SURFACE VEHICLE STANDARD

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(R) Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology

RATIONALE

Electrified powertrains, specifically battery electric and plug-in electric (BEV/PHEV) vehicles, are projected to become more prevalent in production internationally due to environmental factors (such as GHG, CO_2 emissions), regulations (such as the EU, China, U.S. EPA regulations, and the California ZEV mandates), as well as the increasing price of fossil fuels. The main benefits of electrified powertrains are eliminating or significantly reducing local emissions while increasing the overall well-to-wheels efficiency. In addition, automated vehicles are soon to be more commonplace to allow more convenient and safer transportation, especially in traffic settings and long-distance driving.

Standardized wireless power transfer (WPT, also called wireless charging) allows the BEV/PHEV customer an automated, seamless, and more convenient alternative to plug-in (conductive) charging. Essentially, the customer simply needs to park in an SAE J2954-compatible parking space in order to charge the vehicle. WPT offers the additional advantage to automated vehicles enabling autonomous parking with alignment assistance and automated charging (in all weather conditions, such as rain or snow).

This standard is an evolution of SAE J2954, which is based on actual bench testing and vehicle interoperable data taken around the world. SAE J2954 is meant to harmonize with standards developing organizations in order to make a world-wide WPT standard to 11.1 kVA, useful for commercial applications. The SAE Task Force (TF) harmonized with numerous standard organizations (AAMI, ANSI, CISPR, GB, ISO, IEC, UL, VDA) towards these goals and specifically the documents produced in ISO and IEC. The SAE J2954 TF has worked directly with government agencies to gain feedback (U.S. DOE, U.S. FCC, U.S. FDA) and testing actual systems both in government laboratories and private. The SAE J2954 TF has documented the lessons learned from the first stage of testing with real OEM systems in accompanying SAE technical data reports (see Section 2). It is essential that data-based standards are used as a basis for commercialization of this technology.

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SAE WEB ADDRESS: **http://www.sae.org**

For more information on this standard, visit
https://www.sae.org/standards/content/J2954_202010

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1. SCOPE

The SAE J2954 standard establishes an industry-wide specification that defines acceptable criteria for interoperability, electromagnetic compatibility, EMF, minimum performance, safety, and testing for wireless power transfer (WPT) of light-duty plug-in electric vehicles. The specification defines various charging levels that are based on the levels defined for SAE J1772 conductive AC charge levels 1, 2, and 3, with some variations. A standard for WPT based on these charge levels enables selection of a charging rate based on vehicle requirements, thus allowing for better vehicle packaging and ease of customer use. The specification supports home (private) charging and public wireless charging.

In the near term, vehicles that are able to be charged wirelessly under SAE J2954 should also be able to be charged conductively by SAE J1772 plug-in chargers.

SAE J2954 addresses unidirectional charging, from grid to vehicle; bidirectional energy transfer may be evaluated for a future standard. This standard is intended to be used in stationary applications (charging while vehicle is not in motion); dynamic applications may be considered in the future. In this version, only above-ground (surface mounted) installations are covered; flush mounted installations have been discussed but are not yet ready for inclusion.

SAE J2954 contains requirements for safety, performance, and interoperability. It also contains recommended methods for evaluating electromagnetic emissions, but the requirements and test procedures are controlled by regulatory bodies. Development of the interoperability requirements in this standard employed a performance-based evaluation of candidate designs using a standardized test station and procedures, resulting in defining reference devices which are used to determine acceptable performance of products.

1.1 Wireless Power Transfer General System Description

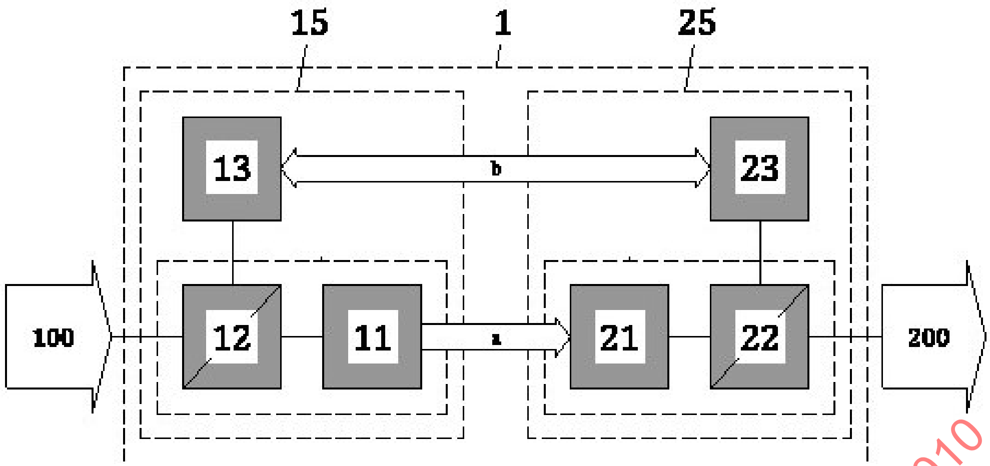
WPT systems consist of a Ground Assembly (GA) Subsystem and a Vehicle Assembly (VA) Subsystem as depicted in Figure 1. The GA broadly consists of a mains-connected Power Factor Correction (PFC) converter, followed by a DC-AC inverter, a filter, and Impedance Matching Network (IMN) that is connected to the GA coil. The magnetic energy created by the GA coil is coupled to the VA coil. The VA consists of the VA coil connected to an IMN and filter, a rectifier, and an optional impedance converter that produces suitable voltages and currents to the connected battery.

In order to ensure safety, a certain set of requirements are met by both the GA and the VA, including monitoring for safe operation (voltage, current, and temperature) and the ability to take corrective action in the event that a limit indicating unsafe operation is being approached.

The GA and the VA share a communication system that allows the GA to know the state of the VA and for the GA to receive and respond to messages from the VA. It is critical that power transfer is not initiated until the GA determines that a vehicle with a compatible VA is in place and properly aligned.

The following steps describe the high-level operation of the closed loop charging system with respect to the sub-system blocks in the diagram in Figure 1, after necessary safety and compatibility checks have been performed and passed.

- Within the VA (25), the power desired to charge the battery is determined.
- The request for power is communicated over the wireless communication channel (b) from the VA to the GA (15).
- The GA recognizes the request, draws power from the grid, converts it to high frequency AC, and sends it to the GA coil (11).
- The high frequency AC couples (a) to the VA coil (21), is rectified and processed in the VA, and charges the batteries.
- This process continues until the VA signals a different power level requirement, including no power required, as would be the case when the batteries are adequately charged.



KEY			
1	WPT system	21	VA coil
11	GA coil	22	VA electronics
12	GA electronics	23	Vehicle communication controller
13	Base communication controller	25	VA - vehicle subsystem
15	GA - ground subsystem	200	Power to battery
100	Power from grid	b	Communication
a	Wireless power flow		

Figure 1 - SAE J2954 WPT flow diagram (harmonized with ISO 19363)

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J1211 Handbook for Robustness Validation of Automotive Electrical/Electronic Modules

SAE J1772 SAE Electric Vehicle and Plug-in Hybrid Electric Vehicle Conductive Charge Coupler

SAE J2836/6 Use Cases for Wireless Charging Communication for Plug-in Electric Vehicles

SAE J2847/6 Communication between Wireless Charged Vehicles and Wireless EV Chargers

SAE J2931/6 Signaling Communication for Wirelessly Charged Electric Vehicles

SAE J3016 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles

Schneider, J., Carlson, R., Sirota, J., Sutton, R. et al., “Validation of Wireless Power Transfer up to 11kW Based on SAE J2954 with Bench and Vehicle Testing,” SAE Technical Paper 2019-01-0868, 2019, https://doi.org/10.4271/2019-01-0868.

Schneider, J., Kamichi, K., Mikat, D., Sutton, R. et al., “Bench Testing Validation of Wireless Power Transfer up to 7.7kW Based on SAE J2954,” SAE Int. J. Passeng. Cars - Electron. Electr. Syst. 11(2):89-108, 2018, https://doi.org/10.4271/07-11-02-0009.

