IEC/TS 61000-5-9

Edition 1.0 2009-07

TECHNICAL SPECIFICATION

BASIC EMC PUBLICATION

Electromagnetic compatibility (EMC) – Part 5-9: Installation and mitigation guidelines – System-level susceptibility assessments for HEMP and HPEM

IEC/TS 61000-5-9:2009(E)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE **XB**

ICS 33.100.20

ISBN 2-8318-1051-0

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 5-9: Installation and mitigation guidelines – System-level susceptibility assessments for HEMP and HPEM

FOREWORD

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC/TS 61000-5-9, which is a technical specification, has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility.

This Technical Specification forms Part 5-9 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107 [1][1].

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
77C/190/DTS	77C/194/RVC

Full information on the voting for the approval of this technical specification 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.

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

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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

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

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 and 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 5-9: Installation and mitigation guidelines – System-level susceptibility assessments for HEMP and HPEM

1 Scope

The aim of this part of IEC 61000 is to present a methodology to assess the impact of High-altitude Electromagnetic Pulse (HEMP) and High Power Electromagnetic (HPEM) environments on electronic systems. In this context a system refers to a collection of sub-systems, equipment and components brought together to perform a function. (A more complete definition is given in 3.20.) The techniques associated with this methodology and their advantages and disadvantages will be presented along with examples of how the techniques can be applied to evaluate the susceptibility of electronic systems such as those found in installations. This work is closely related to the evaluation of EMC system level susceptibility.

The purpose of this Technical Specification is to provide information on available methods for the assessment of system-level susceptibility as a result of HEMP and HPEM environments. The advantages and disadvantages of the methods will be discussed along with examples of how the techniques should be employed.

Typical systems have external connections, wired or wireless, and the assessment of these are included within this specification.

This specification gives general guidance. It does not cover safety issues nor does it conflict with ITU-T efforts concerning the protection of telecommunications equipment [2][2].

2 Normative references

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

IEC 60050(161), *International electrotechnical vocabulary – Chapter 161: Electromagnetic compatibility*

IEC/TR 61000-1-5:2004, *Electromagnetic compatibility (EMC) – Part 1-5: General – High power electromagnetic (HPEM) effects on civil systems*

IEC 61000-2-9:1996, *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 9: Description of HEMP environment – Radiated disturbance. Basic EMC publication*

IEC 61000-2-10:1998, *Electromagnetic compatibility (EMC) – Part 2-10: Environment – Description of HEMP environment – Conducted disturbance*

IEC 61000-2-13:2005, *Electromagnetic compatibility (EMC) – Part 2-13: Environment – High-power electromagnetic (HPEM) environments – Radiated and conducted*

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[2] Figures in square brackets refer to the Bibliography.

IEC/TR 61000-4-32:2002, *Electromagnetic compatibility (EMC) – Part 4-32: Testing and measurement techniques – High-altitude electromagnetic pulse (HEMP) simulator compendium*

IEC 61000-4-33:2005, *Electromagnetic compatibility (EMC) – Part 4-33: Testing and measurement techniques – Measurement methods for high-power transient parameters*

IEC 61000-4-35:2009, *Electromagnetic compatibility (EMC) – Part 4-35: Testing and measurement techniques – HPEM simulator compendium*

IEC/TR 61000-5-3:1999, *Electromagnetic compatibility (EMC) – Part 5-3: Installation and mitigation guidelines – HEMP protection concepts*

IEC/TS 61000-5-4:1996, *Electromagnetic compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 4: Immunity to HEMP – Specifications for protective devices against HEMP radiated disturbance. Basic EMC Publication*

IEC 61000-5-5:1996, *Electromagnetic compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 5: Specification of protective devices for HEMP conducted disturbance. Basic EMC Publication*

IEC/TR 61000-5-6:2002, *Electromagnetic compatibility (EMC) – Part 5-6: Installation and mitigation guidelines – Mitigation of external EM influences*

IEC 61000-5-7:2001, *Electromagnetic compatibility (EMC) – Part 5-7: Installation and mitigation guidelines – Degrees of protection provided by enclosures against electromagnetic disturbances (EM code)*

3 Terms and definitions

For the purposes of this document the terms and definitions of IEC 60050-161 as well as the following apply.

3.1

aperture coupling regime

frequency range where aperture coupling dominates; this is typically between 200 MHz to 18 GHz

3.2

back-door coupling

coupling of EM energy to equipment via connecting cables or apertures (not via antennas or sensors

NOTE Detailed discussion of back-door coupling can be found in Clause 5.

3.3

cable coupling regime

frequency range where cable coupling dominates; this is typically between 500 kHz and 400 MHz

3.4

coupling

transfer of electromagnetic energy from source to victim

3.5

E/E/PE equipment

equipment that employs electrical, electronic or programmable electronic technologies

3.6
equipment
general designation which includes modules, devices, apparatuses, subsystems, complete systems and installations

3.7
equipment under test
EUT
refers to the equipment being tested

3.8
front-door coupling
coupling of EM energy to equipment via antennas and/or sensors

NOTE Detailed discussion of front-door coupling can be found in Clause 5.

3.9
HEMP
High-altitude Electromagnetic Pulse

3.10
high-level illumination
HLI
use of high-level (>100 V/m) signals to assess the immunity or susceptibility

3.11
HPEM
High Power Electromagnetic

3.12
immunity
ability of a device equipment or system to perform without degradation in the presence of an electromagnetic disturbance

[IEV 161-01-20]

3.13
installation
combination of apparatuses, components and systems assembled and/or erected (individually) in a given area

NOTE For physical reasons (e.g. long distances between individual items) it is in many cases not possible to test an installation as a unit.

3.14
low-level continuous wave
LLCW
use of low-level signals (typically <1 V/m) to characterise the coupling of an external electromagnetic environment to an internally induced current, voltage or field (magnetic or electric)

3.15
margin
usually expressed in dB, this in the amount added to a result to improve confidence or to allow for uncertainties

3.16
norm
mathematical function used to describe a parameter of a waveform; several norms can be used to describe the 'uniqueness' of a waveform

3.17
pulsed current injection
PCI
use of current injection methods to assess the immunity or susceptibility with a pulsed waveform as opposed to more traditional continuous wave (CW) signals

3.18
surface current injection
SCI
injection of current directly on to the surface of an equipment box of system skin

3.19
susceptibility
inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance

[IEV 161-01-21]

3.20
system
combination of apparatuses and/or active components constituting a single functional unit and intended to be installed and operated to perform (a) specific task(s)

4 General

4.1 Introduction

HEMP occurs as a result of a high-altitude nuclear explosion and can cover several millions of square kilometres with electric field strengths of up to tens of kV/m. Further discussion of HEMP can be found in IEC 61000-2-9 and IEC 61000-2-10.

HPEM is the collective name given to a set of high power radio frequency (RF) sources that are capable of generating high levels of RF at ranges <1 km. The waveforms generated by these types of sources vary and include Ultra Wideband (UWB), Damped Sine (DS) also known as Non-Nuclear EMP (N2EMP) and High power Microwave (HPM). Further discussion of these sources can be found in IEC 61000-2-13.

This specification discusses methods available for the assessment of systems as defined in 4.2 (not distributed civil infrastructure[3]) to the effects of HEMP and HPEM. Typical system examples are vehicles, aircraft and small ships. The techniques can be applied to larger systems such as buildings, however, with careful consideration.

The assessment methodology discussed in this specification is not appropriate for geographically large connected or distributed systems. However, the techniques may be applicable to individual components, equipments, subsystems or systems contained within a large connected or distributed system.

The assessment methodology may be used to determine the status of a particular system with respect to its hardening to HEMP and/or HPEM environments.

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[3] Distributed civil infrastructure is discussed in IEC 61000-5-8.

It is important to note that the assessment methodology presented within this specification should help to assist in reducing the risk of detrimental system performance due to exposure to HEMP and HPEM environments. This methodology can be applied during the design and development phases of a system. A full system-level test using the HEMP or HPEM environment of interest is an important part of this methodology. Information on worldwide HEMP and HPEM simulators can be found in IEC 61000-4-32 and IEC 61000-4-35 respectively.

4.2 Systems and subsystems

In the context of this specification, a system may consist of several subsystems which are each comprised of several equipments which, in turn, consist of several components. Figure 1 shows a typical system architecture.

A system can also be considered to be a set of **supplied equipments** located within a **defined physical boundary** that are **interconnected** in order to perform a defined function.

The defined physical boundary may be

the outer hull (for systems located on military platforms – vehicles, aircraft and ships),

the outer building wall (for systems located within buildings).

The **interconnection** may be either

wireline (using either metallic or optical cables),

or wireless,

and the interconnection is made for the purpose of either

exchanging information,

or receiving or supplying electrical power.

Any physical connection (i.e. wireline or wireless) with supplied equipment that does not originate from within the system's defined physical boundary is an **interface**. Interfaces may be permanent (in the case of buildings, where a permanent connection with wireline power and telecommunications infrastructure can be expected) or temporary (in the case of military platforms, where the inherent mobility of the platform prevents permanent wireline interfacing).

Individual **supplied** pieces of **equipment** may themselves be individual systems (i.e. subsystems, or sub-subsystems, and so forth) that should themselves have been subject to the methods contained within this specification.

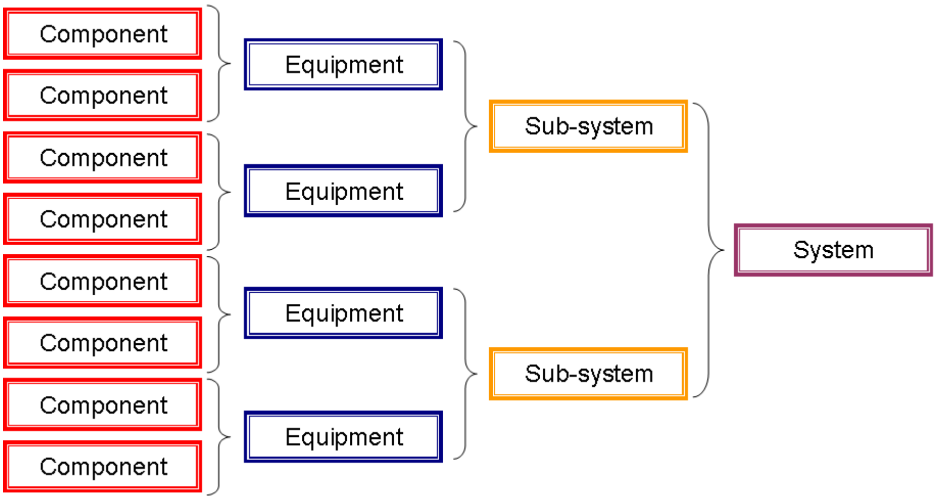


Figure 1 – Example system architecture

For example, a vehicle (system) may consist of an engine management unit (subsystem) which consists of circuit boards (equipment) and integrated circuits (component).

5 Interaction mechanisms and protection methods

5.1 General

Within IEC 61000-1-5, the terms deliberate penetration and inadvertent penetration are used to describe the penetration of EM energy into a system. This specification uses the terms back-door coupling and front-door coupling (see Figure 2) since they better relate to the fundamental difference that exists regarding the possibility to protect a system without degrading its function. While careful back-door shielding should not degrade the function of a system at all, protection against in-band front-door coupling may degrade the function of the system.

5.2 Front-door coupling

The radiation couples to equipment ports intended for wireless communication or other interaction with the external environment. Hence, they cannot easily be fully shielded against electromagnetic radiation without loosing or severely degrading their function. Examples are antennas and sensors.

Front-door coupling can be subdivided into first and second order, as follows.

a) Front-door coupling, first order (in-band)

   The frequency of the radiation coincides, at least partly, with the working frequency of the equipment. An example is a telecom base-station irradiated in its pass band.

b) Front-door coupling, second order (out-of-band)

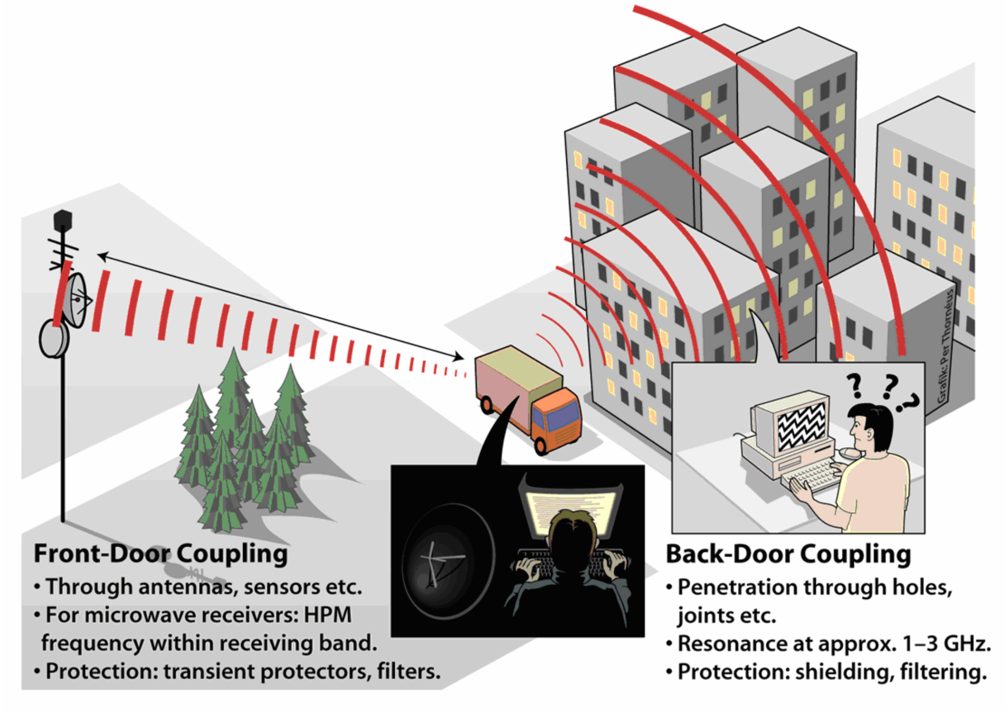
   The frequency of the radiation does not coincide with the working frequency of the equipment. An example is a HF radio antenna exposed to high power microwaves.

5.3 Back-door coupling

The radiation couples to electronic circuits through imperfections (apertures) in the electromagnetic shield enclosing the electronics, or directly to the electronic circuit boards. In the case of a shielded structure this leakage gives rise to a diffuse and complex field pattern within the structure. The apertures can be unintentional or intentional. An example of the former is a paint, or an oxide, layer in a shielding joint between conductive surfaces. Examples of the latter are holes for drainage or ventilation. The radiation may also couple directly to an external wire connected to a component or a subsystem [3]. The reason to define such a wire as back-door coupling and not as a second-order front-door coupling is motivated by the fact that the wire could be shielded without degrading the function of the equipment.

It is important to note that HEMP or HPEM disturbances can be radiated or conducted in nature. It follows therefore, that the source of the front-door or back-door coupling can be radiated or conducted in nature. It should be noted that conducted disturbances cannot only be out-of-band but also occur under normal operating conditions (in-band and out-of-band). Examples of this include transient overvoltages much higher than the voltage under normal operation or surge currents flowing in a system.

This specification deals mainly with back-door coupling although some attention is given to front-door coupling in Annex H.



The van in the centre of the picture contains the HPEM source.

Figure 2 – Example of radiated HPEM at high frequencies [3]

5.4 Protection methods

Front-door coupling: While in-band disturbances are difficult to neutralize, permanent damage effects can be mitigated by use of transient protectors. Out-of-band disturbances, that is, second-order front-door coupling, can be handled by use of filtering, for example for radio equipment, or by use of metallic meshes or thin films for optical equipment. Often, protective measures will lead to some degradation of the intended function of the system.

Back-door coupling: Use of conventional EMC protection techniques, such as shielding and filtering, should suffice to achieve a 30 dB protection level [4], which should be sufficient for the HPEM threat (although not for the military HPM threat). Transient protection devices may be required to protect filters from high-voltage transients and should be carefully combined with filters to increase the level of protection.

An alternative way of considering protection is based on the type of HEMP or HPEM disturbance to be protected against. Radiated disturbances can be mitigated by the use of shielding and conducted disturbances can be mitigated by the use of transient protection devices and filters.

Detailed information on protection methods can be found in IEC/TR 61000-5-3, IEC/TS 61000-5-4, IEC 61000-5-5, IEC/TR 61000-5-6 and IEC 61000-5-7.

6 Description of overall assessment methodology

6.1 Methodology

This clause discusses the overall assessment methodology.

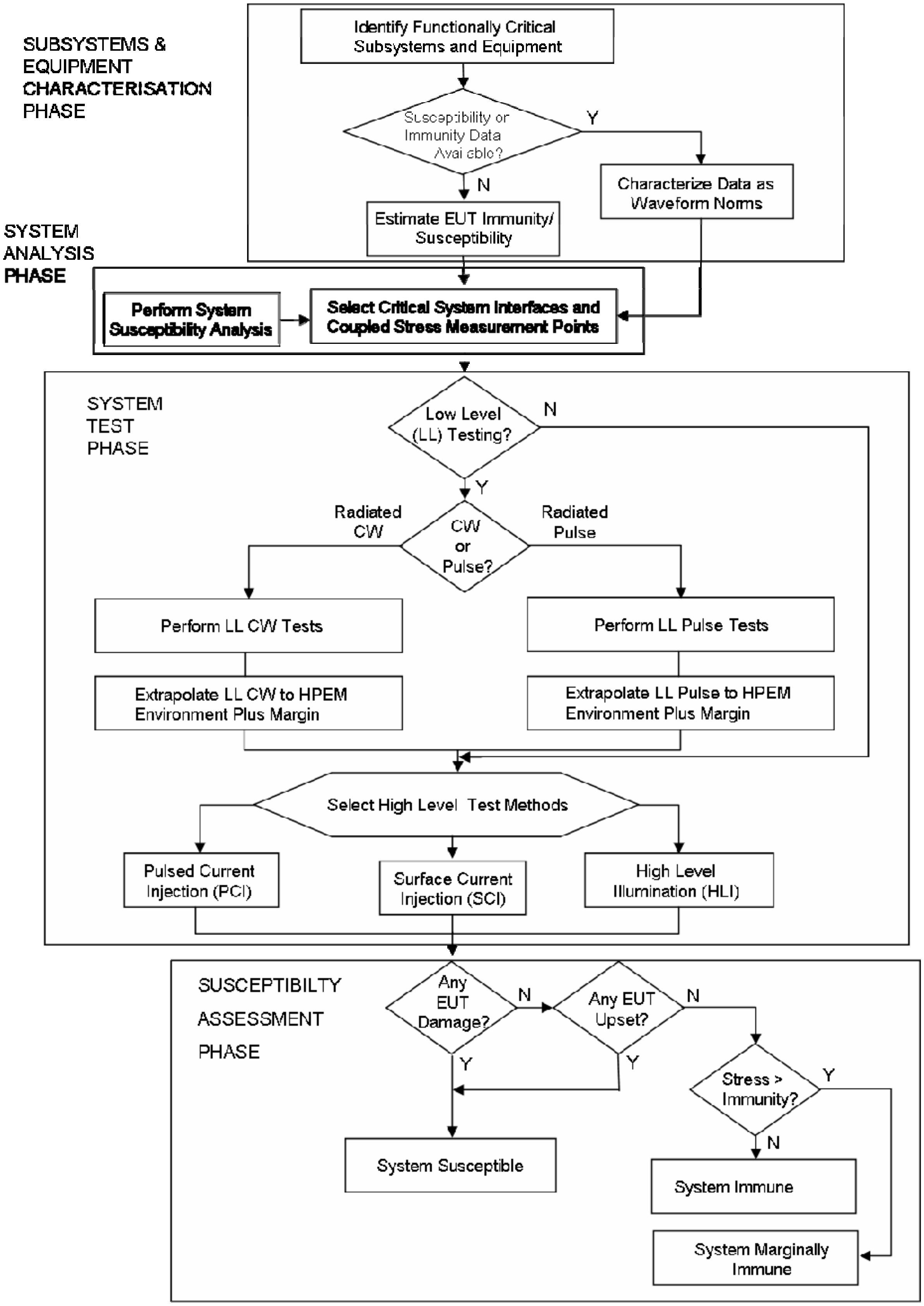


Figure 3 – Methodology flowchart

6.2 Subsystems and equipment characterization phase

Characterization of the subsystems and equipment shall be completed prior to any detailed evaluation or assessment. At this stage, it is essential that functional and topological descriptions of the system are generated to allow for critical aspects of the system to be identified.

