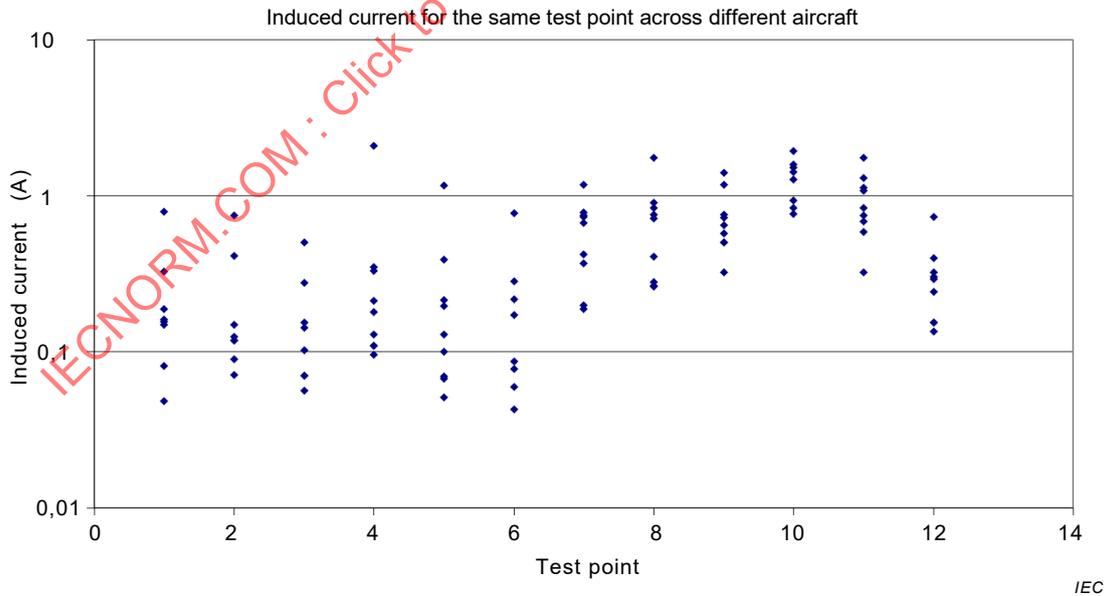
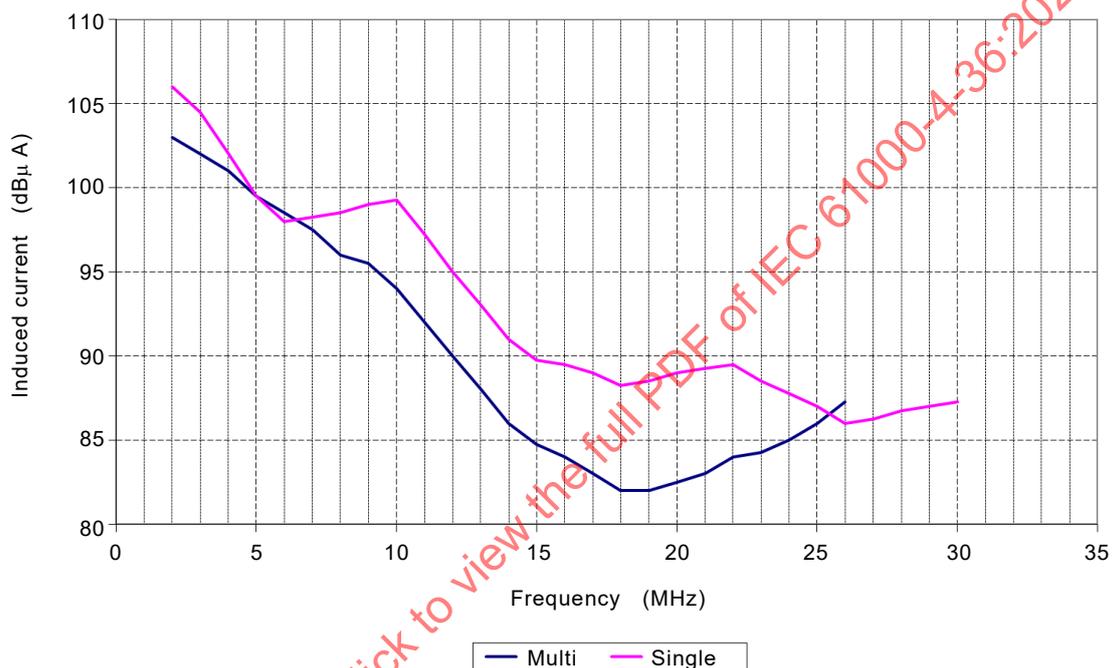


