LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
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Degree Programme in Electrical Engineering

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ACHIEVING EMC TESTING LIMITS IN COMPONENTS AND ELECTRICAL SUB-ASSEMBLIES FOR CONDUCTED EMISSIONS ON DC POWER LINES

Examiners: Professor Pertti Silventoinen
M.Sc. Jussi Hämäläinen

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT

School of Energy Systems

Sähkötekniikan koulutusohjelma

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Achieving EMC Testing Limits in Components and Electrical Sub-Assemblies for Conducted Emissions on DC Power Lines

Diplomityö

2021

51 sivua, 26 kuvaa, 1 taulukkoa, 4 liitettä

Työn tarkastajat: Professori Pertti Silventoinen

DI Jussi Hämäläinen

Hakusanat: sähkömagneettinen yhteensopivuus, sähkömagneettiset häiriöt, johtuvat häiriöt

Työn tavoitteena on tutkia sähkömagneettisia häiriöitä koskevia säännöksiä tekemällä mittauksia, tutkimalla esiin nousevia virheitä ja etsimällä uusia tapoja häiriöiden tavoiterajojen saavuttamiseen. Testit toteutettiin Danfoss Editronin EMC-testilaboratoriossa CISPR25-standardin käytäntöjen mukaisesti.

Tulokset osoittavat, että tavoiteltuihin häiriörajoihin päästään käyttämällä EMI-suodatinta häiriöiden vaimentamiseen. Käyttämällä keloista ja kondensaattoreista rakennettua suodatinta, saadaan häiriöiden testirajat läpäistyä CISPR25-standardia noudattaen.

ABSTRACT

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Achieving EMC Testing Limits in Components and Electrical Sub-Assemblies for Conducted Emissions on DC Power Lines

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51 pages, 26 figures, 1 tables, 4 appendices

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Keywords: electromagnetic compatibility, electromagnetic interferences, conducted emissions

The goal of this thesis is to explore the regulations regarding emission testing by executing measurements, examining any arising errors or difficulties, and finding new ways to achieve the target limits. The tests were performed by using the current probe method according to CISPR25 in Danfoss Editron's EMC test laboratory.

The testing results imply that the desired EMC testing limits can be achieved by using a filter to attenuate interferences. By using a filter comprising of inductors and capacitors, the test limits for maximum interferences can be passed in accordance to CISPR25.

ACKNOWLEDGEMENTS

Firstly, I'd like to thank my supervisor Jussi Hämäläinen, and professor Pertti Silventoinen for guiding me through this thesis. I've had such a great experience working for Danfoss Editron, and studying at LUT University.

Thank you also to my parents for being my inspiration and showing me what hard work looks like. You two are a true example of what it means to make the impossible possible. And last but definitely not least, thank you to my dearest friends for always having my back, through thick and thin, and supporting me with everything that I do. I'm so grateful for you.

The past five years I spent in Lappeenranta gave me so much, much more than I could've ever imagined. I'll hold everything that I learned, and all the memories I made there close to my heart as I embark on this new, exciting phase of my life. As Zig Ziglar wisely once said: "Difficult roads often lead to beautiful destinations. The best is yet to come."

in Helsinki, 1.6.2021
Vaishnave Mohanathas

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LIST OF SYMBOLS AND ABBREVIATIONS

E_1	impinging electric field intensity
E_2	leaking electric field intensity
l_c	cable length
P_{rx}	intercepted power without shielding
$P_{rx'}$	intercepted power with shielding
x_{min}	minimum cable distance

Abbreviations

ALSE	Absorber-lined shielded enclosure
AC	Alternating current
AM	Amplitude modulation
AMN	Artificial mains network
AN	Artificial network
AAN	Asymmetric artificial network
AFC	Audio frequency chokes
CTL	Coaxial transmission line
CTLM	Coaxial transmission line method
CM	Common mode
CMMR	Common mode rejection ratio
DNA	Deoxyribonucleic acid
DUT	Device under test
DM	Differential mode
DC	Direct current
ECE	Economic Commission for Europe
ESA	Electrical sub-assembly
EMC	Electromagnetic compatibility
EMF	Electromagnetic field
EMI	Electromagnetic interference
EMI *SE*	Electromagnetic interference shielding effectiveness

ESD	Electrostatic discharge
EUT	Equipment under test
GPS	Global positioning system
HF	High-frequency
HV	High-voltage
HV-AN	High-voltage artificial network
ICE	Immunity to conducted emissions
IRE	Immunity to radiated emissions
IP	Ingress protection
IEC	International Electrotechnical Commission
CISPR	International Special Committee on Radio Interference
LF	Low-frequency
LISN	Line impedance stabilizing network
LPDA	Log-periodic dipole array
LV	Low-voltage
MESH-CBN	Mesh common bonding network
PCB	Printed circuit board
PEC	Parallel earth conductor
PWM	Pulse with modulation
RC	Resistor-capacitor
RCD	Resistor-capacitor-diode
REESS	Renewable energy storage system
RF	Radio frequency
RFC	Radio frequency choke
RGP	Reference ground plane
RNA	Ribonucleic acid
SOA	Safe operation area
SRF	Self-resonant frequency
STU	Separate tehcnical unit
TEM	Transverse electromagnetic
WHO	World Health Organization

1 INTRODUCTION

The environment is becoming more and more polluted with noise and radio frequencies, and the frequencies used in electronics are increasing. Besides air, water and noise pollution, electromagnetic emission has turned out to be the fourth most crucial provenance of public pollution (Tirkey & Gupta, 2019). As electronic devices are made more complex and vulnerable to disturbances, EMC regulations are augmenting worldwide. A component must function as intended when installed, without disturbing its electrical environment. In regards to this thesis, electromagnetic compatibility (EMC) means exactly that; the ability of components and devices to operate intentionally in their electromagnetic surrounding.

Electromagnetic interference (EMI) is the unintended disturbance that occurs when performance degrading phenomena are sent and received from one device to another. Both manmade and natural sources generate this type of interference where electrical currents and voltages change drastically. Examples of these kinds of disturbances in electrical installations include power changes, surges and lightning. Equivalent distrubances in electronic devices are electromagnetic noise, unwanted radio frequency (RF) signals, and changes in propagation mediums (UNECE, 2014).

An electronic device should be designed for two levels of performance: one to minimize emissions (the energy exiting), and the other to maximize immunity (the energy entering). A device should also be compatible within itself, and the emitting levels within the device shouldn’t compromise its performance.

Besides degrading the performance of electriconic devices and elecrical installations, exposure to electromagnetic fields (EMF) may cause severe health hazards to the human body. According to the World Health Organization (WHO), the main effect of EMFs is heating body tissues. EM waves generate heat in organisms and obstruct regeneration of DNA and RNA cells by the vibration of molecules (Hulle & Powar, 2018). This causes problems like anxiety, insomnia, headaches, hypersensitivity, nausea, fatigue, depression, catarcats, and eye irritation. EMFs may also have effects on pregnancy outcomes and carcinogenesis, the formation of cancer (World Health Organization, 2016).

High risk individuals for EMF effects comprise of engineers working in electrical power plants and laboratories, internet data center employees, and battlefield soldiers (Jia, et al., 2019). Individuals that aren’t considered to be at high risk are increasingly vulnerable to EMFs in daily life activities, such as using mobiles phones, computers, TV screens and microwaves, driving through a highway next to a high-voltage electrical power transmission line, or using X-ray systems at hospitals and airports.

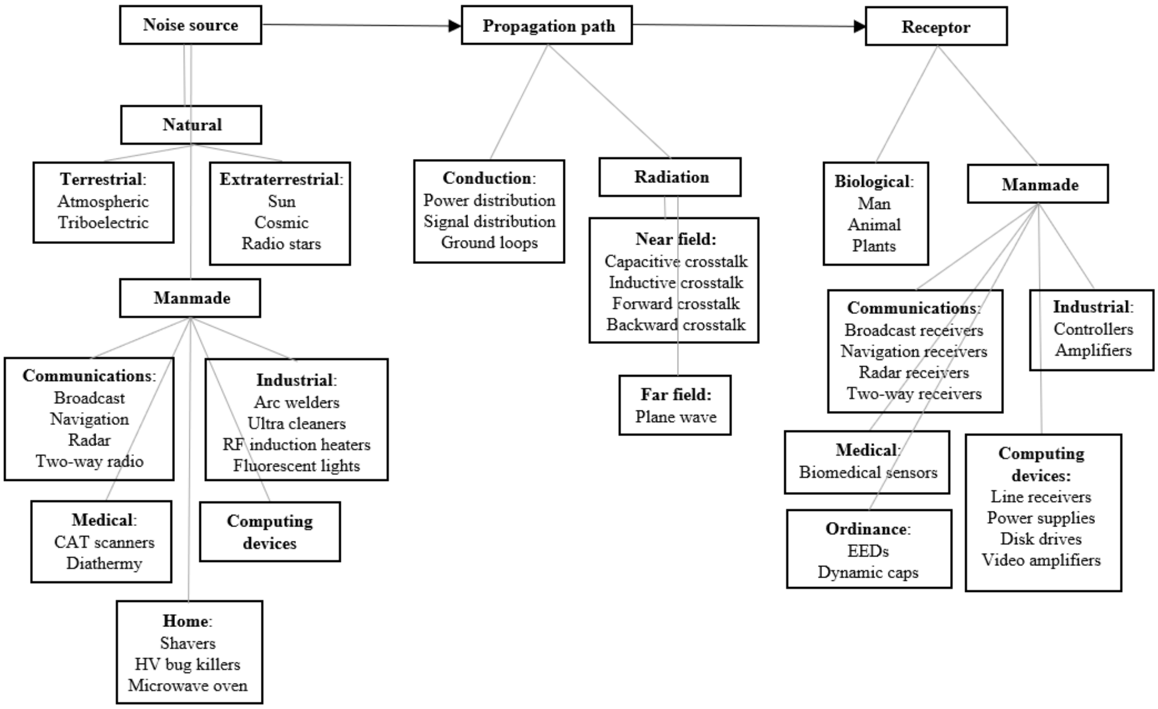

Fig. 1. The three elements of the EMI environment consist of noise sources, propagation paths, and receptors. Noise sources can be caused by frequency generation circuits, incorrect trace grounding, ground bounce from digital logic or common-mode currents. Propagation paths are the mediums that carry RF energy, such as interconnects or free-space. Receptors are devices that accept interference easily from I/O cables or by radiated means. *(Montrose, 2000)*

EMI can be categorized by bandwidth. If a disturbance “has a bandwidth less than or equal to that of a particular measuring apparatus, receiver or susceptible device”, it’s a narrowband disturbance and if a disturbance “has a bandwidth greater than that of a particular measuring apparatus, receiver or susceptible device”, it’s a broadband disturbance (Schaefer, 2006). Narrowband disturbances are typically emanated from intended transmissions as signals from radio and TV stations, cellular networks, and electronic components, such as clocks, oscillators, displays and microprocessors. Narrowband disturbances have usually minor effects on communications or electronic equipment, and can be tuned or filtered out. Broadband disturbances cause most of the EMI disturbances, which are typically unintentional radiation interferences caused by defective electric power transmission lines or power transformers, worn or improperly installed electrical motors and generators, ignition systems of motor vehicles, and arcing of contacts in stepping switches or electrical controllers (East, 1987).

Conducted emission is caused when physical contact occurs, and radiated emission is induced due to capacitance and inductance without physical contact. Conducted emission arises as a result of contact between two cables, in the same way that contact or collision between two vehicles may cause an accident. Conducted emissions are undesirable, because they cause current to be passed out through alternating current (AC) power cords which can cause further issues. Radiated emissions arise as a result of devices sending and receiving interferences through electric and magnetic fields. (Michigan State University, 2015)

The most common source of EMI in power electronics is caused by rapidly changing voltages and currents, following certain pulse with modulation (PWM) techniques. These disturbances are even more significant in today's automotive applications as vehicles are equipped with a large amount of sensitive electronic communication and control systems, along with various switching power converters. The communication and control systems cause radiated emissions with high frequencies, and the converters cause conducted emissions with low frequencies. (Serrao, et al., 2008).

Electric vehicles (EV) and hybrid electric vehicles (HEV) contain drives, typically with AC motors and inverters fed by a direct current (DC) link to either a battery unit, electric generator, a fuel cell, or a combination of the previously mentioned options with an ultracapacitor tank. Having several different power converters makes EMI analysis more challenging as noise propagation and coupling paths can't be analyzed directly. To reduce noise from power cables, an EMI filter can be implemented to the circuit. The EMI filter is a lumped or distributed inductive-capacitive circuit. To minimize conducted emissions, the main EMI sources and coupling paths can be further identified with experimental analysis.

