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Road Vehicles — Electrical disturbance by conduction and coupling —

Part 4:
Electrical transient conduction along shielded high voltage supply lines only

Vehicules routiers — Perturbations electriques par conduction et par couplage —

Partie 4: Conduction transitoire electrique seulement le long des lignes à haute tension blindées

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 32, *Electrical and electronic components and general system aspects*.

A list of all parts in the ISO 7637 series can be found on the ISO website.

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Road Vehicles — Electrical disturbance by conduction and coupling —

Part 4: Electrical transient conduction along shielded high voltage supply lines only

1 Scope

This document specifies test methods and procedures to ensure the compatibility to conducted electrical transients along shielded high voltage supply lines of equipment installed on passenger cars and commercial vehicles fitted with electrical systems with voltages higher than 60 V d.c. and lower than 1 500 V d.c. and a power supply isolated from the vehicle body. It describes bench tests for both, injection and measurement of transients. It is applicable to all types of electrical independent driven, road vehicles (e.g. battery electrical vehicle (BEV) or hybrid electrical vehicle (HEV), plugin hybrid electric vehicle (PHEV)).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7637-1, *Road vehicles — Electrical disturbances from conduction and coupling — Part 1: Definitions and general considerations*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 7637-1 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Test methods

4.1 General

Various types of transients appear on the high voltage supply lines generated by the switching of various devices. Pulse A represents ringing caused by switching operations of high voltage semiconductors. Pulse B represents sinusoidal waves generated by harmonics from the grid and revolutions from, for example, electric propulsion motors.

Methods for measuring the transient emission on shielded high-voltage supply lines and test methods for the immunity of devices against transients are given in this document. These tests, called "bench tests", are performed in a laboratory.

The bench-test methods provide comparable and reproducible results between laboratories. They also give a test basis for the development of devices and systems and may be used during the production phase.

A bench-test method for the evaluation of the immunity of a device against supply-line transients may be performed by a test pulse generator. This might not cover all types of transients which can occur in a vehicle. Therefore, all described test pulses are typical pulses.

In special cases, it may be necessary to apply additional test pulses. However, some test pulses may be omitted, if a device, depending on its function or its connection, is not influenced by comparable transients in the vehicle. It is part of the vehicle manufacturer's responsibility to define the test pulses required for a specific device.

There are two types of disturbances:

— Pulsed sinusoidal disturbances (Waveform A);

— Low frequency sinusoidal disturbances (Waveform B).

Pulsed sinusoidal disturbances on high voltage supply lines are caused by overshoots on square wave signals, e.g. produced by interaction of switching IGBTs in high voltage systems with parasitic capacities and inductivities of electrical engine systems, DC-DC-converters and any other kind of high voltage switching/commutation system. Pulsed sinusoidal disturbances on high voltage supply lines can be both common mode [line-to-ground (HV+ or/and HV- to ground)] and differential mode [line-to-line (HV+ to HV-)].

Test pulse A is used for testing high frequency oscillations, e.g. fast switching.

Test pulse B is used to test equipment against transient voltages.

The device under test (DUT) shall be operated under typical conditions which cause the maximum disturbance and sensitivity during the measurement. This is the worst-case mode for every test and frequency step. Conditions shall be agreed between the vehicle manufacturer and the supplier and shall be documented in the test plan.

4.2 Standard test conditions

Standard test conditions according to ISO 7637-1 shall be used for test temperature and supply voltage (low voltage).

The high supply voltage U_N can vary in a range from 60 V d.c. up to 1 500 V d.c. The used high voltage and its allowed tolerances of battery/generator in operation shall be agreed between vehicle manufacturer and supplier and shall be documented in the test plan.

4.3 Ground plane

The ground plane shall be made of 0,5 mm thick (minimum) copper, brass or galvanized steel.

Unless otherwise specified in the test plan, the minimum width of the ground plane shall be 1 000 mm, or underneath the entire setup width (excluding power supply and transient pulse generator) plus 200 mm, whichever is larger.

Unless otherwise specified in the test plan, the minimum length of the ground plane shall be 2 000 mm, or underneath the entire setup length (excluding power supply and transient pulse generator) plus 200 mm, whichever is larger.

4.4 General test setup conditions

The DUT is arranged and connected according to its requirements. The DUT should be connected to the original operating devices (loads, sensors, etc.) and the test setup described in 4.5.2, 4.6.2.1 and 4.6.3.1 shall be used, unless otherwise agreed between the vehicle manufacturer and the supplier.

If the actual DUT operating signal sources are not available, they may be simulated.

Unless otherwise specified in the test plan, all loads, sensors, grounds (lines, metallic cases) are connected to the ground plane.

To minimize extraneous capacitive coupling to the DUT, it is advisable that the minimum distance between the DUT and all other conductive structures, such as walls of a shielded enclosure (with the exception of the ground plane underneath the test setup), should be more than 0,5 m.

4.5 Voltage transient emissions test along high voltage supply lines

4.5.1 General - Test methodology

A DUT which is considered as a potential source of conducted disturbances shall be tested according to the procedure described in this clause.

Transients shall be measured between HV+ and HV- (line-to-line) and between HV+ respectively HV- and ground (line-to-ground).

Care shall be taken to ensure that the surrounding electromagnetic environment does not interfere with the measurement set-up.