A functional description deals with the intentional flow of information within the system that is the information flow for decision-making and responses from the intentional external interface throughout the system.

A topological description deals with;

a) the physical units that correspond to each function within the functional description (i.e. the individual boxes, cards or units),

b) the intended physical interconnections between the physical electronics (i.e. cabling),

c) the relative location of each physical unit and intended physical interconnection. This allows an assessment to be made of the relative importance of the three fundamental interactions: box-to-box, cable-to-box and box-to-cable radiation.

Together, functional and topological descriptions allow the propagation of front-door and back-door coupling within the system to be understood and hence hardening strategies to be developed. In addition, these descriptions will enable the impact of any HEMP or HPEM induced effect to be correctly assigned as either immunity or susceptibility during the susceptibility assessment phases. Also, areas of potential weakness should be identified based upon information about similar systems or technology types.

During this phase it is necessary to gather immunity and/or susceptibility information that may be relevant. This should be obtained from electromagnetic compatibility (EMC) test data. If waveforms associated with susceptibilities are available, waveform norms that allow parameters of waveforms to be mathematically quantified should be computed for later use. Further details on the use of waveform norms can be found in IEC 61000-4-33, Annex A [5].

A typical subsystem and equipment characterization will breakdown the system into its component subsystems and equipments. Each of these subsystems and pieces of equipment will then be assessed for coupling paths relevant to the frequency density of the illuminating HEMP or HPEM environment of interest. This is performed by translation of the frequency content of the illuminating environment into wavelengths by using the simple expression given in Equation (1).

$$c = f\lambda \tag{1}$$

where

c is the speed of light in a vacuum (3×10^8 m/s),

f is the frequency (Hz),

λ is the wavelength (m).

Depending on the type of coupling path, frequencies corresponding to a wavelength of $L/2$ or $L/4$ (where L is the length of the conductor of interest, for example, a cable) tend to dominate and this provides an indication of the ability of the illuminating HEMP or HPEM environment to couple to the subsystem and equipment being characterised.

Any protection added should be noted during this phase of the assessment and may negate the need for more extensive testing during the later stages. An effective shield at the frequencies of interest may reduce the illuminating HEMP or HPEM environment to a level that is below the immunity requirements for commercial electronics, thus demonstrating that further radiated testing of the commercial electronics is not required. In this case, a conducted test would still be required, unless adequate filtering can be demonstrated to show that anticipated conducted currents and voltages would be attenuated to a level for which the electronics has been demonstrated to be immune. However, testing at the later stages is recommended to assure that the added protection is adequate.

For example, a shield affording 80 dB (a factor of 10 000 in terms of electric field strength) of attenuation would reduce an external illuminating HEMP field of 50 kV/m to 5 V/m. Immunity test data (driven by EMC requirements) are typically amplitude modulated (AM) continuous wave (CW) but the induced current expected from HEMP illumination will be damped sinusoidal in nature. Evaluation of the energy content of a CW and a damped sinusoidal waveform of the same (centre) frequency shows that the CW waveform has much greater energy. Thus, if an equipment or system is immune to 5 V/m CW, it is possible that it will be immune to larger peak amplitudes of transient (damped sinusoidal) signals. For interference the peak amplitude is likely to be the susceptibility driver, but for permanent damage, energy is a key susceptibility driver.

A further consideration here is that EMC tests are driven by the need to demonstrate continued operation in a particular EM environment that is they are required to demonstrate immunity in that environment. Without the appropriate test information, it is generally not possible to make conclusions about susceptibility based on immunity data only. However, in the context of system level assessments, the immunity data plays an important role as it can be used as a lower bound on equipment strength and provide an indication of the range from HPEM environments where continued functionality (immunity) can be expected. Without susceptibility information, this type of calculation will provide the system user with a range at which the system will continue to operate, but does not provide information on the range at which effects can be expected. Detailed susceptibility data is required in order to generate this information.

Knowledge of the shielding effectiveness of equipment, subsystem and system interfaces also provides important information as subsystem immunity of 5 V/m (CW) with system shielding of 26 dB means that the subsystem will continue to operate in an externally illuminating field of 100 V/m (CW).

Information obtained during this phase will be used in the next phase. Waveform norms can be computed to enable a rigorously mathematical method of comparing data. Norms are discussed in more detail in C.2.2.

6.3 System analysis phase

The purpose of the system analysis phase is to identify critical subsystems and equipment, system configurations and operational modes that will be assessed through a combination of low-level and high-level tests to estimate a system's susceptibility to the HEMP and HPEM environments. A key element in this process is selection of a set of measurement or test points at critical interface locations within the system that will be used later in the susceptibility assessment phase to compare coupled stress waveform data (obtained in the system test phase) to EUT immunity or susceptibility waveform data at corresponding interfaces (obtained in the subsystems and equipment characterization phase). During the test point selection process, emphasis should be placed on choosing test points at EUT interfaces that both;

a) are predicted to have the highest level stresses and

b) are functionally critical to proper operation of the system.

6.4 System test phase

6.4.1 General

This phase describes EUT and/or system level testing that can be used to provide information on the system's overall protection against a HEMP or HPEM environment. In some cases, test facilities cannot manage large systems therefore breaking down the system level test into a test for subsystems and/or equipments and combining the results may be an acceptable alternative. If this approach is to be adopted, extreme care shall be taken to ensure that the integration of equipments and subsystems does not impact on the effect of the HEMP or HPEM environment at the system level.

To conduct a complete system level test, all subsystems and equipment should be installed in the system, interconnected and functioning in its normal intended operational state.

6.4.2 Low-level tests

Low-level (LL) tests can be conducted with either continuous wave (CW) or pulsed illuminating fields.

Transfer function and attenuation data should be collected for those cable bundles and areas of interest identified by the system analysis. For HEMP and/or HPEM environments that dominate in the cable coupling regime (500 kHz to 400 MHz, depending on the length of cabling) convolution with cable bundle transfer functions will result in predicted currents as a result of the incident field of the environment of interest. For HEMP and/or HPEM environments that dominate in the aperture coupling regime (400 MHz to 18 GHz) convolution with attenuation data will result in predicted fields within the system enclosure. This data can then be compared with any available electromagnetic compatibility (EMC) test results to provide immunity and possibly, susceptibility thresholds.

As these tests are conducted at low-level, they will not adequately characterise the performance of non-linear phenomenon such as arcing and transient protection devices [6]. The performance of these devices should be carefully considered in the overall assessment.

6.4.3 High-level testing

6.4.3.1 General

High-level (HL) susceptibility tests should be conducted by an appropriate technique. This could include free-field (directional) methods, reverberation chamber methods, or via direct injection methods. Reverberation chamber testing can be said to represent a worst case illumination from a polarisation and orientation perspective, due to the statistically isotropic environment of the chamber. However, for the same reason, it essentially represents only an average case in terms of the stress on the EUT, compared with a plane wave having the same field strength [7]. High-level free field testing will identify susceptibility dependencies on polarisation, orientation and HPEM waveform parameters within the constraints of the facility used for the assessment.

Consideration of the parameters of the HPEM and/or HEMP waveform of interest and the likely upset parameters for the technology contained within the subsystem or equipment under test (EUT) is necessary in order to utilise the optimum test parameters during the assessment.

During this part of the assessment, the EUT should be made to operate in a representative configuration. This must include careful location of cables used during the EUTs deployed state. Any RF link between a screened chamber and the outside world requires hard-wired replacement such that the EUT can be monitored for any induced susceptibility. It is important that the addition of any such link is suitably attached to the EUT, such that changes in the electromagnetic properties of the EUT are minimised. This is particularly the case when replacing RF links for hard-wired links as the RF link has inherent physical isolation but a hard-wired link introduces another path for coupling of RF to the system. The impact of this is typically alleviated by the use of ferrite loaded cables to prevent the circulation of skin currents in the screen of the cable (discussed further in Annex B). Bulkhead connectors should also be used to prevent the transfer of any circulating current entering the inside of the system and re-radiating.

The result of this stage of the assessment will be a set of frequencies at which the system has been affected allowing susceptibilities to be identified. A frequency density spectrum can be generated for all HPEM and/or HEMP sources of interest. This can be compared against the frequency bands for susceptibilities to identify sources that could generate the same effect.

Where applicable, an accurate comparison of the effects of different modulation types at this stage is critical.

6.4.3.2 Pulsed current injection (PCI)

This part of the assessment involves the injection of pulsed waveforms whilst the EUT or system is monitored for susceptibility. This can involve the injection of damped sinusoidal waveforms that are centred on a single frequency or complex transients that consist of many frequencies. For example, it is possible to obtain a predicted induced cable bundle current for an illuminating HEMP or HPEM environment using the transfer functions gathered during 6.4.2.

During this part of the assessment, it is important to consider the impact of single port excitation when the HEMP or HPEM environment may excite many ports simultaneously. In particular, multi-port excitation should be used on EUT where redundancy may be built in during practice. If multi-port excitation is used, the assessment must give due care to ensuring that all ports are excited within the cycle time of the EUT as failure to do this may result in an misleading test result.

The PCI methods described in IEC 61000-4-23 [6], IEC 61000-4-24 [8] and IEC 61000-4-25 [9] may be useful during this phase.

6.4.3.3 Surface current injection (SCI)

Direct drive techniques may be used to inject currents onto either a return conductor built around the system under assessment or the system itself. The current flow, on the return conductor or on the system exterior, cross-couples to the cabling within the system. This method can be used at low level to measure transfer functions or at high levels to monitor for susceptibilities. One of the advantages of this technique is that it can be applied at lower frequencies than the LLCW methods discussed in 6.4.2 [6].

6.4.3.4 High-level illumination (HLI)

This part of the assessment involves exposing the system to high power RF sources indicative of the types of technology that could be used as HPEM and/or HEMP. These include Ultra Wideband (UWB), High Power Microwave (HPM), Damped Sinusoid (DS) and hybrid sources although other more general microwave sources can also be considered. It is essential that the set-up used during the radiated susceptibility phase is used to ensure that the coupling paths to the system remain unchanged. Changes in the set-up could either remove or provide additional modes of ingress into the system that could potentially alter the electromagnetic properties of the system.

Selection of HEMP and/or HPEM waveform parameters should be based around the modulations used during the radiated susceptibility. The effect of variation in pulse length, pulse amplitude and pulse repetition frequency (prf) should be investigated during this stage.

At this stage, it is important to increase the level of the incident environment in stages up to the full level [6, 9]. Experience of HEMP qualification testing shows that the system can exhibit no effects at 10 kV/m and 50 kV/m but many effects at 30 kV/m. In these cases the protection devices did not operate at 30 kV/m but the environment contained enough energy to cause effects in some of the system’s equipments. At 50 kV/m protective devices operated and protected the system.

This stage of the methodology confirms the findings of the radiated assessment discussed in 6.4.2 and 6.4.3.

6.5 Susceptibility assessment phase

The purpose of the susceptibility assessment phase is to evaluate the test data including any observed effects such as EUT upset or damage that occurred during the testing to determine any degradation to normal system operational performance. Typically, test simulators do not exactly reproduce the HEMP or HPEM environments. Therefore the stress waveform data needs to be extrapolated to the actual HEMP or HPEM environment of interest. Susceptibility assessments should be based on high-level test data since linear scaling of low-level test data cannot account for non-linearities in the systems’ response such as unintentional arcing or firing of surge protectors. The assessment process involves comparisons of stress waveform data with the EUT immunity or susceptibility data at corresponding interfaces in the system.

A safety margin is frequently applied in these comparisons to account for uncertainties in the susceptibility assessment process. These uncertainties are due to limitations both in knowledge of system parameters and in testing including, but not limited to, inability to test all system configurations and operational modes, system orientations, and angles of incidence. For example, a factor of two margins (6 dB in terms of electric field strength) applied to each critical interface means that the immunity or susceptibility data must exceed the measured extrapolated stress test data by a factor of two or greater. Higher safety margins are generally applied to more critical systems (e.g. nuclear reactors.) It is important to note that even though no observed effect may have occurred during the test, the system still fails the overall assessment if it fails to meet or exceed its stated safety margin requirements.

If any EUT is damaged or upset during the testing and this degrades the system functionality, then the system is deemed to be susceptible. An exception to this is if the susceptible EUT can be shown to be used in a redundant manner by the system. If this is the case and the susceptibility can be shown to be eliminated by the use of redundancy, then the system is immune.

If no EUT damage or upsets occurred during the testing, or if any damage or upsets observed do not degrade the function of the system, then the system is deemed to be immune. The extent of immunity depends on whether the EUT test results exceed the required safety margin defined earlier in this subclause.

Finally, if the measured stress (e.g. induced current) at each interface in the system is less than the immunity level (e.g. the level achieved during testing with no effects observed) for the same interface then the system is deemed to be immune to the environment of interest. If the stress is greater than the immunity level, then the system is deemed to be marginally immune as immunity levels have been exceeded but effects have not been observed.

6.6 The use of reverberation chambers to characterise immunity

Reverberation chambers provide a means of identifying limits of immunity that may exist within a system, see IEC 61000-4-21 [10]. Within one revolution of the chamber paddle, the EUT is illuminated with an average (in power sense) over all 4-pi directions of incidence and a polarization, thus an average case susceptibility profile can be obtained. This method enables the investigation of peak field, duty cycle and pulse length dependencies.

Figure 4 shows an example of radiated immunity testing in a reverberation chamber. Each effect is given a different label such that susceptibility analysis can be conducted.

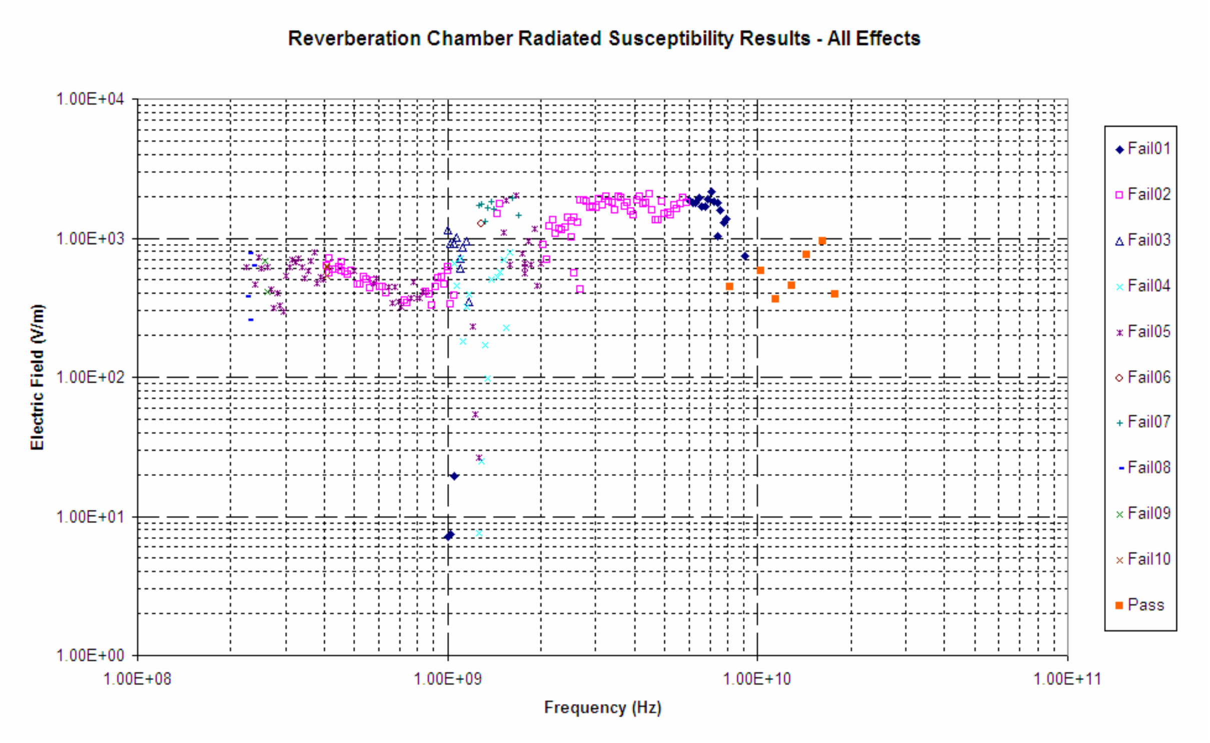


Figure 4 – Reverberation chamber results: all effects

Figure 5 shows the same graph as Figure 4 after analysis of system-level performance degradation. For this system, the susceptibilities are spread between 200 MHz and 2 GHz. In this example, high-level testing should be concentrated on using HPEM environments with energy content across this frequency range. It is important to note that susceptibilities may exist at frequencies outside of the those shown in Figure 5, but may not be identified due to limitations with the facility used for the assessment (for example, the limit of field strength may have been reached resulting in no effect observed).

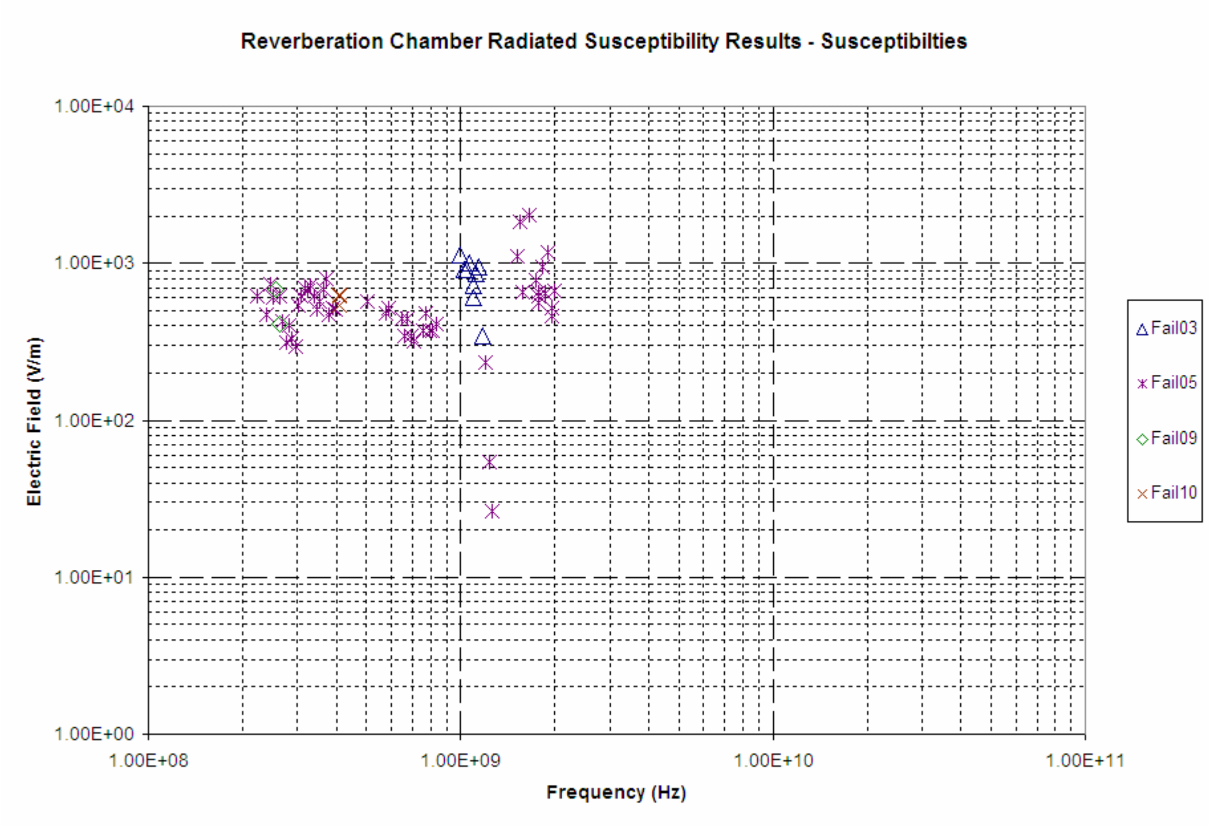


Figure 5 – Reverberation chamber results: susceptibilities

Evaluation of the suitability of available HPEM sources for further assessment can now be made. Analysis of the frequency content of available HPEM sources in conjunction with the susceptibility data obtained during reverberation chamber testing will identify those HPEM sources that are likely to cause an effect. The effect of changing the HPEM source parameters such as pulse length, pulse repetition frequency, polarisation and directionality can then be investigated. Figure 6 shows the frequency content of three example HPEM sources with the frequency ranges for both effects (224 MHz to 9 GHz) and susceptibilities (224 MHz to 2 GHz) identified. The shaded box on the graph highlights the HPEM sources that are likely to cause susceptibility during HPEM assessment.