1.1 Goals and delimitations

The goal of this research is to explore the regulations regarding emission testing by executing measurements, examining any arising errors or difficulties, and improving the design of EMI filters in order to achieve target limits. The research focuses on conducted emission testing on DC power lines in components and electrical sub-assemblies (ESA), delimitating radiated emission testing, AC power lines and assemblies larger than ESAs.

1.2 Research methods

Besides literature research, the conducted emissions limits are analyzed based on experimental tests executed in Danfoss Editron's EMC test laboratory. The tests were executed in a shielded room by using the current probe method according to the CISPR25 standard.

Fig. 2. The testing facility in Lappeenranta conducts EMC and environmental tests, which enables system and machine testing at an earlier stage of the manufacturing process than earlier. Assessments can be performed to conform to international and European standards regarding radiative immunity, radiative emissions, electrostatic discharge, automotive immunity, magnetic field immunity, and conductive emissions. *(Danfoss, 2020)*

1.3 Structure of the thesis

The first portion of the thesis is based around theory concerning EMI testing, standards and regulations related to it, and methods to reduce interferences. After the theory portion comes the manual testing section which is divided into two parts: the first part covering the initial round of tests with assessment of any errors or difficulties that arose, following into the second round of tests with improved design in order to achieve the desired results. Finally, the research is concluded with a summary of the test results, and suggestions for further research.

2 EMI TESTING

This chapter is about immunity and emission testing for both conducted and radiated testing. Immunity testing is assessing how much noise a device under test (DUT) can receive and withstand without interfering operation. Immunity to conducted emissions includes immunity to transients, electrical fast transients (EFT), and surges. Transients are unexpected waveforms and short-lived bursts of energy caused by sudden changes of states in electrical devices. Transients can appear as multiple different voltage spikes during switching and showering arcs, whereas surges are single voltage spikes that can appear as lighting sparks. Transients and surges may cause voltage dips and drops many times the normal line voltage, causing damage to the equipment under test (EUT).

Immunity to radiated emissions comprises of immunity to radio frequency (RF) noise, and magnetic fields. RF noise might cause miss-operation of the EUT as it may interfere with broadcast and radio receivers. Miss-operation of the EUT might also be caused by electrostatic discharge (ESD) which is the sudden release of static electricity when two objects come into contact.

EMI receivers are used in both conducted and radiated emission testing. In the conducted emission measurements, an artificial network (AN) or a measuring sensor is connected to the receiver which converts the measured signal into a suitable form for the input stage of the receiver. In the radiated emission measurements, an antenna is connected to the receiver.

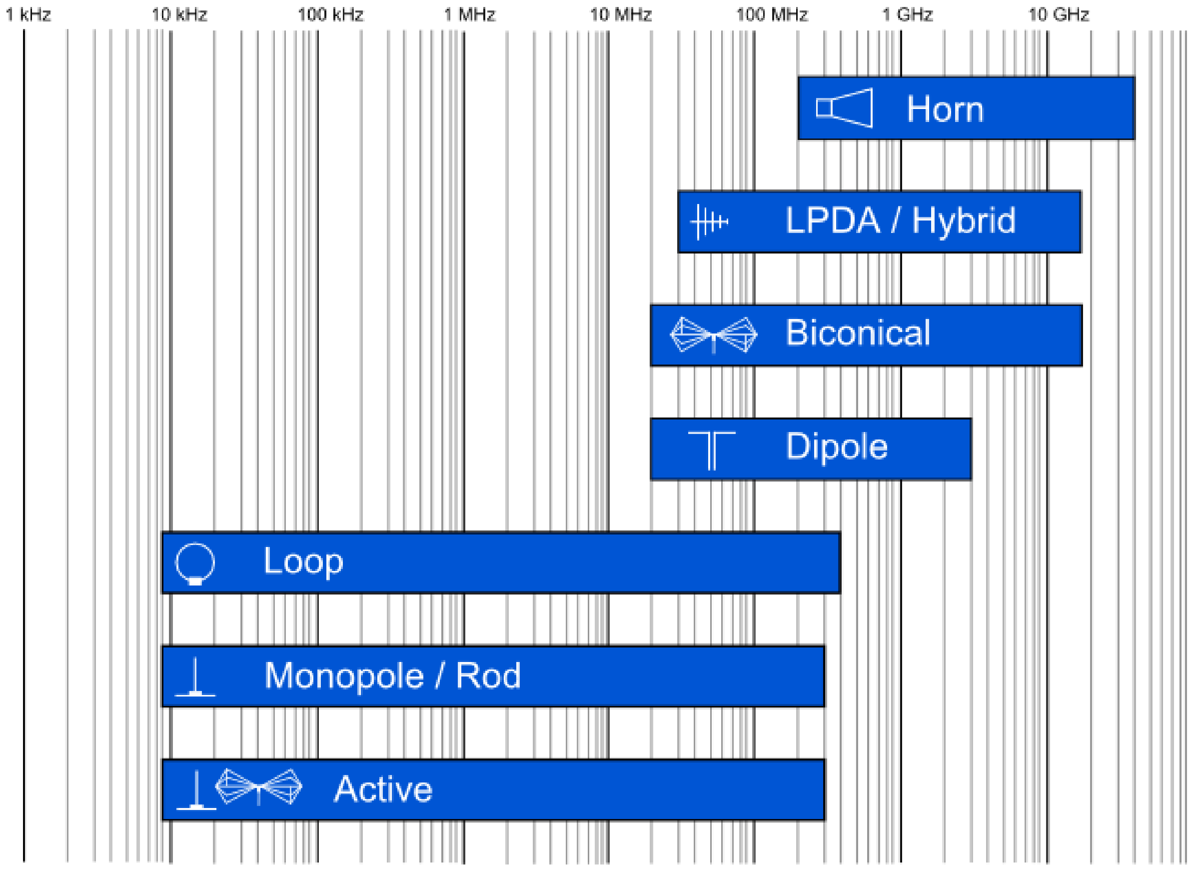

Fig. 3. A selection chart for antennas used in radiated emissions, including monopole/rod, loop, dipole, biconical, log-periodic dipole array (LPDA), and horn antennas. (Schwarzbeck, n.d.)

Assessing these conducted and radiated emissions is vital to ensuring electromagnetic immunity. All components must comply with the regulations and standards set. Even if all the components in a device meet the requirements separately, the assembled device may not. Therefore, the final device must be also tested. Performing tests on components is the responsibility of the supplier, whereas testing of final devices is the responsibility of the end manufacturer.

Shielding is one of the most prominent ways to reduce interferences. In principle, a shield is an enclosure that encases and protects components inside it. When an EMI field impinges on the shield, most of the interferences get either reflected or absorbed, and a small portion gets transmitted to the components inside. EMI shielding effectiveness (EMI *SE*) is the combined effect of these interferences, the ratio of electromagnetic power before shielding to the electromagnetic power after shielding.

The formula for EMI *SE* is

$$SE = 10 \log \left(\frac{P_{\mathrm{rx}}}{P_{\mathrm{rx'}}}\right) \tag{1}$$

where P_{rx} is the power intercepted by the components inside without shielding, and $P_{\mathrm{rx'}}$ is the power intercepted with a shield. (Mathur & Raman, 2020)

Shields can be made of conducive materials such as metals, ferrites, metamaterials, and conductive polymers. The EMI *SE* of a material is determined by its conductivity, permeability, and permittivity. Other contributing factors are the frequency at which the measurement is done, the polarization of the impinging wave, the angle of incidence, and whether the application is near-field or far-field.

Some of the most used methods to test the EMI *SE* of a shielding system include the shielded box method, the free-space method, the shielded room method, the coaxial transmission line method (CTLM), and the dual TEM cell method.

The shielded box method is used for comparative tests of a material. The cons of this method are the limited frequency range of ca. 500 MHz, poor correlation between the results of different laboratories, and the difficulty in achieving adequate electrical contact between the box and the DUT.

The shielded room method has been developed to overcome the defects of the shielded box method. As the name of the method suggests, the EUT is isolated in separate rooms to prevent interferences. Otherwise, the functional principle is similar to the shielded box method.

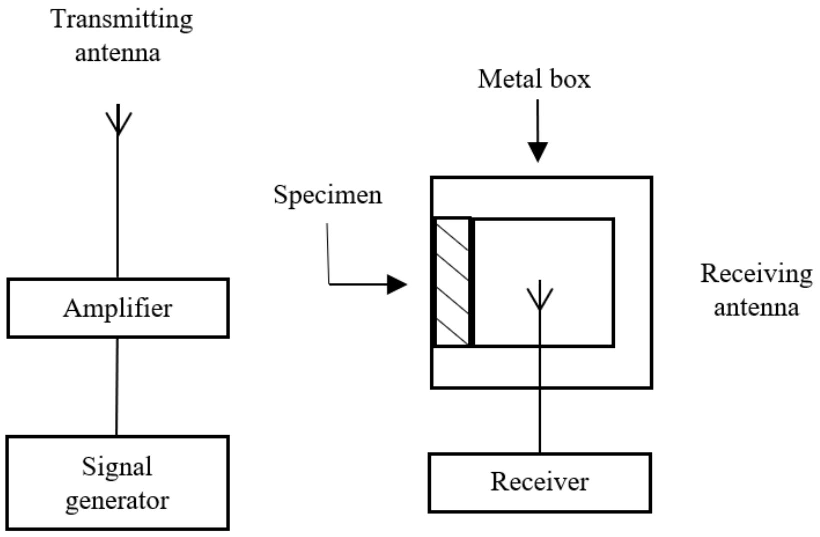

Fig. 4. The shielded box comprises of a metallic box with a port mounted over one of the walls. A receiving antenna is placed inside the box, while another transmitting antenna is placed outside the box. The received power can first be measured by leaving the port open or unloaded, and then measured by fitting the DUT over the port. The received power can be recorded with a measuring receiver.

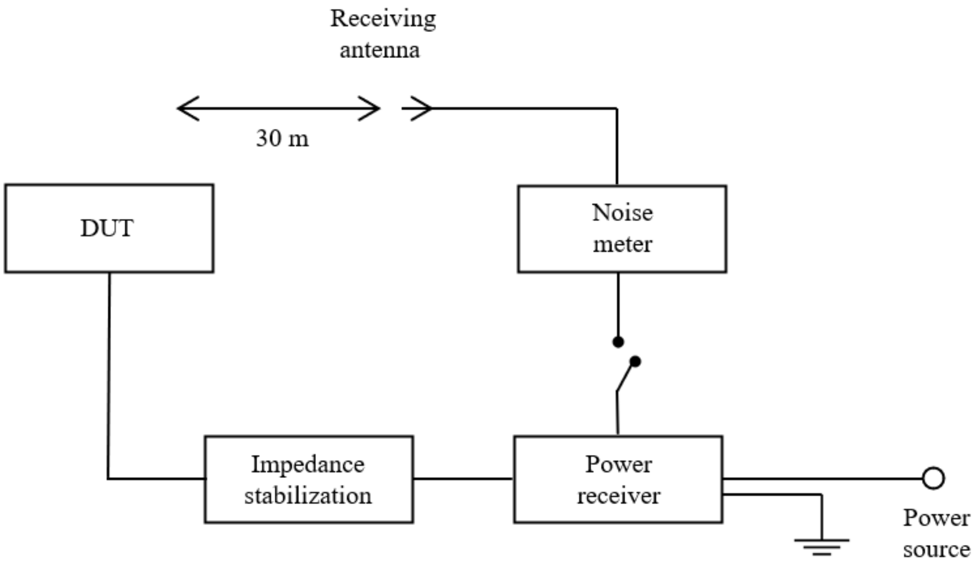

Fig. 5. The free-space or open field method is suitable for testing the practical SE of a device, including both radiated emissions from the DUT and conducted emissions transmitted through the power line. The setup consists of a receiving antenna that’s mounted at a 30 m distance from the DUT.

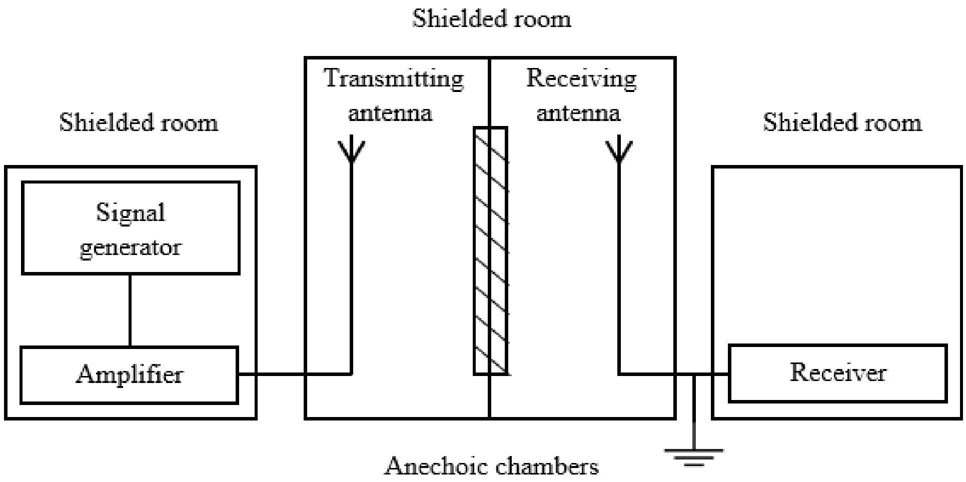

Fig. 6. Setup for the shielded room method. The antennas and the DUT are positioned inside an anechoic chamber, which increases the test specimen area to 2.5 m^2.