2.1.2 ANSI Accredited Publications

Copies of these documents are available online at http://webstore.ansi.org/.

ANSI C63.30	American National Standard for Methods of Measurement of Radio Noise Emissions from Wireless Power Transfer Equipment

2.1.3 CISPR Publications

Available online at https://www.iec.ch/dyn/www/f?p=103:30:27264173884763::::FSP_ORG_ID,FSP_LANG_ID:1412,25.

CISPR 11	Industrial, Scientific and Medical Equipment - Radio-Frequency Disturbance Characteristics - Limits and Methods of Measurement
CISPR 12	Vehicles, Boats and Internal Combustion Engines - Radio Disturbance Characteristics - Limits and Methods of Measurement for the Protection of Off-Board Receivers
CISPR 25	Vehicles, Boats and Internal Combustion Engines - Radio Disturbance Characteristics - Limits and Methods of Measurement for the Protection of On-Board Receivers

2.1.4 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 60204-1	Safety of Machinery - Electrical Equipment of Machines - General Requirements
IEC 60990	Methods of Measurement of Touch Current and Protective Conductor Current
IEC 61000-3-2	Electromagnetic Compatibility (EMC) - Part 3-2: Limits for Harmonic Current Emissions (Equipment Input Current = 16 A per Phase)
IEC 61000-3-3	Electromagnetic Compatibility (EMC) - Part 3-3: Limits - Limitation of Voltage Changes, Voltage Fluctuations and Flicker in Public Low-Voltage Supply Systems, for Equipment with Rated Current ≤16 A per Phase and not Subject to Conditional Connection
IEC 61000-3-7	Electromagnetic Compatibility (EMC) - Part 3-7: Limits - Assessment of Emission Limits for the Connection of Fluctuating Installations to MV, HV and EHV Power Systems
IEC 61000-3-11	Electromagnetic Compatibility (EMC) - Part 3-11: Limits - Limitation of Voltage Changes, Voltage Fluctuations and Flicker in Public Low-Voltage Supply Systems - Equipment with Rated Current ≤75 A and Subject to Conditional Connection
IEC 61000-3-12	Electromagnetic Compatibility (EMC) - Part 3-12: Limits - Limits for Harmonic Currents Produced by Equipment Connected to Public Low-Voltage Systems with Input Current >16 A and ≤75 A per Phase
IEC 61000-4-2	Electromagnetic Immunity - Testing and Measurement - Electrostatic Discharge
IEC 61000-4-3	Electromagnetic Immunity - Testing and Measurement - Radiated EM Immunity
IEC 61000-4-4	Electromagnetic Compatibility (EMC) - Part 4-4: Testing and Measurement Techniques - Electrical Fast Transient/Burst Immunity Test
IEC 61000-4-5	Electromagnetic Compatibility (EMC) - Part 4-5: Testing and Measurement Techniques - Surge Immunity Test
IEC 61000-4-6	Electromagnetic Compatibility (EMC) - Part 4-6: Testing and Measurement Techniques - Immunity to Conducted Disturbances, Induced by Radio-Frequency Fields

IEC 61000-4-8	Electromagnetic Compatibility (EMC) - Part 4-8: Testing and Measurement Techniques - Power Frequency Magnetic Field Immunity Test
IEC 61000-4-11	Electromagnetic Compatibility (EMC) - Part 4-11: Testing and Measurement Techniques - Voltage Dips, Short Interruptions and Voltage Variations Immunity Tests
IEC 61000-4-34	Electromagnetic Compatibility (EMC) - Part 4-34: Testing and Measurement Techniques - Voltage Dips, Short Interruptions and Voltage Variations Immunity Tests for Equipment with Mains Current More Than 16 A per Phase
IEC 61000-6-2	Electromagnetic Compatibility (EMC) - Part 6-2: Generic Standards - Immunity for Industrial Environments
IEC 61786-2	Measurement of DC Magnetic Fields, AC Magnetic and Electric Fields from 1 Hz to 100 kHz with Regard to Exposure of Human Beings - Part 2: Basic Standard for Measurements
IEC 61980 -1/-2/-3	Electric Vehicle Wireless Power (WPT) Systems - Part 1: General Requirements, Part 2: Specific Requirements for Communication between Electric Road Vehicle (EV) and Infrastructure, Part 3: Specific requirements for the Magnetic Field Wireless Power Transfer Systems
IEC 62764-1	Measurement Procedures of Magnetic Field Levels Generated by Electronic and Electrical Equipment in the Automotive Environment with Respect to Human Exposure

2.1.5 International Commission on Non-Ionizing Radiation Protection (ICNIRP) Publications

Copies of these documents are available at https://www.icnirp.org/.

ICNIRP 1998	Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and ElectroMagnetic Fields (up to 300 GHz)
ICNIRP 2010	ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz to 100 kHz)
ICNIRP 2020	ICNIRP Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz)

2.1.6 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

IEEE C95.1	IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz
IEEE C95.3	Recommended Practice for Measurements and Computations of Electric, Magnetic and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz

2.1.7 ISO Publications

Copies of these documents are available online at http://webstore.ansi.org/.

ISO 4130	Road Vehicles - Three-Dimensional Reference System and Fiducial Marks - Definitions
ISO 23374	Intelligent Transport Systems - Automated Valet Parking Systems (AVPS) - System Framework, Communication Interface, and Vehicle Operation
ISO 7637-2	Road Vehicles - Electrical Disturbances from Conduction and Coupling - Part 2: Electrical Transient Conduction Along Supply Lines Only

ISO 7637-3	Road Vehicles - Electrical Disturbances from Conduction and Coupling - Part 3: Electrical Transient Transmission by Capacitive and Inductive Coupling via Lines other Than Supply Lines
ISO 10605	Road Vehicles - Test Methods for Electrical Disturbances from Electrostatic Discharge
ISO 11452-2	Road Vehicles - Component Test Methods for Electrical Disturbances from Narrowband Radiated Electromagnetic Energy - Part 2: Absorber-Lined Shielded Enclosure
ISO 11452-4	Road Vehicles - Component Test Methods for Electrical Disturbances from Narrowband Radiated Electromagnetic Energy - Part 4: Harness Excitation Methods
ISO 14117	Active Implantable Medical Devices - Electromagnetic Compatibility - EMC Test Protocols for Implantable Cardiac Pacemakers, Implantable Cardioverter Defibrillators, and Cardiac Resynchronization Devices
ISO 19363	Electrically Propelled Vehicles - Magnetic Field Wireless Power Transfer - Safety and Interoperability Requirements
ISO 26262	Road Vehicles - Functional Safety

2.1.8 National Fire Protection Agency Publications

Available from NFPA, 1 Batterymarch Park, Quincy, MA 02169-7471, Tel: 617-770-3000, www.nfpa.org.

NFPA 70	National Electric Code (NEC)

NOTE: The applicable edition of NFPA 70 may be called out by the local code and may not be the latest revision.

2.1.9 ITU Publications

ITU-R REPORT SM.2153	Technical and Operating Parameters and Spectrum Use for Short-Range Radiocommunication Devices

2.1.10 NIST Publications

Available from NIST, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, Tel: 301-975-6478, www.nist.gov.

NIST Handbook 44	Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices

2.1.11 UL Publications

Available from UL, 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: 847-272-8800, www.ul.com.

UL 2202	Standard for Electric Vehicle (EV) Charging System Equipment
UL 2594	Standard for Electric Vehicle Supply Equipment
UL 2750	Investigation for Wireless Charging Equipment for Electric Vehicles (under development)

2.1.12 Code of Federal Regulations (CFR) Publications

Available from the United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

CFR Title 47	Telecommunication
CFR Title 49	Transportation

2.1.13 United Nations Regulations

Available from the following website. http://www.unece.org/trans/main/wp29/wp29regs1-20.html

ECE REG 10 Uniform Provisions Concerning the Approval of Vehicles with Regard to Electromagnetic Compatibility

3. DEFINITIONS

3.1 ALIGNMENT

The relative position of the VA coil and the GA coil.

NOTE: When aligned, the VA coil is within the defined allowed offsets for the WPT system, as described in 8.2.2.