4.5.2 Test set-up for emission test

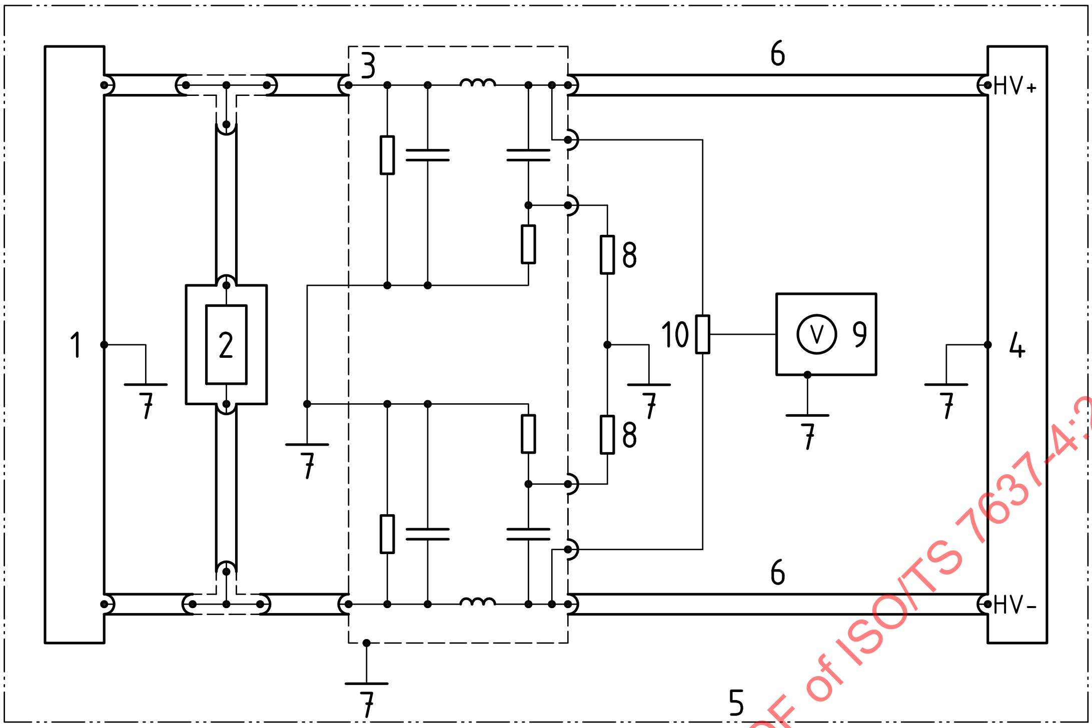
Voltage transients from the DUT, are measured using a high voltage artificial network (HV-AN) (see 5.1) to standardize the impedance loading on the DUT. The DUT is connected via the artificial network to the high voltage power supply (see 5.2) as given in Figure 1.

The length of the high voltage supply line shall be ($500\ ^{+200}_{\ \ 0}$) mm, if not otherwise specified in the test plan. The used cable length shall be documented in the test report.

Ground connection of DUT shall be connected to ground plane. The default length is (200 ±50) mm, if not otherwise specified in the test plan. If the DUT has a metallic case, this case shall be bonded to the ground plane. The DC resistance of the ground connection shall not exceed 2,5 mΩ.

The DUT shall be placed on the ground plane as in the vehicle application. If no other requirements are specified the DUT and all wiring connections between artificial network and DUT shall be placed on a non-conductive, low relative permittivity (dielectric-constant) material ($\varepsilon_r \leq 1{,}4$), at (50 ± 5) mm above the ground plane.

Supply voltage U_N and the disturbance voltage shall be measured close to the DUT terminals using a voltage probe and oscilloscope or waveform acquisition equipment at the power supply terminals (see Figure 1).



Key

1 high voltage power supply (optional: shielded and / or filtered)
2 load for high voltage battery (if necessary, see 5.4)
3 high voltage artificial network (HV-AN)
4 DUT
5 ground plane
6 high voltage supply line
7 ground connection
8 50 Ω termination
9 oscilloscope or waveform acquisition equipment
10 high voltage differential probe

Figure 1 — Transient emission test set-up to measure voltage ripple along high voltage supply lines

Figure 1 shows the test setup for the measurement between HV+ and HV-. For measurement between HV+ and ground or HV- and ground the other terminal of the voltage probe shall be connected to ground.

4.5.3 Test procedure for emission test

The various operating modes and the conditions of the DUT shall be considered for the measurements and specified in the test plan.

The measured transients shall be evaluated according to Annex B. The results shall be documented in the test report.

The voltage amplitude and transient parameters (rise time, fall time, transient duration) shall be recorded and documented in the test report.

4.6 Transient immunity test along high voltage supply lines

4.6.1 General - Test methodology

4.6 provides the test setup and procedure for testing transient immunity.

If not otherwise specified, all transient tests shall be performed between HV+ and HV- (line-to-line) and between HV+ respectively HV- and ground (line-to-ground).

4.6.2 Immunity test for pulsed sinusoidal disturbances (pulse A)

4.6.2.1 Test set-up for immunity test for pulsed sinusoidal disturbances (pulse A)

Figure 2 shows the test setup for coupling between HV+ and HV-.

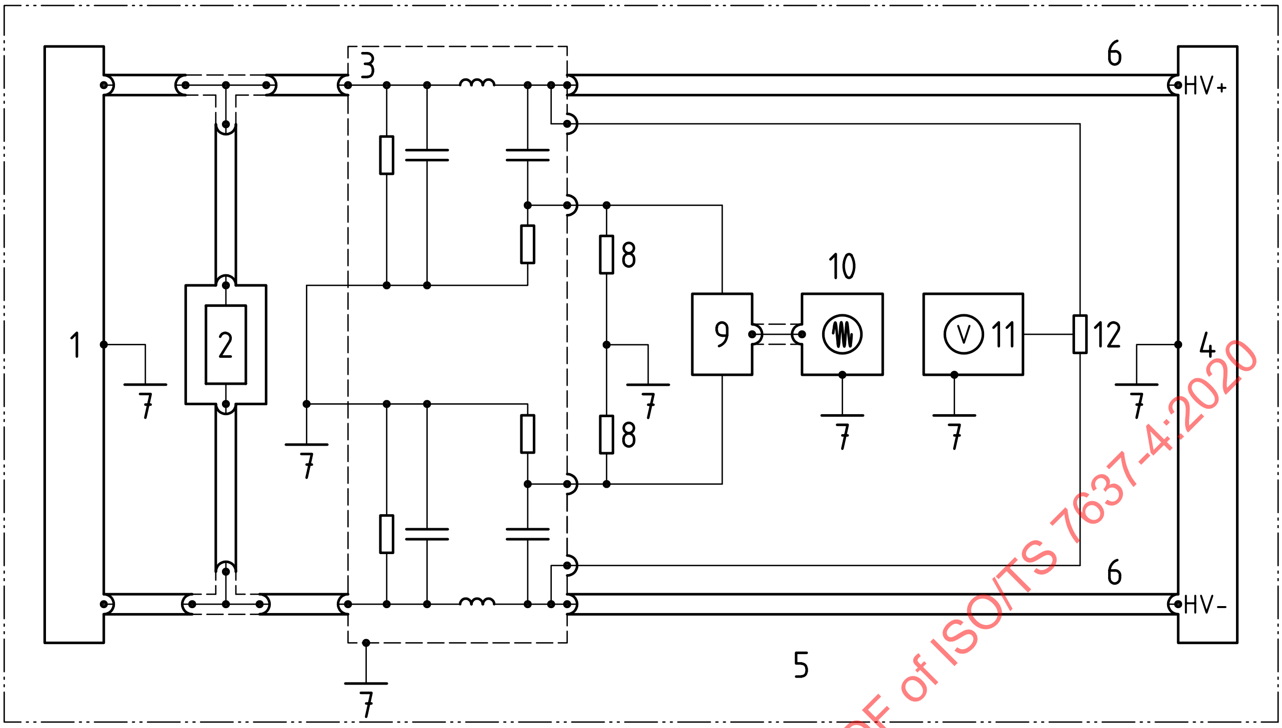
Figure 3 shows an example of test set-up for coupling between HV+ and ground. The lower terminal of generator shall be connected to ground. The upper terminal shall be connected to HV+ via the HV-AN (as shown in Figure 3) or respectively to HV-. The corresponding voltage probe terminal shall be connected to HV+ respectively to HV-; the other voltage probe terminal shall be connected to ground.