Figure F.3 – System variability

F.2.2.4 Synergistic effects

The majority of systems contain numerous cable bundles and testing them all simultaneously is not possible. It is feasible to identify those cable bundles that are associated with a particular function or sub-system but even then significant numbers of cable bundles are likely to require testing at the same time. In reality, the IEMI environment will illuminate the system of interest at the same time such that synergistic excitation of all ports occurs. If single-port injection (excitation) is used as a test method, a test methodology margin can be assigned to the result to allow for differences between single- and multi-port excitation. Figure F.4 shows a comparison of the susceptibility threshold for single- and multi-port injection of a piece of electronics equipment with multiple cable bundles. Each measured frequency point has a susceptibility range of between -1,5 dB¹² and 6,5 dB; the mean is 3,7 dB with a standard deviation of 2,4 dB.



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Figure F.4 – Comparison of single- and multi-port injection

F.2.3 Positive contributions

F.2.3.1 Worst-case (enveloped) transfer functions

Transfer functions are typically measured at 4 illumination positions (orientations) and 2 polarizations, meaning that each cable bundle has 8 transfer functions associated with it. Worst-case transfer functions are computed by taking the maximum coupling at each frequency, effectively providing an envelope of all of the transfer functions associated with one cable bundle. Using a single transfer function as opposed to 8 reduces testing time by a factor of 8, however there is an uncertainty associated with this method that should be considered.

Figure F.5 shows transfer functions from a typical cable bundle and the associated worst-case envelope (referred to as a "generic").

¹² The negative value indicates that less current was required for the single injection case although this only occurred over a narrow frequency range.

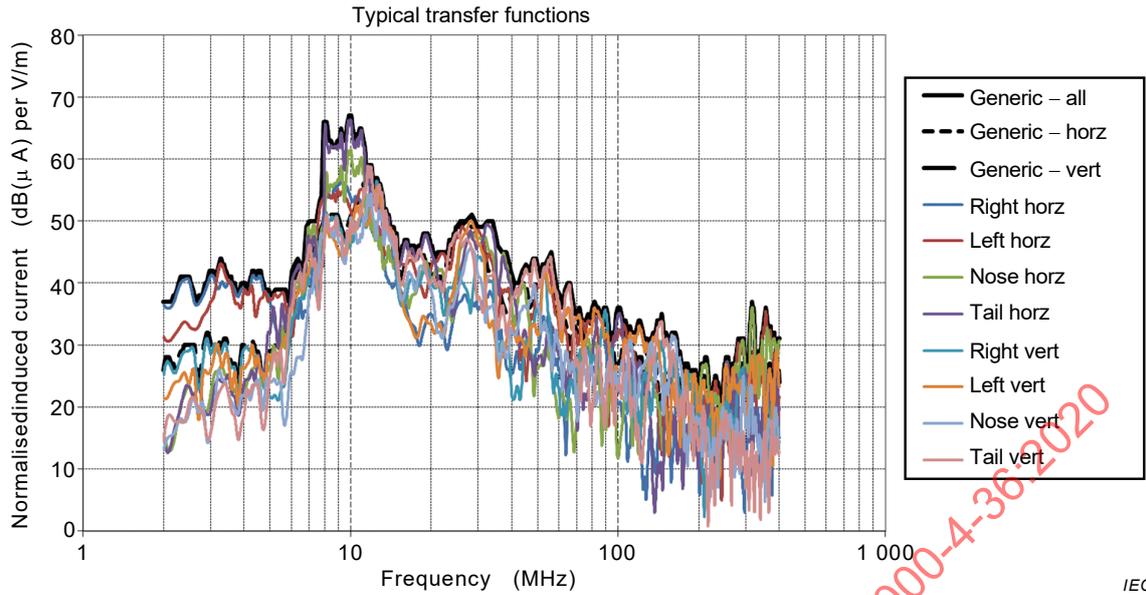


Figure F.5 – Example of transfer functions and worst-case envelope

Data similar to that shown in Figure F.5 has been convolved with a damped sinusoidal IEMI environment and the resulting predicted currents from each polarization and orientation have been compared with their associated worst-case prediction (see Figure F.6). A total of 496 transfer functions were used and the data has a mean of -9,24 dB and a standard deviation of 4,77 dB.

