

# 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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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.

The text of this standard is based on the following documents:

CDV	Report on voting
77C/231/CDV	77C/236/RVC

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,
- withdrawn,
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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

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61000-4-4, *Electromagnetic compatibility (EMC) – Part 4-4: Testing and measurement techniques – Electrical fast transient/burst immunity test*

IEC 61000-4-12, *Electromagnetic compatibility (EMC) – Part 4-12: Testing and measurement techniques – Ring wave immunity test*

IEC 61000-4-18, *Electromagnetic compatibility (EMC) – Part 4-18: Testing and measurement techniques – Damped oscillatory wave immunity test*

#### 3 Terms, definitions and abbreviations

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

##### 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

###### 3.1.2

###### **bandratio**

###### **br**

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 for further details).

###### 3.1.3

###### **bandratio decades**

###### **brd**

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

**3.1.4****burst**

time frame in which a series of pulses occurs with a given repetition rate

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

**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

**3.1.6****continuous wave****CW**

time waveform that has a fixed frequency and is continuous

**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

**3.1.8****electromagnetic disturbance**

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

**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.

**3.1.10****(electromagnetic) shield**

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**

inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance

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

**3.1.12****equipment under test****EUT**

equipment being subjected to the test

**3.1.13****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.

**3.1.14****high-power microwaves****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.

**3.1.15****hyperband signal**

signal or waveform with a pbw (see 3.1.20) value between 163,4 % and 200 % or a bandratio > 10

**3.1.16****hypoband signal**

narrowband signal or waveform with a pbw of < 1 % or a bandratio < 1,01

**3.1.17****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, 3.16]

**3.1.18****L band**

radar frequency band between 1 GHz and 2 GHz

**3.1.19****mesoband signal**

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

**3.1.20****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.

**3.1.21****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.

**3.1.22****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

**3.1.23**

**pulse repetition frequency**

**prf**

number of pulses per unit time, measured in Hz (per second)

**3.1.24**

**radiated HPEM environment**

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

**3.1.25**

$rE_{far}$

electric field normalised at a distance of 1 m from the antenna as derived from an E-field measurement at a given distance in the far-field

**3.1.26**

**sub-hyperband signal**

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

**3.1.27**

**transient**

pertaining to or designating a phenomenon or a 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.

**3.1.28**

**ultrawideband**

**UWB**

signal that has a percent bandwidth greater than 25 %

**3.2 Abbreviations**

DS	Damped sinusoid
EMI	Electromagnetic interference
ESD	Electrostatic discharge
HEMP	High-altitude electromagnetic pulse
HIRF	High-intensity radiated fields
HPD	Horizontally polarized dipole
HPEM	High-power electromagnetic
HPM	High-power microwave
LEMP	Lightning electromagnetic pulse
LLSF	Low level swept field
LLSC	Low level swept current
NEMP	Nuclear electromagnetic pulse
SE	Shielding effectiveness
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]<sup>1</sup>. A summary of failure mechanisms at equipment level is provided in Annex A.

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 (HIRF) generated by radio and radar systems, lightning electromagnetic pulse (LEMP) and electrostatic discharge (ESD). Some of these HPEM environments have similar characteristics to those sources used to cause IEMI but are unintentional EMI sources, i.e. non-malicious. However, it is possible to use information regarding qualification of equipment and systems to these environments to inform the likely response to IEMI.

The IEC defines IEMI within 3.1.17 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 that can generate electromagnetic environments that can potentially be used to cause 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 bandratio. 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,

<sup>1</sup> Numbers in square brackets refer to the Bibliography in Clause 8.

- 2) amplitude of the source vs. distance to the victim system,
  - 3) pulse width, pulse repetition frequency, burst length of the source,
  - 4) source mobility,
  - 5) technical capability of the source user/designer.
- b) The protection level of the fixed 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. The term ' $rE_{far}$ ' describes the electric field normalised at a distance of 1 m from the antenna as derived from an E-field measurement at a given distance in the far-field. It is equivalent to equivalent isotropic radiated power (EIRP) which is derived from the power density at a given distance in the far field.

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

Category	IEMI source type	IEMI source name or technology type	$rE_{far}$ (V)	Near/far distance (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
Specialist	Hypoband	Typical radar	450 000	5 m
	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

### 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 standards such as IEC 61000-4-18 [5], IEC 61000-4-4 [6] and IEC 61000-4-25 [7] 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 such as Mil-Std-461 [8] and Defence Standard 59-411 [9].

### 5.3 Interaction with fixed installations

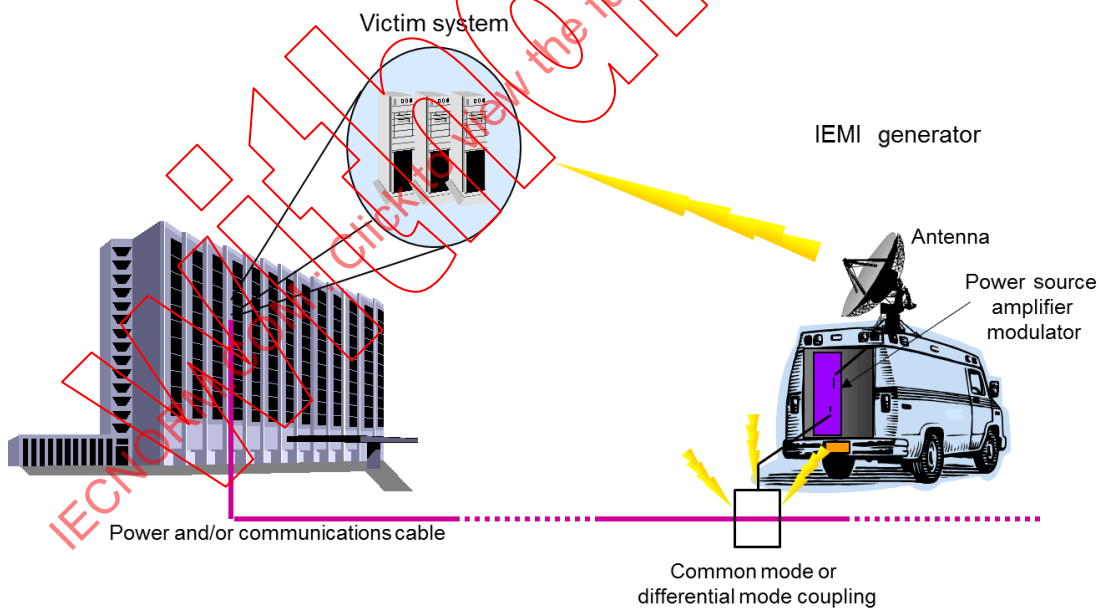
#### 5.3.1 General

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 channel loss, including the properties of intervening barriers (attenuation and absorption).

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.



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**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) may result in very different path losses during the propagation.

### 5.3.2 Protection level

Given the discussion above it can be implied that victim electronic equipment located inside a fixed installation will have a '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.

Example 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 – Example protection levels**

Example 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	28	11	39
EPL5	30	28	18	46
EPL6	35	31	29	60

NOTE Path loss equals the assumed range to victim in dB reference 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 above 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 [10]. 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 2 main categories, namely radiated and conducted, the methods for testing against IEMI fall broadly into the same categories.

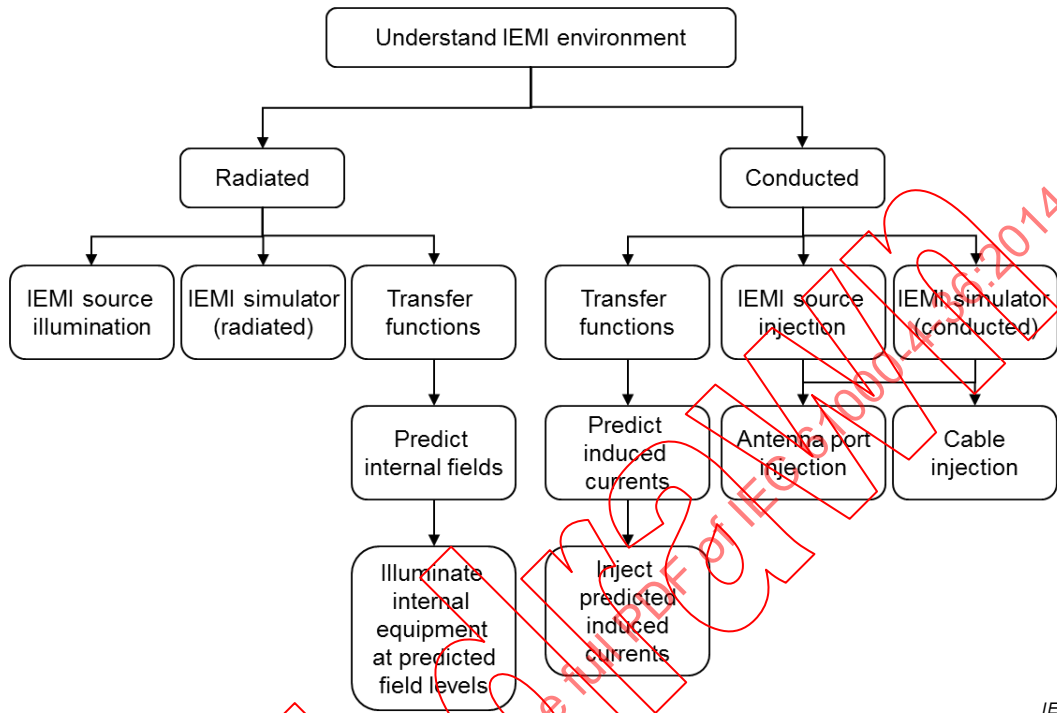
Testing against radiated IEMI can be undertaken with the IEMI source of interest, a simulated environment such as those shown in IEC TR 61000-4-35 [11], or by injecting the signal expected to be induced into conductors by exposure to the IEMI radiated environment. The latter relies on knowledge of the transfer function<sup>2</sup> 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.

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

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 assessment of the effects of IEMI on equipment or systems.



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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 [10]) 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 (~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 [10].

### **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 [11] 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 a fixed installation is not recommended since it may present a significant interference risk.

For applicable test methods and test set-up see IEC TR 61000-4-35 [11].

### **6.4 Radiated tests using a reverberation chamber**

IEC TR 61000-4-35 [11] 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 [12].

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 phenomena. This difference is discussed in Annex D.

For applicable test methods and test set-up see IEC 61000-4-21 [12].

### **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 may respond to an IEMI environment. For applicable test methods and test set-up see IEC 61000-4-12 [13] and IEC 61000-4-18 [5].

### **6.7 Electrostatic discharge (ESD)**

Testing to IEC 61000-4-2 [14] provides confidence of the continuing operation of the EUT as a result of ESD. ESD is generally a fast transient with a rise-time of the order of hundreds of picoseconds and pulse-width of tens of nanoseconds. This information may be used to inform 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 [14].