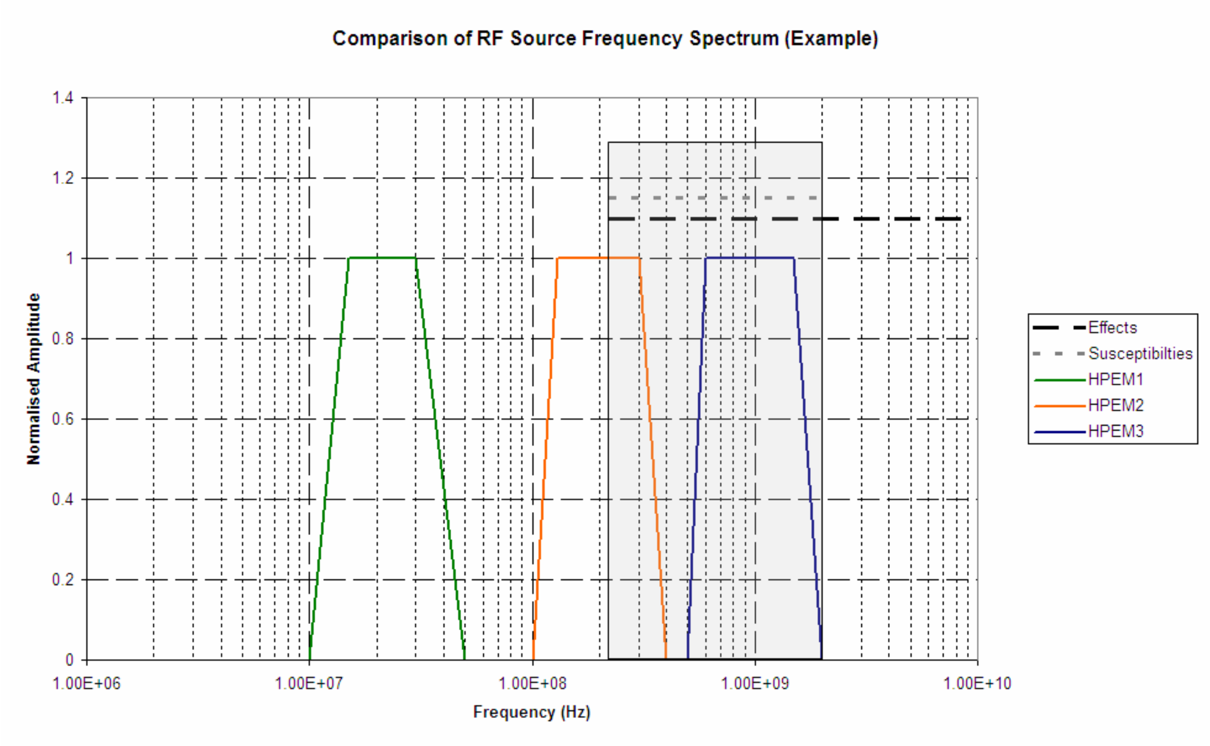


Figure 6 – Frequency spectrum of several HPEM sources

In practice, the graph in Figure 6 can be constructed for each HPEM source of interest. The y-axis is the normalised amplitude to allow for a comparison of the content of each source. It may be useful to produce a graph similar to Figure 6 with representative values such that the y-axis allows a comparison of the relative content of each HPEM source.

It should be noted that the susceptibility cannot be determined with any level of confidence by comparing CW or narrow band susceptibility data to the type of information given in Figure 6. However, this information can be used to identify HPEM environments that have frequency content in the same range that susceptibilities occurred. Ultimately, waveform norms must be used to compare the parameters of the environment used to generate the susceptibility and the environment of concern.

Annex A
(informative)

Classification of effect

A.1 Introduction

The terms immunity and susceptibility have subtly different definitions when used by commercial and military EMC communities. In the military world, equipment is only immune when no effects are observed up to the specified test level. If an effect is observed the equipment is said to be susceptible. It is only when this susceptibility has an impact on the mission of the equipment that it is deemed to be vulnerable. In the commercial community, equipment can show effects during testing and still be immune as long as there is deemed to be no degradation to the performance of the equipment.

Thus, a transient non-critical effect (such as screen interference on a computer monitor) would be deemed as a susceptibility in the military community. If this effect does not degrade the performance of the equipment, the commercial community would state that the equipment is immune.

Figure A.1 shows a flowchart that explains the correct assignment of terminology according to IEC definitions.

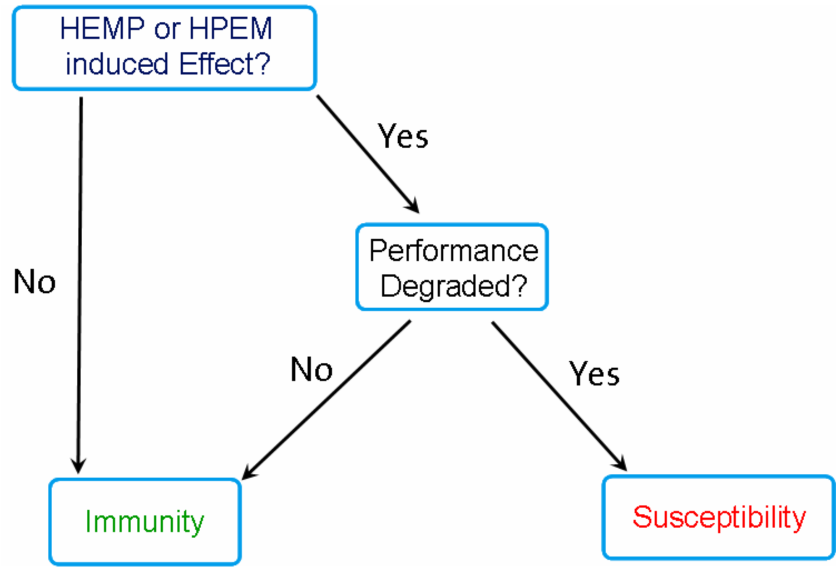


Figure A.1 – Classification of effect

Effects can be further categorised by

a) attributes of the physical interaction mechanism,

b) the impact of the effect on the main (or critical) function of the system,

c) the duration and the need of human intervention, to recover normal operation.

Classification by attributes of the physical interaction mechanism contains less sufficient information to assess the effect with regard to operational value or the main function. For example, a bit flip that occurs only during the exposure to an UWB environment can be detected and corrected by channel coding. Even if the coding is not able to correct the bit flip, the system will be back to full operation after the environment has been removed.

Consequently, classification by attributes of the physical interaction mechanism is not in the scope of this specification and is not considered further.

A.2 Classification by criticality

For a practical assessment of HPEM induced effects it is necessary to classify the observed effects with regard to the operational impact, the functionality of the system and operational condition (e.g. critical periods of time, critical functions, minimum performance). Nitsch and Sabath introduced a classification of effects by its criticality for the main function or mission in [A-1] (see Table A.1). This classification provides the essential information on the functionality isolated from its duration and physical mechanism.

Table A.1 – Categorisation of effect by criticality

Level	Effect	Description
U	unknown	Unable to determine due to effects on another component or not observed.
N	no effect	No effect occurs or the system can fulfil his mission without disturbances.
I	interference	The appearing disturbance does not influence the main function or mission.
II	degradation	The appearing disturbance reduces the efficiency and capability of the system.
III	loss of main function (mission kill)	The appearing disturbance prevents that the system is able to fulfil its main function or mission.
As classification by criticality requires analysis of the observed effect and its impact on the function of the system with regard to a particular application. This classification scheme depends on the system's application and its operational conditions. As a result the assessment usually requires the assistance of a system specialist, who is familiar with the system under test.		

A.3 Classification by duration

Other than the criticality, the duration of an effect provides essential information on the susceptibility or vulnerability of a system under test. For example, degradation could be acceptable if the system recovers without human intervention some time after the environment has been removed. Classification based on the duration of the effect is shown in Table A.2.

The main advantages of this method of classification are that;

a) effects are characterised independently of the particular system and the main function, and

b) criteria are objective.

However, the decision between category T and H does not support aspect b) without restrictions. At this point the reliance on human intervention requires some explanation. In most cases a hang-up in a software or program (e.g. in the system software) can only be solved by a manually initiated reboot of the computer or a restart of the software. The situation becomes more complicated if the system software of an IT system (e.g. computer network or server) runs through an automatic reboot, but the status of normal operation requires a manual start of application software (or data stream). Some test engineers tend to classify this situation as category "T" as the system itself recovers without human intervention. As the main function needs the manual start of software the situation can be categorized as "H". In reality, the decision depends on whether the test focuses on the main application (this will lead to H) or the basic system (T).

Table A.2 – Categorisation of effect duration

Category	Duration	Description
U	unknown	Unable to determine due to effects on another component or no effect is observed or no effect occurs.
E	during exposure only	Observed effect is present only during exposure to HPEM environment; system functionality is completely available after HPEM environment has vanished.
T	temporary	Effect is present some time after HPEM environment has vanished, but system recovers without human intervention. Follow-up time is shorter or equal to typical reaction/operation cycle of the system.
H	resistant until human intervention	Effect is present till human intervention (e.g. reset, restart of function). Due to the effect the system is not able to recover to normal operation within an acceptable period (e.g. typical reaction/operation cycle of the system). No replacement of hardware or reload of software is necessary.
P	permanent or until replacement of HW / SW	Effect is permanent; intervention of an operator or user does not recover normal operation. Effect has damaged hardware to the point that is must be replaced or software to the point that it must be reloaded.

A.4 Combination of both classification schemes

When considering the operational efficiency or operational restrictions which are caused by the HPEM environment, criticality as well as the duration of the status (effect) can both be necessary information. As classification by criticality (Table A.1) and classification by duration (Table A.2) present the information as a function of one isolated criterion, both classifications can be combined. Combinations with practical relevance are listed in Table A.3.

Table A.3 – Combination of criticality level and duration category

		Criticality level				
		U	**N**	**I**	**II**	**III**
Duration category	**U**	U	N			
	E			I.E	II.E	III.E
	T			I.T	II.T	III.T
	H			I.H	II.H	III.H
	P			I.P	II.P	III.P

A.5 References

[A-1] D. Nitsch and F. Sabath, *Electromagnetic Effects on Systems and Components*, Book of abstracts AMEREM 2006, July 2006

[A-2] F. Sabath, *Classification of Electromagnetic Effects at System Level*, Procceedings of the EMC Europe 2008, September 2008

Annex B
(informative)

Good measurement practice

Care must be taken to ensure that the signal recorded during a Low Level (LL) transfer function measurement is only as a result of coupling to the cable bundle under test and not as a result of unwanted coupling to other parts of the measurement chain. One particular problem can occur with the cable used to connect the measurement sensor to the fibre optic link (FOL). Shield currents can be generated in these cables and these can cross-couple to the cable inner giving an erroneous reading. These unwanted shield currents can be removed by the addition of ferrite beads at regular intervals along the connecting cable. The ferrite adds inductance to the equivalent circuit acting as a choke, thus preventing unwanted shield currents from circulating. Figures B.1 to B.4 demonstrates the effectiveness of ferrite chokes when making measurements in a radiated field environment.

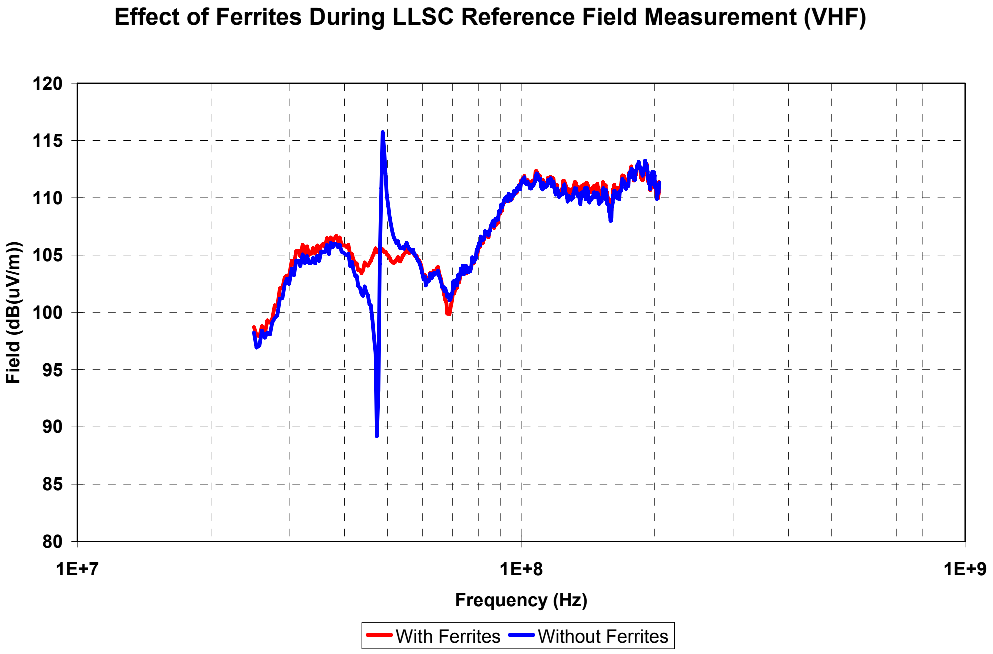


Figure B.1 – Effect of adding ferrites to connecting cable: swept frequency example

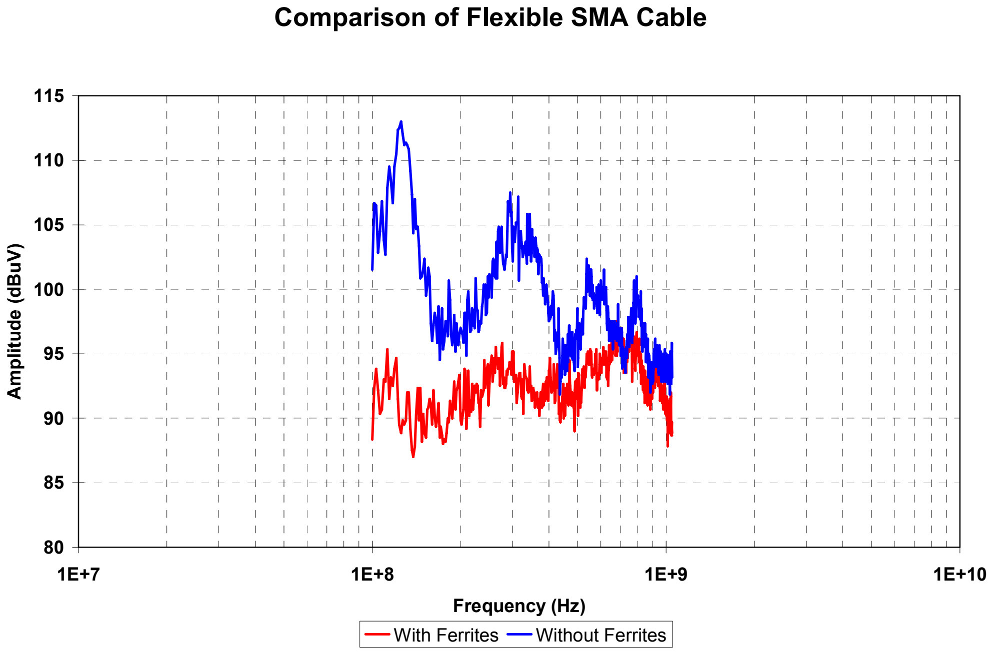


Figure B.2 – Effect of adding ferrite to connecting cable: reverberation chamber example

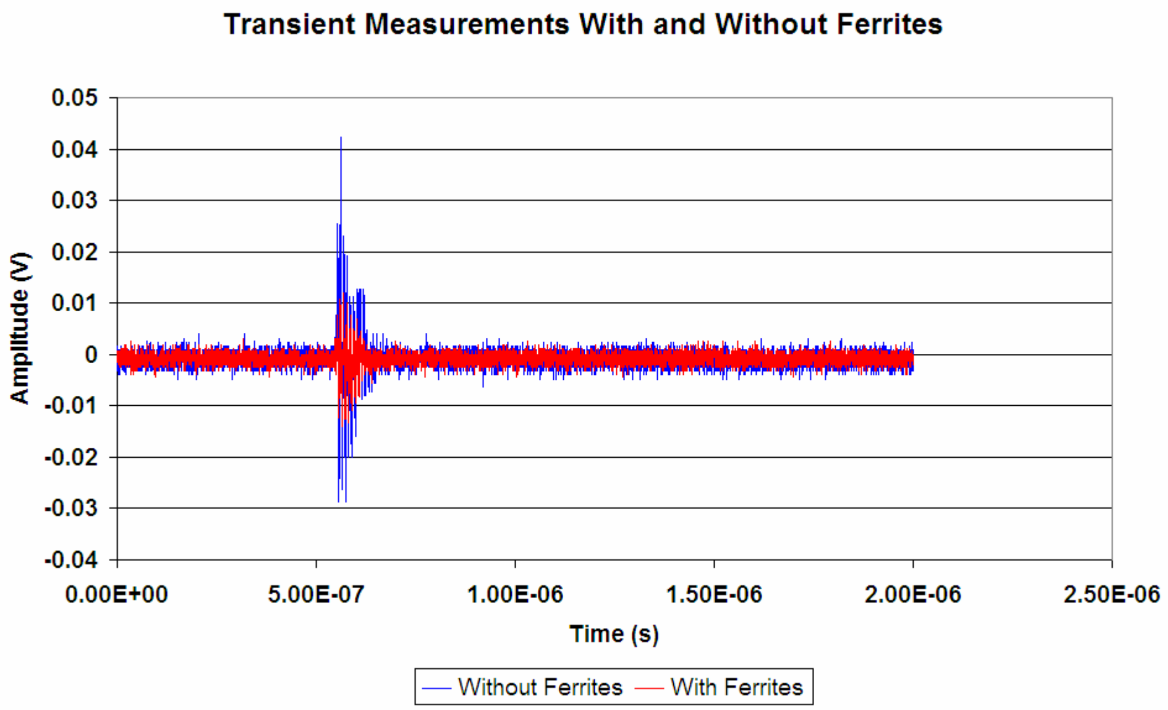


Figure B.3 – Effect of adding ferrite to connecting cable: transient example (time domain)

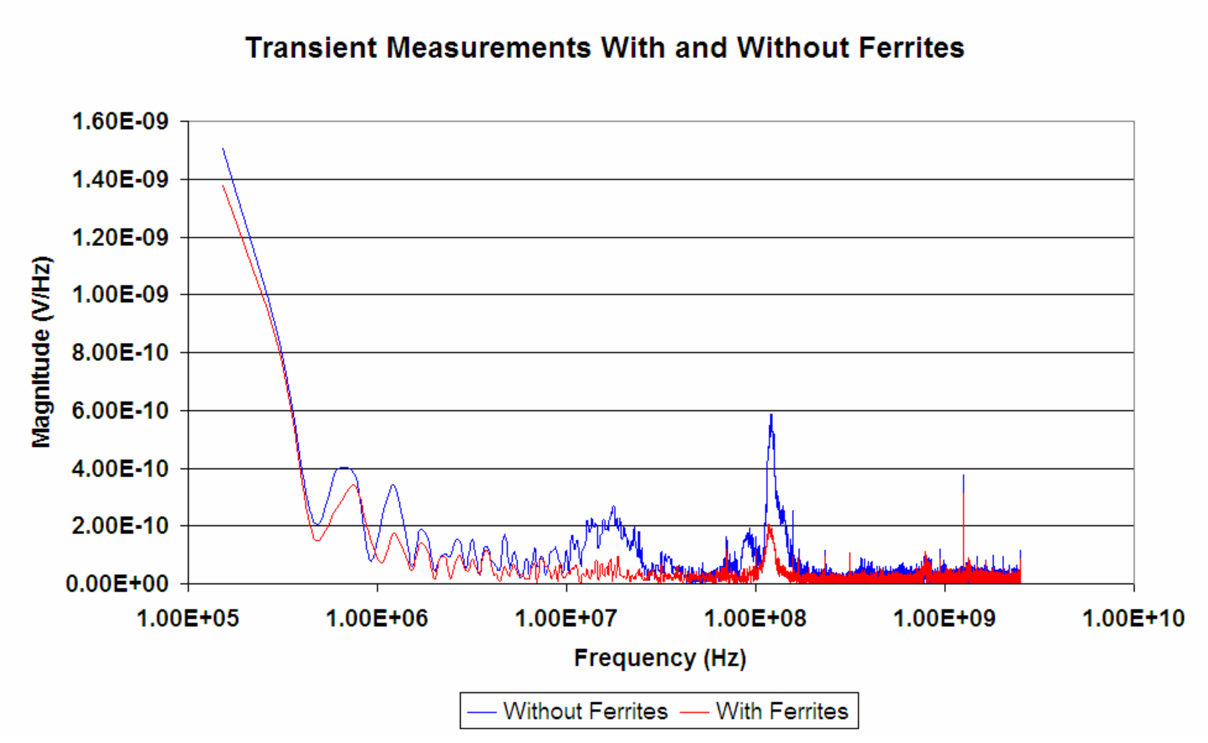


Figure B.4 – Effect of adding ferrite to connecting cable: transient example (frequency domain)

Annex C
(informative)

Computational electromagnetics

C.1 General

One of the important tools available for system-level susceptibility assessments for HEMP and HPEM is computational electromagnetics. Computational electromagnetics (CEM) has evolved over the past decade to a point where extremely accurate predictions can be made for a wide class of problems. The available methods may be classified broadly into two categories:

a) differential equation (DE) solution methods and
b) integral equation (IE) methods.