3.2 AMBIENT TEMPERATURE

The ground-level temperature of the air measured at the subsystem under consideration and not in direct sun light.

3.3 CARDIAC IMPLANTABLE ELECTRONIC DEVICE (CIED)

A classification of implanted medical devices comprising pacemakers and other implanted cardiac devices.

3.4 CENTERED POSITION

The position of the VA coil relative to the GA coil when the VA is placed in the middle of the defined X and Y offsets, as described in 6.4.3.

3.5 ELECTRIC VEHICLE

An automobile, as defined in 49 CFR 523.3, intended for highway use, powered by an electric motor that draws current from an on-vehicle energy storage device, such as a battery, which is rechargeable from an off-vehicle source, such as residential or public electric service, or an on-vehicle fuel-powered generator.

3.6 ESSENTIAL AUXILIARY LOAD

An auxiliary load which is essential to the proper functioning of the WPT system, such as low voltage power supplies, communication, foreign object detection, or live object protection systems.

3.7 GROUND ASSEMBLY (GA)

An assembly on the infrastructure side consisting of the GA coil, a power/frequency conversion unit and controller, as well as the wiring from the grid and between each unit, filtering circuits, housing(s) etc., necessary to function as the power source of wireless power charging system. The GA includes communication elements necessary for communication between the GA and the VA and any auxiliary systems contained on the infrastructure side of the WPT system.

3.8 GA COIL

The portion of the GA comprising the litz wire and ferrite material.

3.9 GA COIL PACKAGE

The ground-based device that is located below the vehicle to allow wireless power transfer. It contains the GA coil and any other components, including housings, fasteners, electronic assemblies, and auxiliary systems, as specified by the manufacturer.

3.10 GA ELECTRONICS

The portion of the GA that is NOT the GA coil. This may include items that are packaged in the GA coil package.

3.11 GEOMETRIC CENTER (of the GA coil or VA coil)

The spatial X, Y center of the GA or VA coil.

NOTE: The GA coil is defined in 3.8, and the VA coil is defined in 3.25.

3.12 GUIDANCE

The method that provides assistance to the vehicle or driver to navigate into the parking bay/slot. See Section 12.

3.13 IMPEDANCE MATCHING NETWORK (IMN) or COMPENSATION NETWORK

An electrical network that transforms an input impedance to an output impedance.

3.14 INDUCTIVE COUPLER

The coupled system formed by the coil in the GA coil and the coil in the VA coil that allows power to be transferred with galvanic isolation.

3.15 INDUCTIVE COUPLING

The coupled system formed by the coil in the GA coil and the coil in the VA coil that allows power to be transferred with galvanic isolation.

3.16 LIGHT DUTY (LD) PLUG-IN ELECTRIC VEHICLE

A three- or four-wheeled vehicle propelled by an electric motor drawing current from a rechargeable storage battery or other energy devices for use primarily on public streets, roads, and highways, and rated at less than 4545 kg gross vehicle weight (GVW).

3.17 MAGNETIC RESONANCE

Inductive wireless power transfer (WPT) that occurs when operating one or more high quality factor coils with their IMN (or compensation network) at or near resonance.

3.18 NATURAL OFFSET

The offset required between the GA coil and VA coil geometric center points when the VA and GA coil topologies are different (e.g., circular and DD) to achieve the centered position for power transfer (see 6.4.3 and 12.4.2).

3.19 POWER ELECTRONICS (PE)

Power electronics is the use of electronic devices to control and convert electric power. PE acts as an interface between the electrical source and the electrical load.

3.20 PLUG-IN ELECTRIC VEHICLE (PEV)

An electric vehicle that recharges the on-vehicle primary battery by connecting to the power grid, such as an SAE J1772 connection.

3.21 PRODUCT GA

An SAE J2954 GA for commercialization which has been verified to meet both operational and safety requirements in this standard.

3.21.1 INTEROPERABILITY CLASS I GA

A Product GA which has been verified to meet the interoperability, performance and safety requirements for an Interoperability Class I GA as described in section 5.4.1.

3.21.2 INTEROPERABILITY CLASS II GA

A Product GA for deployment in a home garage or locations for a captive fleet and not intended to be generally available to the public. It has been verified to meet the interoperability, performance, and safety requirements for an Interoperability Class II GA, as described in 5.4.2.

NOTE: For proprietary WPT systems not compliant to SAE J2954, refer to safety considerations in this standard, UL 2750, and IEC 61980.

3.22 PRODUCT VA

A Product VA is a VA that has been developed for series commercialization that has been verified with SAE J2954 to meet the performance and safety requirements in this standard.

3.23 TEST STATION (VA/GA) COMMUNICATION MODULE

A device which meets the communication requirements of Section 12 and which adds communication capability to Test Station devices to enable validation testing.

NOTE: There is one version used with the Test Station GAs and another version used with the Test Station VAs.

3.24 TEST STATION GA

The GA used to verify the performance of candidate Product VAs. The Test Station GA is listed in Appendix B.

3.25 TEST STATION VA

The test station VA is used to verify the performance of candidate Product GAs. The Test Station VAs are listed in Appendix A.

3.26 VEHICLE ASSEMBLY (VA) COIL

The portion of the VA comprising the litz wire and ferrite material.

3.27 VA COIL GROUND CLEARANCE

The VA coil ground clearance is the vertical distance between the ground surface and the lower surface of the VA coil package. See Figure 2.

3.28 VA COIL PACKAGE

The physical device located on the vehicle which allows wireless power transfer. It contains the VA coil and any other components, including housings, fasteners, electronic assemblies, and auxiliary systems as specified by the manufacturer.

3.29 VEHICLE ASSEMBLY (VA)

The equipment on the vehicle consisting of the VA coil, power electronics, control, and communication necessary to safely transfer power to the vehicle.

3.30 VEHICLE GROUND CLEARANCE

The vertical distance between the ground surface and the lowest part of the vehicle underbody.

3.31 WATCHDOG TIMER

A special purpose timer that will reset the system if it has not been periodically serviced by normal activity.

3.32 WIRELESS CHARGING SYSTEM (WCS)

The system for wireless power transfer and control between the GA and VA including alignment and communications. In the forward direction, this system transfers energy from the electric supply network to the electric vehicle electromagnetically (see Figure 1).

3.33 WIRELESS POWER TRANSFER (WPT)

The transfer of electrical power from the AC supply network to the electric vehicle by contactless means. WPT is a charging system that transfers power across an airgap from a GA to a VA and then rectifies that power into DC voltage to charge the batteries.

4. ABBREVIATIONS

ALSE	Absorber-Lined Shielded Enclosure
CAN	Controller Area Network
CFR	United States Code of Federal Regulations
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
EVCC	Electric Vehicle Communication Controller
EVSE	Electric Vehicle Supply Equipment
FOD	Foreign Object Detection
FCC	Federal Communications Commission (U.S.)
IEC	International Electrotechnical Commission
IMN	Impedance Matching Network
LIN	Local Interconnect Network
LOP	Live Object (Human) Protection
OBC	On-Board Charger
PE	Power Electronics
SECC	Supply Equipment Communication Controller
SOC	State of Charge (in percent)
UL	Underwriters Laboratories
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WPT	Wireless Power Transfer

5. WPT CLASSIFICATIONS

5.1 WPT Power Classes

WPT power classes are defined by the maximum input volt-amps drawn from the grid connection. Power class WPT1 and WPT2 have been defined to align with SAE J1772 for AC levels 1 and 2 charging, respectively. SAE J2954 set WPT3 as 11.1 kVA to align with European three-phase outlet rating.

Additional WPT power classes, with maximum input volt-amps of 22 kVA (WPT4) and 60 kVA (WPT5) are under consideration for the next version of this standard.

Table 1 - SAE J2954 WPT power classifications

	WPT1	WPT2	WPT3
Range of Input Volt-Amps	0 to 3.7 kVA	0 to 7.7 kVA	0 to 11.1 kVA

5.2 WPT Z-Classes

The vertical distance over which the power must be transferred is an important parameter for the WPT system specification. Three Z-classes are defined to classify the range of ground clearances over which systems operate and are specified as VA coil ground clearance.

