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inside

Electromagnetic compatibility (EMC) – Part 4-24: Testing and measurement techniques – Test methods for protective devices for HEMP conducted disturbance

IEC 61000-4-24:2015-11+AMD1:2023-08 CSV(en)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 4-24: Testing and measurement techniques – Test methods for protective devices for HEMP conducted disturbance

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

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This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

IEC 61000-4-24 edition 2.1 contains the second edition (2015-11) [documents 77C/245/FDIS and 77C/250/RVD] and its amendment 1 (2023-08) [documents 77C/330/FDIS and 77C/331/RVD].

In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

International Standard IEC 61000-4-24 has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility.

It forms Part 4-24 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107.

This second edition constitutes a technical revision.

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

a) A new Clause 5: Measurement method for HEMP combination filters, which contains 5.1 Verification setup, 5.2 Measurement setup, 5.3 Measurement instrument, 5.4 Test modes, 5.5 Measurement procedures, 5.6 Evaluation of test results, which introduced performance criteria of filter, and 5.7 Test report.
b) A new informative Annex A: Investigation for the establishment of a measurement setup, which was based on Clause 5.
c) A new informative Annex B: Test method for the quantitative determination of the direct response behaviours of a coaxial surge protector.

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

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

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

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

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This standard is part of the IEC 61000 series of standards, 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

Part 4: Testing and measurement techniques

Measurement techniques
Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines
Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as international standards, 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).

The IEC has initiated the preparation of standardized methods to protect civilian society from the effects of high power electromagnetic (HPEM) environments. Such effects could disrupt systems for communications, electric power, information technology, etc.

This part of IEC 61000 is an international standard that establishes the required test procedures for protective devices for HEMP conducted disturbance, such as gas discharge tubes, varistors, two-port SPDs and HEMP combination filters.

The application of this standard is, however, not dependent on access to other sections and parts of the IEC 61000, except for those specifically referred to.

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 4-24: Testing and measurement techniques – Test methods for protective devices for HEMP conducted disturbance

1 Scope

This part of IEC 61000 deals with methods for testing protective devices for HEMP conducted disturbance. It includes two-terminal elements, such as gas discharge tubes, varistors, and two-port SPDs, such as HEMP combination filters. It covers testing of voltage breakdown and voltage-limiting characteristics but also methods to measure the residual voltage and/or the residual current, peak rate of rise and root action for the case of very fast changes of voltage and current as a function of time.

This standard does not cover insertion loss measurement methods.

2 Normative references

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

IEC 61000-2-10:2021, *Electromagnetic compatibility (EMC) – Part 2-10: Environment – Description of HEMP environment – Conducted disturbance*

3 Terms, definitions and abbreviated terms

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

3.1 Terms and definitions

3.1.1
feed-through device
two-port device, which is designed to feed a signal through an electromagnetic barrier (shield)

Note 1 to entry: Typically it is in good electrical contact with the barrier and has one port on each side of the barrier, thus maintaining the isolation of the barrier.

3.1.2
gas discharge tube
GDT
device with two or three metal electrodes hermetically sealed so that gas mixture and pressure are under control~~,~~ and designed to protect apparatus or personnel from high transient voltages

3.1.3
HEMP
high-altitude electromagnetic pulse
electromagnetic pulse produced by a nuclear explosion outside the earth’s atmosphere

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

[SOURCE: IEC 61000-1-3:2002, 3.10]

3.1.4
HEMP combination filter
filter combined with voltage limiting devices, so that this combination can attenuate the residual current pulse passing through it

3.1.5
norms
scalar quantities that characterise the features of a waveform

Note 1 to entry: Norms are used to characterise features of a waveform that relate to susceptibility mechanisms.

3.1.6
peak rate of rise
maximum absolute value of the first derivative of a current waveform $I(t)$ with respect to time, dI/dt, expressed in units of ampere per second

3.1.7
PCI
pulsed current injection.
test method for measuring the performance of a protective device

Note 1 to entry: A HEMP threat-relatable transient is injected on the input of the protective device and the residual transient stress is measured on its output.

Note 2 to entry: This note applies to the French language only.

3.1.8
peak current
maximum absolute value of a current waveform, $I(t)$, expressed in units of ampere

3.1.9
primary protection element
first protective element seen from the unprotected side of a protection measure, diverting the main part of the surge current

3.1.10
protected side
side of a protection measure where the equipment is situated that has to be protected

3.1.11
protective device
electrical component such as a filter, gas discharge tube, metal oxide varistor (or other), for protection against conducted disturbance, or a shield, gasket, waveguide trap (or other), for protection against radiated disturbance, which is used to limit any conducted or radiated stress. Such an element or a combination of several of them thus forms part of the conceptual EM barrier for a system

[SOURCE: IEC 61000-5-5:1996, 3.20]

3.1.12
root action
norm of a current waveform $I(t)$ defined by

$$\sqrt{\int_0^\infty |I(t)|^2 dt}$$

Note 1 to entry: Where the load impedance is known, the energy in W/s or J can be calculated.

3.1.13
SPD
surge protective device

device that is intended to limit transient over-voltages and divert surge currents. It contains at least one non-linear component that is intended to limit surge voltages and divert surge currents

Note 1 to entry: This note applies to the French language only.

[SOURCE: IEC TR 61000-5-6:2002, 3.23, modified – a note has been added.]

3.1.14
two-port SPD

SPD which is not only a shunting device, but consists of a separated input port on the unprotected side and an output port on the protected side

Note 1 to entry: Typically two-port SPDs are “black boxes” with non-linear shunting devices to ground and a circuit between input and output ports.

3.1.15
two-terminal element

electrical element where a current enters in one terminal and leaves through a second terminal

Note 1 to entry: A two-terminal element is a one-port device. Typically two-terminal SPD’s are devices shunting to ground.

3.1.16
unprotected side

side of a protection measure from which the surge event is expected

3.1.17
waveform norm

parameter that is determined from a mathematically well-defined operation on a waveform or signal (such as an integration of the waveform), which yields a scalar number that permits a comparison of various waveforms or their effects

[SOURCE: IEC 61000-4-33:2005, 3.10]

3.2 Abbreviated terms

DUT	Device under test

4 Test methods for protective devices (excluding filter) for conducted disturbance

4.1 General

The actual behaviour of a protective device under HEMP conditions depends very much on how it is integrated into its place of use and other attendant circumstances (e.g. quality of shielding between the protected and unprotected side of a protection element). The following test methods take this into account. They are defined so that the results obtained are as far as possible related to the qualities of the device under test (DUT), and the test arrangement does not differ too much from practical protection arrangements.

NOTE Clause 4 is intended to apply for a protective device such as gas discharge tubes, varistors and two-port SPDs, excluding the HEMP combination filter. For a HEMP combination filter, Clause 5 applies.

4.2 Test setup

The test setup consists of a pulse generator (G), a launching line, a test fixture for the DUT, and a termination with a connecting line and oscilloscope (see Figure 1). Various source impedances may be used, but the example shown in Figure 1 uses 50 Ω. Other values could be specified.

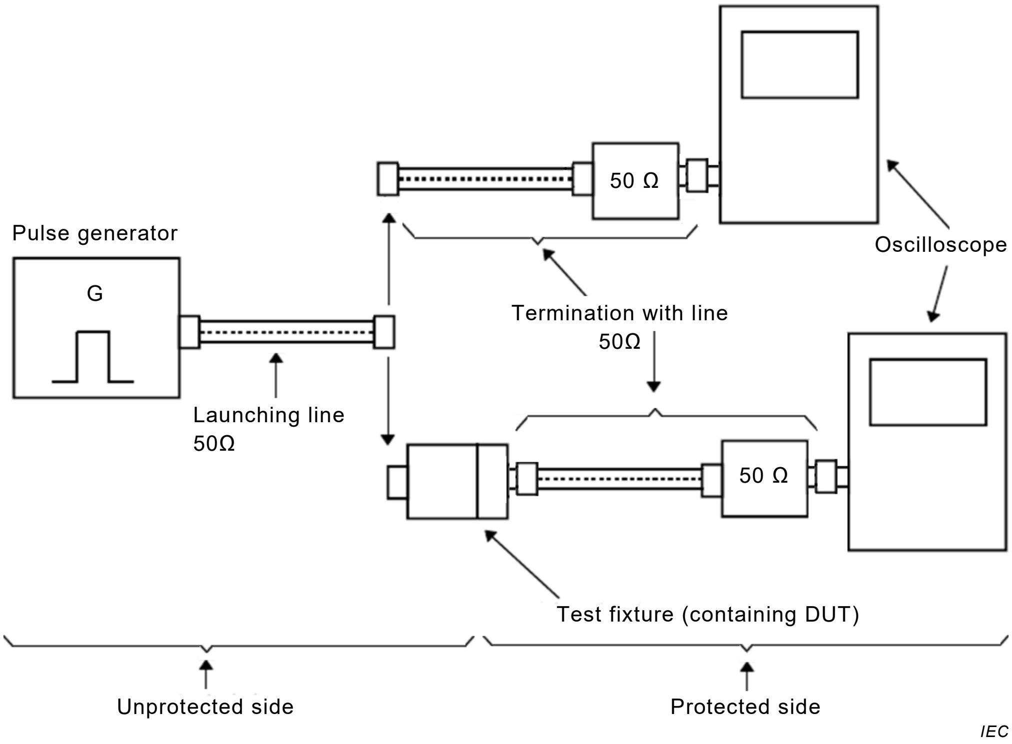


Figure 1 – Test setup for testing protective devices

To prevent parasitic coupling between the pulse generator and the oscilloscope, both the unprotected and protected side of the setup shall be entirely shielded. It is recommended to use cables with multiple braided wire shields or solid shields. The cable and connectors shall be capable of withstanding the high voltage pulse without a breakdown. Grounding loops shall be avoided.

4.3 Pulse generator

The pulse generator shall produce a normally rectangular voltage pulse into a matched termination. The output voltage (into a matched termination) shall be adjustable to a value 2 times higher than the expected limiting voltage of the DUT. Both polarities shall be available. The characteristics of a pulse generator are as follows:

– characteristic impedance:	50 Ω or an alternative value
– pulse wavefront , du/dt:	at least 1 kV/ns
– pulse duration:	at least 20 ns

4.4 Launching line

The launching line consists of a coaxial cable with a characteristic impedance of 50 Ω or the value specified. The cable between the pulse generator and the DUT shall be long enough so that reflections from the DUT do not arrive at the pulse generator during the pulse front. To achieve this condition, the one-way propagation time along the cable shall be greater than half the front time of the pulse. Due to the frequency-dependent attenuation of the cable, the steepness of the pulse front may be lowered and thus adjusted to the desired value, by further extending the launching line.

4.5 Test fixtures

4.5.1 General

Test fixtures are mechanical setups with coaxial connectors on both the unprotected and the protected terminals. Their task is to hold the DUT. Two different types of test fixtures may be used. They are referred to as type A and type B as described below.

4.5.2 Type A fixtures

Gas discharge tubes intended to be used for protection of coaxial high-frequency applications may be tested in corresponding, commercially available holders. The protective device is inserted between the inner and outer conductor of the coaxial setup, with a minimum of influence on the characteristic impedance. Such holders allow the inherent properties of the device to be measured explicitly and with good repeatability.

4.5.3 Type B fixtures

4.5.3.1 General

Type B fixtures are universal and apply in principle to all kinds of two-terminal or two-port protective devices, whether they have a feed-through or non-feed-through configuration. However, measurements on low-voltage devices like protective diodes and varistors may be strongly influenced by inductive overshoot due to high di/dt.

NOTE By ensuring the test fixture lead lengths are as short as practically possible, the risk of inductive influence can be mitigated.

The fixture is composed of three parts: the unprotected shell, the partition screen and the protected shell (see Figure 2).

4.5.3.2 Unprotected shell

The dimensions and cross-section shape may be adapted to the size of the DUT. The shell may be cut into two parts in the axial direction for better access to the solder points. If not otherwise stated, the length of the wire from the unprotected connector (P_1) to the input-contact of the DUT (P_2) shall not be longer than the length of the current path in the DUT between points P_2 and the grounding contact of the DUT (P_3).

4.5.3.3 Partition screen

Feed-through protective devices shall be inserted in the partition screen in the same way as in actual application.

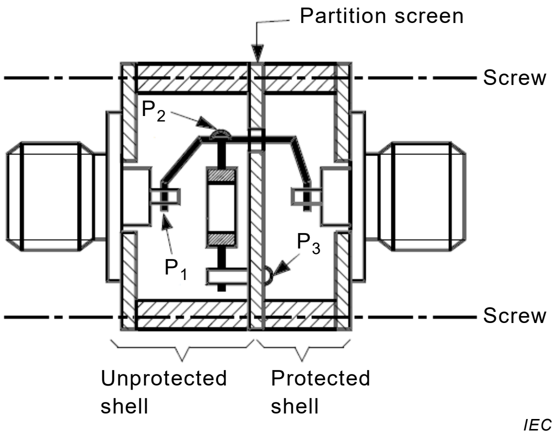
Non-feed-through devices shall be passed through a hole in the partition screen as shown in Figure 2a) and 2b). The wire passing through the partition screen shall be insulated. A feed-through capacitor or other feed-through element shall not be used. A non-feed-through DUT may be placed close to the screen but shall not touch it, except if it is to be installed on to a metal wall in actual applications (as shown in Figure 2c)).

4.5.3.4 Protected shell

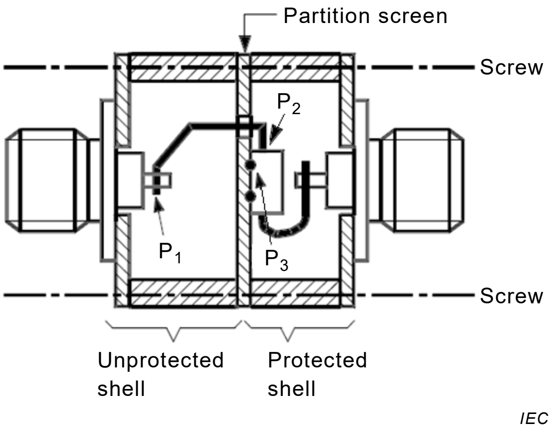
The protected shell serves as transition to the protected connector. The protected shell shall be made as short as possible. The length of the connection between point P_2 and the protected connector shall be as short as possible.

4.6 Termination

The termination shall be matched to the characteristic impedance of the test setup within the 3 dB-bandwidth of the oscilloscope. It shall be of the feed-through type, followed by a high-impedance, voltage-dividing probe of the oscilloscope or be part of the first stage of an attenuator in front of the oscilloscope. The line between the test fixture and termination shall have the same impedance as the termination. It shall be as short as possible. Its attenuation shall be less than 0,5 dB at the upper 3 dB cut-off frequency of the oscilloscope. Make sure that the termination withstands the test pulses without degradation.

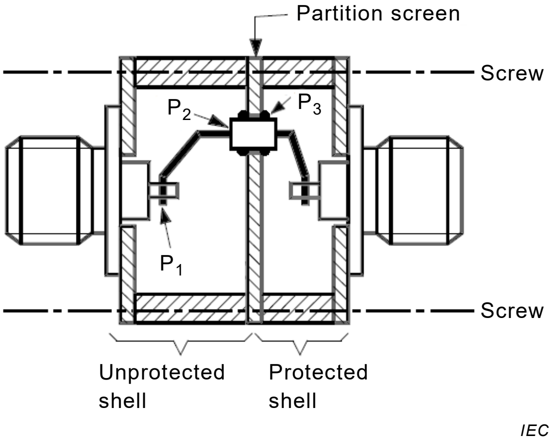


a) **Example of a type B test fixture with a two-terminal DUT in non-feed-through configuration**



The DUT may alternatively be in the unprotected shell.

b) **Example of a test fixture with a two-port DUT in non-feed-through configuration**



c) Example of a test fixture with a DUT in a feed-through configuration

Figure 2 – Example of a type B test fixture (universal)

4.7 Oscilloscope

The bandwidth of the oscilloscope and the other components of the test setup shall be wide enough that the overall tolerance of the peak values of u and du/dt due to bandwidth limitations and other system errors is not higher than ±20 %.

4.8 Test procedure

4.8.1 Adjustment of the pulse generator

The launching line is first connected directly to the line leading to the termination (see Figure 1).

The pulse generator is adjusted as follows:

a) if the DUT, or the primary protection element of a four-terminal DUT, is a gas discharge tube, the steepness of the leading front of the prospective pulse shall be at least 1 kV/ns at the impulse spark-over voltage of the gas discharge tube during the test;

b) if the DUT, or the primary protection element of a four-terminal DUT, is a voltage-limiting device (e.g. protective diode or varistor), the highest tangential steepness of the leading front of the prospective pulse is as described by

$$du/dt = (1/2) \times Z_c \times di/dt \qquad (1)$$

where Z_c is the characteristic impedance and di/dt is the specified value.

NOTE The specified di/dt corresponds to the actual di/dt in the DUT during the test. As the DUT has a very low impedance compared with 50 Ω or the specified impedance, the current i and therefore also di/dt is doubled during the test.

4.8.2 Verification procedures

The launching line is then connected to the test fixture (see Figure 1).

If a test fixture type B is used, the internal connection between the protected and the unprotected connector shall be tested for transmission characteristics.

For this purpose the DUT is removed and the same pulse as under 4.8.1 (adjustment of the pulse generator) is applied. The measured output shall not differ from the output measured under 4.8.1 by more than 10 %. If it differs by more than 10 %, the diameter of the connecting wire should be increased (a higher capacity will lower the characteristic impedance and improve the match between the pulse generator and the load).

To make sure that no undesired coupling between the unprotected and the protected side of the test setup is present, verification tests shall be made with the following modifications on the test setup:

If the DUT is a two-terminal element, it shall be replaced by a short-circuit connection of the same length and form as the current path through the DUT. The connection between P_2 and the centre-pin of the protected connector (see Figure 2) shall be removed. One test shall be made with the centre-pin of the protected connector left open and another one with this pin connected to the ground (within the protected shell).

If the DUT is a feed-through device, it shall be replaced by a device of the same dimensions (dummy DUT) made entirely of well-conducting metal and thus representing an ideal short-circuit. The centre-pin of the protected connector shall be connected to the output pin of the dummy DUT.

The peak value of the residual voltage measured under these conditions shall be less than 5 % of the peak value measured in the final test.

4.8.3 Test

The dummy DUT is replaced by the DUT, and the residual voltage is measured and compared to the verification criteria.

4.8.4 Final examination of the DUT

After the test, the DUT shall be examined for visible damage. If visible damage is observed, the DUT will be deemed to fail the test. If there is no visible damage a functional test shall be performed to verify that the DUT is within its specification.

4.9 Referring to this standard

When reference is made to this standard, the following additional information shall be given.

Standard procedure:

– for gas discharge tubes:	type of test fixture used (4.5)
– for measurement on two-terminal elements in fixture B:	length of connection wires, see overall length of DUT between solder points (4.5.3)

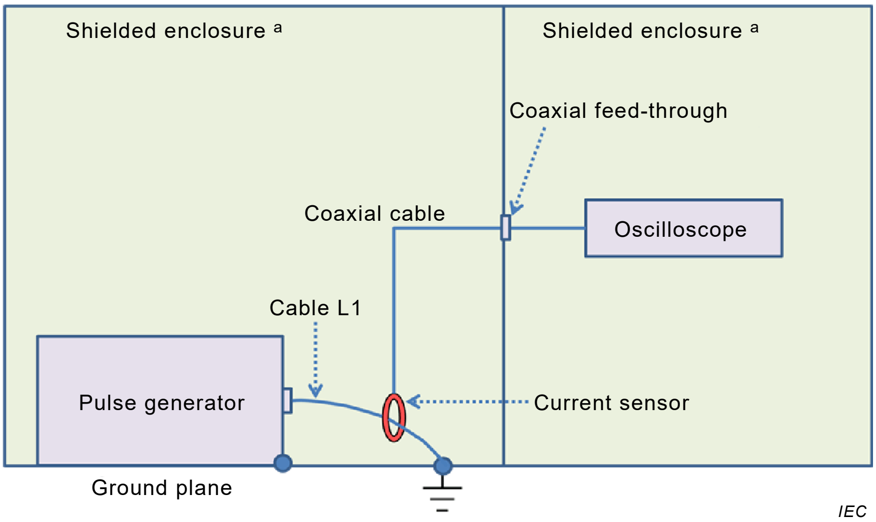
Modifications from standard procedure:

– characteristic impedance:	if other than 50 Ω (4.2)
– steepness of prospective pulse, du/dt:	if higher than 1 kV/ns (4.3)
– actual di/dt:	if higher than 40 A/ns (4.8.1)
– modification of DUT:	if connecting wires of gas discharge tubes are cut away for measurement in type A fixture
– additional components to the DUT	for example additional circuit components; different wire lengths to those specified.

5 Measurement method for HEMP combination filters

5.1 Verification setup

The output of the pulse generator shall be verified prior to applying a pulse to a DUT. The typical setup for verification of the pulse test level is illustrated in Figure 3.



[a] At least one of the two enclosures shall be shielded. Care should be taken to minimize radiated and conducted interference.

Figure 3 – Typical setup for verification of the pulse test level

The pulse generator shall be connected to the ground plane. The output cable L1 shall also be connected to the ground plane to enable the short-circuit pulse current to be measured. The length and geometry of cable L1 shall be chosen to minimize the inductance and shall be the same as when the DUT is connected (see Annex A). The insulation of the cable to the ground should be sufficient to avoid breakdown for all impulse voltages.

If the size or setup of the DUT requires a long cable L1, then the cable may be coaxial to achieve the required pulse rise time at the DUT. If the cable selected is coaxial, the shield should be pared back, and the inner conductor shall be exposed and bonded to the ground. The current probe shall be placed around the exposed inner conductor. Alternatively a coaxial current shunt can be used.

The position of the current sensor shall be within 0,15 m from the ground connection. Care shall be taken to electrically isolate the body of the current sensor from metallic surfaces to avoid ground loops.

5.2 Measurement setup

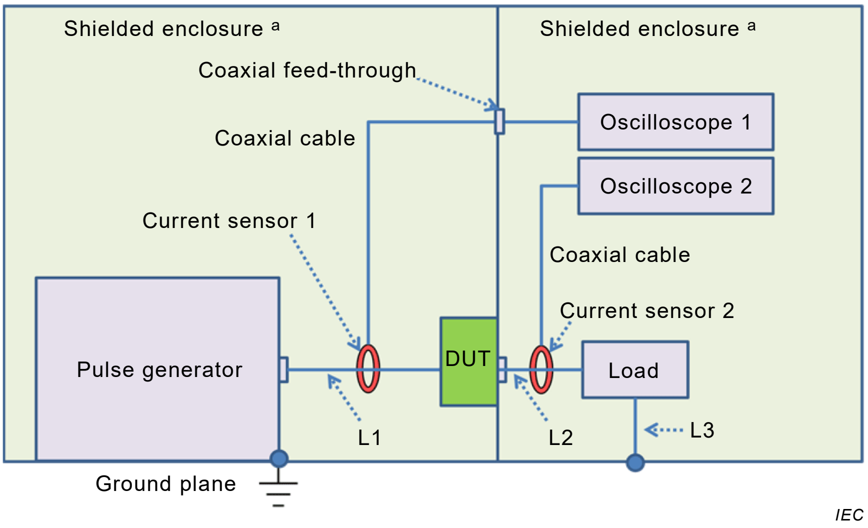
Two typical measurement setups are illustrated in Figure 4 and Figure 5. The pulse generator output shall be directly connected to the input terminal of the DUT through the same cable as used for verification.

The current sensor 1 and oscilloscope 1 can be used optionally to monitor the injected current into the DUT.

The current sensor 2 for the measurement of residual current into the dummy load shall preferably be within 0,15 m of the output terminal of the DUT. Alternatively a grounded measuring shunt can be used in series with the load impedance. The load shall be a dummy resistor as described in 5.3.4.

The cables L2 and L3 shall be as short as possible.

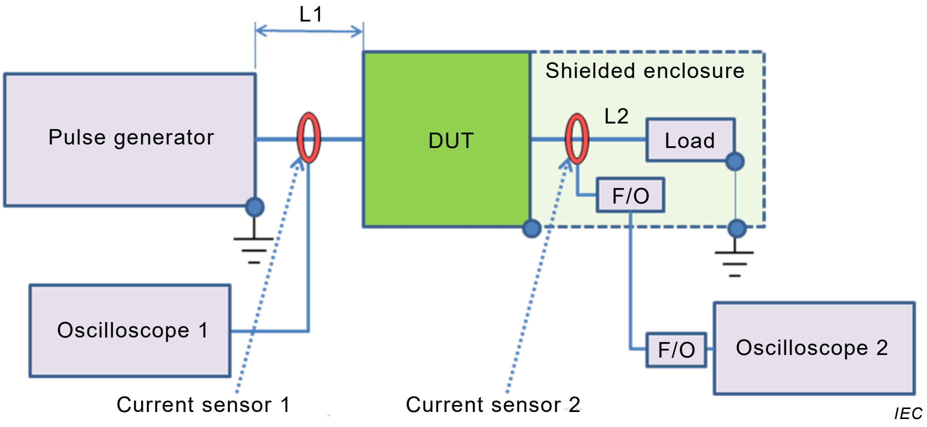
It may be necessary to shield the measurement instrument and to isolate the power supply to avoid interference due to ground loops.



If a voltage probe is used it should be connected across the load resistor.

[a] At least one of the two enclosures shall be shielded. Care should be taken to minimize radiated and conducted interference.

Figure 4 – Example of test setup using one or two shielded enclosures



F/O means fibre optic converter. Fibre links may be used as an option to provide a degree of isolation so that the pulse generator and oscilloscopes can be physically separated to minimize interference.

If pulse generator and injection cable L1 are not shielded, then oscilloscopes 1 and 2 should be in a shielded enclosure to avoid pick-up. Care should be taken to minimize radiated and conducted interference.

Figure 5 – Example of test setup using a shielded enclosure

5.3 Measurement instrument

5.3.1 Pulse generators

Short-circuit current is defined as current driven through a short-circuit connected to the generator output. Source impedance is defined as the generator peak open circuit voltage divided by the peak short-circuit current. The tolerance is ±10 %.

Pulse test requirements can be selected from Table 1 and Table 2, for early-time HEMP and intermediate-time HEMP respectively.

Table 1 – Overview of conducted early-time HEMP (CEP) test requirements defined in other specifications

Type	**Rise time**	**FWHM [a]**	**Source impedance [b]**	**Peak short-circuit current**	**Specifications**
CEP$_1$	< 10 ns	100 ns ±30 %	400 Ω ±15 Ω	4 000 A ±10 %	IEC 61000-2-10, 99 % severity for elevated conductor, for cable length longer than 200 m
CEP$_2$	< 10 ns	100 ns ±30 %	400 Ω ±15 Ω	1 500 A ±10 %	IEC 61000-2-10, 90 % severity for elevated conductor, for cable length longer than 200 m
CEP$_3$	< 10 ns	100 ns ±30 %	400 Ω ±15 Ω	500 A ±10 %	IEC 61000-2-10, 50 % severity for elevated conductor, for cable length longer than 200 m
CEP$_4$	< 25 ns	500 ns ±30 %	50 Ω ±5 Ω	400 A ±10 %	IEC 61000-2-10, for buried conductor in the ground conductivity of 10^{-4}, for cable length longer than 10 m
CEP$_5$	≤ 20 ns	500 ns +10 %	≥ 60 Ω	2 500 A ±10 %	According to [1][1], wire-to- ground
CEP$_6$	≤ 20 ns	500 ns +10 %	≥ 60 Ω	5 000 A ±10 %	According to [1], common-mode, under installed conditions only

[a] FWHM is an acronym for full-width at half-maximum (amplitude).

[b] In all cases, for practical reasons lower source impedance may be used. However the source impedance should not be less than typically 10 Ω to ensure that the applied pulse voltage is greater than the breakdown voltage of the non-linear components in the DUT.