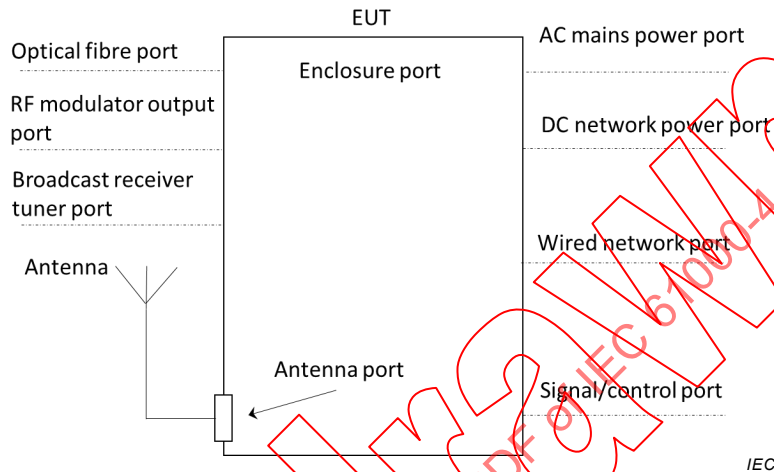
### **6.8 Electrically fast transient (EFT)**

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 effect 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.

For applicable test methods and test set-up see Mil-Std-461 test method CS116 [5].

## 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 may 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 example protection levels indicated in Table 3.

## 7.2 Radiated test parameters

### 7.2.1 Generic hyperband test parameters (skilled capability group)

Subclause 7.2.1 defines the immunity test levels for hyperband IEMI environments (i.e. those with a band ratio  $\geq 10$ ). This is summarised in Table 4.

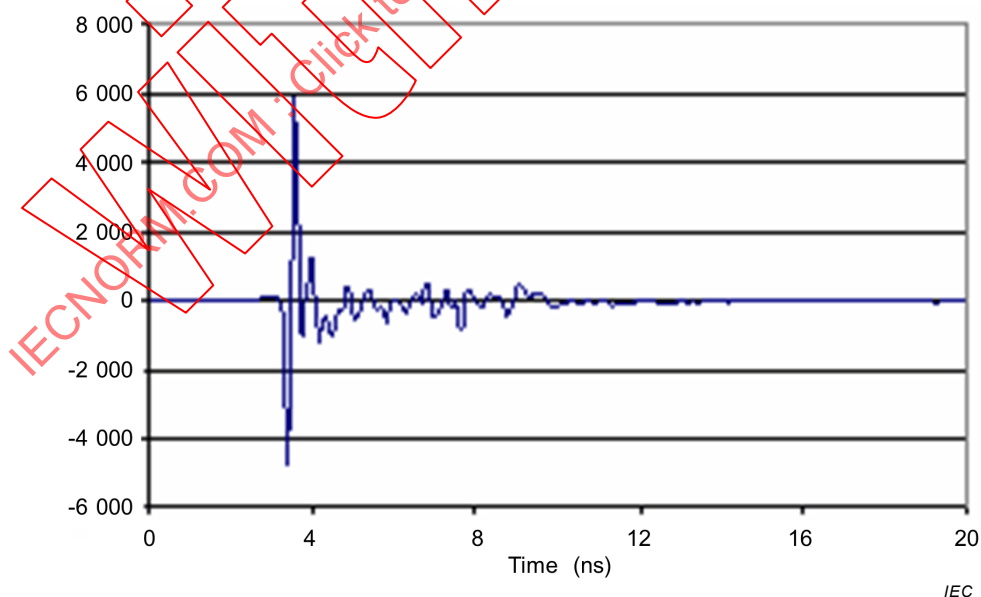
**Table 4 – Generic hyperband test parameters (skilled capability group)**

EPL	Amplitude (V/m)	Risetime (ps)	Pulse width (ns)	Pulse repetition frequency (Hz)	Pulse length/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	675				
EPL5	300				
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 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 hyperband waveform is given in Figure 4.



**Figure 4 – Typical 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 5 contains the test levels and associated parameters. It should be noted that any combination

of waveform parameters in Table 5 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 5 – Generic mesoband test parameters (skilled capability group)**

EPL	Amplitude, $E_C$ (V/m)	Centre frequency, $f_C$ (MHz)	Damping factor, $Q$	PRF (Hz)	Pulse length/surst 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	1 350				
EPL5	600				
EPL6	120				

The waveforms are well described by damped sine waves as shown in Equation (1) with the characteristics  $E_C$ ,  $f_C$  and  $Q$  found in Table 5. The normalizing constant  $k$  is defined so that the maximum value of  $E_C$  will be equal to  $E_{pp}/2$ . Further information can be found in IEC 61000-2-10.

$$E_C(t) = k(E_{pp}/2)e^{-\frac{\pi f_C t}{Q}} \sin(2\pi f_C t) \tag{1}$$

Immunity data from relevant test standards (for example IEC 61000-4-18, DO160 [15], Mil-Std-461 [5]) may cover some of the requirements in Table 5 or assist in the identification of frequencies that require further investigation.

It should be noted that not all combinations of the parameter ranges given in Table 5 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.

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

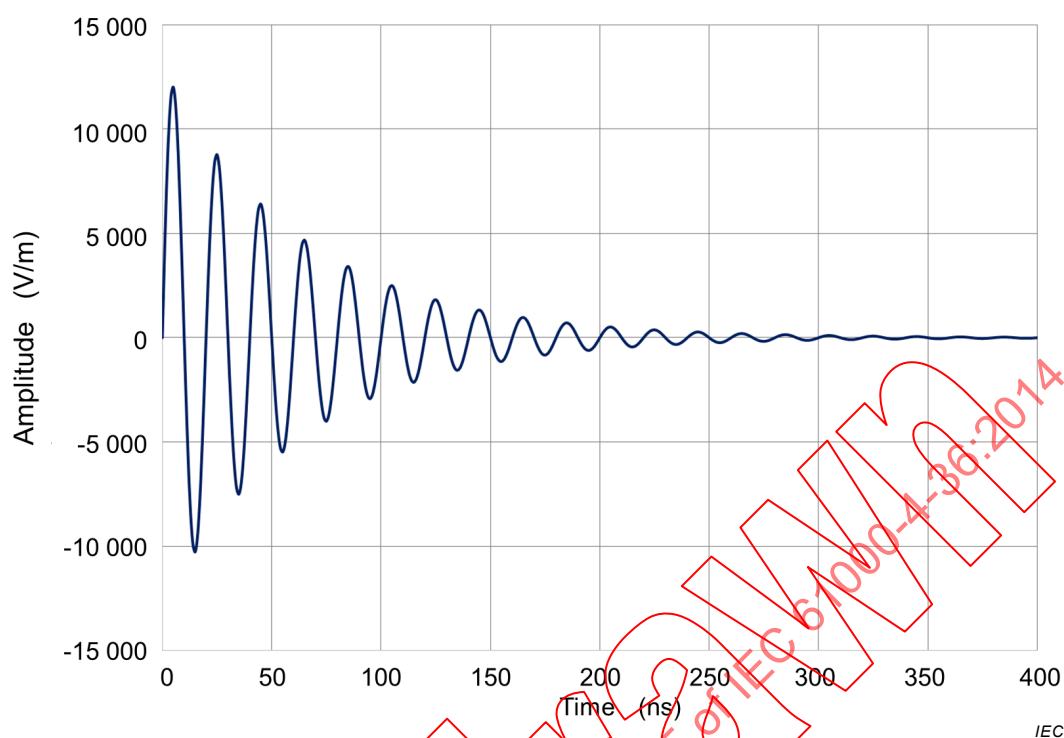


Figure 5 – Typical mesoband waveform

### 7.2.3 Generic hypoband/narrowband test parameters (skilled capability group)

Table 6 gives the test levels for narrowband IEMI which are characterised by low relative bandwidth, centre frequencies of  $\geq 1$  GHz and an associated pulse repetition frequency (PRF) of  $\leq 100$  Hz.

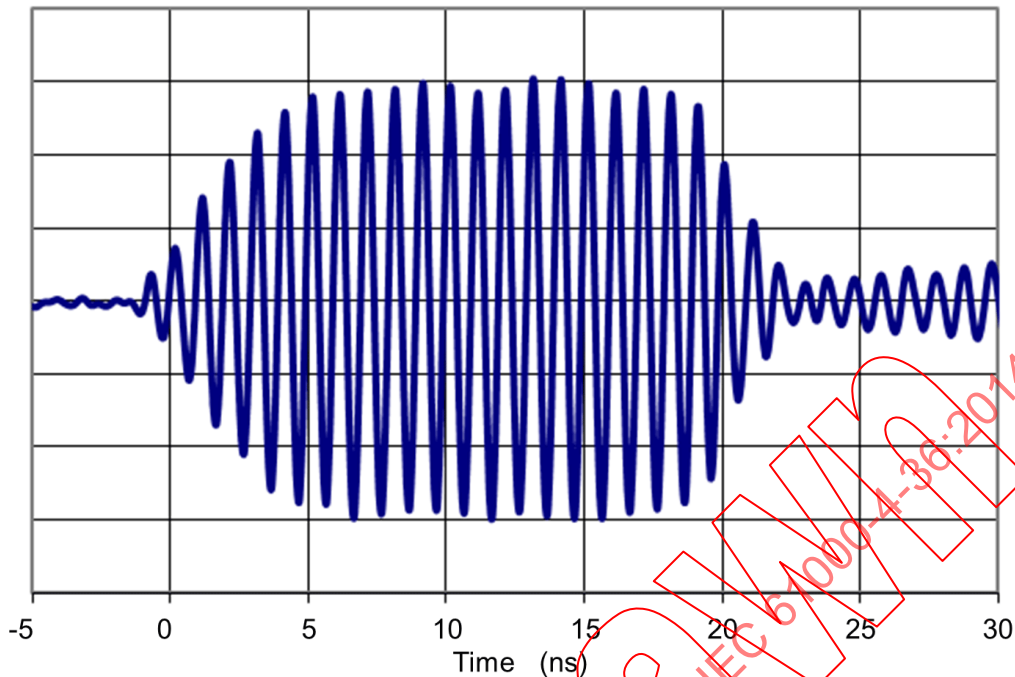
Table 6 – Generic hypoband/narrowband test parameters (skilled capability group)

EPL	Amplitude (V/m)	Pulse width ( $\mu$ s)	PRF (Hz)	Pulse length/burst duration (s)
EPL0	225 500	0,01 to 10	Single shot to 1 000	1 to 10
EPL1	45 000			
EPL2	22 550			
EPL3	11 300			
EPL4	5 050			
EPL5	2 250			
EPL6	450			

NOTE 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 severe when considering the overall content or the associated maximum derivative of the applied waveform.

All combinations of the parameter ranges given in Table 6 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 standard defines conducted IEMI test levels in Table 7. The user shall define specific test levels relevant to a specific IEMI environment by following the process in Clause 6.