The VA coil ground clearance is the vertical distance between the ground surface and the lower surface of the VA coil package (Figure 2).

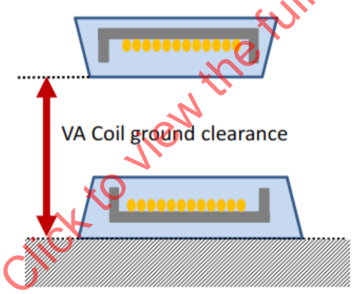


Figure 2 - VA coil ground clearance

The VA coil ground clearance range for each SAE J2954 Z-class is specified in Table 2.

Table 2 - Specification of the SAE J2954 VA Z-classes

Z-Class	VA Coil Ground Clearance Range (mm)
Z1	100 to 150
Z2	140 to 210
Z3	170 to 250

5.2.1 Z-Class Related to Test Station VAs

The SAE J2954 Test Station VAs are characterized by Z-Class, since they are used to validate the performance of Product GAs over a range of VA coil ground clearances.

5.2.2 Z-Class Related to Product VAs

A Product VA does not need to be classified by Z-Class, but rather by the range of VA coil ground clearances over which it operates. The ground clearance for a Product VA is dependent on the vehicle, and it will vary depending on factors such as tire pressure, vehicle loading and mounting location. When testing a Product VA, whether as a component test or a vehicle test, it is tested with a Test Station GA which covers the range required by the Product VA.

5.2.3 Z-Class Related to Test Station and Product GAs

The operating range for a SAE J2954 Test Station GA is specified in terms of the minimum and maximum VA coil ground clearance over which it operates.

The operating range for a Product GA is specified in terms of the minimum and maximum VA coil ground clearance over which it has been tested to operate.

See Table 3 for the specification of the SAE J2954 Z-class for a GA.

Table 3 - Specification of the SAE J2954 GA Z-classes

GA Z-Class	Range of VA Ground Clearances (mm)
Z1	100 to 150
Z2	100 to 210
Z3	100 to 250

5.3 Ground Assembly Installation Categories

Ground Assemblies could be installed differently relative to the ground surface:

- Above ground mounting of the Ground Assembly (e.g., private garage or covered parking structure). The GA is mounted on top of a ground surface.
- Flush mounting of the Ground Assembly (e.g., public parking lot). The outer casing of the GA is flush mounted with the ground surface.
- Buried mounting of the Ground Assembly. The outer casing of the GA is buried at a distance under the ground surface.

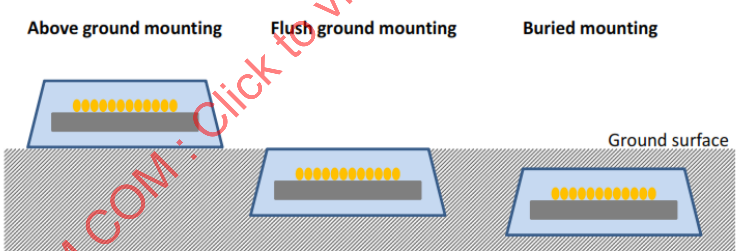


Figure 3 - GA mounting schemes

NOTE: SAE J2954 currently only specifies above ground mounting. Proposed specifications for flush ground mounted and buried mounted assemblies will be considered in a future version of this standard.

5.4 SAE J2954 Interoperability Classifications

Product GAs are classified by their intended application interoperability.

5.4.1 Interoperability Class I GA

Interoperability Class I is the classification of a GA that is intended for public usage. An Interoperability Class I GA will work over the full VA coil ground clearance range and input power range.

Full performance is expected by a VA system when charging over an Interoperability Class I GA. The performance requirements and the test configurations for an Interoperability Class I GA are covered in Section 8.

5.4.2 Interoperability Class II GA

Interoperability Class II is the classification of a GA which is intended to be primarily for a specific application, such as a fleet operation or a home system for a specific vehicle or vehicle family. An Interoperability Class II GA may operate over less than the full VA coil ground clearance range and input power range.

Full performance is expected from a specific set of VAs for which this GA was optimized to work with while limited performance is expected from other J2954-compliant Product VAs that are within the VA coil ground clearance range of the Interoperability Class II GA. There is an expectation of prevention of operation with a VA outside of these ranges. The performance requirements and the test configurations for an Interoperability Class II GA are covered in Section 8.

NOTE: For proprietary WPT systems not compliant to SAE J2954, reference safety considerations in this standard, IEC 61980, and UL 2750.

6. WIRELESS CHARGING SYSTEM FUNCTIONS AND OPERATION

A wireless charging system consists of several functional elements:

- A power transfer function
- A communication function
- Safety related functions are required to:
  - Protect against damage from heating of metal foreign objects
  - Protect humans from exposure to electromagnetic fields

6.1 Power Transfer Functional Description

The WCS consists of a grid interface, high frequency power inverter, filter, compensation network, power transfer coils, compensation network, filter, rectifier, optional regulator, and communications between the vehicle energy charging/storage system and the grid connected power inverter. The grid interface is similar to an existing EVSE connection for single or three-phase AC power. Figure 4 illustrates the major functional components of an example wireless charging system.

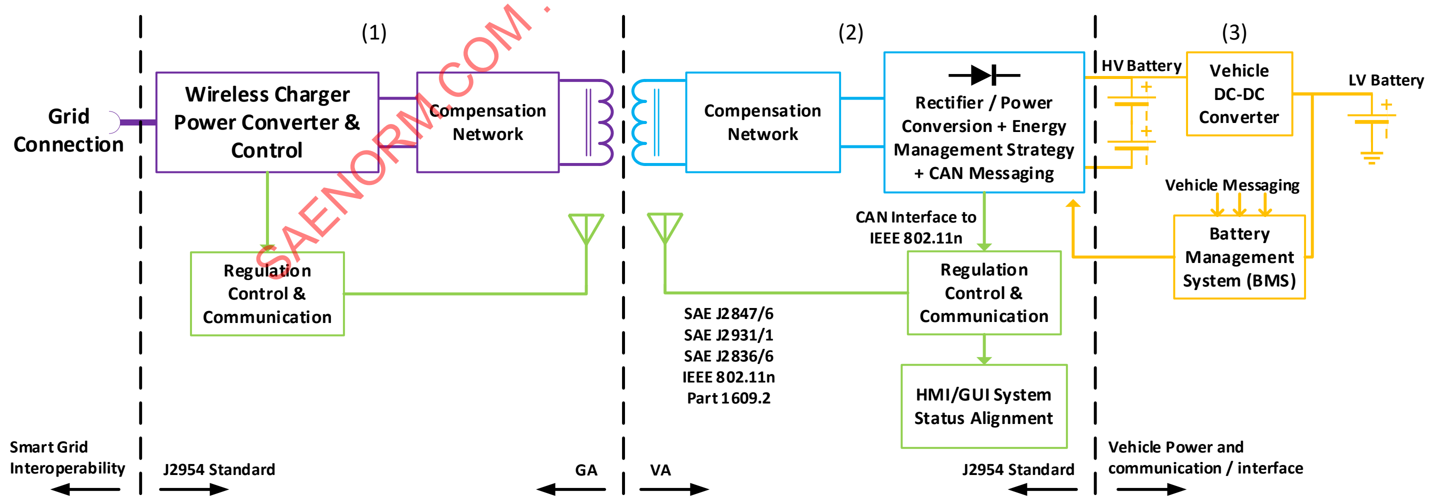


Figure 4 - Typical functional elements of a wireless charging system

6.1.1 Physical Partitions of the Power Transfer Function

Wireless charging technology for electric vehicles consists of three major partitions: (1) the grid-connected converter with its attendant GA coil for power coupling, with a communication link to the vehicle system (the GA); (2) the vehicle-mounted VA coil with rectification, filtering components, and charging control power electronics necessary for regulation/safety/shutdown when required, with a communications link to the infrastructure side (the VA); (3) the secondary energy storage system, battery management system components, and associated modules necessary for in-vehicle communications (CAN, LIN) required for battery SOC, charge rate, and other necessary information (the vehicle energy storage system). See Figure 4.

