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Pre-Compliance EMC Testing for EV Charging Station

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Abstract

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The thesis project aimed to conduct pre-compliance electromagnetic compatibility (EMC) testing on prototype of the electric vehicle (EV) charging station as part of Big-Flash project in Metropolia University of Applied Sciences. The charging station was developed by Greenele Oy. It also involved study of suitable equipment available in Metropolia UAS to conduct required tests. Additionally, the process of debugging and flashing the Zephyr RTOS based software program to the board that controls the EV charger module was explored.

Fundamental pre-compliance EMC tests were conducted on the device following applicable SFS-EN IEC 61851-21-2:2021:en, general IEC, CISPR EMC standards to assess radiated and conducted emissions, electrostatic discharge (ESD) immunity, and EMC scan. Due to time constraints, the remaining general emission and immunity tests, such as electrical fast transient (EFT) and voltage surge, were not carried out, despite the availability of the required equipment on the premises. Though the test setup did not fully align with the standard requirements, it was still adequate for estimating emissions and immunity of the EV charging station during the initial stage of product development.

Compared to generic IEC and CISPR standards, radiated and conducted emissions of EUT were below the emission limit for class B device. During the ESD immunity test result, the EUT passed the test with ‘B’ performance criteria. EMC scan identified the areas of radiated PCB emissions near specific components on the PCB. It also detected minor emission issues related to soldering, indicating emission points near AC/DC power supply, voltage regulator and differential current sensor.

The results of pre-compliance EMC testing conformed to standard outlined in SFS-EN IEC 61851-21-2:2021:en standard for electric vehicle conductive charging system, including CISPR and IEC standards, suggesting EUT is compliant to EMC standards. The project facilitated identification and resolution of potential EMC issues of the EUT.

Keywords: EMC, EMI, pre-compliance test, EV, EVSE, emission, radiation, conduction, immunity, noise, frequency, PCB.

Contents

List of Abbreviations

AC:	Alternating Current
CCS:	Combined Charging Standard
CE:	Conducted Emission
CI:	Conducted Immunity
DC:	Direct Current
E:	Electric Field
EMC:	Electromagnetic Compatibility
EMI:	Electromagnetic Interference
ESD:	Electrostatic Discharge
EV:	Electric Vehicle
EVSE:	Electric Vehicles Supply Equipment
H:	Magnetic Field
HF:	High Frequency
IC-CPD:	Integrated in-Cable Control and Protection Device
IEC:	International Electrotechnical Commission
IEEE:	Institute of Electrical and Electronics Engineers
ISO:	International Organization for Standardization
LF:	Low Frequency
LISN:	Line Impedance Stabilization Network

OATS: Open-Area Test Site

RCM: Residual Current Monitor

RE: Radiated Emission

RI: Radiated Immunity

RF: Radio Frequency

SAE: Society of Automotive Engineers

UAS: University of Applied Sciences

1 Introduction

Technology is rapidly evolving with many new electronic products entering the market every day. Circuits in such devices are typically scaled down enclosing hundreds and thousands of passives as well as active components to perform multiple operation simultaneously. However, all such circuits in vicinity of each other affect adversely, causing devices to malfunction or subsequently emitting unwanted radiation beyond regulated standard, as well as potentially harming neighbouring devices. Hence electromagnetic interference (EMI) is huge challenge for any electronic hardware designer or manufacturer, to develop a product that is not only functional but also electromagnetically compatible, complying with the regulated standard. EMC testing is mandatory to guarantee safe operation, quality, and accuracy, and also to launch the device in market. Pre-compliance EMC testing is a cost-effective procedure that enables companies or manufacturers to design their product better, starting from early development stages.

The objective of this thesis project was to conduct fundamental pre-compliance EMC testing on a prototype of an EV charging station developed by Greenele Oy, a start-up company associated with Big-Flash project. The growing popularity of electric vehicles (EVs) driven by environmental concerns and rising fuel expenses has resulted in demand for affordable and portable EV charging solutions. Greenele Oy, a Finnish company specializing in the installation of EV chargers, has designed an affordable, portable, tabletop EV charging station for residential use.

As a part of this project, study was done on the resources and equipment available for performing pre-compliance tests at the Metropolia UAS premises. Additionally, explored the installation and debugging process of a software program that utilizes the Zephyr based RTOS to control the EV charger module. The pre-compliance EMC testing of the prototype of the EV charger was performed using the available EMC testing equipment in Metropolia University of

Applied Sciences in collaboration with Big Flash project. It was found that although the campus has necessary equipment to conduct all general pre-compliance EMC tests, however due to certain limitations, basic tests were performed. Hence this thesis project primarily intended to conduct pre-compliance testing which included general EMC tests of radiated emission, conducted emission, EMC scanning of PCB and ESD immunity test. Those fundamental testing and measurements procedure were carried out following the applicable guidelines and EMC standard of electric vehicle conductive charging system of Finnish Standard Association (SFS) that is SFS-EN IEC 61851-21-2:2021:en, along with other general IEC and CISPR standards for EMC tests. The project helps the company to identify and fix potential EMC issues, speed up time to market with improved product quality and ensure regulatory compliance. Certain test required to remove the control board from the enclosure. Thus, such test was conducted under the supervision of an authorized person in the power electronics lab for safety because of the presence of high voltage lines on the back of the control board of the EV charging station.

2 Electromagnetic Compatibility (EMC)

Electronic devices are extensively used in modern days for communication, automation, computation, smart system, and other multiple purposes. Present-day circuitry is becoming smaller and smaller with dramatically evolving sophisticated processor running on high-speed clock frequency, in many cases above gigahertz. This intensifies the probability of interference. Hence electric products and system must be designed such that they should not be affected by nearby and external electromagnetic sources and should not themself be a source of electromagnetic noise. However, every electronic device produces some level of electromagnetic interference through conduction or radiation since electricity flowing through its circuits and wires can never be entirely contained. Electromagnetic compatibility (EMC) guarantees proper functioning of various equipment that employ or react to different electromagnetic phenomenon within common electromagnetic environment. [1.]

Electromagnetic compatibility (EMC) is the ability of electronic device to operate as it is intended within its electromagnetic environment by limiting unintended radiation, transmission, and reception of electromagnetic energy that could lead to undesired interference or harming the operational functionality of the equipment. Electromagnetic environment comprises of radiated and conducted energy. EMC has three main aspects, emissions, susceptibility, and immunity. [1.]

2.1 Emission, Immunity and Susceptibility

Emission pertains to the generations of intentional or unintentional electromagnetic energy from a particular source into the environment. By curbing the emission of the designed product, the likelihood of interference with other devices can be eliminated.

Immunity is the capability of the equipment to operate satisfactorily without degradation of its functionality with established safety standard when exposed to external as well as internal interference within its operational electromagnetic environment. Whereas , susceptibility is lack of immunity, that denotes the extent to which an electronic device may be impacted or fail due to external electrical disturbance. It measures how vulnerable the device is, to interference or noise, which is opposite to immunity.

2.2 Waves and EMC Units

Electrical dimensions of radiating structure such as antenna, in wavelength are more significant in determining the ability of the structure to radiate electromagnetic energy (E and H), rather than physical dimension of the structure. Wavelength refers to the distance between two consecutive points of a repeating wave pattern, typically measured from peak to peak. Wavelength in free space (air) can be calculated by following equation 1, where ‘λ’ is wavelength, ‘c’ is speed of light and ‘f’ is frequency.

$$\lambda = \frac{c}{f} \quad (1)$$

The decibel is relative unit of measurement which is logarithmic ratio between two units. dB for voltage level can be expressed as follows in equation 2, where ‘V1’ is measured voltage and ‘V2’ as reference voltage.

$$dB = 20.\log_{10}\frac{V1}{V2} \quad (2)$$

In EMC measuremnets, dBuV is a measurement unit to express voltage or power level of an electrical signal in decibel in relation to a reference level of 1 microvolt (μV). The formula to convert signal amplitude (in volts) to dBuV is shown in equation 3 where ‘V’ is signal amplitude in volts.

$$dBuV = 20.\log_{10}\frac{V}{1\,uV} \quad (3)$$

Conversely, to convert a signal level from dBuV to volts is given in equation 4.

$$V = 10^{(\left(\frac{dBuV}{20}\right)-6)} \quad (4)$$

Electric component of radiated electromagnetic fields are given in term of electric field intensity (strength), in units of volt per meter (V/m). This unit is to quantify the strength of RF signals like radio and communication signals and EMI. It is defined using the following formula, where ’E’ is the electric field strength being measured in microvolts per meter. [2.]

$$dBuV/m = 20.\log_{10}(\frac{E}{1\,uV/m}) \quad (5)$$

2.3 Near Field and Far Field

The near field refers to the region where the distance between the source and the receiver is significantly less than the wavelength of the radiation. Conversely, in the far field, the distance between the source and the receiver is much larger

than the wavelength of the emitted radiation as shown in figure 1 [3] below. Signal in far field should be able to seen in near field but signal in near field may not necessarily radiate out in far field.

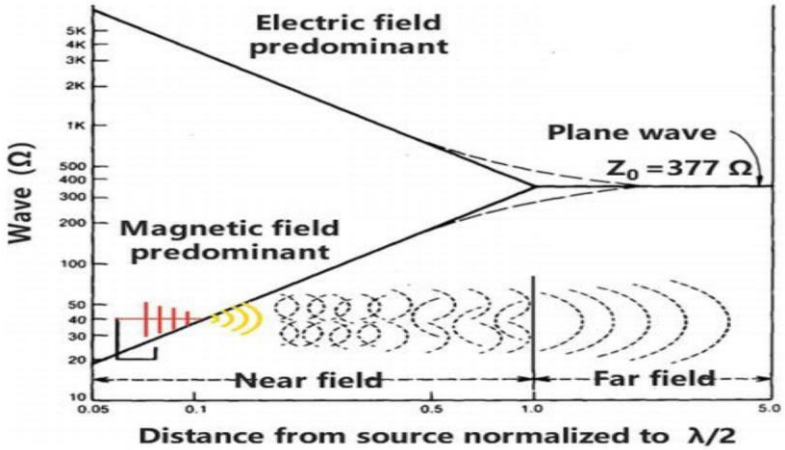
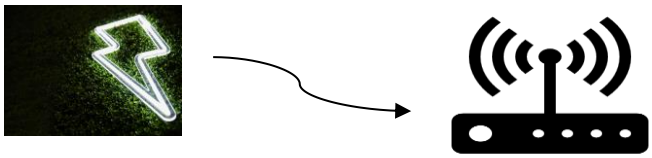


Figure 1. Electromagnetic wave in far field and near field. [3]

3 Electromagnetic interference (EMI)

Electromagnetic interference (EMI) is unwanted noise or signals also known as radio frequency interference (RFI) occurs when electromagnetic energy disrupts the functioning of an electronic device. Clock oscillators, IO ports, cables, connectors, LEDs, and other components are common sources of EMI. Switch mode power supplies are especially common, as their switching frequencies have increased over the years to improve efficiency. There are three components to every EMI source as shown in figure 2, an energy source, a coupling path or mechanism through which the energy is transferred, and an antenna which can be any wire, metal enclosure, or PCB trace that can potentially act as a radiator and emit energy into the environment. [4.]



Noise Source + Coupling Path + Antenna = EMI

Figure 2. Components of energy transfer source, coupling path and antenna.

EMI is electromagnetic wave that consist of oscillating perpendicular electric (E) and magnetic (H) field components which is shown in figure 3 [4] below. These components react differently to factor such as frequency, voltage, distance and current. Electric field is usually the major component of the interference in modern technology. [3.]

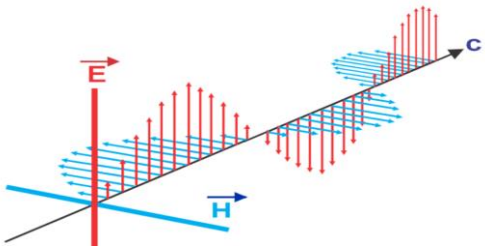


Figure 3. Electric and magnetic field propagating perpendicularly to each other. [4]

3.1 EMI and Noise

The origin of electromagnetic interference (EMI) is often called noise. It is any unwanted electrical signal that degrade the performance of electronic devices by introducing undesirable voltage and currents in a circuit other than required signal. Noise can lead to improper orientation of circuit which is known as interference. Sometime these interferences even completely breakdown the device which might then could be life threatening to user. Based on various factors such as source, duration and characteristics of signal, electromagnetic interference can be divided into many categories. [3.][4.]

3.2 Source of EMI

EMI can be broadly classified into three groups depending on how it originates from the source: natural, artificial, and intrinsic. [4.][5.]

3.2.1 Natural Noise

Natural noise source is noise originated from various natural phenomenon such as cosmic rays, solar flares, snow, storms, rain, and thunder which cause electromagnetic interference in circuits.

3.2.2 Artificial Noise

Artificial noise sources are man-made, such as motors, heating, welding, switches, computer, digital and electronic appliances, power grid and electrical network, that cause detrimental interference to electronic devices. Moreover, release of static electricity through rubbing certain types of clothing material generate an electrostatic residue up to 10-25 kV that can harm delicate electronic products.

3.2.3 Intrinsic Noise

Intrinsic noise source is noise, unintentionally generated interference from random fluctuation within physical systems (PCB), causing device to break or malfunction, such as thermal and shot noise. This problem frequently arises from inadequate design practices that do not undergo sufficient testing. It is difficult to prevent as the interference originates from the device itself. The figure 4 [1] below illustrates the intrinsic thermal noise observed on wideband oscilloscope. The frequency distribution of thermal noise power level is uniform across the frequency bandwidth.