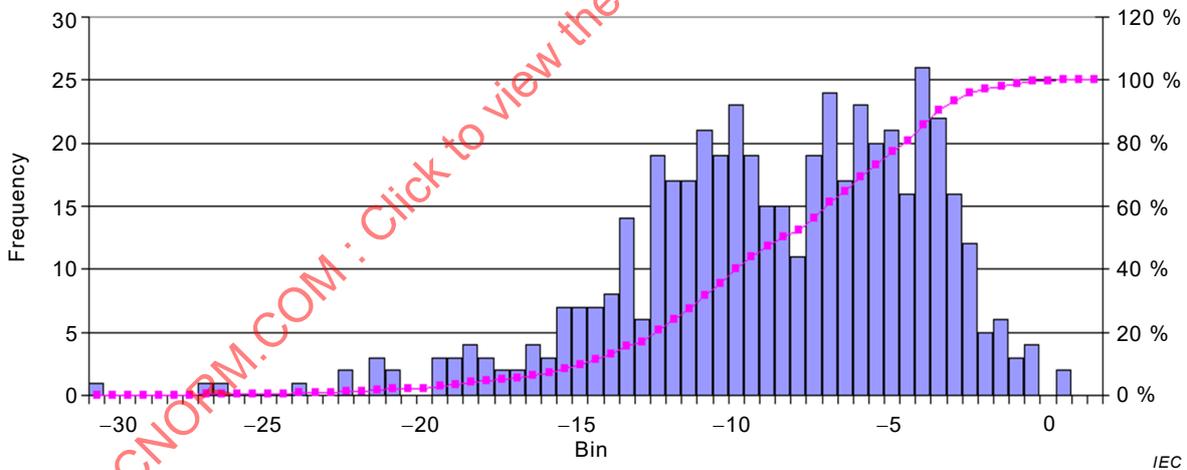


Figure F.6 – Comparison of individual and worst-case transfer function predictions

F.2.3.2 Phase reconstruction methods

Magnitude-only transfer functions require some phase reconstruction method to allow them to be used for the prediction of induced currents as a result of illumination by an IEMI environment [F.3]. A common method used here is that of the "minimum phase algorithm" which uses a Hilbert Transform to generate phase and results in the energy of the resulting prediction being concentrated towards $t = 0$; in many cases this results in an overestimation of the predicted current [F.4].

Figure F.7 shows a comparison of predicted induced currents using the minimum phase algorithm and measurements made using an HPD EMP simulator. The data has a mean of ~ 7 dB and a standard deviation of $\sim 2,5$ dB. This means that, on average, the minimum phase algorithm results in predicted currents that are, on average, ~ 7 dB higher than expected in reality [F.5].