Table 2 – Overview of conducted intermediate-time HEMP (CIP) test requirements defined in other specifications

Type	**Rise time**	**FWHM [a]**	**Source impedance [b]**	**Peak short-circuit current**	**Specifications [c]**
CEP$_1$	25 µs ±30 %	1 500 µs ±30 %	400 Ω ±15 Ω	600 A ±10 %	IEC 61000-2-10, for elevated conductors, for cable lengths longer than 1 km
CEP$_2$	25 µs ±30 %	1 500 µs ±30 %	400 Ω ±15 Ω	75 A ±10 %	IEC 61000-2-10, for elevated conductors, for cable lengths from 200 m to 1 km
CEP$_3$	25 µs ±30 %	1 500 µs ±30 %	50 Ω ±5 Ω	450 A ±10 %	IEC 61000-2-10, for buried conductors, for cable lengths longer than 1 km
CEP$_4$	25 µs ±30 %	1 500 µs ±30 %	50 Ω ±5 Ω	50 A ±10 %	IEC 61000-2-10, for buried conductors, for cable lengths from 200 m to 1 km
CEP$_5$	≤ 1,5 µs	3 000 µs to 5 000 µs	≥ 10 Ω	250 A ±10 %	According to [1], for cable lengths longer than 200 m

[a] FWHM is an acronym for full-width at half-maximum (amplitude).

[b] In all cases for practical reasons lower source impedance may be used. However the source impedance should not be less than typically 10 Ω to ensure that the applied pulse voltage is greater than the breakdown voltage of the non-linear components in the DUT.

[c] No test is required for line lengths shorter than 200 m.

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

The short-circuit current of the pulse generator has a double exponential waveform (see Figure 6).

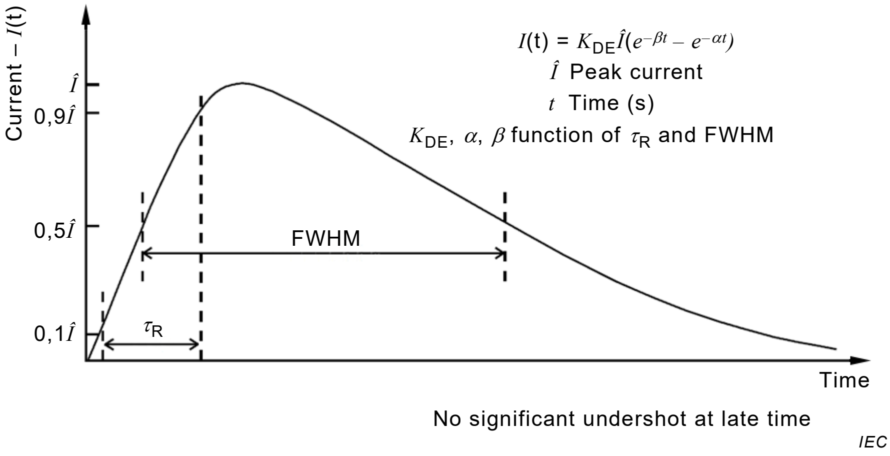


Figure 6 – Double exponential waveform

5.3.2 Oscilloscope

The bandwidth of the oscilloscope shall be wide enough to resolve the fastest rise time (< 10 ns, DC to > 100 MHz for the early-time HEMP and DC to > 1 MHz for the intermediate-time HEMP) and shall have minimum sensitivity as required for measurement sensitivity. The required input impedance of the scope amplifier depends on the type of voltage or current probe and shall be selected accordingly (typically 50 Ω or 1 MΩ).

5.3.3 Current sensors

The measurement bandwidth of the current sensors should cover the frequency range of 100 kHz to 100 MHz for the early-time HEMP and DC to 1 MHz for the intermediate pulse. The total measurement range in combination with the scope's vertical amplifier range shall be 0 A to 5 000 A for the early-time HEMP and 0 A to 250 A for the intermediate-time HEMP. For the measurement of currents to ground a resistive current shunt might give the most accurate results.

5.3.4 Test loads

During all tests a DUT test load according to the test mode and a DUT wiring setup as defined in Table 3 shall be used. The tolerance of the test load shall be ±10 % if not stated otherwise.

5.4 Test modes required

The test modes can be selected from the following list, depending on the application of the DUT. As a minimum, the nominal load mode(s) shall be performed.

- ETM1: Early-time HEMP / open-circuit
- ETM2: Early-time HEMP / nominal load
- ETM3: Early-time HEMP / short-circuit
- ITM1: Intermediate-time HEMP / open-circuit
- ITM2: Intermediate-time HEMP / nominal load
- ITM3: Intermediate-time HEMP / short-circuit

NOTE Test pulses can be selected from Table 1 and Table 2.

Since open-circuit measurements are difficult, a ≥ 1 MΩ load might be a good choice since typical voltage probes of oscilloscopes have a ≥ 1 MΩ input impedance.

Table 3 shows the test modes as required for different types of DUTs. The termination load impedances of the DUT for the early-time HEMP shall be chosen according to Table 3.

The DUT wiring setups (WSs) are as follows:

- WS1: Single line or multiple single lines DUT (see Figure 7)

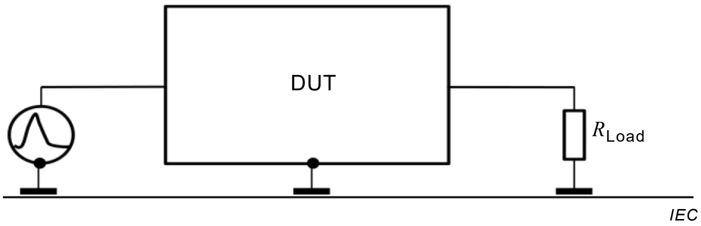


Figure 7 – Example of wiring setup of a single line DUT

- WS2: One example of a wiring setup for a mutually coupled or symmetric multi-line DUT (see Figure 8)

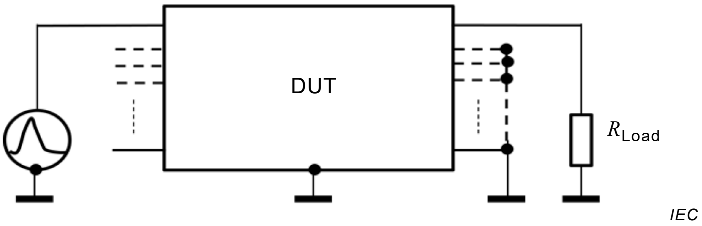


Figure 8 – Example of wiring setup for a mutually coupled multi-line DUT

WS2 is an example of wiring setup, which may be used for a multi-line DUT with lines which are coupled to each other either electrically or magnetically (e.g. by current-compensated inductors or if there are differential mode protection components). One line is tested at a time and the second and all other lines (dashed lines) are connected together at the output side and grounded. The lines that are not tested should remain open at the input side to avoid mutual coupling issues.

This setup is optional and other setups may be more applicable depending on the DUT circuit.

Table 3 – Test mode and DUT wiring setup

DUT application	Required test modes	Wiring setup	DUT load, R_{Load}
AC/DC power line	ETM1	WS 1/WS 2 [a]	Open circuit (≥ 1 MΩ)
	ETM2	WS 1/WS 2 [a]	2 Ω
	ETM3	WS 1/WS 2 [a]	Short-circuit (< 50 mΩ)
	ITM1	WS 1/WS 2 [a]	Open circuit (≥ 1 MΩ)
	ITM2	WS 1/WS 2 [a]	50 Ω
	ITM3	WS 1/WS 2 [a]	Short-circuit (< 50 mΩ)
Symmetric data line (Ethernet, etc.)	ETM1	WS 2	Open circuit (≥ 1 MΩ)
	ETM2	WS 2	50 Ω
	ETM3	WS 2	Short-circuit (< 50 mΩ)
	ITM1	WS 2	Open circuit (≥ 1 MΩ)
	ITM2	WS 2	50 Ω
	ITM3	WS 2	Short-circuit (< 50 mΩ)
Non-symmetric or individual data/signal/control/audio line	ETM1	WS 1	Open circuit (≥ 1 MΩ)
	ETM2	WS 1	50 Ω
	ETM3	WS 1	Short-circuit (< 50 mΩ)
Coaxial line	ETM2	WS 1	50 Ω (or coax-cable impedance)
	ITM2	WS 1	50 Ω (or coax-cable impedance)

[a] Depending on the DUT design, either WS1 or WS2 shall be applied. The 2 Ω load has been defined in MIL-STD-188-125-1 for power lines. Short-circuit and open-circuit load conditions are optional, therefore no requirement is defined in this standard.

5.5 Measurement procedure

5.5.1 General

To minimize the possibility of DUT damage, a series of pulses at increasing amplitudes shall be applied for all applicable test modes ETM1 to ETM3 and ITM1 to ITM3.

CAUTION: The DUT may have limited pulse life. It should be checked for degradation before using in service or further test.

5.5.2 Verification of pulses

Perform the verification of the test level with 10 %, 20 %, 40 %, 80 % and 100 % of the maximum test current (see Figure 3) and record the verified levels, the charging voltage and generators settings required to achieve these test levels.

NOTE The amplitude of 10 % and 20 % of the maximum test level may not be possible for certain pulse generators.

5.5.3 Measurement procedure

The measurement procedures shall be as follows:

a) Set up a DUT and measurement instruments according to 5.2.

b) Set up the test circuit configuration in the desired test modes (see 5.4).

c) Inject a pulse into the DUT with the verified generator charging voltages in 5.5.2.

d) Record the measurement results of the residual waveform. Either the current waveform or voltage waveform shall be measured.

e) Compare the results to the performance criteria (see 5.6).

5.6 Evaluation of test results

The pass/fail results shall be classified in terms of the peak current or voltage, the peak rate of rise and root action at the output of a HEMP combination filter. The required performance criteria are given in Table 4, Table 5 and Table 6 for the early-time HEMP test.

Table 4 – Performance criteria of filter against early-time HEMP – AC power port with nominal load 2 Ω

Severity Level	**Protection Concepts**	**Peak residual current or voltage**		**Peak rate of rise**	**Root action**
		I_{Load}, A	U_{Load}, V	A/s	$A\sqrt{s}$
Level 1	IEC 61000-6-2 (industrial)	$U_{\text{Load}} / R_{\text{Load}}$	$2 \cdot \hat{U}_{\text{Nom}}$ [a]	2×10^{8}	3,2
Level 2	Critical infrastructures	50	100	5×10^{7}	$8{,}0 \times 10^{-1}$
Level 3	Special case (Mil-Std-188-125-1)	10	20	10^{7}	$1{,}6 \times 10^{-1}$
Level X	User defined	UD [b]	UD	UD	UD

[a] $\hat{U}_{\text{Nom}}$ is the peak value of the nominal operating voltage.

[b] UD means “user defined”.

Table 5 – Performance criteria of filter against early-time HEMP – DC power port with nominal load 2 Ω

Severity Level	**Protection Concepts**	**Peak residual current or voltage**		**Peak rate of rise**	**Root action**
		I_{Load}, A	U_{Load}, V	A/s	$A\sqrt{s}$
Level 1	IEC 61000-6-2 (industrial)	$U_{\text{Load}} / R_{\text{Load}}$	$\hat{U}_{\text{Nom}}$ [a]	2×10^{8}	3,2
Level 2	Critical infrastructures	50	100	5×10^{7}	$8{,}0 \times 10^{-1}$
Level 3	Special case (Mil-Std-188-125-1)	ND [b]	ND	ND	ND
Level X	User defined	UD [c]	UD	UD	UD

[a] $\hat{U}_{\text{Nom}}$ is the peak value of the nominal operating voltage.

[b] ND means that a value is not defined within the protection concept reference.

[c] UD means “user defined”.

Table 6 – Performance criteria of filter against early-time HEMP – Signal, data and control port with nominal load 50 Ω

Severity Level	Protection Concepts	Peak residual current or voltage		Peak rate of rise	Root action
		I_{Load}, A	U_{Load}, V	A/s	$A\sqrt{s}$
Level 1	IEC 61000-6-2 (industrial)	$U_{\text{Load}}/R_{\text{Load}}$	$\hat{U}_{\text{Nom}}$ [a]	2×10^{8}	$3{,}2 \times 10^{-1}$
Level 2	Critical infrastructures	1	50	5×10^{7}	$8{,}0 \times 10^{-2}$
Level 3	Special case (Mil-Std-188-125-1)	0,1[b] 1[c]	5[b] 50 [c]	10^{7}	$1{,}6 \times 10^{-3}$ [b] $1{,}6 \times 10^{-2}$ [c]
Level X	User defined	UD [d]	UD	UD	UD

[a] $\hat{U}_{\text{Nom}}$ is the peak value of the nominal operating voltage.

[b] Applies to the device with an operating voltage less than 90 V.

[c] Applies to the device with an operating voltage of 90 V and greater.

[d] UD means “user defined”.

For the intermediate-time HEMP test, residuals are not defined. However the test shall be performed to ensure that the HEMP combination filter is not damaged during the test. This shall be checked by ensuring that the HEMP combination filter operates normally after the test.

5.7 Test report

For each step in the testing sequence, the following parameters should be included in the test report:

a) Waveform, peak current and source impedance of verified pulse.
b) Test mode, wiring set up (including connection diagram if different from examples given).
c) Test load resistance.
d) Peak current or voltage of residual pulse.
e) Measured waveform of residual pulse.
f) Maximum di/dt, and root integral of residual pulse, if required.
g) Comparison of results with required performance criteria.

The total number of pulses applied to the DUT during the test sequence should be recorded.

6 Measurement method of HEMP protectors for RF antenna ports

6.1 General

For the early-time HEMP, the high-amplitude electric field couples efficiently to antennas which are used within the frequency spectrum of HEMP. The HEMP coupling into the antenna is called front-door coupling. The antenna coupling mechanism is extremely variable and dependent on the details of the antenna design. The near worst-case peak response of a vertical electric monopole to the HEMP early-time waveform is considered for the test level for RF antenna ports. The waveforms for the conducted environments at antenna ports are damped sinusoids with a frequency approximately equal to the designed dominant response frequency f_{c} of the antenna.

6.2 Test level and injection waveform specification

Table 7 – Pulsed current injection test level for RF antenna ports

Type of Injection	Dominant response frequency f_c, MHz	Peak current injection [a] test level, A	Injection waveform	Rise time ns	FWHM ns
Inner conductor to outer shield	≤ 30	1 200	[b] Double exponential	Refer to Table 1	Refer to Table 1
	[c] $30 < f_c \leq 1\ 000$	$36\ 000/f_c$, in MHz	Damped sinusoidal	3 ± 2	30 ± 20

[a] The test level in the current is measured with the condition of short-circuit of the output of the generator.

[b] Double exponential waveform of conducted early-time HEMP shown in Table 1.

[c] Above 1 GHz, the HEMP requirement is under consideration.

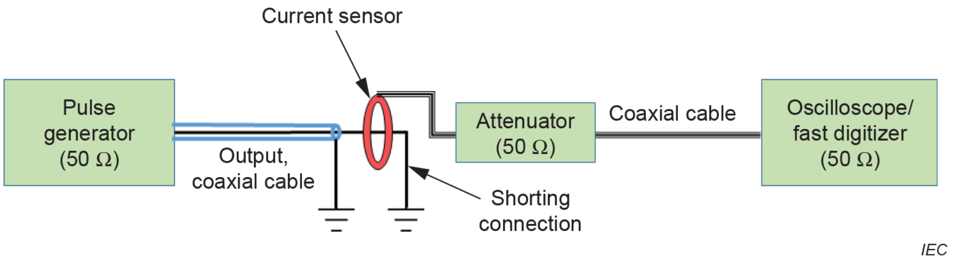
The early-time HEMP double exponential waveform shall be used for antenna port testing at a dominant response frequency ≤ 30 MHz. The double exponential generator is used because most of the energy content of early time HEMP is below 30 MHz. The double exponential generator specified in Table 1 is needed to reach the peak test level.

A damped sinusoidal waveform shall be used for antenna port testing when its dominant response frequency is 30 MHz $\leq f \leq$ 1 000 MHz. A recommended waveform is provided in IEC 61000-2-10:2021, Annex E. If the required current injection level exceeds the damped sinusoidal pulse generator capability, an early-time HEMP double exponential waveform shall be used.

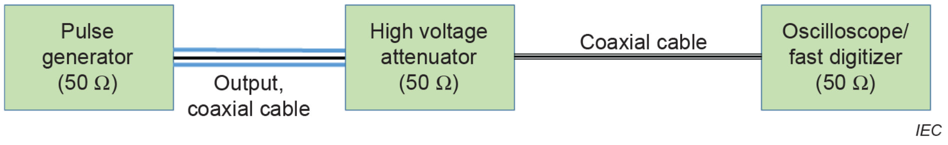
If the output voltage of a damped sinusoidal pulse generator is measured instead of short-circuit current, the test level voltage shall be determined by multiplying the required current test level, specified in Table 7, with the antenna load impedance (usually 50 Ω).

6.3 Verification of test level

The configuration for test level verification is shown in Figure 9.



(a) Configuration of verification for short-circuit current test level



(b) Configuration of verification for test level in voltage

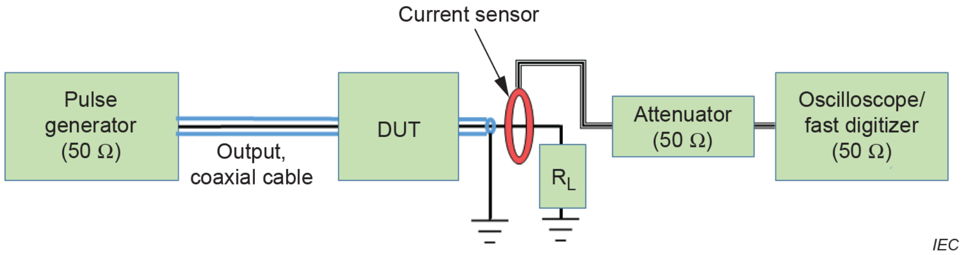
Figure 9 – Typical verification setup

Parasitic coupling between the pulse generator and the oscilloscope shall be avoided. It is recommended to use cables with multiple braided wire shields or solid shields. The cable and connectors shall be capable of withstanding the high voltage pulse without a breakdown. The shorting connection shall be as short as possible.

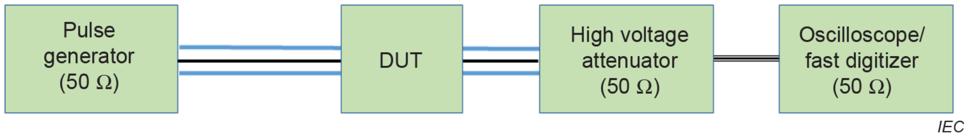
Perform the verification of the test level with 10 %, 25 %, 50 % and 100 % of the maximum test current and record the verified levels, the charging voltage and settings of the pulse generator required to achieve these test levels.

6.4 Measurement procedure

The measurement setup is shown in Figure 10.



(a) Setup for current measurement at DUT output with a 50 Ω resistive load (R_L)



(b) Setup for voltage measurement at DUT output

Figure 10 – Typical measurement setup

The measurement procedures shall be as follows:

a) Set up the DUT and measurement instruments as shown in Figure 10.
b) Inject a pulse three times into the DUT with the generator charging voltages verified in 6.3.
c) Record the measurement results of the DUT output waveform. Either the current waveform or voltage waveform shall be measured.
d) Compare the results to the performance criteria (see 6.5).

6.5 Evaluation of test results

The pass/fail results shall be classified in terms of the peak current or voltage at the output of a HEMP protector for an RF antenna. The required performance criteria are given in Table 8 for the early-time HEMP test.

Table 8 – Performance criteria of filters against early-time HEMP – RF antenna ports

RF antenna port mode	Peak residual norms	
	I_{Load}, A	U_{Load}, V
For receive only systems	< 0,5	$I_{\text{Load}} \times R_L$

The test shall be performed to ensure that the DUT is not damaged during the test. This shall be checked by ensuring that the DUT operates normally after the test.

In general, the manufacturer of the DUT shall specify the peak residual voltage and the residual energy into the nominal load. These values have to be compared with the immunity levels of the device to be protected (receiver, transmitter, antenna matching unit etc). Refer to Annex C.

6.6 Test report

For each step in the testing sequence, the following parameters should be included in the test report:

a) waveform, peak current and source impedance of verified pulses;

b) test mode;

c) test load resistance;

d) peak current or voltage of residual pulses;

e) measured waveforms of residual pulses;

f) comparison of results with immunity levels of equipment to be protected;

g) performance of additional tests with equipment to be protected as a load to verify proper protection.

Annex A
(informative)

Investigation for the establishment of a measurement setup

A.1 General

With the measurement setup some variations were investigated for improvement of the repeatability and reproducibility of the measurement result. Annex A summarises this investigation to illustrate the sensitivity of the test procedure to the test setup.

A.2 Variation of the cable connected for the measurement of short-circuit current

The output of the pulse generator shall be calibrated prior to applying a pulse to a protective device. The setup for calibration is illustrated in Figure A.1.

For the calibration of the short-circuit current waveform, the output of the pulse generator shall be shorted to the ground of the generator through a cable, L1. The current on the cable shall be measured using a current sensor and an oscilloscope.

It was investigated how the wave shape is affected by the variation of the size and the length of the cable. Measurements were performed with the cables having a cross-section of 9 mm^2 and 4 mm^2, and varying the length of the cable L1 as follows: 0,2 m, 0,3 m, 0,4 m, 0,5 m, 0,6 m, 0,7 m, 0,8 m, 0,9 m, 1,0 m, 1,2 m, 1,4 m, 1,6 m, 1,8 m and 2,0 m.

The measurement results are shown in Table A.1 and Figure A.2 to Figure A.7.

It was concluded that cable L1 for the waveform calibration of short-circuit current shall be as thick and short as possible. It is recommended that the cable L1 shall have a cross-section of 4 mm^2 or more and a length of 0,8 m or less. The cable L1 used in calibration shall be also used in the measurement setup.

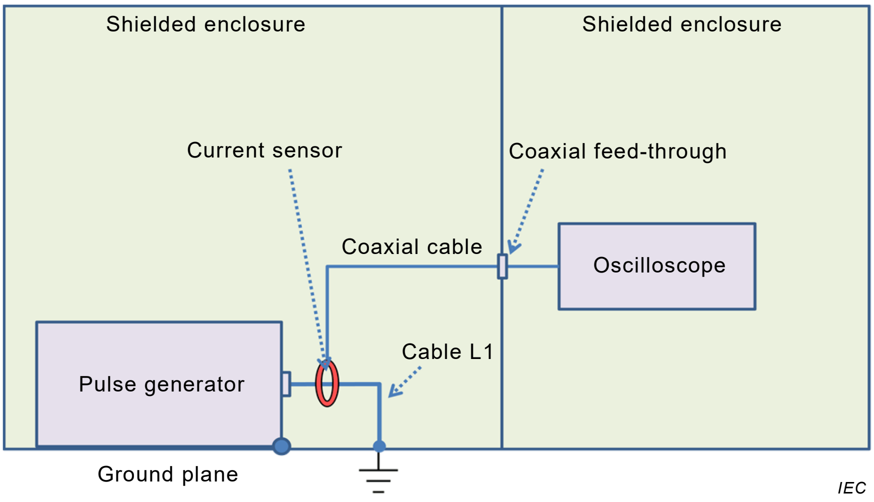


Figure A.1 – Setup for calibration

Table A.1 – Measurement results for the waveform calibration of short-circuit current

Cross-section, 9 mm^2				Cross-section, 4 mm^2		
L1, m	**Peak current,** A	**Rise time, (< 20 ns)**	**FWHM, (500 ns~ 550 ns)**	**Peak current,** A	**Rise time, (< 20 ns)**	**FWHM, (500 ns ~ 550 ns)**
0,2	1 040,0	12,1	505,8	1 005,0	12,6	497,8
0,3	1 049,0	12,6	525,2	999,6	13,8	506,5
0,4	1 004,8	16,0	525,8	1 030,0	14,4	522,3
0,5	991,4	16,5	521,9	981,4	17,1	532,8
0,6	987,8	17,7	531,6	1 000,4	17,5	531,1
0,7	985,2	19,1	539,9	978,4	18,3	536,8
0,8	973,2	20,1	544,6	989,6	19,0	546,4
0,9	1 001,4	20,6	549,5	964,6	22,4	555,0
1,0	983,2	20,9	544,7	960,0	23,1	552,1
1,2	1002,0	21,4	546,1	959,2	21,7	547,2
1,4	985,0	31,9	564,8	952,2	25,2	563,5
1,6	959,6	23,5	564,8	948,8	32,6	571,9
1,8	969,4	28,8	566,4	937,2	35,8	579,0
2,0	982,6	39,1	582,1	927,0	41,7	585,4