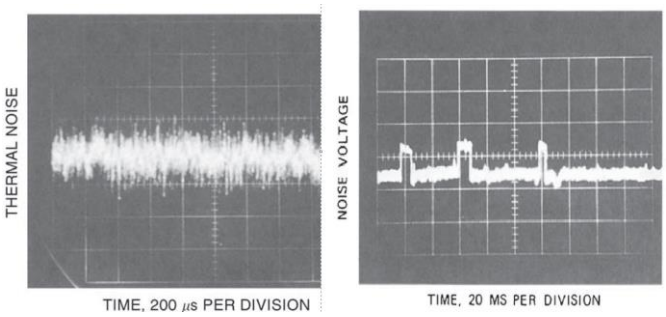


Figure 4.Image of thermal noise with evenly distributed power level, and second image is random noise on baseline and top of burst with thermal noise. [1]

3.3 Duration of EMI

EMI can also be classified into various types depending on the duration of the interference, referring to period for which interference is experienced. Types of EMI depending on duration are continuous and transient EMI, described as follows [4.]:

1. Continuous EMI occurs when source continuously emits at range of frequencies until coupling mechanism exists such as in wireless, television, audio, and radio devices.
2. Transient or impulse EMI occurs intermittently or for a very short duration, as in case of lightening, switching, ESD and similar circumstances that cause disturbance in voltage or current equilibrium of connected neighbouring system.

3.4 Bandwidth of EMI

Based on rage of experienced frequencies bandwidth, EMI can also be classified as narrowband and broadband EMI which is described in following points [5.] :

1. Narrowband EMI is usually of a single frequency or narrowband of interference frequencies, usually generated by an oscillator or spurious signals emitted due to intermodulation and distortion in transmitter.

2. Broadband EMI differs from narrowband EMI in a way that broadband EMI is not limited to single or discrete frequencies but rather disperse its energy throughout hundreds of megahertz or beyond due to impulse or random sources. Example of sources of broadband EMI include radar, communication transmitters, electric switch contacts, voltage regulators, intermittent ground connection, sparks during welding, arcing in ignition system, and defective power lines. Figure 5 [5] demonstrates broadband and narrow band signal with noise.

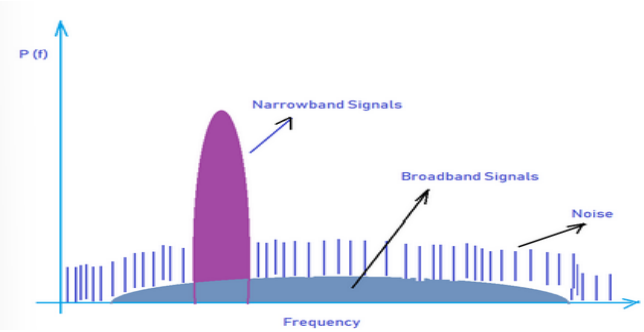


Figure 5. Broadband and narrow band with noise. [5]

3.5 EMI Coupling Mechanism

The coupling mechanism refers to the various modes through which electrical energy is transmitted from a noise source to the device. The figure 6 [5] illustrates how interference can be coupled from source to victim. Different types of coupling mechanism are explained in following points [5.]:

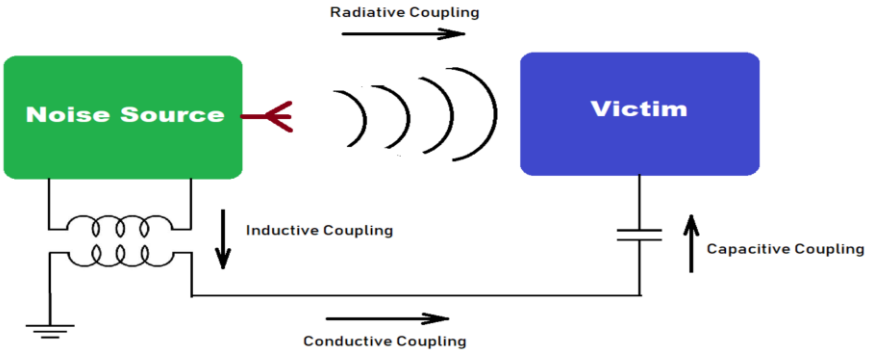


Figure 6. Types of coupling mechanism. [5]

1. Conductive coupling is type of interference caused by the transmission of electromagnetic waves through physical conductors. It happens when devices with varying frequencies are connected to each other via cable.
2. Radiative coupling occurs when undesired signal propagates in air from source as radiation resulted from current flowing around loops formed by conductors in the circuit or due to undesired voltage drop in the conductors.
3. Capacitive coupling is observed when an internal component emits excessive noise that disrupts another electrical component through an electric field.
4. Inductive coupling is experienced when magnetic field generated by an electrical current induces an effect on another component, where source and victim is coupled by magnetic field.

The risks posed by electromagnetic interference in technology are considered unacceptable, and therefore, various measures are taken to limit EMI. These measures involve identifying and understanding the potential threats, establishing emission and susceptibility standards, designing in compliance with those standards, and conducting compliance tests to minimize the harmful effect of interference.

4 EMC Measurements and Testing

Electromagnetic compatibility (EMC) testing is measures taken to ensure that electronic devices or system can function as intended in their electromagnetic environment without introducing unwanted electromagnetic disturbances or being interfered with by other electronic devices. Its objective is assessing electromagnetic compliance. Figure 7 [6] shows various kinds of emission and immunity EMC tests required for a product (EUT) along with respective standards.

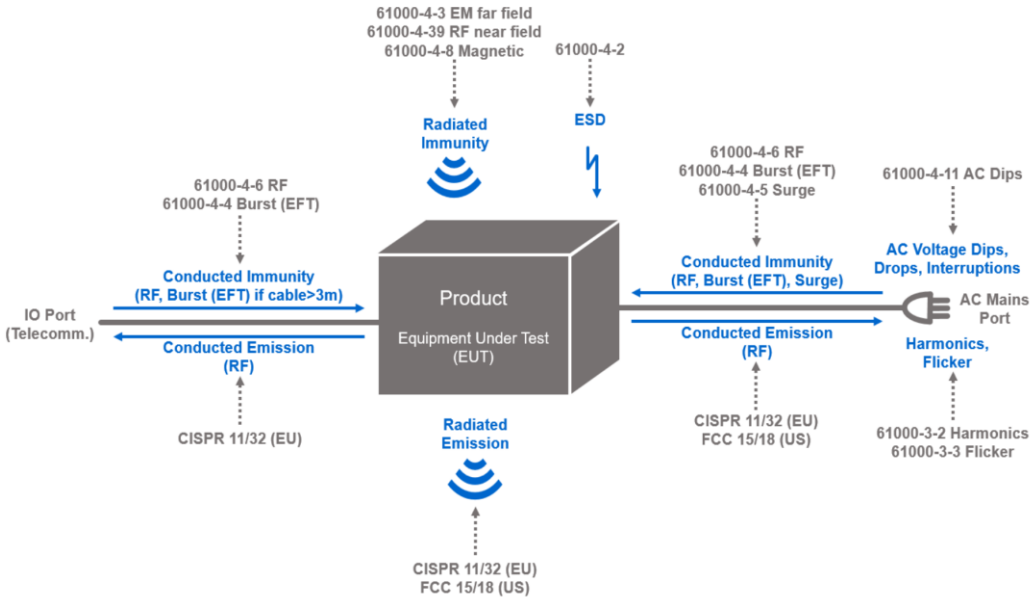


Figure 7. General composite EMC requirements. [6]

Regulatory organization around the world have imposed restrictions on generated emissions by radio devices for specific type of products. Hence electromagnetic emission and immunity testing is obligatory. Following are the basic reasons behind necessity for EMC testing [7-10.]:

- To safeguard congested electromagnetic spectrum, ensuring device operate properly without causing any interference.
- Rigorous EMC testing can ensure the safety.

- EMC testing aims to maintain product quality and performance. It prevents low quality electronic device being flooded on market.

EMC testing is typically broken down into two main categories and into further subdivision as show in figure 8 below.

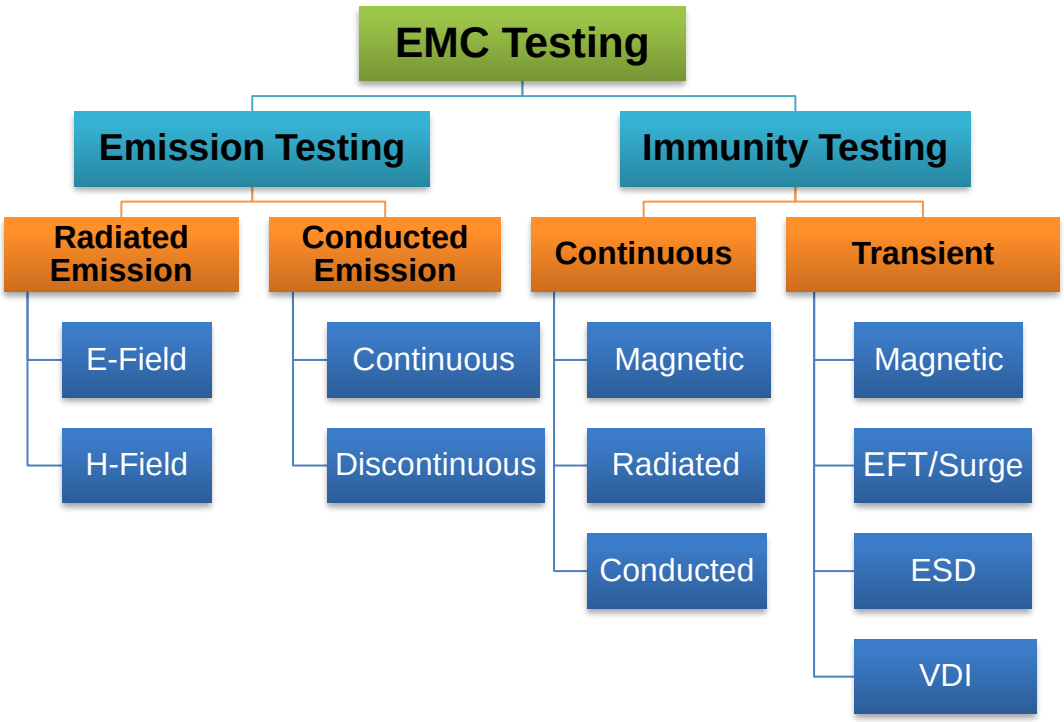


Figure 8. Classification of EMC Testing.

4.1 Emission Testing

Emission testing is the process of measuring RF emission from electronic equipment or EUT to determine its emission level do not exceed the limit. Unwanted emission from power cables, wires, resistors, capacitors, op-amps, can go up to GHz range and can be radiated through antenna, also known as EMI. It is further subdivided into radiated and conducted emission.

Radiated emission testing entails measuring the strength of electromagnetic field emitted unintentionally by device over air, which consists of radiated E-Field and H-Field. The field is result of switching voltage and currents within any digital

circuit. In general, radiated emission is measured using spectrum analyser with suitable measuring antenna. Near-field emission of PCB can be assessed using emission (EMC) scanner. Magnetic field can be measured using specific antenna as per CISPER 15 such as Van Veen Loop. Similarly, conducted emission testing is done to estimate the conducted noise level in the form of electric current or voltage generated by electronic device due to sudden change in voltage.

4.2 Immunity Testing

In contrast to emission testing that measures the interference generated by EUT, immunity testing involves subjecting EUT to hostile environment and observing that if any modifications occur in the performance of EUT. Immunity test can be considered either continuous or transient in nature. The result of immunity is not measured in value. Instead, based on loss of function or degradation of performance of EUT in relation to expected minimum performance level during immunity tests, results are classified as ‘A’, ‘B’, ‘C’ and ‘D’ as shown in Table 1 [1]. [7; 9; 10.]

Table 1. Performance Criteria for Immunity test result. [1]

Test Result	**Performance Criteria during or after test**
A	Normal performance.
B	Temporary loss of function after the exposure to disturbance but EUT can recover itself without operator intervention.
C	Temporary loss of function but require operator intervention for correction to bring back EUT into normal operation.
D	Non recoverable damage to EUT due to damage in hardware or software or loss of data.

4.2.1 Continuous Immunity Testing

The objective of continuous immunity testing is to evaluate whether the EUT can operate properly while being subjected to ongoing interference, typically

modulated waves, over a varying duration of minutes to hours. It can be further classified into following categories:

1. Magnetic field immunity refers to the ability of the EUT to withstand the effects of generated fluctuating magnetic field. Switched mode power supplies generate strong magnetic fields that might cause many problems. This test is solely applicable to magnetically susceptible devices.

2. Radiated Immunity (RI**)** testing is done to determine the ability of EUT to withstand electromagnetic energy present in its surrounding environment. While testing, EUT is exposed to radiated signals with specific amplitude and modulation for defined period.

3. When power cable is bent, it can generate radiated emission or induced inductance and capacitance. Conducted immunity testing is to regulate the radiation that comes from public AC mains supply, caused by noise current that are conducted back into the power line. Testing is applicable to AC and DC ports as well as signal cables longer than 3 meters.

4.2.2 Transient Immunity Test

Electronic control circuits that utilize digital technology such as resets mechanism, interrupts, and control lines are susceptible for sudden bursts of high voltage transients. When electronic device is exposed to EMI such as lightening, electromagnetic pulses, ESD, voltage fluctuation, fast switching and relaying for very short duration, such phenomenon can damage the device or degrade the performance. Transient immunity test is process that involves subjecting EUT to short bursts of energy for brief period. Following five points describe different transient immunity tests in brief:

1. ESD is abrupt and brief movement of significant amount of electrical charge from one item to another when they come into contact, through

friction or rubbing. ESD immunity test is described in detail in later chapter 6.5.