The length of the high voltage supply line shall be ($500\ ^{+200}_{\ \ 0}$) mm, if not otherwise specified in the test plan. The used cable length shall be documented in the test report.

Ground connection of DUT shall be connected to ground plane. The default length is (200 ±50) mm, if not otherwise specified in the test plan. If the DUT has a metallic case, this case shall be bonded to the ground plane. The DC resistance of the ground connection shall not exceed 2,5 mΩ.

The DUT shall be placed on the ground plane as in the vehicle application. If no other requirements are specified the DUT and all wiring connections between artificial network and DUT shall be placed on a non-conductive, low relative permittivity (dielectric-constant) material ($\varepsilon_r \leq 1,4$), at (50 ± 5) mm above the ground plane.

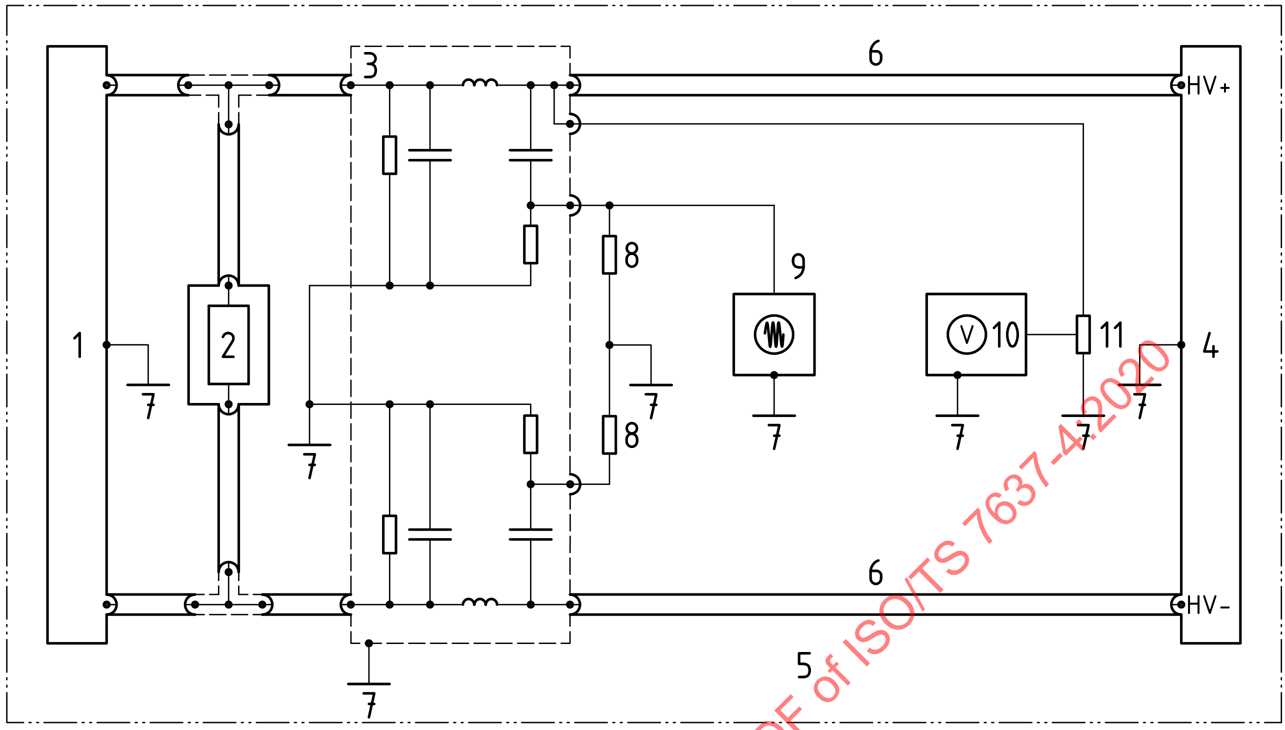
For sine wave generator description/characteristics see C.2.



Key

1 high voltage power supply (optional: shielded and / or filtered)
2 load for high voltage battery (if necessary, see 5.4)
3 shielded high voltage artificial network
4 DUT
5 ground plane
6 high voltage supply line
7 ground connection
8 50 Ω termination
9 balun transformer (see Figure C.2)
10 sine wave generator
11 oscilloscope or waveform acquisition equipment
12 high voltage differential probe

Figure 2 — Transient immunity test set-up for pulsed sinusoidal disturbances pulse A (e.g. "line-to-line")



Key

1 high voltage power supply (optional: shielded and / or filtered)
2 load for high voltage battery (if necessary, see 5.4)
3 shielded high voltage artificial network
4 DUT
5 ground plane
6 high voltage supply line
7 ground connection
8 50 Ω termination
9 sine wave generator
10 oscilloscope or waveform acquisition equipment
11 high voltage differential probe

Figure 3 — Transient immunity test set-up for pulsed sinusoidal disturbances pulse A (e.g. "HV+ line-to-ground")

4.6.2.2 Test procedure for immunity test for pulsed sinusoidal disturbances (pulse A)

Test voltage and waveform of pulse A shall be set prior to the test as described in 4.6.2.3 and 4.6.2.4. Test levels are described in Table A.1.

The test shall be performed for both configurations shown in Figure 2:

— with generator (key 10) connected to HV+ and HV- via balun (key 9) and HV-AN (key 3), oscilloscope (key 11) and HV probe (key 12) connected to HV+ and HV-,

and Figure 3:

— with generator (key 9) connected to HV+ and respectively HV- via HV-AN (key 3), oscilloscope (key 10) and HV probe (key 11) connected to HV+ and respectively to HV-.