6.1.2 Main Functional Elements of the Power Transfer Function

Proceeding from left to right in Figure 4, the grid connected converter should be situated at a parking space. The function of this converter is to process grid supplied and metered electricity into a nominal 85 kHz frequency current suitable for magnetic coupling under resonance. This converter includes active front-end power electronics to control the power factor. The converter is matched to one (or more) GA coils located on or embedded in the residential garage floor or public parking space.

The vehicle system functional elements consist of a VA coil operating under magnetic resonance with the GA coil and adhering to the requirements of this standard, power conversion electronics to process the received energy or to shut down the system under a fault condition, and the interface to the vehicle energy storage system.

6.2 Communication Function

The communication system transfers information between the VA and the GA for the purpose of regulating the level of transmitted power and to communicate enable and inhibit signals depending on vehicle energy storage system status.

In addition to the communication that is mentioned above in support of safe power transfer, bidirectional communication between the GA and VA is utilized for guidance, alignment, positioning, position verification, compatibility verification and other purposes prior to the start of power transfer. See Section 12 for additional details.

6.3 Safety Functions

Prior to and during power transfer, it is important to detect any objects which might be heated to a dangerous temperature during power transfer. See 16.2.1 for description and requirements regarding detection of foreign objects.

During power transfer, it is important to prevent humans from exposure to harmful electromagnetic fields. While general exposure is covered in Section 10 for accessible regions, exposure in the case of unusual circumstances, such as crawling under the vehicle while charging, need to be protected against. See 16.2.2 for live object protection (LOP) requirements.

Vehicle components in a WPT system shall be designed according to functional safety in ISO 26262 related to possible hazards caused by malfunctioning behavior of safety-related electrical systems, including interaction of these systems. WPT system designs should avoid a single point failure wherever possible.

6.4 Description of Wireless Charging Operation

6.4.1 General

During parking in a parking space that is equipped with an SAE J2954-compliant GA, the driver begins the guidance and alignment process. The GA and the VA exchange information to ascertain compatibility. If compatible, positioning information is exchanged. When the vehicle is within the charging tolerance area and stopped, information is exchanged to confirm that it is allowable to start charging.

Unless the vehicle has confirmed that it is compatible with the GA and that it is within the allowable position tolerance area, the VA shall not request power transfer, and the GA shall not initiate power transfer.

Following confirmation that the VA coil is properly aligned with the GA coil, the VA shall exchange information with the GA to activate and initiate power transfer according to the requests from the vehicle energy storage system. This information is relayed to the GA to set the power level for proper charging. Control over the charging process can be performed through the vehicle's dedicated charger or directly from the VA using messages provided over the wireless communication path between the GA and VA.

The GA and the VA shall ensure their own safe operation with regards to parameters such as temperature, current and voltage. Should an unsafe condition develop, the system shall take corrective action, including—if necessary—causing system shutdown and the safe cessation of power transfer.

6.4.2 Power Transfer Frequency

Since the power transfer systems in this standard are based on principles of magnetic resonance, a common power transfer frequency between the GA and the VA shall exist.

The SAE J2954 frequency range of 79 to 90 kHz shall be used for wireless power transfer. Frequency is controlled by the GA.

The nominal power transfer frequency of the SAE J2954 frequency range is 85 kHz. In order to optimize performance, if it is necessary to use a different power transfer frequency, determination of that frequency shall be done at the start of a charge session and shall be accomplished at no more than 25% of the full power of the charging system (the lower of the GA input power rating and the VA output power rating). The power transfer frequency shall remain constant (within a ±50 Hz range) for the duration of the charge session.

6.4.3 Centered Position and Natural Offset

In order to be able to compare performance and determine interoperability, a centered position of the VA coil relative to the GA coil is described.

The centered position in the XY-plane of a VA with respect to any GA is specified by determining the position of the VA coil relative to the GA coil when the VA is placed in the middle of the defined X and Y alignment tolerance offsets.

In the case where the VA coil topology is the same as the GA coil topology, the centered position is typically the position where the geometric centers of the GA and the VA are aligned.

In the case where the VA coil topology is NOT the same as the GA coil topology, the centered position may require the use of a "natural offset," relative to the position that aligns the geometric centers of the VA and the GA.

See 12.4.2 for additional information about the natural offset.

7. PHYSICAL DIMENSIONS AND PARAMETERS

7.1 GA Coil Dimensions

The length of the GA coil is specified along the direction of travel of the vehicle; i.e., the X direction. The width of the GA coil is specified in the transverse direction of the vehicle, the Y direction.

The actual size of the assembly is determined by system requirements for interoperability and safety. Assembly sizes of the SAE J2954 Test Station devices for interoperability evaluations are specified in their respective appendices.

7.2 GA Coil Mounted Height

The GA coil mounted height is the distance from the ground surface to the top surface of the GA coil package outer case (see Figure 5).

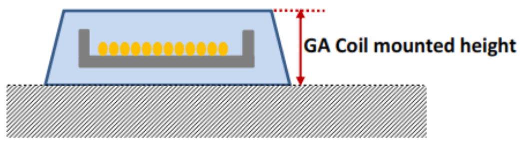


Figure 5 - Definition of GA coil mounted height

The maximum recommended allowable protrusion above the ground surface is 70 mm. This maximum protrusion height may be subject to local installation rules and may be more or less than the value recommended here.

7.3 GA Coil Location

The recommended location of the GA coil within a parking space is given in Section 14 and Appendix D.

7.4 VA Coil Size

The size of a Product VA coil is dependent on OEM considerations.

Sizes of the Test Station VA coils used for interoperability testing are specified in Appendix A.

7.5 VA Coil Ground Clearance

The installed Product VA coil ground clearance is dependent on the specific vehicle and conditions such as the loading condition and tire pressure.

7.6 VA Coil Mounting Location

The mounting location of the VA coil on the vehicle is determined by the OEM.

The geometric center of the VA coil is recommended to be installed on the centerline of the vehicle in the Y direction.

The geometric center of the VA coil in the driving direction (X) is determined by the OEM and could be near the front of the vehicle for forward parking locations or near the rear for reverse parking locations.

8. PERFORMANCE, INTEROPERABILITY, AND SAFETY REQUIREMENTS

8.1 General

The requirements, test configurations, and tests described in this standard ensure that the systems meet the interoperability and performance requirements and are safe to operate under normal conditions.

EMC requirements and recommended procedures are covered in Section 9, EMF and touch current requirements are covered in Section 10. Electrical safety requirements and tests are specified in UL 2750 (under development) (see Section 11). Communication and alignment requirements are referenced in Section 12.

The tests to verify conformance with the listed power transfer performance requirements are in Section 16; they ensure the correct degree of interoperability. Unless otherwise specified, they are intended to be test station tests, with one side being Test Station devices/communication module and the other side being product device candidates. Some tests are intended to be vehicle level tests and are so noted.

All systems, at the system level, require:

- Compatible communication method/sequence/messages.
- The necessary output power to be delivered within the expected operating conditions of the system (e.g., with a GA/VA pair at its centered position and at the specified offsets) while operating within thermal limits over the power transfer duration, and responding safely to any incidents (e.g., FOD/LOP detection).
- Compliance with EMC requirements.
- Compliance with EMF protection requirements.

An Interoperability Class I GA:

- Shall (for the first version of this Standard) use a circular coil topology, and it is recommended that it follows the normative GA in Appendix B.
- Shall have equivalent functionality as the GA in Appendix B and meet all safety and EMC limits in SAE J2954.
- Shall follow the communications and the control protocols detailed in Sections 12 and 13.
- Shall operate with the SAE J2954 Test Station VAs.
- Shall be certified by a national recognized testing lab to meet SAE J2954 requirements and shall also meet UL 2750 (or equivalent) requirements.
- Shall have an applicable "weights and measure" certification and test according to local and/or national regulations (e.g., NIST Handbook 44, PTB, etc.) or equivalent for deployment in a commercial environment.