The CTLM method is one of the most used methods to test SE using far-field simulation. The pros of this method are its repeatability when used with a flanged coaxial transmission line (CTL), and accurate results in the 30 MHz to 1.5 GHz frequency range. The results obtained in different laboratories are thus comparable, and dividing data into reflected, absorbed, or transmitted components is possible. However, the cons include inaccuracy in results when a flanged CTL isn’t used.

The dual TEM cell method is suitable for testing SE of a material using near-field sources within the 1 MHz to 1000 MHz frequency range. This method consists of two rectangular CTL cells placed on top of each other. The first cell acts as a driving cell, to which the energy is coupled to the second cell, acting as a receiving cell.

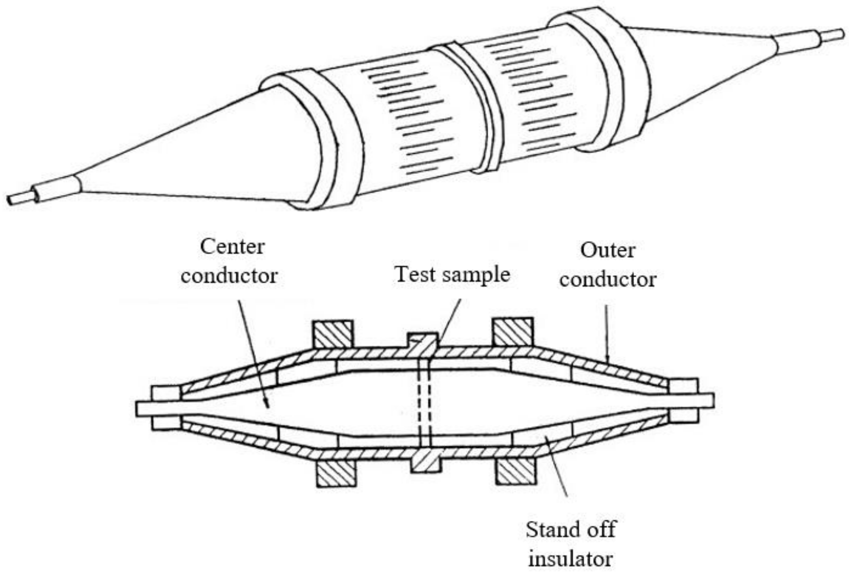

Fig. 7. In the CTLM method, a torus-shaped device is placed in the middle of a coaxial cell. The inner and outer dimensions of the DUT are matched with the dimensions of the cell. Both ends of the cell are also tapered to match the required 50 Ω impedance. (Geetha, et al., 2009)

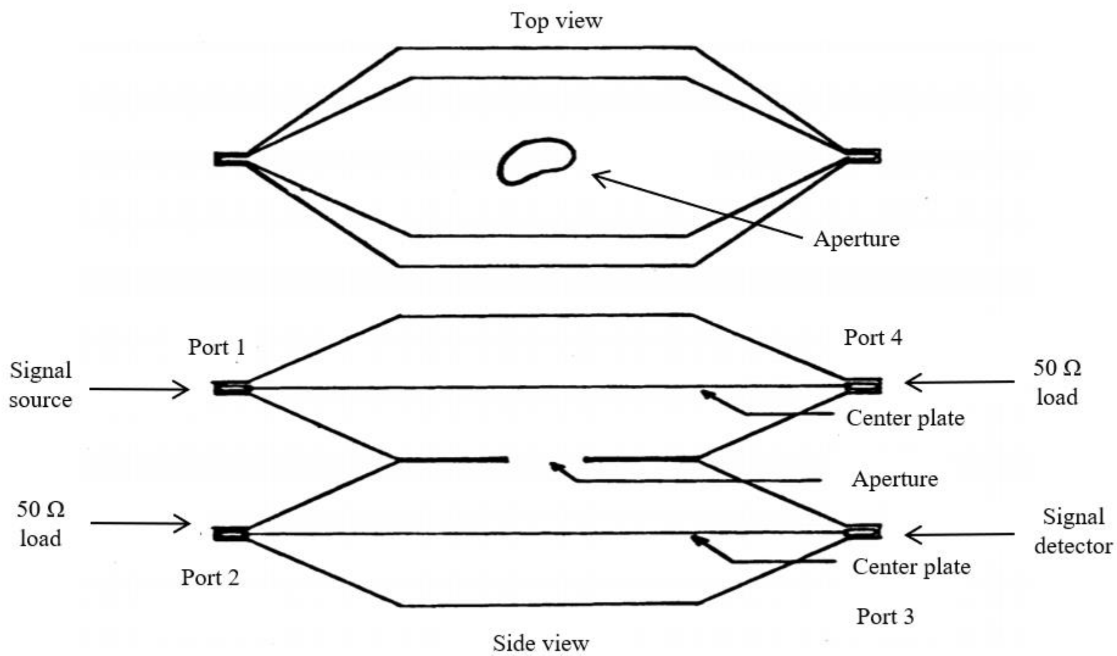

Fig. 8. The dual TEM cell method with common aperture has two cells with tapered ends and 50 Ω loads. To hold the DUT, there is a rectangular slot in between the cells. (Wilson & Ma, 1985)

3 STANDARDS AND REGULATIONS

The following section presents standards and regulations that are associated with conducted emissions testing in components and modules. The standards and regulations explored include CISPR25 and ECE R10.

3.1 CISPR25

3.1.1 Scope

CISPR25 is a standard containing limits and testing procedures for radio disturbances in the frequency range of 150 kHz to 2500 MHz. The standard sets guidelines for protection of vehicles, boats, internal combustion engines, and on-board receivers. The standard applies to vehicle types involving passenger cars, trucks, agricultural tractors and snowmobiles. Vehicle test limits are provided for guidance, based on a typical radio receiver with an antenna provided as part of the vehicle, or a test antenna if no other unique antenna is specified. Receivers to be protected include Bluetooth, GPS, WiFi, broadcast receivers (television and satellites), and radios (land mobile and telephones).

The limits in CISPR25 are subject to modification as agreed between the vehicle manufacturer and the component supplier. The vehicle manufacturer must define in which countries the vehicle is to be marketed, determine applicable frequency bands and limits, and specify radio services likely to be used. CISPR25 covers radio services in most parts of the world.

3.1.2 Test setup

According to the standard, tests should be executed in an absorber-lined shielded enclosure (ALSE) room in order to eliminate any additional noise source from the environment. The ALSE's noise level should be 6 dB lower than the lowest level being measured. This level can be achieved by using certain RF reducing elements in the interior of the room, such as foam absorbers on the walls and ferrite tiles on the floor.

Electric vehicles comprise of two categories of electric systems: low-voltage (LV) systems and high-voltage (HV) systems. The LV category typically consists of common unshielded systems with an operating DC voltage below 60 V, e.g. nominal voltages of 12 V, 24 V or 48 V. The HV category typically consists of shielded systems with an operating voltage between 60 V to 1000 V. Examples of HV power supply parts are inverters with electrical motors, onboard chargers, DC-DC-converters, electrical heaters, HV batteries, and all devices which have a HV power connection in addition to the LV power supply.

CISPR25 suggests two methods for conducted emissions testing: the voltage method and the current probe method. LV and HV systems have their own tests, so all in all there's four different tests for conducted emissions. Besides the probe methods, other conduction emission testing methods include the 1 Ω method and the transverse electromagnetic (TEM) cell method. Regarding the goal of this research, the methods researched in are the probe methods since they are used on DC power lines.

The voltage method for LV systems, presented in appendix 1, is suitable for EUTs with a remotely grounded power line. The method characterizes emissions only on single leads, without being able to characterize the total EUT emission. However, voltage emissions ensure more dynamic range at lower frequencies, e.g. in the AM (amplitude modulation) bands, compared to radiated emissions. The test set-ups vary for remote and local groundings of the EUT, alternators and generators, and ignition system components.

In the voltage method for HV systems, presented in appendix 2, EUTs and loads are grounded using impedance. Either the vehicle HV battery or an external HV power supply should be used. Shielded supply lines for the positive HV+ and negative HV- terminal DC lines, and three phase HV AC lines should be separated by using coaxial cables, common shields, or vehicle harnesses. Voltage measurements must be performed on HV+ and HV- lines by connecting the measuring instruments to the measuring port of the related HV artificial network (HV-AN).

The current probe method for LV systems, presented in appendix 3, requires that the EUT is be placed on a non-conductive, low relative permittivity material above the reference ground plane (RGP). The current probe should be mounted around the complete harness, including all wires.

The current probe method for HV systems, presented in appendix 4, is suitable for EUTs with shielded power supply systems. EUTs and loads are grounded using impedance as defined in the test plan. The shielding configuration and any protective ground connection must also be defined in the test plan, and it should be representative of the vehicle application. Either the vehicle HV battery or an external HV power supply can be used in this method.

3.1.3 Artificial networks

Artificial networks (AN) are networks inserted in the supply lead or signal/load lead of an apparatus to be tested. ANs provide a specified impedance for the measurement of disturbance voltages in a given frequency range. ANs are used for emission tests and impedance simulation in battery supply systems, designed to meet the requirements of CISPR 25 and CISPR 16-1-2. ANs are utilized in the tests in this research because they are made specifically for DC power supplies. Other networks include the line impedance stabilization network (LISN), also known as the artificial mains network (AMN) which is used only for AC power mains, and the asymmetric artificial network (AAN) which is used only for communication or signal lines.

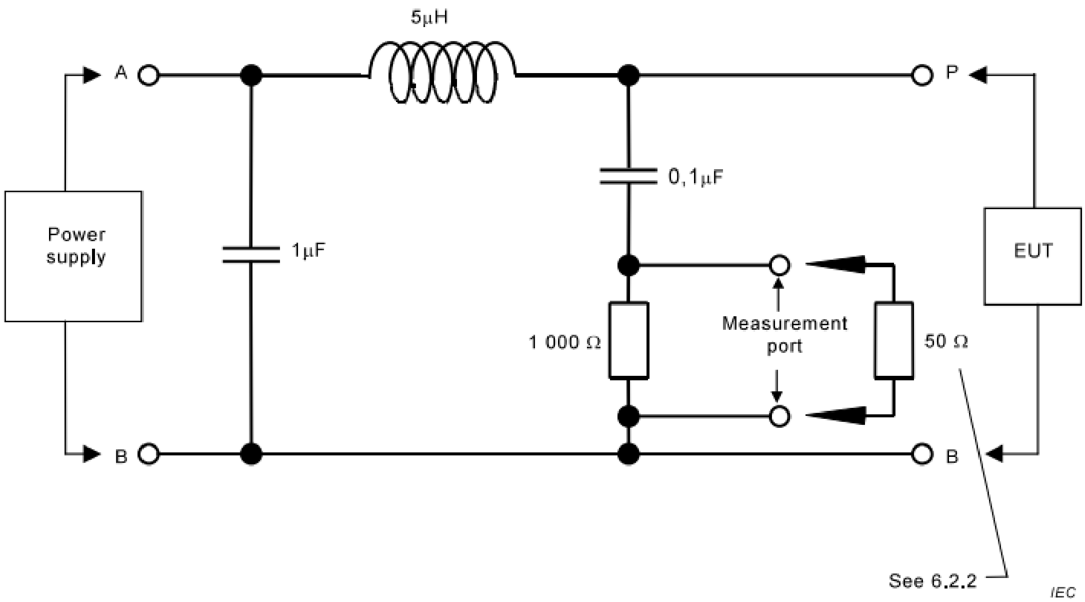

Fig. 9. An example of 5 µH AN schematic. When choosing the right network, specific load impedances, different types of power supplies, and power supply cabling must be considered. (IEC, 2016)**.**

LISNs are filter circuits that are composed of capacitors, inductors, and resistors. The purpose of LISNs is to maintain a constant impedance of 50 Ω for measurements in devices in the 0.15 to 30 MHz frequency range, in order to enable repeatable tests under the same conditions, even if the impedance of the power supply side differs (TDK Electronics, n.d.).

Another important function of a LISN is to prevent intrusion of conduction noises coming from outside the power source.

There are three types of LISNs: V-LISNs, T-LISNs and Delta-LISNs. The V-LISN is the most commonly used one, and it measures the disturbance voltage between two lines L_1 and ground or L_2 and ground respectively. V-LISNs come in two types with 5 µH and 50 µH impedance.