**Table 7 – Conducted IEMI test levels**

$V_{oc}$ V	$I_{sc}$ A	Waveform	Basic standard
100	2	Damped sinusoids <sup>a</sup>	IEC 61000-4-18
250	5	Damped sinusoids <sup>a</sup>	IEC 61000-4-18
500	10	Damped sinusoids <sup>a</sup>	IEC 61000-4-18
1 000	20	Damped sinusoids <sup>a</sup>	IEC 61000-4-18
2 000	40	Damped sinusoids <sup>a</sup>	IEC 61000-4-18
4 000	80	Damped sinusoids <sup>a</sup>	IEC 61000-4-18
4 000	80	5/50 ns	IEC 61000-4-4
8 000	160	5/50 ns	IEC 61000-4-4
16 000	320	5/50 ns	IEC 61000-4-4

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

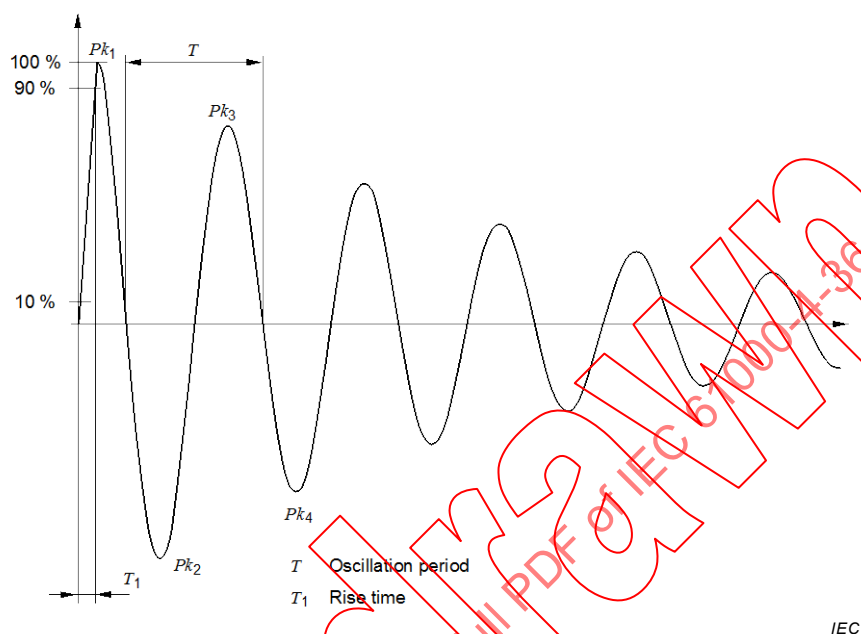
NOTE 2 For the two highest immunity test levels, it is sufficient to test with a single pulse.

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

### 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 7, footnote a.

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



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

Open circuit specifications associated with Figure 7 are given in Table 8:

**Table 8 – Open circuit specifications**

Voltage rise time ( $T_1$ in Figure 7)	5 ns $\pm$ 30 %
Voltage oscillation frequencies <sup>a</sup>	3 MHz, 10 MHz and 30 MHz $\pm$ 10 %
Repetition rate	5 000/s $\pm$ 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 $\Omega$ $\pm$ 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
<sup>a</sup> 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 9:

**Table 9 – 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 <sup>a</sup>	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 %
<sup>a</sup> 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 1.	

**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) 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 may 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, e.g., 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 may 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 [16], CISPR 16-4-2 [17], CISPR 16 4-3 [18] and CISPR16-4-4 [19] and are equally applicable to the determination of measurement uncertainty for IEMI test results.

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## 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 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 [1]<sup>3</sup>, [2], [3], [4] and [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 summarize 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

<sup>3</sup> 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:

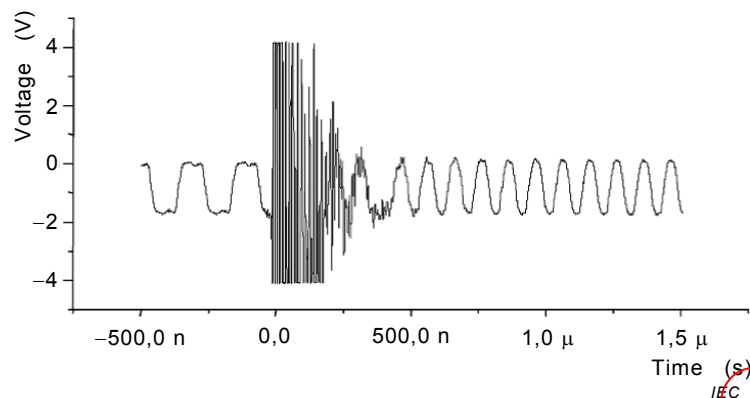


Figure A.2 – Collision of an induced disturbance with data bits [1]

#### 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).

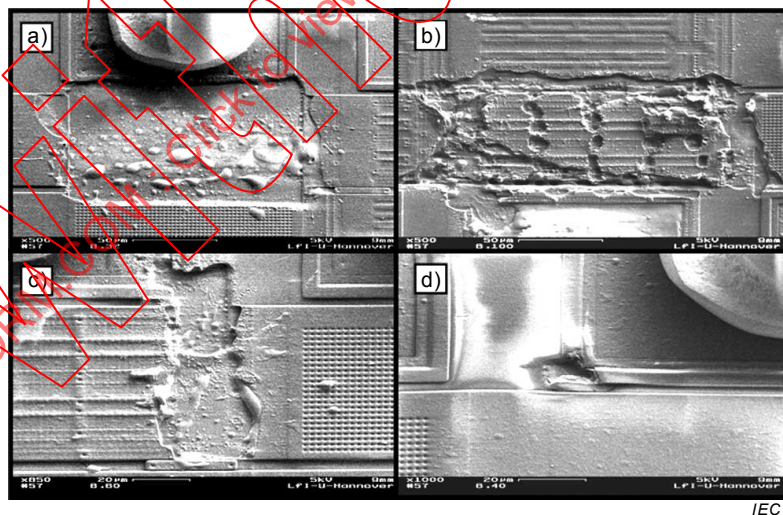


Figure A.3 – Examples of destruction on a chip [2]

The identification of which destruction mechanism occurs requires additional detailed examinations of the system (e.g. opening of 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 [6], [7], [8], [9], [10], [11], and the trend from this data is summarised in Figure A.4.

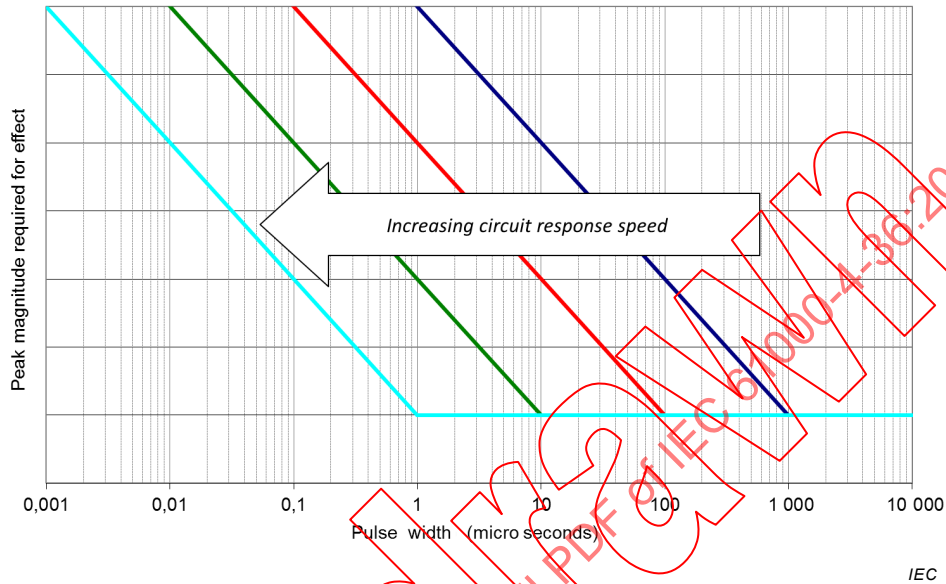


Figure A.4 – Generic failure trend as a function of pulse width

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.

### 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

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- [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
- [8] 'Measuring the upset of CMOS and TTL due to HPM-Signals', by Norbert Esser and Bernd Smailus, ABB AG Corporate Research Center
- [9] 'Pulse Length and Power Dependency of the failure threshold of a Low Noise Amplifier', by Rolf Jonsson, Magnus Hoijer, Swedish Defence Research Agency
- [10] 'HPM Effects on Electronic Components and the Importance of this knowledge in Evaluation of System Susceptibility', by Gunnar Goransson, FOA Defence Research Establishment

- [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

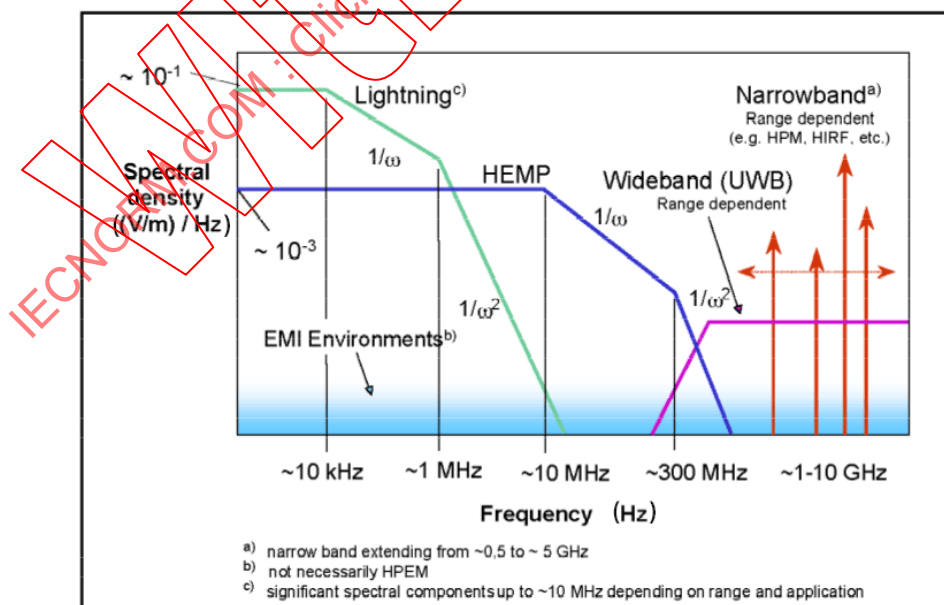
#### B.1 General

The use of electromagnetic sources [1]<sup>4</sup> 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 [2], [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 (HIRF) 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 EMI 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.

Recently two new terms have arisen in the EMC field – EM terrorism [4] and intentional electromagnetic interference (IEMI) [5]. Over the past 12 years the scientific community has decided to accept the more generic term IEMI, which includes EM terrorism. 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 [6].