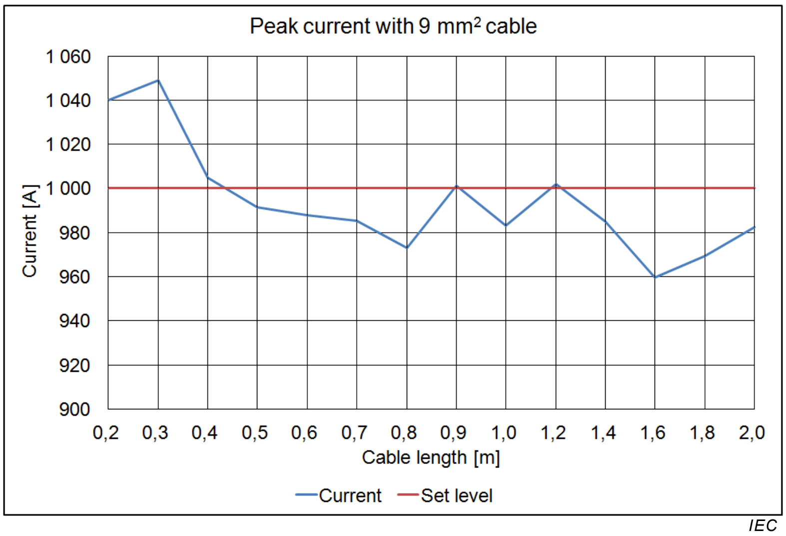


Figure A.2 – Peak current calibration results with 9 mm^2 cables: 1 000 A ± 4 %

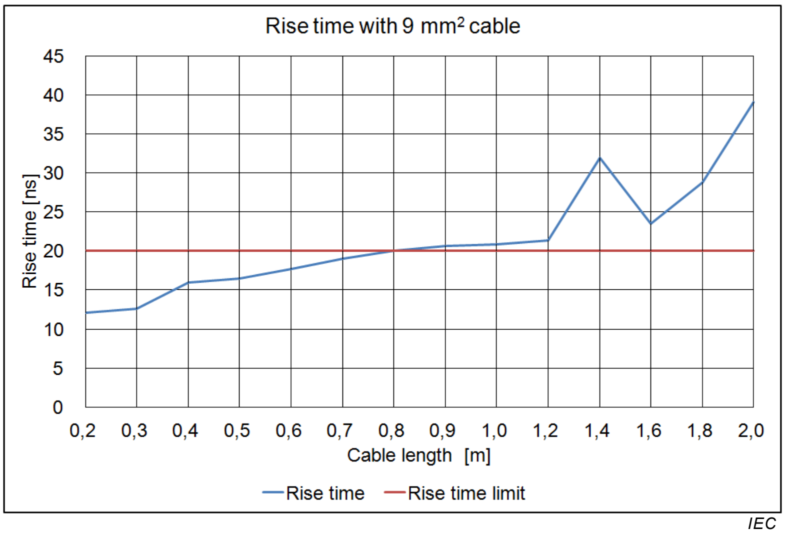


Figure A.3 – Rise time calibration results with 9 mm^2 cables

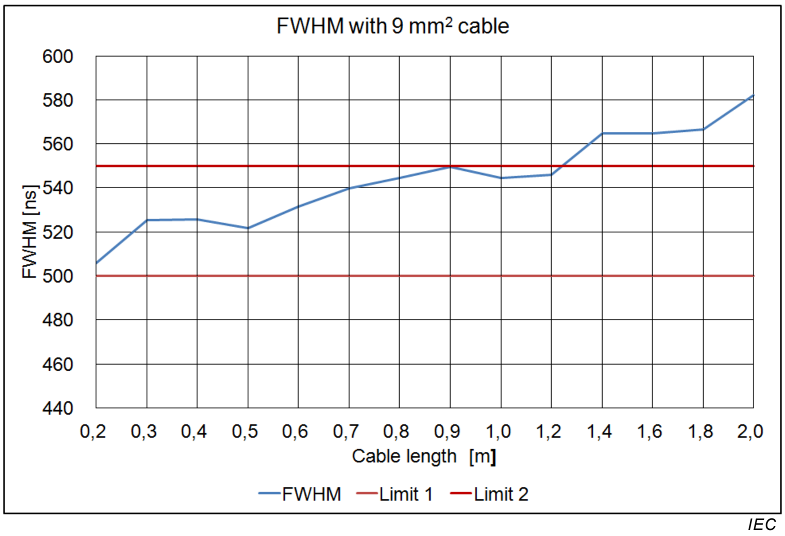


Figure A.4 – FWHM calibration results with 9 mm^2 cables

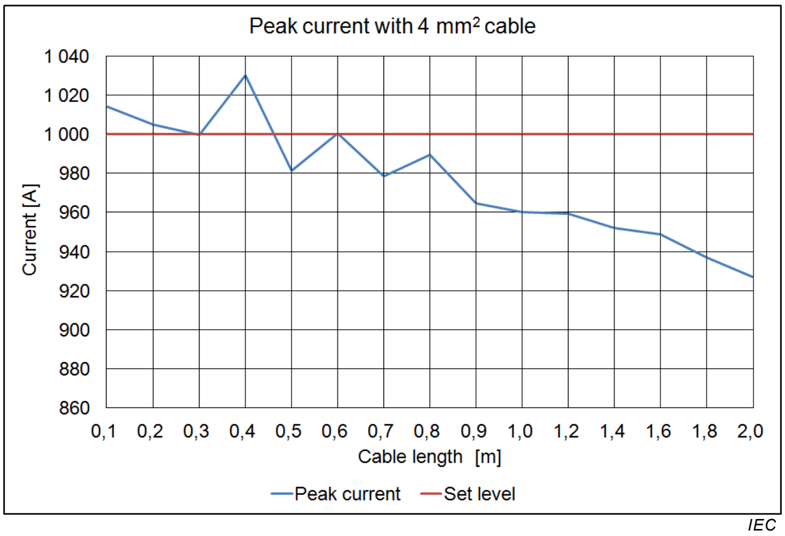


Figure A.5 – Peak current calibration results with 4 mm^2 cables: 1 000 A ± 8 %

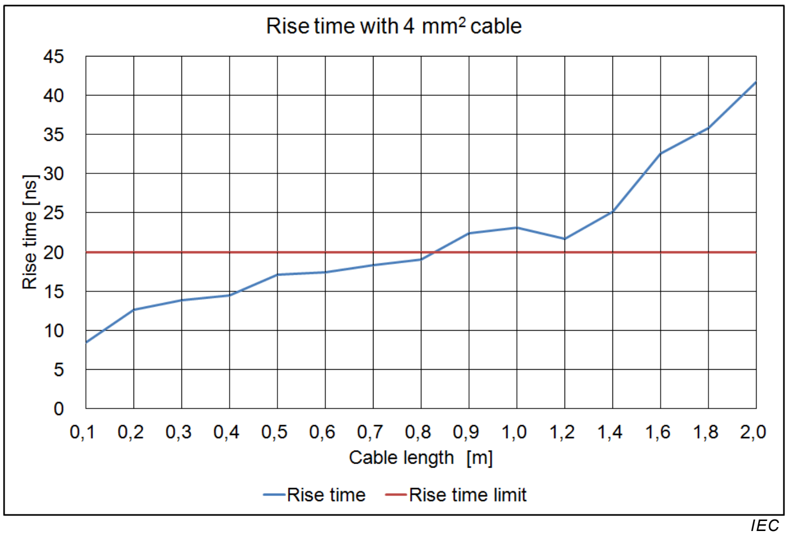


Figure A.6 – Rise time calibration results with 4 mm^2 cables

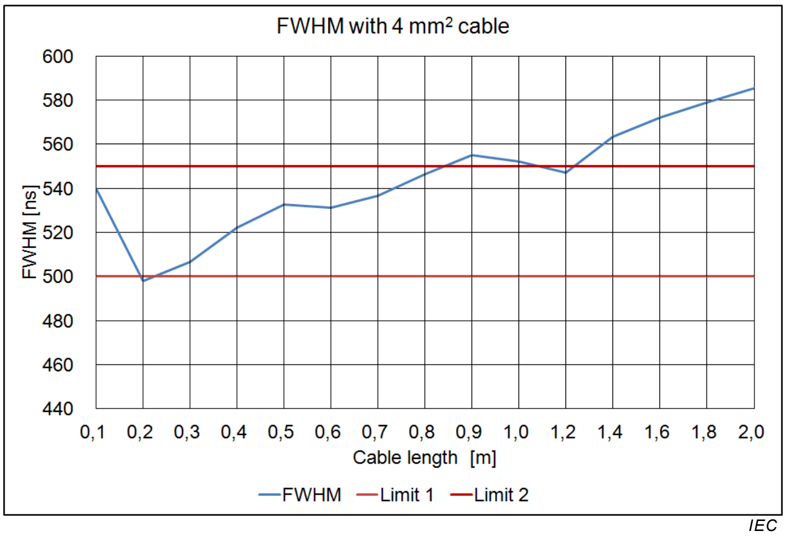


Figure A.7 – FWHM calibration results with 4 mm^2 cables

A.3 Variation of the length of the cable L2 connected for the measurement of residual current

The setup for the residual current measurement is shown in Figure A.8. Residual current is measured on the cable L2 at the output of the protective device using current sensor 2 when a pulse is injected to the input of the protective device.

It is generally required to measure the peak current, peak rate of rise and root action of the residual current waveform when the protective device performance is measured.

It was investigated how the wave shape is affected by the variation of the cable length L2.

A short pulse of 1 kA current is injected to a HEMP combination filter using a 0,4 m cable L1; the measurement was performed with the cables having a cross-section of 4 mm^2, and varying the length of the cable L2 as follows: 0,2 m, 0,3 m, 0,4 m, 0,5 m, 0,6 m, 0,7 m, 0,8 m, 0,9 m and 1,0 m. In this case, the load impedance was 2 Ω.

The measurement results are shown in Table A.2 and Figure A.9 to Figure A.11.

It was concluded that the length of cable L2 for residual current measurement was not so much affected with the variation of the length in this measurement, because the rise time of the residual current was already slowed by the action of the protective device.

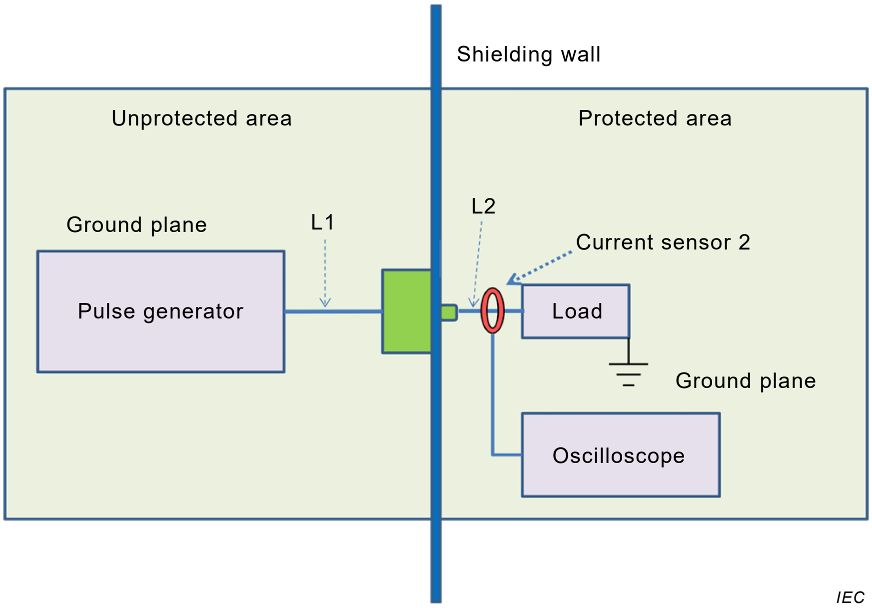


Figure A.8 – Measurement setup for residual current

Table A.2 – Measurement results for variation of the cable length at the measurement points

Cross-section, 4 mm^2						
L2, m	Measurement results			Limit		
	Peak current A	Peak rate of rise	Root action	Peak current A	Peak rate of rise	Root action
0,2	0,45	9,0 × 10^4	1,85 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
0,3	0,45	8,5 × 10^4	1,85 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
0,4	0,44	8,5 × 10^4	1,80 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
0,5	0,44	8,5 × 10^4	1,84 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
0,6	0,42	9,0 × 10^4	1,75 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
0,7	0,46	9,0 × 10^4	1,89 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
0,8	0,44	9,0 × 10^4	1,82 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
0,9	0,44	9,0 × 10^4	1,82 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
1,0	0,46	9,0 × 10^4	1,92 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
2,0	0,43	8,5 × 10^4	1,81 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}
3,7	0,45	8,5 × 10^4	1,95 × 10^{-3}	≤ 10	≤ 1,0 × 10^7	≤ 1,6 × 10^{-1}

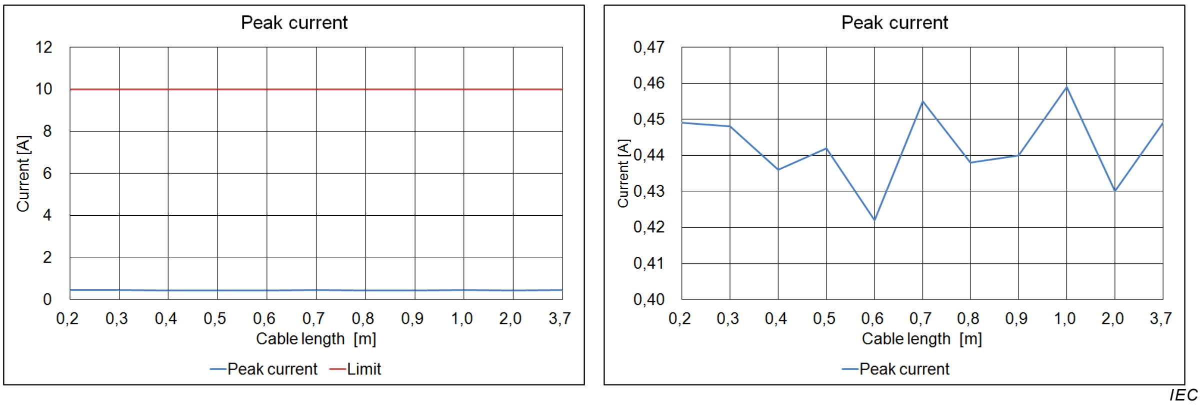


Figure A.9 – Measurement result of peak current with variation of measurement cable L2

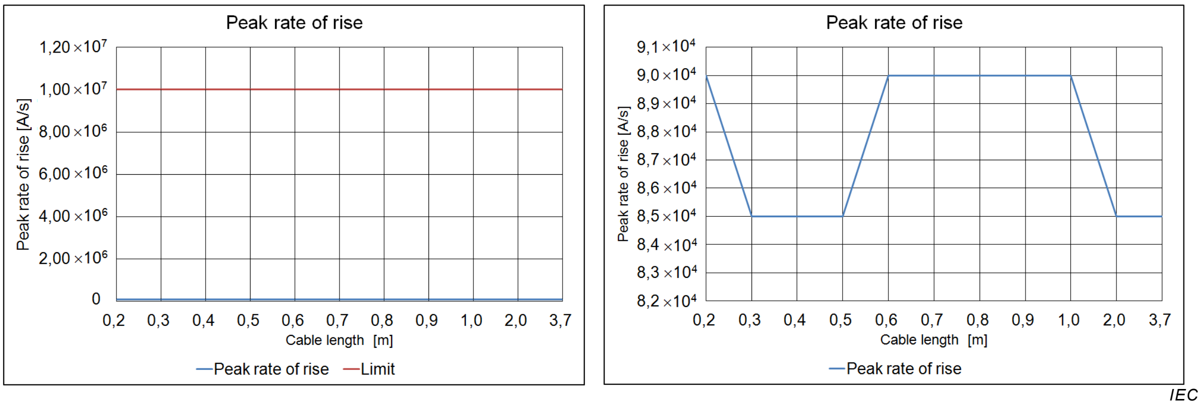


Figure A.10 – Measurement result of peak rate of rise with variation of measurement cable L2

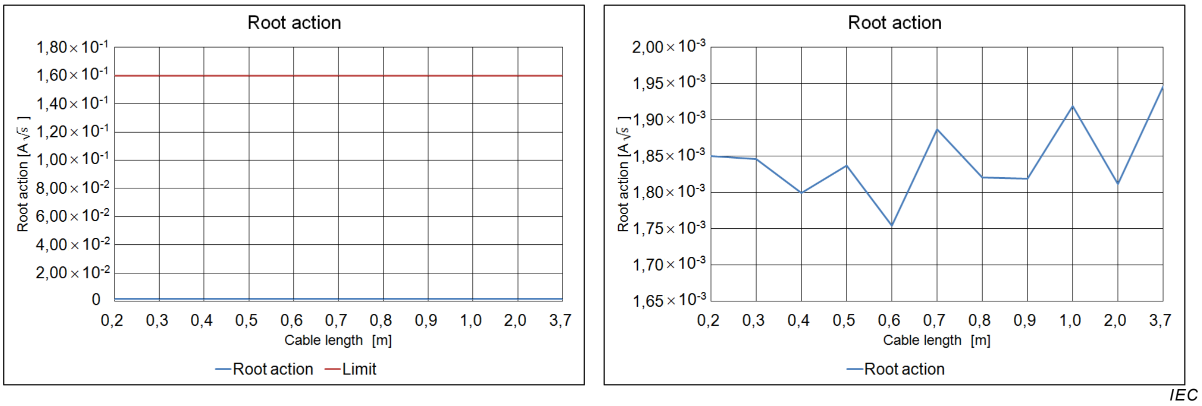


Figure A.11 – Measurement result of root action with variation of measurement cable L2

In addition, the measurement was performed with the three different positions as follows (see Figure A.12):

- Position 1: current sensor 2 is at the terminal side of the output (protected area) of a protective device.
- Position 2: current sensor 2 is at the middle point of the cable L2, which is different depending on the cable length.
- Position 3: current sensor 2 is at the end of the cable at load side.

Measurement results are shown in Figure A.13 to Figure A.15.

It was concluded that the positions of current sensor 2 for residual current measurement were not so much affected by the measurement results, because the rise time of the residual current was already slowed by the action of the protective device. Therefore, it is recommended that current sensor 2 shall be placed within 0,15 m from the output terminal (protected area) of the protective device.

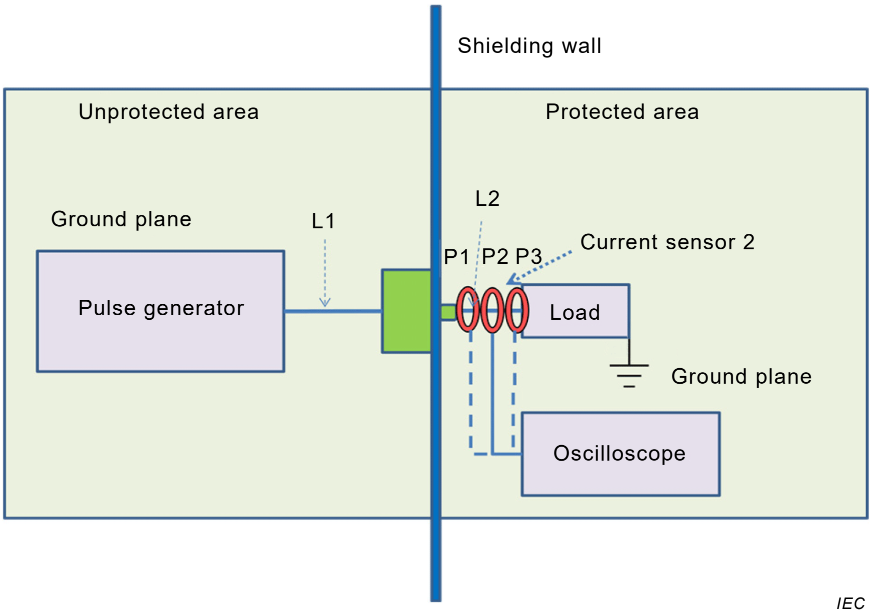


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Figure A.12 – Variation of the position of current sensor 2 on the measurement cable L2

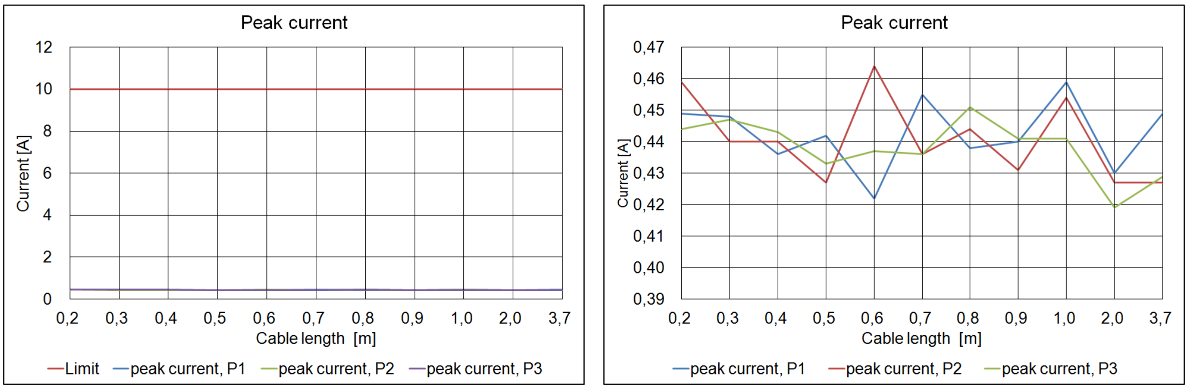

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Figure A.13 – Peak current with variation of cable L2 and at different positions

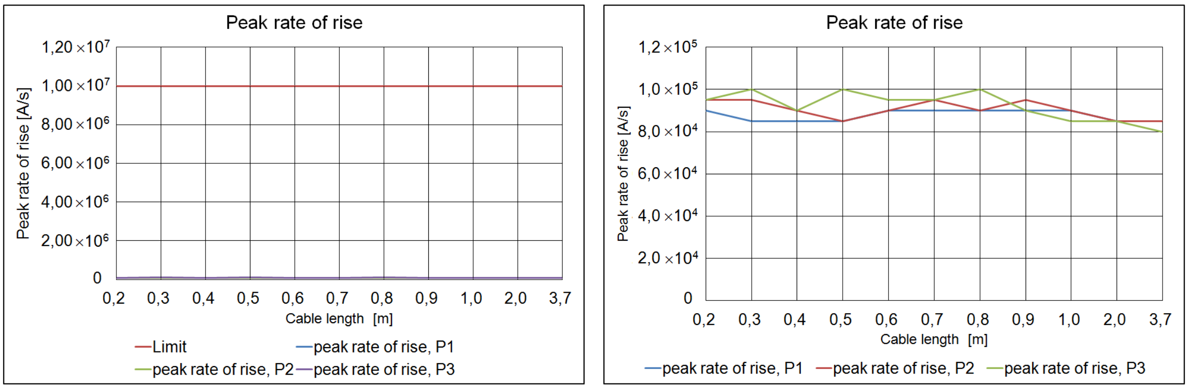

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Figure A.14 – Peak rate of rise with variation of cable L2 and at different positions

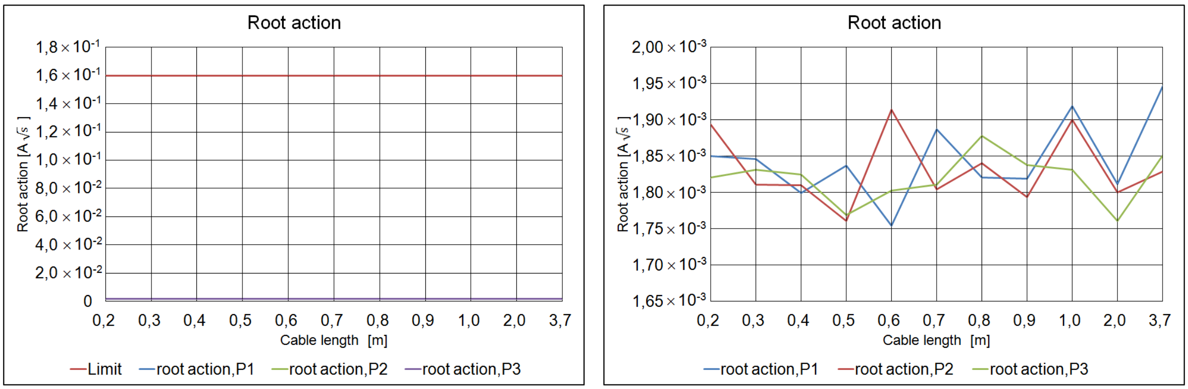

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Figure A.15 – Root action with variation of cable L2 and at different positions

A.4 Variation of load impedance and cable length for connection between load and ground

For the measurement setup (see Figure A.8), the measurement results of a variation of load impedance are shown in Table A.3 and Figure A.16 to Figure A.18.

It was concluded that increasing the load impedance for residual current measurement could reduce the measurement dynamic range. Therefore, it is recommended that load impedance for the measurement of residual current is low. In this case, the voltage measurement is possible for the residual current with the voltage probe at the defined load impedance. The measured voltage can be converted to current.

Table A.3 – Measurement results for variation of the load impedance

Cross-section, 4 mm^2							
Load	Measurement results				Limit		
	Peak current A	Calculated voltage V	Peak rate of rise	Root action	Peak current A	Peak rate of rise	Root action
5 Ω	0,16	0,78	$1,3 \times 10^4$	$1,1 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
10 Ω	0,09	0,86	$6,3 \times 10^3$	$7,7 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
20 Ω	0,05	0,96	$2,5 \times 10^3$	$5,6 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
30 Ω	0,03	0,94	$1,7 \times 10^3$	$4,1 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
35 Ω	0,03	0,95	$1,4 \times 10^3$	$3,7 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$

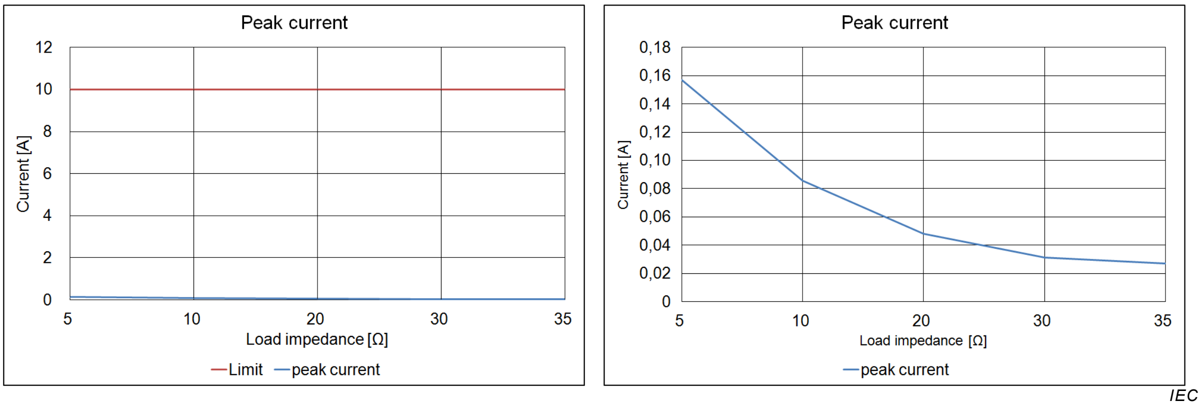


Figure A.16 – Measurement result of peak current with variation of load impedance.

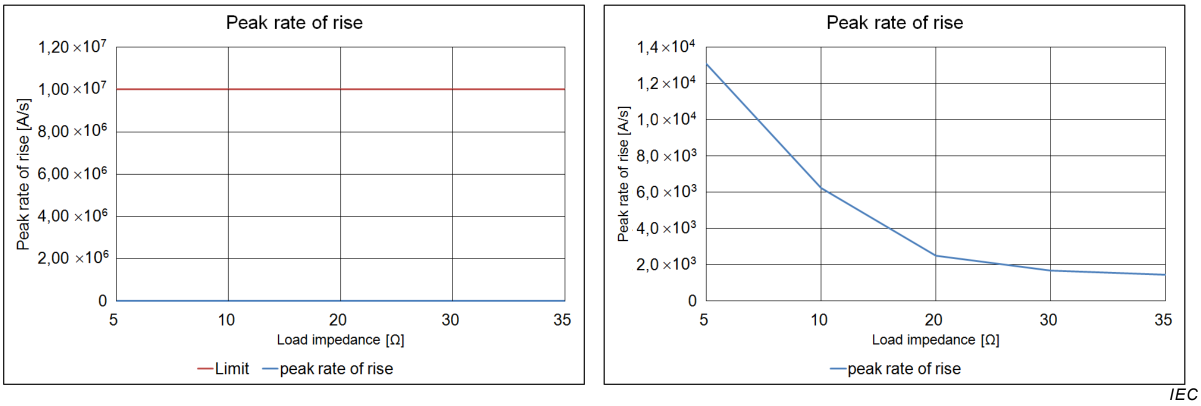


Figure A.17 – Measurement result of peak rate of rise with variation of load impedance

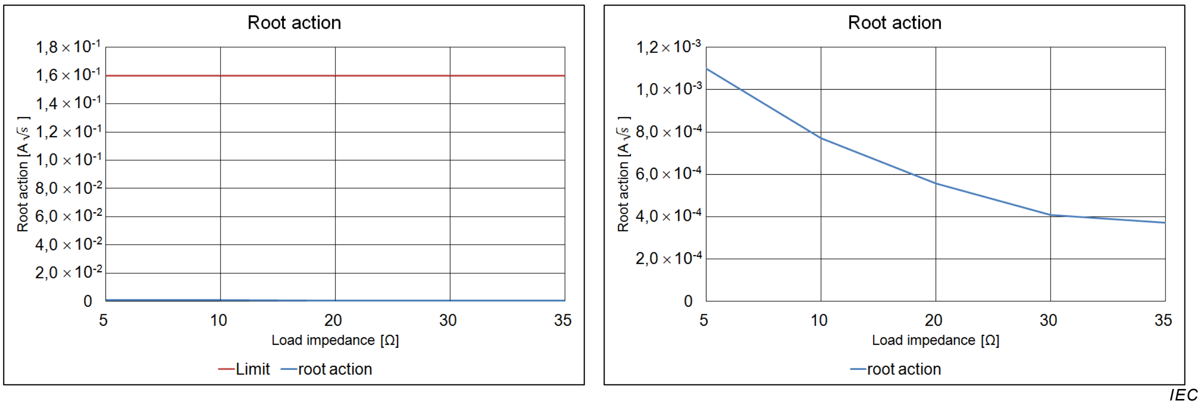


Figure A.18 – Measurement result of root action with variation of load impedance.

A.5 Variation of the cable length between load and ground

Measurement setup of the variation of the cable length L3 between load and ground is shown in Figure A.19.

The measurement results are shown in Table A.4 and Figure A.20 to Figure A.22.

It was concluded that the length of cable (L3) connected between load and ground plane for residual current measurement was not so much affected with the variation of the length in this measurement, because the rise time of the residual current was already slowed by the action of the protective device.