Although Maxwell's curl equations are usually first encountered in the time domain (TD*),* that is with time as an explicit, independent variable, until relatively recently, most electromagnetic instruction and research has taken place in the frequency domain (FD) where time-harmonic dependence is assumed. A principal reason for favouring the FD over the TD in the pre-computer era had been that a FD approach was generally more tractable analytically. Furthermore, the experimental hardware available for making measurements in past years was largely confined to the FD.

Time domain electromagnetics (EM) became more in vogue with the arrival of the digital computer, which has not only profoundly affected what can be accomplished numerically (or computationally), but also experimentally. Since the beginning of what has come to be called computational electromagnetics (CEM) in the early 1960s, there has been a steady growth in both TD and FD modelling. This growth, which began slowly at first, was primarily confined to integral-equation (IE) treatments, but has grown almost explosively recently as TD differential-equation (DE) modelling has attracted wide attention.

We now review the essential elements of CEM environments, as follows;

- Time Domain Differential Equation (TDDE) models, the use of which has increased tremendously over the past several years, primarily as a result of much larger and faster computers.
- Time Domain Integral Equation (TDIE) models, although available for well over 30 years, have gained increased attention in the last decade. The recent advances in this area make these methods very attractive for a large variety of applications.
- Frequency Domain Integral Equation (FDIE) models which remain the most widely studied and used models, as they were the first to receive detailed development.
- Frequency Domain Differential Equation (FDDE) models whose use has also increased considerably in recent years, although most work to date has emphasized low frequency applications.

These four choices can actually be narrowed down to two broad choices, that is;

a) IE models and
b) DE models, depending on the mathematical formulation.

The well-known method of moments (MoM) in general, involves IE modelling whereas the well-known finite element method (FEM) uses DE formulation.

C.2 Statistical electromagnetics

Although there is a plethora of computational EM tools available for application to the study of the interaction of high power electromagnetics with systems, the challenge of CEM tools is that not all of the boundary conditions can be known in advance. As a result, an alternative paradigm needs to be developed. Statistical electromagnetics provides such an alternative.

One of the challenges in treating problems pertaining to the coupling of HEMP and HPEM with systems is the short-wavelength nature of the radiation. The coupling properties of systems (an enclosure) depend in great detail on its size and shape, the structure of the apertures that act to facilitate or inhibit routes for the electromagnetic energy, and on the frequency of the electromagnetic radiation. Furthermore, the nature of the modal patterns within the enclosure is extremely sensitive to subtle changes in frequency, the shape of the enclosure, and the orientation of the internal disturbances (which could be critical assets).

At present, even with the plethora of fast and powerful computers that utilize efficient 3-D CEM tools, addressing this problem is a great challenge. The main issue is the large aspect-ratio problem, which is a consequence of the ratio of the largest-to-smallest dimensions in the problem. Most of the CEM tools apply Maxwell’s equations after “meshing” the entire simulation region of the problem. For low frequencies (say 100 MHz and lower), these tools have proven to be reliable for calculating internal electromagnetic fields for large-scale systems. However, when attempting to resolve higher frequencies (GHz and above), the entire simulation region will have to be “meshed” with increasingly fine resolution. As a result, the number of mesh-points that would be required cause such an approach to be impractical.

Statistical electromagnetics seeks to address the question, “Given an electromagnetic environment and an electronic system, what is the probability that the system’s performance will be unacceptably degraded?” [C-1]. The proponents then construct stochastic models based on certain fundamental assumptions for the fields within complicated enclosures. These predictions can then be validated with measurements performed in mode-stirred chambers.

The coupling of high-frequency electromagnetic energy into complicated enclosures falls within a larger class of similar problems previously encountered by physicists in the fields of acoustics, mesoscopic transport, and nuclear physics [C-2]. These seemingly disparate systems comprise short-wavelength waves (electromagnetic, acoustic, or quantum mechanical) that are trapped within an irregularly-shaped enclosure or “cavity,” in the limit where the perimeter of the cavity is many wavelengths. This limit is termed the “Ray Limit”. In this limit, the enclosure can be approximated as rays undergoing specular reflection off of the boundaries of the enclosure.

The study of such wave-systems, in the short-wavelength or ray-limit, is widely termed “wave chaos” or “quantum chaos” (when referring to quantum-mechanical wave systems such as atomic nuclei or mesoscopic condensed-matter systems).

This emerging field will likely be of use to the ‘HEMP/HPEM coupling to systems’ problem.

C.3 Analytical methods

C.3.1 General

Analytical methods play an important role in system-level HEMP and HPEM assessments, in particular the use of Fourier transforms are key in extracting frequency information from time-domain waveforms. Additionally, the use of waveform norms enables the unique characterisation of a waveform and this technique can be useful during system-level assessments.

C.3.2 Fourier analysis

Fourier analysis is a method applied to time-domain waveforms to evaluate their frequency content. The method computes a frequency density spectrum which is referred to as the result of a Fourier transform. This frequency density spectrum can be used to identify the frequencies that contribute the largest amount of energy to the transient.

C.3.3 Waveform norms

Waveform norms are a method of uniquely characterising a waveform by computation on various properties. Strictly, a norm is a mathematical description of a property of a waveform; waveform norms are discussed in detail in IEC 61000-4-33, however, for the evaluation of system-level susceptibility, three properties are of key significance:

a) maximum rate-of-rise – this specification gives an indication of the maximum frequency within the waveform;
b) peak – this specification provides the peak level for direct comparison with immunity/susceptibility test results;
c) action integral – this specification provides an indication of the energy contained within a waveform.

These three properties enable the evaluation of a waveform with respect to the primary susceptibility drivers, namely stress (maximum rate-of-rise and peak) and energy (action integral).

Further discussion on waveform norms can be found in IEC 61000-4-33.

C.4 References

[C-1] R. Holland and R. St. John, *Statistical Electromagnetics,”* (Taylor and Francis, London, UK, 1999) and references therein.

[C-2] S.D. Hemmady, “*A Wave-Chaotic Approach to Predicting and Measuring Electromagnetic Field Quantities in Complicated Enclosures*,” Ph.D. Dissertation, University of Maryland (College Park, MD, 2006).

Annex D
(informative)

System level assessment – HEMP

D.1 General

This annex provides an example of a system level assessment to HEMP. The assessment applies to a fictional building that contains a simple computer network.

The first stage of the methodology requires that critical aspects of the system are identified. In this case, the primary concern is the continued operation of the server computer that all other computers connect to. The server is located within an office with no specific EM protection employed. Thus, this assessment assesses the survivability of the server computer in a HEMP environment. During this phase, details on the immunity of the server computer would be obtained either from EMC measurements, if available, or by assuming immunity to standards such as IEC 61000-4-2 (ESD) [D-1], IEC 61000-4-3 (radiated immunity) [D-2], IEC 61000-4-4 (EFT) [D-3], IEC 61000-4-5 (surge) [D-4], IEC 61000-4-6 (conducted immunity) [D-5].

This example addresses the three components of the HEMP waveform separately. Although not considered in this example, the effects of the earlier time waveforms could change the system and impact the assessment of the intermediate and late-time HEMP. For example, changes in connections to earth could alter the late-time HEMP impact.

D.2 Early-time HEMP assessment

The initial measurement phase would include LLCW measurements on all the server PC connecting cables such as mouse lead, keyboard lead, power leads (both computer and monitor, if applicable), monitor VGA lead and network leads. Attenuation measurements would also be made in the area where the server computer is located. From this information, incident server computer field strengths can be predicted and compared to immunity levels. Also, predicted currents can be predicted for comparison with immunity levels. This will result in an understanding of the protection required to ensure that the server computer remains unaffected by an incident HEMP.

By way of a simple example, if the attenuation measurement showed that the inherent protection afforded by the building was 20 dB over the frequency range of interest, the field strength incident upon the server computer would be 500 V/m. If the server computer is immune to 3 V/m, additional protection of 44,4 dB would be required to ensure that the field strength does not exceed the immunity level.

The same analysis can be performed for the conducted aspects of the incident HEMP by considering the difference between conducted immunity levels and predicted currents as a result of an incident HEMP.

If further information on the immunity level of the server computer is required, high-level testing could be conducted. This could be with the aid of free-field radiating simulators that simulate the early-time component of HEMP or by injecting the predicted current using damped sinusoidal injection (direct drive) methods. Both techniques could yield effects the threshold of which would determine the minimum level of protection required to ensure continued operation of the server computer.

D.3 Intermediate-time HEMP

For the intermediate-time HEMP, the main threat to a building with a simple computer network is the conducted environment produced by the coupling to long lines outside of the building. This should include both the power system and the communications system.

To assess the levels of conducted environment, it is not necessary to consider whether the long lines are fully exposed in the air or whether they are below ground as this is not an important factor. If no lightning protection is found, then test level IC3 from IEC 61000-4-25 should be applied. The test level is 4 kV (common mode) using the ITU-T test from IEC 61000-4-5. This waveform rises in 10 µs and has a pulse width of 700 µs. The test should be performed at the point the communications cables enter the building (or at the main panel) or at the point where the power line reaches the power panel. As described in IEC 61000-4-25, it is also necessary to test (or evaluate) at the lower voltage levels of 1 kV and 2 kV to ensure that non-linear effects are not important.

D.4 Late-time HEMP

The late-time HEMP couples to the long lines power lines outside of the building and can be a concern for both the medium voltage power lines and long communications cables (in the air or buried). If there is a building transformer that reduces the voltages from medium to low voltage before entering the building, tests or analyses should be performed for level LC3 (400 V, 25 A) from IEC 61000-4-25. The waveform to be used rises in approximately 1 s and has a pulse width of 60 s. Some test generators producing these types of pulses have been made from car batteries.

In the case of the power system, an important test to perform at the equipment level is to inject high levels of harmonics into the power port. These harmonics are caused by the quasi-d.c. currents injected upstream by the late-time HEMP into transformers that are then driven into half-cycle saturation. IEC 61000-4-13 is recommended in IEC 61000-4-25 with levels of 5 % of residual voltage, V_r for the second harmonic and 8 % of V_r for the third harmonic.

For telecommunications cables entering the building, the threat level LC2 (400 V, 1,33 A) is recommended with the same 1 s rise and 60 s pulse width shape. The test or analysis should be performed for an external (to the building) injection or an injection into the main telecommunications panel inside the building.

D.5 References

[D-1] IEC 61000-4-2:2008, *Electromagnetic compatibility (EMC – Part 4-2: Testing and measurement techniques – Electrostatic discharge immunity test*

[D-2] IEC 61000-4-3:2006, *Electromagnetic compatibility (EMC) – Part 4-3: Testing and measurement techniques – Radiated, radio-frequency, electromagnetic field immunity test*

[D-3] IEC 61000-4-4:2004, *Electromagnetic compatibility (EMC) – Part 4-4: Testing and measurement techniques – Electrical fast transient/burst immunity test*

[D-4] IEC 61000-4-5:2005, *Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test*

[D-5] IEC 61000-4-6:2008, *Electromagnetic compatibility (EMC) – Part 4-6: Testing and measurement techniques – Immunity to conducted disturbances, induced by radio-frequency fields*

Annex E
(informative)

System level assessment – HPEM

E.1 Rail traffic management system

Assessment of the threat from front door in-band radiated disturbances towards the European rail traffic management system.

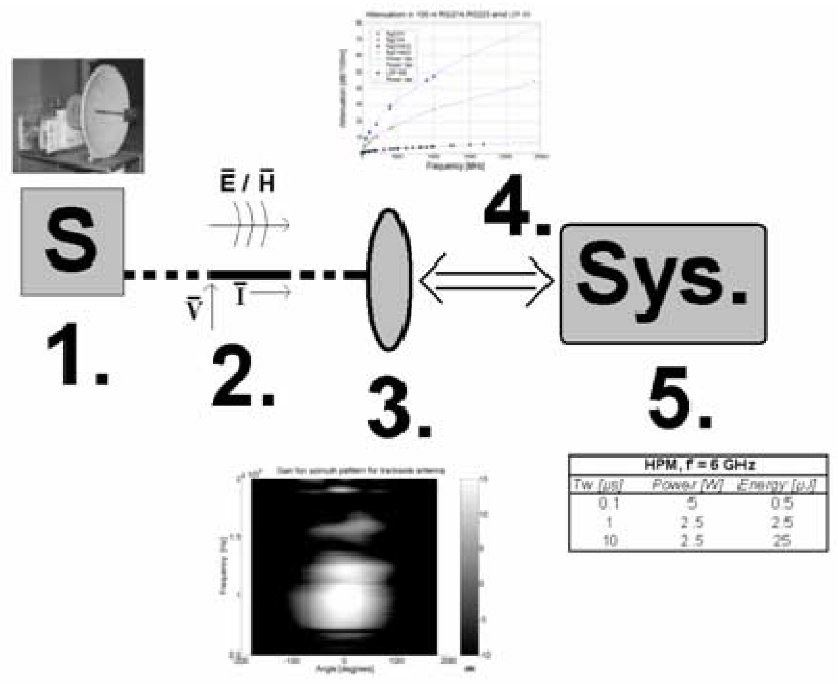
E.2 Background

During the first decades of this century the railways in Europe will implement the European Rail Traffic Management System (ERTMS) which consists of the ETCS (European Train Control System) and the GSM-R (GSM mobile communications standard for railway usage). This system, will greatly increase the capacity and safety of the European railways, but will rely heavily on wireless communication [E-1], [E-2] for train communication and control. Due to the utilization of antennas that are distributed along the tracks and on the trains, assessment of susceptibility from radiated HPEM sources is important. Trackside antennas are normally positioned on masts 30 m to 40 m high and connected to a communication system/base station at the bottom of the mast. A low noise amplifier (LNA) is normally positioned at the input port of the communication system and will be a critical component of the system. For the rolling stock, the antenna is normally positioned in the front of the engine and connected through a cable to a cab-radio, with a LNA at the input port.

E.3 Assessment

E.3.1 Steps in system assessment

The system assessed here ranges from the antenna to the connected communication system with a LNA as a critical component. The example follows the methodology described in Clause 6 and Figure 3 and is described in detail in [E-3]. Figure E.1 shows the steps taken in the system assessment for this example.



Steps:

1. source characterization
2. coupling path to the system (here free-space propagation)
3. system exterior (here GSM-R antenna)
4. coupling to system interior (here cable properties
5. system effect/response (here LNA threshold levels)

Figure E.1 – Steps taken in the system assessment

In Figure E.1, the source used is a low-tech source made from a commercially available microwave oven. The coupling path to the system has been considered to be free space propagation with the system exterior being a GSM-R antenna where the gain of the antenna is a function of frequency and angle of incidence of the HPEM environment as shown. The coupling to the system interior is a function of the cable properties and is shown in attenuation per meter for different cables as a function of frequency. Finally, the system response is shown for a HPM environment of different pulse durations.

An in-band front-door attack on the GSM-R antennas at trackside or on the engine of the train is considered more likely to cause interference and permanent damage than illumination of the communication system itself inside the building or engine (back-door). With in-band front-door disturbance the specified gain of a targeted antenna will, besides the intended communication signals, increase the received power of any disturbance (in the specified band). Thus, even weak sources can be a problem.

Front-door system assessment is divided into:

a) possible sources used by attacker (Step 1 in Figure E.1),
b) coupling to system; characteristics and behaviour of the antennas (Steps 2 and 3 in Figure E.1),
c) propagation; propagation and attenuation in cables (Step 4 in Figure E.1),
d) effect; susceptibility levels of the LNA (Step 5 in Figure E.1).

A similar approach can also be used for a back-door coupled interference or a transient directly injected into a conductor system.

E.3.2 Details of assessment phases

E.3.2.1 HPEM source

HPEM sources can be categorized [E-4] according to many characteristics, but the main division for radiated sources is between narrowband (HPM) and wideband (such as UWB and DS) sources. A correct assessment of the source is vital since the assumed source determines much of the assessment.

E.3.2.2 Antennas – coupling to system

Upon investigation of the reflection coefficient and gain pattern of the antennas, it became clear that the actual bands of use (frequency and lobe widths) were much wider than specified by the manufacturer. This is, of course, unfavourable from a susceptibility point-of-view since it opens up for a wider range of sources. The antenna investigation was carried out in an anechoic chamber following experimental praxis (as in [E-3]).

E.3.2.3 Cable – propagation path

The attenuation in the cables connecting the antennas to the systems will decrease the stress on the critical component and thus act to reduce the vulnerability. Assuming that the cables are matched with the antennas (and communication system, thus disregarding reflections at these points) the attenuation in the signal is due to the electrical properties of the cable. Adding a mismatch factor is not difficult.

E.3.2.4 Low noise amplifier, LNA – system susceptibility

The LNA, which amplifies the weak signal captured by the antenna, is a critical component of the communication system. The susceptibility tests performed should match the assumed source waveform (step 1 above). Alternatively, a careful analysis has to be carried out to derive the thresholds.