2. Electrical fast transient (EFT) / burst is phenomenon, when inductive load such as motor or relay is switched from one state to another then burst of short pulses of currents and voltages is generated on electric power distribution system, of high amplitude and repetition frequency with short rise time. EFT immunity test simulates switching of inductive loads where disturbance happens very quickly.

3. Surges are generated by high power switching events, magnetic and inductive coupling or even due to lightening, resulting in overvoltage and currents which is low in frequency and high in energy. Surge testing is applicable to AC ports and sometime to DC ports.

4. Voltage dips, interruption and variations immunity tests simulate faults and imperfection in power network for testing the tolerance of the electronic system. Such test is applicable only to device with AC input ports.

5. Magnetic field immunity test verifies the proper function of a device in the presence of magnetic field generated by nearby mains AC power cable.

4.3 Pre-Compliance EMC Test

The production development phase of electronic device involves numerous steps, as shown in figure 9 [11] starting from early-stage research and idea development to mass production. Electronic equipment must comply with government EMC regulation, and it must pass EMC tests at certified in-house test facility to launch product in market. For product to pass these tests, good EMC design is crucial, which requires collaboration and discussion among various members of the design team, including system engineers, electrical engineers, mechanical engineers, EMC engineers, software/firmware designers, and PCB

designers. Lack of knowledge in EMC principles, compliance testing at final stage is incorrect and can result in costly mistakes, and if the product fails the EMC tests, it can delay the product development, requiring a complete redesign.

It is crucial to consider compliance testing early in the development process, with all potential risks identified. Performing practical and straightforward pre-compliance tests can save time and money by identifying potential failures early. Therefore, it is essential to conduct such tests to ensure that EUT passes the final compliance tests. It is simple, quick, and easy to perform test and can be carried out early in the product development stage at workbench. Failing to pass EMC compliance testing can result in fines and product recalls. [11.]

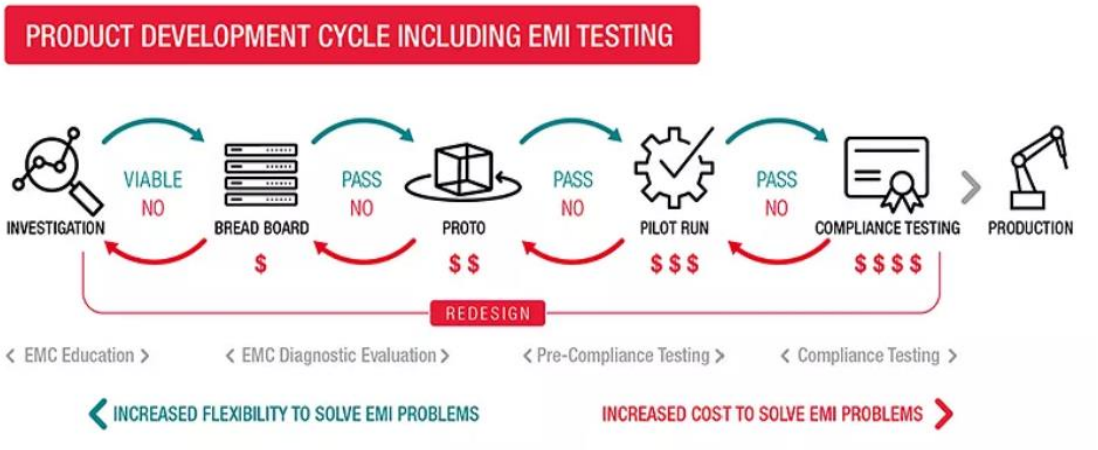


Figure 9. Pre-Compliance Testing during product development cycle. [9]

Following are the advantages of pre compliance tests:

- Enhance the likelihood of successfully passing the ultimate compliance test.
- Reduce the necessity for multiple retests at EMC test laboratory for compliance.
- Avoid unexpected EMC failures late in the design process.
- Ensure that EMC considerations are integrated into the design.

5 EVSE and Greenele EV Charging Station

Electric vehicle supply equipment (EVSE) is device or system that supplies electric power to an electric vehicle (EV) and uses it to recharge the battery of EV, which is commonly called charging station or charging dock. It provides connection between EVs and the power to charge the batteries. EVSE can have microcontrollers with software which are capable of being programmed to carry out specific tasks that include modifying the output power, monitoring the charging progress, connection to internet and remote access with mobile or web application that control the charging station in real time.

EVSE system may consists of three main parts software, enclosure, and connector. Software includes communication protocols that deliver energy efficiently and safely to vehicle. The enclosure can be like mini electric shelf that contains main relay for switching power to vehicle on or off, control module(PCB) which manages relay with a power supply typically 12V DC that powers control board and relay. Plug or connector connects to EV. EV charger can be powered by AC or DC charge. DC charging station could be much faster to charge but it is more expensive as compared to AC charging system. [12.]

5.1 Geenele EV Charging Station

The Greenele EV charging station is AC powered, portable and cost-effective tabletop charging system, intended for residential use. It operates in mode 3 according to the IEC standard, providing an output power of 3.7 kW. The charging station is designed with an enclosure box resembling a mini electric shelf, housing a power supply, relays, RCM (Residual Current Monitor), and a control module running the firmware based on Zephyr RTOS. To connect with electric vehicles for charging, the station utilizes a connector type 2 with an in-cable control and protection device(IC-CPD). The IC-CPD performs the required control and safety functions. The charger can also be connected to a tester for testing or simulation purposes. When plugging the charging station into AC mains, it must be connected correctly to ensure safety. The plug is marked with polarity, with "+"

indicating the live line and "-" indicating the neutral line. This step is crucial because the device acts as a mini electric shelf, housing relays and a high voltage 230 V AC power line directly connected to its control module. The control module of the charger includes an AC/DC power supply that converts high AC 230V to +12V/-12V DC. The 12V DC is further regulated down to 5V and 3.3V DC using voltage regulators in PCB. Additionally, the charging dock features another control panel with an RFID reader, which was not in use during this pre-compliance test and remained unpowered. Greenele EV Charging dock is for residential use which is class B device.

The EV charging station is equipped with a Type 2 male connector, adhering to the IEC 61851/62196 standard, commonly known as the Mennekes connector. This connector is used to establish a connection between the charging station and an electric vehicle (EV). The Type 2 connector features a 7-pin AC charging port that includes a latch, PE for ground connection, L1 for the live line, N for the neutral line, as well as a control pilot (CP) and a proximity pilot (PP) for communication and control purposes, along with a polarity pin. Figure 10 [14] provides a visual representation of the typical pin configuration for the Type 2 connector used in the charging station, that enables fundamental functions. [13.]

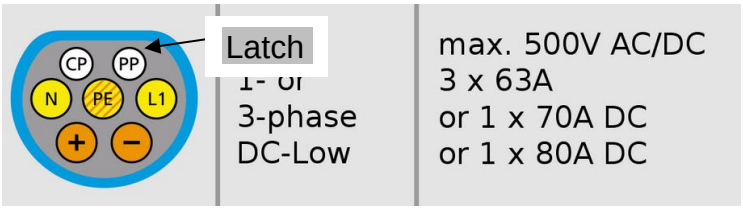


Figure 10. Pin configuration of connector Type 2. [14]

5.1.1 Tester EVA-500-D

The EV-500-D test adapter which is shown in figure 11 [14] below was used for testing the device as simulater during pre-compliance EMC tests which was connected to Greenele EV chraging prototype (EUT). EV-500 series is designed to test function and safety of charging stations of mode 3 for AC charging. CP

(control pilot) state selector was used to simulate different state of connection to EV. The selection state of tester A, B, C and D while connecting to the charging station (EUT) is described in Table 2 [15].

Figure 11. EV-500-D Tester. [15]

Table 2. State of the tester to simulate connection of EV charger to vehicle. [15]

Vehicle State	Description	PWM voltage at CP terminal
A	Electric vehicle (EV) not connected	+/- 12 V, 1 kHz
B	EV connected, not ready to charge	+9 V / -12 V, 1 kHz
C	EV connected, ventilation not required, ready to charge	+6 V / -12 V, 1 kHz
D	EV connected, ventilation required, ready to charge	+3 V / -12 V, 1 kHz

5.1.2 Software Installation, Debugging and Flashing

Software programme developed for the device was based on open-source Zephyr RTOS. To develop, build, debug, and flash the application to the microcontroller, one needs to install compatible IDE and SDK. In-order to debug or flash the firmware, the cross-platform framework 'nRF Connect' SDK was installed from the download link for 'nRF Connect for Desktop'. For command-

line setup of the development environment, instructions can be followed from zephyrproject.org. The framework has many integrated apps for development and other functionalities. Once the application is installed, open the application, then click on the "Apps" tab. Install "Programmer" and "Toolchain Manager," as shown in the figure 12 below. To develop software with the SDK, open the "Toolchain Manager" and install the required SDK. Then, proceed with the instruction and development process by following the guidelines provided in the documentation section of the above-mentioned link.

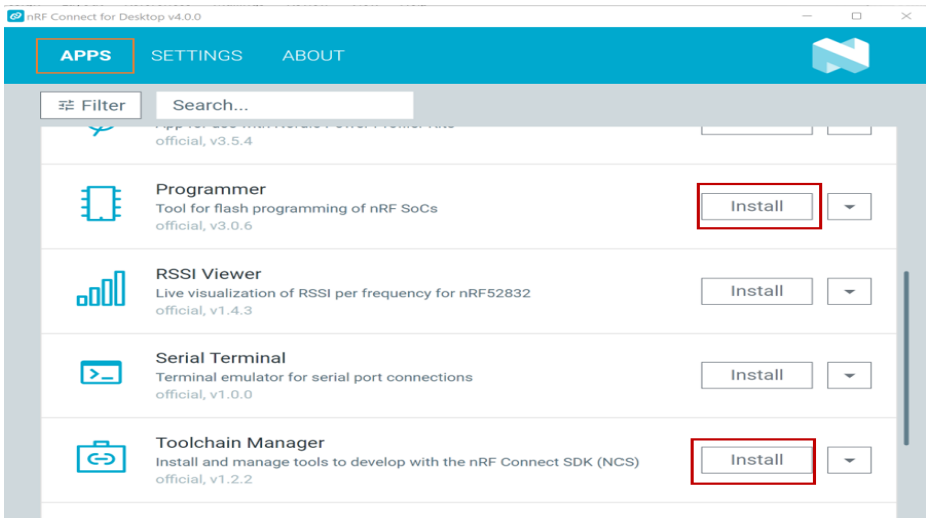


Figure 12. nRF Connect application window.

The control board of the charging station is equipped with a JTAG interface, which enables debugging capabilities. For debugging and flashing the firmware to the microcontroller, a J-Link debug probe was used, while the control board was powered using an external power supply during the process. To flash the firmware, open the "Programmer" tool, if the connected device is not automatically detected, select the device manually. Then, click on the "Add file" button to select the firmware or binary file developed to handle background processes of the charging station. Flash the firmware by clicking on the "Erase & write" button. The process is illustrated in the application window shown in the figure 13 below. Following these steps, the device will be ready for pre-compliance EMC testing.

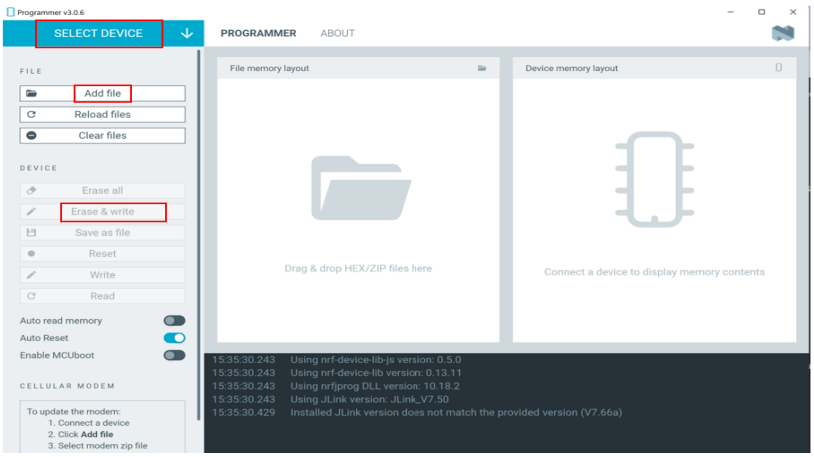


Figure 13. nRF Connect tool “Programmer” to flash firmware.

5.1.3 Connection setup of EUT and Safety Guidelines

The Greenele EV charger is connected to the tester EVA-500-D, which serves as a simulator for testing purposes. To simulate different states of the charger, the CP (control pilot) state rotary switch selector is utilized. This selector allows for the selection of various connection states of the charger when the test adapter is connected to the EV charging station during testing. Before powering up the EV charging station directly from the AC mains power supply, it is crucial to follow the following safety precautions:

- Always ensure that the lid of the EUT enclosure box is closed while conducting tests and plugging in the device. This precaution is necessary due to the presence of high voltage current at the back of the control board. Failing to close the lid poses a significant risk of electric shock. Therefore, it is essential to prioritize safety by keeping the enclosure box securely closed throughout the testing process.
- Make sure that the EUT is plugged into the AC mains power supply socket with the correct polarity, for the safe and reliable operation of the EUT. The positive pin should be connected to the live line and the negative pin should be connected to the neutral line. Always double-check the polarity

of socket before plugging in the EUT to avoid any risks associated with incorrect polarity connection.

5.2 Feasible Pre-Compliance EMC Test

As a part of the project, resources and equipment available at Metropolia UAS were explored that are essential for conducting general pre-compliance EMC testing for EV charging station. After evaluating the resources and equipment available on campus and the required EMC testing for electric vehicle supply equipment (EVSE), it was observed that, it is feasible to conduct at least following pre-compliance EMC tests which is listed below in Table 3 along with required equipments and general applicable standard.