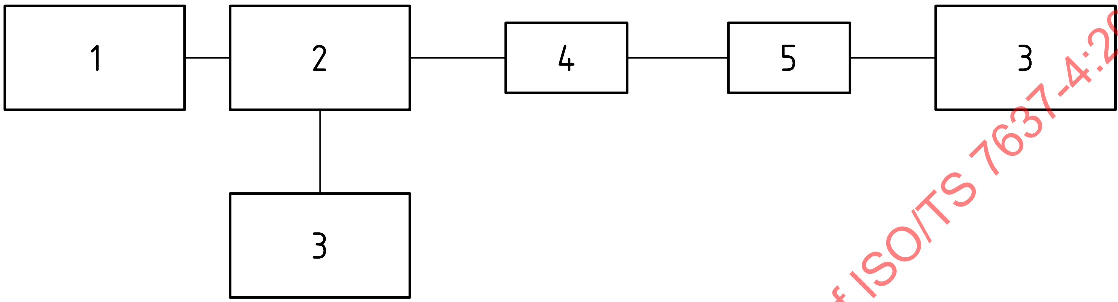
Attach the generator to the test setup.

4.6.2.3 Level setting procedure (line to ground)

1. Set pulse frequency.
2. Connect a power meter to measure the output of the test generator (see Figure 4).

   NOTE An attenuator can be needed to protect the power meter input.

3. Record the forward power to obtain the desired test level (follow Table A.2) (without modulation) measured at the output of the test generator.
4. Repeat steps 1 to 2 for all pulse frequencies.



Key

1 generator
2 directional coupler
3 power meter
4 50 Ω load (not needed if used measurement devices have a 50 Ω impedance)
5 attenuator (optional)

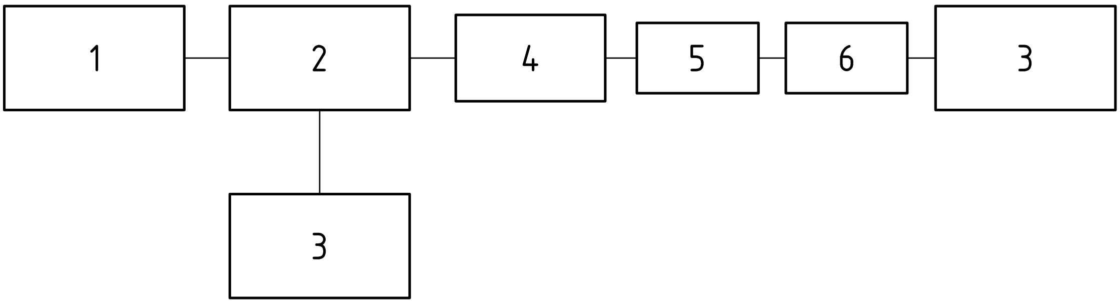
Figure 4 — Test setup for level setting line to ground

4.6.2.4 Level setting procedure (line to line)

1. Set pulse frequency.
2. Connect a power meter to measure the output of the test generator. The balun shall be terminated with a 50 Ω load (see Figure 5).

   NOTE An attenuator can be needed to protect the power meter input.

3. Record the forward power to obtain the desired test level (see Table A.1) (without modulation) measured at the output of the test generator.
4. Correct the forward power by adding the correction factor of the balun transformer at the respective pulse frequencies.
5. Repeat steps 1 to 4 for all pulse frequencies.



Key

1 generator
2 directional coupler
3 power meter
4 balun
5 50 Ω load (not needed if used measurement devices have a 50 Ω impedance)
6 attenuator (optional)

Figure 5 — Test setup for level setting line to line

4.6.3 Immunity test for pulsed sinusoidal disturbances (pulse B)

4.6.3.1 Test set-up for immunity test for Low frequency sinusoidal disturbances (pulse B)

Figure 6 shows the test setup for in-line coupling in HV+ or respectively HV-.

Figure 7 shows the example of test setup for coupling between HV+ and ground. The lower terminal of the coupling transformer shall be connected to ground via capacitor. The upper terminal shall be connected to HV+ (as shown in Figure 7) or respectively to HV-. Corresponding one voltage probe terminal shall be connected to HV+ or respectively to HV-. The other voltage probe terminal shall be connected to ground.

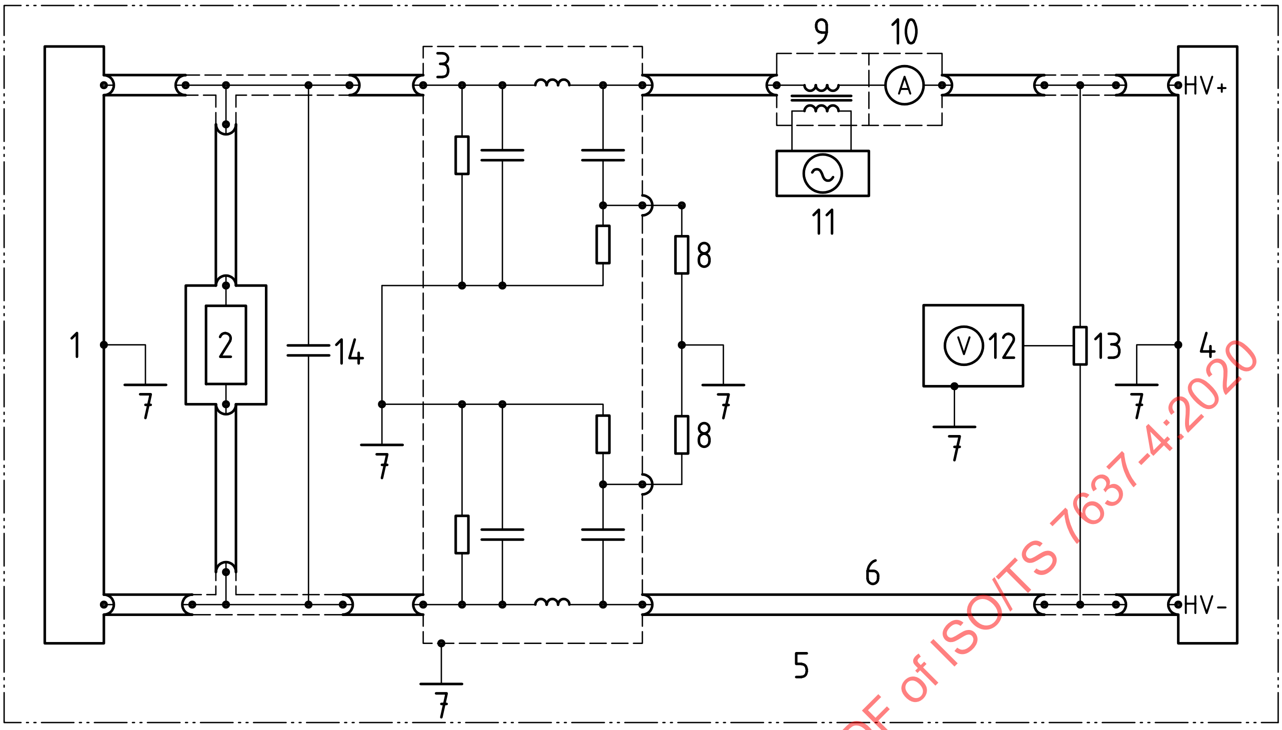
A capacitor of minimum 100 µF depending on the DUT and power supply shall be connected across the high voltage power supply.