E.3.3 Threshold distance for permanent damage to the communication system

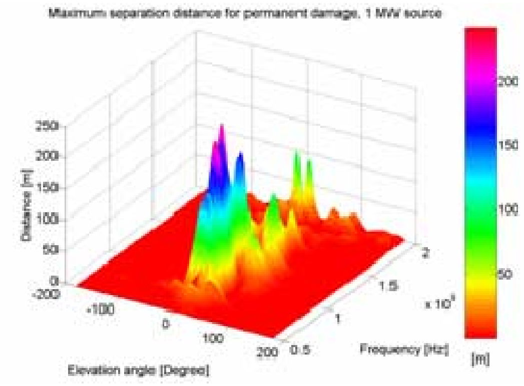
Combining the knowledge on HPEM sources, antenna characteristics, cable attenuation and LNA susceptibility thresholds, an overall assessment on the ERTMS system from front-door interference can be made. A maximum separation distance to induce a permanent damage in the communication systems can be estimated (using the Friis transmission equation),

$$R = \frac{\lambda}{4\pi}\sqrt{\frac{P_{\mathrm{trans}} \cdot G_{\mathrm{rec}} \cdot G_{\mathrm{trans}} \cdot e}{P_{\mathrm{received\,LNA}}}}$$

where

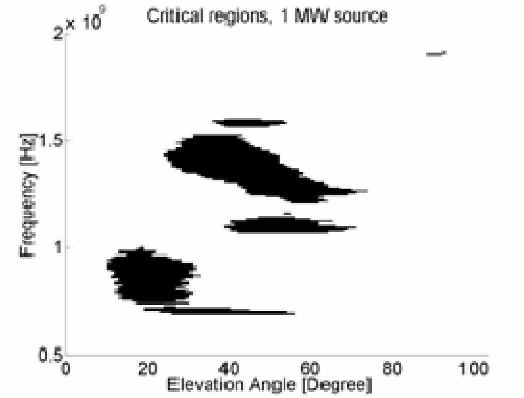
G_{rec}	is the receiver antenna gain,
G_{trans} and P_{tran})	are the assumed transmitter antenna gain and power,
$P_{\mathrm{receivedLNA}}$	is the susceptibility data from the LNA and e are attenuation factors (including polarisation mismatches and cable attenuation for example),
R	is the approximate maximum distance for achieving different susceptibility levels to the communication system (see Figure E.2).

If a wideband source is assumed some Fourier analyses are required.



Maximum free-space separation distances between transmitting source and receiving trackside GSM-R antenna to destroy the LNA for elevation angle for a source with power level of 1 MW. The transmitter is placed aiming at the antenna (adapted from [E-3]).

Figure E.2 – Maximum free-space separation distances



An example of critical regions for permanent damage to a trackside antenna when illuminated by a 1 MW source. The transmitter is placed on the ground (height approximately 2 m) and the receiver is placed at the top of a tower (30 m). The transmitter is aiming at the GSM-R antenna (adopted from [E-3]).

Figure E.3 – Critical regions for permanent damage

However, not all angles and frequencies can, for a given situation, be a threat since for low elevation angles the distance from the HPM generator placed at ground to the GSM-R receiver grows very large. The critical regions, see Figure E.3, are here defined as the regions where the maximum separation distances to induce permanent damage (from Figure E.2) minus the physical distances from transmitter to the antenna (on the 30 m tower) are larger than zero ($R_{\text{max-threshold}} - R_{\text{phys}} > 0$). This is shown in Figure E.3. The critical regions grow with increased transmitted power.

E.4 References

[E-1] http://www.ERTMS.com

[E-2] http://www.botniabanan.se

[E-3] D. Månsson, R. Thottappillil, M. Bäckström, O. Lundén "*Vulnerability of European Rail Traffic Management System to Radiated Intentional EMI*", IEEE Trans. on EMC, Vol. 50, No. 1, February 2008

[E-4] IEC 61000-2-13:2005, *Electromagnetic compatibility (EMC) – Part 2-13: Environment – High-power electromagnetic (HPEM) environments – Radiated and conducted*

Annex F
(informative)

Limitations

F.1 Technical limitations

This annex discusses potential technical limitations of the techniques discussed within this specification. The purpose of this discussion is to highlight the potential deficiencies such that an appropriate margin can be considered and applied to the system. These limitations are listed below.

F.2 Single point illumination

Many test techniques illuminate the test object from a single discrete location. However, the system may be exposed from a direction or directions by the threat environment which is different to that tested (see also discussion on directivity).

F.3 Facility limitations

It is generally not possible for a single test facility to provide all of the required test parameters. There also may be physical limitations of the facility such as the size of system which can be accommodated within the test volume or the availability of the correct power supplies.

F.4 Cumulative effects

Susceptibility testing generally requires a step by step increase in the stress environment until the susceptibility threshold is found and recorded. However, some systems may be weakened by repeated exposure to the stress environment.

F.5 Degradation/ageing

Consideration should be given to the life cycle of the system. It is well known that the system hardness can be reduced over the lifetime of the system due to issues such as corrosion, misuse and poor maintenance.

F.6 Non-linearity

The low-level techniques discussed in this specification provide a transfer function for the system in a relatively benign environment. High-level illumination may excite non-linearities within the system such as flashover, ‘rusty bolt effects’, saturation and activation of protective devices which may affect the transfer function.

F.7 Synergistic effects

In some cases, cable bundles may be tested in isolation whereas in reality all cable bundles would be excited simultaneously. This can lead to a difference in the susceptibility level of the system.

F.8 Statistical confidence

A one-off system would need a complete assessment whereas a production line approach requires re-measurement of transfer functions and susceptibility data at various stages to confirm that the overall system response to the HEMP or HPEM environment of interest is not impacted.

F.9 Directivity

Directivity is a property of the radiation, or receiving, pattern produced by an antenna. It is defined as the ratio of the power radiated (or received) in a given direction to the average of the power radiated (received) in all directions. A EUT subjected to a radiated susceptibility test can be regarded as a receiving antenna. The directivity reflects the angular dependence of its susceptibility, that is, the EUT is most susceptible in the direction corresponding to the maximum directivity. Due to the random location of coupling paths, (for example apertures on the skin), the maximum directivity at a given frequency is smaller than that of a deliberate antenna of the same size. Expression that can be used to estimate the maximum directivity for a typical EUT is given in [F-1].

The directivity of a EUT appears as a complex lobe pattern. The differences between peaks and nulls might be 20 dB or even larger. The width of the lobes decreases with increasing frequency. At a few GHz the width is typically of the order of 10° or less for a EUT having a size of approximately 0,2 m [F-2]. This means that hundreds, or even thousands of angles of incidence may be needed in a plane wave susceptibility test in order to achieve an uncertainty of a couple of decibels. If the test is instead carried out in a reverberation chamber this problem disappears due to its statistically isotropic environment. On the other hand, since the available energy is spread out in an isotropic fashion, thereby irradiating the EUT from many angles of incidence simultaneously, most of the energy is wasted in directions for which the EUT is not susceptible. Therefore, a margin related to the maximum directivity of the EUT has to be added in order to simulate worst case plane wave irradiation. This margin is typically of the order of 10 dB to 15 dB [F-3]. It should be noted that worst-case plane wave illumination may be difficult to perform [F-4].

F.10 Ageing/degradation

The impact of ageing and corrosion on the performance of shielding joints has been investigated in various studies, see [F-5] and references therein. Corrosion is governed by materials, material combinations, atmospheric conditions, etc. Effects of corrosion on the electrical performance are governed by amounts and properties of corrosion products formed, as well as by the design and mechanical properties of the joint. Avoiding unsuitable combinations of materials is thus not sufficient for ensuring continued shielding performance. In [F-5] results are reported from a test where different kinds of gaskets, materials and coatings were combined. The specimens were exposed for one year under a hood outdoors, immediately north of Stockholm City Centre. The study shows that fingerstock gaskets offer good shielding performance, but are sensitive to corrosion. Performance of wire mesh gaskets varies depending on design. Wire mesh gaskets with an elastomer core did not show as good performance as fingerstock gaskets initially, but suffered virtually no effects from the one-year weather protected exposure. Other types of gaskets, likely to provide lower contact force, offer lower shielding effectiveness and, in many cases, suffer deterioration from exposure. Results with and without chromate conversion coatings show that corrosion protection offered by a conversion coating is no guarantee for preserved shielding properties.

F.11 Non-linear effects

Determination of shielding effectiveness is a vital part in the analysis of a systems capability to withstand HPEM. It is usually assumed that the shielding effectiveness, determined at low field levels, is valid also at threat levels. This assumption might be refuted by the presence of non-linear effects. These may result in generation of new frequency components in the spectrum of the transmitted pulse. Irradiation at threat levels may also result in damage of shielding joints. 31 corroded EMC joints from two groups of specimens, one subjected to laboratory exposures (see IEC 60062-2-28 [F-6]) and the other to a one year outdoor exposure immediately north of the Stockholm City Centre, were investigated [F-7]. The specimens were exposed to radiation from a 3 GHz radar source. The pulse length was 1 µs and the maximum electric field strength about 50 kV/m. Non-linear effects were revealed by changes in the time-domain shape and frequency analysis. Degradation was studied by comparing the transmission cross-section of the specimens before and after irradiation. No major degradation could be detected after the HPM irradiation. Most of the objects showed none, or only a moderate, generation of harmonics.

F.12 References

[F-1] G. Koepke, D. Hill and J. Ladbury, "*Directivity of the test device in EMC measurements*," in Proc. 2000 IEEE Int. Symp. Electromagnetic Compatibility, Washington, DC, Aug. 21–25, 2000, pp. 535–539., P. F. Wilson et al., "*On Determining the Maximum Emissions From Electrically Large Sources*", IEEE Trans. on Electromagnetic Compatibility, Vol. 44, No. 1, February 2002

[F-2] M. Höijer, M. Bäckström, and J. Lorén, "*Angular pattern in low-level coupling measurements and in high-level radiated susceptibility testing*," in Proc. 15th Zurich Int. Symp. Technical Exhibition on Electromagnetic Compatibility, Zurich, Switzerland, Feb. 18–20, 2003

[F-3] M. Bäckström, J. Lorén, G. Eriksson, and H.-J. Åsander, "*Microwave coupling into a generic object. Properties of measured angular receiving pattern and its significance for testing*," in Proc. 2001 IEEE Int. Symp. Electromagnetic Compatibility, Montreal, QC, Canada, Aug. 13–17, 2001

[F-4] G. Freyer and M. Bäckström, "*Comparison of Anechoic and Reverberation Chamber Coupling Data as a Function of Directivity Pattern – Part II*", in Proceedings of 2001 IEEE International Symposium on Electromagnetic Compatibility, Montreal, Canada, August 2001

[F-5] L. Sjögren and M. Bäckström, "*Ageing of shielding joints. Shielding performance and corrosion*", in proc. from 16th Int. Zurich Symp. on electromagnetic Compatibility, February 13-18 2005, Zurich Switzerland, pp. 575-578.

[F-6] IEC/TS 62228:2007, *Integrated circuits – EMC evaluation of CAN transceivers*

[F-7] M. Bäckström, O. Lundén and T. Martin, "*Degradation and Non-linear effects in Corroded EMC Joints Exposed to High Power Microwaves (HPM)*", URSI XXIXth General Assembly, Chicago, USA, August 07-16, 2008 or "*Experimental investigation of degradation and non-linear effects in corroded EMC joints exposed to high power microwaves (HPM)*", FOI-R--1246—SE, 2004, www.foi.se

Annex G
(informative)

Detailed description of low-level techniques

G.1 Application

These techniques can be applied at system level to understand system-level response to HPEM and HEMP environments.

Transfer functions allow the identification of resonant frequencies for the system under evaluation. This information can be used to identify environments that will transfer the highest amount of RF to the system. This does not necessarily identify the frequencies at which susceptibilities will occur. It is useful, however, to identify which high power test sources are likely to couple to the system most effectively.

Limitations of the following techniques are discussed in Annex F.

G.2 Transfer functions

Cable bundle transfer functions can be measured in the frequency domain or the time domain. A transfer function is a ratio of two electrical responses and is valid only for a linear system.

Time domain transfer functions are measured by using a transient source with knowledge of the incident excitation. Thus, the measured induced cable bundle current transient can be normalised to the incident field.

The quality of transfer functions measured in this way is dependent on frequency range of the incident waveform. For example, if a transfer function is required between 1 MHz and 200 MHz, the incident time domain waveform must have sufficient content over this frequency range to enable measurement. Deficiencies in the content of the incident waveform will lead to those same deficiencies in the transfer function.

G.3 Cable bundle transfer functions

Transfer functions allow one to identify the significant resonant frequencies in a system under test and this information can be used to identify EM environments that will transfer the highest amount of RF energy to the system. Transfer functions do not necessarily identify the frequencies at which susceptibilities will occur. However, they are useful to identify which high power test sources are likely to couple to the system most effectively. A transfer function may consist of measured magnitude and phase components or be magnitude-only and require phase reconstruction prior to prediction of induced current via convolution (see Annex I for further information).

To illustrate transfer function definitions and their use, consider the case of a facility illuminated by an external antenna with wire currents being measured inside the facility at selected points of interest. Figure G.1 shows the interaction sequence diagram describing the progression of EM energy into the facility. This diagram and its implications are discussed in more detail below.

To start, a source of electrical energy, either transient or continuous wave (CW), produces an output voltage V_{S}, which is applied to the terminals of an antenna that illuminates the facility or other test object. The antenna, in turn, produces a local E-field, say in the aperture of the antenna, which is denoted by E_{aperture}.

This E-field is radiated by the antenna and propagates to the outer walls of the facility under test, at which point the E-field has been reduced in amplitude and its waveshape modified by the radiation characteristics of the antenna. This incident E-field on the facility is denoted as E_{incident}. Notice that this incident field is that existing in the *absence* of the facility and as such, it does not contain any reflected fields from the facility, its appendages or the earth.

At the facility outer surface, the incident EM field interacts with the facility enclosure and ultimately penetrates into the interior regions of the facility. In doing so, the penetrating field acquires the influences of the external natural resonances of the facility. This interior E-field, E_{inside}, will propagate further inside the facility and it takes on additional natural resonances of the interior volume. Upon arrival to a cable, the internal field is denoted by E_{cable} and it induces a current on the cable, which is denoted as I_{cable}.

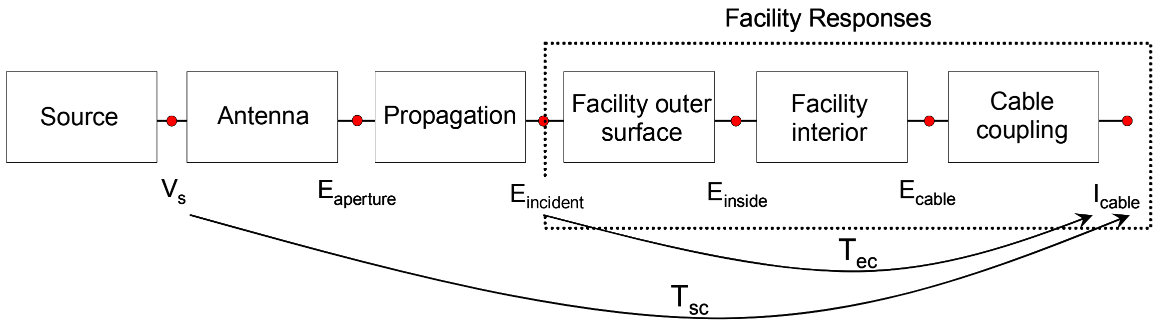


Figure G.1 – Electromagnetic interaction sequence diagram for a facility illuminated by an external antenna

Ratios of any two of the EM responses of Figure G.1, when written in the frequency domain, can be used to define a spectral function. For example, as we are interested primarily in the induced cable current, we can define a source voltage-to-cable current transfer function T_{sc} as the ratio of the following frequency domain responses

$$T_{\text{x}}(f) = \frac{I_{\text{cable}}(f)}{V_{\text{s}}(f)} \text{ (S)} \tag{G.1}$$

Similarly, if one is interested in the transfer function between the incident E-field at the facility boundary to the cable current, $T_{\text{ec}}(f)$, the following definition may be used:

$$T_{\text{ec}}(f) = \frac{I_{\text{cable}}(f)}{E_{\text{inc}}(f)} \text{ (S − m)} \tag{G.2}$$

From the diagram of Figure G.1 it is clear that the transfer function $T_{\text{ec}}(f)$ serves as a useful indication of the facility current response if the incident field information is known. It contains all of the external coupling, penetration and internal coupling factors, but any information about the spectral content of the pulser and antenna has been removed by using the incident field as a reference.

As such, this transfer function can be used to compute the cable current response produced by a *different* incident field, $E_{\text{inc}2}(f)$, that might be produced by another source or antenna. In this manner the cable current spectrum for this alternate excitation is given by

$$I_{\text{cable}}(f) = T_{\text{ec}}(f) = E_{\text{inc2}}(f) \text{ (A/Hz)} \tag{G.3}$$

The transfer function between the antenna source and current in Equation (G.1) contains both the effects of the facility and the antenna radiation producing the incident E-field. It can be used to determine the cable current if a new source having a different excitation spectrum is used with the same antenna, much like the case involving the alternate E-field in Equation (G.3). Thus, this source to current transfer function is useful in cases where the same antenna, but a different excitation source is used.

As will be noted later, transfer function measurements involving the source voltage as a reference are easier to make and they are often more commonly obtained in test programs. However, the most useful transfer function is the one used in Equation (G.2) relating the current to the incident E-field on the facility to the induced cable current. In order to use a measured excitation source-to-current transfer function $T_{\mathrm{ec}}(f)$ to compute the current for a specified incident field excitation, it is necessary to modify this transfer function to remove the source and antenna characteristics. This is accomplished by writing

$$T_{\mathrm{ec}}(f)=\frac{I_{\mathrm{cable}}(f)}{E_{\mathrm{inc}}(f)}=\frac{I_{\mathrm{cable}}(f)}{V_{\mathrm{s}}(f)}\frac{V_{\mathrm{s}}(f)}{E_{\mathrm{inc}}(f)} \quad \text{(S-m)} \qquad \text{(G.4)}$$

or

$$\begin{aligned}T_{\mathrm{ec}}(f)&=\frac{T_{\mathrm{sc}}(f)}{E_{\mathrm{inc}}(f)/V_{\mathrm{s}}(f)}\\&=\frac{T_{\mathrm{sc}}(f)}{T_{\mathrm{se}}(f)}\end{aligned} \quad \text{(S-m)} \qquad \text{(G.5)}$$

In this last expression, a source voltage-to-incident E-field transfer function $T_{\mathrm{se}}(f)$ is defined as

$$T_{\mathrm{se}}(f)=\frac{E_{\mathrm{inc}}(f)}{V_{\mathrm{s}}(f)} \quad \text{(1/m)} \qquad \text{(G.6)}$$

As a result, if one measures the source voltage-to-current transfer function in Equation (G.1) and then computes or measures the source voltage-to-incident field transfer function in Equation (G.6), the facility transfer function between the incident E-field on the facility and the current can be determined by Equation (G.3) using the “corrected” transfer function of Equation (G.5).

It is important to recognize that while an incident field transfer function for a facility can be developed using Equation (G.5), it may not be suitable for describing cable response due to a *plane wave* incident field. This is because the illuminating antenna used to provide the incident field on the facility most likely does not provide a plane wave at the facility. Rather, it provides a narrow spot-light beam, as shown in Figure G.2.

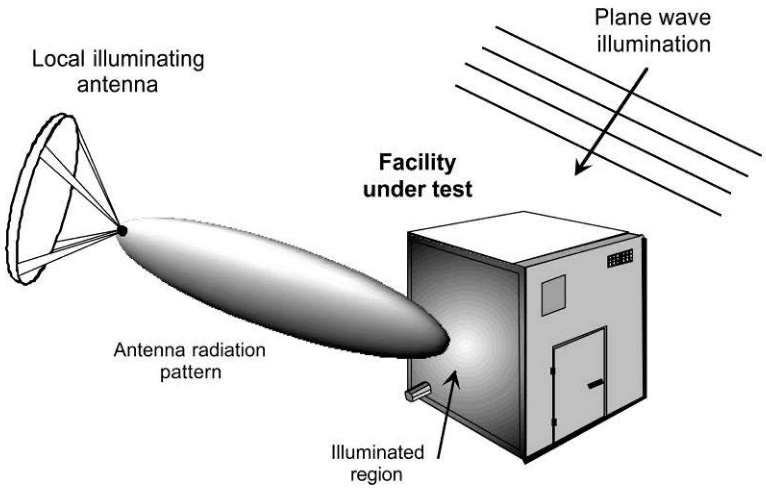


Figure G.2 – Illustration of the difference of a directed, narrow-beam antenna exciting the facility with a spot beam, along with a plane wave providing illumination to the entire facility

Baum [G-1] has described a method in which the facility can be illuminated by the spot antenna at a number of different locations and the resulting measured current responses can be combined analytically to synthesize the plane wave response. Doing this requires maintaining the phase coherence between all of the antenna illuminations and this is difficult to do in practical cases. Alternatively, one can combine the *magnitudes* of the various current responses for different antenna locations and construct an average current transfer function magnitude. While phase information cannot be accurately extracted from such an averaged magnitude response, it can be approximated using a minimum phase approximation to the actual plane wave spectrum [G-2].