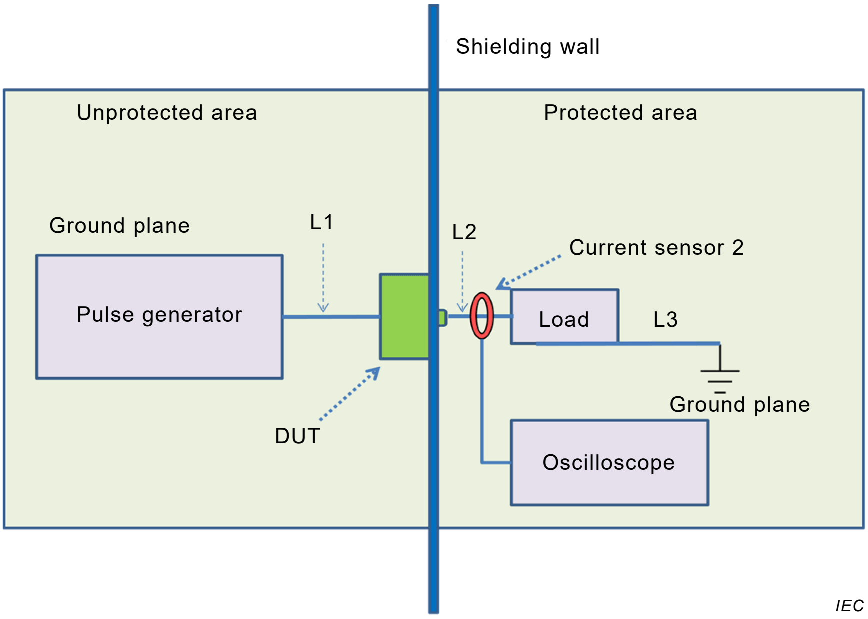


Figure A.19 – Variation of the length of cable L3 connected between load and ground plane

Table A.4 – Measurement results for variation of the cable length between load and ground

Cross-section, 4 mm^2						
L3, m	**Measurement results**			**Limit**		
	Peak current, A	**Peak rate of rise,**	**Root action**	**Peak current,** A	**Peak rate of rise**	**Root action**
0,1	0,027	$1,4 \times 10^{3}$	$3,7 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$
0,2	0,027	$1,6 \times 10^{3}$	$3,7 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$
0,3	0,026	$1,5 \times 10^{3}$	$3,6 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$
0,4	0,027	$1,4 \times 10^{3}$	$3,6 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$
0,5	0,026	$1,4 \times 10^{3}$	$3,5 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$

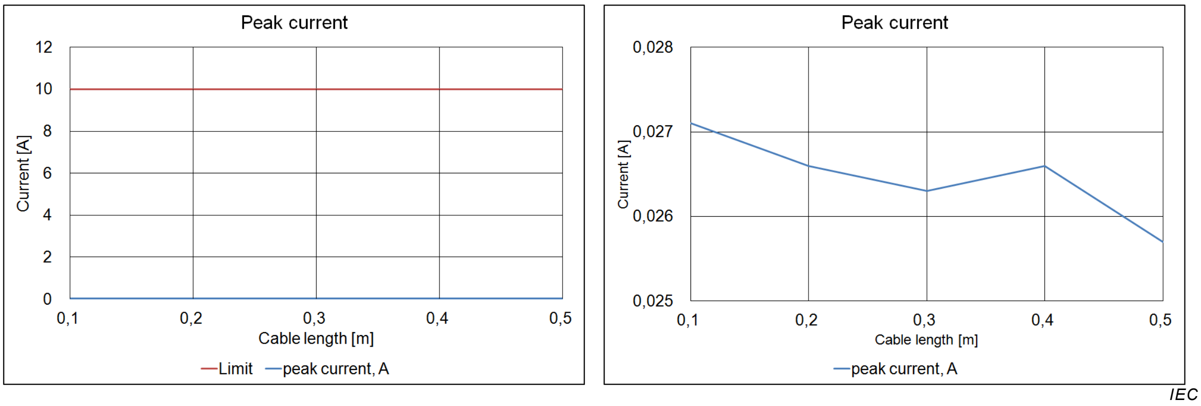


Figure A.20 – Measurement result of peak current with variation of measurement cable L3

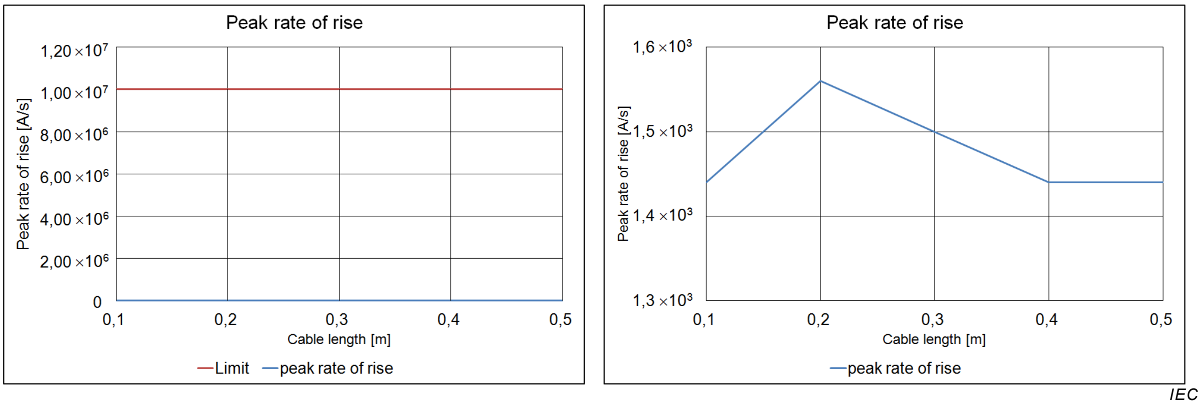


Figure A.21 – Measurement result of peak rate of rise with variation of measurement cable L3

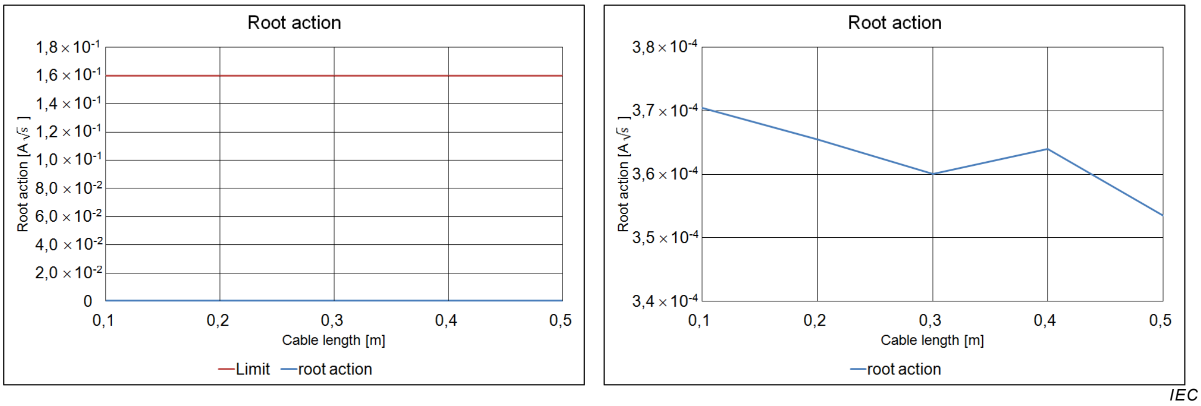


Figure A.22 – Measurement result of root action with variation of measurement cable L3

Annex B
(informative)

Test method for the quantitative determination of the direct response behaviours of a coaxial surge protector

Annex B provides a practical method to obtain the direct response behaviours of a surge protective device (SPD), especially the coaxial type protector, and of a voltage breakdown device, for example a gas discharge tube (GDT). This method covers the residual voltage measurement, the response time measurement and the direct voltage-limiting response behaviour flowing through an SPD in the time domain.

The test setup consists of a pulse generator, launching line, wide-band power divider, attenuators, oscilloscope and coaxial cables as shown in Figure B.1.

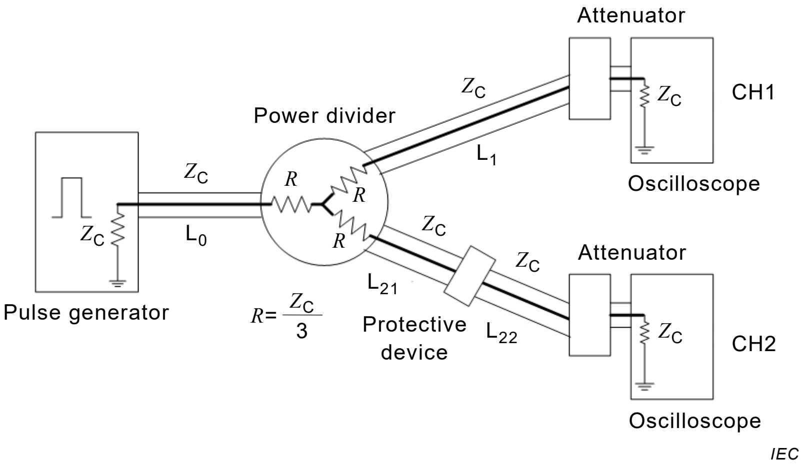


Figure B.1 – Test setup with a power divider for testing protective devices

The launching line is connected to the power divider, and the DUT is connected to one of the circuit branches of a power divider.

A power divider is used to match the impedance at each branch circuit in order to keep the same surge impedance along the direction of the propagating wave. Cables, attenuators and termination loads in the test setup are well matched. The power divider should be designed to avoid breakdown and to confirm the accuracy of the resistances inside the power divider to mitigate symmetric error.

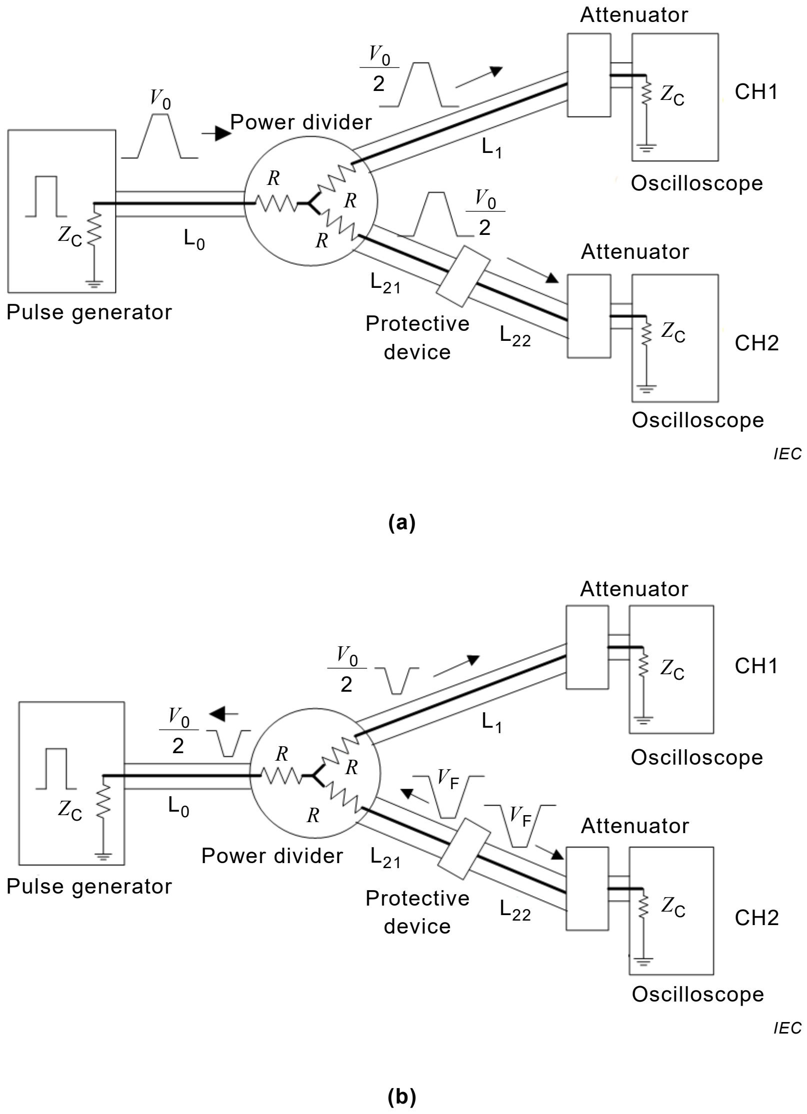
The three branches are the launching branch (L_0), the normal branch (L_1) and the DUT branch (L_2), respectively. The characteristic impedance of each branch is equal to Z_c, for example 50 Ω or 75 Ω.

One has to be aware of the following aspects:

- In order to match the forward and backward travelling wave propagating along the cables, the terminal loads of each branch should also be equal to Z_c and the value of each resistance inside the power divider should be $\frac{Z_c}{3}$.
- It is reasonable to neglect the waveform distortion due to the propagation along the branch cable since the length of the cable is sufficiently short.

The waveform at the terminal of the normal branch and the DUT branch should be recorded by two channels of the same oscilloscope.

Figure B.2 shows V_0 (before the surge arrester firing) and V_F (after the surge arrester firing) propagating along the branches.



(a)

(b)

Figure B.2 – Waves propagating along the branches

The measured waveforms at each branch terminal are shown as follows:

- Normal branch:

$$V_{CH1}(t) = \frac{1}{A} \cdot \left[\frac{V_0(t - \tau_{L0} - \tau_{L1})}{2} + \frac{V_0(t - \tau_{L21} - \tau_{L1})}{2} \right] \quad \text{(B.1)}$$

- DUT branch:

$$V_{CH2}(t) = \frac{1}{A} \cdot \left[\frac{V_0(t - \tau_{L0} - \tau_{L21} - \tau_{L22})}{2} + V_F(t - \tau_{L22}) \right] \quad \text{(B.2)}$$

where A is the attenuation factor of the attenuator, $A = \frac{V_{\text{in}}}{V_{\text{out}}}$ (for a commercial attenuator, the attenuation factor is usually given in decibels, thus conversion to a ratio is essential), and τ_{L0} τ_{L1} τ_{L21} τ_{L22} stand for the time delays on the corresponding coaxial cable. Notice that if the dimension of the DUT or the power divider is not negligible, the time delay within the devices should be taken into consideration as well.

One can directly get the response time of the SPDs by comparing the two measured waveforms. Moreover, by solving the equation set (B.1) and (B.2), we can obtain the output pulse of generator $V_0(t)$, the applied pulse on the DUT $\frac{V_0(t)}{2}$ and the induced pulse $V_{\text{F}}(t)$ which is the direct response behaviour flowing through the SPD in the time domain.

For practical applications, a simplified test setup could be applied when the dimension of the power divider or the DUT is small enough to neglect the time delay when the wave propagates through these devices. Figure B.3 shows the simplified test setup for this case.

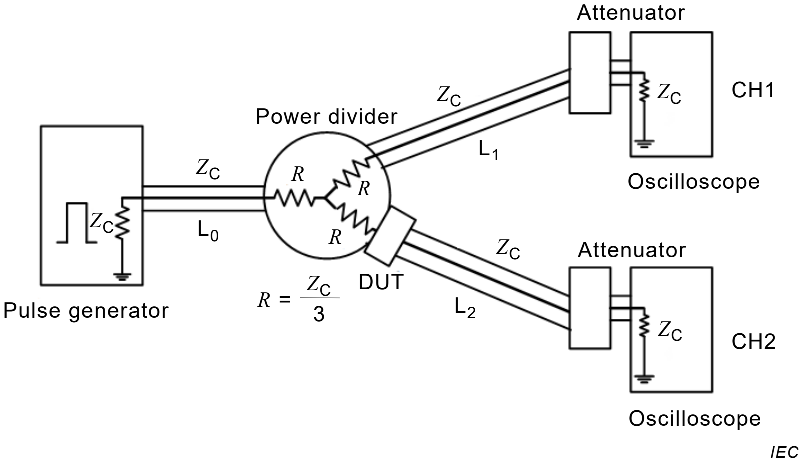


Figure B.3 – Simplified test setup for testing protective devices

The distinctive features of the simplified proposed test setup are as follows:

- The power divider and the DUT are connected directly, and the dimension of the power divider and the DUT are small enough to neglect time delay τ_{L21}.
- Choose the same length for cable L_1 and cable L_2, to make sure the two branches' waveforms reach the terminals at the same time to simplify the computation.

With $\text{L}_1 = \text{L}_2 = \text{L}$, the measured waveforms at each branch terminal could be simplified as follows:

- Normal branch:

$$V_{\text{CH1}}(t) = \frac{1}{A} \cdot \left[\frac{V_0\left(t - \tau_{\text{L0}} - \tau_{\text{L}}\right)}{2} + \frac{V_{\text{F}}\left(t - \tau_{\text{L}}\right)}{2} \right] \tag{B.3}$$

- DUT branch:

$$V_{\text{CH2}}(t) = \frac{1}{A} \cdot \left[\frac{V_0\left(t - \tau_{\text{L0}} - \tau_{\text{L}}\right)}{2} + V_{\text{F}}\left(t - \tau_{\text{L}}\right) \right] \tag{B.4}$$

Where, τ_{L0} and τ_{L} stand for the time delays of the corresponding coaxial cable.

The time delays of the applied pulse V_0 on the two branches are the same, along with the induced wave $V_{\mathrm{F}}(t)$. From the DUT point of view, we can obtain the applied pulse and the induced pulse by the following computation.

- Applied pulse:

$$\frac{V_0(t-\tau_{\mathrm{L0}}-\tau_{\mathrm{L}})}{2} = A \cdot \left[2V_{\mathrm{CH1}}(t) - V_{\mathrm{CH2}}(t)\right] \tag{B.5}$$

- Induced pulse caused by the “fired” test device:

$$V_{\mathrm{F}}(t-\tau_{\mathrm{L}}) = 2A \cdot \left[V_{\mathrm{CH2}}(t) - V_{\mathrm{CH1}}(t)\right] \tag{B.6}$$

The time delay of the induced waveform V_{F} with respect to the applied pulse $\frac{V_0}{2}$ is the response time of the voltage breakdown device.

Annex C
(informative)

Residual measurements for antenna port protectors

C.1 Evaluating the required protection for RF antenna ports

When evaluating the effectiveness of conducted HEMP protection for any type of point of entry or point of egress (POE) it is typically the case that some type of residual current or voltage is measured. This is done quite effectively for conducted signal or power lines, which can use an electric surge arrestor (ESA) filter combination to reduce the residual currents or voltages into the device being protected. It is natural then to specify a similar method for evaluating the performance criteria of a HEMP protector for RF antenna ports against early-time HEMP. But there are a number of difficulties with this approach on RF antenna ports. This is especially the case for HF antennas where the early-time HEMP is in-band of both a transmitter and receiver RF port.

Most modern day HF antenna ports connect to equipment that uses the antenna as both a receiving antenna and a transmitter antenna.

This transmit/receive equipment is typically referred to as a transceiver and it is widely used in commercial and military applications.

Thus, the equipment antenna port has two functions; it serves as a receiver port and a transmitter port as shown in Figure C.1.

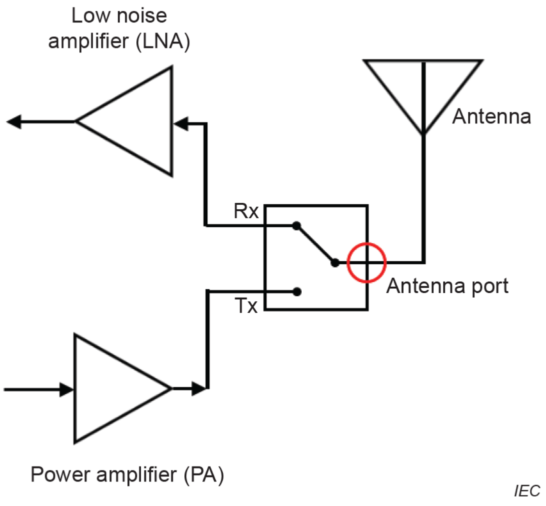


Figure C.1 – Transceiver with antenna port shown

While it can be fairly straightforward to select a protector with particular residuals for the transmitter side, on the receive mode the same protector could not work at protecting the receiver front end of the equipment.

The reason for this is that on transmit, much higher levels of current and voltage are present on the RF port than on the receive mode. Thus a protector external to the equipment's RF port for a transceiver would not protect the equipment when on receive mode operation.

Specifying residuals for an external RF port protector can only be made for the transmit mode of the transceiver and yet this would leave the receive mode vulnerable to breakdown during an early time pulse while on receive operation.

One solution would be to require transceiver manufacturers to add early-time protection internally to the transceiver on the signal path of the receive and transmit modes as shown in Figure C.2.

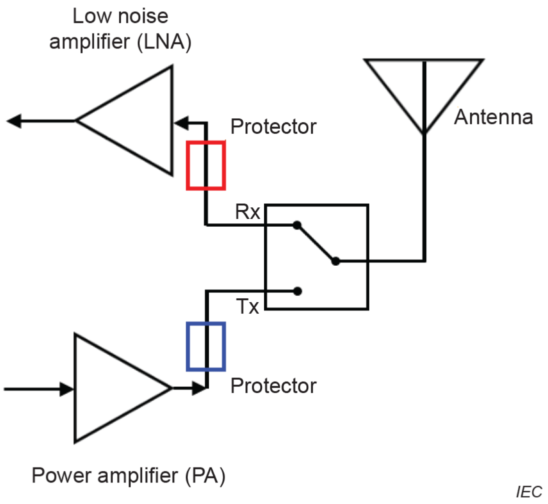


Figure C.2 – Protectors on RX and TX signal path internal to the transceiver after the RF port

This scheme, however, has the disadvantage that it leaves the RF port itself vulnerable to breakdown during an early-time pulse event.

Since the receive front end of the transceiver is the most vulnerable to high voltages and quite sensitive to small signals, it makes sense then that early-time protection should be added internally to the transceiver directly in front of the receiver front end.

In addition, in order to protect both the transmitter side of the transceiver and the antenna RF port itself, the protector for the antenna port may be placed by the equipment owner just outside the RF port as shown in Figure C.3.

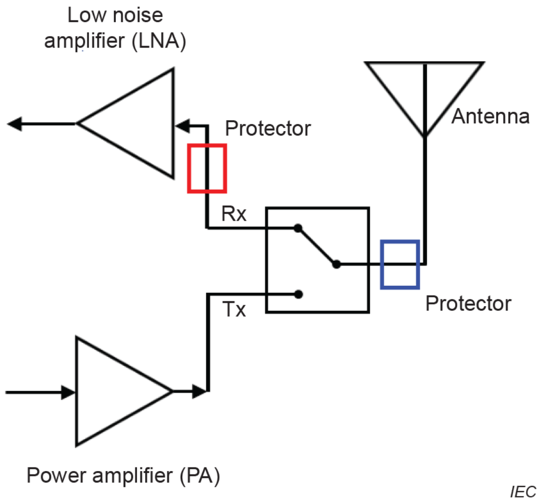


Figure C.3 – Protector internal to equipment for RX side protection and outside the equipment at the antenna port for transmit and port protection

Residuals for the protector of the RF port and transmit side can actually be simple to calculate if the maximum output power of the transmitter is known or the maximum power that the port can handle is known, whichever is lower.

For example, a typical N-type RF connector has a maximum operating RMS voltage of 707 V and a maximum operating power of 10 kW.

In this case, the residual for a protector can be measured in amperes and be limited to a peak current $I_{\text{pk}} = I_{\text{RMS}} \times \sqrt{2}$ of no more than 20 A, where $I_{\text{RMS}} = \sqrt{P/R}$ and R is the typical 50 Ω load of RF systems.

If, however, the transmitter has a maximum operating RF output of 1 000 W, then the residual for a protector should measure a peak of less than 6,3 A.

Allowing the residuals to be higher in this case might damage the transmitter front end even though it would not damage the RF port.

Figure C.4 shows a typical commercially available port protector. However, these devices have typically not been tested for an early-time pulse and let through residual currents are not readily available.

Figure C.4 – N-type RF antenna port protector using GDTs

Computing safe residuals for a protective device on the receive side of the transceiver, as shown in Figure C.3, is a far more complicated problem. Since receivers are sensitive to very small levels of signal, in the order of microvolts, it is incumbent upon the manufacturer to know at what voltage the front end of the receiver will saturate, overload, or stop working.

With this information, protective devices may be added in the receive signal path that can react fast and clamp the early-time pulse peak voltage to a safe level. But because the characteristics of each receiver are different and the semiconductors used can vary in type, it is practically impossible to define a level at which protective devices can be tested in order to ensure survivability of the equipment during an early-time pulse event.

Because HF transceivers (3 MHz to 30 MHz) are in-band of an early-time pulse, transceivers, antennas, and antenna ports in these units are especially vulnerable to damage by a HEMP.

While the use of external port protectors at the antenna port can be useful in protecting against damaging the port or the transmitter sections of a transceiver, it does nothing for the protection of the receive side.

Manufacturers of both protective devices and transceivers may need to come together in this area and devise practical ways of protecting receiver front-ends in transceivers; standardization can then be attempted.

C.2 Evaluating the required protection for RF antenna ports

Effective HEMP-protection of an RF antenna port requires considering the complete system (see Figure C.5). This typically consists of an antenna, a balun (integrated in the antenna), possibly an integrated coarse protection (SPD) in the antenna socket (to protect the balun and the coaxial cable especially against lightning), and an RF SPD at the building entrance or equipment port (or both). Typically a HEMP-protection device (DUT) is located close to the equipment port. This means that in typical RF systems, various protection devices are present in different locations and therefore these need to be well coordinated in order to protect against both lightning and HEMP-transients.

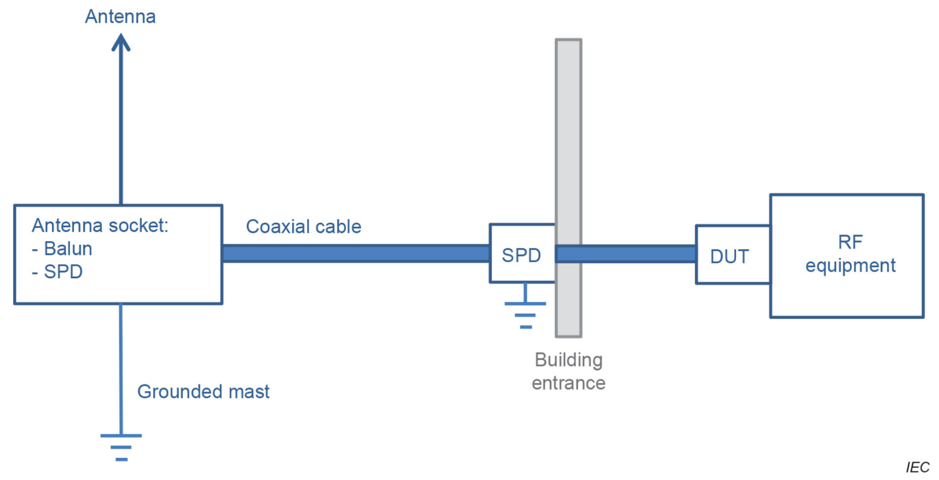


Figure C.5 – Typical antenna system with RF-HEMP protector (DUT)

In order to estimate the required protection level of the DUT in a first step, one has to consider the following characteristics of the RF signals in the coaxial cable:

- maximum RF power (receiver, transmitter or transceiver, modulation etc.);
- operating frequency range and instantaneous bandwidth;
- parameters of the remote power supply on the coaxial cable if applicable (often AC or DC power for the remote supply of amplifiers on the antenna mast is present).

In a second step, two parameters are important to assess the quality of the protection device (DUT): the maximum residual voltage and the maximum residual energy under threat level test conditions. Both the residual voltage and the maximum residual energy can be determined from the tests described in this document.

The residual voltage/current values of the DUT have to be compared with the maximum RF power and the remote power supply characteristics. The peak RF power present in the system also determines the maximum RF operating voltage. For many DUTs, especially those for broadband applications, the protection level should be implemented at a level that is higher than the maximum operating voltage.

The residual energy of the DUT into the nominal load impedance is the second important protection parameter. From the measured residual pulse shape (voltage $U(t)$ or current $I(t)$ as described in the test procedure) and the known load impedance (usually 50 Ω), the residual energy can be easily calculated (it is the integral of $U(t)^2 / R_L$ or the integral of $I(t)^2 \cdot R_L$). The achievable residual energy depends on the protection principle and also on the required system bandwidth. Typical residual energy values of DUTs range from a few µJ to several tens of mJ.

Unfortunately, not much information is available about the immunity of RF systems against transients. Nowadays many systems can have at least some level of ESD protection (electrostatic discharge) built-in. If the residual levels of the DUT are lower than the system's immunity levels, then the system is likely to be sufficiently protected against HEMP by the DUT. If there is a choice of several DUTs then the one having the lowest residual voltage and the lowest residual energy is best suited to protect against HEMP.