The optional current monitor is intended to measure the coupled pulse current and not the EUT current.

Ground connection of DUT shall be connected to ground plane. The default length is 200 mm (±50 mm), if not otherwise specified in the test plan. If the DUT has a metallic case, this case shall be bonded to the ground plane. The DC resistance of the ground connection shall not exceed 2,5 mΩ.

The DUT shall be placed on the ground plane as in the vehicle application. If no other requirements are specified the DUT and all wiring connections between artificial network and DUT shall be placed on a non-conductive, low relative permittivity (dielectric-constant) material ($\varepsilon_r \leq 1{,}4$), at (50 ± 5) mm above the ground plane.

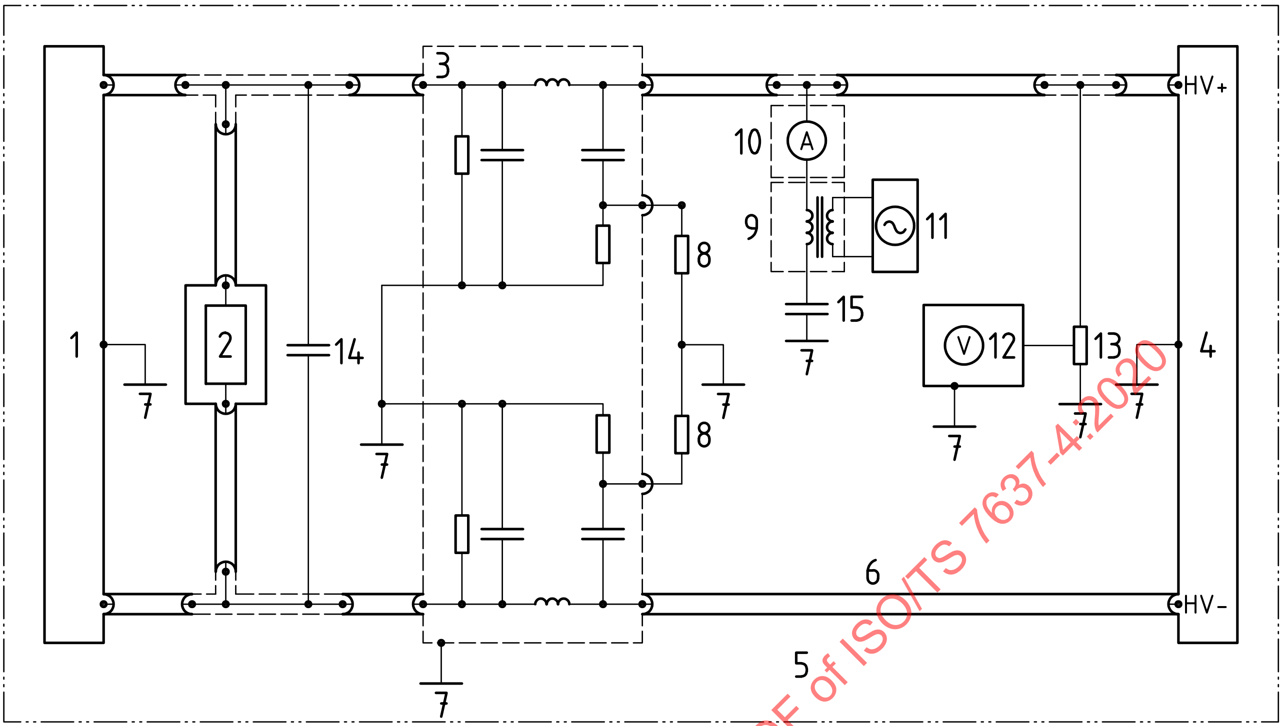
The low frequency sinusoidal generator and coupling transformer is described in C.2.3 and C.2.4.



Key

1 high voltage power supply (optional: shielded and / or filtered)
2 load for high voltage battery (if necessary, see 5.4)
3 shielded high voltage artificial network (HV-AN)
4 DUT
5 ground plane
6 high voltage supply line
7 ground connection
8 50 Ω termination
9 coupling transformer
10 current monitoring (optional)
11 low frequency generator
12 oscilloscope or waveform acquisition
13 high voltage differential probe
14 capacitor ≥100 µF if using high voltage power supply instead of a battery

Figure 6 — Transient immunity test set-up for low frequency sinusoidal disturbances pulse B (e.g. "in-line HV+")



Key

1 high voltage power supply (optional: shielded and / or filtered)
2 load for high voltage battery (if necessary, see 5.4)
3 shielded high voltage artificial network (HV-AN)
4 DUT
5 ground plane
6 high voltage supply line
7 ground connection
8 50 Ω termination
9 coupling transformer
10 current monitoring (optional)
11 low frequency generator
12 oscilloscope or waveform acquisition
13 high voltage differential probe
14 capacitor ≥100 µF if using high voltage power supply instead of a battery
15 capacitor, e.g. 100 nF (value is adjusted for the frequency at which it is used)

Figure 7 — Transient immunity test set-up for low frequency sinusoidal disturbances pulse B (e.g. “HV+ line-to-ground”)

4.6.3.2 Test procedure for immunity test for low frequency sinusoidal disturbances (pulse B)

Test voltage and waveform of pulse B shall be set without load and prior to the test. Test levels are described in Table A.2.

The test shall be performed for both configurations:

— with generator (key 11) and coupling transformer (key 9) connected in-line in HV+, oscilloscope (key 12) and HV probe (Key 13) connected between HV+ and HV-,

— with generator (key 11) and coupling transformer (key 9) connected between HV+ and ground, oscilloscope (key 12) and HV probe (Key 13) connected to HV+.

Attach the generator to the test setup.