The measurement quality provided by the LISN is dependent on its grounding condition. It has been found that a more accurate measurement can be achieved by using a LISN with a metal enclosure, because it can be bonded directly to the RGP, making it more noiseless (Ananda, et al., 2017). When measuring conducted emissions of EUTs, ground loops may occur, which must be taken into consideration. The loops can be suppressed by using protective earth (PE) chokes and sheath current absorbers on coaxial cables.

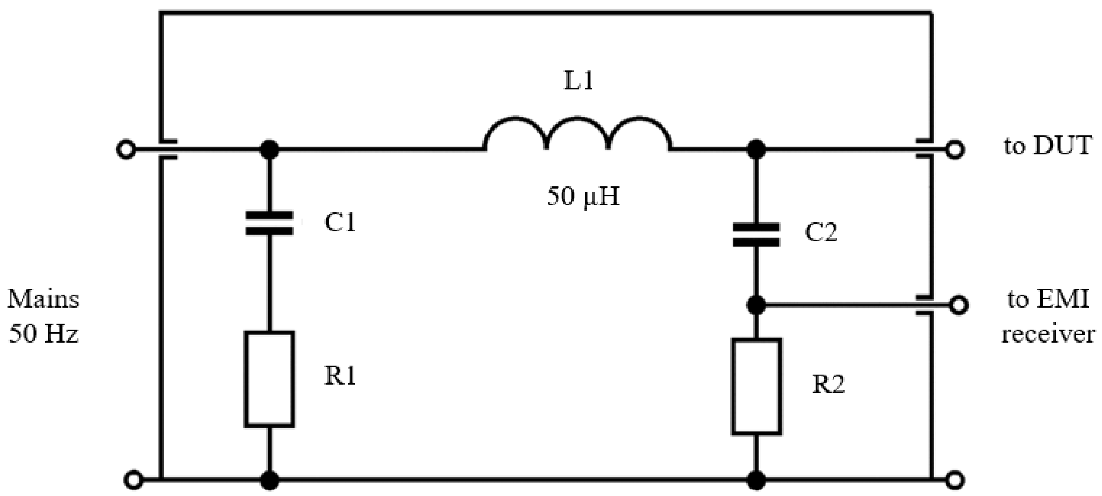

Fig. 10. An example of a 50 µH V-LISN schematic according to CISPR 16-1-2, MIL STD 461 and ANSI C63.4. This type of V-LISN operates at 50-60 Hz frequencies, whereas the other type of V-LISN with 5 µH impedance is used for vehicles, boats, and aircrafts connected to onboard mains with DC or 400 Hz. (Schwarzbeck Mess-Elektronik, n.d.)

3.2 ECE R10

ECE R10 is the regulation no. 10 by United Nations for uniform provisions concerning the approval of vehicles with regard to electromagnetic compatibility. It covers various requirements regarding conducted emissions for different functions related to vehicle distrurbances and protection. However, in regards to this thesis, the focal point is only in the section related to electrical sub-assemblies (ESA).

ESA stands for an electrical device or a set of multiple devices which is intended to be part of a vehicle with any associated electrical connections and wiring, performing specialized functions. An ESA can be approved by the manufacturer or an authorized representative as either a component or a separate technical unit (STU). ECE R10 regulates vehicles and ESAs providing coupling systems for charging renewable energy storage systems (REESS) regarding the control of emissions and immunity from this connection between the vehicle and power grids.

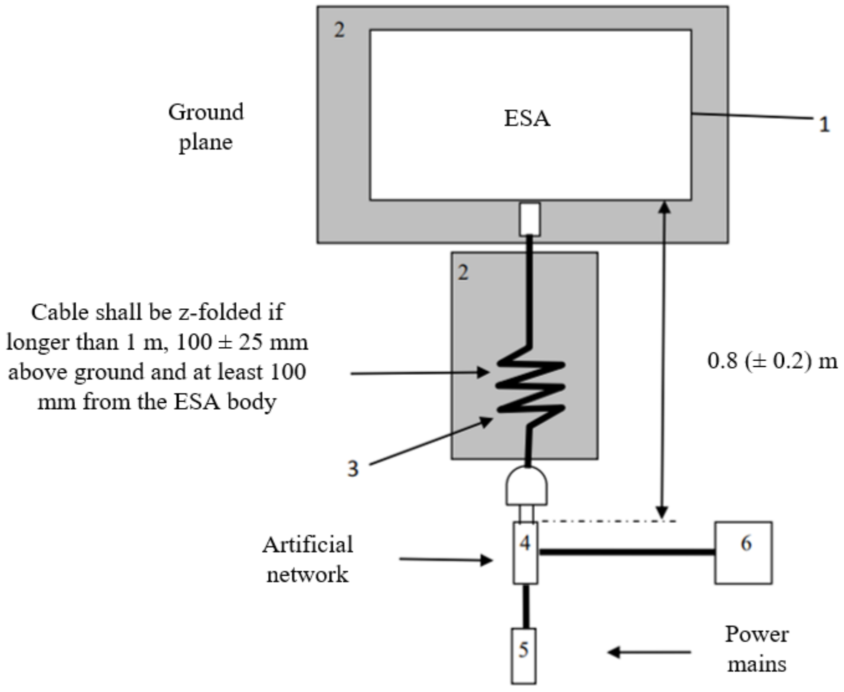

Fig. 11. Test setup for testing emission of RF conducted disturbances from an ESA on AC or DC power lines. The legends are: (1) ESA under test, (2) insulating support, (3) charging cable, (4) AC or DC artificial network(s) grounded, (5) power mains socket, and (6) measuring receiver. (UNECE, 2014).

An ESA must be tested for conducted and radiated emissions on both AC and DC power lines. According to ECE R10, methods to testing generated emissions from an ESA include:

1) Measurement of radiated broadband electromagnetic emissions
2) Measurement of radiated narrowband electromagnetic emissions
3) Testing for immunity to electromagnetic radiation
4) Testing for immunity to and emission of conducted transients
5) Testing for emission of harmonics generated on AC power lines
6) Testing for emission of voltage changes, voltage fluctuations and flicker on AC power lines
7) Testing for emission of RF conducted disturbances on AC or DC power lines
8) Testing for emission of RF conducted disturbances on network and telecommunication access
9) Testing for immunity to electrical fast transient/burst disturbances conducted along AC and DC power lines
10) Testing for immunity to surges conducted along AC and DC power lines

4 EMI REDUCTION

Besides following the requirements set by standards and regulations, there is additional practices for reducing EMI in circuits. These practices include minimizing current loops and wires, keeping the loops as small as possible and the wires as short as possible. Choosing the correct cable type, ensuring proper cable segregation and routing, creating functioning cable connections, forming 360° electrical bonds along with shielding, gasketing, filtering, grounding , decoupling, isolation and separation, circuit impedance control, I/O interconnect design, and printed circuit board (PCB) design are all important factors to consider during installation.

The most common causes for EMI in system-level design involve incorrect use of containment measures (plastic versus metal housing), grounding of cables and connectors, and poor PCB design, layout, and implementation. The PCB layout includes clocks and periodic signal trace routing, stackup arrangement of the PCB and signal routing layer allocation, selection of components with high spectral RF energy distribution, common-mode and differential-mode filtering, ground loops, and insufficient bypassing and decoupling. (Montrose, 2005)

4.1 Cabling

Cables can be roughly divided into two sections: unshielded cables and shielded cables. In order to prevent mechanical and environmental damage, cables can be shielded in various different ways, including conduits, sleeving, foils, binding, heat shrink tubing, and twisted-pair cabling.

Conduits can be metallic or plastic. Metal conduits have high load-bearing capabilities and are often used for heavy duty protection and fire resistance in industrial and commercial applications. Metal conduits can be grounded and bonded, which is important when it comes to minimizing EMI (Essentra Components, 2019). Plastic conduits are typically used in domestic applications for light mechanical protection in chemical resistance. Some plastic conduits include a metal sleeve which makes it possible to use them in EMC purposes (Eland Cables, n.d.).

Sleeving can be made from plastic, metal, or fiber. Both sleeving types are made from either fine plastic strips or metallic wires tightly woven into a meshed tube. The plastic sleeve gives protection against moisture, temperature changes and abrasion. Metallic sleeving protects cables from EMI, heat, and abrasion. Sleeving made from fibers can be used for thermal protection and abrasion resistance.

Foil shielding can be used as an alternative to metal sleeving. The foil is a metallic tape that protects cables against HF signals. Braiding is more expensive than foil shielding but is remarkably more durable than foil shielding (Regole, 2019). Binding is usually made from plastic spiral tubes and is used to organize and group cables together in order to prevent them from coming into contact with other conductors. In heat shrink tubing, cables are encased in plastic tubes by using heat to form close-fitting casing. Heat shrink tubing provides particularly durable strain relief and abrasion resistance.

Twisted-pair cables are made by intertwining two separate insulated wires. This type of cabling can be further divided into unshielded twisted-pair (UTP) and shielded twisted-pair (STP) cabling. The latter has fine wire mesh surrounding the inner wires.

Fig. 12. Illustration of the interior of an unshielded twisted-pair cable (on left) and a shielded twisted-pair cable (on right). Shielded cables are mostly used in telephone and data communication networks to reduce external interferences. (Computer Hope, 2018)

Cables have their own standards and are divided into different classes according to the type of signal that they carry and their levels of immunity and emission. According to the IEC 61000-5-2:1997 standard, the cable classes are:

Class 1) Cables carrying very sensitive signals
Class 2) Cables carrying slightly sensitive analogue signals
Class 3) Cables carrying slightly interfering signals
Class 4) Cables carrying strongly interfering signals
Class 5) Cables carrying medium voltage signals

Class 6) Cables carrying high voltage signals

Cables with varying classes and cables that connect different devices need to be spaced correctly in order to prevent any disturbances. Cables carrying high voltage signals in interfering frequencies must be separated from other cables, even within shielded enclosures. Minimum spacing requirements for cables up to 30 meters are presented below. Cable trays are useful for maintaining precise spacings. In order to prevent emissions, minimum requirements must be met in the spacing between trays, both vertically and horizontally.

Table 4.1. Cable segregation minimum distances for cables up to 30 m.

Minimum cable distances	x_{min}
Very sensitive cables and highly interfering cables	600 mm
Very sensitive signals and mildly interfering cables	450 mm
Very sensitive signals and mildly sensitive cables	150 mm
Mildly sensitive signals and mildly interfering cables	300 mm
Mildly sensitive signals and highly interfering cables	450 mm
Mildly interfering signals and highly interfering cables	150 mm

The formula for assessing the cable segregation distance x_{min} for a cable over 30 meters is

$$x = \frac{x_{\mathrm{min}} * l_{\mathrm{c}}}{30\ \mathrm{m}} \tag{2}$$

where x_{min} is the minimum cable distance (referred in Table 4.1) and l_{c} is the cable length (Danfoss, n.d.).

Cable glands are devices that are used to convey cables through cabinets and enclosures, and to ensure HF connections for the cable shield at connections without leaking EMI. Cable glands are used or electrical devices with ingress protection (IP) rating. When using cable glands, it’s important to make sure that the bonding to cables is secure by forming a 360° contact. Any paint between cable glands and cables must be removed, the shields or screens of cables must be covered until the termination point, and precautions to avoid the corrosion of exposed metal must be considered. Adequate safeguards and gaskets can also be used for sealed point of entries.

If cable glands are used, the cable must have cable screen exposed and clamped by cable screen clamps, which create a secure grip while holding cables close to the mounting surface. Cable screen clamps can be used for fastening, routing, or separating cables.

4.2 Routing

Cables must be routed following the same route between equipment, while maintaining the minimum spacing requirements. Right angles must be taken into consideration when routing for cables intersecting each other so that the cables don't run towards each other without adequate spacing. The return path of a cable should always follow the send path, while keeping any deviations as minimal as possible.

Different routing methods for cables along ground planes include the use of:

1) Solid metal conduit or tube
2) Channel type conduit with a lid
3) Open channel conduit
4) Wide conduit
5) Lightning tape
6) Heavy gauge earth wire
7) Mesh common bonding network (MESH-CBN) tray

Using method 1, a solid metal conduit or a tube, is the most efficient method. It's suitable for routing cables of all frequencies and requires 360° electrical bonds at every joint or gland. Method 2 utilizes a channel type conduit with a lid. If this method is used, the lid must be bonded along the whole length. Method 3 makes use of open channels, like narrow ducts, and method 4 makes use of wide conduits, such as trays. In method 4, cables can be laid either in the corners or in the center.

Method 5 is to use a lightning tape along the length of the cable, and method 6 is to use heavy gauge earth wire running in parallel with the cable. In method 7, cables can be routed directly to the MESH-CBN trays, attached to a wire parallel earth conductor (PEC), or run along the metal work of a building. The main purpose of PECs is to divert heavy earth loop currents, and for this purpose it's enough that PECs have low resistance and sufficient current-carrying capacity (Williams, 2016). Method 6 and 7 give protection up to 50/60 Hz.