An Interoperability Class II GA:

- Shall meet all performance, safety and EMC requirements with all Product VAs it is intended to work with and the normative SAE J2954 Test Station VAs within the specified GA ground clearance range.
- Shall follow the communication, control, and alignment requirements detailed in Sections 12 and 13 and shall use these protocols when operating with all SAE J2954-compliant VAs, including the Test Station VAs.
- Shall be certified by a national recognized testing lab as meeting UL2750 (or equivalent) requirements.

NOTE: A GA can use proprietary alignment, communications and controls with a specific Product VA it is intended to work with, in addition to the requirements listed above.

8.2 Power Transfer Performance Requirements

Testing procedure is given in Section 15.

8.2.1 Test Configurations

8.2.2 Product VA

A Product VA is tested with the SAE J2954 Normative Test Station GA described in Appendix B using the Test Station GA communication module.

8.2.2.1 Interoperability Class I Product GA

An Interoperability Class I GA is tested with each of the Normative Test Station VAs described in Appendix A along with Test Station VA communication module. As a result, the performance of the Interoperability Class I GA will be verified over all three Z classes, at a full range of power levels, output voltages, and alignment tolerances.

8.2.2.2 Interoperability Class II Product GA

An Interoperability Class II GA is tested with the specific VAs it is intended to work with and with Normative Test Station VAs described in Appendix A.

The Interoperability Class II GA is tested with only the Normative Test Station VAs which are specified to operate at the same VA coil ground clearance as the GA. Communication (Section 12) provides information to the GA about the VA coil ground clearance. The GA shall not begin power transfer (for Interoperability Class II) if the VA is outside the GA's specified and tested VA coil ground clearance range.

8.2.3 Alignment Tolerance

The SAE J2954 WPT system (for any interoperability class) shall operate safely over a range in X, Y, and Z to allow for parking misalignment and variations in vehicle height. The worst-case misalignment in the XY plane occurs when both X and Y are at a maximum distance from the centered position.

8.2.3.1 SAE J2954 Alignment Tolerance for Product VAs

Table 4 - X, Y, Z operating range requirements for Product VAs

Offset Direction	Value (mm)
ΔX	±75
ΔY	±100
Z range	Specified by manufacturer

8.2.3.2 SAE J2954 Alignment Tolerance for Product GAs

Table 5 - Ground clearance operating range requirements for Product GAs

Offset Direction	Value (mm) Interop Class I GA	Value (mm) Interop Class II GA
ΔX	±75	±75
ΔY	±100	±100
Z range	All Z-Classes	Manufacturer specification

8.2.4 Roll Pitch and Yaw

Product VAs are required to operate over a range of roll, pitch, and yaw.

Table 6 - SAE J2954 roll, pitch, and yaw operating range requirements for Product VAs

Type	VA Offset
Roll	2 degrees
Pitch	2 degrees
Yaw	3 degrees

8.2.5 Output Voltage and Power

8.2.5.1 Output Voltage and Power from Product VA

The manufacturer shall specify the range of voltages and power that the VA provides.

NOTE: Some vehicle architectures have voltages up to 900 V.

8.2.5.2 Output Voltage and Power with a Product GA

8.2.5.2.1 Output Voltage and Power for an Interoperability Class I Product GA

The output voltage from the normative SAE J2954 Test Station VA shall cover the range of 280 to 420 V at full output power over the full ground clearance range and alignment tolerance area.

8.2.5.2.2 Output Voltage and Power for an Interoperability Class II Product GA

For the manufacturer-specified VAs, the output voltage range and power output level shall be specified by the manufacturer over the full ground clearance range at the centered position. The power level delivered over the alignment tolerance area shall be at least 50% of the power delivered at the centered position.

The output voltage from these specified VAs shall cover the voltage range specified by the manufacturer at the power levels specified by the manufacturer.

For the normative reference VAs:

- If the VA WPT class is less than the maximum power rating of the GA, the output voltage shall cover the range of 280 to 420 V at full output power from the VA.
- If the VA WPT class is greater than the maximum power rating of the GA, the output voltage shall cover the range of 280 to 420 V at the rated input kVA to the GA.
- If the VA WPT class covers the maximum power rating of the GA, the output voltage shall cover the range of 280 to 420 V at the lower of the rated input kVA to the GA or full output power from the VA.
- For any of the above cases, the power level delivered over the alignment tolerance area shall be at least 50% of the power delivered at the centered position.

8.2.6 Input Power

An Interoperability Class I Product GA shall cover the input kVA range up to 11.1 kVA, the entire range of input kVA covered by this standard.

An Interoperability Class II Product GA may be specified to any input kVA maximum limit up to 11.1 kVA; it does not need to accept the full input kVA of any WPT Power Class

See Table 7 for the required ranges.

Table 7 - Range of input kVA by class of Product GA

Interoperability GA Class	Minimum Input kVA Rating	Maximum Input kVA Rating
Class I	1 kVA	11.1 kVA
Class II	1 kVA	Specified by manufacturer

The manufacturer of a Product GA shall specify the input voltage range over which the GA is specified to meet the performance requirements.

8.2.7 Power Factor

Power factor is an important parameter to ensure that the system operates safely and efficiently. Although power factor is not a criterion for compliance with this standard, it should be greater than 99% during normal charging operations and always greater than 95%. Power factor requirements may be subject to local regulation.

8.2.8 Frequency

See 6.4.2.

8.2.9 System Efficiency

System efficiency is measured from the AC grid connection to the HV battery connection (Figure 4).

8.2.9.1 Product VA System Efficiency

For each Product VA being tested, the system efficiency at full output power shall be ≥85% when operating at full output power with the VA at the middle of the relevant Z range at center position, and when the GA input voltage and VA output voltage are at the mid-point (nominal) of the range. The system efficiency shall be ≥80% over the full range of variations specified in 8.2.2 to 8.2.4. For this purpose, full power is the lower of the rated input kVA to the GA or the rated output power of the VA, when increasing the power levels.

8.2.9.2 SAE J2954 Interoperability Class I GA System Efficiency

For each Interoperability Class I Product GA, under all the variations in the requirements in 8.2.2 to 8.2.4, the system efficiency shall meet or exceed the system efficiency requirement listed in Table 8 while operating at full power. For this purpose, full power is the lower of the rated maximum input kVA to the GA or the rated output power of the VA.

Table 8 - Class I minimum system efficiency requirements

WPT Class of Test VA	At Centered Position	In Alignment Tolerance Area
WPT1	80%	75%
WPT2	82%	77%
WPT3	85%	80%

8.2.9.3 SAE J2954 Interoperability Class II GA System Efficiency

For the manufacturer-specified VAs, the system efficiency shall be ≥85% when operating at full output power with the VA in the middle of the relevant Z range at center position, and when the GA input voltage and VA output voltage are at the mid-point (nominal) of the range. The efficiency shall be ≥80% over the full range of variations specified in 8.2.2 to 8.2.4.

For operation with the applicable normative VAs, the system efficiency shall be per Table 9 when operating at the lower of the input kVA rating of the GA and the maximum output power of the VA, within the Z range specified in 8.2.2.2 and at the range of variations in the requirements in 8.2.2 to 8.2.4. Outside of the Z range specified for this Interoperability Class II GA, power transfer shall not be initiated.

Table 9 - Class II minimum system efficiency requirements

WPT Class Difference of Test VA	At Centered Position and Over Alignment Tolerance Area
Same Power Class	80%
One Power Class Difference	77%
Two Power Class Difference	75%

SAE J2954 WPT shall be tested for efficiency according to 15.1.7 and shall not exceed the acceptable heat generation.

8.3 Ramp Rates and Control Loop Bandwidth

The GA and VA together form a closed-loop control system, with possible separate but interacting closed or open-loop control systems on the GA and VA.

In all interoperable testing scenarios, the criteria in 13.2.3 shall be met.

8.4 Interoperability Across Power Classes

Interoperability Class I GAs, which are required to meet the WPT3 input level, shall also be able to meet the requirements for WPT2 and WPT1 GAs.

Interoperability Class II GAs shall meet the requirements for input kVA range from minimum WPT1 level to the maximum input power specified by the manufacturer.

8.5 Interoperability Regarding Z Class

Interoperability Class I GAs shall work with VAs of any Z class.

Interoperability Class II GAs are designed to work at a specific VA ground clearance range. VAs outside of this range are not compatible and as a result, power transfer shall not be initiated.