5 Test instrument description and specifications

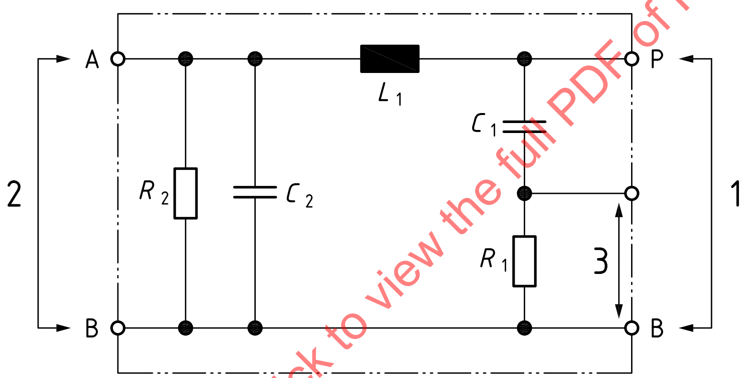
5.1 High voltage artificial network (HV-AN)

The 5 µH/50 Ω high voltage artificial network (HV-AN) as shown in Figure 8 shall be used.

The HV-AN(s) shall be mounted directly on the ground plane. The ground connection of the HV-AN(s) shall be bonded to the ground plane. The DC resistance of the ground connection shall not exceed 2,5 mΩ.

Measurement ports of HV-AN(s) shall be terminated with a 50 Ω load.

The HV-AN impedance characteristic Z_{PB} (tolerance ±20 %) in the measurement frequency range of 0,1 MHz to 100 MHz is shown in Figure 9. The impedance Z_{PB} is measured between the terminals P and B shown in Figure 9 with a 50 Ω load on the measurement port while terminals A and B shown in Figure 8 are short circuited.



Key

1 port for the DUT

2 power supply port

3 measurement port

L_1 5 µH

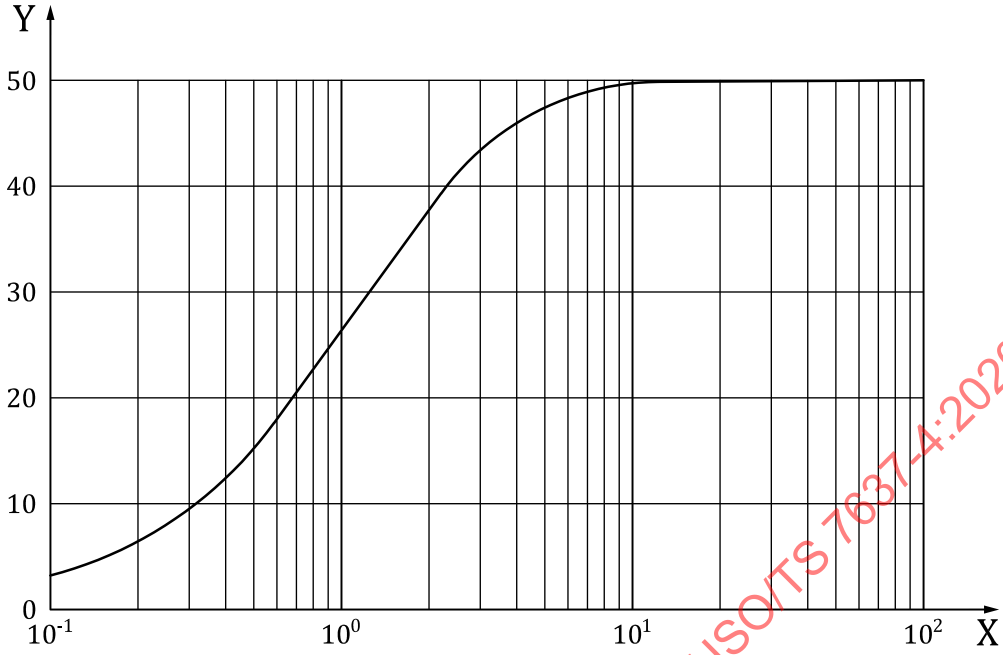
C_1 0,1 µF

C_2 0,1 µF (default value)

R_1 1 kΩ

R_2 1 MΩ (discharging C_2 to < 50 Vd.c. within 60 s)

Figure 8 — Example of 5 µH/50 Ω HV-AN schematic



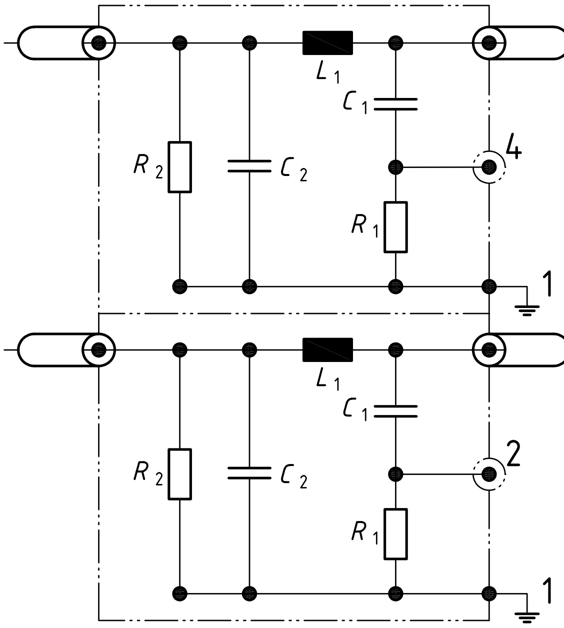
Key

X frequency (MHz)

Y Z_{PB} impedance (Ω)

Figure 9 — Characteristic impedance of the HV-AN

If unshielded HV-ANs are used in a single shielded box, an inner shield between the HV-ANs shall be placed as shown in Figure 10.