Table 3. Pre-Compliance EMC Test with available equipment with standard.

No	EMC Tests	Equipment	Standard
1	Radiated Emission (RE) test in OATS	Antenna, Rotating table, EMI receiver (Spectrum analyzer)	CISPER 11
2	Conducted Emission (CE)	Isolation Transformer, LISN, Spectrum Analyzer	CISPR 11
3	Radiated Immunity (RI)	Log Periodic Antenna, Signal Generator, RF broadband Power Amplifier, GTEM, Attenuator, EMI receiver	IEC 61000-4-3
4	Conducted Immunity (CI)	Signal Generator, Amplifier, Power meter, SDN or EM-Clamp, Spectrum Analyzer	IEC 61000-4-6
5	Electrostatic Discharge (ESD) Immunity	ESD Gun, Capacitor, Resistor	IEC 61000-4-2
6	Electrical Fast Transients (EFT) Immunity	EFT 500, Coupling/Decoupling Network (CDN), Power Amplifier, Signal Generator, Oscilloscope	IEC 61000-4-4
7	Surge Immunity (SI)	VCS 500, CDNs, Power Amplifier, Signal Generator, Oscilloscope	IEC 61000-4-5

8	Voltage dips, interruption, and variations immunity (VDI)	VCS 500, CDNs, Power Amplifier, Signal Generator, Oscilloscope	IEC 61000-4-11
9	Near Field EMC Scanner	EMC Scanner with probe, Computer with software, EMI receiver	

6 Standard, Measurement Setup and Procedure

6.1 EMC Standard for EVSE

The EMC directive aims to standardize the electromagnetic compatibility of electronic devices.The EMC standards specify limits and procedures which is dependant on the type of device and region. Conducting EMC compliance testing involves utilizing appropriate methods, equipment, and measurement sites that adhere to national or international standards and procedures. In Europe, the International Electrotechnical Commission (IEC) and CISPR have established specific limits on the level of unwanted emissions that a device can emit and how well products can resist EMI. Some examples could be IEC complient specialized EMI test chamber/OATS or CISPR 16 compliant EMI receiver and antenna.

In this thesis project, the emission limits and pre-compliance EMC test procedure for the Greenele EV charging station were conducted in accordance with relevant standards, closely aligned with SFS-EN IEC 61851-21-2:2021:en, as well as general IEC and CISPR standards for EVSE. SFS-EN IEC 61851-21-2:2021:en is a standard defined by the Finnish Standard Association (SFS) that specifically outlines the electric vehicle requirements for conductive connection to an AC/DC supply. It also encompasses the EMC requirements for both on-board and off-board electric vehicle charging systems.

Although the tests conducted were pre-compliance EMC tests, it is important to note that the performed tests and their procedures may not be ideal as per the

standard, efforts were made to ensure that the emission limits and EMC test procedures closely aligned with the specified standards. These tests aimed to assess the electromagnetic compatibility of the Greenele EV charging station and verify its compliance with the relevant requirements. This report only discusses and explains the measurement setups and general equipment used according to the general IEC or CISPR standards for EVSE however many procedures, equipment used, defined limits follow SFS-EN IEC 61851-21-2:2021 standard which are not discussed in this report. It was discovered that several essential pre-compliance tests were feasible to perform on the prototype of the EV charging station. However, radiated and conducted emission tests, ESD immunity tests, and EMC scanning were successfully carried out within the given time frame. These tests were fundamental to evaluate emission and immunity characteristics of the EV charging station at such early stage of product development.

6.2 Radiated Emission (RE) Test

6.2.1 RE Standard and Test Setup

Radiated emission testing aims to determine whether a product emits unwanted radiation below a certain level and to verify if the product's emissions comply with the limits set by the specified standard. For radiated emissions testing, OATS are the preferred methods over semi-anechoic chambers. While testing in OATS, the antenna used to measure emissions is exposed to the surrounding environment, which can result in the antenna picking up external signals such as FM radio or cell phone, Wi-Fi, and TV signals. This is due to the lack of a shielded chamber in an OATS.

Commonly followed radiated testing stanard is CISPR 16 Standard. Radiated emission testing typically begins at 30 MHz and can extend to 1 GHz or up to 6 or 40 GHz which is measured using EMI receiver of corresponding frequency range. The test can be conducted in an OATS according to the setup illustrated in figure 14 [16]. The EUT is positioned on a rotating chair, 80 cm above the

ground, and 1, and 3-10 meters away from the biconical antenna with frequency range of 30 MHz to 1 or 6 GHz, which is connected to spectrum analyzer.

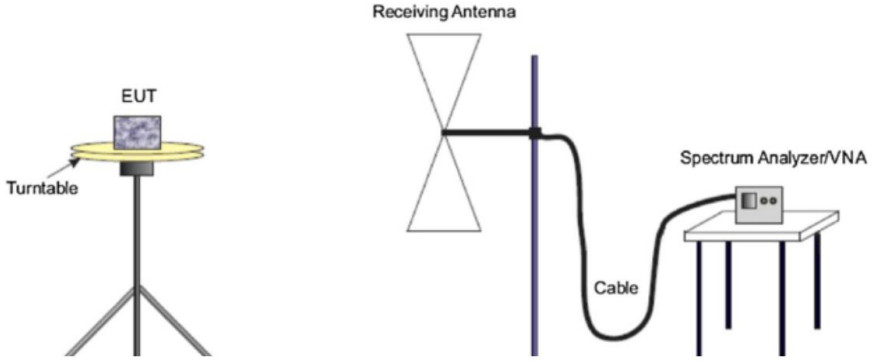


Figure 14. Test setup for radiated emission test. [16]

Ideal Open Area Test Site (OATS) is open ground plane surface like floor, free from overhead wires, reflective structures and far from all external signals. Figure 14 [1] illustrates the quasi peak and average radiated emission limit standard for class B devices at 1 meter distance as per CISPR.

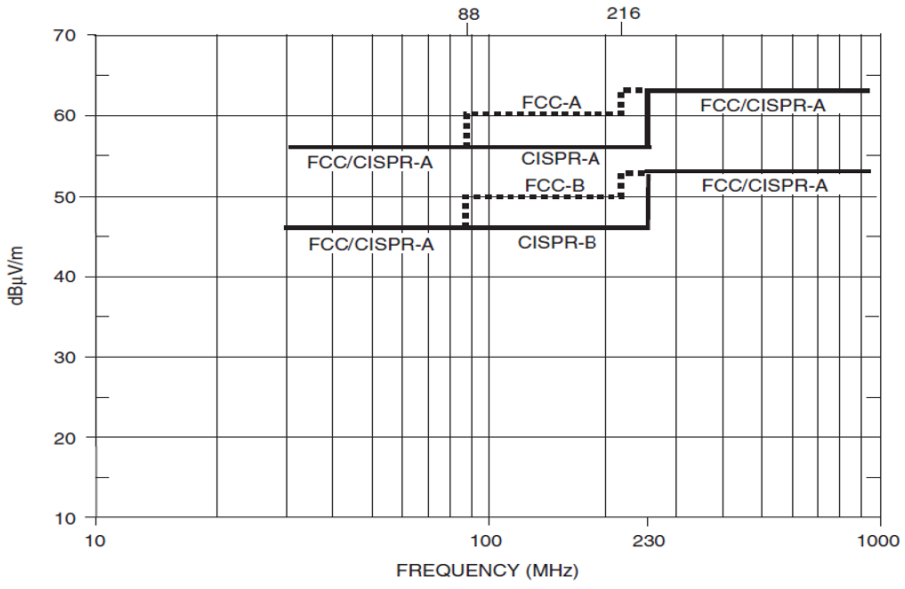


Figure 15. Radiated Emission limit as per CISPR. [1]

6.2.2 RE Measurement Lab Setup and Test Procedure

An ideal OATS should have a continuous ground plane over its entire area. However, the measurement conducted in electronics labs where such a ground plane was not available. Although the test area used in this lab setup did not fully meet these criteria, there were no additional objects between the EUT and the measurement equipment. Test setup of lab while performing measurement is displayed in following figure 16. 3142E BiConiLog antenna of 30 MHz to 6 GHz frequency range, was used for measuring radiated emission which was connected to spectrum analyzer of frequency range of 9 kHz to 6 GHz.

Figure 16. RE measurement setup during test.

After setting up the connection. Initial measurement was done when EUT was unplugged. The reference voltage level was unknown, so reference noise levels were measured before proceeding ahead, to measure the radiating signal strength of EUT. These measurements were taken in different states, including

varying antenna orientations and heights while the device was unplugged. The purpose of measuring reference noise levels in different states was to establish a baseline understanding of the ambient or background noise level present in the testing environment. Also, considering the uncertainty of the radiating frequency, attempts were made to find radiating frequency of EUT by observing spikes or emission at different frequencies while the device was both unplugged and running. When EUT was turned ON, in the beginning spectrum analyzer was configured to measure signal strength from 30 MHz to 1 GHZ as well as up to 6 GHz . The radiation from EUT was observed only around 255 MHz, but no radiating signal was detected from EUT in the frequency range higher than 1 GHz apart from detection of Wi-Fi and cell phone signals. Thus, for this pre-compliance RE test, the start and stop frequency of the EMI was set to 30 MHz and 1 GHz respectively with bandwidth resolution of 120 kHz. Moreover, for the rest of RE tests, measurements were conducted for the frequency range of 255 MHz.

According to general standard, RE measurements of EUT can be done at distance of 3 meters from antenna in horizontal polarization for EVSE . However, to measure maximum radiating signal strength and compare the potential impact of different distances, antenna polarizations and heights, and angles of EUT, several measurements were conducted with various parameters. Measurements were carried out at distance of 3m, 2m and 1m from EUT to antenna at heights of 1, 1.5 and 1.85 meters in both horizontal and vertical polarity. The EUT was positioned on rotating table at height of 80cm and the measurements were taken at different angles of 0º, 30º, 60º, 90º, and 270º by rotating the table in all states of EUT.

The peak-to-peak measurement method was employed to measure radiated as well conducted emission, which tends to yield higher results compared to average and quasi-peak values. This method takes into consideration of the maximum fluctuations and spikes present in the signal, providing a comprehensive assessment of the emission levels.

6.3 Conducted Emission (CE) Test

6.3.1 CE Standard and Test Setup

Conducted emission test measures the noise component called conducted emission, which is generated by a device and transferred to another device via cables or power and ground planes in AC mains. Conducted emission is generally measured between 9 kHz to 30 MHz. The testing typically requires a line impedance stabilization network (LISN), a spectrum analyzer, and a ground plane. The LISN (Line Impedance Stabilization Network) can be connected to the AC mains network directly. However, if isolation transfer is necessary, the LISN is first connected to an isolation transformer. The isolation transformer is then connected to the AC mains, and finally, the power cord of the EUT is plugged into the LISN. To measure the level of conducted emissions, the EMI receiver is connected to the measurement port of the LISN as shown in below figure 17 [9;17].

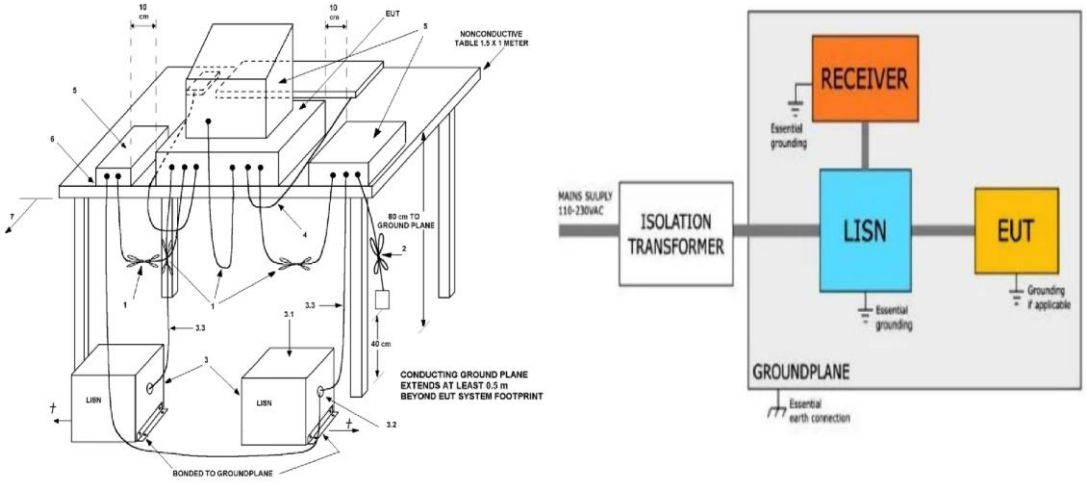


Figure 17.Test setup for conducted emission as per CISPR. [9; 17]

LISN also known as “Artificial Mains Network” (AMN) or a “V Network” that provides stable impedance (50ohm) on the mains end of the EUT AC power line and block the unwanted RF signals from the power source. Conducted emission limit set by IEC standard in quasi peak and average is illustrated in figure 18 [1].