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

<sup>4</sup> 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” [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

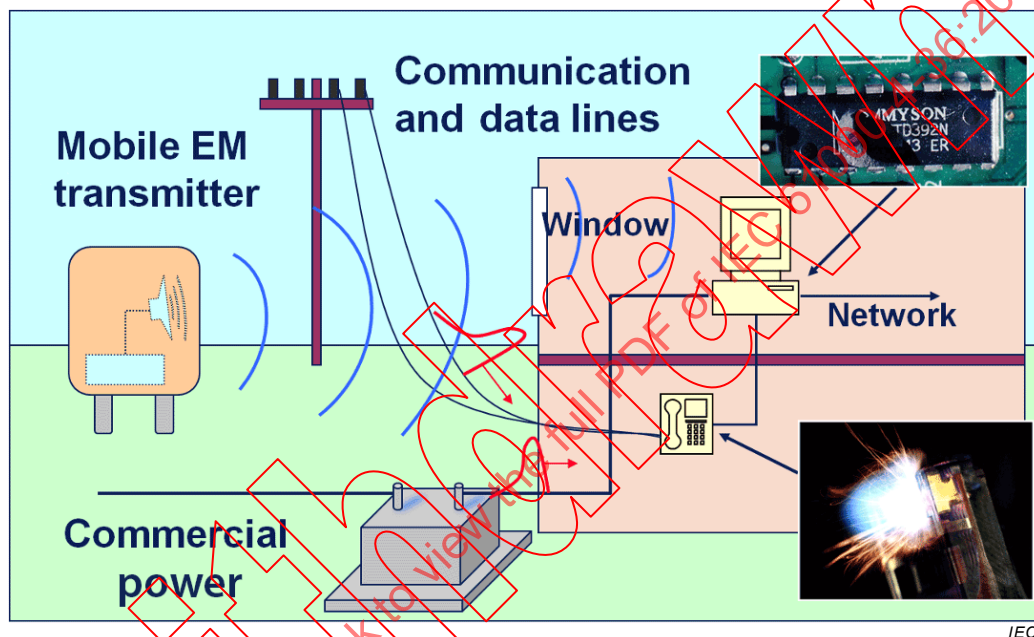
In order to understand the nature of IEMI threats it is necessary to understand the different types of electromagnetic environments that can be produced and that can affect exposed equipment. This document focuses mainly on radiated threats, although injected threats will be summarised.

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 on the order of many kV/m at a single frequency. Of course each system under test may 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 [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.* [9].

While the waveform characteristics are defined above, there are two primary ways that they may 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 [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 may illuminate and couple to system electronics through apertures (e.g., windows) and through building wiring [3].

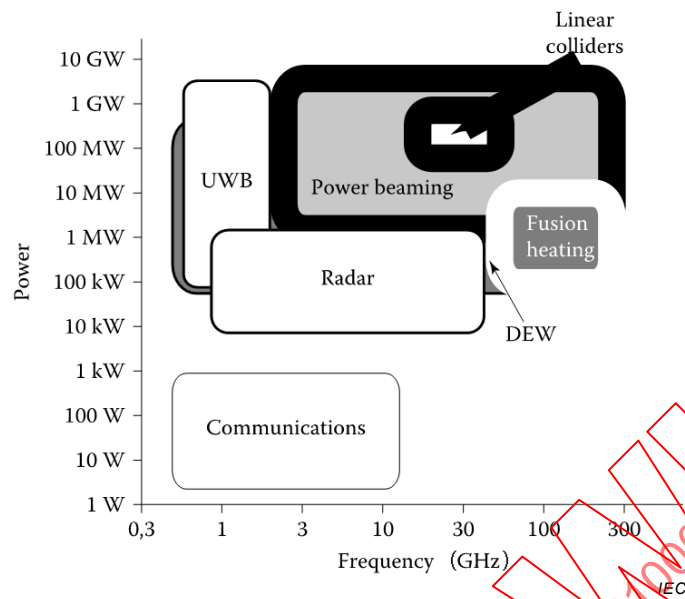


**Figure B.2 – Representation of typical IEMI radiation and coupling onto systems [3]**

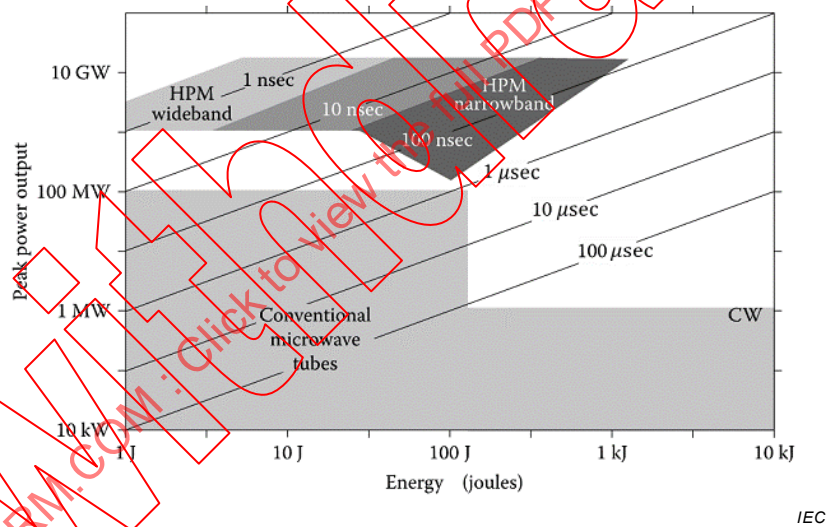
For injected voltages and currents, there are some differences in terms of the frequency range of interest. It is well established that if common-mode conducted signals are injected into the power supply or telecom cables outside of a building, frequencies below 10 MHz (and pulsewidths wider than 50 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 [11].

### B.3 IEMI sources

The nature of IEMI sources [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 [1]. Note that the UWB (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.3). 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 [12].

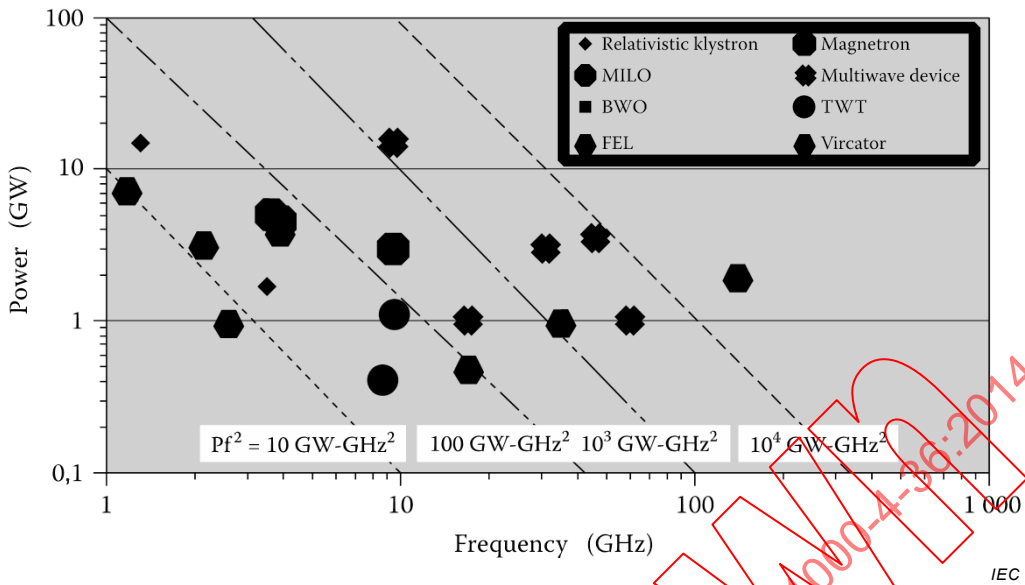


**Figure B.3 – Parameter space in power/frequency occupied by sophisticated IEMI (i.e. DEW) sources [1]**



**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 [16]. 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 HPM sources [1]

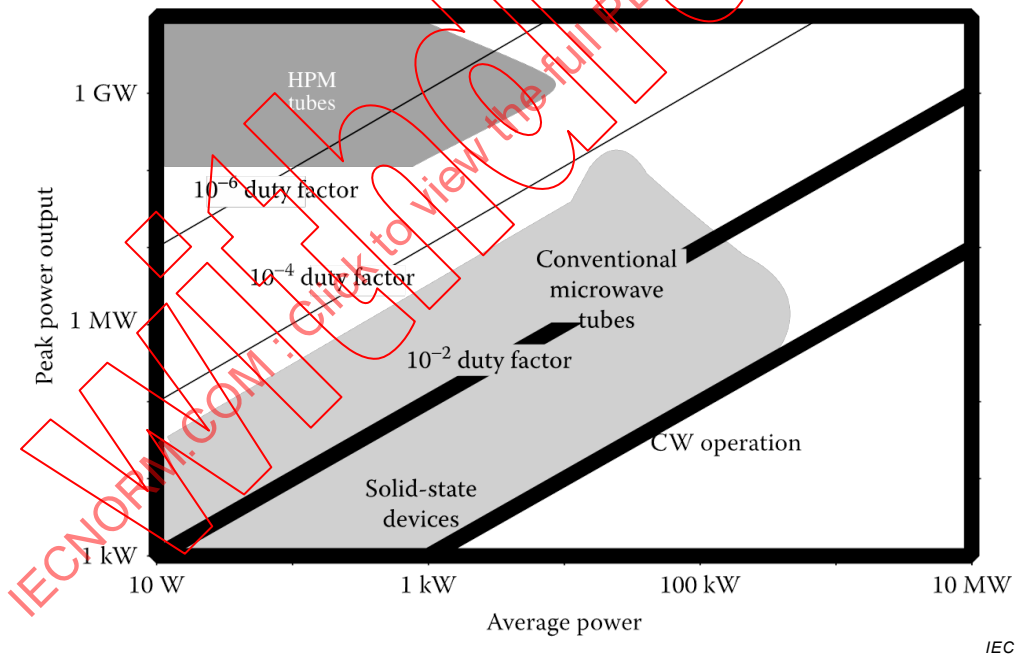
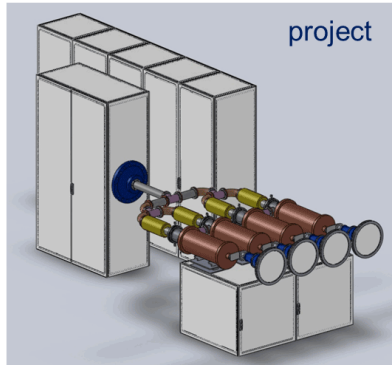


Figure B.6 – Peak vs. average power for microwave sources with duty factors indicated

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 type of UWB source is the Diehl-Rheinmetall briefcase sources, shown in Figure B.8 [3].

### Multi-channel HPM systems?



Generation frequency	10 GHz
Microwave pulse duration	0,8 ns
Peak pulse power	4 x 1,5 GW
HVG type - Tesla transformer	
FL impedance	25 Ohm
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 [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 meter (omni-directional antenna)
  - 30-minute continuous operation (5 pulses per second or 3 hours in bursts)
  - 20 inches x 16 inches x 8 inches and 62 pounds
- Demonstration in the summer of 2004



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

The narrowband and UWB HPM sources just described are examples of sophisticated sources that took considerable resources to design and develop. On 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.



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

An example of a Russian industrial scale electromagnetic weapon is the RANETS-E, 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 [1].

## B.4 Published radiated IEMI environments

### B.4.1 IEC 61000-2-13

IEC 61000-2-13 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 [16] contains a list of multiple HPM<sup>5</sup> threats with an overall compilation of these threats.

Table B.2 and Table B.3 are taken from Mil-Std-464C. Table B.2 provides field strengths that exist at one kilometre for the hypoband/narrowband threat high-power microwave (HPM) environment. HPM is a military term used to describe a class of IEMI systems which can be

<sup>5</sup> The Mil-Std uses HPM to define a threat, which radiates high peak power electromagnetic pulses intended to disrupt or damage electronic systems. This part of IEC 61000 uses the more accurate term, IEMI, as not all IEMI sources operate in the microwave part of the radio frequency spectrum.

used in military scenarios. Table B.3 provides a spectral magnitude description for wideband HPM at a distance of 100 meters.