Ultimately, the safest method to assess the protection is to test the DUT under real operating conditions, i.e. to perform a threat-level test with the system to be protected connected and in operation. For mission critical systems this is the recommended solution.

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Part 4-24: Testing and measurement techniques – Test methods for protective devices for HEMP conducted disturbance

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This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

IEC 61000-4-24 edition 2.1 contains the second edition (2015-11) [documents 77C/245/FDIS and 77C/250/RVD] and its amendment 1 (2023-08) [documents 77C/330/FDIS and 77C/331/RVD].

This Final version does not show where the technical content is modified by amendment 1. A separate Redline version with all changes highlighted is available in this publication.

International Standard IEC 61000-4-24 has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility.

It forms Part 4-24 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107.

This second edition constitutes a technical revision.

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

a) A new Clause 5: Measurement method for HEMP combination filters, which contains 5.1 Verification setup, 5.2 Measurement setup, 5.3 Measurement instrument, 5.4 Test modes, 5.5 Measurement procedures, 5.6 Evaluation of test results, which introduced performance criteria of filter, and 5.7 Test report.
b) A new informative Annex A: Investigation for the establishment of a measurement setup, which was based on Clause 5.
c) A new informative Annex B: Test method for the quantitative determination of the direct response behaviours of a coaxial surge protector.

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

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

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

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

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This standard is part of the IEC 61000 series of standards, 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

Part 4: Testing and measurement techniques

Measurement techniques
Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines
Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as international standards, 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).

The IEC has initiated the preparation of standardized methods to protect civilian society from the effects of high power electromagnetic (HPEM) environments. Such effects could disrupt systems for communications, electric power, information technology, etc.

This part of IEC 61000 is an international standard that establishes the required test procedures for protective devices for HEMP conducted disturbance, such as gas discharge tubes, varistors, two-port SPDs and HEMP combination filters.

The application of this standard is, however, not dependent on access to other sections and parts of the IEC 61000, except for those specifically referred to.

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 4-24: Testing and measurement techniques – Test methods for protective devices for HEMP conducted disturbance

1 Scope

This part of IEC 61000 deals with methods for testing protective devices for HEMP conducted disturbance. It includes two-terminal elements, such as gas discharge tubes, varistors, and two-port SPDs, such as HEMP combination filters. It covers testing of voltage breakdown and voltage-limiting characteristics but also methods to measure the residual voltage and/or the residual current, peak rate of rise and root action for the case of very fast changes of voltage and current as a function of time.

This standard does not cover insertion loss measurement methods.

2 Normative references

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

IEC 61000-2-10:2021, *Electromagnetic compatibility (EMC) – Part 2-10: Environment – Description of HEMP environment – Conducted disturbance*

3 Terms, definitions and abbreviated terms

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

3.1 Terms and definitions

3.1.1
feed-through device
two-port device, which is designed to feed a signal through an electromagnetic barrier (shield)

Note 1 to entry: Typically it is in good electrical contact with the barrier and has one port on each side of the barrier, thus maintaining the isolation of the barrier.

3.1.2
gas discharge tube
GDT
device with two or three metal electrodes hermetically sealed so that gas mixture and pressure are under control and designed to protect apparatus or personnel from high transient voltages

3.1.3
HEMP
high-altitude electromagnetic pulse
electromagnetic pulse produced by a nuclear explosion outside the earth’s atmosphere

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

[SOURCE: IEC 61000-1-3:2002, 3.10]

3.1.4
HEMP combination filter

filter combined with voltage limiting devices, so that this combination can attenuate the residual current pulse passing through it

3.1.5
norms

scalar quantities that characterise the features of a waveform

Note 1 to entry: Norms are used to characterise features of a waveform that relate to susceptibility mechanisms.

3.1.6
peak rate of rise

maximum absolute value of the first derivative of a current waveform $I(t)$ with respect to time, dI/dt, expressed in units of ampere per second

3.1.7
PCI

pulsed current injection.

test method for measuring the performance of a protective device

Note 1 to entry: A HEMP threat-relatable transient is injected on the input of the protective device and the residual transient stress is measured on its output.

Note 2 to entry: This note applies to the French language only.

3.1.8
peak current

maximum absolute value of a current waveform, $I(t)$, expressed in units of ampere

3.1.9
primary protection element

first protective element seen from the unprotected side of a protection measure, diverting the main part of the surge current

3.1.10
protected side

side of a protection measure where the equipment is situated that has to be protected

3.1.11
protective device

electrical component such as a filter, gas discharge tube, metal oxide varistor (or other), for protection against conducted disturbance, or a shield, gasket, waveguide trap (or other), for protection against radiated disturbance, which is used to limit any conducted or radiated stress. Such an element or a combination of several of them thus forms part of the conceptual EM barrier for a system

[SOURCE: IEC 61000-5-5:1996, 3.20]

3.1.12
root action

norm of a current waveform $I(t)$ defined by

$$\sqrt{\int_0^\infty |I(t)|^2 dt}$$

Note 1 to entry: Where the load impedance is known, the energy in W/s or J can be calculated.

3.1.13
SPD
surge protective device

device that is intended to limit transient over-voltages and divert surge currents. It contains at least one non-linear component that is intended to limit surge voltages and divert surge currents

Note 1 to entry: This note applies to the French language only.

[SOURCE: IEC TR 61000-5-6:2002, 3.23, modified – a note has been added.]

3.1.14
two-port SPD

SPD which is not only a shunting device, but consists of a separated input port on the unprotected side and an output port on the protected side

Note 1 to entry: Typically two-port SPDs are “black boxes” with non-linear shunting devices to ground and a circuit between input and output ports.

3.1.15
two-terminal element

electrical element where a current enters in one terminal and leaves through a second terminal

Note 1 to entry: A two-terminal element is a one-port device. Typically two-terminal SPD’s are devices shunting to ground.

3.1.16
unprotected side

side of a protection measure from which the surge event is expected

3.1.17
waveform norm

parameter that is determined from a mathematically well-defined operation on a waveform or signal (such as an integration of the waveform), which yields a scalar number that permits a comparison of various waveforms or their effects

[SOURCE: IEC 61000-4-33:2005, 3.10]

3.2 Abbreviated terms

DUT	Device under test

4 Test methods for protective devices (excluding filter) for conducted disturbance

4.1 General

The actual behaviour of a protective device under HEMP conditions depends very much on how it is integrated into its place of use and other attendant circumstances (e.g. quality of shielding between the protected and unprotected side of a protection element). The following test methods take this into account. They are defined so that the results obtained are as far as possible related to the qualities of the device under test (DUT), and the test arrangement does not differ too much from practical protection arrangements.

NOTE Clause 4 is intended to apply for a protective device such as gas discharge tubes, varistors and two-port SPDs, excluding the HEMP combination filter. For a HEMP combination filter, Clause 5 applies.

4.2 Test setup

The test setup consists of a pulse generator (G), a launching line, a test fixture for the DUT, and a termination with a connecting line and oscilloscope (see Figure 1). Various source impedances may be used, but the example shown in Figure 1 uses 50 Ω. Other values could be specified.

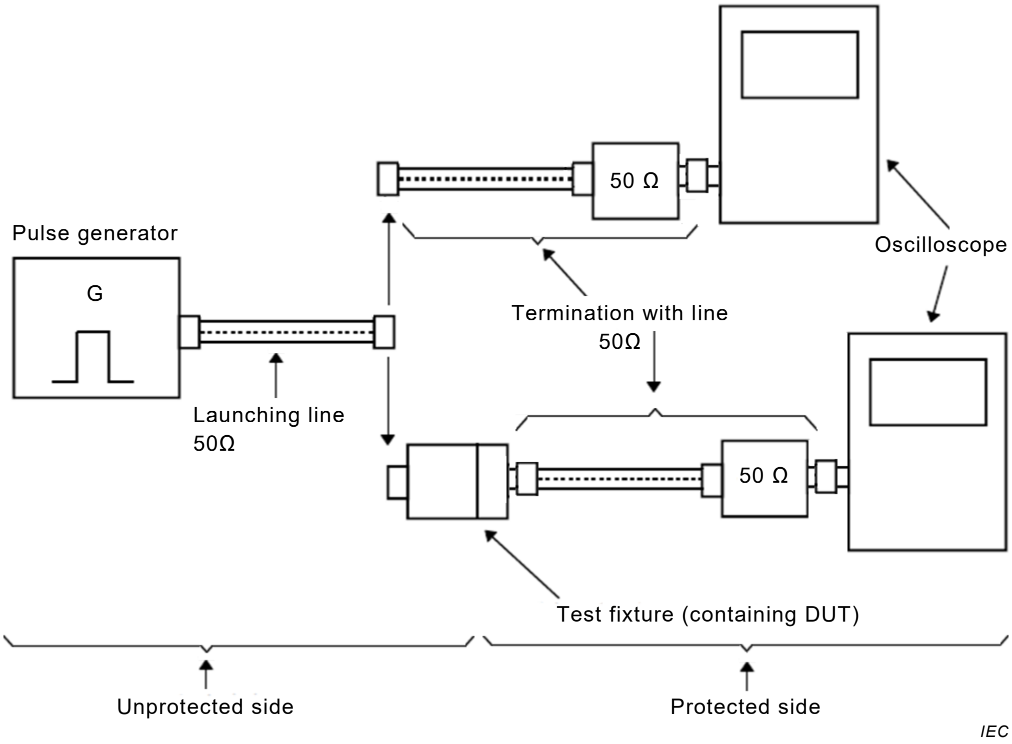


Figure 1 – Test setup for testing protective devices

To prevent parasitic coupling between the pulse generator and the oscilloscope, both the unprotected and protected side of the setup shall be entirely shielded. It is recommended to use cables with multiple braided wire shields or solid shields. The cable and connectors shall be capable of withstanding the high voltage pulse without a breakdown. Grounding loops shall be avoided.

4.3 Pulse generator

The pulse generator shall produce a normally rectangular voltage pulse into a matched termination. The output voltage (into a matched termination) shall be adjustable to a value 2 times higher than the expected limiting voltage of the DUT. Both polarities shall be available. The characteristics of a pulse generator are as follows:

– characteristic impedance:	50 Ω or an alternative value
– pulse wavefront , du/dt:	at least 1 kV/ns
– pulse duration:	at least 20 ns

4.4 Launching line

The launching line consists of a coaxial cable with a characteristic impedance of 50 Ω or the value specified. The cable between the pulse generator and the DUT shall be long enough so that reflections from the DUT do not arrive at the pulse generator during the pulse front. To achieve this condition, the one-way propagation time along the cable shall be greater than half the front time of the pulse. Due to the frequency-dependent attenuation of the cable, the steepness of the pulse front may be lowered and thus adjusted to the desired value, by further extending the launching line.

4.5 Test fixtures

4.5.1 General

Test fixtures are mechanical setups with coaxial connectors on both the unprotected and the protected terminals. Their task is to hold the DUT. Two different types of test fixtures may be used. They are referred to as type A and type B as described below.

4.5.2 Type A fixtures

Gas discharge tubes intended to be used for protection of coaxial high-frequency applications may be tested in corresponding, commercially available holders. The protective device is inserted between the inner and outer conductor of the coaxial setup, with a minimum of influence on the characteristic impedance. Such holders allow the inherent properties of the device to be measured explicitly and with good repeatability.

4.5.3 Type B fixtures

4.5.3.1 General

Type B fixtures are universal and apply in principle to all kinds of two-terminal or two-port protective devices, whether they have a feed-through or non-feed-through configuration. However, measurements on low-voltage devices like protective diodes and varistors may be strongly influenced by inductive overshoot due to high di/dt.

NOTE By ensuring the test fixture lead lengths are as short as practically possible, the risk of inductive influence can be mitigated.

The fixture is composed of three parts: the unprotected shell, the partition screen and the protected shell (see Figure 2).

4.5.3.2 Unprotected shell

The dimensions and cross-section shape may be adapted to the size of the DUT. The shell may be cut into two parts in the axial direction for better access to the solder points. If not otherwise stated, the length of the wire from the unprotected connector (P_1) to the input-contact of the DUT (P_2) shall not be longer than the length of the current path in the DUT between points P_2 and the grounding contact of the DUT (P_3).

4.5.3.3 Partition screen

Feed-through protective devices shall be inserted in the partition screen in the same way as in actual application.

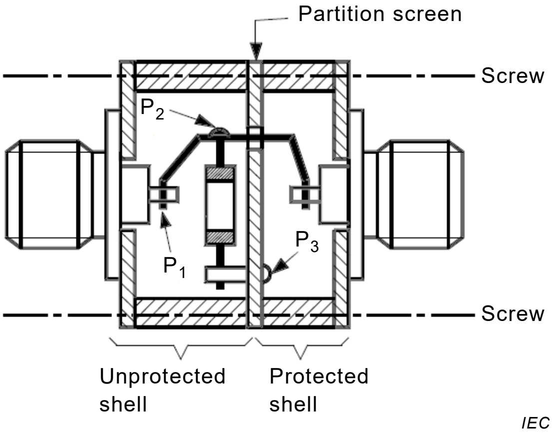
Non-feed-through devices shall be passed through a hole in the partition screen as shown in Figure 2a) and 2b). The wire passing through the partition screen shall be insulated. A feed-through capacitor or other feed-through element shall not be used. A non-feed-through DUT may be placed close to the screen but shall not touch it, except if it is to be installed on to a metal wall in actual applications (as shown in Figure 2c)).

4.5.3.4 Protected shell

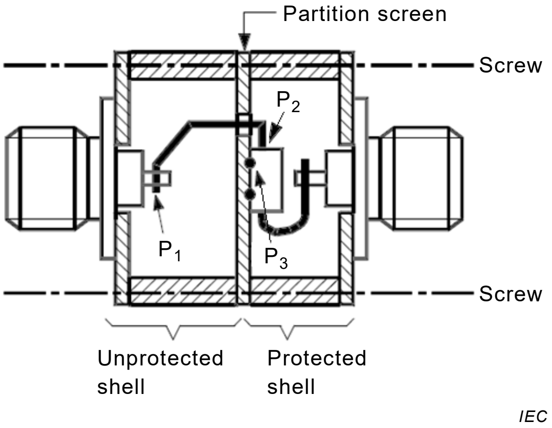
The protected shell serves as transition to the protected connector. The protected shell shall be made as short as possible. The length of the connection between point P_2 and the protected connector shall be as short as possible.

4.6 Termination

The termination shall be matched to the characteristic impedance of the test setup within the 3 dB-bandwidth of the oscilloscope. It shall be of the feed-through type, followed by a high-impedance, voltage-dividing probe of the oscilloscope or be part of the first stage of an attenuator in front of the oscilloscope. The line between the test fixture and termination shall have the same impedance as the termination. It shall be as short as possible. Its attenuation shall be less than 0,5 dB at the upper 3 dB cut-off frequency of the oscilloscope. Make sure that the termination withstands the test pulses without degradation.

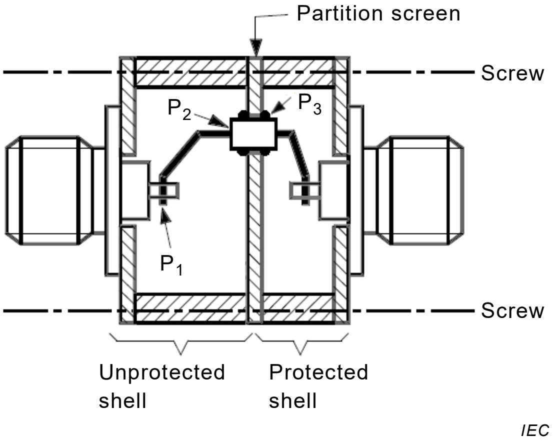


a) Example of a type B test fixture with a two-terminal DUT in non-feed-through configuration



The DUT may alternatively be in the unprotected shell.

b) Example of a test fixture with a two-port DUT in non-feed-through configuration



c) Example of a test fixture with a DUT in a feed-through configuration

Figure 2 – Example of a type B test fixture (universal)

4.7 Oscilloscope

The bandwidth of the oscilloscope and the other components of the test setup shall be wide enough that the overall tolerance of the peak values of u and du/dt due to bandwidth limitations and other system errors is not higher than ±20 %.

4.8 Test procedure

4.8.1 Adjustment of the pulse generator

The launching line is first connected directly to the line leading to the termination (see Figure 1).

The pulse generator is adjusted as follows:

a) if the DUT, or the primary protection element of a four-terminal DUT, is a gas discharge tube, the steepness of the leading front of the prospective pulse shall be at least 1 kV/ns at the impulse spark-over voltage of the gas discharge tube during the test;

b) if the DUT, or the primary protection element of a four-terminal DUT, is a voltage-limiting device (e.g. protective diode or varistor), the highest tangential steepness of the leading front of the prospective pulse is as described by

$$du/dt = (1/2) \times Z_c \times di/dt \tag{1}$$

where Z_c is the characteristic impedance and di/dt is the specified value.

NOTE The specified di/dt corresponds to the actual di/dt in the DUT during the test. As the DUT has a very low impedance compared with 50 Ω or the specified impedance, the current i and therefore also di/dt is doubled during the test.

4.8.2 Verification procedures

The launching line is then connected to the test fixture (see Figure 1).

If a test fixture type B is used, the internal connection between the protected and the unprotected connector shall be tested for transmission characteristics.

For this purpose the DUT is removed and the same pulse as under 4.8.1 (adjustment of the pulse generator) is applied. The measured output shall not differ from the output measured under 4.8.1 by more than 10 %. If it differs by more than 10 %, the diameter of the connecting wire should be increased (a higher capacity will lower the characteristic impedance and improve the match between the pulse generator and the load).

To make sure that no undesired coupling between the unprotected and the protected side of the test setup is present, verification tests shall be made with the following modifications on the test setup:

If the DUT is a two-terminal element, it shall be replaced by a short-circuit connection of the same length and form as the current path through the DUT. The connection between P_2 and the centre-pin of the protected connector (see Figure 2) shall be removed. One test shall be made with the centre-pin of the protected connector left open and another one with this pin connected to the ground (within the protected shell).

If the DUT is a feed-through device, it shall be replaced by a device of the same dimensions (dummy DUT) made entirely of well-conducting metal and thus representing an ideal short-circuit. The centre-pin of the protected connector shall be connected to the output pin of the dummy DUT.

The peak value of the residual voltage measured under these conditions shall be less than 5 % of the peak value measured in the final test.

4.8.3 Test

The dummy DUT is replaced by the DUT, and the residual voltage is measured and compared to the verification criteria.

4.8.4 Final examination of the DUT

After the test, the DUT shall be examined for visible damage. If visible damage is observed, the DUT will be deemed to fail the test. If there is no visible damage a functional test shall be performed to verify that the DUT is within its specification.

4.9 Referring to this standard

When reference is made to this standard, the following additional information shall be given.

Standard procedure:

– for gas discharge tubes:	type of test fixture used (4.5)
– for measurement on two-terminal elements in fixture B:	length of connection wires, see overall length of DUT between solder points (4.5.3)

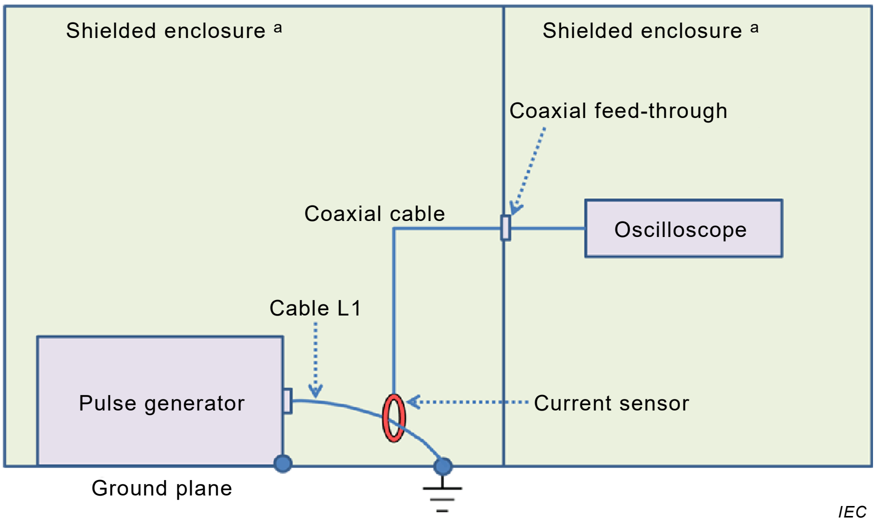
Modifications from standard procedure:

– characteristic impedance:	if other than 50 Ω (4.2)
– steepness of prospective pulse, du/dt:	if higher than 1 kV/ns (4.3)
– actual di/dt:	if higher than 40 A/ns (4.8.1)
– modification of DUT:	if connecting wires of gas discharge tubes are cut away for measurement in type A fixture
– additional components to the DUT	for example additional circuit components; different wire lengths to those specified.

5 Measurement method for HEMP combination filters

5.1 Verification setup

The output of the pulse generator shall be verified prior to applying a pulse to a DUT. The typical setup for verification of the pulse test level is illustrated in Figure 3.



[a] At least one of the two enclosures shall be shielded. Care should be taken to minimize radiated and conducted interference.

Figure 3 – Typical setup for verification of the pulse test level

The pulse generator shall be connected to the ground plane. The output cable L1 shall also be connected to the ground plane to enable the short-circuit pulse current to be measured. The length and geometry of cable L1 shall be chosen to minimize the inductance and shall be the same as when the DUT is connected (see Annex A). The insulation of the cable to the ground should be sufficient to avoid breakdown for all impulse voltages.

If the size or setup of the DUT requires a long cable L1, then the cable may be coaxial to achieve the required pulse rise time at the DUT. If the cable selected is coaxial, the shield should be pared back, and the inner conductor shall be exposed and bonded to the ground. The current probe shall be placed around the exposed inner conductor. Alternatively a coaxial current shunt can be used.

The position of the current sensor shall be within 0,15 m from the ground connection. Care shall be taken to electrically isolate the body of the current sensor from metallic surfaces to avoid ground loops.

5.2 Measurement setup

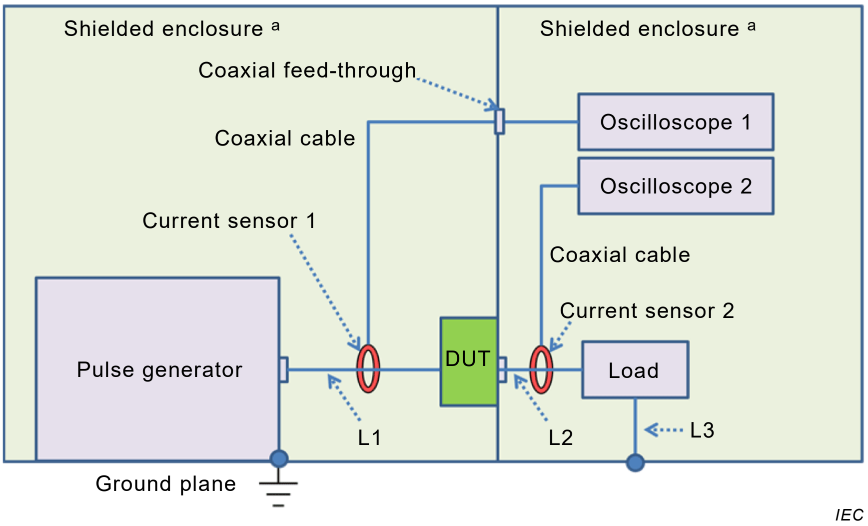
Two typical measurement setups are illustrated in Figure 4 and Figure 5. The pulse generator output shall be directly connected to the input terminal of the DUT through the same cable as used for verification.

The current sensor 1 and oscilloscope 1 can be used optionally to monitor the injected current into the DUT.

The current sensor 2 for the measurement of residual current into the dummy load shall preferably be within 0,15 m of the output terminal of the DUT. Alternatively a grounded measuring shunt can be used in series with the load impedance. The load shall be a dummy resistor as described in 5.3.4.

The cables L2 and L3 shall be as short as possible.

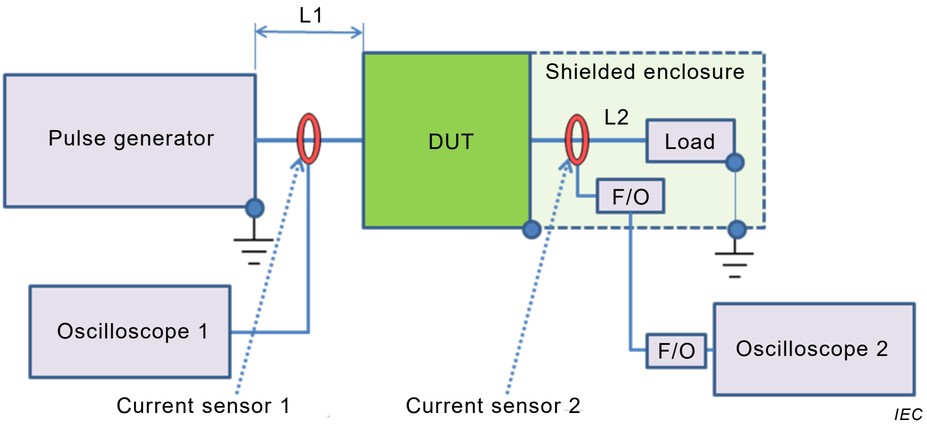
It may be necessary to shield the measurement instrument and to isolate the power supply to avoid interference due to ground loops.



If a voltage probe is used it should be connected across the load resistor.

[a] At least one of the two enclosures shall be shielded. Care should be taken to minimize radiated and conducted interference.

Figure 4 – Example of test setup using one or two shielded enclosures



F/O means fibre optic converter. Fibre links may be used as an option to provide a degree of isolation so that the pulse generator and oscilloscopes can be physically separated to minimize interference.

If pulse generator and injection cable L1 are not shielded, then oscilloscopes 1 and 2 should be in a shielded enclosure to avoid pick-up. Care should be taken to minimize radiated and conducted interference.

Figure 5 – Example of test setup using a shielded enclosure

5.3 Measurement instrument

5.3.1 Pulse generators

Short-circuit current is defined as current driven through a short-circuit connected to the generator output. Source impedance is defined as the generator peak open circuit voltage divided by the peak short-circuit current. The tolerance is ±10 %.

Pulse test requirements can be selected from Table 1 and Table 2, for early-time HEMP and intermediate-time HEMP respectively.

Table 1 – Overview of conducted early-time HEMP (CEP) test requirements defined in other specifications

Type	Rise time	FWHM [a]	Source impedance [b]	Peak short-circuit current	Specifications
CEP$_1$	< 10 ns	100 ns ±30 %	400 Ω ±15 Ω	4 000 A ±10 %	IEC 61000-2-10, 99 % severity for elevated conductor, for cable length longer than 200 m
CEP$_2$	< 10 ns	100 ns ±30 %	400 Ω ±15 Ω	1 500 A ±10 %	IEC 61000-2-10, 90 % severity for elevated conductor, for cable length longer than 200 m
CEP$_3$	< 10 ns	100 ns ±30 %	400 Ω ±15 Ω	500 A ±10 %	IEC 61000-2-10, 50 % severity for elevated conductor, for cable length longer than 200 m
CEP$_4$	< 25 ns	500 ns ±30 %	50 Ω ±5 Ω	400 A ±10 %	IEC 61000-2-10, for buried conductor in the ground conductivity of 10^{-4}, for cable length longer than 10 m
CEP$_5$	≤ 20 ns	500 ns +10 %	≥ 60 Ω	2 500 A ±10 %	According to [1][1], wire-to- ground
CEP$_6$	≤ 20 ns	500 ns +10 %	≥ 60 Ω	5 000 A ±10 %	According to [1], common-mode, under installed conditions only

[a] FWHM is an acronym for full-width at half-maximum (amplitude).

[b] In all cases, for practical reasons lower source impedance may be used. However the source impedance should not be less than typically 10 Ω to ensure that the applied pulse voltage is greater than the breakdown voltage of the non-linear components in the DUT.