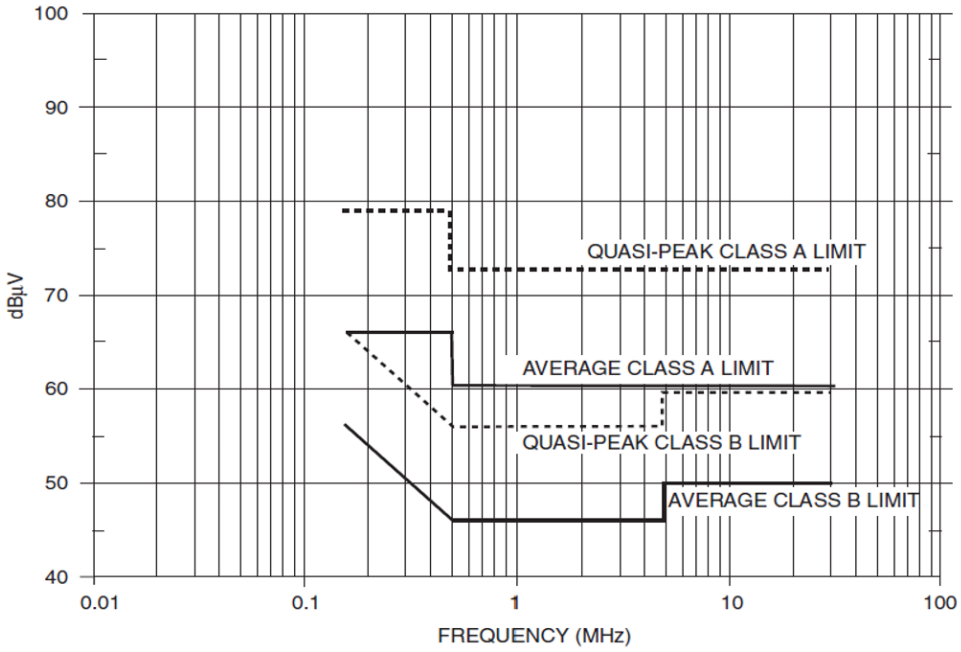


Figure 18. Test setup for conducted emission as per CISPR. [1]

6.3.2 CE Measurement Lab Setup and Test Procedure

Conducted emission tests measure the amount of emission that the EUT couples back to the power supply cord. To avoid interference from the EUT to other nearby equipment, the AC mains socket was connected to an isolation transformer, which was then connected to the LISN, as per the recommendation for the ESH3-Z5 LISN used during testing. Then the positive and negative pins of the EUT were connected to the L1 and N side of the LISN respectively, then the LISN ground was connected to earth. The measurement of conducted emissions was observed using a spectrum analyzer, which was connected to the measurement port of the LISN. The spectrum analyzer was configured for frequency range of 150 kHz to 30 MHz with 100 kHz bandwidth for conducted measurements. The connection of the device and measurement setup of the lab is shown in the following figure 19. Measurements were done for different states of the EUT by selecting A, B, C, and D states of the tester connected to EUT, following the standard that is possible.

Figure 19. Lab setup of conducted emission test.

6.4 ESD Immunity Test

6.4.1 ESD Standard and Test Setup

Electrostatic discharge (ESD) is a sudden flow of electricity between two objects that are electrically charged. ESD may be caused by electrostatic induction. ESD testing is done to evaluate the susceptibility of electronic devices to sudden electrical discharges between two charged objects. There are three commonly used models for ESD testing: the human-body model (HBM), machine model (MM), and charged device model (CDM). Such immunity test results are rated on a four-step scale from A-D as performance criteria. Achieving criteria A or B is desirable in EMI immunity testing. The IEC standard test setup is shown in figure 20 [18] below. The EUT is placed on top of a horizontal ground plane on a table, over a 0.5 mm thick insulator. Both the vertical coupling plane and the horizontal ground plane are grounded by connecting them with a resistor of 470 ohms. Electrostatic discharge is applied to the product using an ESD discharge gun equipped with a capacitor and resistor of specific values determined by the standard and simulation model used for testing. ESD immunity can be tested for both contact and air discharge at various test levels, as defined by the relevant standard for chosen test points defined in test plan.

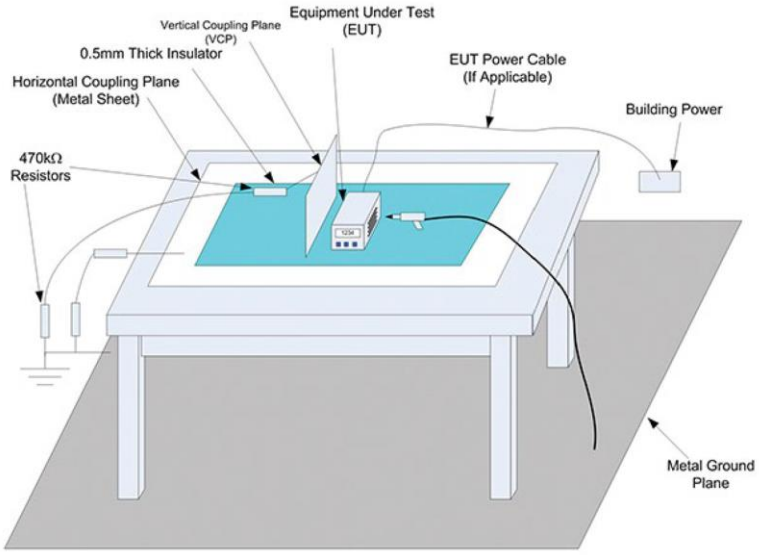


Figure 20. Ideal ESD test setup. [18]

6.4.2 Measurement Lab setup and Test procedure

ESD immunity test was performed using a setup similar to the one shown in the above figure 20 [18]. However, the difference in lab test setup was that the horizontal ground plane was not large enough, and the metal ground plane on the floor was missing, whereas the vertical coupling plane was placed at a distance of 10 cm from EUT, as shown in the following figure 21. Two specific test points were chosen for testing the EUT. The middle front side of the EUT is labelled as 'Test Point 1', while the upper front side is labelled as 'Test Point 2'. Haefely PESD 3010 ESD discharge gun was used with a capacitor value of 150 pF and a resistor value of 330 Ω at frequency of 5 Hz basd on IEC standard.

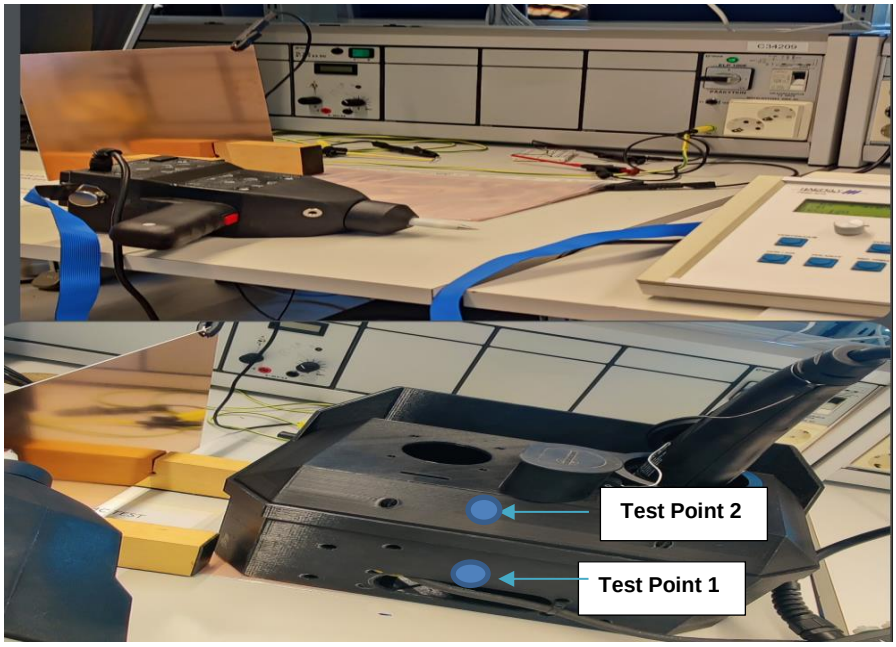


Figure 21. Lab setup of ESD Test.

During the direct discharge test, the ESD gun was positioned on the designated test point of the EUT. The discharge was applied continuously for 10 times, with a 1-second interval between each discharge. This process was repeated for both positive and negative polarities. For contact discharge, the testing was conducted using ESD voltage levels of 4 kV. Additionally, for air discharge and indirect discharge, the ESD voltage levels were set at 8 kV. These voltage levels were applied for both polarities (positive and negative) at different states of the EUT.

6.5 Near Field EMC Scan Test Setup and Procedure

A printed circuit board (PCB) can generate both conducted and radiated emissions which sometime can be near field but cannot be detected in far field with antenna. Near field emission is disturbance originated from frequencies generated internally in circuit board. Conducted emissions are caused by currents in the common mode and differential mode, which can come from power cables. Radiated emissions are caused by electromagnetic waves, which may originate from sources such as clock signals or ESD. The wires and traces on the PCB can act as an antenna for these emissions. Example of such PCB emission

is shown in figure 22 [1]. [1.] EMC scan helps to identify potential emission areas in PCB and determine the root cause of emissions resulting from PCB-related issues.

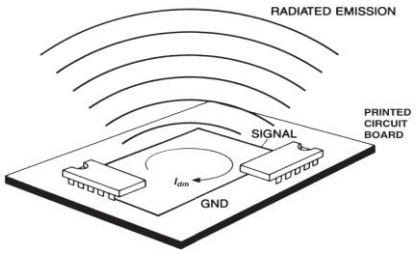


Figure 22. Differential-mode radiation from PCB. [1]

Due to the fact that the emissions being measured were in the near field, the Detectus AB DS642 EMC scanner equipped with an X-Y-Z robot near field probe were utilized for the measurement which was connected to computer and spectrum analyzer. Emission scanning was carried out by executing the Detectus scanner software program on the computer that was connected to the scanner. The scanner can generate 2D or 3D heat maps of the emission area and is useful for pre-compliance testing to detect and locate radiation sources. A near field probe HP11941A, with a frequency range of 9 kHz – 30 MHz and 30 MHz – 1 GHz probe, was attached to the scanner based on measuremnet frequency range of emission. Probe was positioned as close as possible to the EUT. The EMI signals were received by a spectrum analyzer connected to the probe. The scanner was controlled using the Detectus scanner software on a computer. The EUT in this case was a PCB of EV charging station, which was placed on the scanner, and its position was selected on the software. The lab setup connection for EMC scan is shown in Figure 23. In this test, it was required to remove the PCB from the enclosure for scanning the near-field emission from the board. However, due to the presence of high voltage lines on the back of the control board of the EV charger, for safety reasons, this test was conducted in the power electronics lab as shown in Figure 23, under the supervision of an authorized person.

Figure 23. Lab setup for EMC scan during test.

7 Measurements Results and Analysis

7.1 Radiated Emission Test Result

The result of noise levels measured when EUT was in off-state are presented in Table 1 in Appendix 1. Maximum measured noise level at radiating frequency was 29.67 dBuV/m. For calculating actual radiated emissions of EUT, the measured background noise level should be taken into consideration. These measured noises serve as a crucial reference point for subsequent analysis and interpretation of the EUT's emissions, enabling a more accurate evaluation of its compliance with applicable standards and regulations.

After comparing the measurement result obtained when EUT was both connected and disconnected to power supply, it was found that EUT was emitting at the frequency somewhere around 255 MHz. The Marker 'M1' in figure 24, indicates the voltage level of conducted emission measurements taken at 255 MHz, when the EUT was turned both ON and OFF. Along with radiated signal from EUT, there are higher spikes exceeding the limit lines, which can be attributed to radiation from FM radio and TV frequency bands, as well as other nearby radiating devices, since test was performed in OATS.

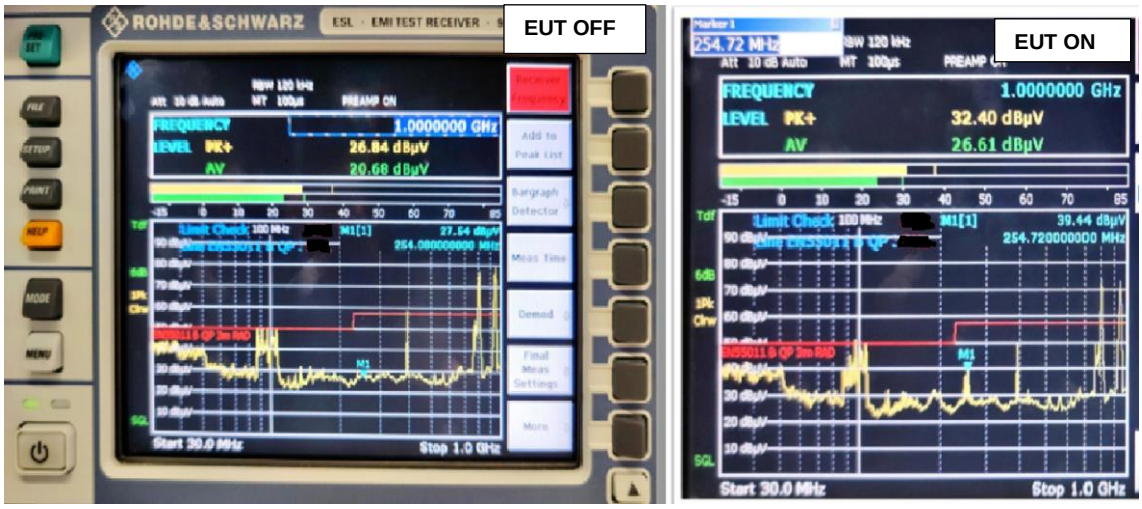


Figure 24. Measu red emission at 255 MHZ while EUT was On and Off state.

The measurement data of radiated emissions from EUT at a radiating frequency of 255 MHz is presented in Table 4 when the device was running at different states. It includes the measurements at three different antenna heights (h): 1 meter, 1.5 meters, and 1.85 meters, at various angles of EUT in both horizontal and vertical polarities of antenna. As the measurements were conducted in four different CP (Control Pilot) states of the tester connected to EUT, denoted as A, B, C, and D, the table shows the emission levels for each CP state and distance (d) combination. In the vertical polarity, the states are represented by A', B', C', and D'. According to the data, the highest recorded radiation level was 41.15 dBuV/m, observed when the EUT was positioned at a 90-degree angle, 1 meter away from the antenna in the horizontal orientation and state C. The lowest emission level of 27.6 dBuV/m occurred when the EUT was placed straight (0°) at 3 meters from the antenna, with a height of 1.5 meters in the vertical orientation, also in state C.