The preceding discussion of the transfer function has all involved frequency domain (spectral) responses within the system. In the time domain, it is also possible to define a transient transfer function, but unfortunately, it is ***not*** defined as a simple ratio of waveforms as $T_{sc}(t)=\frac{I_{cable}(t)}{V_s(t)}$. This is because the inverse Fourier transform of Equation (G.3) which provides the time domain counterpart of the product of two frequency domain spectra is given by the *convolution* operation and not by a simple multiplication.

Letting F represent the time to frequency domain Fourier transform, as in $G(f) = F[\ g(t)\ ]$, and F^{-1} be the inverse Fourier transformation where $g(t) = F^{-1}[\ G(f)\ ]$, the transient cable current is calculated from Equation (G.1) is expressed as

$$I_{\text{cable}}(t)=F^{-1}[I_{\text{cable}}(f)]=F^{-1}[T_{\text{sc}}(f)\,V_{\text{s}}(f)] \text{ (A)} \qquad \text{(G.7)}$$

Fourier transform theory [G-3] states that if the above spectral functions $T_{\text{SC}}(f)$ and $V_{\text{S}}(f)$ have time domain counterparts as

$$T_{\text{sc}}(t)=F^{-1}[T_{\text{sc}}(f)] \text{ (S/s)} \qquad \text{(G.8a)}$$

and

$$V_{\text{s}}(t)=F^{-1}[V_{\text{s}}(f)] \text{ (V)} \qquad \text{(G.8b)}$$

then the expression for the transient current in Equation (G.7) is given by the *convolution* ($*$) operation.

$$\begin{aligned} I_{\text{cable}}(t) &= T_{\text{sc}}(t) * V_{\text{s}}(t) \\ &\equiv \int_{-\infty}^{\infty} T_{\text{sc}}(\tau - t) V_{\text{s}}(\tau)\,\mathrm{d}\tau \quad \text{(A)} \\ &\equiv \int_{-\infty}^{\infty} T_{\text{sc}}(\tau) V_{\text{s}}(\tau - t)\,\mathrm{d}\tau \end{aligned} \tag{G.9}$$

In a similar manner, the incident E-field to cable current transfer function in the time domain is defined by the equation

$$I_{\text{cable}}(t) = T_{\text{ec}}(t) * E_{\text{inc}}(t) \ \text{(A)} \tag{G.10}$$

In both Equations (G.9) and (G.10), the transient transfer functions $T_{\text{ec}}(t)$ and $T_{\text{sc}}(t)$ may be used to compute the cable currents using one of the convolution operations defined in Equation (G.9). In most instances, the transient transfer functions are obtained by performing a numerical inverse Fourier transform on the measured frequency domain transfer functions of Equation (G.1) or (G.2). However, if time domain transfer functions are desired from measured transient data, say $I_{\text{cable}}(t)$ and $V_{\text{s}}(t)$, then both the response and reference transient functions must first be transformed into the frequency domain, then divided as in Equation (G.1) or (G.2) and then converted back into the time domain.

At times, it may be desired to compute the transient transfer function directly in the time domain using the measured transient excitation and response. This essentially is a deconvolution (defined as 1/$*$) of the operation in Equation (G.9) and is denoted symbolically as

$$T_{\text{sc}}(t) = I_{\text{cable}}(t) \left(\frac{1}{*} \right) V_{\text{s}}(t) \ \text{(S/s)} \tag{G.11}$$

where both $I_{\text{cable}}(t)$ and $V_{\text{s}}(t)$, are known. For the case where these functions are known at N equally-spaced sample points, the discrete waveforms are represented by $I_{\text{cable}}(k)$ and $V_{\text{s}}(k)$, (k = 0, 1, … N-1). Nahman [G-4] has shown how the transient transfer function can be written directly in terms of the transient waveforms as

$$T_{\text{sc}}(k) = \frac{1}{V_{\text{s}}(1)} \left[I_{\text{cable}}(k) - \sum_{i=1}^{k-1} T_{\text{sc}}(i) V_{\text{s}}(k+1-i) \right] \ \text{(S/s) for } k = 0, 1, \ldots, N\text{-}1 \tag{G.12}$$

As pointed out in [G-4] and [G-5], the evaluation of Equation (G.12) can be very sensitive to numerical noise in the $I_{\text{cable}}(t)$ and $V_{\text{s}}(t)$. One solution is to use an alternate iterative technique, which are described in these last references. Furthermore, the evaluation of the transfer function in the frequency domain can also be sensitive to noise, as will be displayed in the next clause.

G.4 Transfer functions determined from transient measurements

As an example of cable current transfer functions obtained from transient measurements, data acquired in a test program described in reference [G-6] can be employed. For these measurements, the instrumentation shown in Figure G.3 was used. A pulsed voltage source (pulser) having a peak amplitude of 2,8 kV with a rise time of about 100 ps and a 1/e fall-time of 2 ns was used to excite an “impulse radiating antenna” (IRA), the operation of which has been described elsewhere in [G-7, G-8]. This antenna illuminated a buried facility from the outside, and inside the facility the transient currents on various cables were measured with a wideband response sensor and recording instrumentation.

The quality of transfer functions measured in this manner is dependent on frequency range of the incident waveform. For example, if a transfer function is required between 10 MHz and 1 GHz, the incident time domain waveform must have sufficient content over this frequency range to enable measurement. Deficiencies in the content of the incident waveform will lead to those same deficiencies in the transfer function.

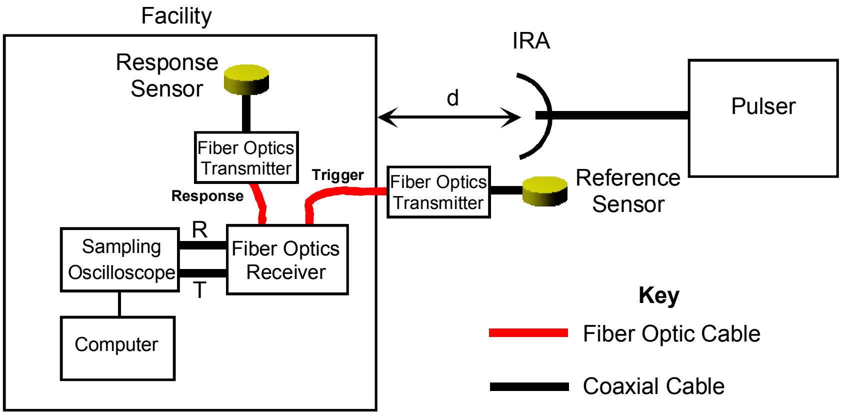


Figure G.3 – Measurement equipment and configuration for measuring transient responses in a buried facility, as reported by [G-6]

As an example of the measured cable currents in the facility, Figure G.4a presents the transient current due to the IRA illumination of the facility. Figure G.4b shows the resulting frequency domain spectrum that is calculated numerically from the waveform. The measured waveform had 10 000 sample points with a sampling interval of Δt = 20 ps, with the result that the waveform duration was from t = 0 to t = $t_{\max}$ = 200 ns. For this waveform, the maximum frequency, its computed spectrum, is at the Nyquist frequency $f_{\max}$ = $1/(2\Delta t)$ = 25 GHz.

Because the transient waveform is assumed to be repetitive with a period of 200 ns when a discrete Fourier transform is used, the spectral response is also discretely sampled from 0 to $f_{\max}$ with 5 001 sample points and a sampling interval of $1/t_{\max}$ = 5 MHz. Note that the negative frequency portion of the spectrum is just the complex conjugate of the positive frequency portion and is generally not included in the plots.

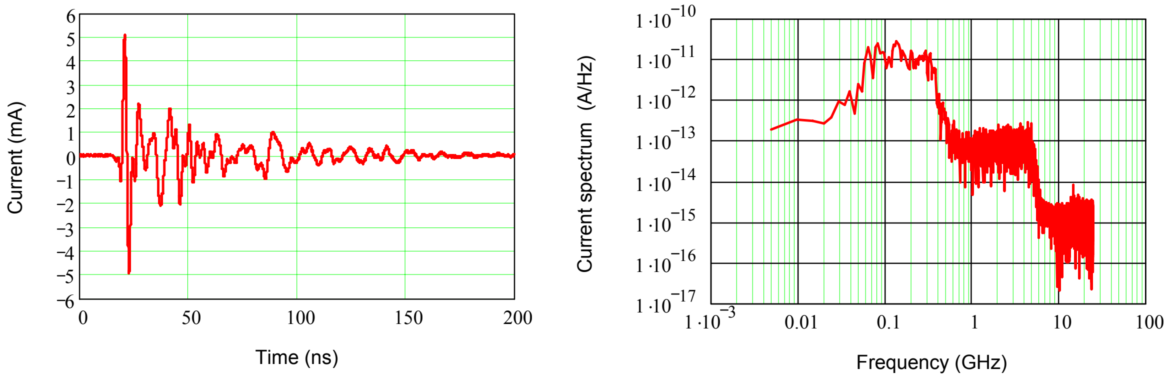


Figure G.4a – Measured transient current **Figure G.4b – Computed current spectrum**

Figure G.4 – Example of a measured transient cable current (a) and the resulting spectral magnitude, as computed by a Fourier transform (b)

It is important to observe that while the sampling oscilloscope is able to provide a measured waveform with a 20 ps sampling interval and a resulting Nyquist frequency of 25 GHz, the spectrum of the measured signal is by no means accurate up to this frequency. There are limits to the upper operational frequency of the fibre optics links and the oscilloscope usually has an analog bandwidth that is significantly lower than the Nyquist frequency. As a result, the spectrum computed from the transient waveform is usually valid up to a certain frequency, and above this frequency the spectrum is noise-dominated. In Figure G.4b, this upper frequency is seen to be about 600 MHz. Consequently, any transfer functions computed for frequencies higher than this are questionable.

The reference quantity for computing the source voltage to current transfer function T_{sc} is the voltage applied to the antenna. Instead of measuring this quantity directly with a reference sensor, as suggested in Figure G.3, an analytical representation of the pulser voltage waveform may be used. The voltage waveform is shown in Figure G.5a, and the corresponding spectral magnitude for the voltage is presented in part b of the figure.

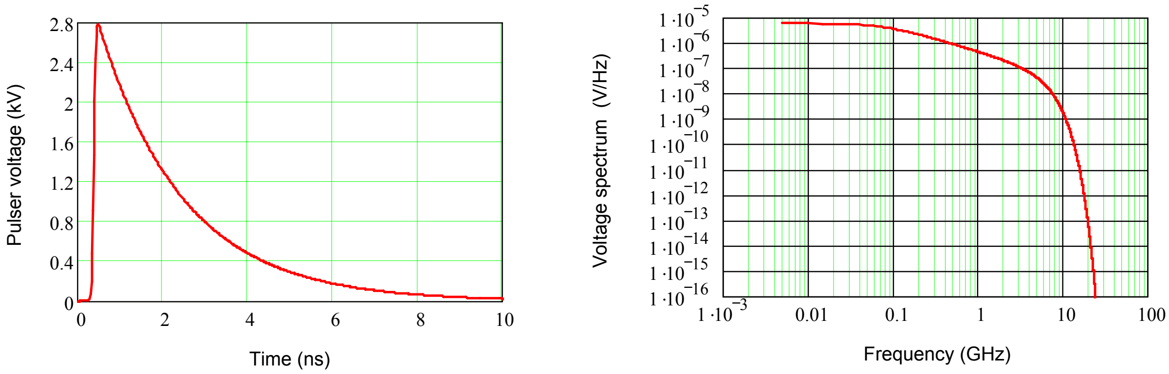


Figure G.5a – Transient pulser voltage **Figure G.5b – Computed voltage spectrum**

Figure G.5 – Plots of the analytical pulser output open circuit voltage waveform (a) and spectral magnitude (b), which are used as reference for computing the transfer function T_{sc}

For the transfer function relating the incident E-field to the cable current, T_{ec}, it is necessary to specify the distance between the IRA antenna and the observation point, where the incident E-field is to be specified. In the measurements of [G-6], this distance was estimated to be roughly 6 meters. Reference [G-9] provides an analytical model for the on-axis E-field radiated by the IRA and for a range of 6 meters Figure G.6 presents the transient radiated E-field (Figure G.6a) and the computed E-field spectrum (Figure G.6b).

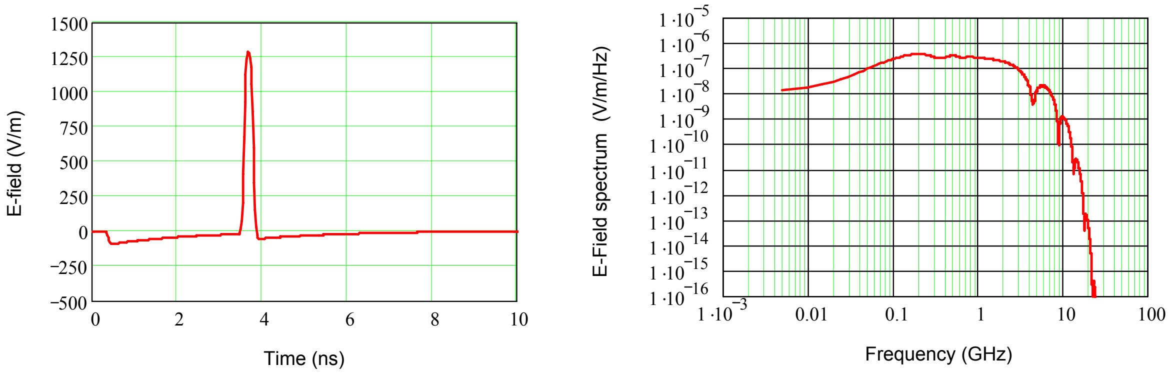


Figure G.6a – Transient radiated E-field **Figure G.6b – Computed E-field spectrum**

Figure G.6 – The radiated E-field from the IRA at a distance of 6 meters for the analytical pulser excitation (a) and the resulting spectral magnitude (b)

Using the measured current spectrum of Figure G.4b and the voltage and E-field spectra of Figure G.5 and Figure G.6, the frequency domain transfer functions can be computed using Equations (G.1) and (G.2). Considering first the frequency-domain source voltage-to-current transfer function T_{SC}, Equation (1) can be evaluated numerically and the results are shown as the blue curve in Figure G.7. In this plot, the transfer function looks reasonable up to about 800 MHz, but for higher frequencies the transfer functions begins to show the results of the noise in the measured current spectrum. At very high frequencies (above 8 GHz in Figure G.4b) the current spectrum is roughly a constant, which is the noise floor, but the analytical voltage spectrum in Figure G.5b continues to decrease. This gives rise to the unphysical growth in the high frequency transfer function. Any reconstruction of a transient response for the transfer function using this data will lead to a noise dominated response, which is unphysical.

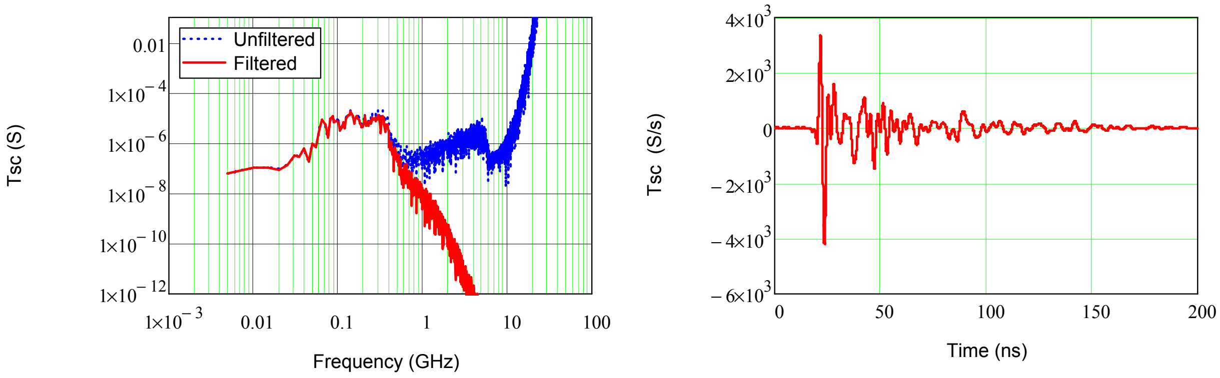


Figure G.7a – Computed spectral magnitude **Figure G.7b – Computed transient transfer function**

Figure G.7 – The spectral magnitude of the computed transfer function T_{sc} (a) and the corresponding transient transfer function (b)

To minimize this high frequency noise effect in the spectrum, it is possible to filter the spectral data with a low-pass filter, as shown in the red curve in Figure G.7a. Details of the cut-off frequency for the filter, together with the number of poles (or sections) for the filter depend on the nature of the spectral data to be filtered and must be estimated on a case-by-case basis by examining the original and filtered data. As an example, the red curve in Figure G.7a provides the transfer function with a 10-pole low-pass filter having a cutoff frequency of 1 GHz, and this transfer function looks more reasonable at high frequencies.

Figure G.7 presents the result of Fourier transforming the filtered spectral data, and this is the transient transfer function $T_{sc}(t)$. Note that the units of this function is (S/s) and is must be used as a distribution function in Equation (G.9) to evaluate the cable current for a particular pulser voltage waveform.

The results of a similar calculation for the incident E-field to current transfer function are shown in Figure G.8. Part a shows the filtered spectrum, and part b is the transient transfer function waveform. Note that there still is a problem in the transfer function at a frequency of about 3,6 GHz, where there is a null in the pulser voltage spectrum and for the transfer function has a small peak. However, the filter has minimized the effect of this spectral error and is it not evident in the transient response.

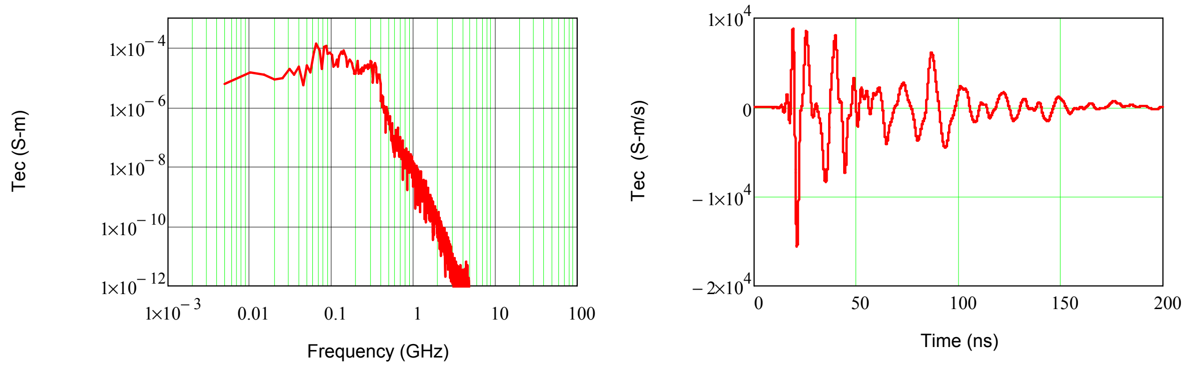


Figure G.8a – Computed spectral magnitude

Figure G.8b – Computed transient transfer function

Figure G.8 – The spectral magnitude of the computed transfer function T_{ec} (a) and the corresponding transient transfer function (b)

G.5 Frequency domain transfer functions

Continuous Wave (CW) frequency sources can be used to measure frequency domain transfer functions using either spot frequencies or swept frequencies.