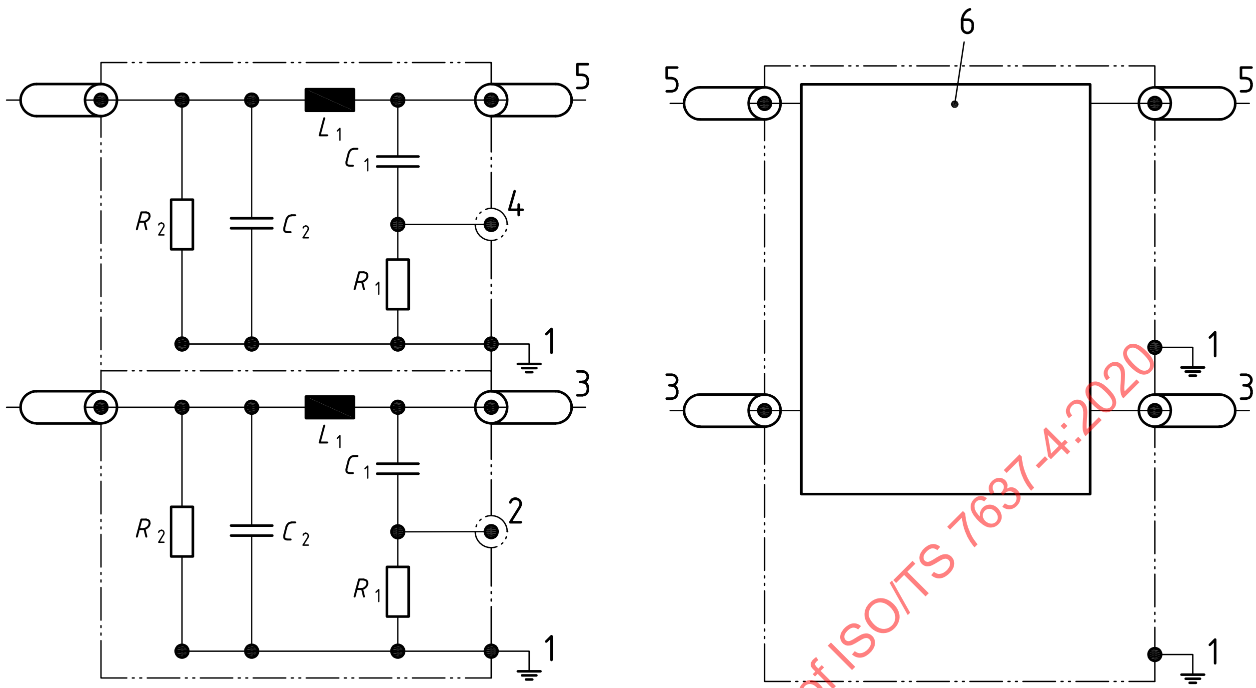


Key

1 ground
2 measuring port HV-
3 supply line HV-
4 measuring port HV+
5 supply line HV+
L_1 5 μH
C_1 0,1 μF
C_2 0,1 μF (default value)
R_1 1 kΩ
R_2 1 MΩ (discharging C_2 to < 50 V d.c. within 60 s)

Figure 10 — Example of 5 μH/50 Ω HV-AN combination in a single shielded box

An optional impedance matching network as shown in Figure 11 (key 6) may be used to simulate a common mode/differential mode impedance seen by the DUT connected to HV power supply. If used, this impedance matching network shall be defined in the test plan.



Key

1 Ground
2 measuring port HV-
3 supply line HV-
4 measuring port HV+
5 supply line HV+
6 differential and common mode impedance matching network (optional, to be specified in the test plan)
L_1 5 µH
C_1 0,1 µF
C_2 0,1 µF (default value)
R_1 1 kΩ
R_2 1 MΩ (discharging C_2 to ≤ 50 V d.c. within 60 s)

Figure 11 — HV-ANs with impedance matching network connected to DUT

5.2 HV power supply

The HV power supply shall be able to supply the DUT within its specified nominal voltage range and supply current. Maximal noise ripple shall be U_{pp} ≤ 1,5 % of nominal voltage.

5.3 Measurement instrumentation

An oscilloscope or waveform acquisition device with voltage probes meeting the following parameters shall be used.

— Bandwidth d.c. to at least 400 MHz;

— Sampling rate: at least 2 Giga samples per second (single shot mode).

Voltage measurement can be performed either with a differential probe or two matched probes.

NOTE The two high-voltage probes are connected to HV+ and HV- respectively. Both ground straps are connected to the ground plane together for voltage reference and its safety. The oscilloscope shows differential voltage between HV+ and HV- (e.g. CH1-CH2 function).

Differential mode probe characteristics:

Bandwidth	d.c. to at least 100 MHz;
Input impedance	Z ≥ 1 MΩ at d.c.

Voltage probe, characteristics:

Bandwidth	d.c. to at least 200 MHz;
Input impedance	Z ≥ 1 MΩ at d.c.
Capacitance	≤10 pF
Attenuation	100:1

5.4 Load for high voltage battery or power supply

For a base load of the high voltage battery or power supply a resistor in parallel to a capacitor can be used with the following parameters:

—	Resistor	R = 500 Ω ±5 %
—	Capacitor	C = 10 µF ±10 % equivalent series resistance ESR < 5 mΩ at 10 kHz minimal current bearing capacity: 50 A_{rms} at 10 kHz (current bearing capacity shall be adapted to the test-voltage).

Annex A
(normative)

Example of test severity levels associated with functional performance status classification

A.1 General

This annex gives examples of test severity levels which should be used in line with the principle of functional performance status classification (FPSC) described in ISO 7637-1.

A.2 Classification of high voltage test pulse severity levels

The suggested minimum and maximum severity levels for high voltage systems are given in Tables A.1 and A.2.

A selected level and test time for testing at or in between these values may be chosen according to the agreement between vehicle manufacturer and supplier. In cases where no specific values are defined, it is recommended to use levels from Tables A.1 and A.2.

A.2.1 Test pulse A, pulsed sinusoidal disturbances

Table A.1 — Parameters for test pulse A, pulsed sinusoidal disturbances

Pulse frequency (MHz)	Test voltage U_{pp} (V) [a] severity level				Oscillations per pulse packet	Repetition time (µs)	Test duration (minutes)	Test coupling
	I	II	III	IV				
1	20	50	100	[b]	10	200 / 100 / 50	5 / 5 / 5	HV+ to HV- HV+ to ground HV- to ground
2								
5								
10								

[a] Test voltage shall be set at 50 Ω load. Details shall be defined in the test plan.
Severity level is related to the HV nominal voltage (e.g. 5 % to 10 %).

[b] Severity level class for special applications: Details shall be defined in the test plan.

A.2.2 Test pulse B, low frequency sinusoidal disturbances

Table A.2 — Parameters for test pulse B, low frequency sinusoidal disturbances

Test frequency f_{PWM}	Frequency step	Test voltage U_{pp} (V) [c] severity level				Dwell time per step (s)	Test coupling
		I	II	III	IV		
Optional: <3 kHz [a]	[a]	[a]	[a]	[a]	[b]	2	HV+ to HV- HV+ to ground HV- to ground
3 kHz - 30 kHz	e.g. 1 kHz	5	15	25	[b]		
30 kHz - 300 kHz	e.g. 10 kHz	0,5	1,5	2,5	[b]		

[a] Optional test frequencies and severity levels for applications with relevant harmonics <3 kHz: Details shall be defined in the test plan.