Table 4. Radiated emission at t 1.5 m Height of antenna.

Distance	Height	Angle	Horizontal (dBuV/m)				Vertical			
d (m)	h (m)	(°)	A	B	C	D	A'	B'	C'	D'
1,00	1,00	0	35,90	29,97	40,26	37,09	39,26	37,83	28,54	37,00
1,00	1,00	30	36,16	31,51	39,70	38,34	39,53	37,17	35,60	39,38
1,00	1,00	60	36,19	29,44	40,99	38,75	39,31	38,31	36,01	40,42
1,00	1,00	90	30,89	31,38	41,15	38,16	37,84	38,84	37,75	37,60

1,00	1,00	270	36,00	30,73	38,32	35,06	38,29	38,82	37,31	35,65
1,00	1,50	0	36,23	35,53	37,32	34,07	35,21	35,65	35,38	35,54
1,00	1,50	30	36,32	36,4	36,37	34,97	36,51	35,22	35,95	37,08
1,00	1,50	60	35,41	35,56	37,82	34,94	35,42	35,41	33,42	36,42
1,00	1,50	90	32,83	35,09	37,75	34,21	37,05	37,01	34,29	36,98
1,00	1,50	270	31,68	31,3	28,61	31,39	37,09	33,71	36,15	35,6
1,00	1,85	0	35,03	29,15	32,80	34,26	30,01	29,15	30,5	29,03
1,00	1,85	30	33,52	32,06	34,95	34,16	31,67	32,06	30,95	31,53
1,00	1,85	60	33,07	34,2	36,80	33,62	34,6	34,2	33,82	34,46
1,00	1,85	90	32,20	36,39	36,88	32,29	35,4	36,39	36,42	35,26
1,00	1,85	270	30,40	32,46	31,31	30,36	32,16	32,46	29,3	33,14
2,00	1,00	0	33,68	32,59	34,94	32,96	28,95	29,18	29,76	31,25
2,00	1,00	30	32,81	35,47	33,84	33,59	28,80	30,81	29,04	28,83
2,00	1,00	60	32,92	34,44	35,94	35,06	30,32	32,73	29,10	29,82
2,00	1,00	90	32,81	31,06	35,69	35,01	29,80	31,98	29,49	29,70
2,00	1,00	270	30,74	29,80	32,40	32,32	29,30	33,13	33,94	34,71
2,00	1,50	0	35,09	32,62	33,37	32,99	29,5	29,87	28,85	28,14
2,00	1,50	30	36,77	34,02	36,59	33,84	30,03	30,24	30,23	28,58
2,00	1,50	60	34,11	31,68	36,15	32,76	31,94	32,69	30,09	29,09
2,00	1,50	90	32,2	29,36	34,41	30,2	31,32	31,22	30,85	30,01
2,00	1,50	270	32,92	31,65	33,17	31	29,01	30,44	30,31	30,96
2,00	1,85	0	33,13	28,92	31,96	31,11	29,63	28,92	29,60	29,18
2,00	1,85	30	32,77	29,16	32,49	32,46	30,61	29,16	30,86	30,85
2,00	1,85	60	33,99	30,43	35,57	33,05	29,83	30,43	30,38	30,45
2,00	1,85	90	32,10	29,75	34,19	33,74	29,94	29,75	30,56	31,32
2,00	1,85	270	30,10	27,87	33,91	32,31	28,77	27,87	30,73	29,89
3,00	1,00	0	38,12	34,85	32,87	35,07	29,87	33,14	30,32	32,85
3,00	1,00	30	36,41	33,63	30,69	36,22	29,90	31,34	29,91	32,76
3,00	1,00	60	32,00	32,46	30,95	35,02	30,55	31,20	30,71	31,17
3,00	1,00	90	33,50	31,10	34,68	31,61	30,20	30,82	29,97	30,71
3,00	1,00	270	30,01	29,13	29,62	28,92	29,65	29,15	31,35	28,69
3,00	1,50	0	28,92	28,65	33,2	31,14	31,04	30,55	27,6	28,57
3,00	1,50	30	28,38	29,57	32,38	29,28	32,03	30,27	29,71	32,16
3,00	1,50	60	30,96	31,22	32,36	28,68	31,86	30,32	29,92	31,1
3,00	1,50	90	30,95	29,58	32,35	32,67	30,68	30,85	30,71	32,24
3,00	1,50	270	27,93	28,08	30,4	30,18	29,87	29,73	28,63	28,77
3,00	1,85	0	30,83	32,71	27,99	29,04	33,57	32,71	32,72	31,86
3,00	1,85	30	29,94	33,50	28,19	29,50	32,70	33,50	34,96	32,88
3,00	1,85	60	29,30	33,67	33,07	29,07	33,80	33,67	33,00	33,94
3,00	1,85	90	28,87	33,75	30,63	28,95	32,72	33,75	33,05	32,41
3,00	1,85	270	31,53	29,96	32,76	29,92	28,22	29,96	30,25	29,38

Higher radiated emissions were observed when the EUT was closer to the antenna, especially at 1 meter, in state C, and with a reduced antenna height of

1 meter. The pattern was prominent when the EUT was rotated to a lesser degree or at a 90-degree angle in the horizontal polarity. In the vertical polarity, radiation levels remained consistently high at shorter distances, irrespective of other parameters. While the measurements for the various distances, 1, 2 and 3 meters of distances are provided for the purpose of comparison to detect any significant differences. Increasing the distance between the EUT and the antenna resulted in decreased radiation levels, and this trend was consistent when the antenna height was increased to the maximum measurable height of 1.85 meters in lab. When considering the vertical orientation of the antenna and various parameters, it can be observed that there are no significant changes in emission levels when the distances between the EUT and the antenna were increased from 2 to 3 meters. Measurements at 3 meters are considered important for compliance evaluation of the emission limits for class B products. Figure 25 presents a bar graph illustrating the radiated emissions for corresponding data from Table 4, when the EUT was positioned 3 meters away from the antenna in combination of various other above discussed parameters.

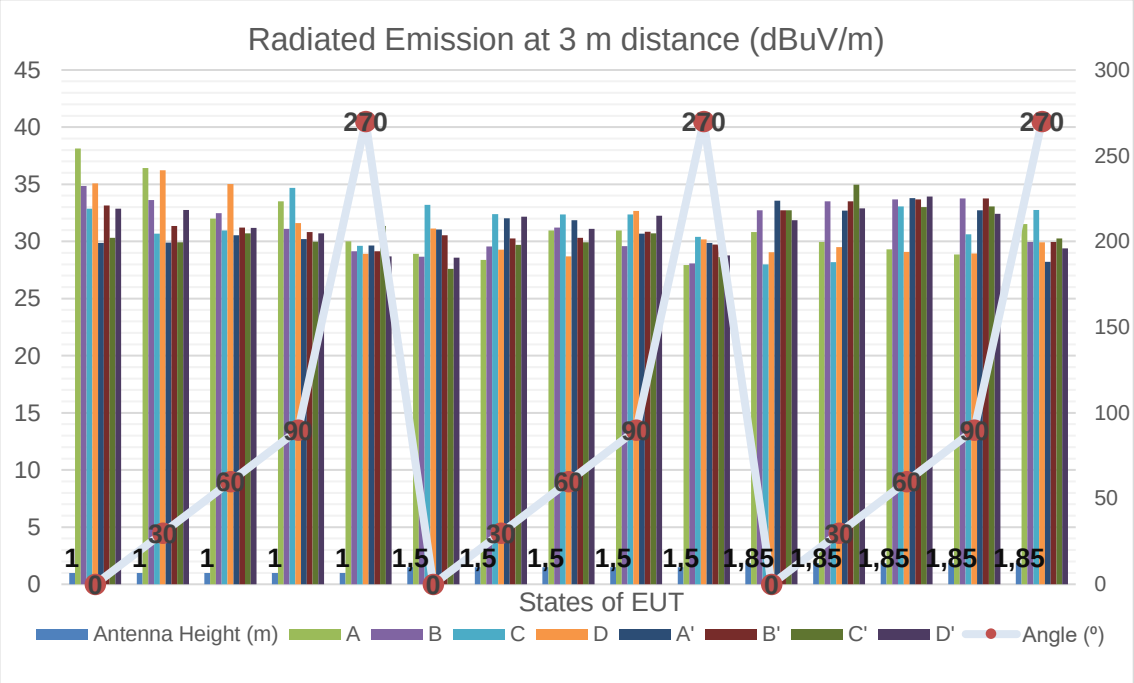


Figure 25. Bar graph of radiated emission at 3 m.

In the graph, it is evident that higher radiated emissions were recorded when the antenna was at height of 1 meter, particularly at lower angles in the horizontal polarity. At 3m the highest emission level of 38.12 dBuV/m was observed in state A when the EUT was placed at a 0° angle. At an angle of 270° in both horizontal and vertical antenna orientation, radiation levels remained consistently low maintaining almost uniform emission. However, at an antenna height of 1.5 meters, emission levels remained stable with minimal fluctuations when the EUT was positioned 3 meters away. These emission levels ranged between 33.2 dBuV/m and 27.6 dBuV/m, close to the background noise level. Highest radiated emission of 41.15 dBuV/m is still below the limit of 45-55 dBuV/m outlined by CISPR standard for measured frequency range at 1 meter. Overall, the insights from the data assist in assessing compliance with radiated emission standards of EVSE.

7.2 Conducted Emission Test Results

When the EUT was turned off, the noise level was measured as a reference and found to be below 20 dBuV. Once the EUT was plugged into the AC mains, conducting emission with thermal noise of wave pattern and various spikes were observed at different frequencies in all states, as shown in figure 26.

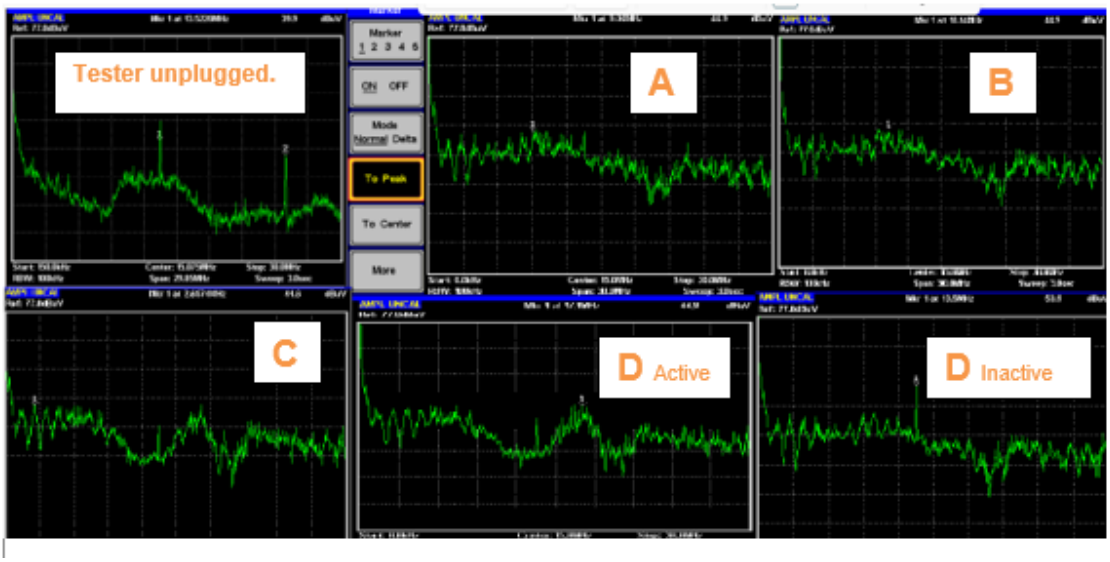


Figure 26.Wave form of conducted emission of EUT in all states.

The conducted emission levels were measured when the EUT was both off and running, simulating different connection states and their corresponding frequencies. The results of these measurements are presented in Table 5.

Table 5. Measured conducted emission.

State of Device	Frequency (MHz)	Emission (dBuV)
O(Tester unplugged)	13.52	32.9
A	9.06	44.9
	13.5	49.4
B	9.1	44.9
	10.14	44.9
	13.52	47.4
C	2.5	44.9
	3.62	44.9
	4.62	43.9
	16.63	44.4
	17.2	43.9
D	1.5	44.9
	2.5	45.4
	3.6	43.9
	9.9	45.9
	10.02	44.4
	13.5	43.9
	17.1	44.9

The measurements showed spikes within the frequency range of 1.5 MHz to 17.2 MHz, suggesting the presence of conducted emissions at specific frequencies. When the tester was disconnected while the EUT remained connected to the AC mains, a typical conducted emission level of 32.9 dBuV was measured, which represented the lowest conducted emission among all states (A, B, C, and D) of the EUT. Surprisingly, in states A and B, despite having fewer spikes, the highest amount of conducted emission was observed, reaching 49.4 dBuV at a frequency of 13.5 MHz. This indicates that even with fewer spikes, the overall emission level was higher in these states compared to others. The measured data of conducted

emissions is visualized in a bar graph in figure 27, enabling analysis and comparison of emission levels at different frequencies and states of the EUT.