8.6 Allowance for Reactance Variation (in the GA)

The GA coil reactance will vary due to changes in VA height or alignment, or variations in the values of the electronic components. The system shall be able to operate with and/or compensate for this variation. Compensation can reduce stress on the GA electronics, and reduce loss associated with higher inverter currents and the presence of harmonics.

An alternative approach to determining the suitability of a GA that includes new Product GA coils and/or Product GA electronics is presented in Informative Appendix J. This approach has yet to be fully evaluated, agreed to, and validated. The intention is to remove critical dependence during design phases on the Test Station GAs and Test Station VAs.

8.7 Safety Requirements

8.7.1 Safe Operation/Non-Operation

If the exchange of information between the VA and GA does not confirm compatibility, power transfer shall not be initiated. If the vehicle is not aligned within the alignment tolerance specified in 8.2.2, the VA and GA shall be able to guarantee that all EMF requirements are met; otherwise, power transfer shall not be initiated. If power transfer has already been initialized but the VA is moved outside the alignment tolerance, then EMF requirements shall be guaranteed to be met; otherwise, power transfer shall be immediately terminated.

8.7.2 Heating of Foreign Object

The magnetic fields used in wireless power transfer can cause heating of metallic objects. As a result, a hazard could exist if the object causes ignition of flammable material; if the object is hot when it becomes accessible; or the object could become so hot, even while not accessible, to cause damage to the GA coil package surface.

Section 16 specifies a test for minimum requirements to prevent damage from these hazards. A manufacturer might specify additional requirements based on the specifics of the coil design and detection system.

8.7.3 Exposure to Electromagnetic Fields

High levels of time-varying electromagnetic fields may be a hazard to humans. ICNIRP has issued guidelines in 1998, 2010, and 2020 specifying recommended exposure limits for given frequencies. These limits are based on a large safety margin to ensure no adverse health effects due to heating or nerve stimulation.

Guidelines for exposure to electromagnetic fields have also been developed for users of implanted medical devices, such as cardiac implantable electronic devices (CIED).

8.7.3.1 Cardiac Implantable Electronic Devices

For the safety of CIEDs, requirements and testing methods are specified in Section 10.

8.7.3.2 Living Object Protection (LOP)

For living object protection (LOP) in accessible areas of the vehicle, the electromagnetic fields shall be less than the applicable ICNIRP recommended limits, measured as specified in Section 10.

In order to transfer power at levels called for in this standard, the field strength under the vehicle is likely to be much higher than the ICNIRP recommended limits. This area is generally considered to be inaccessible under normal circumstances. However, if a person does attempt to reach under the vehicle while power is being transferred, the system shall detect such an intrusion into the area where the fields are above ICNIRP levels and cause immediate system shutdown. See 16.2.2.

9. ELECTROMAGNETIC COMPATIBILITY/ELECTROMAGNETIC EMISSIONS

This section addresses electromagnetic compatibility (EMC); electromagnetic safety (EMF) is covered in Section 10. This section applies to all Product GAs and Product VAs.

This section is informative; it contains suggestions for process, but normative requirements are based on the geographic region of use. Systems should be tested for EMC compliance using a reference device in Appendices A or B.

EMC testing is separated into two parts: component testing and vehicle testing. While component testing can provide valuable data, vehicle-level EMC testing should be used to determine compliance with applicable regulatory requirements of the complete system for specific standalone systems as supplied by the vehicle OEM for private use.

If the WPT system is to be sold as aftermarket or for public use (as in the case of a charge station with GA), then an appropriate vehicle mimic shall be used and shall meet all regulations for the region of intended use.

9.1 Component EMC

Component-level tests should be performed before integration into a vehicle system. The component-level EMC testing is for evaluation purposes only. Table 10 is to be used as guide to determine which tests may need to be completed on the components.

Table 10 - Component-level EMC - off-board components

	Test Parameters		Test Documentation		Test Limits per Use Environment[1]	
	Interface	**Mode**	**Description**	**Standard**	**Residential**	**Occupational**
EMI	AC Power	Charging and Standby	Harmonics	IEC 61000-3-2 (<16 A) IEC 61000-3-12 (<75 A)	Class A limits as defined in standard (2nd to 40th harmonics)	Class A limits as defined in standard (2nd to 40th harmonics)
EMI	AC Power	Charging and Standby	Fluctuations and Flicker	IEC 61000-3-3 (<16 A) IEC 61000-3-11 (<75 A)	P_{st} < 1.0, P_{lt} < 0.6 d_c < 3.3%, d_{max} < 4 to 7% device dependent d(t) > 3.3% only <500 ms	P_{st} < 1.0, P_{lt} < 0.6 d_c < 3.3%, d_{max} < 4 to 7% device dependent d(t) > 3.3% only <500 ms
EMI	AC Power	Charging and Standby	Conducted Emissions	FCC 18/15	150 kHz to 30 MHz	150 kHz to 30 MHz
EMI	Comm Lines	Charging and Standby	Conducted Emissions	FCC 15	150 kHz to 30 MHz	150 kHz to 30 MHz
EMI	WPT System Level	Charging and Standby	Radiated Emissions	FCC 18	9 kHz to 30 MHz	9 kHz to 30 MHz
EMI	WPT System Level	Charging and Standby	Radiated Emissions	FCC 15	30 MHz to X GHz	30 MHz to X GHz
CW EMS	AC Power	Charging and Standby	Conducted Immunity	IEC 61000-4-6	150 kHz to 80 MHz: 30 Vrms	150 kHz to 80 MHz: 30 Vrms
CW EMS	WPT System Level	Charging and Standby	Radiated Immunity	IEC 61000-4-3	80 MHz to 1 GHz: 30 V/m 1 GHz to 4.2 GHz: 3 V/m 2 GHz to 2.7 GHz: 3 V/m	80 MHz to 1 GHz: 30 V/m 1 GHz to 4.2 GHz: 3 V/m 2 GHz to 2.7 GHz: 3 V/m
CW EMS	WPT System Level	Charging and Standby	Magnetic Field Immunity	IEC 61000-4-8	30 A/m	100 A/m
TRANSIENT EMS	WPT System Level	Charging and Standby	ESD	IEC 61000-4-2	8 kV/4 kV air/contact	8 kV/4 kV air/contact
TRANSIENT EMS	AC Power	Charging and Standby	EFT	IEC 61000-4-4	1 kV (5/50 ns, 100 kHz)	2 kV (5/50 ns, 100 kHz)
TRANSIENT EMS	AC Power	Charging	Surge	IEC 61000-6-2 (IEC 61000-4-5)	1 kV Line-to-Line 2 kV Line-to-Ground	1 kV Line-to-Line 2 kV Line-to-Ground
TRANSIENT EMS	Signal Line	Charging	Surge	IEC 61000-6-2 (IEC 61000-4-5)	1 kV Line-to-Ground	1 kV Line-to-Ground
TRANSIENT EMS	AC Power	Charging and Standby	Voltage Dips and Interrupts	IEC 61000-4-11 (<16 A) IEC 61000-4-34 (>16 A)	30% reduction for 25 cycles 60% reduction for 10 cycles >95% reduction for 1 cycle 100% reduction for 250 cycles	30% reduction for 25 cycles 60% reduction for 10 cycles >95% reduction for 1 cycle 100% reduction for 250 cycles
TRANSIENT EMS	AC Power	Charging and Standby	Harmonic Distortion	IEC 60204-1	Harmonic distortion <10% of the total rms voltage between live conductors for the sum of the 2nd to the 5th harmonic	Harmonic distortion <10% of the total rms voltage between live conductors for the sum of the 2nd to the 5th harmonic

1 Please refer to the referenced standard for complete test limits and conditions.

For all component-level testing, the default vehicle mimic pan is accomplished by the use of a metal plate (e.g., high strength steel) with minimum dimensions of 1.5 x 1.5 m, with a thickness of 0.7 to 1 mm. These minimum dimensions of the plate have been shown to reasonably simulate the smallest actual electric vehicle.