Table 2 – Overview of conducted intermediate-time HEMP (CIP) test requirements defined in other specifications

Type	Rise time	FWHM [a]	Source impedance [b]	Peak short-circuit current	Specifications [c]
CEP$_1$	25 μs ±30 %	1 500 μs ±30 %	400 Ω ±15 Ω	600 A ±10 %	IEC 61000-2-10, for elevated conductors, for cable lengths longer than 1 km
CEP$_2$	25 μs ±30 %	1 500 μs ±30 %	400 Ω ±15 Ω	75 A ±10 %	IEC 61000-2-10, for elevated conductors, for cable lengths from 200 m to 1 km
CEP$_3$	25 μs ±30 %	1 500 μs ±30 %	50 Ω ±5 Ω	450 A ±10 %	IEC 61000-2-10, for buried conductors, for cable lengths longer than 1 km
CEP$_4$	25 μs ±30 %	1 500 μs ±30 %	50 Ω ±5 Ω	50 A ±10 %	IEC 61000-2-10, for buried conductors, for cable lengths from 200 m to 1 km
CEP$_5$	≤ 1,5 μs	3 000 μs to 5 000 μs	≥ 10 Ω	250 A ±10 %	According to [1], for cable lengths longer than 200 m

[a] FWHM is an acronym for full-width at half-maximum (amplitude).

[b] In all cases for practical reasons lower source impedance may be used. However the source impedance should not be less than typically 10 Ω to ensure that the applied pulse voltage is greater than the breakdown voltage of the non-linear components in the DUT.

[c] No test is required for line lengths shorter than 200 m.

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

The short-circuit current of the pulse generator has a double exponential waveform (see Figure 6).

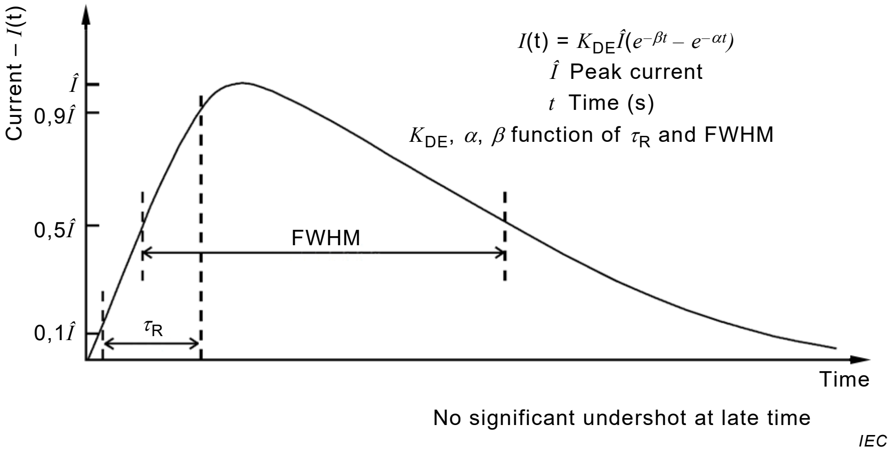


Figure 6 – Double exponential waveform

5.3.2 Oscilloscope

The bandwidth of the oscilloscope shall be wide enough to resolve the fastest rise time (< 10 ns, DC to > 100 MHz for the early-time HEMP and DC to > 1 MHz for the intermediate-time HEMP) and shall have minimum sensitivity as required for measurement sensitivity. The required input impedance of the scope amplifier depends on the type of voltage or current probe and shall be selected accordingly (typically 50 Ω or 1 MΩ).

5.3.3 Current sensors

The measurement bandwidth of the current sensors should cover the frequency range of 100 kHz to 100 MHz for the early-time HEMP and DC to 1 MHz for the intermediate pulse. The total measurement range in combination with the scope's vertical amplifier range shall be 0 A to 5 000 A for the early-time HEMP and 0 A to 250 A for the intermediate-time HEMP. For the measurement of currents to ground a resistive current shunt might give the most accurate results.

5.3.4 Test loads

During all tests a DUT test load according to the test mode and a DUT wiring setup as defined in Table 3 shall be used. The tolerance of the test load shall be ±10 % if not stated otherwise.

5.4 Test modes required

The test modes can be selected from the following list, depending on the application of the DUT. As a minimum, the nominal load mode(s) shall be performed.

- ETM1: Early-time HEMP / open-circuit
- ETM2: Early-time HEMP / nominal load
- ETM3: Early-time HEMP / short-circuit
- ITM1: Intermediate-time HEMP / open-circuit
- ITM2: Intermediate-time HEMP / nominal load
- ITM3: Intermediate-time HEMP / short-circuit

NOTE Test pulses can be selected from Table 1 and Table 2.

Since open-circuit measurements are difficult, a ≥ 1 MΩ load might be a good choice since typical voltage probes of oscilloscopes have a ≥ 1 MΩ input impedance.

Table 3 shows the test modes as required for different types of DUTs. The termination load impedances of the DUT for the early-time HEMP shall be chosen according to Table 3.

The DUT wiring setups (WSs) are as follows:

- WS1: Single line or multiple single lines DUT (see Figure 7)

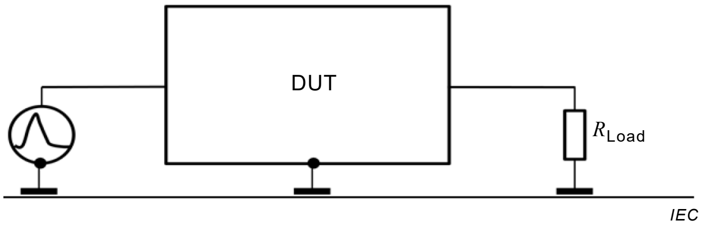


Figure 7 – Example of wiring setup of a single line DUT

- WS2: One example of a wiring setup for a mutually coupled or symmetric multi-line DUT (see Figure 8)

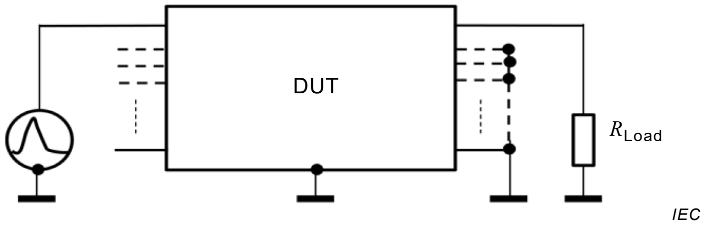


Figure 8 – Example of wiring setup for a mutually coupled multi-line DUT

WS2 is an example of wiring setup, which may be used for a multi-line DUT with lines which are coupled to each other either electrically or magnetically (e.g. by current-compensated inductors or if there are differential mode protection components). One line is tested at a time and the second and all other lines (dashed lines) are connected together at the output side and grounded. The lines that are not tested should remain open at the input side to avoid mutual coupling issues.

This setup is optional and other setups may be more applicable depending on the DUT circuit.

Table 3 – Test mode and DUT wiring setup

DUT application	Required test modes	Wiring setup	DUT load, R_{Load}
AC/DC power line	ETM1	WS 1/WS 2 [a]	Open circuit (≥ 1 MΩ)
	ETM2	WS 1/WS 2 [a]	2 Ω
	ETM3	WS 1/WS 2 [a]	Short-circuit (< 50 mΩ)
	ITM1	WS 1/WS 2 [a]	Open circuit (≥ 1 MΩ)
	ITM2	WS 1/WS 2 [a]	50 Ω
	ITM3	WS 1/WS 2 [a]	Short-circuit (< 50 mΩ)
Symmetric data line (Ethernet, etc.)	ETM1	WS 2	Open circuit (≥ 1 MΩ)
	ETM2	WS 2	50 Ω
	ETM3	WS 2	Short-circuit (< 50 mΩ)
	ITM1	WS 2	Open circuit (≥ 1 MΩ)
	ITM2	WS 2	50 Ω
	ITM3	WS 2	Short-circuit (< 50 mΩ)
Non-symmetric or individual data/signal/control/audio line	ETM1	WS 1	Open circuit (≥ 1 MΩ)
	ETM2	WS 1	50 Ω
	ETM3	WS 1	Short-circuit (< 50 mΩ)
Coaxial line	ETM2	WS 1	50 Ω (or coax-cable impedance)
	ITM2	WS 1	50 Ω (or coax-cable impedance)

[a] Depending on the DUT design, either WS1 or WS2 shall be applied. The 2 Ω load has been defined in MIL-STD-188-125-1 for power lines. Short-circuit and open-circuit load conditions are optional, therefore no requirement is defined in this standard.

5.5 Measurement procedure

5.5.1 General

To minimize the possibility of DUT damage, a series of pulses at increasing amplitudes shall be applied for all applicable test modes ETM1 to ETM3 and ITM1 to ITM3.

CAUTION: The DUT may have limited pulse life. It should be checked for degradation before using in service or further test.

5.5.2 Verification of pulses

Perform the verification of the test level with 10 %, 20 %, 40 %, 80 % and 100 % of the maximum test current (see Figure 3) and record the verified levels, the charging voltage and generators settings required to achieve these test levels.

NOTE The amplitude of 10 % and 20 % of the maximum test level may not be possible for certain pulse generators.

5.5.3 Measurement procedure

The measurement procedures shall be as follows:

a) Set up a DUT and measurement instruments according to 5.2.
b) Set up the test circuit configuration in the desired test modes (see 5.4).
c) Inject a pulse into the DUT with the verified generator charging voltages in 5.5.2.
d) Record the measurement results of the residual waveform. Either the current waveform or voltage waveform shall be measured.
e) Compare the results to the performance criteria (see 5.6).

5.6 Evaluation of test results

The pass/fail results shall be classified in terms of the peak current or voltage, the peak rate of rise and root action at the output of a HEMP combination filter. The required performance criteria are given in Table 4, Table 5 and Table 6 for the early-time HEMP test.

Table 4 – Performance criteria of filter against early-time HEMP – AC power port with nominal load 2 Ω

Severity Level	Protection Concepts	Peak residual current or voltage		Peak rate of rise	Root action
		I_{Load}, A	U_{Load}, V	A/s	$A\sqrt{s}$
Level 1	IEC 61000-6-2 (industrial)	$U_{\text{Load}} / R_{\text{Load}}$	$2 \cdot \hat{U}_{\text{Nom}}$ [a]	2×10^{8}	3,2
Level 2	Critical infrastructures	50	100	5×10^{7}	$8,0 \times 10^{-1}$
Level 3	Special case (Mil-Std-188-125-1)	10	20	10^{7}	$1,6 \times 10^{-1}$
Level X	User defined	UD [b]	UD	UD	UD

[a] $\hat{U}_{\text{Nom}}$ is the peak value of the nominal operating voltage.

[b] UD means “user defined”.

Table 5 – Performance criteria of filter against early-time HEMP – DC power port with nominal load 2 Ω

Severity Level	Protection Concepts	Peak residual current or voltage		Peak rate of rise	Root action
		I_{Load}, A	U_{Load}, V	A/s	$A\sqrt{s}$
Level 1	IEC 61000-6-2 (industrial)	$U_{\text{Load}} / R_{\text{Load}}$	$\hat{U}_{\text{Nom}}$ [a]	2×10^{8}	3,2
Level 2	Critical infrastructures	50	100	5×10^{7}	$8,0 \times 10^{-1}$
Level 3	Special case (Mil-Std-188-125-1)	ND [b]	ND	ND	ND
Level X	User defined	UD [c]	UD	UD	UD

[a] $\hat{U}_{\text{Nom}}$ is the peak value of the nominal operating voltage.

[b] ND means that a value is not defined within the protection concept reference.

[c] UD means “user defined”.

**Table 6 – Performance criteria of filter against early-time HEMP –
Signal, data and control port with nominal load 50 Ω**

Severity Level	Protection Concepts	Peak residual current or voltage		Peak rate of rise	Root action
		I_{Load}, A	U_{Load}, V	A/s	$A\sqrt{s}$
Level 1	IEC 61000-6-2 (industrial)	U_{Load} / R_{Load}	$\hat{U}_{\text{Nom}}$ [a]	2×10^{8}	$3{,}2 \times 10^{-1}$
Level 2	Critical infrastructures	1	50	5×10^{7}	$8{,}0 \times 10^{-2}$
Level 3	Special case (Mil-Std-188-125-1)	0,1[b] 1[c]	5[b] 50[c]	10^{7}	$1{,}6 \times 10^{-3}$ [b] $1{,}6 \times 10^{-2}$ [c]
Level X	User defined	UD [d]	UD	UD	UD

[a] $\hat{U}_{\text{Nom}}$ is the peak value of the nominal operating voltage.

[b] Applies to the device with an operating voltage less than 90 V.

[c] Applies to the device with an operating voltage of 90 V and greater.

[d] UD means "user defined".

For the intermediate-time HEMP test, residuals are not defined. However the test shall be performed to ensure that the HEMP combination filter is not damaged during the test. This shall be checked by ensuring that the HEMP combination filter operates normally after the test.

5.7 Test report

For each step in the testing sequence, the following parameters should be included in the test report:

a) Waveform, peak current and source impedance of verified pulse.
b) Test mode, wiring set up (including connection diagram if different from examples given).
c) Test load resistance.
d) Peak current or voltage of residual pulse.
e) Measured waveform of residual pulse.
f) Maximum di/dt, and root integral of residual pulse, if required.
g) Comparison of results with required performance criteria.

The total number of pulses applied to the DUT during the test sequence should be recorded.

6 Measurement method of HEMP protectors for RF antenna ports

6.1 General

For the early-time HEMP, the high-amplitude electric field couples efficiently to antennas which are used within the frequency spectrum of HEMP. The HEMP coupling into the antenna is called front-door coupling. The antenna coupling mechanism is extremely variable and dependent on the details of the antenna design. The near worst-case peak response of a vertical electric monopole to the HEMP early-time waveform is considered for the test level for RF antenna ports. The waveforms for the conducted environments at antenna ports are damped sinusoids with a frequency approximately equal to the designed dominant response frequency f_{c} of the antenna.

6.2 Test level and injection waveform specification

Table 7 – Pulsed current injection test level for RF antenna ports

Type of Injection	Dominant response frequency f_c, MHz	Peak current injection [a] test level, A	Injection waveform	Rise time ns	FWHM ns
Inner conductor to outer shield	≤ 30	1 200	[b] Double exponential	Refer to Table 1	Refer to Table 1
	[c] 30 < f_c ≤ 1 000	36 000/f_c, in MHz	Damped sinusoidal	3 ± 2	30 ± 20

[a] The test level in the current is measured with the condition of short-circuit of the output of the generator.

[b] Double exponential waveform of conducted early-time HEMP shown in Table 1.

[c] Above 1 GHz, the HEMP requirement is under consideration.

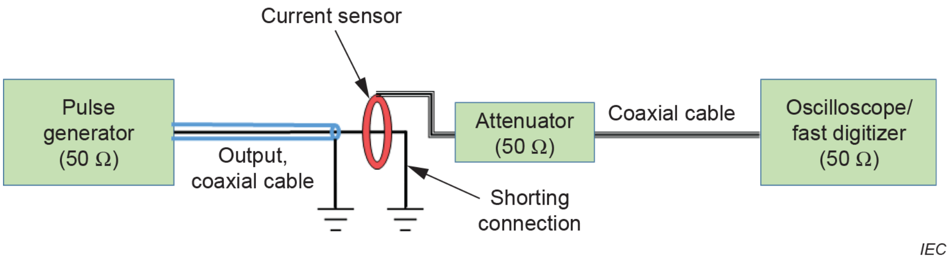
The early-time HEMP double exponential waveform shall be used for antenna port testing at a dominant response frequency ≤ 30 MHz. The double exponential generator is used because most of the energy content of early time HEMP is below 30 MHz. The double exponential generator specified in Table 1 is needed to reach the peak test level.

A damped sinusoidal waveform shall be used for antenna port testing when its dominant response frequency is 30 MHz ≤ f ≤ 1 000 MHz. A recommended waveform is provided in IEC 61000-2-10:2021, Annex E. If the required current injection level exceeds the damped sinusoidal pulse generator capability, an early-time HEMP double exponential waveform shall be used.

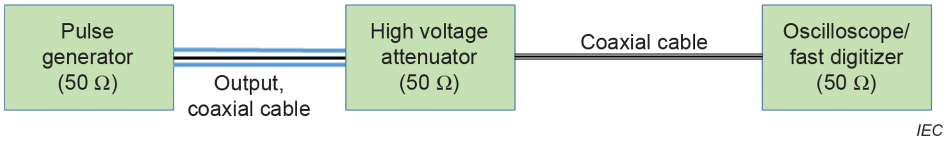
If the output voltage of a damped sinusoidal pulse generator is measured instead of short-circuit current, the test level voltage shall be determined by multiplying the required current test level, specified in Table 7, with the antenna load impedance (usually 50 Ω).

6.3 Verification of test level

The configuration for test level verification is shown in Figure 9.



(a) Configuration of verification for short-circuit current test level



(b) Configuration of verification for test level in voltage

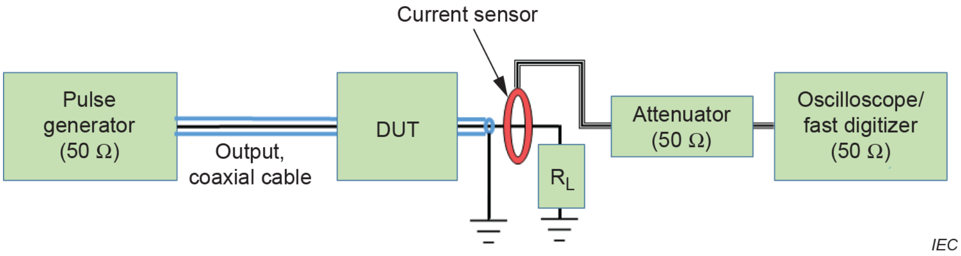
Figure 9 – Typical verification setup

Parasitic coupling between the pulse generator and the oscilloscope shall be avoided. It is recommended to use cables with multiple braided wire shields or solid shields. The cable and connectors shall be capable of withstanding the high voltage pulse without a breakdown. The shorting connection shall be as short as possible.

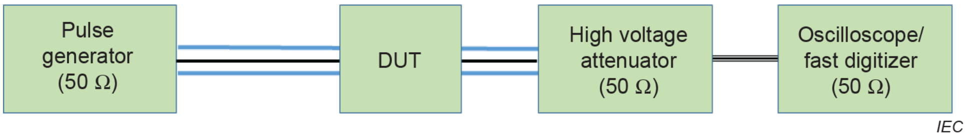
Perform the verification of the test level with 10 %, 25 %, 50 % and 100 % of the maximum test current and record the verified levels, the charging voltage and settings of the pulse generator required to achieve these test levels.

6.4 Measurement procedure

The measurement setup is shown in Figure 10.



(a) Setup for current measurement at DUT output with a 50 Ω resistive load (R_L)



(b) Setup for voltage measurement at DUT output

Figure 10 – Typical measurement setup

The measurement procedures shall be as follows:

a) Set up the DUT and measurement instruments as shown in Figure 10.
b) Inject a pulse three times into the DUT with the generator charging voltages verified in 6.3.
c) Record the measurement results of the DUT output waveform. Either the current waveform or voltage waveform shall be measured.
d) Compare the results to the performance criteria (see 6.5).

6.5 Evaluation of test results

The pass/fail results shall be classified in terms of the peak current or voltage at the output of a HEMP protector for an RF antenna. The required performance criteria are given in Table 8 for the early-time HEMP test.

Table 8 – Performance criteria of filters against early-time HEMP – RF antenna ports

RF antenna port mode	Peak residual norms	
	I_{Load}, A	U_{Load}, V
For receive only systems	< 0,5	$I_{\text{Load}} \times R_L$

The test shall be performed to ensure that the DUT is not damaged during the test. This shall be checked by ensuring that the DUT operates normally after the test.

In general, the manufacturer of the DUT shall specify the peak residual voltage and the residual energy into the nominal load. These values have to be compared with the immunity levels of the device to be protected (receiver, transmitter, antenna matching unit etc). Refer to Annex C.

6.6 Test report

For each step in the testing sequence, the following parameters should be included in the test report:

a) waveform, peak current and source impedance of verified pulses;
b) test mode;
c) test load resistance;
d) peak current or voltage of residual pulses;
e) measured waveforms of residual pulses;
f) comparison of results with immunity levels of equipment to be protected;
g) performance of additional tests with equipment to be protected as a load to verify proper protection.

Annex A

(informative)

Investigation for the establishment of a measurement setup

A.1 General

With the measurement setup some variations were investigated for improvement of the repeatability and reproducibility of the measurement result. Annex A summarises this investigation to illustrate the sensitivity of the test procedure to the test setup.

A.2 Variation of the cable connected for the measurement of short-circuit current

The output of the pulse generator shall be calibrated prior to applying a pulse to a protective device. The setup for calibration is illustrated in Figure A.1.

For the calibration of the short-circuit current waveform, the output of the pulse generator shall be shorted to the ground of the generator through a cable, L1. The current on the cable shall be measured using a current sensor and an oscilloscope.

It was investigated how the wave shape is affected by the variation of the size and the length of the cable. Measurements were performed with the cables having a cross-section of 9 mm^2 and 4 mm^2, and varying the length of the cable L1 as follows: 0,2 m, 0,3 m, 0,4 m, 0,5 m, 0,6 m, 0,7 m, 0,8 m, 0,9 m, 1,0 m, 1,2 m, 1,4 m, 1,6 m, 1,8 m and 2,0 m.

The measurement results are shown in Table A.1 and Figure A.2 to Figure A.7.

It was concluded that cable L1 for the waveform calibration of short-circuit current shall be as thick and short as possible. It is recommended that the cable L1 shall have a cross-section of 4 mm^2 or more and a length of 0,8 m or less. The cable L1 used in calibration shall be also used in the measurement setup.

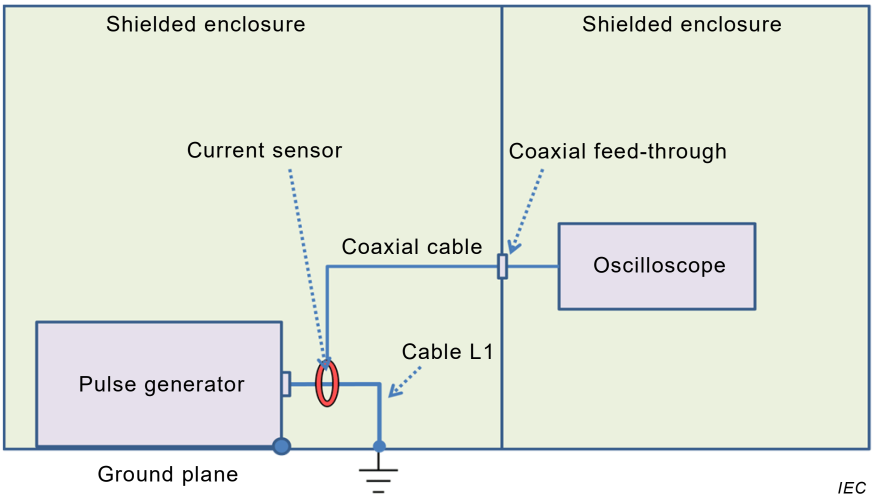


Figure A.1 – Setup for calibration

Table A.1 – Measurement results for the waveform calibration of short-circuit current

	Cross-section, 9 mm^2			Cross-section, 4 mm^2		
L1, m	**Peak current,** A	**Rise time, (< 20 ns)**	**FWHM, (500 ns~ 550 ns)**	**Peak current,** A	**Rise time, (< 20 ns)**	**FWHM, (500 ns ~ 550 ns)**
0,2	1 040,0	12,1	505,8	1 005,0	12,6	497,8
0,3	1 049,0	12,6	525,2	999,6	13,8	506,5
0,4	1 004,8	16,0	525,8	1 030,0	14,4	522,3
0,5	991,4	16,5	521,9	981,4	17,1	532,8
0,6	987,8	17,7	531,6	1 000,4	17,5	531,1
0,7	985,2	19,1	539,9	978,4	18,3	536,8
0,8	973,2	20,1	544,6	989,6	19,0	546,4
0,9	1 001,4	20,6	549,5	964,6	22,4	555,0
1,0	983,2	20,9	544,7	960,0	23,1	552,1
1,2	1002,0	21,4	546,1	959,2	21,7	547,2
1,4	985,0	31,9	564,8	952,2	25,2	563,5
1,6	959,6	23,5	564,8	948,8	32,6	571,9
1,8	969,4	28,8	566,4	937,2	35,8	579,0
2,0	982,6	39,1	582,1	927,0	41,7	585,4