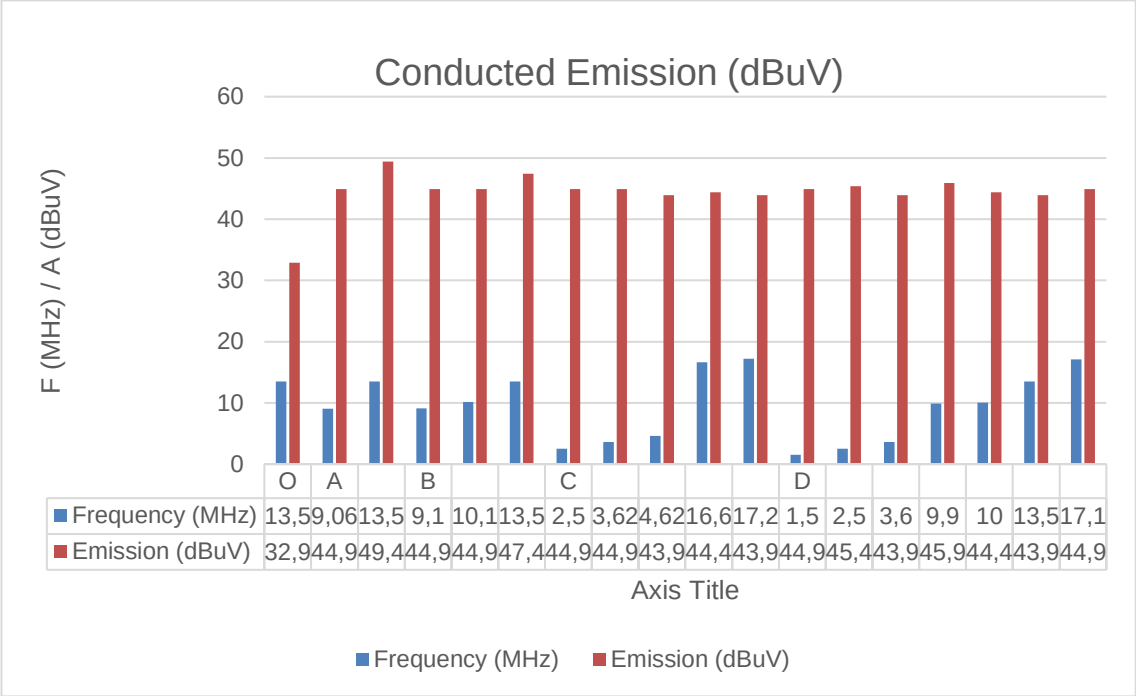


Figure 27. Bar chart representing conducted emission at different frequency.

Although the floor noise levels of conducted emissions appeared high with multiple spikes across various frequencies, even the highest measured peak to peak value of 49.4dBuV remained below the limit specified by the CISPR standard for quasi-peak value of 55-60 dBuV. This indicates that the conducted emissions were within acceptable limits. The presence of intrinsic thermal noise was detected during the conducted emission test, which increases the baseline voltage level. This noise could be due to defects in junctions or noise generated by semiconductor devices on the PCB. By analysing the highest emissions and spikes at different frequencies, appropriate measures can be taken to mitigate conducted emissions and improve the overall EMC performance of the EUT.

7.3 ESD Immunity Test Results

The ESD immunity test was conducted according to the generic IEC standard, specifically at Test Level 2 (L2) voltage for contact discharge. The test involved

applying 4kV voltage with both polarities to the two test points that ‘Test Point 1’ and ‘Test Point 2’ of the EUT as shown in figure 20 of the ESD immunity setup test. During the test, the EUT maintained its functionality without any interruptions and was operating as intended in all states. As a result, the criteria for all conditions of contact discharge were classified as 'A', as indicated in Table 6.

Table 6. Measuremnt results for contact discharge with IEC Standard used for ESD immunity test.

Contact Discharge			
Device State	**Voltage (L2)**	**Test Point (Sides of device)**	**Resulted Criteria**
A	+4kV	Test Point 1 (Middle-front)	A
		Test Point 2 (Upper-front)	A
	-4kV	Test Point 1	A
		Test Point 2	A
B	+4kV	Test Point 1	A
		Test Point 2	A
	-4kV	Test Point 1	A
		Test Point 2	A
C	+4kV	Test Point 1	A
		Test Point 2	A
	-4kV	Test Point 1	A
		Test Point 2	A
D	+4kV	Test Point 1	A
		Test Point 2	A
	-4kV	Test Point 1	A
		Test Point 2	A

According to the same standard used for contact discharge, a voltage level of Level 2 (L2) was selected for indirect discharges and a voltage level of Level 3 (L3) was chosen for air discharges in the ESD immunity test. The results of the indirect and air discharge tests are presented in Table 7. In case of air discharges, the results were classified as 'A' for all tests, indicating that the charging station passed the test successfully. However, during the indirect discharge test in the C state of the EUT, when 8kV of negative polarity discharge was applied from the ESD gun, the tester's LED blinked. As a result, the

performance criteria for this specific test were classified as 'B'. Despite the fact LED blinked once, the charging station continued to function properly without any intervention. For the remaining indirect discharge tests, the results were consistently 'A', indicating successful performance.

Table 7. Measuremnt results for indirect and air discharge as per IEC standard.

	Indirect Discharge		**Air Discharge**	
Device State	**Voltage (L2)**	**Result**	**Voltage (L3)**	**Result**
A	+8kV	A	+8kV	A
	-8kV	A	-8kV	A
B	+8kV	A	+8kV	A
	-8kV	A	-8kV	A
C	+8kV	A	+8kV	A
	-8kV	B (Led on tester blinked during discharge)	-8kV	A
D	+8kV	A	+8kV	A
	-8kV	A	-8kV	A

Taking all the test results into account, the final ESD result for the EUT can be classified as 'B'.

7.4 EMC Scan Results

The emission measurements from the control board of the charging station were conducted using a Detectus AB DS642 EMC scanner equipped with two measurement probes: the low frequency (LF) probe for frequencies ranging from 9 kHz to 30 MHz. and the high frequency (HF) probe for frequencies ranging from 30 MHz to 1 GHz.

Pre-scan was initially conducted while the EUT was powered off to measure the radiating floor noise level and identify frequency characteristics. The LF probe detected radiated emissions at a single frequency of 600 kHz with a radiated noise level of 68.04 dBuV, while the HF probe revealed emissions at three

frequencies ranging from 800 MHz to 937.9 MHz with low noise floor, around 28 dBuV. Same emission levels were detected regardless of the EUT's operational status for HF probe in these same frequencies. But while scanning with LF probe, various emission levels at different radiated frequencies were observed from PCB of the EUT. Hence LF probe was used for performing rest of the measurements. Figure 28 illustrates the noise floor and the resulting waveform for the detected frequency band observed during the pre-scan with both probes when device was powered off.

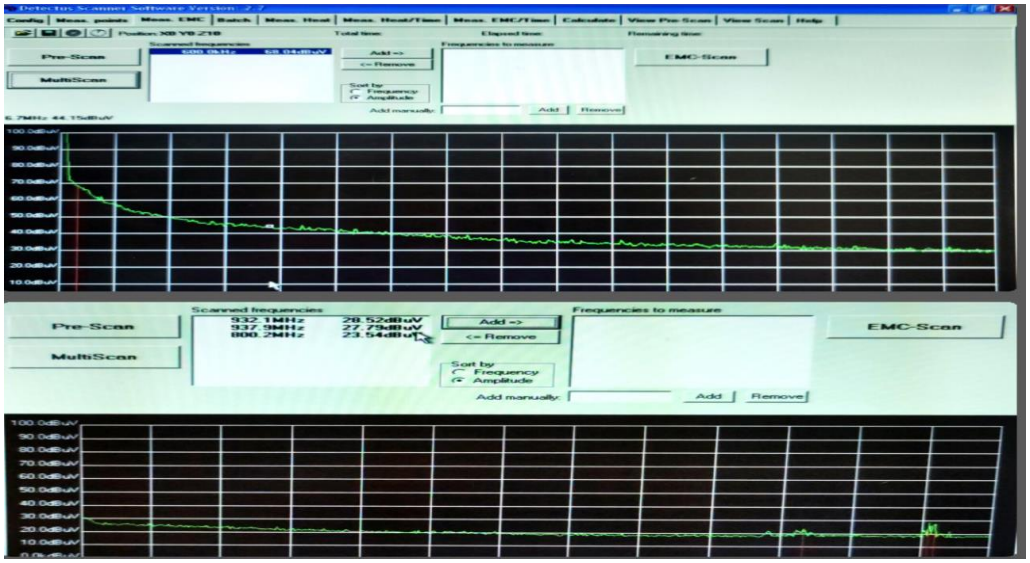


Figure 28. Measured noise level at LF probe at top and HF probe at bottom when EUT was turned Off.

Pre-scanning was conducted using the LF probe when EUT was switched ON and scanner detected various levels of radiation from the PCB of the EV charging station at different frequencies. All the measured emissions data obtained during pre-scan in all CP states of the tester connected to EUT are listed in Table 8.

Table 8. Pre-scan emission when EUT was OFF as well as ON with HF and LF probe.

EUT ON / OFF	**Probe / CP State**	**Frequency (MHz)**	**Emission (**dBuV**)**
ON/=	HF Probe	932.1	28.52
		937.9	27.79
		800.2	23.54

OFF	LF Probe	0.6	68.04
ON	A	1.00	94.96
		3.8	75.46
	B	1.1	94.72
		3.8	75.74
		23.6	43.57
	C	1	95.39
		3.6	77.78
		4.6	71.69
	D	1	95.8
		3.8	76.66

A bar graph, presented in figure 29, depicted the emissions and their corresponding frequencies during the EMC scanning of the PCB. The highest recorded radiation level from the PCB was 95.39 dBuV at a frequency of 1 MHz. Conversely, the lowest recorded radiation level was 43.57 dBuV at a frequency of 23.6 MHz within the frequency band of 1-23.6 MHz. The data specify that higher radiation levels were detected at lower frequencies, while lower radiation levels were observed at higher frequencies. This suggested an inverse relationship between the emission level and the frequency of radiation. It is noteworthy that the emission level depends on the frequency, while the number of emitted frequencies is influenced by the CP state of the EUT. However, the emission level itself is not necessarily dependent on the CP state.

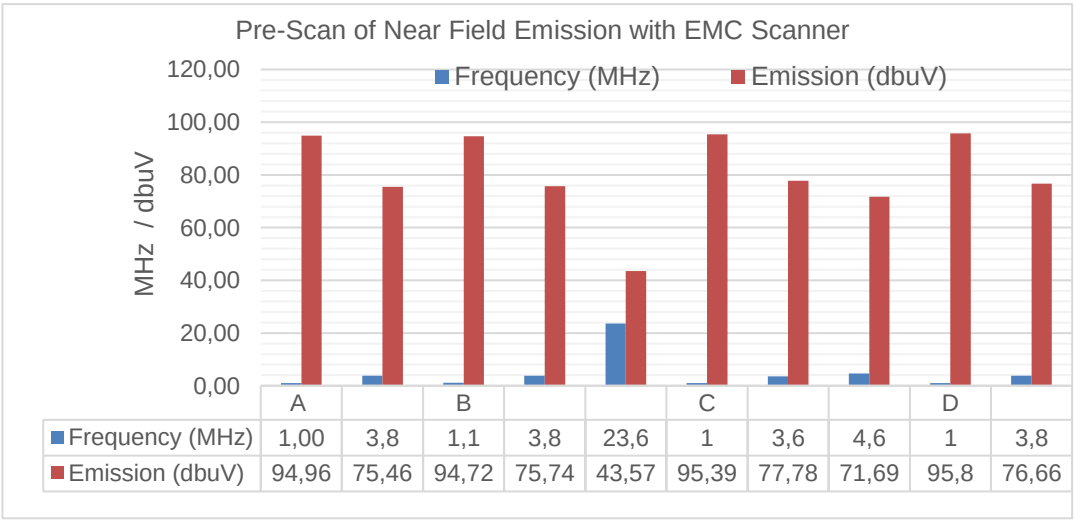


Figure 29. Bar chart of near field emission scan frequency vs emission.

The frequencies identified in the pre-scan were used for the subsequent EMC scanning of the PCB of EUT. Analysis of heat maps generated from EMC scan of EUT in B state in figure 30 accurately portrays the emitting frequencies pattern and their locations on the PCB or within specific component regions. The analysis revealed radiating frequencies and their specific locations, such as vertical emissions along the Y-axis at 1.1 MHz and low-level emissions along the X-axis on the right side at 23.6 MHz. These EMC scan images served as important visualizations for understanding near field emission patterns and identifying the frequency and the location of radiation on the PCB or within specific components.

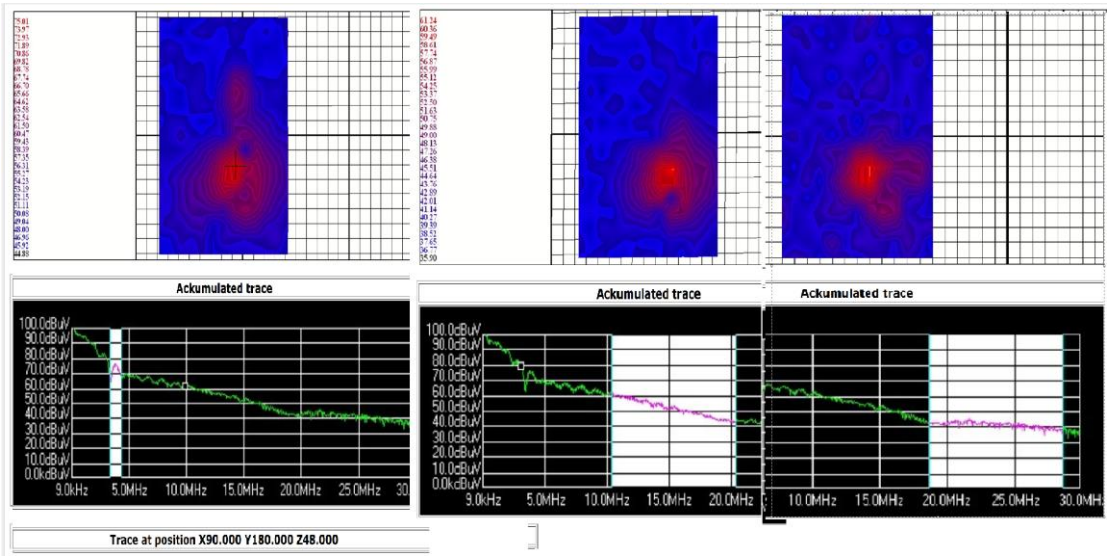


Figure 30. Report on heat map of emission points at different frequencies at sate B of EUT.