Interferences can be controlled only at low frequencies up to 50 Hz or 60 Hz when using lengthy wires. The frequency at which interference can be controlled can be increased by using shorter wires, or short fat braid straps, or multiple of both.

Besides routing along ground planes, cables can also be routed along the metalwork of buildings, or ground frames. When using ground frames, routing cables on sides or near the corners are suitable only for DC frequencies up to 60 Hz. HF cables must be routed within the frame, or close to the rib of the frame.

4.3 Grounding

Devices are subject to external risks such as lightning strikes and power surges, which may cause dangerous voltage differences. Grounding protects both devices and personnel if this type of incident occurs. Other purposes of grounding are to provide EMC by bonding over a wide range of signal frequencies to ensure equipotential voltage, and to provide a low impedance to divert currents from power faults such as lighting and HF currents, without allowing them to pass through the devices.

Each electrical device must be grounded properly to avoid any interferences. If devices can’t be grounded individually, or if they’re placed close to each other, equalizing cables can be used to ground the different devices together. Different types of grounding consist of serial single-point grounding, parallel single-point grounding, and multi-point grounding.

Serial single-point grounding is when ground wires of several devices are connected together, with the grounding wire of the last device connected the ground point. This type of grounding isn’t recommended, because it creates an excessive amount of strain on the first device. The second type of grounding is parallel single-point grounding, in which all devices are connected separately through grounding wires at the same point. This type of ground is most recommended. Multi-point grounding is the third grounding type, which is when all devices are separately connected through grounding wires at different points. This type of individual grounding should be avoided.

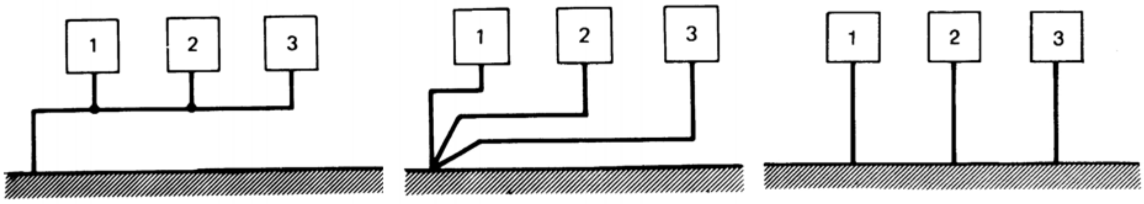

Fig. 16. From left to right: serial single-point grounding, parallel single-point grounding, and multi-point grounding. (University of Oslo, n.d.)

All ground connections have a certain amount of impedance. A device connected between two distant ground points creates a ground loop, as well as two devices grounded at two different points that have a potential difference between them. To reduce impedance, the ground connector must have an adequate cross-section of 10 mm².

There is a common misconception that shielded cables should be grounded only at one end in order to avoid ground loops. However, this results in limited plane wave shielding in the electric field and hardly any shielding in the magnetic field. Shielded cables should therefore be grounded at both ends for high-frequency shielding. When grounded at both ends, high-power and RF currents should be routed on separate return conductors. If the shielded cables carry noise, RF capacitive ground connections can be used to shunt RF currents and to present a high impedance to the low frequencies. Another option is to use differential signal and receiver sets, where potential interference is coupled in common mode (CM) voltage. The interference is reduced by the common mode rejection ratio (CMMR) of the amplifier stage receiving signals. (Marino, n.d.)

4.4 Shielding structures

Many EMI disturbances may not occur until the final stages of designing a system, leaving limited time and resources for intricate redesign. These disturbances can be eliminated by using shielding structures. In addition to the shielding methods referred to in chapter 2, EMI *SE* depends on the structure of the DUT. Some of the most common shielding structures include the Faraday cage, EMI absorbers, EMI shielding gaskets, and EMI shielding textiles.

The Faraday cage is one of the oldest, yet relevant ways to execute an electromagnetic shield. A Faraday cage encloses the fixed volume of space that relates charge and electric fields, and prevents external interferences inducing electric fields within that volume when the cage is made of a conductive material (Backyard Brains, 2020). The structure of the cage consists of a conductible container made of wire mesh or metal plates, which separates the DUT inside from external electric fields. When an electric field occurs on a surface of a cage, electrons mobilize in a manner that cancels the electric field on the other side of the surface and create an electrically neutral area inside the cage (Mathur & Raman, 2020). In other words, when a moving magnetic wave hits the cage, it generates current and electromagnetic induction. The current, in turn, creates a magnetic field that opposes the field of the oncoming wave, and thus blocks it from the interior of the cage (Murphy, 2016).

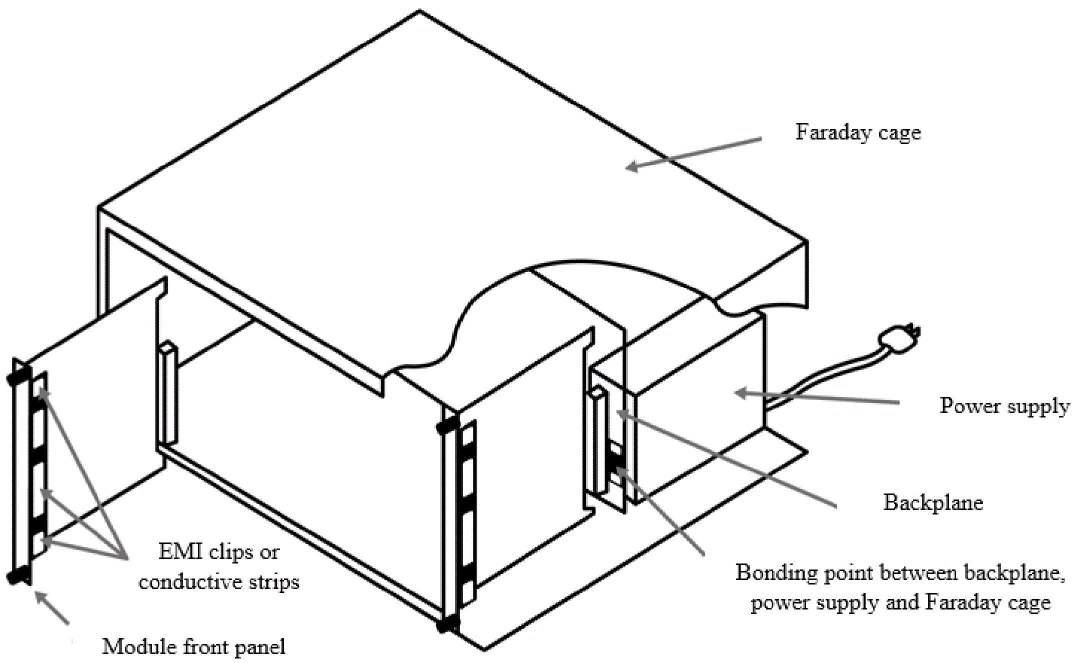

Fig.17. An example of a card cage based on the Faraday cage theory. (Knack, 2019)

As electronic systems are getting more and more compact in size, components are placed closer to each other and wavelengths get shorter. This results in wavelengths approaching physical dimensions of the components and systems, and an increased antenna effect of noise. To break down this effect, EMI absorbers can be used to suppress or eliminate transmissions and reflections from near-field radiations, covering frequencies from a few hundred MHz to high GHz ranges (Nakauchi, 2011).

EMI absorbers are usually made from polymers into different forms, e.g. polyurethane foam, silicone, sheet form, adhesives, and tape. These materials are insulators as such, which means that they need to be doped with an electrically conductive substance, a lossy substance, or a substance that conducts magnetic flux.

The absorber thickness is directly correlated to the absorber capacity. Optimum shielding requires the absorber thickness to be a quarter wavelength of the offending noise frequency it's tuned to (Robjohns & White, 2007). EMI absorbers can be used as an addition to other shields because apertures in other shielding options may be prone to leakage.

EMI shielding gaskets are used to fill in narrow gaps and seams between each panel of an enclosure. Making sure that each joint is properly secured prevents radiated leakages and provide low impedance paths between the seams to reduce potential difference. The SE of an EMI gasket is "the ratio of the impinging incident field intensity on one side of the gasketed seam to the radiated leakage field intensity on the opposite side" as presented in the following equation

$$SE = 20 \log \left(\frac{E_1}{E_2}\right) \tag{3}$$

where E_1 is the impinging electric field intensity and E_2 is the leakage electric field intensity (Moongilan & Mitchell, 2008).

EMI shielding textiles can be used as wearable clothing to those who are at risk of being exposed to EMFs or as sheet covers for electronic equipment and spaces. Mixing woven, knitted and nonwoven textile fibers with electrically conducting and ferromagnetic metals create shielding against electromagnetic radiation. The adequacy of EMI shielding textiles depends on the geometry of the fabric, such as thickness and pore size, and the metal content of the textile. Compared to other solutions, textiles have the advantage of flexibility, durability, and light weight. (Hulle & Powar, 2018)

4.5 EMI filters

Any internally generated noise can be kept contained within a device by using an EMI filter and simultaneously reduce current noise from power cables, and to prevent any external AC line noise from entering the device. EMI filters provide protection only against conducted EMI, so they are often paired with shields that block radiated EMI. Adding a shield can efficiently block all forms of EMI, because an unshielded EMI filter might still damage the device by transmitting noise through air. Noise can get emitted from a wire on one side of the EMI filter and then recouple with the wire on the other side, travelling to the device.

EMI filters are usually made from inductors and capacitors to form LC circuits. The inductive part of an EMI filter acts as a low-frequency (LF) pass device for the AC line frequencies and as a HF blocking device since unwanted EMI signals are at a significantly higher frequencies than other signals (Berman, 2008). The capacitors used in EMI filters are called shunting capacitors, because they function by shunting or bypassing HF noise away from a component or a circuit.

Commercial and industrial EMI filters consist of AC and DC filters. AC filters can be further divided into single-phase and three-phase filters, and DC filters into different variations of differential mode (DM) and common mode (CM) filters. DM signals carry data or information, and DM is always present between two power supply lines. DM noise is caused by pulsating currents, and turn-on/turn-off transients of devices. CM signals carry no useful information and are a major source of RF radiated energy. CM noise is just a side effect or a byproduct of DM transmission, and can also be a consequence of insulation leakage, electromagnetic coupling, and secondary effects due to parasitic components.

CM noise is often the most troublesome problem when it comes to EMC compliance. It develops through a lack of DM cancellation, or in the presence of poor CM rejection which results from imbalance between two transmitted signal paths. Signals will not be cancelled out, if they aren’t exactly opposite and in phase to each other. When designing an EMI filter, CM and DM noises must be taken into consideration separately because they come from different sources, and have their own propagation paths (Serrao, et al., 2008).

Noise suppression capacitors are used to reduce conducted RF disturbances on AC power lines, to protect humans from electrical shocks, and to protect electrical systems against voltage surges and transients. A capacitor can absorb the energy and voltage surges caused by lightning, while blocking and attenuating voltage spikes that cause transients.

Noise suppression capacitors can be divided into class X capacitors that are connected from line to line, and class Y capacitors that are connected from line to ground. DM noise can be suppressed by using X capacitors, and CM noise can be suppressed by using Y capacitors as shown in the figures below.

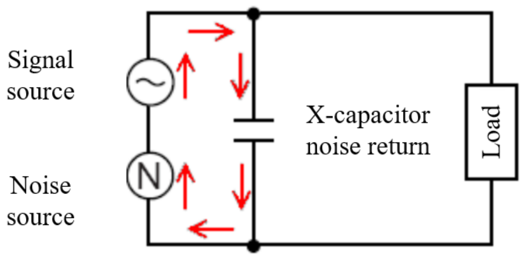

Fig. 18. Suppressing DM noise with a X capacitor. The noise is conducted on signal lines and electrical power lines in the opposite direction to each other. Installing the X capacitor between the line phase suppresses the DM noise. (Capakor, n.d.).

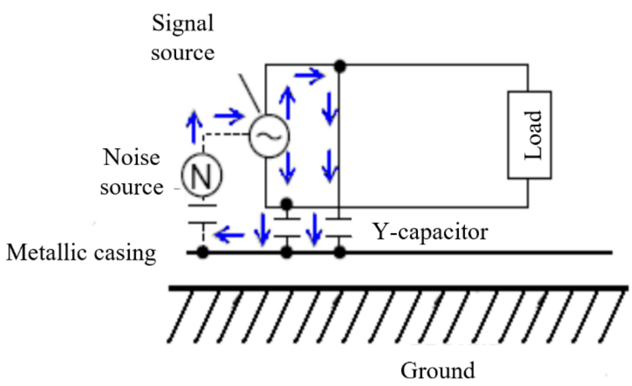

Fig. 19. Suppressing CM noise with a Y capacitor. The circuit is floating from ground, and there is stray capacitance between the circuit and the metallic casing. The stray capacitance is directly related to the CM noise, which is suppressed by connecting the metallic casing to all the lines where the noise is conducted by the Y capacitors. (Capakor, n.d.).