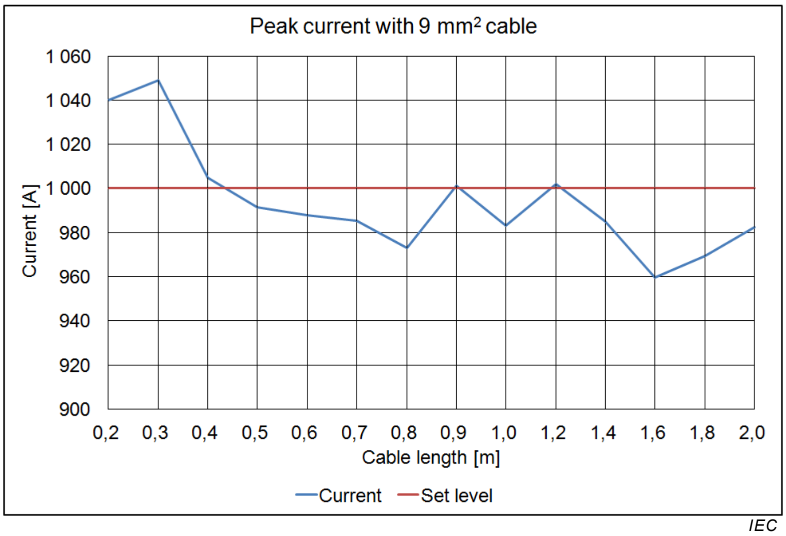


Figure A.2 – Peak current calibration results with 9 mm^2 cables: 1 000 A ± 4 %

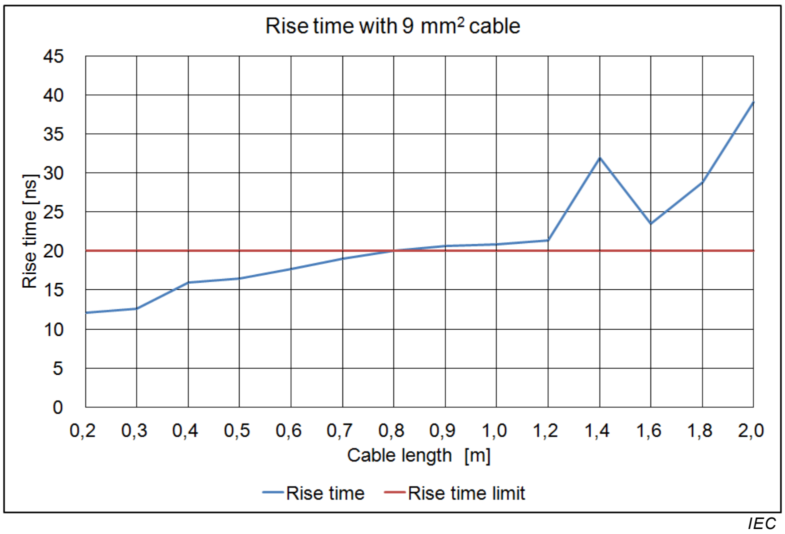


Figure A.3 – Rise time calibration results with 9 mm^2 cables

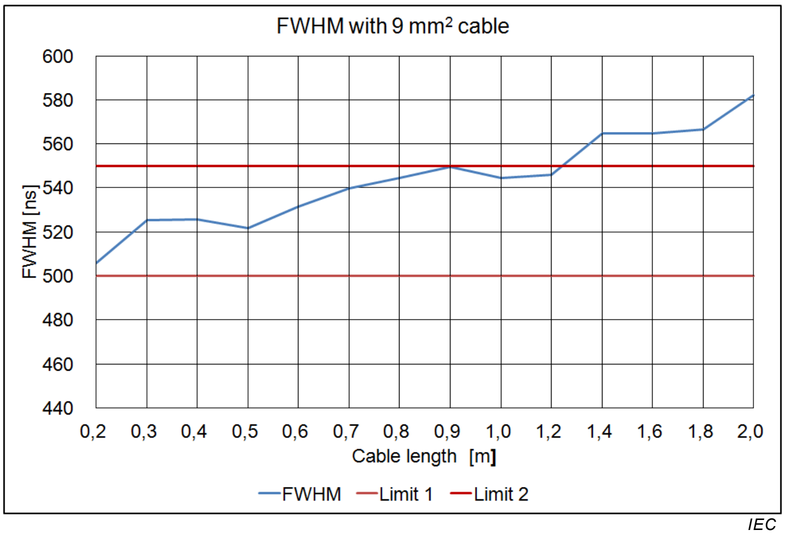


Figure A.4 – FWHM calibration results with 9 mm^2 cables

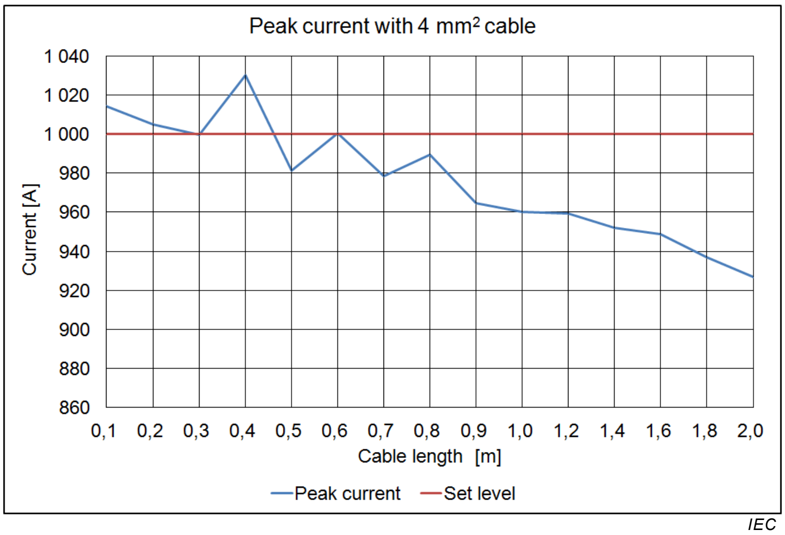


Figure A.5 – Peak current calibration results with 4 mm^2 cables: 1 000 A ± 8 %

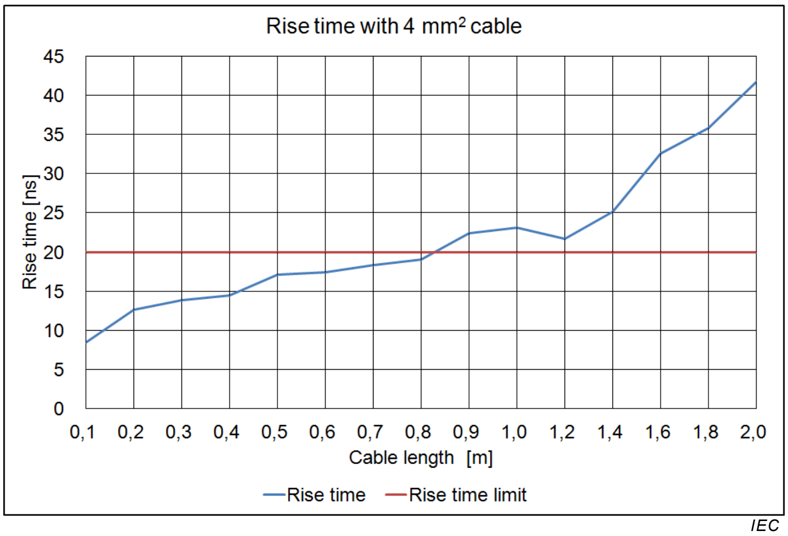


Figure A.6 – Rise time calibration results with 4 mm^2 cables

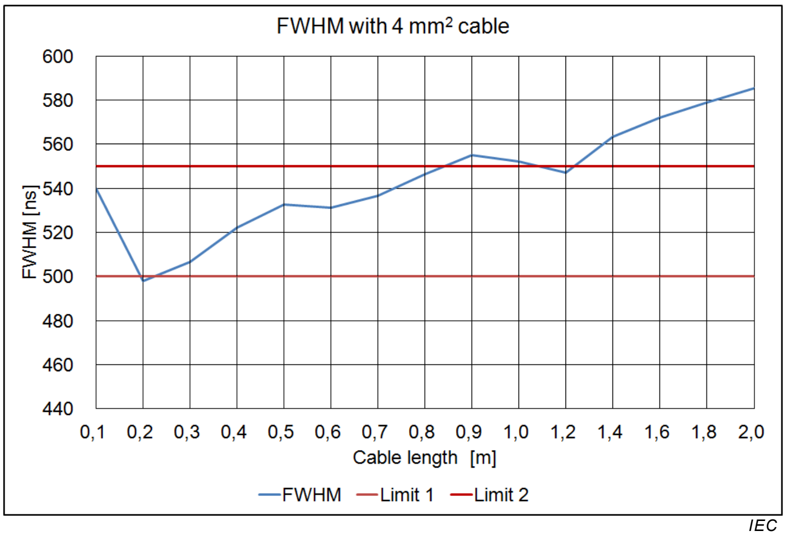


Figure A.7 – FWHM calibration results with 4 mm^2 cables

A.3 Variation of the length of the cable L2 connected for the measurement of residual current

The setup for the residual current measurement is shown in Figure A.8. Residual current is measured on the cable L2 at the output of the protective device using current sensor 2 when a pulse is injected to the input of the protective device.

It is generally required to measure the peak current, peak rate of rise and root action of the residual current waveform when the protective device performance is measured.

It was investigated how the wave shape is affected by the variation of the cable length L2.

A short pulse of 1 kA current is injected to a HEMP combination filter using a 0,4 m cable L1; the measurement was performed with the cables having a cross-section of 4 mm^2, and varying the length of the cable L2 as follows: 0,2 m, 0,3 m, 0,4 m, 0,5 m, 0,6 m, 0,7 m, 0,8 m, 0,9 m and 1,0 m. In this case, the load impedance was 2 Ω.

The measurement results are shown in Table A.2 and Figure A.9 to Figure A.11.

It was concluded that the length of cable L2 for residual current measurement was not so much affected with the variation of the length in this measurement, because the rise time of the residual current was already slowed by the action of the protective device.

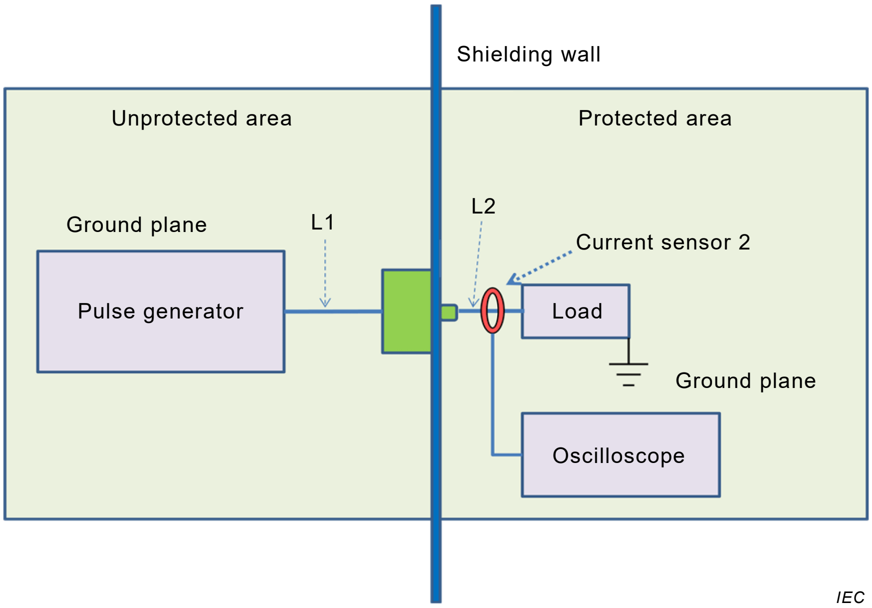


Figure A.8 – Measurement setup for residual current

Table A.2 – Measurement results for variation of the cable length at the measurement points

Cross-section, 4 mm^2						
L2, m	**Measurement results**			**Limit**		
	Peak current A	**Peak rate of rise**	**Root action**	**Peak current** A	**Peak rate of rise**	**Root action**
0,2	0,45	$9,0 \times 10^4$	$1,85 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,3	0,45	$8,5 \times 10^4$	$1,85 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,4	0,44	$8,5 \times 10^4$	$1,80 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,5	0,44	$8,5 \times 10^4$	$1,84 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,6	0,42	$9,0 \times 10^4$	$1,75 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,7	0,46	$9,0 \times 10^4$	$1,89 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,8	0,44	$9,0 \times 10^4$	$1,82 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,9	0,44	$9,0 \times 10^4$	$1,82 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
1,0	0,46	$9,0 \times 10^4$	$1,92 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
2,0	0,43	$8,5 \times 10^4$	$1,81 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
3,7	0,45	$8,5 \times 10^4$	$1,95 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$

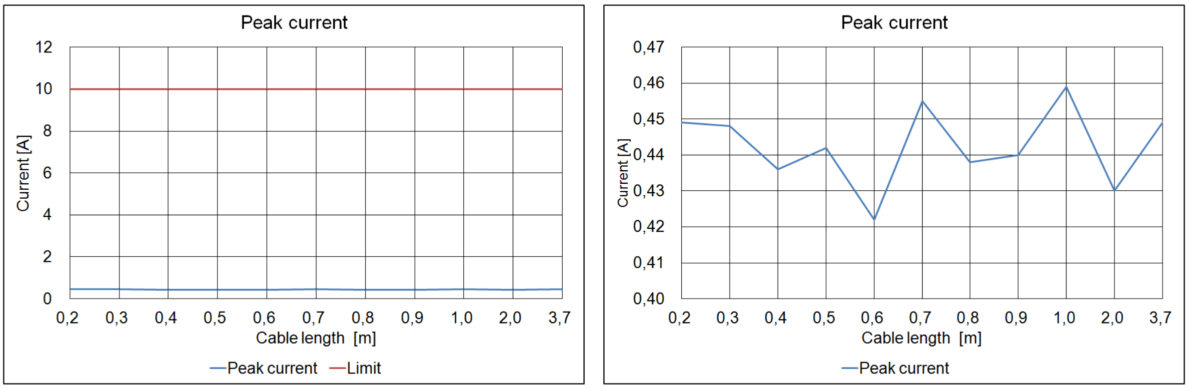


Figure A.9 – Measurement result of peak current with variation of measurement cable L2

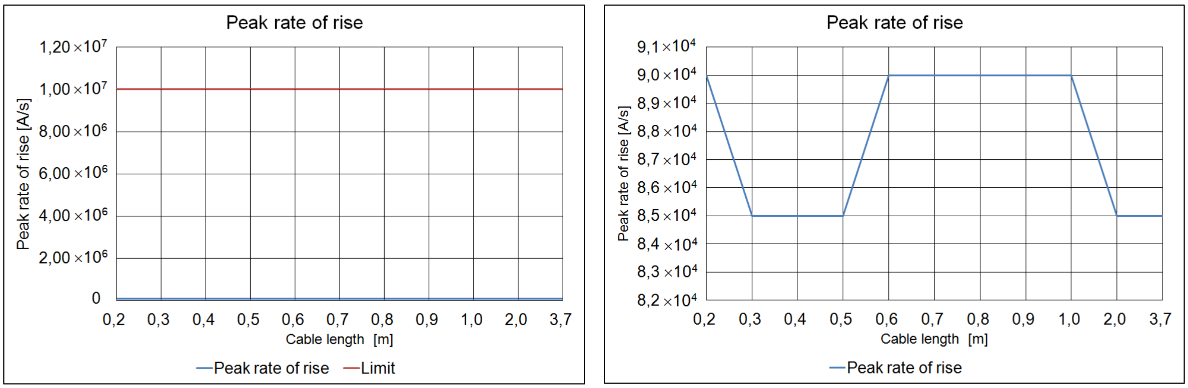


Figure A.10 – Measurement result of peak rate of rise with variation of measurement cable L2

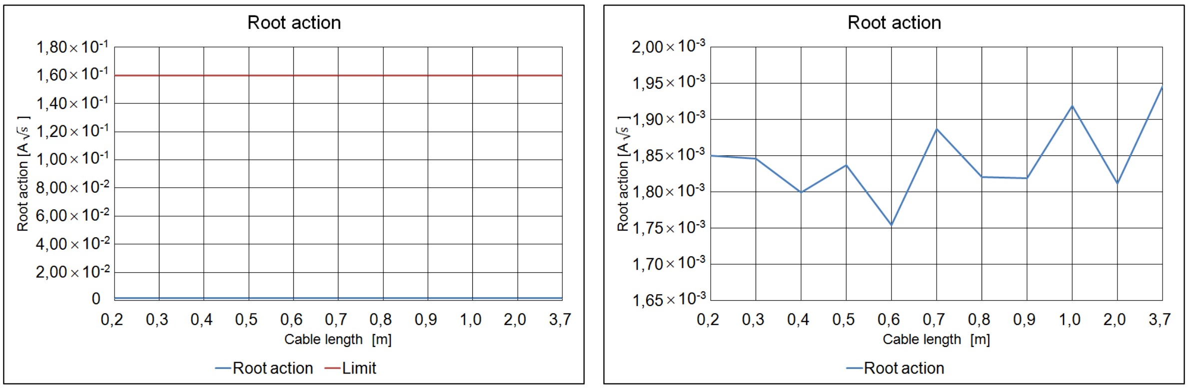


Figure A.11 – Measurement result of root action with variation of measurement cable L2

In addition, the measurement was performed with the three different positions as follows (see Figure A.12):

– Position 1: current sensor 2 is at the terminal side of the output (protected area) of a protective device.

– Position 2: current sensor 2 is at the middle point of the cable L2, which is different depending on the cable length.

– Position 3: current sensor 2 is at the end of the cable at load side.

Measurement results are shown in Figure A.13 to Figure A.15.

It was concluded that the positions of current sensor 2 for residual current measurement were not so much affected by the measurement results, because the rise time of the residual current was already slowed by the action of the protective device. Therefore, it is recommended that current sensor 2 shall be placed within 0,15 m from the output terminal (protected area) of the protective device.

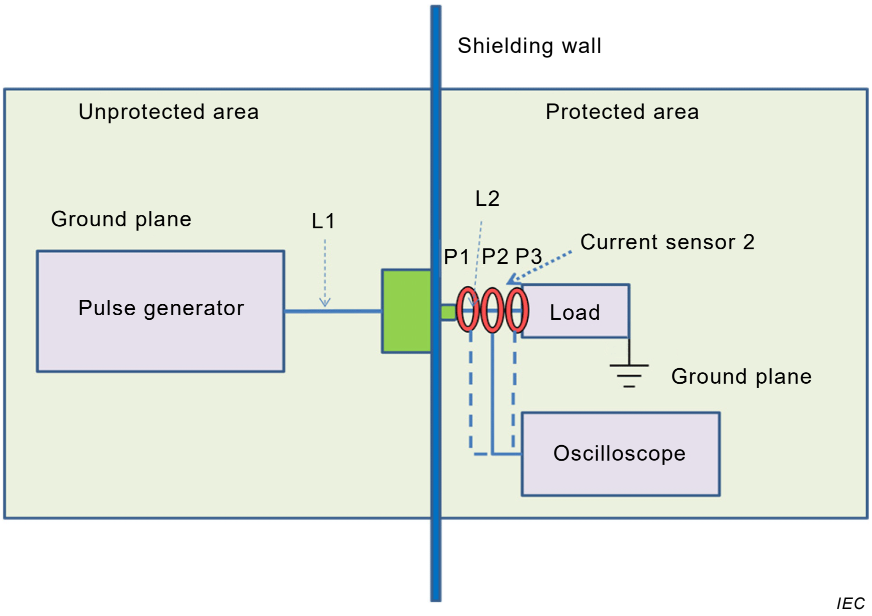


Figure A.12 – Variation of the position of current sensor 2 on the measurement cable L2

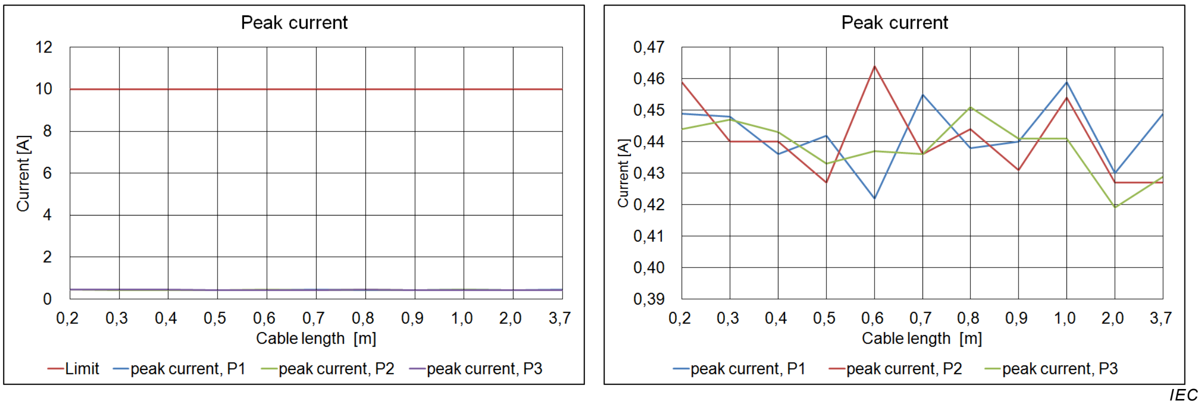


Figure A.13 – Peak current with variation of cable L2 and at different positions

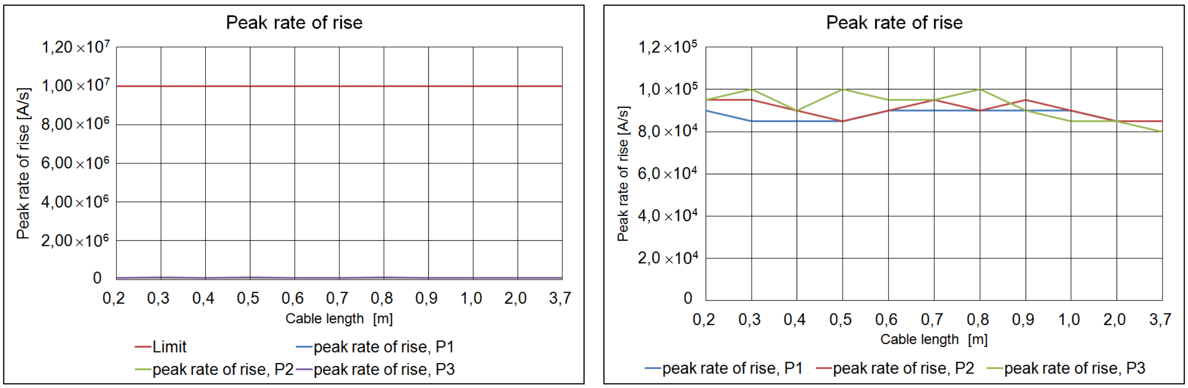


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Figure A.14 – Peak rate of rise with variation of cable L2 and at different positions

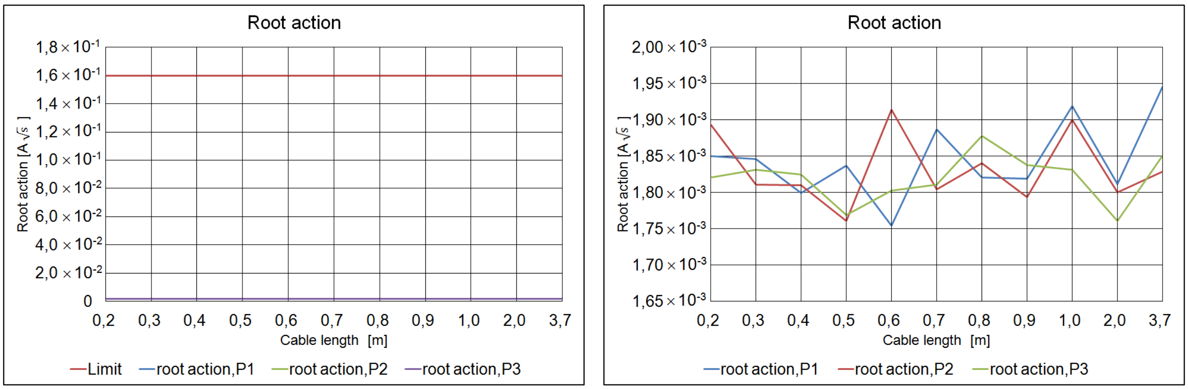

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Figure A.15 – Root action with variation of cable L2 and at different positions

A.4 Variation of load impedance and cable length for connection between load and ground

For the measurement setup (see Figure A.8), the measurement results of a variation of load impedance are shown in Table A.3 and Figure A.16 to Figure A.18.

It was concluded that increasing the load impedance for residual current measurement could reduce the measurement dynamic range. Therefore, it is recommended that load impedance for the measurement of residual current is low. In this case, the voltage measurement is possible for the residual current with the voltage probe at the defined load impedance. The measured voltage can be converted to current.

Table A.3 – Measurement results for variation of the load impedance

Cross-section, 4 mm^2							
Load	Measurement results				Limit		
	Peak current A	Calculated voltage V	Peak rate of rise	Root action	Peak current A	Peak rate of rise	Root action
5 Ω	0,16	0,78	$1,3 \times 10^{4}$	$1,1 \times 10^{-3}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$
10 Ω	0,09	0,86	$6,3 \times 10^{3}$	$7,7 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$
20 Ω	0,05	0,96	$2,5 \times 10^{3}$	$5,6 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$
30 Ω	0,03	0,94	$1,7 \times 10^{3}$	$4,1 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$
35 Ω	0,03	0,95	$1,4 \times 10^{3}$	$3,7 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^{7}$	$\leq 1,6 \times 10^{-1}$

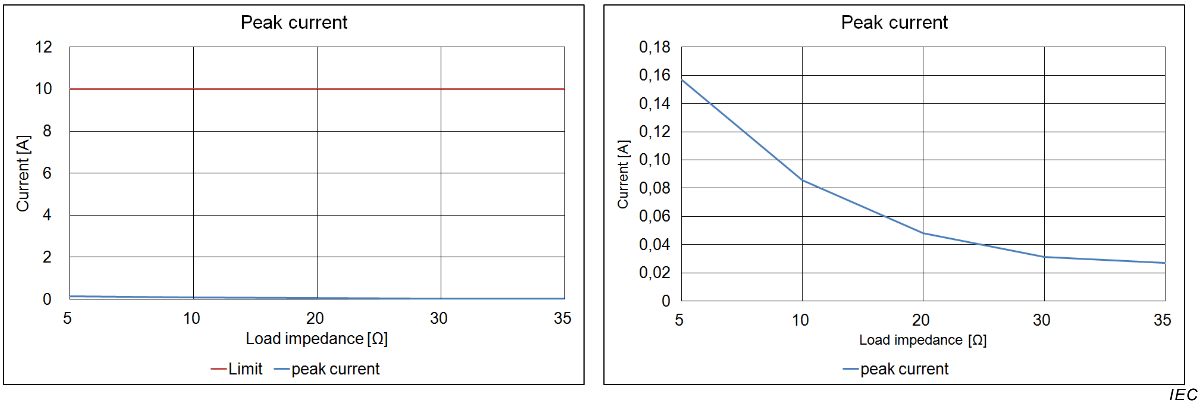


Figure A.16 – Measurement result of peak current with variation of load impedance.

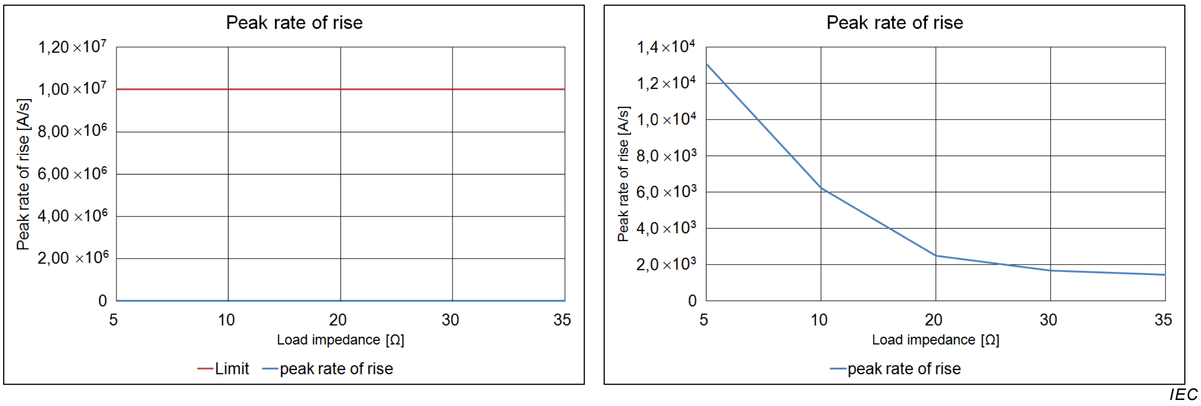


Figure A.17 – Measurement result of peak rate of rise with variation of load impedance

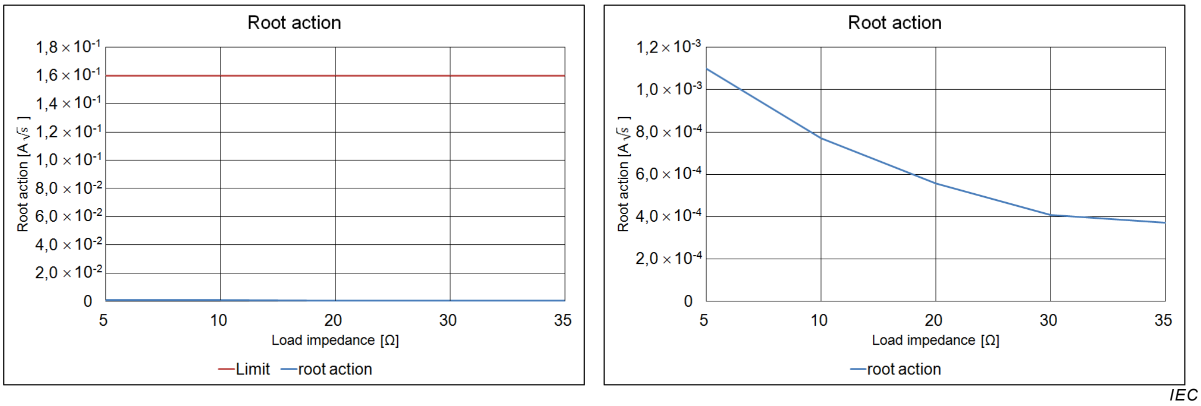


Figure A.18 – Measurement result of root action with variation of load impedance.

A.5 Variation of the cable length between load and ground

Measurement setup of the variation of the cable length L3 between load and ground is shown in Figure A.19.

The measurement results are shown in Table A.4 and Figure A.20 to Figure A.22.

It was concluded that the length of cable (L3) connected between load and ground plane for residual current measurement was not so much affected with the variation of the length in this measurement, because the rise time of the residual current was already slowed by the action of the protective device.