**Table B.2 – Hypoband/narrowband HPM environment**

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 – Hyperband/wideband HPM environment**

Frequency range (MHz)	Broad-band electric field distribution (mV/m/MHz at 100 m)
30 to 150	33 000
150 to 225	7 000
225 to 400	7 000
400 to 700	1 330
700 to 790	1 140
790 to 1 000	1 050
1 000 to 2 000	840
2 000 to 2 700	240
2 700 to 3 000	80

#### B.4.3 The International Telecommunication Union (ITU)

The International Telecommunication Union (ITU) has published a 'High-power electromagnetic immunity guide for telecommunication systems' [17] that also contains published levels of IEMI environments.

#### B.4.4 Practical determination of a tailored test level – An example

An electronic system is to be installed within a facility with a secure perimeter such that the system is at least 100 m away from any insecure location (i.e. the IEMI source cannot get closer than 100 m to the system of interest). The facility operator has been tasked to ensure that a mesoband IEMI source radiating 60 MHz with an electric field of 10 kV/m at 10 m and variable prf (< 1kHz) cannot disrupt the system.

There are 4 ways to approach this problem.

- 1) The maximum field that can be generated at the system is 1 kV/m (assuming far field conditions such that the IEMI source magnitude is inversely proportional to an increase in distance). An assessment is made of the impedance of all cables that are connected to the system and the lowest value is used to determine the highest current that could be induced. All cables are then tested to the maximum current amplitude with a 60 MHz mesoband signal with 1 kHz prf and a similar decay factor of the IEMI source whilst being monitored for effects.
- 2) Measurements of the transfer functions of all cables connected to the system of interest are taken and used to predict the induced currents as a result of the 60 MHz mesoband source. These predictions can then be either injected directly into the cables or a worst-

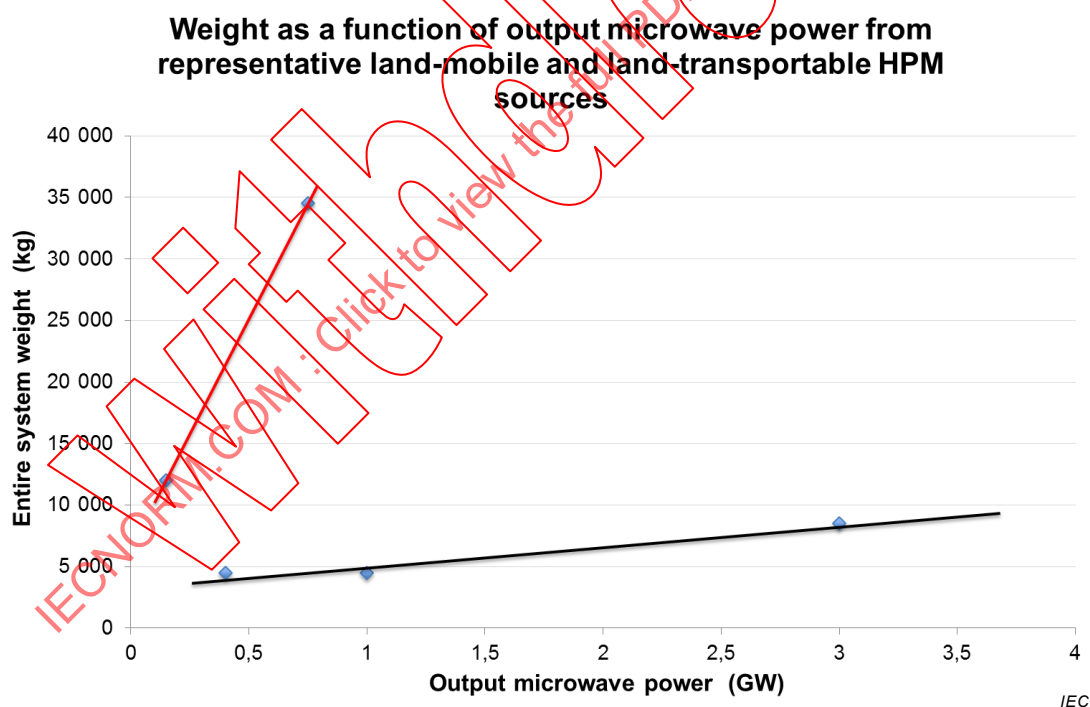
case envelope generated of the predicted norms (the latter methods will result in an over-test for many cables).

- 3) Set-up the system of interest within a test facility and use an IEMI simulator (such as the ones described within IEC TR 61000-4-35) to undertake controlled exposure. Care shall be taken when considering building attenuation that might be present in the real case.
- 4) Obtain the IEMI source of interest and illuminate the facility with the system of interest inside. The testing shall commence at a low level and build up to the normal operating output to ensure that any effects observed will allow the termination of the testing before damage is caused. It should be noted that this method is likely to affect other electronic systems and EM spectrum users and that permission from telecommunication authorities is likely to be required.

If the system shows no effects when tested, it is assessed as immune to the IEMI source of interest.

## 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.10 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 [14] for the HPM sources, and models from HEIMDALL [15] for the weight of the hypoband system components.

**Figure B.10 – 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.

## B.6 References

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- [16] Mil-Std-464C, 'Department of Defense Interface Standard – Electromagnetic Environmental Effects Requirements for Systems', 1 December 2010
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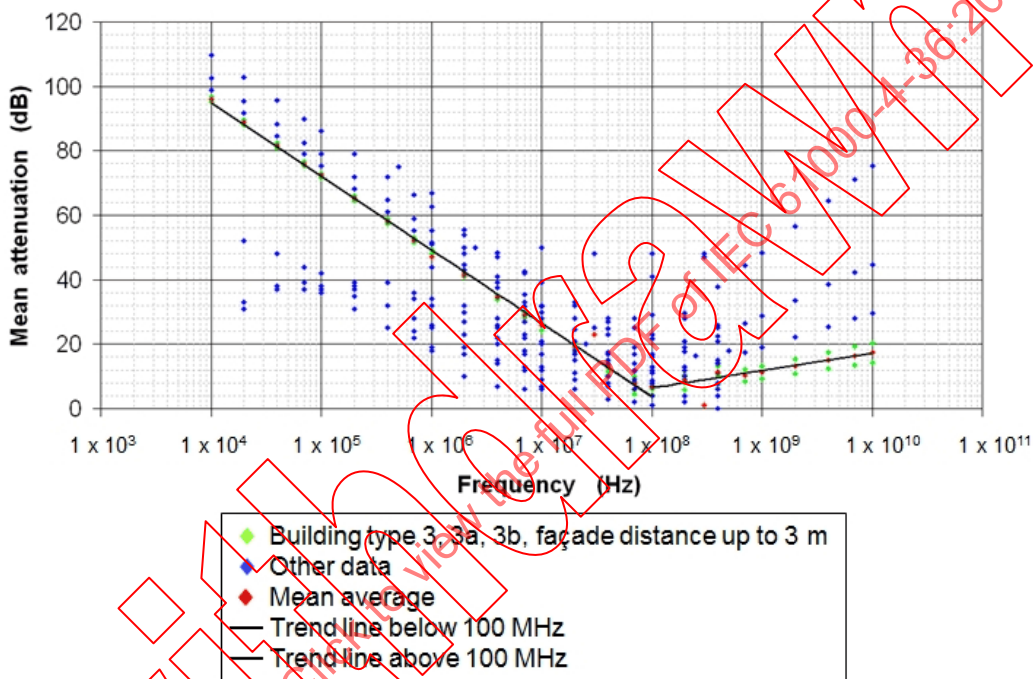
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## Annex C (informative)

### 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 [1] to [7]<sup>6</sup>.



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

<sup>6</sup> 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**

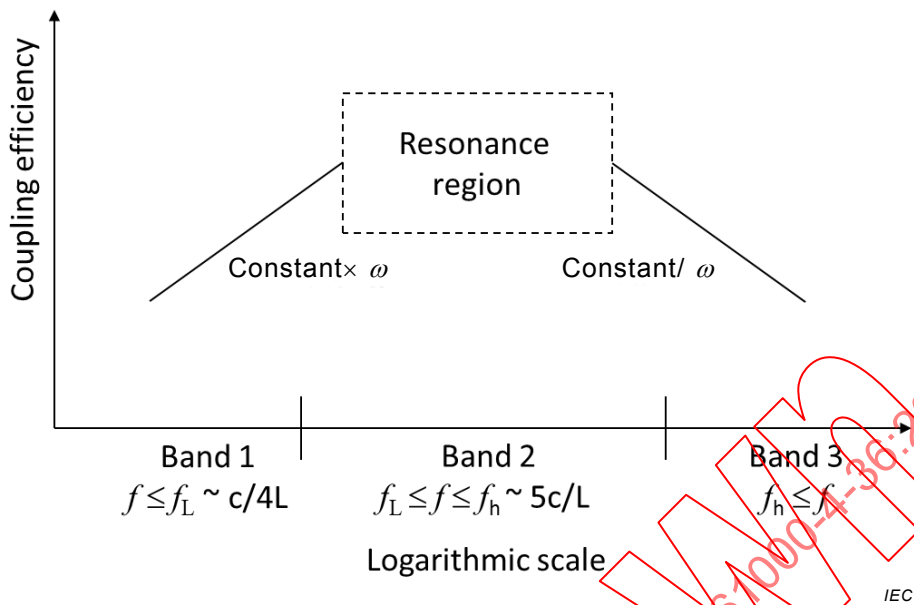
Description	Shielding (dB)
Wood building	2
Room under wood roof	4
Wood building, room 1	4
Concrete, no re-bar	5
Wood building, room 2	6
Concrete and re-bar, room 1	7
Concrete and re-bar, room 2	11
Concrete and re-bar, room 3	11
Concrete and re-bar, room 4	18
Metal building	26
Concrete and re-bar, well 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 [9].