To identify specific emission points on the PCB and determine the circuit area and components responsible for radiation, a heat map obtained from the EMC scan was superimposed onto the image of the EUT's PCB. This alignment of X-Y coordinates is illustrated in figure 31. Through this analysis, it was discovered that the highest radiated emission point was located near the AC/DC power supply, voltage regulator, and differential current sensor. Further examination of the PCB image and its components suggested that smaller radiation points were caused by soldering issues, as shown in figure 31. Additionally, the presence of a wire acting as an antenna in close proximity to the AC/DC power supply module

and voltage regulator might have contributed to emissions. This analysis helped to pinpoint emission sources and analyzing the factors contributing to radiation on the PCB. This assessment provided insights into the emission sources and their locations on the PCB, allowing for a better understanding of the factors contributing to the radiation.

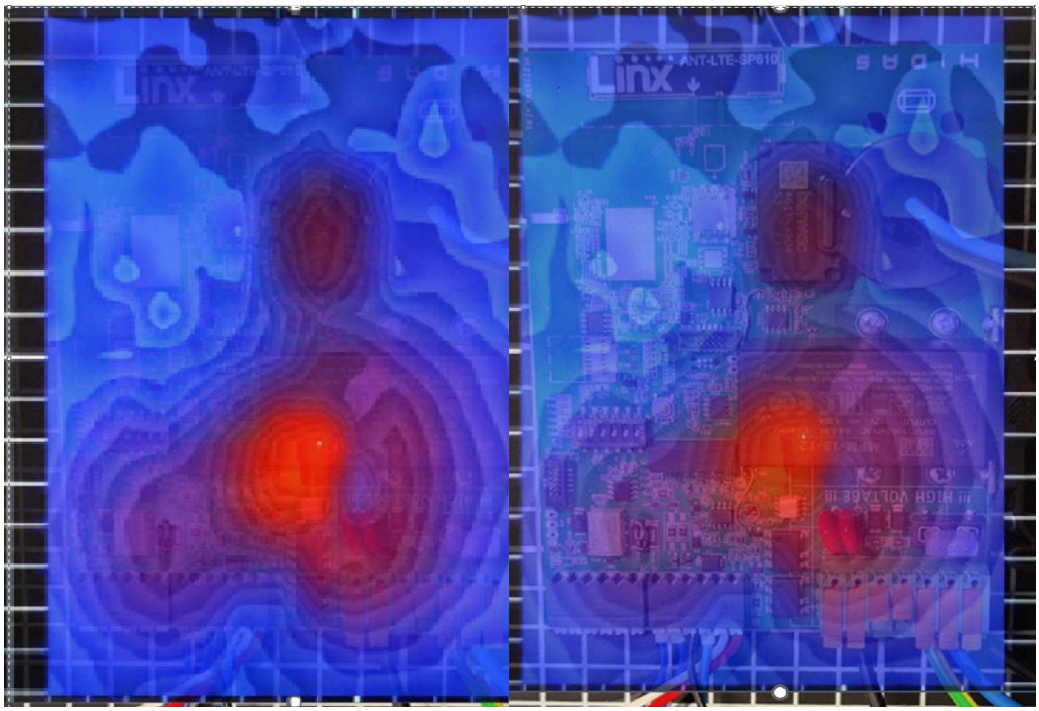


Figure 31. Near-filed radiation points of the control board of EV while scanning.

8 Conclusion

The main objective of the thesis project was to conduct pre-compliance tests on an EV charging station and explore suitable equipment for these tests. Though required equipment were available for performing comprehensive pre-compliance EMC tests, such as radiated and conducted emissions, ESD immunity, EFT or surge, voltage dip, interruption and variation tests, and PCB emission scan. Due to time constraints and limitations, only fundamental pre-compliance tests for radiated and conducted emissions, ESD immunity, and PCB emission scan were performed. In addition to that the test setups were not ideal and did not exactly match the standards. It is important to note that the

measurement equipment may not have been perfectly calibrated, and the baseline noise level were high. As a result, the measured data might appear higher than the actual emissions from the EUT. Despite these factors, these were sufficient for conducting pre-compliance tests and estimating emissions and immunity at an early stage of production. The obtained data were compared to SFS-EN IEC 61851-21-2:2021:en, IEC and CISPR standards of EVSE and the analysis was based on those standards.

In the radiated emission test, the measured highest radiated emissions level remained below 34 dBuV/m at 3 meters and an antenna height of 1.5 meters. This emission level is close to the baseline noise level. Importantly, all the measured radiated emissions as well as highest of peak to peak 41.15 dBuV/m at 1 meter are below the limit of 55 dBuV/m in 1 meter, as specified in CISPR standard for a class B device. These findings and observations provide valuable insights into the emission behaviour of the EUT considering different distances, angles, antenna heights, and polarities.

During the conducted emission test, various spikes at different frequencies were observed, indicating the presence of intrinsic thermal conducted noise. This noise may have been generated randomly in the control board, leading to an increase in the baseline voltage level. Based on the nature of the noise, it can be assumed that there might be defects in junctions, or probably noise might have been originated from certain semiconductor devices on the PCB which cannot be eliminated. Analysing the data, peak to peak highest measured conducted emission of 49.4 dBuV at the frequency of 13.5 is yet below limit of CISPR standard that is average of 50 dBuV and quasi peak of 60 dBuV. Appropriate measures can be taken to mitigate the conducted emissions and support the development of strategies aimed at improving the overall EMC performance of the EUT.

The ESD immunity tests assessed the EUT's ability to withstand electrostatic discharge, and its immunity to disruptions caused by ESD. Considering all the ESD test results, the EUT has passed as product of ‘B’ performance criteria. The

EMC scanning results helped to identify areas of radiated emissions near the differential current sensor, voltage regulator, and AC/DC power supply on the PCB. Minor emission issues related to soldering and the presence of possibility of a radiating wire on the PCB were also detected. Comparing the radiating frequency of RE in OATS and near field EMC scan of PCB results, it can be concluded that the Radiated Emissions (RE) measured in the Open Area Test Site (OATS) was not originated from the Printed Circuit Board (PCB) but from other electrical components within the Equipment Under Test (EUT) enclosure, such as relays, electric switches, or RCM. Furthermore, the radiating frequency observed in the Electromagnetic Compatibility (EMC) scan aligned with the conducting frequency of the conducted emissions. Therefore, the radiation observed in the EMC scanner can be attributed to interference generated from the conducted emissions.

Measurements of radiated emissions, conducted emissions, and ESD immunity were used to assess compliance. The EUT underwent peak-to-peak measurements for radiated and conducted tests. Despite this, the maximum radiated and conducted emissions remained below limit of specified standards. The tests confirmed that the EUT is in compliance with the SFS-EN IEC 61851-21-2:2021:en and CISPR standards for electric vehicle charging system of class B products. It should be noted that complete elimination of emissions is not possible due to the presence of conducting circuits and active/passive components on the PCB. Although no significant radiated emissions were observed, there were spikes detected in conducted emissions at lower frequencies. These spikes should be addressed and considered for further development and improvement of the EUT.

In summary, the overall basic pre-compliance tests were conducted successfully for prototype of Greenele EV Charging station ensuring electromagnetic compatibility at current stage of product development. In the future, additional pre-compliance tests can be performed for the remaining radiated immunity (RI) and conducted immunity (CI) tests, as well as transient immunity tests by implementing the safety measures outlined in the report.

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Appendices

Appendix 1. Measurement Data

Table 1. Measurement of radiated noise level while EUT was off at 255 MHz.

Noise at different state	Frequency (MHz)	Emission (dBuV/m^2)
Without connecting to wire	254.64	25.92
Wire connected but without connecting to Antenna	254.88	26.69
Antenna at 1 m of height in horizantal orientation	254.72	28.69
At 1 m of height in vertical orientation	254.52	27.96
At 1.5 m of height in horizantal orientation	254.40	29.67

Appendix 2. Measurement Images

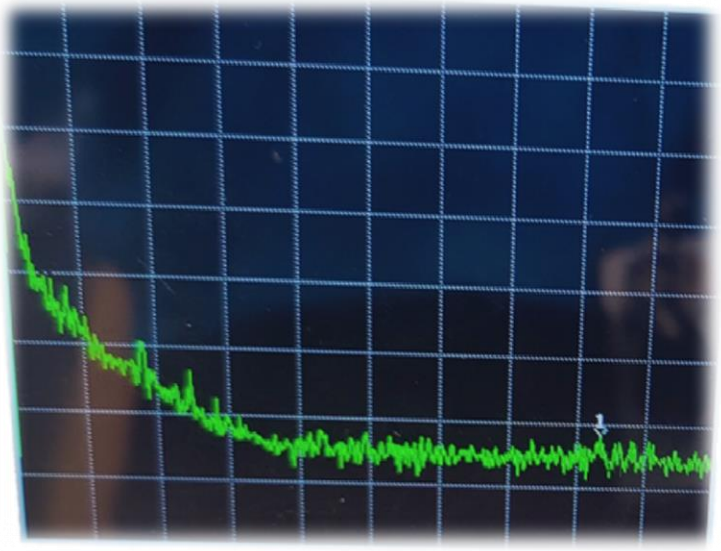

Figure 1. Conducted noise level when EUT was turned Off.

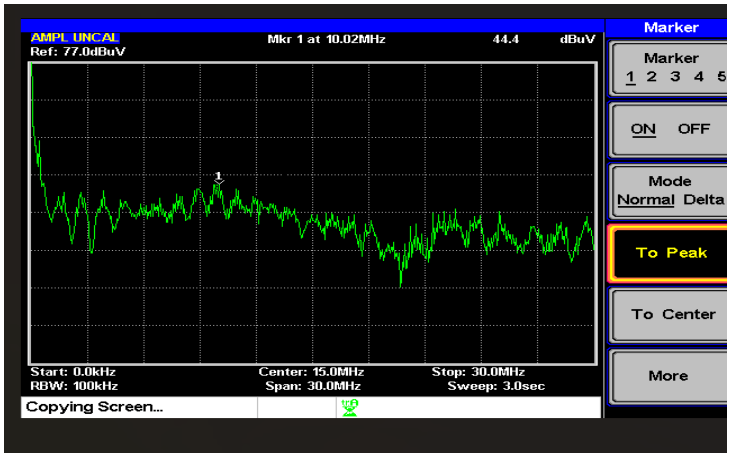

Figure 2. Conducted emission measured at D state.

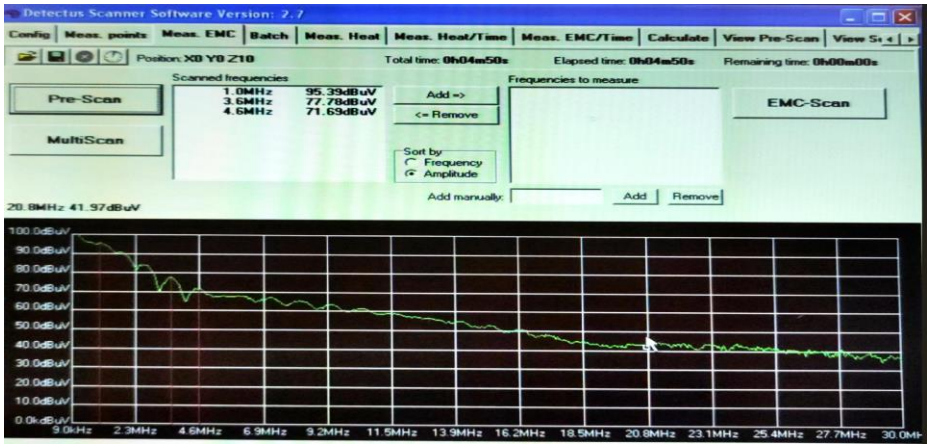

Figure 3. Pre-scan at D sate with LF probe during EMC scan.

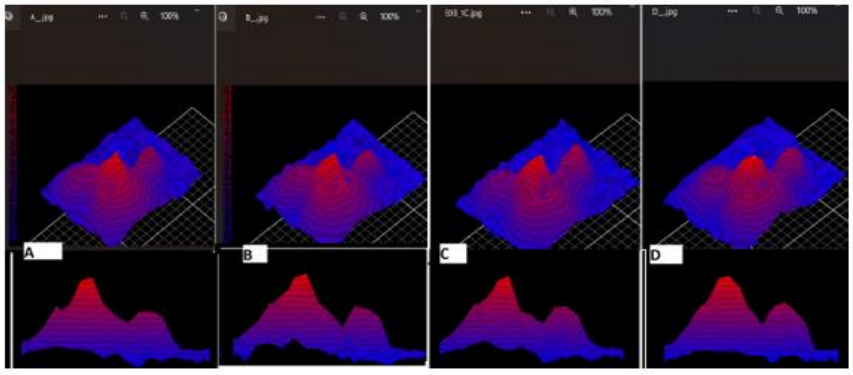

Figure 4. Heat map of PCB at different sates of EUT