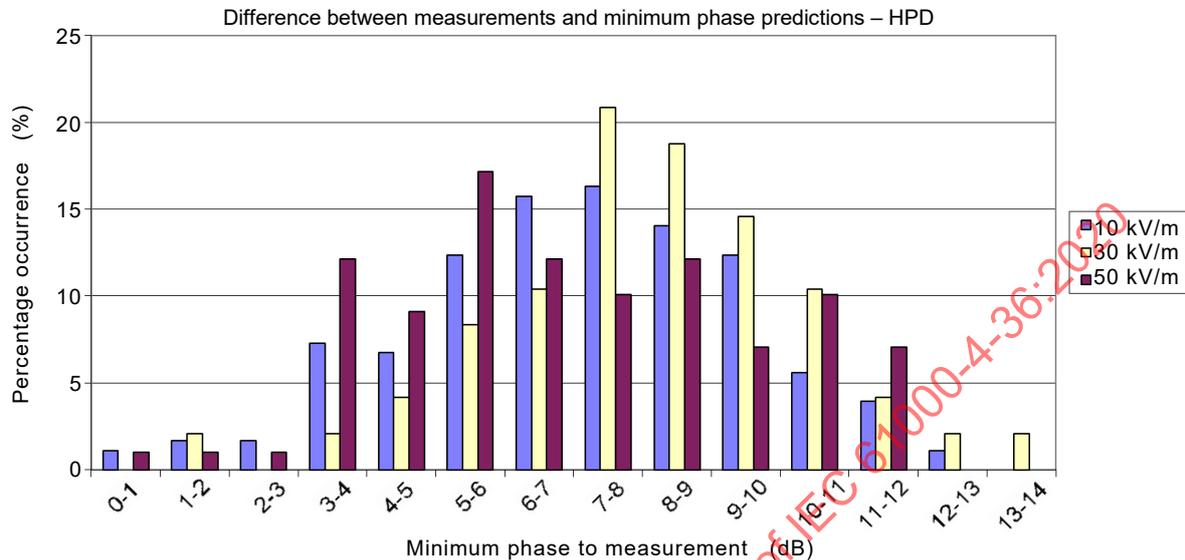


Figure F.7 – Comparison between predicted and measured induced currents

F.2.4 Summary

The total uncertainty associated with measurements is complex as there are many opportunities for "uncertainty" in the process. Some data relevant to the determination of the test methodology margin to account for limitations in test methods has been given within Annex F, however, it is important to note that a system-specific assessment should be made to understand the uncertainty associated with the specific measurement methods applied.

A good understanding of the individual contributions is essential and all identified uncertainties and margins should be combined through analytical treatment, numerical analyses or empirical measurements.

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Annex G (informative)

Intentional EMI – The issue of jammers

G.1 General

Problems with intentional jamming of global positioning systems (GPS)/global navigation satellite systems (GNSS) ground-based receivers, mobile phone base stations and handsets, automobile locking systems, and wireless WIFI/WLAN receivers which can be used for cameras, alarm systems and other applications are now being widely reported [G.1], [G.2]¹³.

To a certain extent the problem can be traced back to the fact that it is very easy to find and buy cheap and easy to use jammers from the Internet. For a price of around 100 Euros one can buy a man-portable battery-operated or automobile 12-V powered jammer typically having a range of some tens of meters. [G.3]

These kinds of narrowband deliberate jamming sources, tailored to be used against a certain kind of system like WiFi or GPS, operate at low power levels, of the order of 1 W. Some of the available devices are alleged to cover several bands at once. More powerful and advanced jamming devices can also be acquired or built.

A powerful HPEM narrowband source will enable the perpetrator to operate at a much larger distance, and can also be used in situations where the purpose is to, at a close distance, cause permanent damage to the receiver.

The technologies and modalities described above seem to fit within the broad definition of IEMI.

G.2 Effects

Studies of permanent damage show that pulse energies typically of the order of μJ , corresponding to a field strength of the order of 1 kV/m or less, are sufficient to destroy a receiver [G.4], [G.5], [G.6]. For an experimental low noise amplifier (LNA) device, damage level as low as 20 nJ has been reported [G.6]. Alternatively, a wideband HPEM source, i.e. a radiation source that transmits pulses having a wide spectral content, can be of interest. The advantage of wideband jamming is that no information is needed beforehand about the operating frequency of the victims, and it also means that different types of radio equipment can be interfered with simultaneously.

Due to their extremely high sensitivity GNSS/GPS receivers are particularly vulnerable to jamming. The extreme sensitivity of GPS receivers is due to the fact that satellite signals, because of the limited supply of energy, are very weak. As a rule of thumb, an interference signal that exceeds the normal signal level of the receiver by 20 dB to 30 dB is sufficient to block the communication of a GPS receiver. This means that a very modest output power of a jammer can be enough to block the communication, even from a fairly long distance.

In [G.8] it is claimed that the Russian GPS jammer Aviaconvertsija MAKS 1999 has a radius of action for interference of 45 km. This jammer has an output power of 8 W, is powered by a 12 V battery and has a weight of about 3 kg. From those data one can estimate that a field strength of the order of only a few tenths of 1 mV/m is sufficient to block a GPS receiver. This result is consistent with other findings (see [G.5], [G.7], [G.9]). As a comparison, levels of in-band interference of WLAN have been reported to be around 1 V/m [G.5].