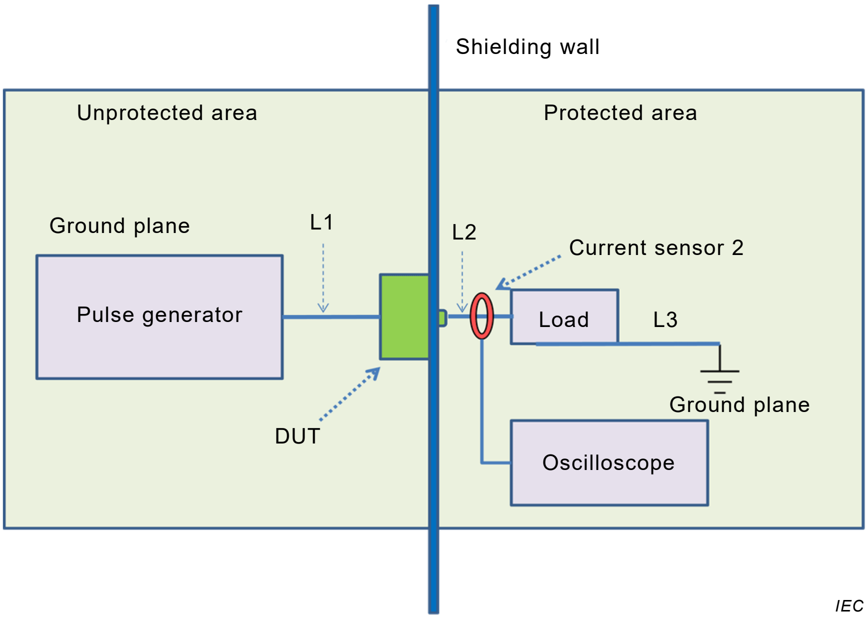


Figure A.19 – Variation of the length of cable L3 connected between load and ground plane

Table A.4 – Measurement results for variation of the cable length between load and ground

Cross-section, 4 mm^2						
L3, m	**Measurement results**			**Limit**		
	Peak current, A	**Peak rate of rise,**	**Root action**	**Peak current,** A	**Peak rate of rise**	**Root action**
0,1	0,027	$1,4 \times 10^3$	$3,7 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,2	0,027	$1,6 \times 10^3$	$3,7 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,3	0,026	$1,5 \times 10^3$	$3,6 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,4	0,027	$1,4 \times 10^3$	$3,6 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$
0,5	0,026	$1,4 \times 10^3$	$3,5 \times 10^{-4}$	≤ 10	$\leq 1,0 \times 10^7$	$\leq 1,6 \times 10^{-1}$

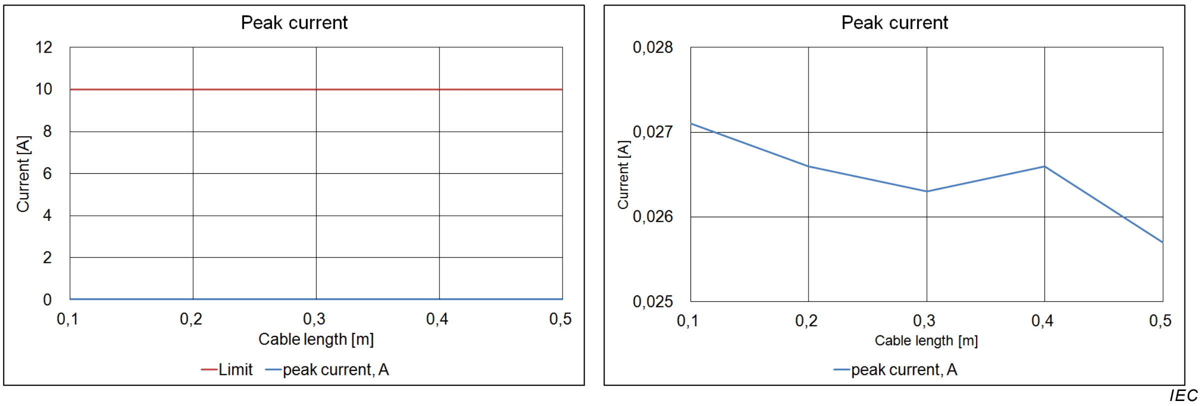


Figure A.20 – Measurement result of peak current with variation of measurement cable L3

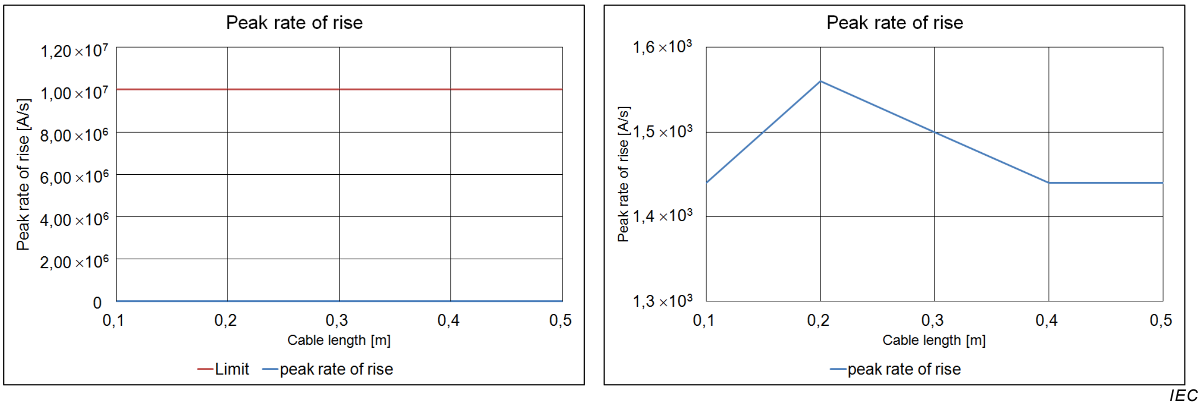


Figure A.21 – Measurement result of peak rate of rise with variation of measurement cable L3

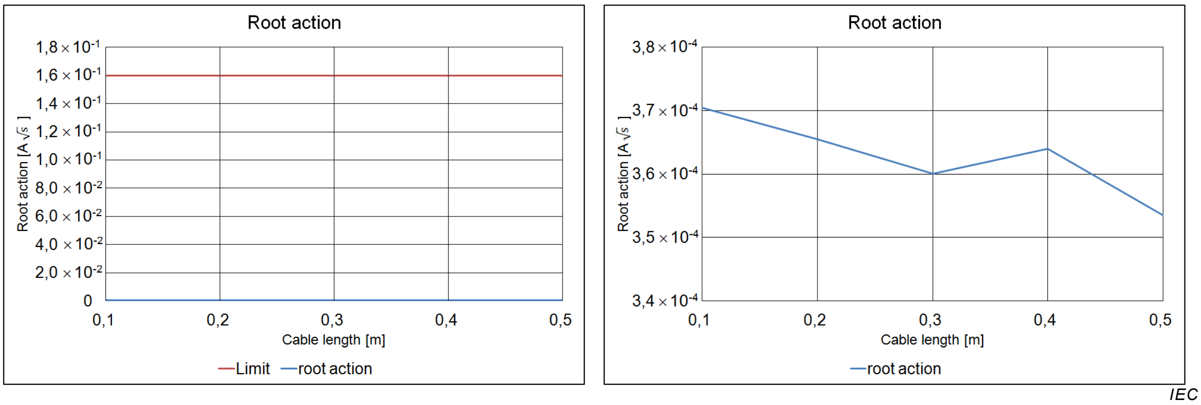


Figure A.22 – Measurement result of root action with variation of measurement cable L3

Annex B
(informative)

Test method for the quantitative determination of the direct response behaviours of a coaxial surge protector

Annex B provides a practical method to obtain the direct response behaviours of a surge protective device (SPD), especially the coaxial type protector, and of a voltage breakdown device, for example a gas discharge tube (GDT). This method covers the residual voltage measurement, the response time measurement and the direct voltage-limiting response behaviour flowing through an SPD in the time domain.

The test setup consists of a pulse generator, launching line, wide-band power divider, attenuators, oscilloscope and coaxial cables as shown in Figure B.1.

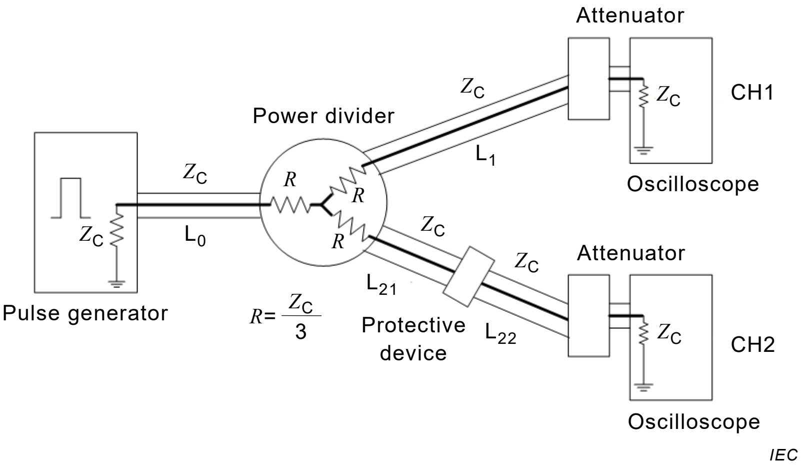


Figure B.1 – Test setup with a power divider for testing protective devices

The launching line is connected to the power divider, and the DUT is connected to one of the circuit branches of a power divider.

A power divider is used to match the impedance at each branch circuit in order to keep the same surge impedance along the direction of the propagating wave. Cables, attenuators and termination loads in the test setup are well matched. The power divider should be designed to avoid breakdown and to confirm the accuracy of the resistances inside the power divider to mitigate symmetric error.

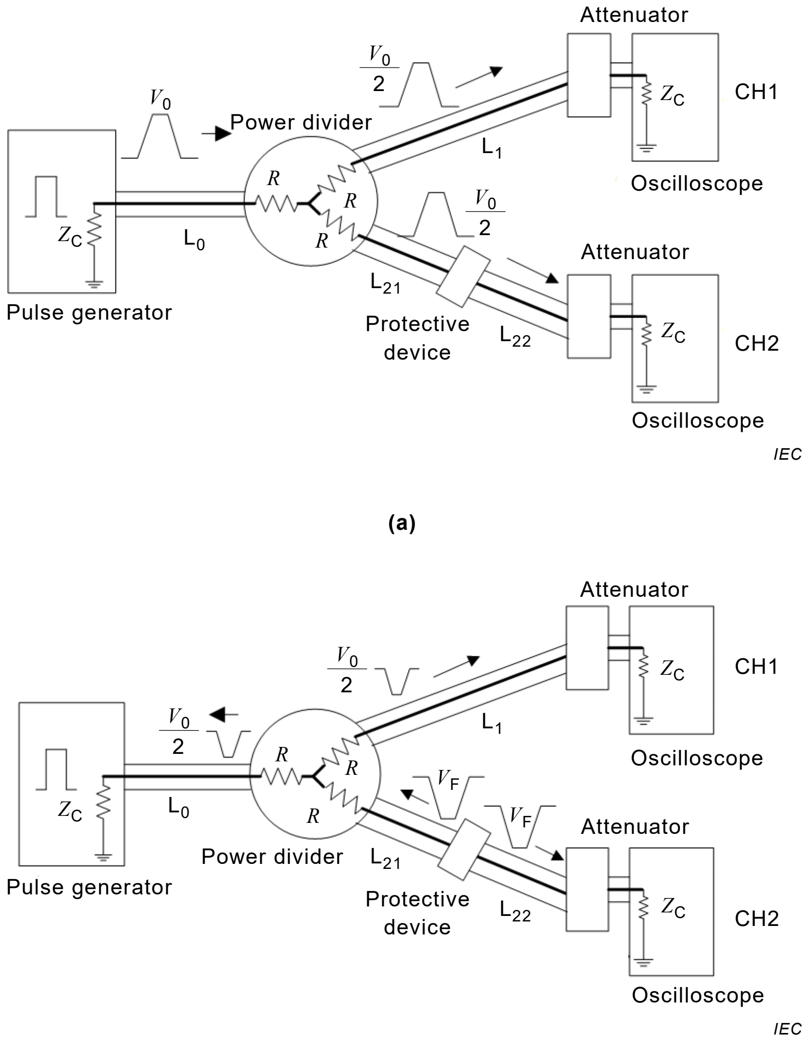
The three branches are the launching branch (L_0), the normal branch (L_1) and the DUT branch (L_2), respectively. The characteristic impedance of each branch is equal to Z_c, for example 50 Ω or 75 Ω.

One has to be aware of the following aspects:

- In order to match the forward and backward travelling wave propagating along the cables, the terminal loads of each branch should also be equal to Z_c and the value of each resistance inside the power divider should be $\frac{Z_c}{3}$.
- It is reasonable to neglect the waveform distortion due to the propagation along the branch cable since the length of the cable is sufficiently short.

The waveform at the terminal of the normal branch and the DUT branch should be recorded by two channels of the same oscilloscope.

Figure B.2 shows V_0 (before the surge arrester firing) and V_F (after the surge arrester firing) propagating along the branches.



(a)

(b)

Figure B.2 – Waves propagating along the branches

The measured waveforms at each branch terminal are shown as follows:

- Normal branch:

$$V_{CH1}(t) = \frac{1}{A} \cdot \left[\frac{V_0\left(t - \tau_{L0} - \tau_{L1}\right)}{2} + \frac{V_0\left(t - \tau_{L21} - \tau_{L1}\right)}{2} \right] \tag{B.1}$$

- DUT branch:

$$V_{CH2}(t) = \frac{1}{A} \cdot \left[\frac{V_0\left(t - \tau_{L0} - \tau_{L21} - \tau_{L22}\right)}{2} + V_F\left(t - \tau_{L22}\right) \right] \tag{B.2}$$

where A is the attenuation factor of the attenuator, $A = \frac{V_{\mathrm{in}}}{V_{\mathrm{out}}}$ (for a commercial attenuator, the attenuation factor is usually given in decibels, thus conversion to a ratio is essential), and τ_{L0} τ_{L1} τ_{L21} τ_{L22} stand for the time delays on the corresponding coaxial cable. Notice that if the dimension of the DUT or the power divider is not negligible, the time delay within the devices should be taken into consideration as well.

One can directly get the response time of the SPDs by comparing the two measured waveforms. Moreover, by solving the equation set (B.1) and (B.2), we can obtain the output pulse of generator $V_0(t)$, the applied pulse on the DUT $\frac{V_0(t)}{2}$ and the induced pulse $V_{\mathrm{F}}(t)$ which is the direct response behaviour flowing through the SPD in the time domain.

For practical applications, a simplified test setup could be applied when the dimension of the power divider or the DUT is small enough to neglect the time delay when the wave propagates through these devices. Figure B.3 shows the simplified test setup for this case.

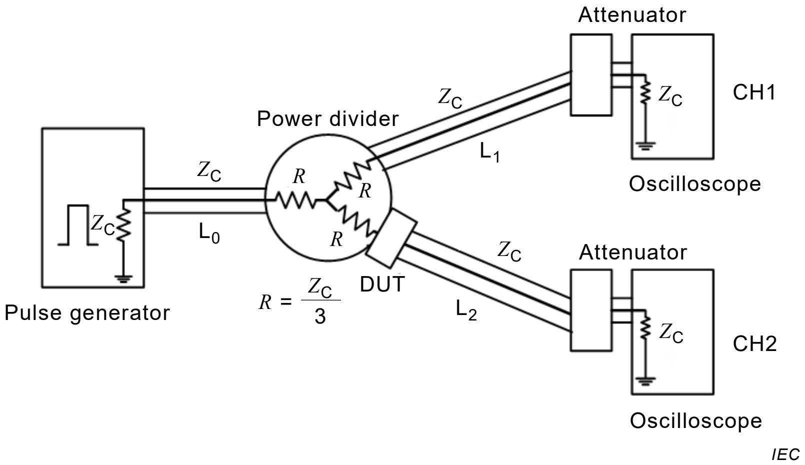


Figure B.3 – Simplified test setup for testing protective devices

The distinctive features of the simplified proposed test setup are as follows:

- The power divider and the DUT are connected directly, and the dimension of the power divider and the DUT are small enough to neglect time delay τ_{L21}.
- Choose the same length for cable L$_1$ and cable L$_2$, to make sure the two branches' waveforms reach the terminals at the same time to simplify the computation.

With $\mathrm{L}_1 = \mathrm{L}_2 = \mathrm{L}$, the measured waveforms at each branch terminal could be simplified as follows:

- Normal branch:

$$V_{\mathrm{CH1}}(t) = \frac{1}{A} \cdot \left[\frac{V_0(t - \tau_{\mathrm{L0}} - \tau_{\mathrm{L}})}{2} + \frac{V_{\mathrm{F}}(t - \tau_{\mathrm{L}})}{2} \right] \tag{B.3}$$

- DUT branch:

$$V_{\mathrm{CH2}}(t) = \frac{1}{A} \cdot \left[\frac{V_0(t - \tau_{\mathrm{L0}} - \tau_{\mathrm{L}})}{2} + V_{\mathrm{F}}(t - \tau_{\mathrm{L}}) \right] \tag{B.4}$$

Where, τ_{L0} and τ_{L} stand for the time delays of the corresponding coaxial cable.

The time delays of the applied pulse V_0 on the two branches are the same, along with the induced wave $V_{\mathrm{F}}(t)$. From the DUT point of view, we can obtain the applied pulse and the induced pulse by the following computation.

- Applied pulse:

$$\frac{V_0(t-\tau_{\mathrm{L0}}-\tau_{\mathrm{L}})}{2} = A \cdot [2V_{\mathrm{CH1}}(t) - V_{\mathrm{CH2}}(t)] \quad \text{(B.5)}$$

- Induced pulse caused by the “fired” test device:

$$V_{\mathrm{F}}(t-\tau_{\mathrm{L}}) = 2A \cdot [V_{\mathrm{CH2}}(t) - V_{\mathrm{CH1}}(t)] \quad \text{(B.6)}$$

The time delay of the induced waveform V_{F} with respect to the applied pulse $\frac{V_0}{2}$ is the response time of the voltage breakdown device.

Annex C
(informative)

Residual measurements for antenna port protectors

C.1 Evaluating the required protection for RF antenna ports

When evaluating the effectiveness of conducted HEMP protection for any type of point of entry or point of egress (POE) it is typically the case that some type of residual current or voltage is measured. This is done quite effectively for conducted signal or power lines, which can use an electric surge arrestor (ESA) filter combination to reduce the residual currents or voltages into the device being protected. It is natural then to specify a similar method for evaluating the performance criteria of a HEMP protector for RF antenna ports against early-time HEMP. But there are a number of difficulties with this approach on RF antenna ports. This is especially the case for HF antennas where the early-time HEMP is in-band of both a transmitter and receiver RF port.

Most modern day HF antenna ports connect to equipment that uses the antenna as both a receiving antenna and a transmitter antenna.

This transmit/receive equipment is typically referred to as a transceiver and it is widely used in commercial and military applications.

Thus, the equipment antenna port has two functions; it serves as a receiver port and a transmitter port as shown in Figure C.1.

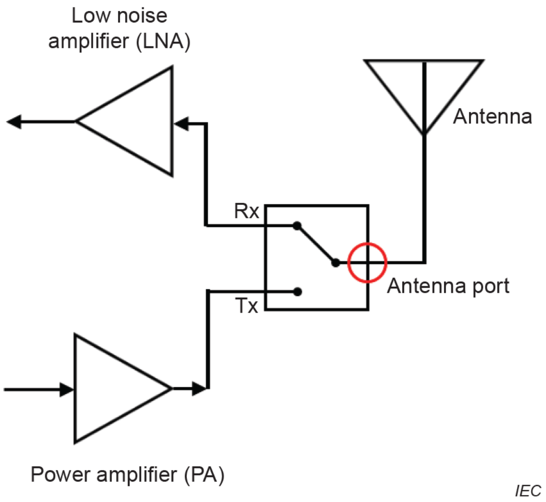


Figure C.1 – Transceiver with antenna port shown

While it can be fairly straightforward to select a protector with particular residuals for the transmitter side, on the receive mode the same protector could not work at protecting the receiver front end of the equipment.

The reason for this is that on transmit, much higher levels of current and voltage are present on the RF port than on the receive mode. Thus a protector external to the equipment's RF port for a transceiver would not protect the equipment when on receive mode operation.

Specifying residuals for an external RF port protector can only be made for the transmit mode of the transceiver and yet this would leave the receive mode vulnerable to breakdown during an early time pulse while on receive operation.

One solution would be to require transceiver manufacturers to add early-time protection internally to the transceiver on the signal path of the receive and transmit modes as shown in Figure C.2.

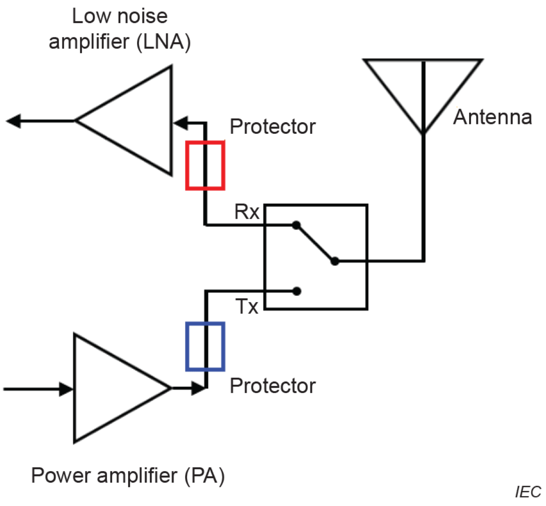


Figure C.2 – Protectors on RX and TX signal path internal to the transceiver after the RF port

This scheme, however, has the disadvantage that it leaves the RF port itself vulnerable to breakdown during an early-time pulse event.

Since the receive front end of the transceiver is the most vulnerable to high voltages and quite sensitive to small signals, it makes sense then that early-time protection should be added internally to the transceiver directly in front of the receiver front end.

In addition, in order to protect both the transmitter side of the transceiver and the antenna RF port itself, the protector for the antenna port may be placed by the equipment owner just outside the RF port as shown in Figure C.3.

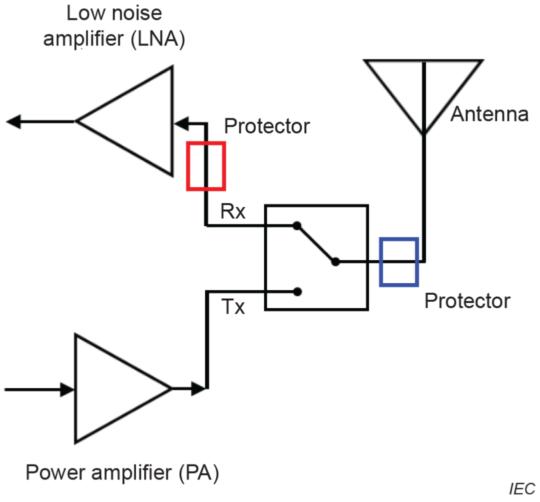


Figure C.3 – Protector internal to equipment for RX side protection and outside the equipment at the antenna port for transmit and port protection

Residuals for the protector of the RF port and transmit side can actually be simple to calculate if the maximum output power of the transmitter is known or the maximum power that the port can handle is known, whichever is lower.

For example, a typical N-type RF connector has a maximum operating RMS voltage of 707 V and a maximum operating power of 10 kW.

In this case, the residual for a protector can be measured in amperes and be limited to a peak current $I_{\text{pk}} = I_{\text{RMS}} \times \sqrt{2}$ of no more than 20 A, where $I_{\text{RMS}} = \sqrt{P/R}$ and R is the typical 50 Ω load of RF systems.

If, however, the transmitter has a maximum operating RF output of 1 000 W, then the residual for a protector should measure a peak of less than 6,3 A.

Allowing the residuals to be higher in this case might damage the transmitter front end even though it would not damage the RF port.

Figure C.4 shows a typical commercially available port protector. However, these devices have typically not been tested for an early-time pulse and let through residual currents are not readily available.

Figure C.4 – N-type RF antenna port protector using GDTs

Computing safe residuals for a protective device on the receive side of the transceiver, as shown in Figure C.3, is a far more complicated problem. Since receivers are sensitive to very small levels of signal, in the order of microvolts, it is incumbent upon the manufacturer to know at what voltage the front end of the receiver will saturate, overload, or stop working.

With this information, protective devices may be added in the receive signal path that can react fast and clamp the early-time pulse peak voltage to a safe level. But because the characteristics of each receiver are different and the semiconductors used can vary in type, it is practically impossible to define a level at which protective devices can be tested in order to ensure survivability of the equipment during an early-time pulse event.

Because HF transceivers (3 MHz to 30 MHz) are in-band of an early-time pulse, transceivers, antennas, and antenna ports in these units are especially vulnerable to damage by a HEMP.

While the use of external port protectors at the antenna port can be useful in protecting against damaging the port or the transmitter sections of a transceiver, it does nothing for the protection of the receive side.

Manufacturers of both protective devices and transceivers may need to come together in this area and devise practical ways of protecting receiver front-ends in transceivers; standardization can then be attempted.

C.2 Evaluating the required protection for RF antenna ports

Effective HEMP-protection of an RF antenna port requires considering the complete system (see Figure C.5). This typically consists of an antenna, a balun (integrated in the antenna), possibly an integrated coarse protection (SPD) in the antenna socket (to protect the balun and the coaxial cable especially against lightning), and an RF SPD at the building entrance or equipment port (or both). Typically a HEMP-protection device (DUT) is located close to the equipment port. This means that in typical RF systems, various protection devices are present in different locations and therefore these need to be well coordinated in order to protect against both lightning and HEMP-transients.

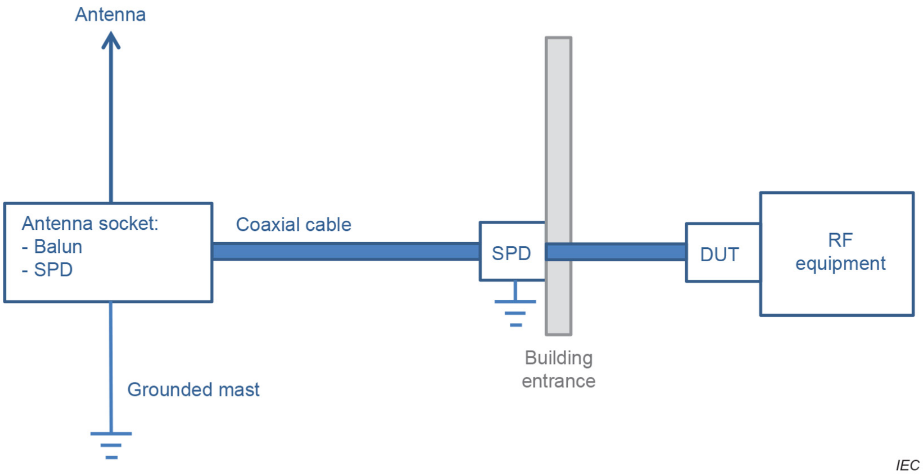


Figure C.5 – Typical antenna system with RF-HEMP protector (DUT)

In order to estimate the required protection level of the DUT in a first step, one has to consider the following characteristics of the RF signals in the coaxial cable:

- maximum RF power (receiver, transmitter or transceiver, modulation etc.);
- operating frequency range and instantaneous bandwidth;
- parameters of the remote power supply on the coaxial cable if applicable (often AC or DC power for the remote supply of amplifiers on the antenna mast is present).

In a second step, two parameters are important to assess the quality of the protection device (DUT): the maximum residual voltage and the maximum residual energy under threat level test conditions. Both the residual voltage and the maximum residual energy can be determined from the tests described in this document.

The residual voltage/current values of the DUT have to be compared with the maximum RF power and the remote power supply characteristics. The peak RF power present in the system also determines the maximum RF operating voltage. For many DUTs, especially those for broadband applications, the protection level should be implemented at a level that is higher than the maximum operating voltage.

The residual energy of the DUT into the nominal load impedance is the second important protection parameter. From the measured residual pulse shape (voltage $U(t)$ or current $I(t)$ as described in the test procedure) and the known load impedance (usually 50 Ω), the residual energy can be easily calculated (it is the integral of $U(t)^2 / R_\mathrm{L}$ or the integral of $I(t)^2 \cdot R_\mathrm{L}$). The achievable residual energy depends on the protection principle and also on the required system bandwidth. Typical residual energy values of DUTs range from a few µJ to several tens of mJ.

Unfortunately, not much information is available about the immunity of RF systems against transients. Nowadays many systems can have at least some level of ESD protection (electrostatic discharge) built-in. If the residual levels of the DUT are lower than the system's immunity levels, then the system is likely to be sufficiently protected against HEMP by the DUT. If there is a choice of several DUTs then the one having the lowest residual voltage and the lowest residual energy is best suited to protect against HEMP.

Ultimately, the safest method to assess the protection is to test the DUT under real operating conditions, i.e. to perform a threat-level test with the system to be protected connected and in operation. For mission critical systems this is the recommended solution.

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