Generally, these transfer functions are measured with low-level RF fields such that the impact on other spectrum users is minimised. This approach is known as a low-level CW (LLCW) method.

Swept frequency transfer function measurements are used internationally for the clearance of civil and military aircraft to High Intensity Radiated Fields (HIRF). Low-level (typically <1 V/m) RF fields are used to gather cable bundle transfer functions using a series of transmit antennas that are effective in the cable coupling regime (500 kHz to 1 GHz). Dipole antennas are used to cover the HF band (500 kHz to 25 MHz) and Bi-log antennas can be used to cover the VHF and UHF bands (25 MHz to 1 GHz). Longer dipoles can be used to extend the lower frequency if required however, field uniformity and beam width must be considered. The low-level radiation used during this technique enables the assessment to be conducted outside whilst not impacting on other spectrum users. If the assessment is to be conducted in a harsh electromagnetic environment, this environment can be used to provide the illuminating field thus negating the need to generate high-level fields. In this case, the ambient should be used as the reference field and the measured transfer functions normalised accordingly.

Initially, a reference field measurement is made without the system to be measured present (shown in Figure G.9).

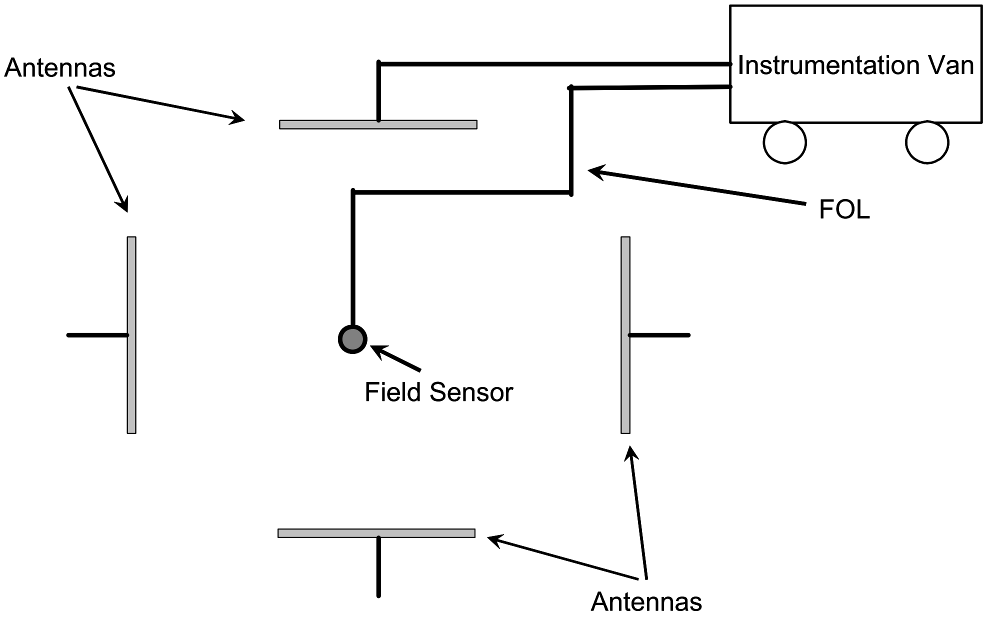


Figure G.9 – LLCW reference field measurement

A field sensor is used to measure the field at the centre point of where the EUT is to be located. Typically, a spectrum analyser with tracking source is used to excite the transmit antenna at a particular frequency whilst measuring the field at the same frequency. The field is measured via a Fibre Optic Link (FOL) to ensure that no additional coupling paths (antennas) are generated.

The measurement is then repeated with the EUT present and thus illuminated (as shown in Figure G.10).

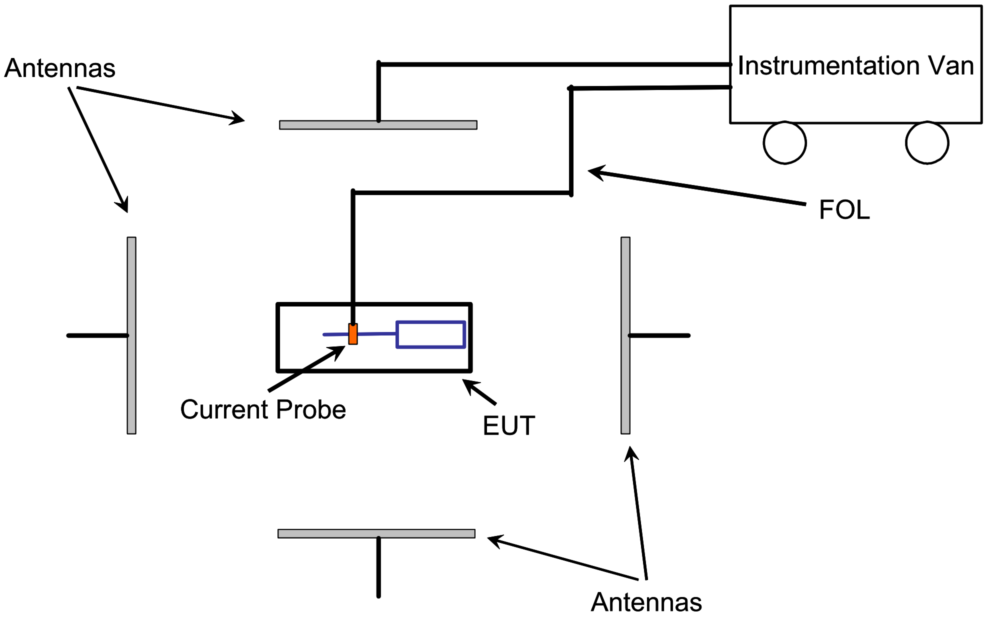


Figure G.10 – LLCW induced current measurement

Induced currents are measured in the cable bundles of interest using the same method as for the reference field measurement but using current probes in place of the field sensor. These induced currents can then be normalised to the incident field. Thus, the resulting transfer function is expressed in terms of induced current per unit field (an example is shown in Figure G.11).

Swept frequency transfer functions can be used to measure transfer functions for cable bundles in an office building. Careful consideration must be given to the transmit antennas such that adequate beam width and field uniformity is achieved.

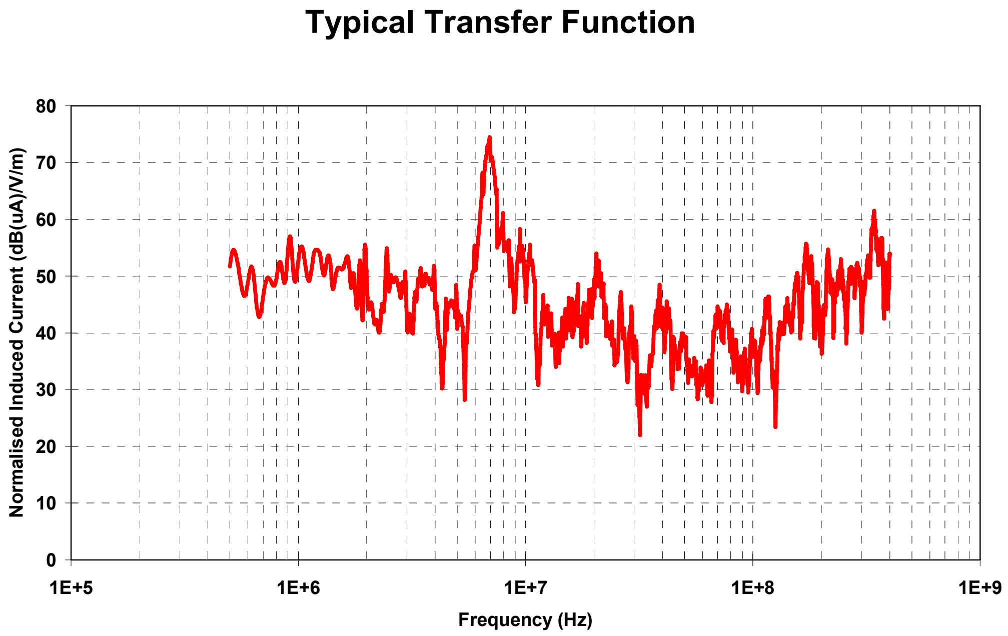


Figure G.11 – Typical magnitude-only transfer function

Care must be taken to ensure that the measured transfer function is a function of the externally illuminating field and not affected by the measurement chain. Annex B gives some examples of good measurement practice.

The LLCW method can be used to also be used to measure voltage and surface current transfer functions.

It is important to note that the extrapolation of measurements made using low-level techniques to high-level environments needs careful consideration of any non-linear effects that may occur. An example of this is the activation of transient protection devices that do not operate during a low-level measurement but would in a high-level environment. In this instance, the current flow could be changed significantly such that the extrapolation becomes inaccurate. For this reason, it may be necessary to conduct a system level test to obtain confidence in the performance of the overall system. Low-level methods are a useful way of reducing the risk of observing effects during a system level test.

G.6 Alternative techniques

Alternative techniques include using a reverberation chamber to measure the transfer function. However, the primary limitation here is that the size of the system dictates the size of chamber required, and the lowest usable frequency is determined by the reverberation chamber dimensions.

Direct injection techniques can be used to gain transfer function data at low frequencies. This technique uses the direct attachment of an injection point to one end of the system with a return point being taken at the opposite end. Current flows along the skin of the system and the cable looms of interest are monitored for induced currents.

G.7 Attenuation measurements

Attenuation measurements can be made in the aperture coupling regime (200 MHz to tens of GHz) to determine the protection afforded by areas to an incident HPEM and/or HEMP environment.

As with transfer functions, these measurements can be made in the time domain or the frequency domain and the same limitations apply. Antenna changes are required to ensure the field uniformity is maintained across the frequency range of interest.

Prediction of incident field inside the area of interest as a result of an incident HEMP and/or HPEM environment can be calculated using a similar technique to that discussed Annex I.1

If the assessment is to be conducted in a harsh electromagnetic environment, it may be possible to use this environment to provide a measure of system shielding effectiveness at spot frequencies across a wide frequency range. For example, it is possible to measure the E-field due to a broadcast radio/TV service outside a telecommunications centre, at many points within the centre (i.e. in many different rooms) and the associated common-mode current flowing on associated cabling. Further information on this technique can be found in IEC 61000-4-23.

The LLCW method can be extended in frequency range to make field transfer function measurements or attenuation measurements. Typically this is conducted from 200 MHz to 18 GHz and results in a measure of the attenuation of externally illuminating EM field incident upon an enclosure. This information can be used to define the internal enclosure environment as a result of an illuminating HEMP or HPEM environment.

G.8 References

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Annex H
(informative)

Detailed description of high-level test techniques

H.1 High-level techniques

H.1.1 Front-door coupling, first order

Analyses of levels for permanent damage can be handled by use of “galvanic” injection [H-1] and [H-2], see Figure H.1.

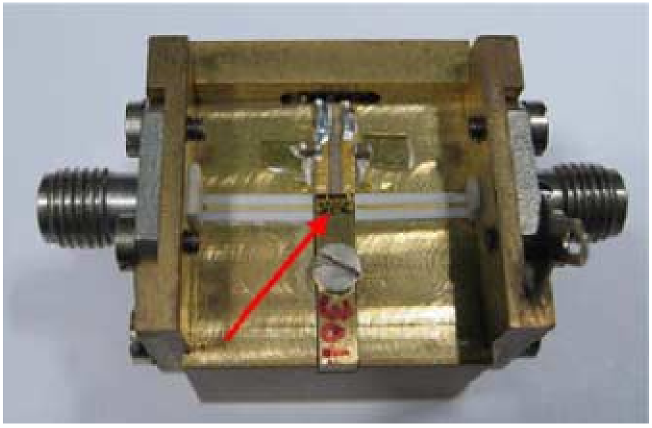

Figure H.1 – Microwave injection testing of a low noise amplifier, LNA [H-2]. LNA at the tip of the arrow

Due to the well-defined coupling path damage levels are rather easy to determine compared to the back-door coupling case. In first order front-door coupling the susceptibility can often be determined from knowledge of the transfer function, taken from the external field to the power or energy delivered to the antenna port of the equipment, in combination with susceptibility data derived from injection of pulses into that port. It is often the first component, typically a low noise amplifier (LNA) that breaks down. A typical investigation includes damage level vs. pulse length. Statistical matters include variation between different samples of the same equipment. Determination of levels for interference is much more complicated since it depends on how smart the disturbing signal is and how well designed the system-under-test is to deal with interference. In the case of HPEM it is presumably most relevant to determine the noise saturation level, that is, the level at which the receiver becomes saturated by the disturbing signal. Determination of damage level can also be achieved by irradiating the receiving antenna, this could be appropriate if, for example, the directional properties of the receiving antenna are not known or accessible.

H.1.2 Back-door coupling and front-door coupling, second order

Susceptibility testing can be made in a plane wave environment such as an anechoic or semi-anechoic chamber, or in a TEM-cell. At higher frequencies, testing can alternatively (or as a complement) be carried out in the statistically isotropic environment of a reverberation chamber (RC). The choice between a plane wave and an isotropic environment can be made from a technical standpoint, for example that the choice of the test environment shall reflect the kind of threat environment the equipment-under-test (EUT) is expected to be subjected to. The choice can also be made from a more economical point-of-view. In a plane wave test at microwave frequencies the EUT should, at each frequency, be subjected to a great number of angles of incidence, typically several hundreds or more, in order to find the worst case within an acceptable level of uncertainty [H-3]. In the statistically isotropic environment of a reverberation chamber this problem vanishes. However, in order to simulate the stress corresponding to the worst angle of incidence in a plane wave environment a margin has to be added to the test level in the RC. In other words, the test level has to be increased beyond the specified plane wave threat level. This increase stands in proportion to the maximum directivity of the test object, which for typical, normal-sized objects, require a margin of around 10 – 15 dB [H-4], [H-5] and [H-6]. There are also some other matters that should be considered when simulating a plane wave threat using a reverberation chamber. One is that the shape of the pulse injected into a reverberation chamber becomes distorted due to the normally long relaxation time of the reverberation chamber. Even if the chamber is loaded in order to decrease the time constant some distortion of the pulse still takes place. Also, the question of the significance of the different nature of excitation with respect to the number of point-of-entries that are irradiated simultaneously in the two rest environments shall be noticed.

High-level testing of large systems such as aircraft (as shown in Figure H.2) can usually, due to lack of radiation sources, be made at only a limited number of frequencies [H-3].

Figure H.2 – Aircraft testing at the Swedish Microwave Test Facility, MTF [H-3]

However, the frequency variations of shielding, coupling to cables and component susceptibility often means that the total transfer function from incident field to the stress on an internal critical component shows a large variation versus frequency. It may change tens of decibels across an octave (as shown in Figure H.3).

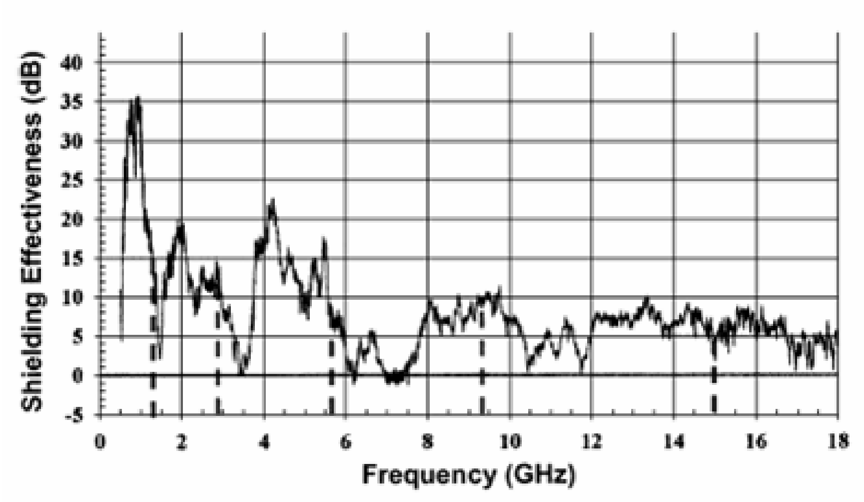

Figure H.3 – Measured shielding effectiveness of an equipment compared to the MTF test frequencies (dashed bars) [3]

This constitutes a severe limitation for fixed frequency high-level testing. The problem has to be taken into account by supporting high-level testing with a comprehensive analysis based on low-level swept frequency coupling measurements, in combination with knowledge about the susceptibility of the internal equipment. On the other hand, since these kinds of analyses often involve considerable uncertainties high-level testing is an invaluable tool for validation of these indirect (low-level) methods. Another weakness with high-level testing, which is rather due to financial than technical reasons, is the fact that usually only a very limited number of angles of incidence and polarizations can be afforded in a test.

H.2 Damped Sinusoidal Injection (DSI)

In order to assess equipments against the effects of coupled HEMP and/or HPEM environments, a DSI assessment may be required. During DSI, damped sinusoids of various core frequencies are injected onto all power and signal lines comprising the EUT. Limit lines are determined by the current expected to be induced in the looms of interest during illumination by the HEMP and/or HPEM environment. Typically this technique involves the injection of a damped sinusoidal waveform consisting of one dominant frequency with some associated bandwidth. Complex injection can be conducted using multiple damped sinusoidal waveforms with the aid of an arbitrary waveform generator.

H.3 Synergistic effects

When conducting a DSI assessment it is important to consider the synergistic nature of the incident pulse. More specifically, multi-frequency excitation is expected in the event of a broad band transient like EMP illuminating a system. DSI only considers injection of signals that are centred around a main frequency. Consideration of norms is required to cover the synergistic nature of the induced current, this is discussed further within IEC 61000-4-33.

In addition DSI as typically performed only excites one port on an EUT at a time. Any synergistic effects due to multi-port excitation are not assessed. Thus analysis is needed to ensure that port responses are independent of other EUT ports. Further information is provided in Annex F.

H.4 Anechoic chamber methods

Many conventional methods of radiated immunity and susceptibility testing rely on screened rooms internally lined with Radar Absorbing Material (RAM) to simulate a free space environment. In principle, an accurate simulation of free space has the advantage that the results of immunity or emissions testing can be related to the EUT directivity. Consequently, investigative measurements within well-lined anechoic chambers can yield valuable information about the system being evaluated. This information, which can include identifying specific weaknesses in the shielding, can be used to improve the EMC design. However, this type of testing can be time consuming and proper lining of the test chamber has been found to present difficulties that can be very costly to overcome.

In practice, reflections within the chamber are inevitable and these result in a stationary field distribution within the test volume which is very dependent on the test setup. Consequently, poor measurement repeatability is common. Additionally, discrepancies in immunity testing can result from the EUT being exposed to non-uniform fields. Moreover, the losses of the absorbing material lining the walls ‘damp’ the field reducing the available field strength per Watt of input power.

H.5 Reverberation chamber methods

Despite the conceptual difficulties involved in relating Reverberation chamber and free space measurements, reverberation chamber techniques offer many advantages over open site or anechoic chamber testing, namely:

a) the field strengths available are much higher per Watt of input power than a conventional anechoic or open area test;

b) the peak field strengths at different locations within the room are more uniform (time averaged over one paddle/tuner rotation) than is possible whilst employing an anechoic chamber/room;

c) the EUT will be subjected to the total average field in a multitude of polarisation’s and angles of arrival, which is prohibitively expensive in an anechoic room or open area test site. This can be considered as worst case illumination from a polarisation and orientation perspective and an average case from a field perspective, and it has been argued that this is more representative of the true EM environment when the equipment is in service [H-7];

d) all parts or faces of the system will experience the peak field levels over the time for one paddle or tuner rotation. Therefore the lay out of the EUT and in particular the orientation of cables has less bearing on the susceptibility threshold;

e) the repeatability is better than conventional anechoic techniques, due to time averaging which produces a more consistent test method;

f) most importantly the uncertainty is better than that of anechoic techniques. Some [H-8, H-9] have quoted the expanded uncertainty of the reverberation technique to be of the order of ±1,5 dB to ±1,8 dB at a 95 % confidence level;

The disadvantages of the reverberation chamber technique are:

a) for mode stirring (i.e. continuous stirrer rotation), the duration that the peak field dwells on the EUT can become an important factor if the cycle time of the system is long;

b) some authors find it conceptually difficult to relate the susceptibility levels recorded using the reverberation method to anechoic and open area techniques;

c) the size of the smallest dimension of the chamber dictates the lowest usable frequency at which the chamber can be used;

d) the pulse rise-time which can be used is limited by the Q-factor of the chamber, this restricts the pulse modulations which can be used;

e) the directivity characteristics of the EUT are not preserved. This means that the critical illumination angle cannot be revealed and any ‘enhancement’ in EUT coupling efficiency is cancelled out [H-10].