A typical EMI filter includes X and Y capacitors, and CM chokes. CM noise can be attenuated by using a CM choke and a Y capacitor. Leakage inductance, DM current, and self-resonance of LF CM paths can cause saturation in CM chokes. Self-resonance of a LF

CM path and saturation of a CM choke could be reduced by connecting a Y capacitor in parallel with a damping resistor (Cadirci, et al., 2005).

The impedance of a CM choke can be calculated according to Ohm's law as follows

$$Z_{\mathrm{CM}} = \frac{V_{\mathrm{CM}}}{I_{\mathrm{CM}}} \tag{3}$$

where V_{CM} is the voltage magnitude of each frequency point and I_{CM} is the current magnitude of this point (Chen, et al., 2019).

Saturation caused by self-resonance in CM chokes can be easily prevented by changing the switching frequency. However, this method limits the application range and practicality of a product. In order to ensure that the CM choke is not saturated, a larger magnetic core can be used, but it will require more space and a higher cost. Another option would be to connect a damping resistor in parallel to the capacitance which would attenuate self-resonance in the CM path.

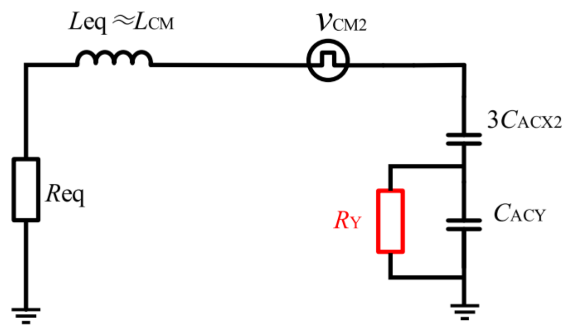

Fig. 20. A simplified CM path with a damping resistor to help reduce self-resonance within an EMI filter. The resistor R_{Y} is in parallel with the capacitance C_{ACY}. (Chen, et al., 2019)

The impedance of R_{Y} and C_{ACY} in the presented in figure above can be calculated with the following formula

$$Z_{\mathrm{Y}} = \frac{R_{\mathrm{Y}}}{1 + jwC_{\mathrm{ACY}}R_{\mathrm{Y}}} \tag{4}$$

where j is the jerk and w is the angular frequency (Chen, et al., 2019).

An example of a simple and practical design EMI filter presented in the figure below, is designed based on CM and DM conducted EMI separation according to the MIL-STD 461 standard. The prototype is implemented for a unity-power-factor boost converter, operating at a 20 kHz switching frequency and 4 kW output power. An iron-powder material with a distributed airgap was selected as the core material for the EMI filter. The selection criteria were having low core losses at 50 Hz, while having high core losses at the noise frequencies. The material was also required to withstand a significant 50 Hz flux-density component without saturating.

The capacitors were chosen based on their capability to present a high resistance to voltage surges, current surges, and against ionization. The layout was implemented by using a same metal plate to ground the filter and the noise source, keeping the connection between the filter and the noise source as short as possible, shielding the CM choke coils and the CM inductor, and keeping the spacing between the first and last winding in the inductors at least 30° to raise the self-resonant frequency (SRF). The only ground was made between the CM node and the Y-capacitors to avoid any other current flows through ground paths, increasing the SRF of capacitors by keeping their leads as short as possible (Cadirci, et al., 2005)

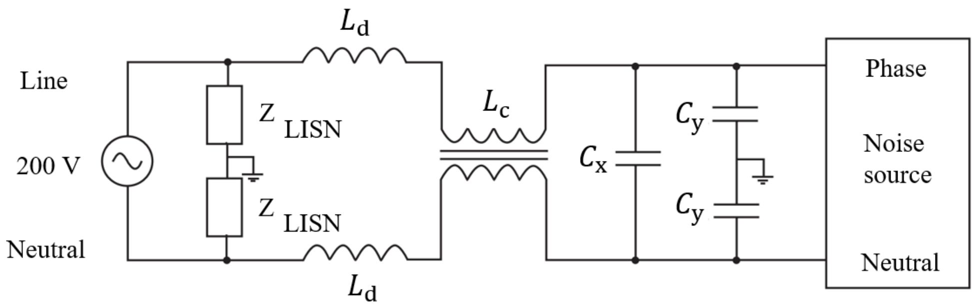

Fig. 21. The EMI filter topology, consisting of a single-stage DM port. Minimizing the radiated coupling between the noisy and filtered circuits to the by keeping the input and output of the filter as far as possible from each other, and using a screened cable to connect the load and the noise source, was taken into account in the filter layout. (Cadirci, et al., 2005)

4.6 Additional components

Chokes, also known as inductors, are used to eliminate HF AC signals, typically made from coils of insulated wires on a magnetic core. Chokes can be divided into two main categories:

audio frequency chokes (AFC) and radio frequency chokes (RFC). The AFC has an iron core and is made for blocking AC audio and power line frequencies, while the RFC has an air core and is used for blocking RF signals (Kourtessis, n.d.).

Ferrite beads, also known as ferrite rings or ferrite chokes, are passive components that can be used as filters on power lines to eliminate HF noise and conducted EMI from a DC power supply. They operate by transforming interferences into heat, becoming resistive and heat dissipating when the intended frequency range is exceeded. A ferrite bead is typically connected in series with the power supply, combined with capacitors to ground each side of the bead. (Limjoco & Eco, 2016)

Snubbers are used to reduce EMI by damping voltage and current ringing, and to protect the EUT from transient voltage and current spikes that are formed when switches open in the circuit. Snubbers can transfer power dissipation from the switch to a resistor or another useful load and ensure that the load line stays in a safe operation area (SOA) during turn-on and turn-off. The most commonly used snubbers include resistor-capacitor (RC) snubbers, diode snubbers, and resistor-capacitor-diode (RCD) snubbers. (Severns, 2008).

5 TESTING

The manual testing section is divided into two parts: the first part covering the initial round of tests with assessment of any errors or difficulties that arose, following into the second round of tests, with improved design and an EMI filter in order to achieve better results. Both tests were performed according to CISPR25, by using the current probe method. The testing was executed in a shielded room because of its ability to fit large devices inside. The test equipment consisted of:

- The DUT (a charger in this case)
- 2 pcs of 12 V Bosch batteries in series
- 1 Rohde & Schwarz ESR 7 EMI receiver
- 2 pcs of EM Test AN 200N100 single line artificial networks
- 2 pcs of Teseq HV-AN 150 single line artificial networks
- 1 Rohde & Schwarz EZ-17 current clamp
- 1 resistive load of 12.7 Ω
- Coaxial cable

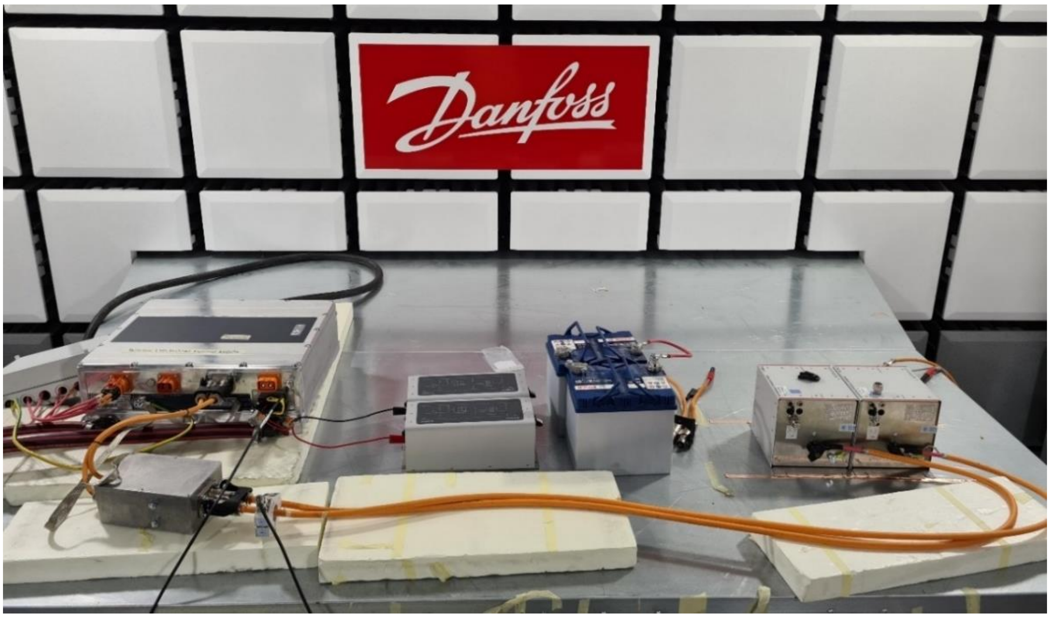

Fig. 22. The test equipment consisted of a charger, batteries, an EMI receiver, single line artificial networks, a current clamp, a resistive load, and coaxial cable. The photograph above was taken in the shielded room where all the tests were executed.

5.1 Testing #1

Interference levels from the first round of testing exceed the maximum allowed interference levels set by CISPR25, especially in the 400 kHz to 5 MHz range. This implies that the circuit needs to be further improved with additional filtering.

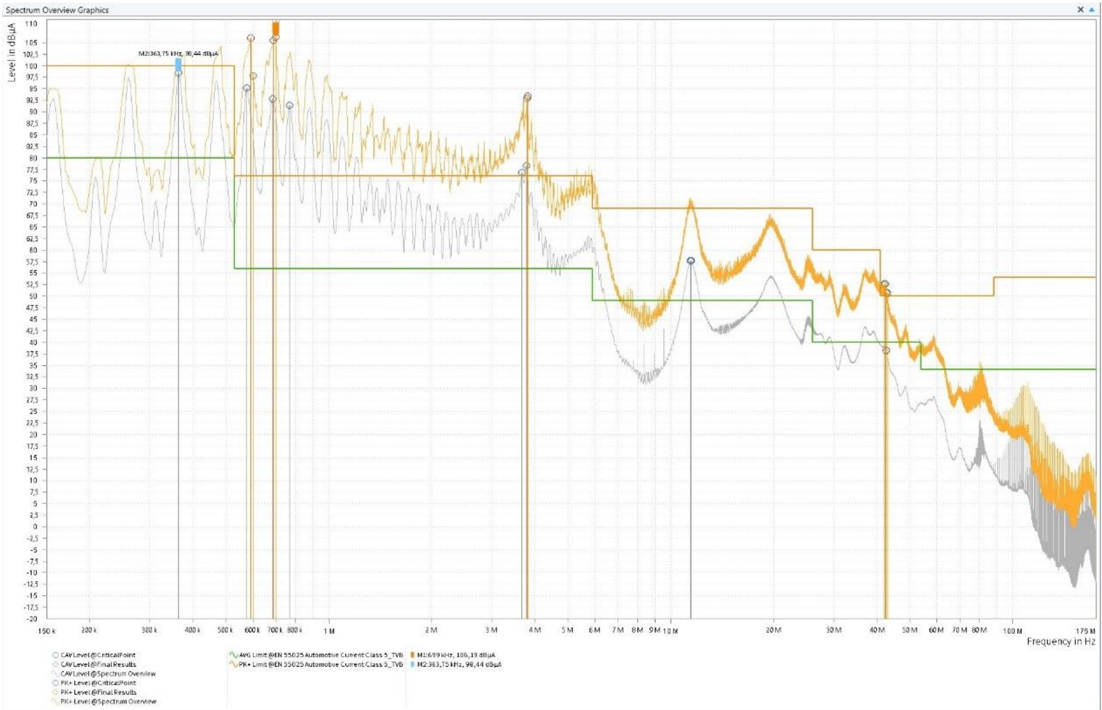

Fig. 23. In this graph, interference levels from the first test are presented as a function of frequency. The orange curve is the maximum interference level that was measured, and the gray curve is the average interference level. The orange line signifies the maximum allowed interference level, and the green line signifies the average interference level according to CISPR25. The results indicate that emissions do not pass the EMC limits without an EMI filter.

5.2 Testing #2

In order to achieve better results than in the first test, an EMI filter was added in the next round of testing. After adding the EMI filter, as presented in figure 24, the results from the second round of tests indicated that emissions do successfully pass the EMC limits set by CISPR25. The operation of the filter was also simulated with MATLAB, as demonstrated in figure 26. The graphs from the tests and simulations share similar patterns and proportions.