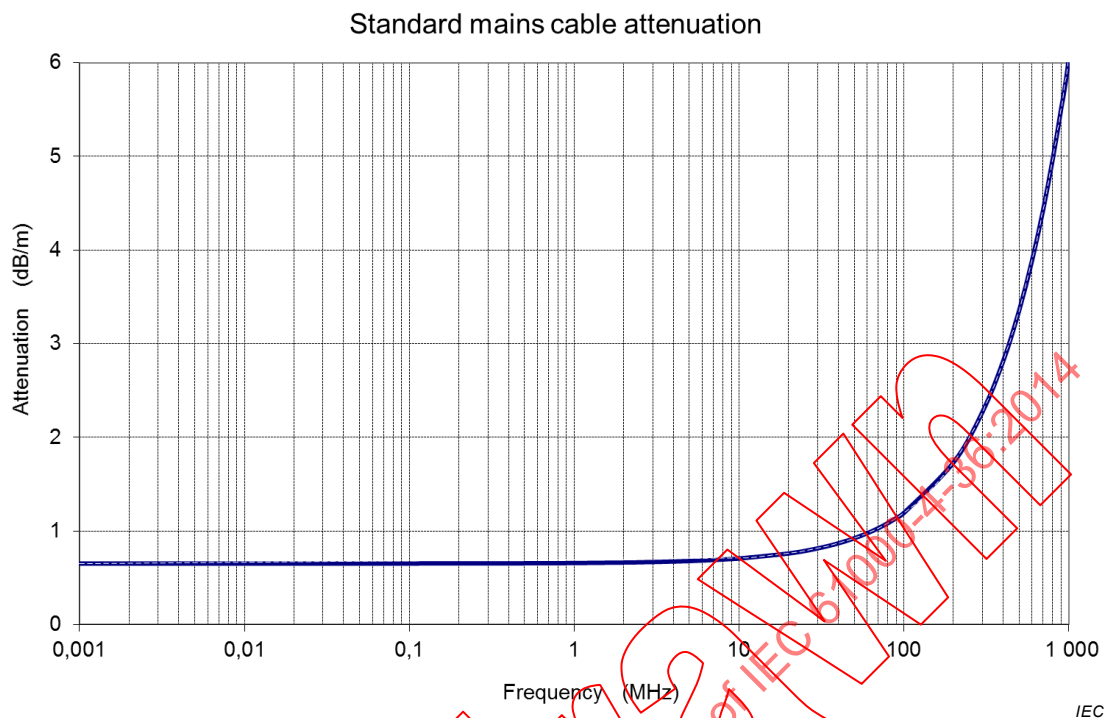


**Figure C.2 – Cable coupling – Resonance region**

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;  $\omega$  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 [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.

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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 [1]<sup>7</sup>. 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 [24]. 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 [2]<sup>8</sup>. 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 [3], [4], [5]:

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

where  $\lambda$  is the wavelength,  $D$  is the directivity (sometimes denoted the directive gain),  $\eta$  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. Equation (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 Equation (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 may 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 may 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.

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

<sup>7</sup> Numbers in square brackets refer to the references in Clause D.5.

<sup>8</sup> It has been shown [18] that good isotropy also prevails at each position of the stirrer.

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, we regard the EUT with its internal field sensor as an antenna. The receiving cross-section,  $\langle \sigma_p \rangle$ , of an antenna is given by [7]:

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

where (see Equation (D.1) above)  $\lambda$  is the wavelength,  $G$  is the antenna gain and  $D(\theta, \phi)$  is the directivity, and where  $\theta$  and  $\phi$  denote the angle of incidence of the plane wave. The parameter  $\eta$  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  $\eta$ , are very high, i.e.  $\eta \ll 1$ .

In a reverberation chamber, the scalar power density,  $S_{sc}$ , is defined by [8]:

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

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 Equation (D.1) above):

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

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

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

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

If we equate the power densities in the two facilities, i.e.  $S_{sc} = S_{AC}$ , we get:

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

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 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 Equation (D.3) above (see [9]). 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:

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

Equation (D.7) represents a simple and fruitful way to define shielding effectiveness in a reverberation chamber (see [25]). 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 for 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 characterize the field external to the EUT. If we use Equation (D.3) to define an equivalent scalar power density inside the EUT we get:

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

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

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

i.e. the same relation as given by Equation (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 [10].

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 Equations (D.6) and (D.9) above. 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 [11] 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 [12], [21].

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 [13]:

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

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 Equation (D.12) is solved for  $n$ , we get:

$$n = \frac{k^2}{z} \left( \frac{\frac{d}{10^{d/20}} + 1}{\frac{d}{10^{d/20}} - 1} \right)^2 \quad (D.13)$$

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

### 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 [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 Equation (D.3) above), 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 [14]).

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 [15] standard for civil aircraft the former has been chosen while the latter has been chosen for the IEC 61000-4-21 [16] standard and for MIL-Std-461 [17]. 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 [18], [19]. The total electric field, on the other hand, may be of interest for example in direct heating of the bulk of a component (see the discussion in [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 [20], 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 Equation (D.8) in [14]), 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 may 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 [12], [21].

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 [11]. In [23] 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 [26]. 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 [15], [16], [17]). The field strengths can also be estimated from a measurement of the average (see [15]), or maximum (see [16], [17]) 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 [18]. Figure 8 in [18] 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  $\pm 3$  dB for  $N = 100$  (as for the average

case above, the probability density function is not symmetric). The result can also be stated (see [18]) that one, for  $N = 100$ , has to subtract a security margin of 2,3 dB from the power measured by the reference antenna to assure 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 [18]).
- 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 is 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 [16] and the discussion in [22]).

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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 methods such as DCS05 and DCS08 defined in Defence Standard 59-411 [1] or the Mil-Std-461 [2] equivalent (CS116). These test methods use 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 [3]. LLSC involves illuminating a system with a uniform low power, swept frequency, 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 the cable bundle being measured, and the position of the current probe on the bundle affects the final result. For frequencies above 200 MHz (to allow an overlap between the cable and aperture coupling regimes) the transfer function of the platform

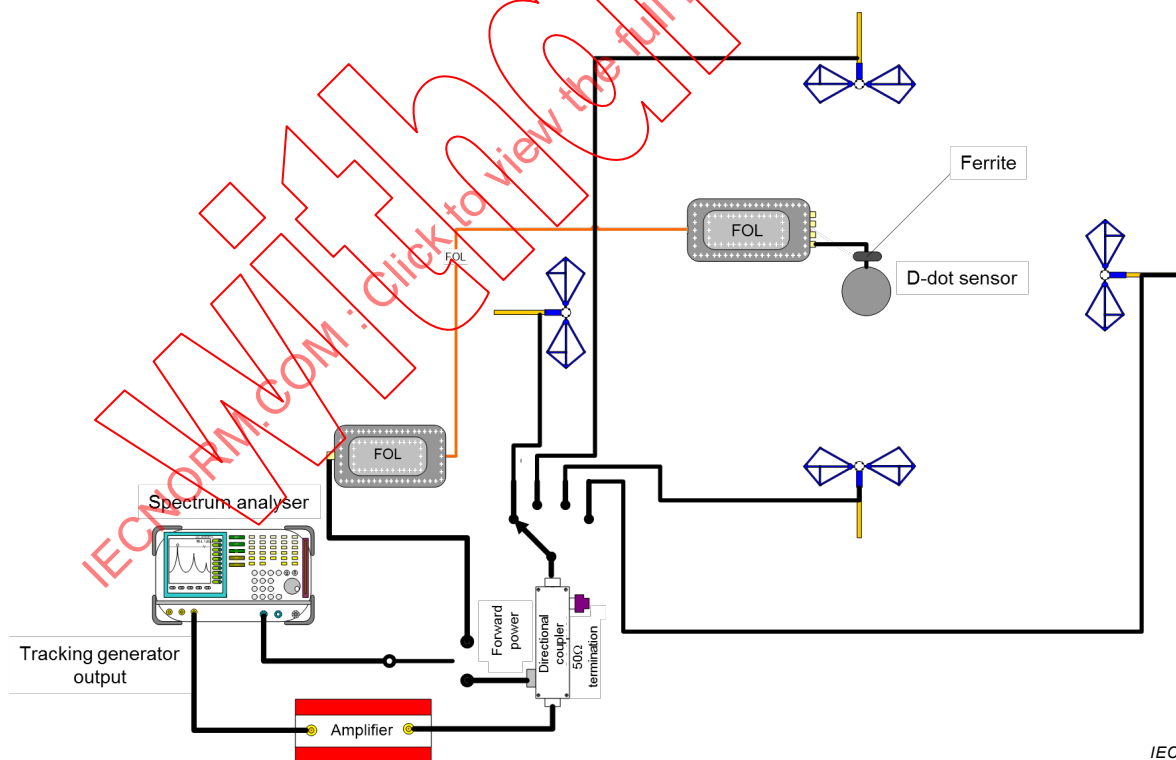
shielding is measured with the low level swept field (LLSF) technique as it has been observed that aperture coupling is the main driver for equipment susceptibilities at these frequencies. Transfer functions obtained using the LLSC method are the focus of Annex E.

The first stage of LLSC is to measure the incident (reference) field. The second stage is to measure the induced current in the cable bundle of interest whilst the reference field is illuminating the system. The final stage involves the processing of the measurements such that a transfer function is generated. The LLSC technique results in 24 data files for each cable bundle (three bands, two polarizations, and four orientations) all of which have been normalized to the measured reference field.

Initially, the data is frequency tied to repackage the dataset into 8 files (two polarizations and four orientations). In some cases, the processing stops here, resulting in polarization and orientation dependent transfer functions for each cable bundle measured. However, for the case of frequency domain HIRF testing, a generic transfer function is calculated which is the highest measured coupling for any frequency; these transfer functions are polarization and orientation independent. Generic transfer functions introduce an inherent safety-margin into the resulting equipment susceptibility assessment. This susceptibility assessment, known as bulk current injection (BCI) is not addressed in Annex E. Polarization dependent but orientation independent transfer functions can also be obtained if required.

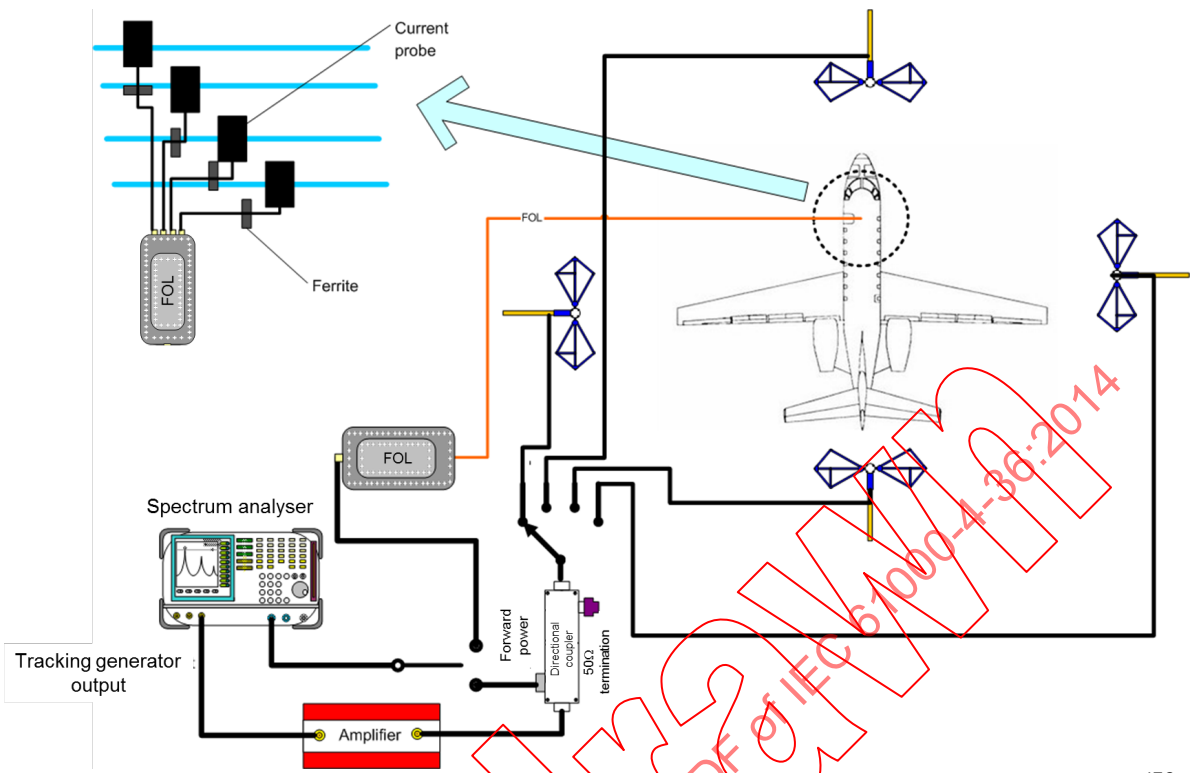
The resulting transfer function is expressed in terms of current per incident field (dB $\mu$ A/(V/m)).