Mode stirred and mode tuned techniques are now routinely used for immunity measurements and involve the energising of a resonant cavity to generate high field strengths. The objective of reverberation chamber immunity testing is to produce fields with a high level of statistical uniformity across a defined working volume. The statistically homogeneous electromagnetic environment is produced through the rotation of a conductive stirrer or tuner (or other boundary perturbation method). Continuous rotation of the stirrer constitutes mode stirred testing, whereas the newer technique of mode tuning involves rotation of the tuner in discrete steps.

A photograph of a reverberation chamber is shown in Figure H.4.

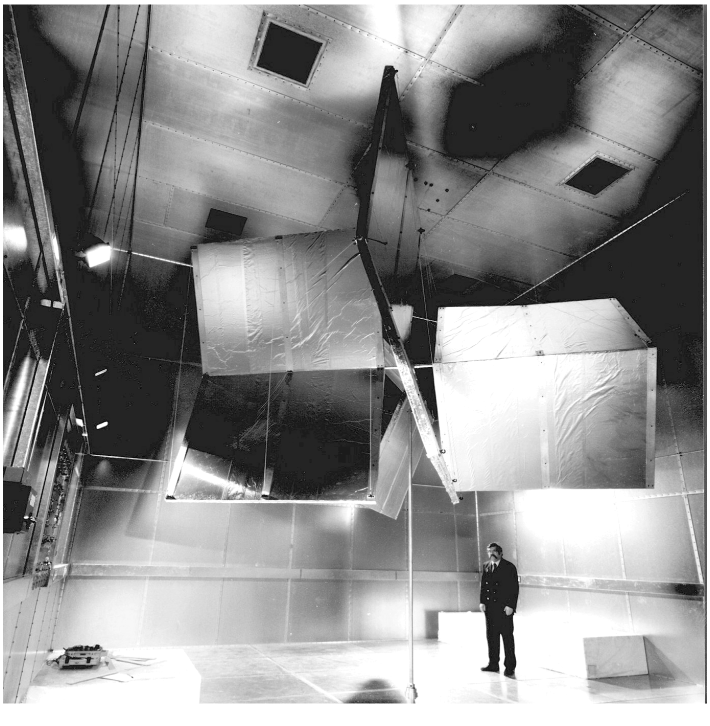

Figure H.4 – Reverberation chamber

Reverberation chambers have recently been shown to be a useful environment for achieving a better worst case test than conventional anechoic methods of testing. The thoroughness of exposure in a reverberation chamber and the test repeatability (effect reproducibility) is difficult to achieve in practice with any other test method.

Initially the mode stirred test was introduced in various standards, notably the early versions of IEC 61000-4-21 [H-11] and DO160D [H-12]. More recently, the mode stirred requirements have been superseded by the mode tuned technique. A full mode tuned immunity testing procedure is now offered in DO160F [H-13] and Mil Std 461E [H-14] as a valid alternative to conventional radiated testing in an anechoic chamber

If further understanding of how a reverberation chamber operates is required then [H-15] gives a good overview of the subject.

H.6 HEMP simulators

HEMP simulators are used to generate the electromagnetic environment anticipated from the detonation of a nuclear weapon outside of the earth’s atmosphere. Typically, these simulators generate the early-time HEMP environment and are used to assess the response of equipment, subsystems and systems. Further information can be found within IEC 61000-2-9 [H-16], IEC 61000-2-10 [H-17] and IEC 61000-4-32 [H-18].

H.7 HPEM simulators

HPEM simulators are used to generate the electromagnetic environment anticipated from the use of high power RF sources. Further information can be found in IEC 61000-2-13 [H-19] and 61000-4-35 [H-20].

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Annex I
(informative)

Data processing and analysis

I.1 Prediction of induced current

It is possible to predict the level of current expected on a cable bundle of interest by convolving the transfer function with the incident environment. Typically, phase is not measured[4] during swept frequency transfer function measurements due to the many external influences that can impact on the accuracy of the measured phase. At wavelengths that are small compared to the test object, phase becomes highly dependent on the location and position of the current probe. To overcome this lack of information, phase information is constructed and one approach is to use minimum phase constraints. This forces the energy in the predicted current to be focussed at t = 0 and results in a realistic worst-case prediction. The phase is constructed using a Minimum Phase Algorithm (MPA) and the actual prediction process is shown in Figure I.1.

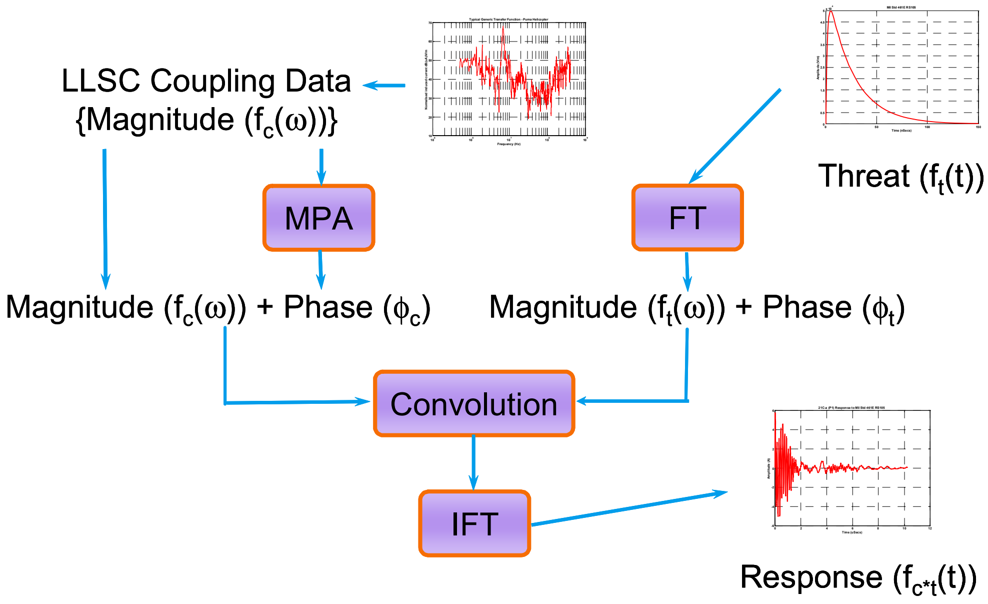

Figure I.1 – Prediction of induced current using magnitude-only transfer functions [I-1]

The process starts with the magnitude-only measured transfer function recorded for a cable bundle using the LLCW techniques (as discussed in G.5). The MPA uses a Hilbert Transform to create phase information that is related to the measured magnitude component. Once the phase is constructed, a complex function exists for the transfer function ($f_c(\omega) + \Phi_c$). In parallel to this process, the Fourier transform (FT) of the incident environment is computed such that a complex function now exists for that environment ($f_t(\omega) + \Phi_t$). These two complex functions are convolved resulting in the frequency and phase information of the prediction. The final stage of the process is to calculate the inverse Fourier transform (IFT) of the complex result which gives the final time domain waveform.

Other phase re-construction methods are possible. An important consideration here is that the predicted result must remain stable and causal such that it relates to a real prediction.

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[4] Phase information may be measured at low frequencies with more accuracy but care must be taken to ensure that the phase is representative of reality.

I.2 Example

I.2.1 Prediction process

The following figures provide an example of the prediction process. Figure I.2 shows the incident environment (taken from IEC 61000-2-9), Figure I.3 shows both the transfer function and the environment in the frequency domain during the convolution and Figure I.4 shows the final predicted result.

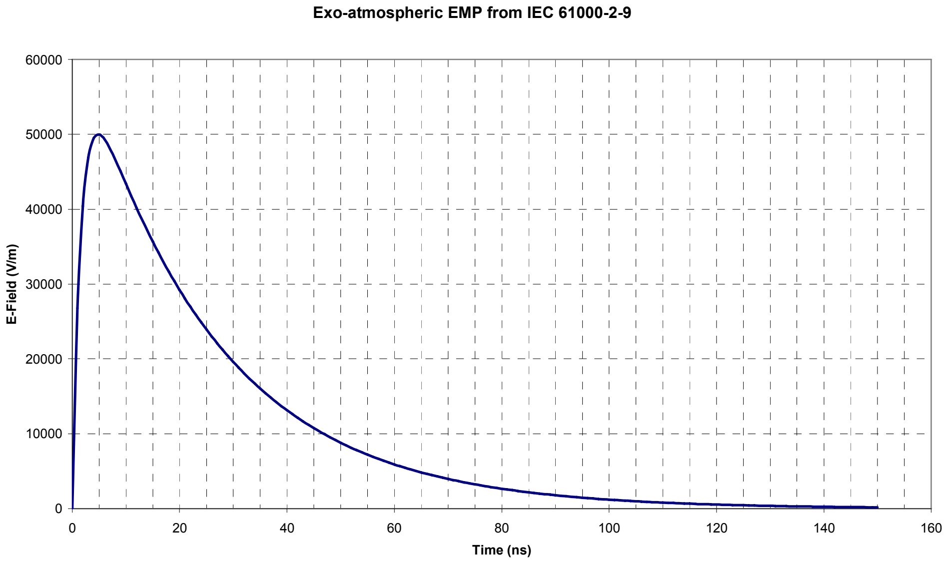

Figure I.2 – IEC 61000-2-9 HEMP waveform

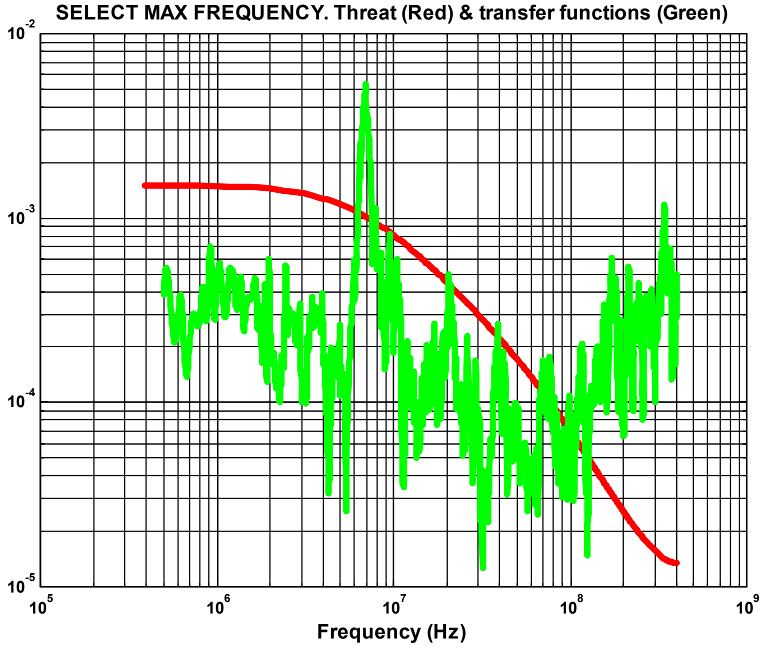

Figure I.3 – Convolution process

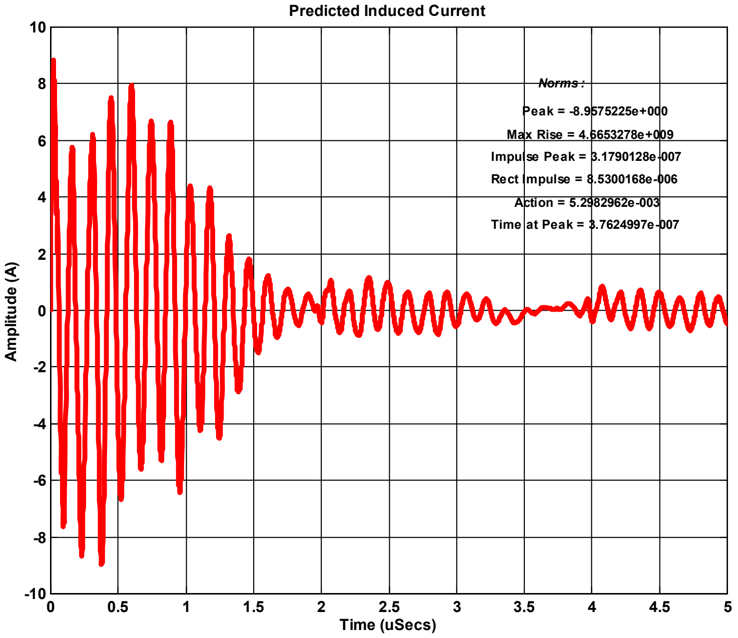

Figure I.4 – Predicted induced current

This process can be used for any incident environment that is in-band to the measured transfer function.

I.2.2 Validation

This technique has been validated by many trials that have taken the predicted currents and compared them to measured currents as a result of a simulated EMP. The most notable of this validation took part during trials on one of the UK's air platforms during the 1980s. The LLSC trials were completed in the UK by the Royal Aircraft Establishment (RAE) and the EMP trials were conducted at Kirtland AFB in New Mexico, USA. The ratios of predicted to measured currents (in terms of peak amplitude) are given in Table I.1 and Figure I.5.

Table I.1 – Comparison of transfer function predictions and simulator measured currents

Ratio (Prediction to Measurement)	% Occurrence – HPD	% Occurrence – VPD
0-1	9	1
1-2	22	10
2-4	57	72
4-8	10	15
8-16	1	0

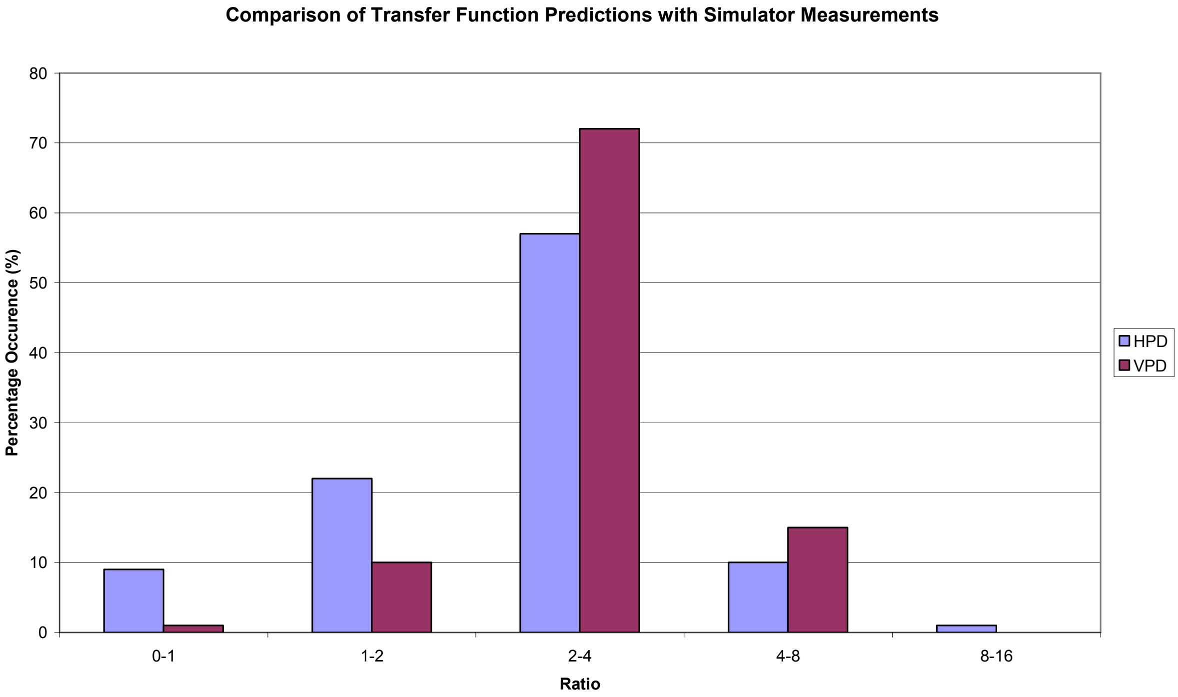

Figure I.5 – Comparison of transfer function predictions with simulator measurements

HPD and VPD in Figure I.5 refer to measurements made with the Horizontally Polarised Dipole (HPD) and Vertically Polarised Dipole (VPD) respectively. As can be seen, for the majority of cases the predictions over estimated the induced currents by a factor or 2 to 4 times (6 dB to 12 dB). In only a small percentage of occurrences, the predicted currents were less than those measured as a result of the incident environment.

I.3 Extrapolation of measured transients

It is sometimes necessary to perform a measurement or susceptibility assessment with a HEMP and/or HPEM environment that is different to that specified. In this case, measured current can be extrapolated to the environment specified by considering the frequency content of the measured transient, the test environment and the specified environment. The extrapolation process is shown in Figure I.6.

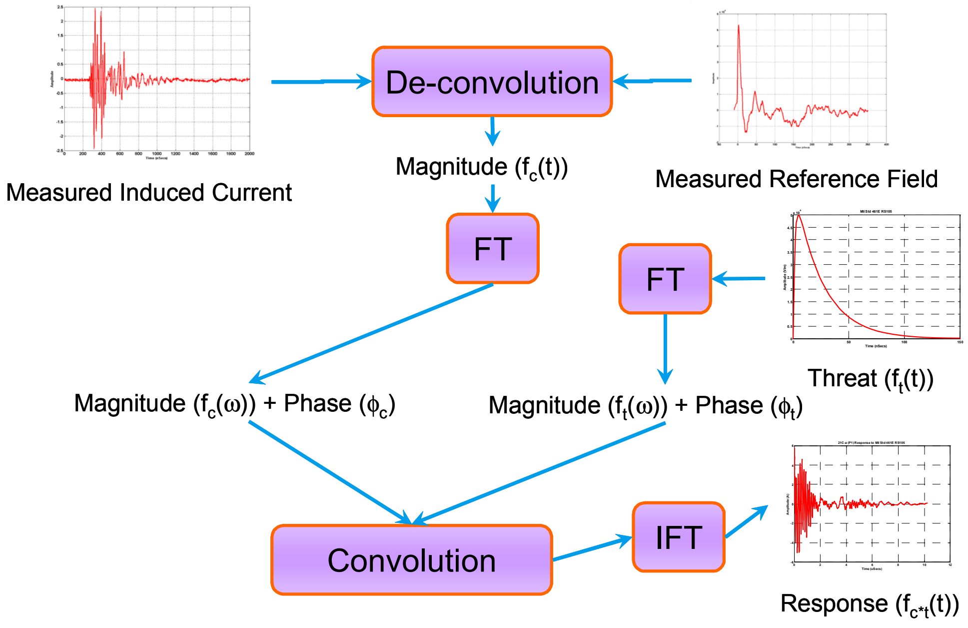

Figure I.6 – Extrapolation of measured transients

The process starts with the measured induced current which is de-convolved from the measured reference field resulting in a time domain transfer function. A Fourier Transform is computed which gives a complex magnitude and phase transfer function ($f_c(\omega)+\Phi_c$). In parallel to this process, the FT of the incident environment is computed such that a complex function now exists for that environment ($f_t(\omega) + \Phi_t$). These two complex functions are convolved resulting in the frequency and phase information of the prediction. The final stage of the process is to calculate the inverse Fourier transform (IFT) of the complex result which gives the final time domain extrapolated waveform.

I.4 References

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
www.iec.ch