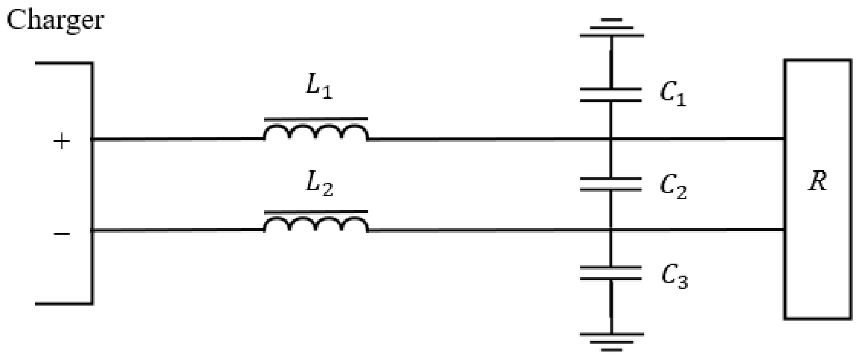

Fig. 24. The EMI filter topology for the filter used in the testing, including a charger, two inductors, three capacitors, and a load. The values for the components are: U = 24 V, L_1 = L_2 = 24 μH, C_1 = 3.3 nF, C_2 = 1.5 μF, C_3 = 3.3 nF, and R = 12.7 Ω.

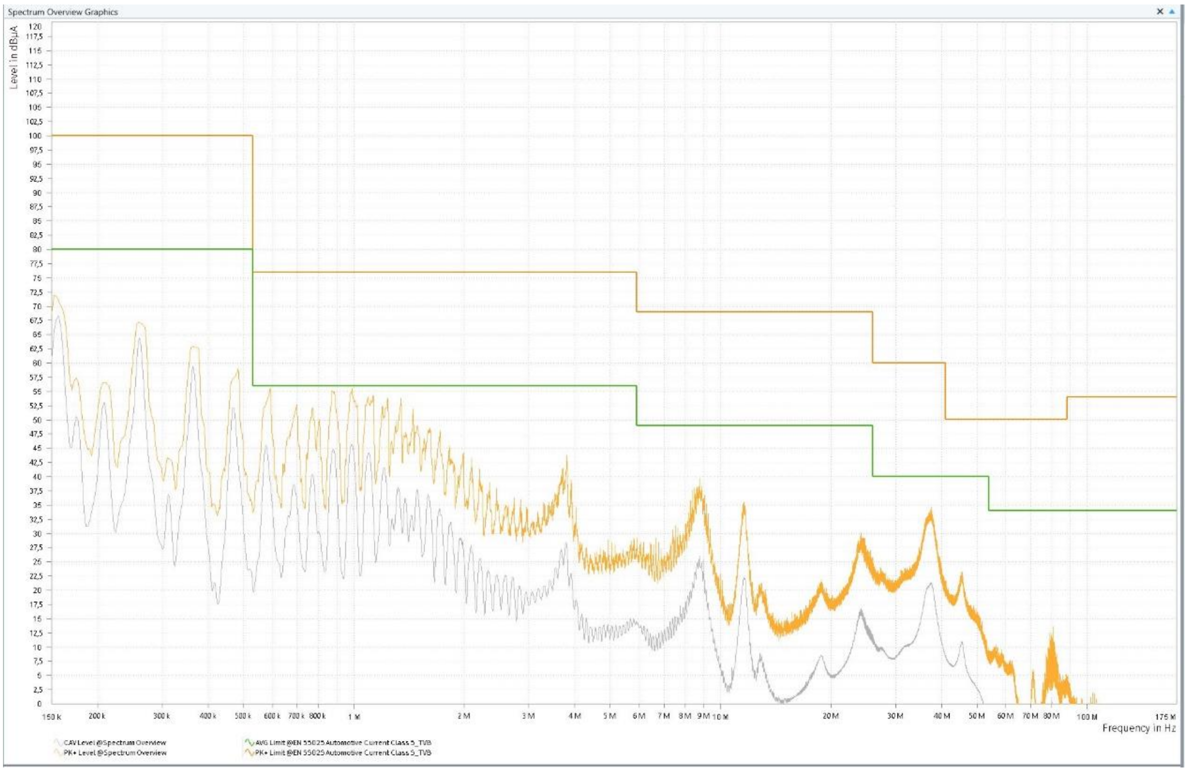

Fig. 25. The second round of tests imply that EMC limits are passed by using an EMI filter. The interference levels from this test are well below the maximum allowed interference levels. The graph presents the interference level as a function of frequency. The orange curve is the maximum interference level that was measured, and the gray curve is the average interference level. The orange line signifies the maximum allowed interference level, and the green line signifies the average interference level according to CISPR25.

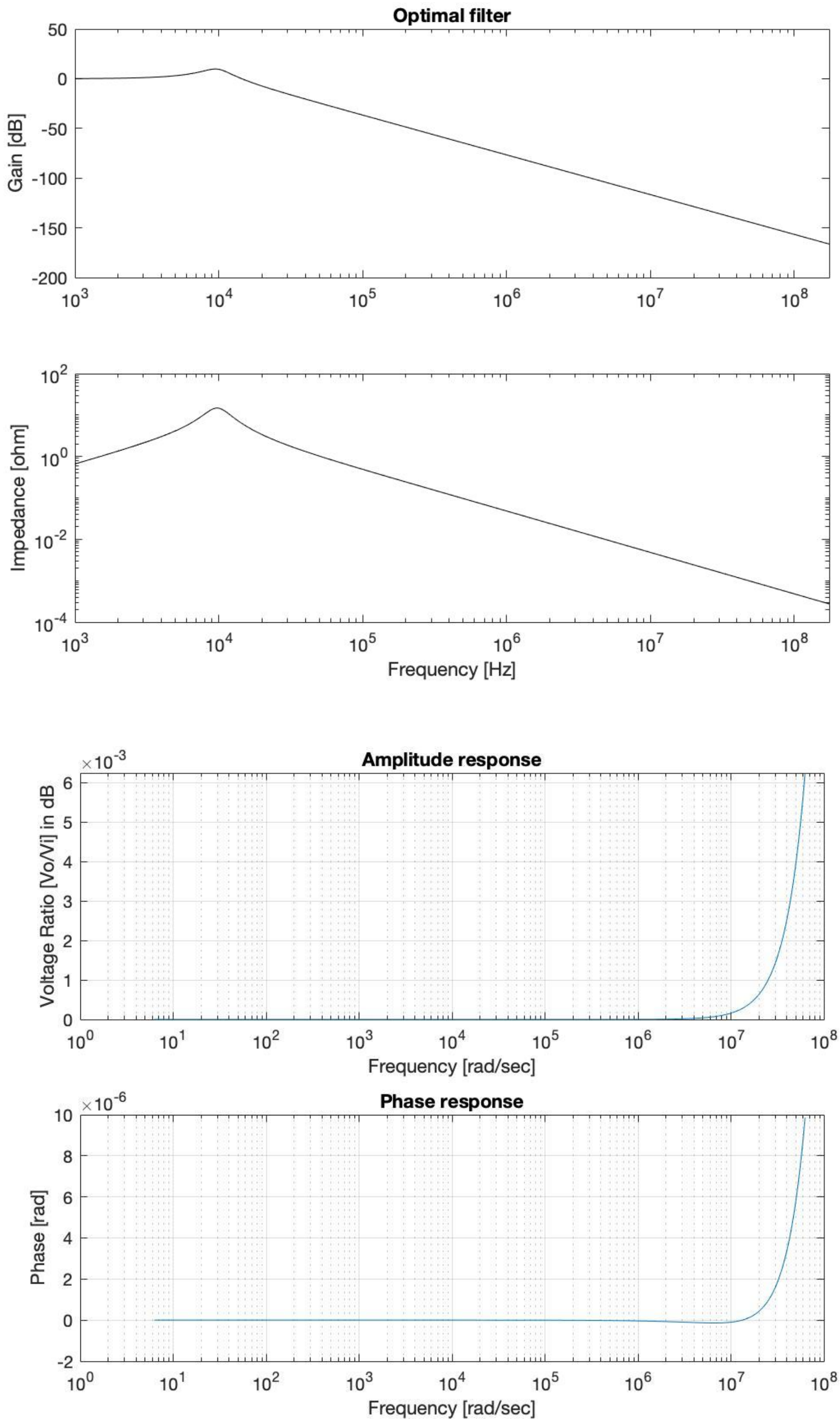

Fig. 26. The operation of an optimal EMI filter was simulated by using MATLAB. The first graph presents how much attenuation is obtained at each frequency with an optimal filter. The second graph demonstrates impedance in relation to frequency. The third and fourth graph illustrate amplitude and phase responses in relation to frequency.

6 CONCLUSIONS

The majority of today's electronic devices require shielding to meet their mandatory EMC requirements for both emissions and immunity. With devices becoming more compact in size and more densely populated, some need shielding even just to avoid interference within their own operation. EMC regulations are increasing continuously as electronic devices are made more intricate and susceptible to disturbances. A device must function as intended without disturbing its electrical environment.

In this thesis, the regulations regarding emission testing have been explored by executing tests and resolving any errors that occurred. The tests were performed in a shielded room by using the current probe method according to CISPR25. New ways to achieve the target limits were found by implementing an EMI filter.

The results substantiate that the desired EMC testing limits can be achieved by using a filter to attenuate interferences. By using a filter comprising of inductors and capacitors as suggested in the previous chapter, the test limits for maximum interferences can be passed in accordance to CISPR25. The EMI filter attenuation is also demonstrated with MATLAB simulations.

The results of this thesis could be used to provide information and guidance on how to reduce EMI in future testing, especially in components and ESAs. Since the focus of this thesis was on conducted emissions, DC power lines, and smaller devices, future research could consist of studying how to reduce EMI in radiated emission testing, AC power lines, and larger assemblies.

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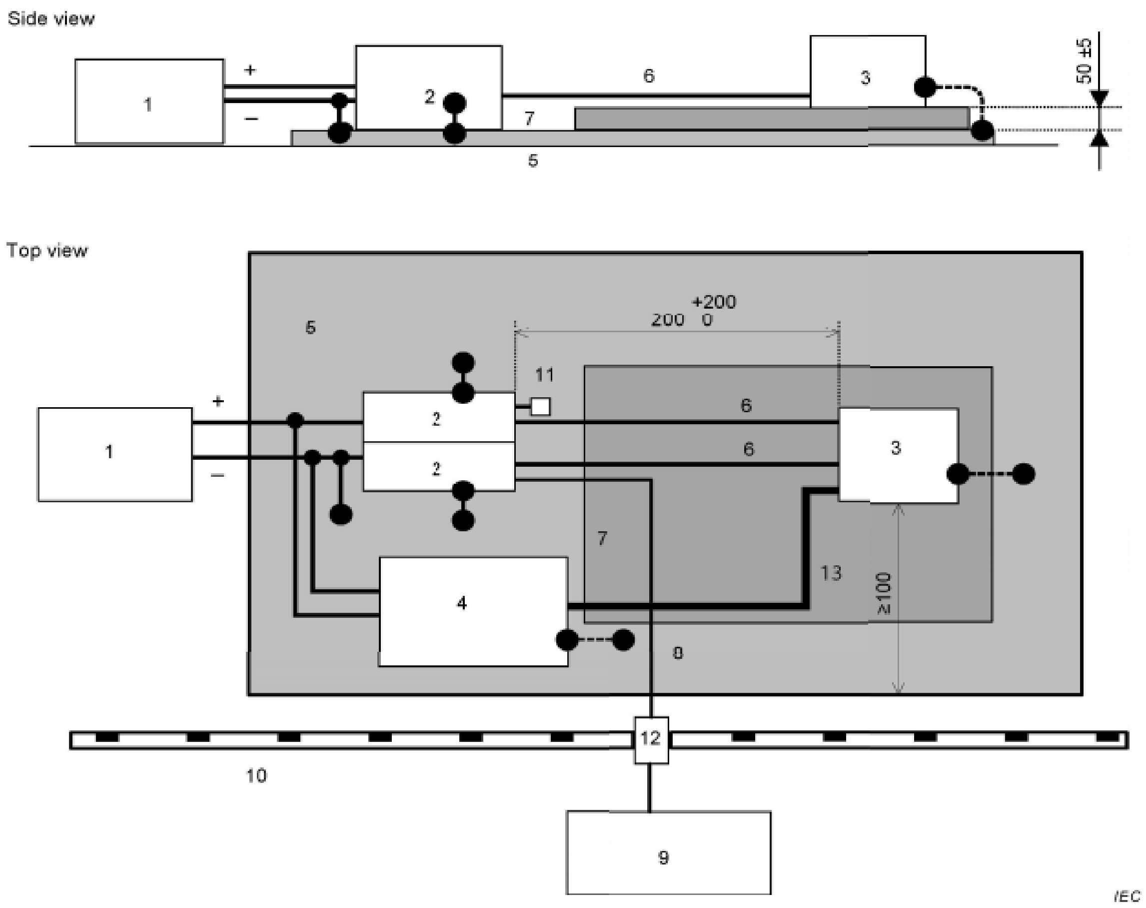
APPENDIX 1. Voltage method setup (LV)