A typical LLSC reference field measurement set-up is shown in Figure E.1 and an induced current set-up is shown in Figure E.2.



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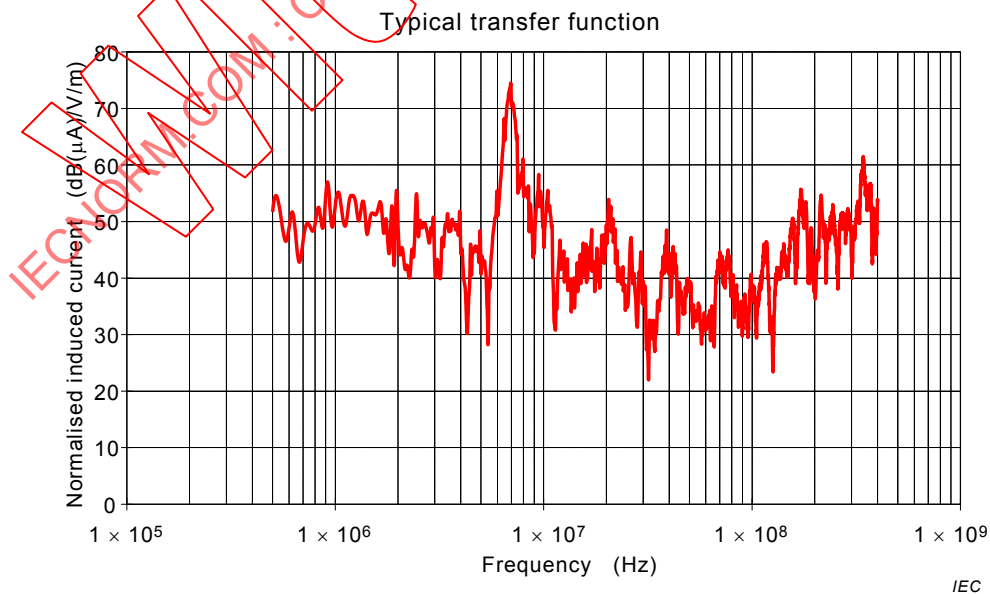
**Figure E.1 – LLSC reference field measurement set-up**



**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

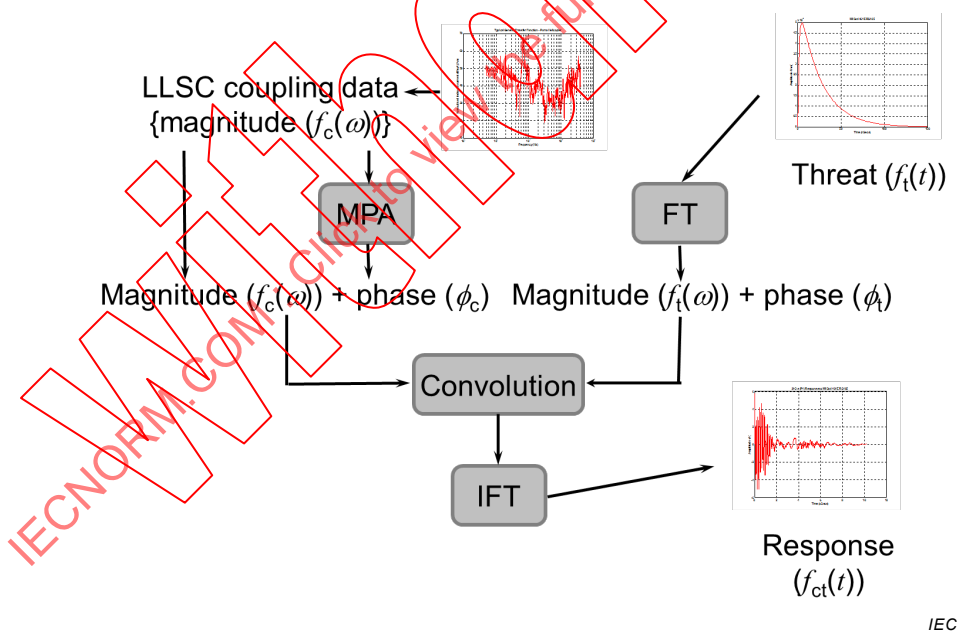
transfer function can simply be extrapolated to the frequency domain environment as it is expressed in terms of induced current normalised to the incident electric field across the relevant frequency range. However, for time domain HPEM environments, the prediction is complicated by the lack of phase 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 (Equation (E.1)):

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

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 [4]<sup>9</sup>. Although the minimum phase response will not be the true response of the system [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 may not be adequately predicted.

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



**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.

<sup>9</sup> Numbers in square brackets refer to the references in Clause E.6.

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 ultra wideband (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 [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.

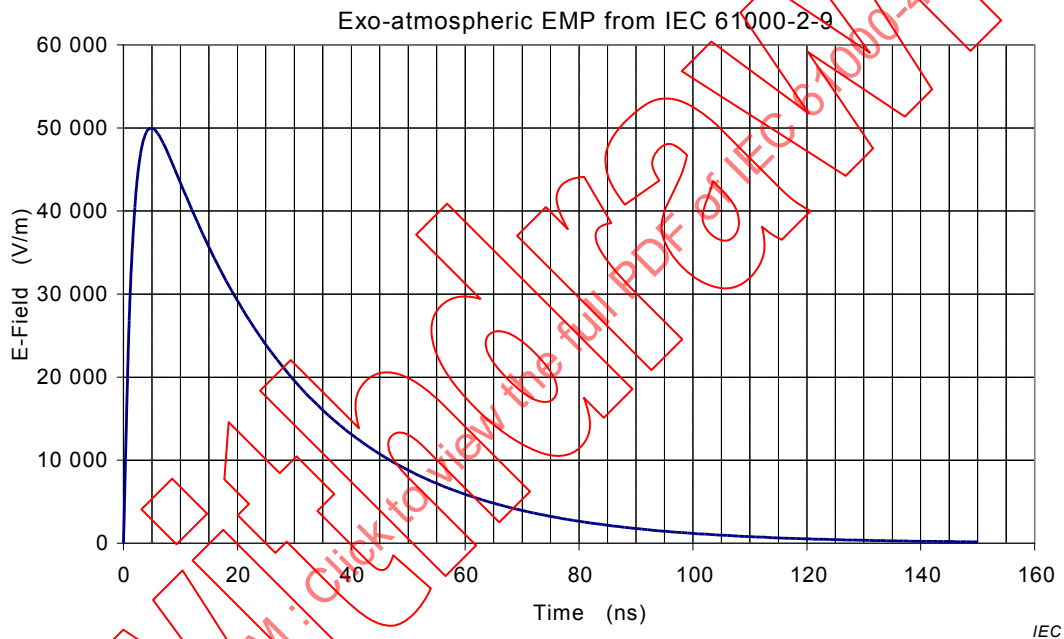


Figure E.5 – IEC 61000-2-9 early-time (E1) HEMP environment

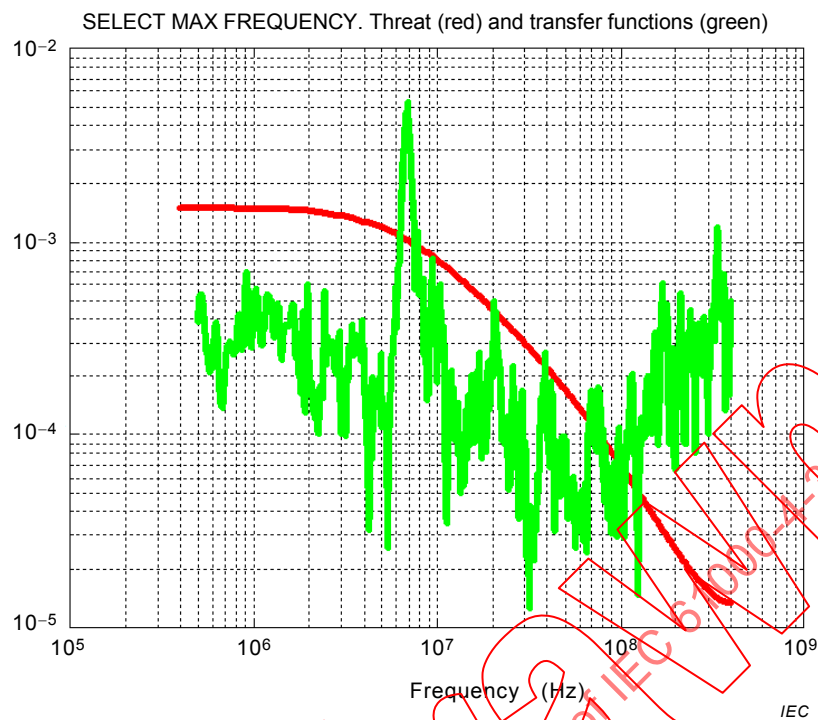


Figure E.6 – Overlay of transfer function and threat (frequency domain)

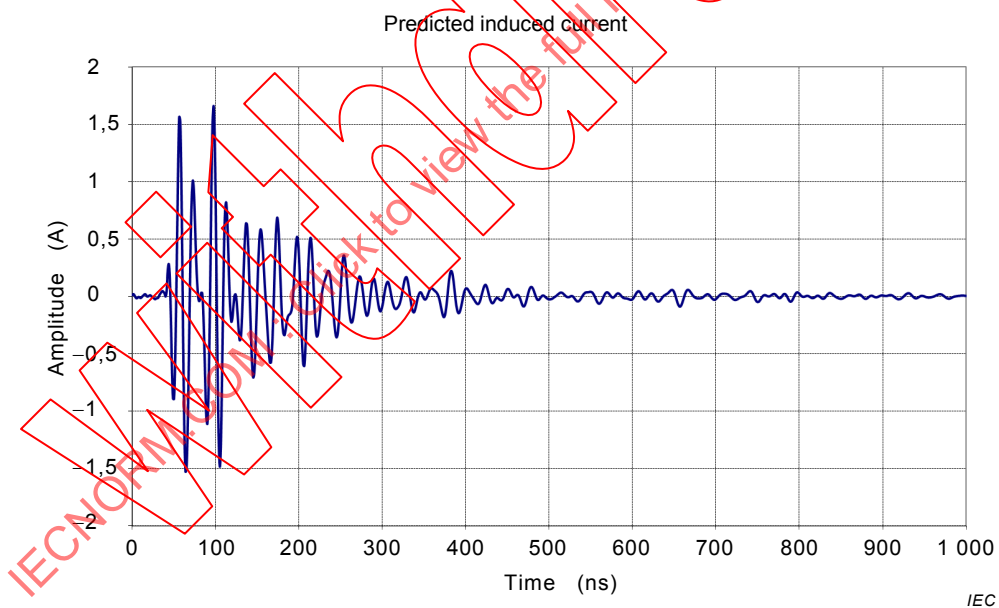


Figure E.7 – Predicted current

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 during 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 decomposition algorithm used for this process is based upon a variation of the MPA that results in non-minimum phase predictions [7]. The Stieglitz-McBride algorithm [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.