Severity level is related to the HV nominal voltage (e.g. 5 % to 10 %).

[b] Severity level class for special applications: Details shall be defined in the test plan.

[c] The test voltage is set under open load condition.

A.3 Example of FPSC application, using test pulse severity levels

An example of severity levels is given in Table A.3. This table might be different for each kind of pulse, and for different high voltage electrical vehicle systems (levels from Tables A.1 to A.2).

Table A.3 — Example of FPSC Levels

	Category 1	Category 2	Category 3
L_{4i}	Level IV	Level IV	Level IV
L_{3i}	Level III	Level IV	Level IV
L_{2i}	Level III	Level III	Level IV
L_{1i}	Level III	Level III	Level III

Annex B
(normative)

Transient voltage waveform evaluation

B.1 General

The purpose of this annex is to provide an evaluation method to characterise transient emissions from disturbance sources as measured according to the definitions in 4.5.

B.2 Essential elements of transient emission waveform characteristics

The following waveform parameters shall be taken into consideration for the evaluation of waveform characteristics (see ISO 7637-1:2015 for definitions).

The emission limits shall be derived from severity levels in Annex A.

Abbreviations have been assigned to the waveform parameters as given in Table B.1

Table B.1 — Terms and abbreviations

Parameter	Definition see ISO 7637-1:2015	Abbreviation
Peak amplitude	3.12	U_s (U_{S1}, U_{S2})
Pulse duration	3.13.1	t_d
Pulse rise time	3.13.4	t_r
Pulse fall time	3.13.2	t_f
Pulse repetition time	3.13.3	t_1
Burst duration	3.2.2	t_4
Time between bursts	3.2.3	t_5
Burst cycle time	3.2.1	$t_4 + t_5$

B.3 Voltage waveform characteristics and classification of transient emissions

B.3.1 Test pulse A, pulsed sinusoidal disturbances

Figure B.1 shows the waveform of pulse A. The parameters are specified in Table B.2.

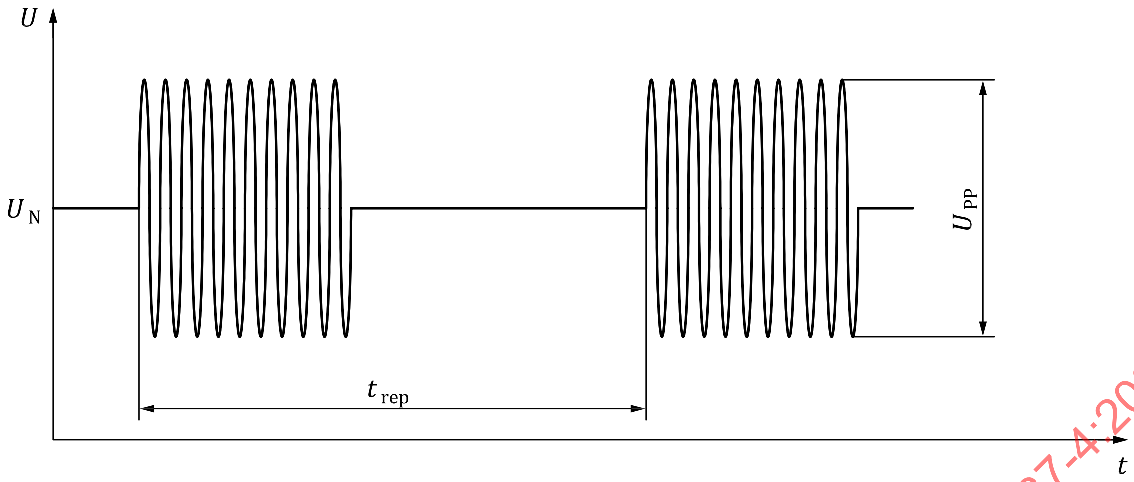


Figure B.1 — Test pulse A, sine wave pulses, e.g. on HV+

Table B.2 — Parameters for test pulse A, pulsed sinusoidal disturbances

Parameters	Nominal values
t_{rep}	Repetition time, Refer to Table A.1
Oscillations per burst	10
U_{pp}	Test pulse voltage, refer to Table A.1
U_N	Nominal voltage of DUT (HV+ to HV-)

B.3.2 Test pulse B, low frequency sinusoidal disturbances

Figure B.2 shows the waveform of pulse B. The parameters are specified in Table B.3.

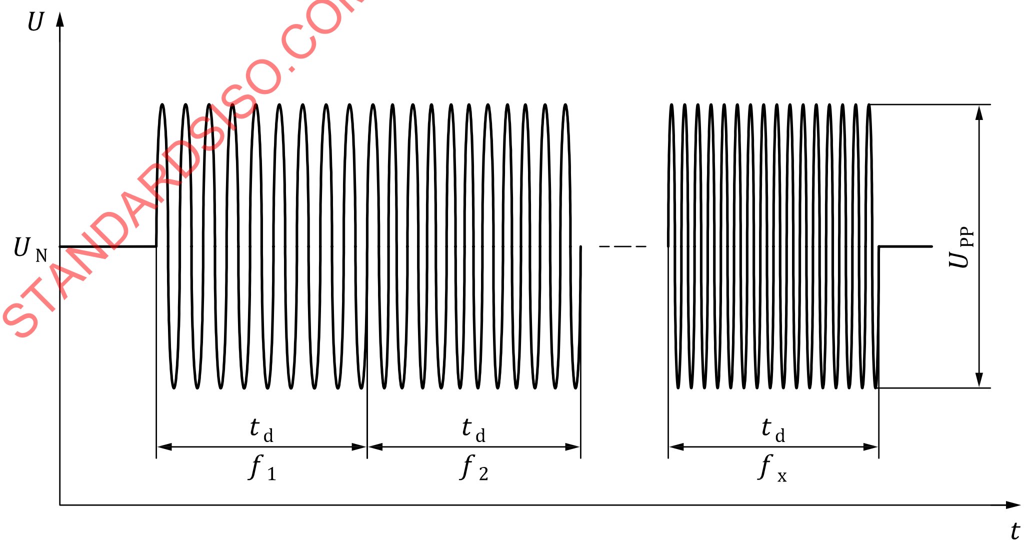


Figure B.2 — Test pulse B, low frequency sinusoidal disturbances