Key

1 Power supply (may be placed on the reference ground plane)

2 Artificial network

3 EUT (housing grounded if required in test plan)

4 Load simulator (metallic casing grounded if required in test plan)

5 Reference ground plane

6 Power supply lines

7 Low relative permittivity support ($\varepsilon_r \leq 1,4$)

8 High-quality coaxial cable e.g. double-shielded (50 Ω)

9 Measuring instrument

10 Shielded enclosure

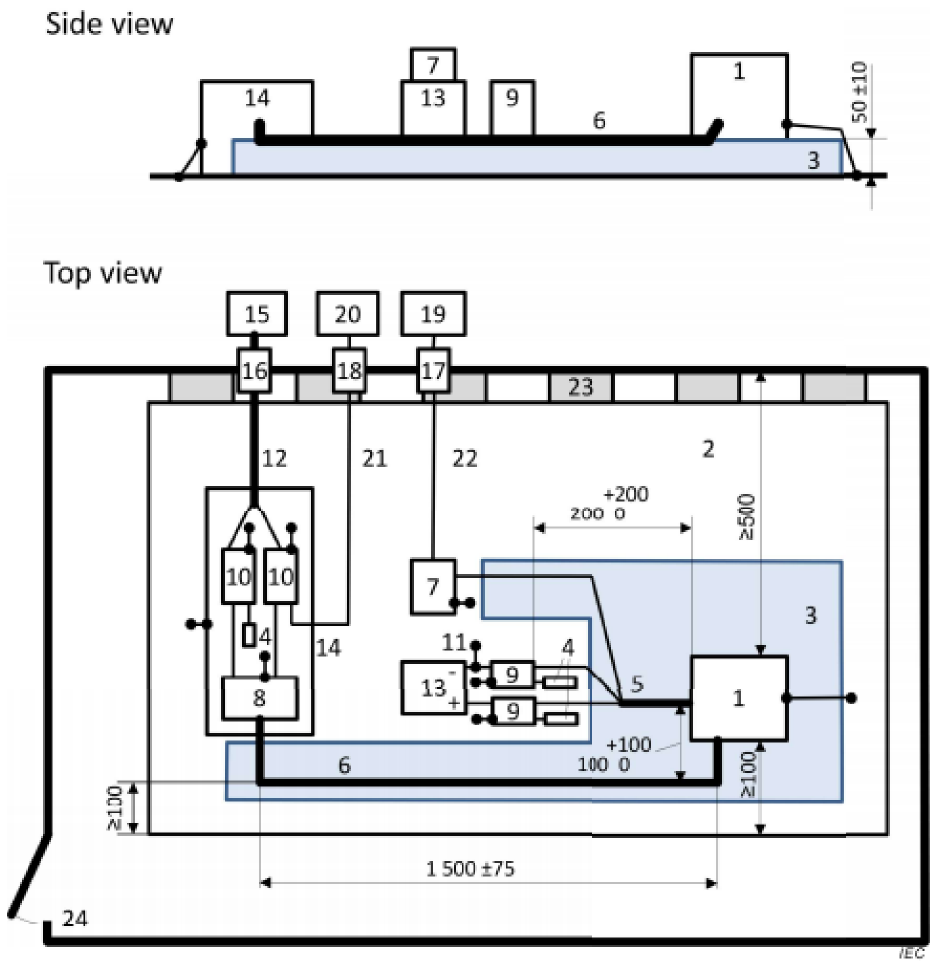
11 50 Ω load

12 Bulkhead connector

13 Test harness (excluding power lines)

The EUT housing ground lead, when required in the test plan, should not be longer than 150 mm.

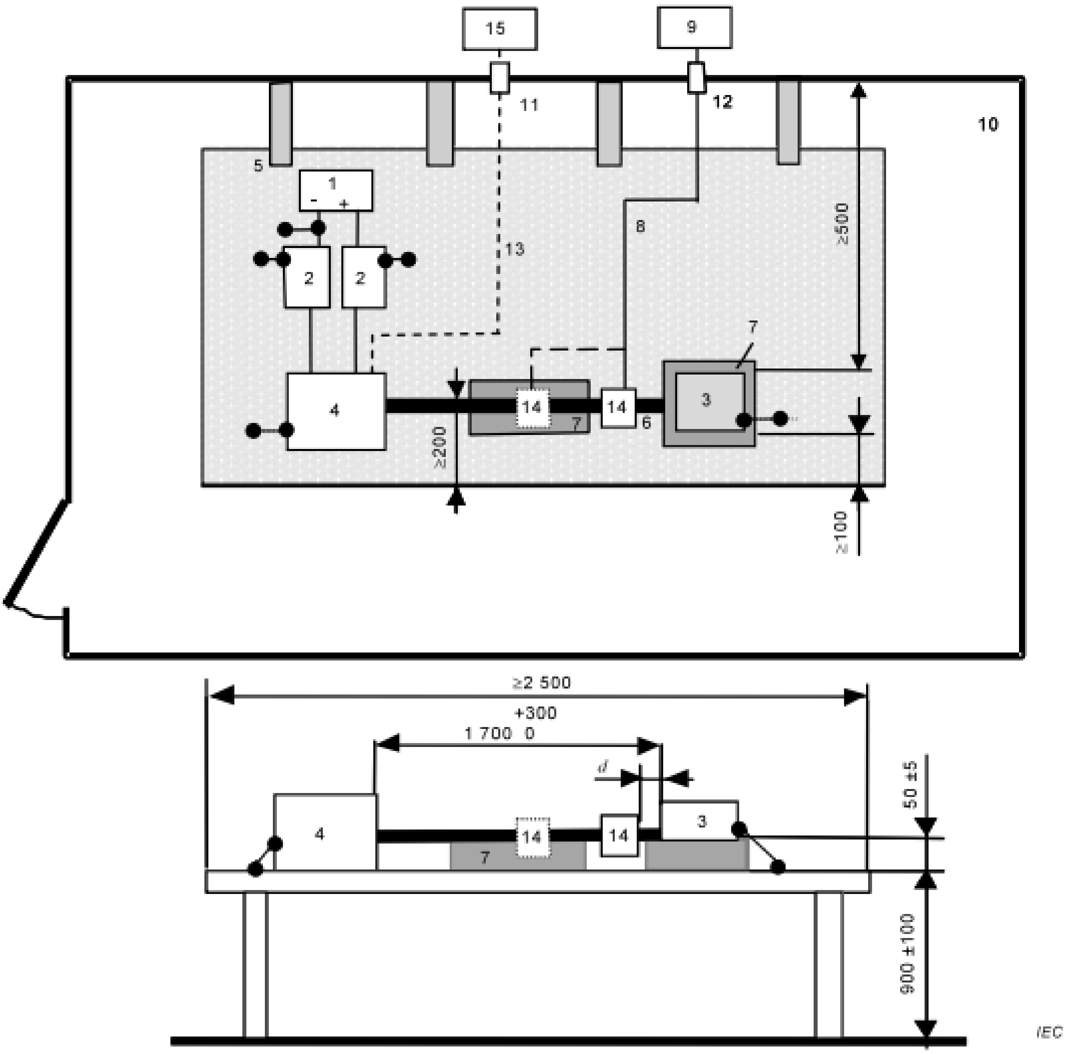
APPENDIX 2. Voltage method setup (HV)



Key

1	EUT	13	LV power supply 12 V / 24 V / 48 V (should be placed on the reference ground plane)
2	Ground plane	14	Additional shielded box
3	Low relative permittivity support ($\varepsilon_r \leq 1,4$) thickness 50 mm	15	HV power supply (shielded if placed inside shielded enclosure)
4	50 Ω load	16	Power line filter
5	LV harness	17	Fibre optic feed through
6	HV lines (HV+, HV−)	18	Bulk head connector
7	LV load simulator	19	Stimulating and monitoring system
8	Impedance matching network (optional)	20	Measuring instrument
9	LV AN	21	High quality coaxial cable, e.g. double shielded (50 Ω)
10	HV AN	22	Optical fibre
11	LV supply lines	23	Ground straps (see 6.2.1)
12	HV supply lines	24	Shielded enclosure

APPENDIX 3. Current probe method setup (LV)



Key

1 Power supply

2 Artificial network

3 EUT (connected to ground if specified in the test plan)

4 Load simulator (metallic casing grounded if required in test plan)

5 Reference ground plane

6 Wiring harness

7 Low relative permittivity support ($\varepsilon_r \leq 1,4$)

8 High-quality coaxial cable e.g. double-shielded (50 Ω)

9 Measuring instrument

10 Shielded enclosure

11 Fibre optic feed through

12 Bulkhead connector

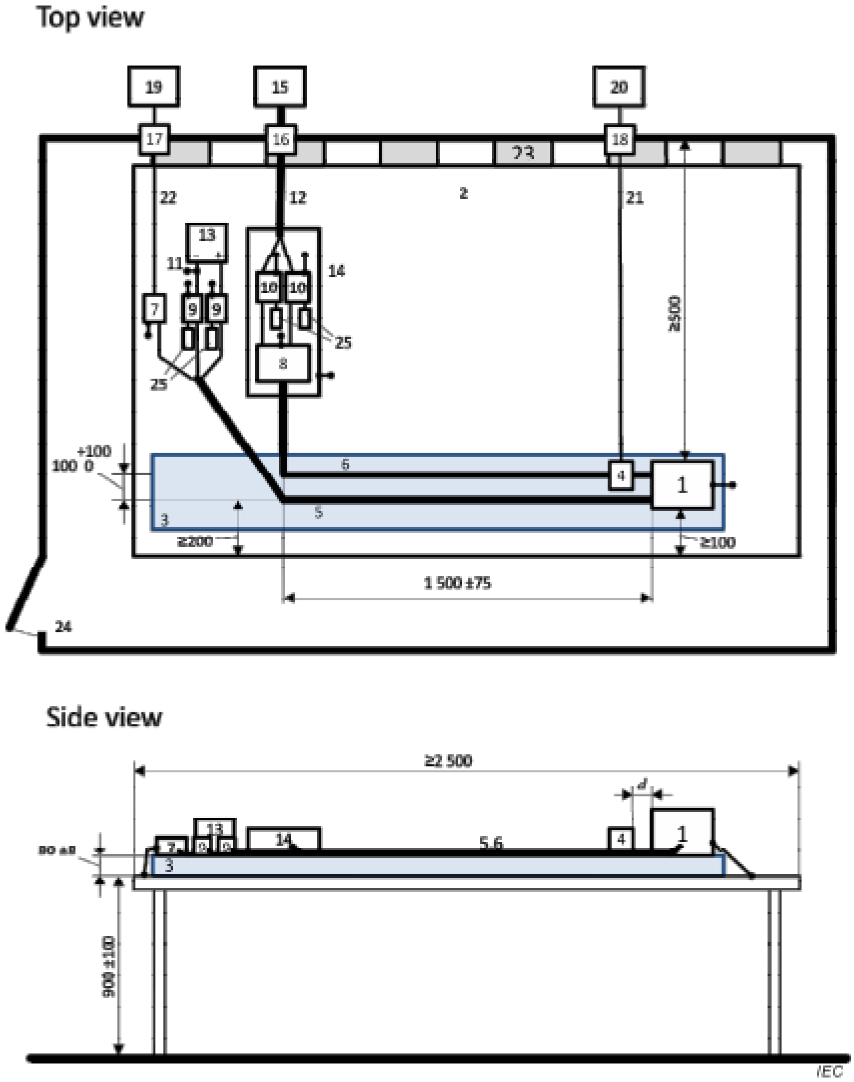
13 Optical fibres

14 Current probe (represented at 2 positions)

15 Stimulation and monitoring system

d The distance from the EUT to the closest probe position

APPENDIX 4. Current probe method setup (HV)



Key

1	EUT	14	Additional shielded box
2	Reference ground plane	15	HV power supply (should be shielded if placed inside the shielded enclosure)
3	Low relative permittivity support ($\varepsilon_r \leq 1{,}4$) thickness 50 mm	16	Power line filter
4	Current probe ("d" see I.3.2)	17	Fibre optic feed through
5	LV harness	18	Bulk head connector
6	HV lines (HV+, HV−)	19	Stimulating and monitoring system
7	LV load simulator	20	Measuring instrument
8	Impedance matching network (optional)	21	High quality coaxial cable e.g. double shielded (50 Ω)
9	LV AN	22	Optical fibre
10	HV AN	23	Ground straps (see 6.2.1)
11	LV supply lines	24	Shielded enclosure
12	HV supply lines	25	50 Ω load
13	LV power supply 12 V / 24 V / 48 V (should be placed on the reference ground plane)		