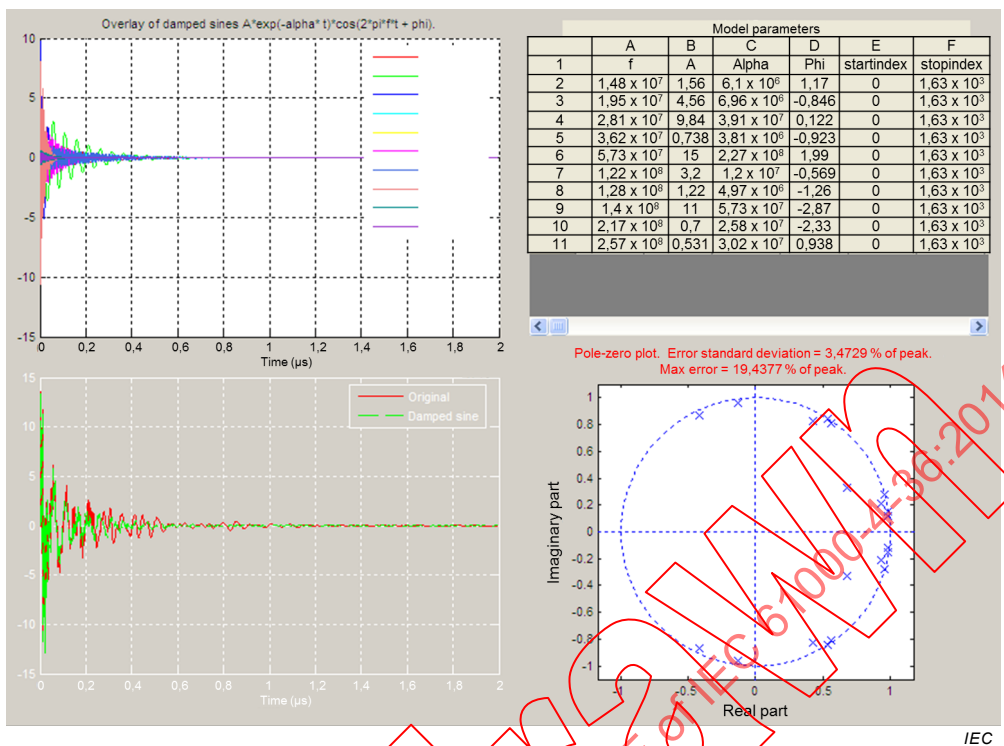


Figure E.8 – Example of de-convolution result

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

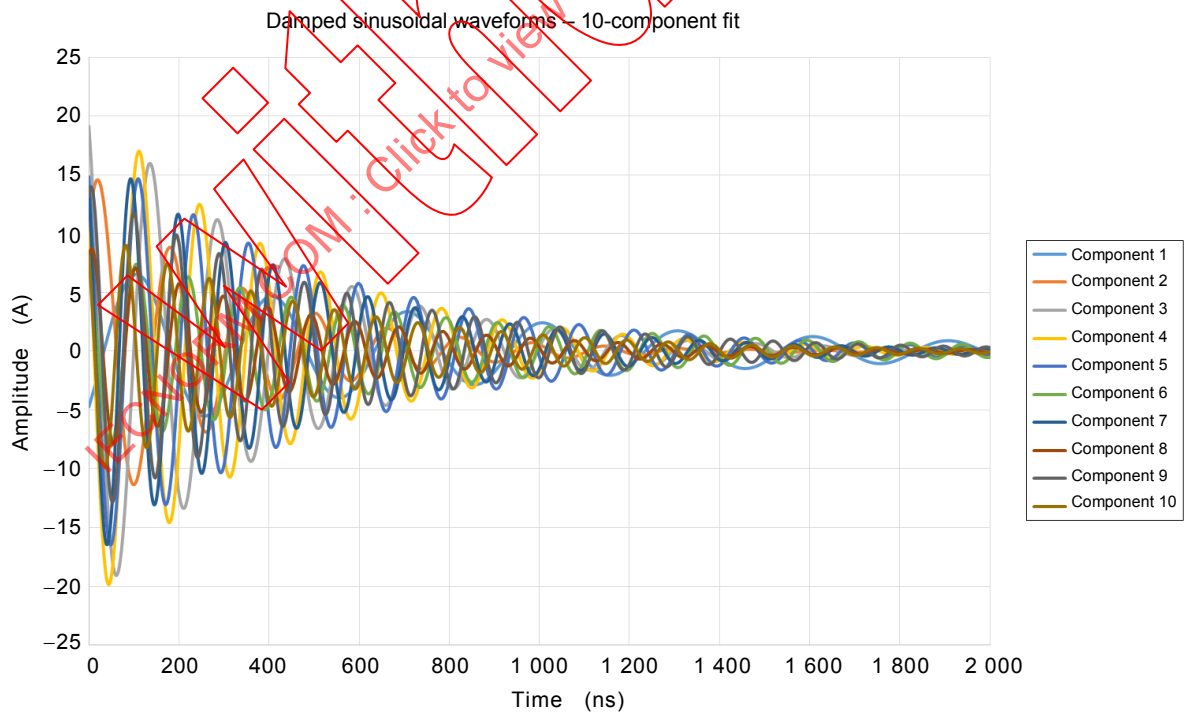
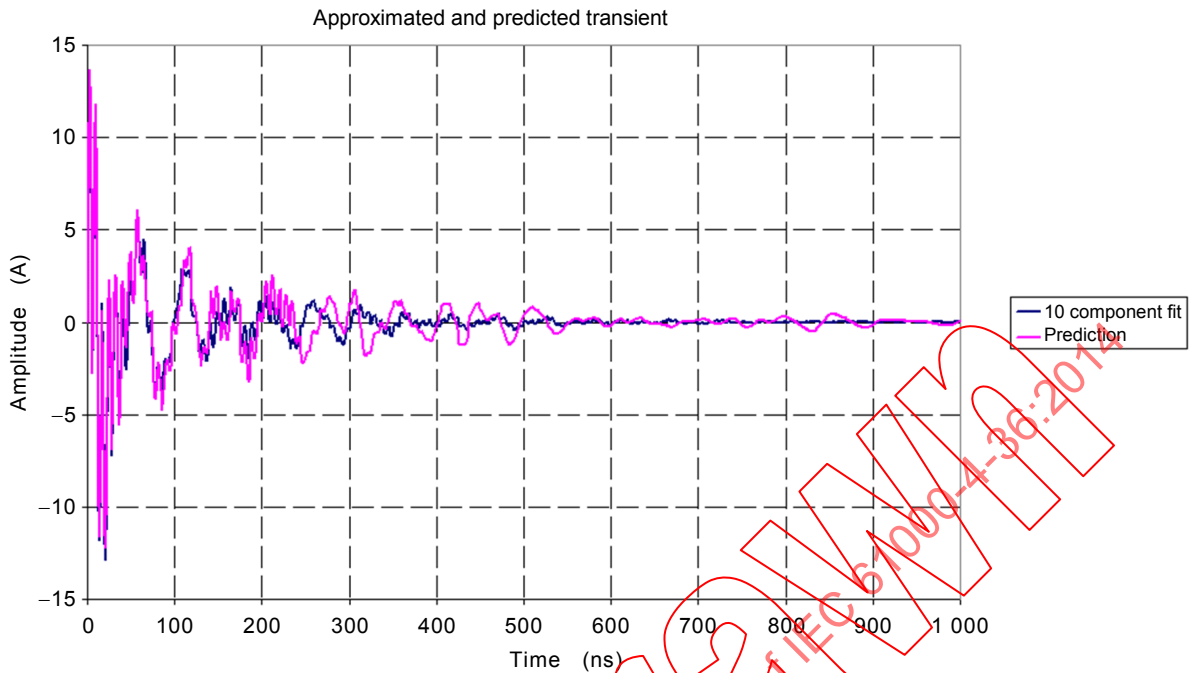


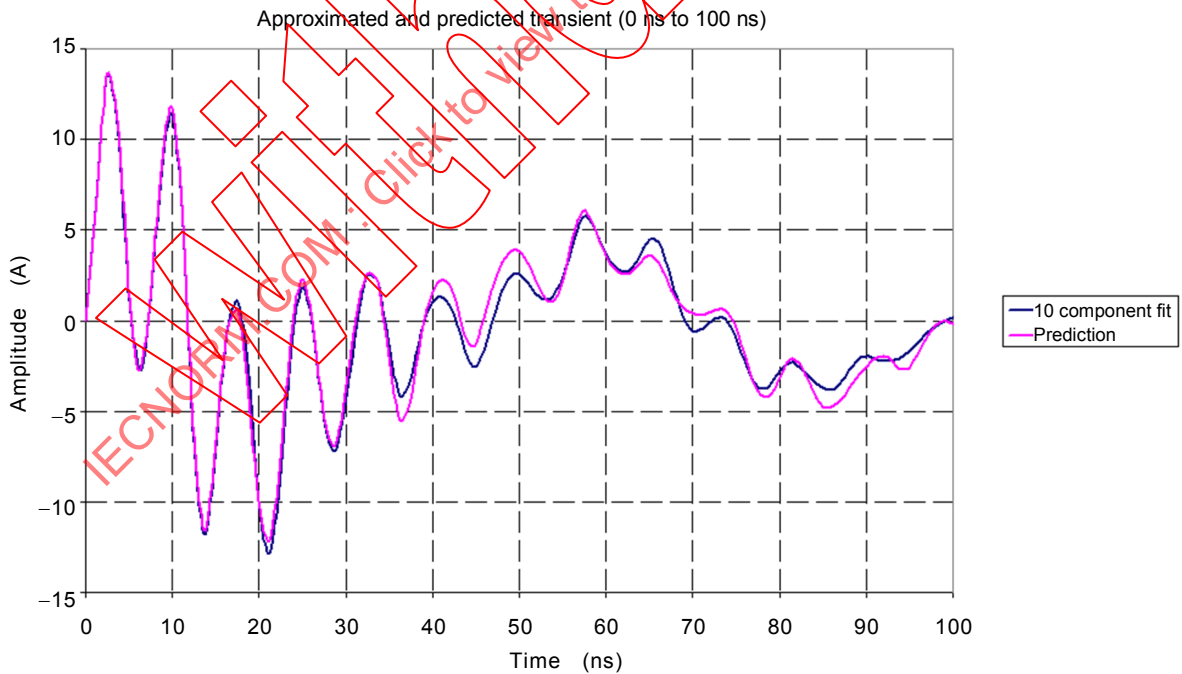
Figure E.9 – Damped sinusoidal waveforms – Ten-component fit



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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.