¹³ Numbers in square brackets refer to the references in Clause G.6.

G.3 Published accounts of jamming

In June 2012, it was reported [G.10] that jamming of GPS signals by North Korea may have contributed to the fatal crash of a unmanned aerial vehicle (UAV) in South Korea. The small helicopter crashed into its own ground control vehicle which led to the death of an engineer and injured the two remote pilots. The jamming reportedly started on April 28 2012 and disrupted passenger flights into Seoul's two main airports.

In recent years, numerous cases of inadvertent interference with GPS have been reported [G.9], [G.13]. Reportedly [G.11] the introduction of a new telecommunications system, consisting of 40 000 high-power transmitters, was stopped in the United States because it was shown to interfere with the GPS system.

In [G.12] results from a study of the vulnerability of telecommunication networks to intentional EMI are presented. The study deals mainly with attacks leading to permanent damage on receivers (and to some extent interference on electronics through back-door coupling) but it is noted that it is easy to jam communication links.

G.4 Risk assessment

The introduction of a wireless system for critical functions in railway applications, for example in the European Rail Traffic Management System (ERTMS), has brought the question of its resilience against electromagnetic interference, intentional as well as unintentional, into focus (see [G.14], [G.15]). In ERTMS the light signals along the tracks are essentially replaced by radio communication via Global System for Mobile – Railways (GSM-R) to the driver. In [G.14] it is concluded that a 1 MW source might cause permanent damage to the GSM-R receiver at a distance of up to 200 m and, of course, induce interference at a much larger distance. The threat from IEMI against modern railway systems is the topic of an EU project, SECRET, started in mid-2012 [G.16], [G.17], [G.18]. EMI issues in railway systems, for example regarding GSM-R, are also addressed in another EU project, TREND [G.19]. There are other EU projects, HIPOW [G.20] and STRUCTURES [G.21], which carried out the analysis of the risk against intentional electromagnetic interference (IEMI) posed to electronics infrastructure assets on which civilized society depends.

In recent years, several cases of interference with wireless commercial electronics such as mobile phones, GPS receivers, car locks and anti-theft alarms in shops have been reported. In the case of car locks, an interfering signal can be used to block the communication between the car key and the car, thus preventing the owner, unaware about the jamming, from locking the car. Jamming of shop alarms seems to be quite common. In this case the purpose is evidently to leave the shop with stolen goods without being noticed. There are many videos online that show the use of jammers (search, e.g., "phone jammer").

G.5 Mitigation

There are methods which can mitigate the risk for interference. Of course the obvious solution is not to rely on RF reception for functionally critical and in particular safety critical systems and to employ alternative solutions. However, for the types of low cost narrow-band jammers that can be found on for example the Internet mitigations can include modulation techniques such as spread spectrum modulation, i.e. techniques that distribute the energy in frequency or time (see [G.22]). Another of these modulation techniques is frequency hopping, in which the transmitted signals carrier frequency switches in a random fashion between many frequency channels. As an example, Bluetooth®¹⁴ uses frequency hopping to make it more robust against interfering signals. Another technique is called direct sequence, in which case the initial power

¹⁴ Bluetooth® is the trade name of a product supplied by Bluetooth SIG. This information is given for the convenience of users of this standard and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

of the signal is spread out across a larger bandwidth. An interesting technique is the so-called UWB radio, or impulse radio, where extremely short wide-band pulses are used to transmit the information. In order not to interfere with other radio communication the output power of a UWB radio is very low, which makes it useful only for short distances, some tens of meters or so.

Another technique to neutralize interference is to use adaptive antennas, i.e. phased-array antennas that can suppress a hostile signal from a given direction. Protection against permanent damage can be attained by use of transient protection devices [G.4], [G.7].

Jamming detection [G.23] can also be employed to identify whether jamming is actually taking place and perhaps ascertain if the disturbance is unintentional or malicious.

It should be noted that jamming, and methods to prevent it, are a part of the extensive military electronic warfare technology area.

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