9.1.1 Electromagnetic Immunity

The component-level wireless charging system should be tested to the requirements for electromagnetic field immunity, refer to IEC61000-4-3; 80 to 2000 MHz, 30 V/m carrier test severity level. See Figure 6 for setup for testing the charge station and Figures 7 and 8 for testing of charging to vehicle components.

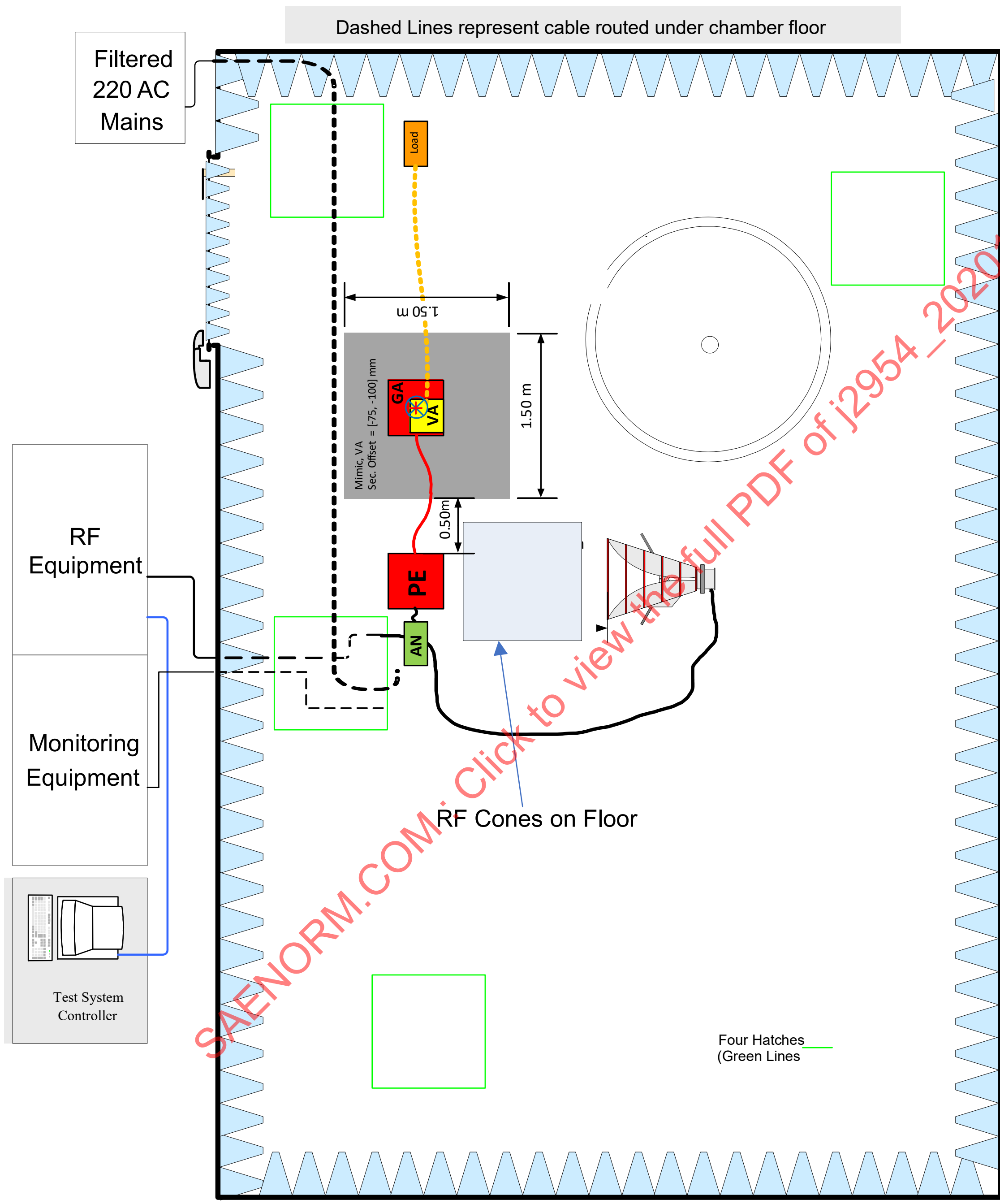


Figure 6 - RI ALSE test setup for component-level wireless charging system for base station top view

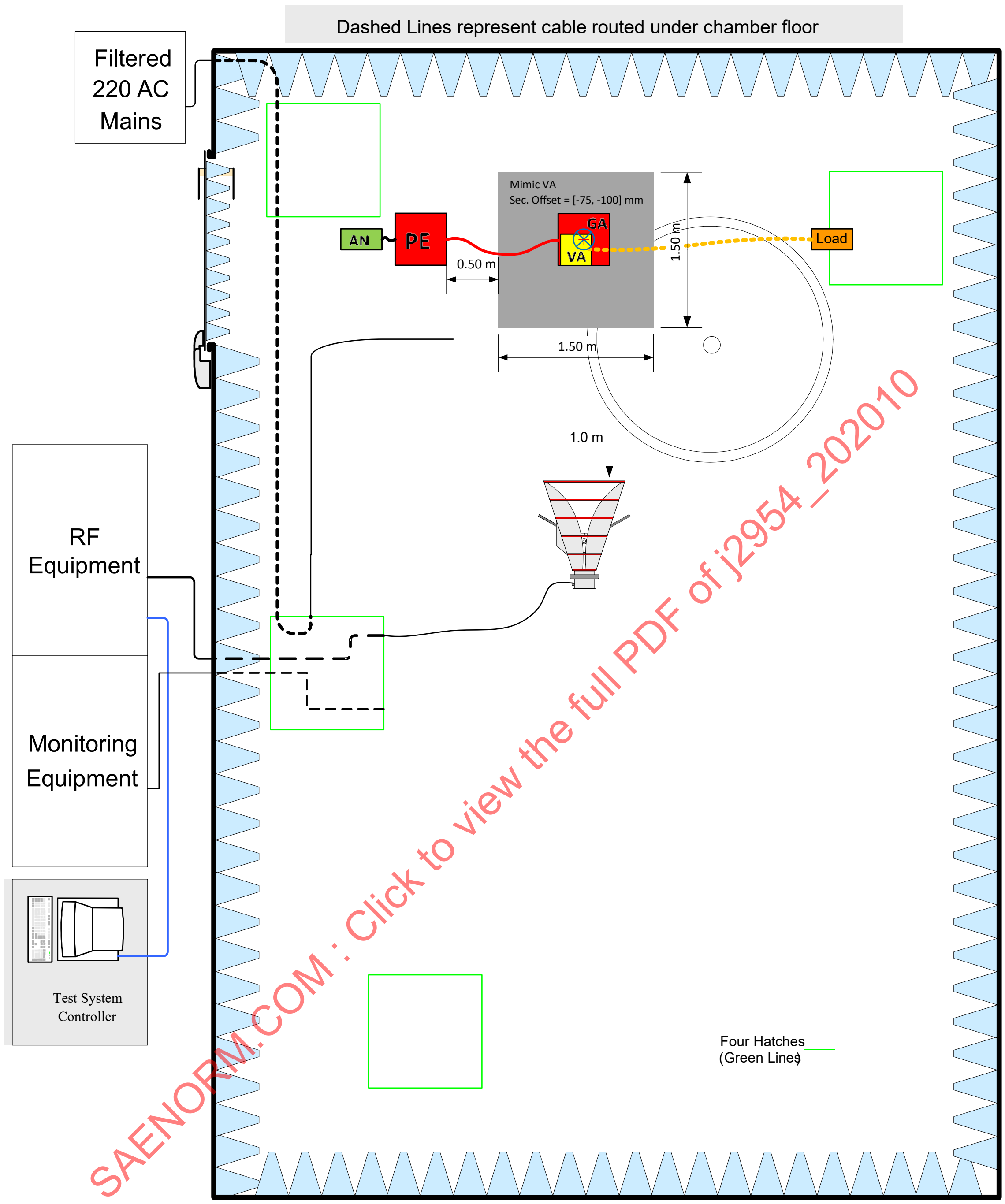


Figure 7 - RI ALSE test setup for component-level wireless charging system for vehicle components top view

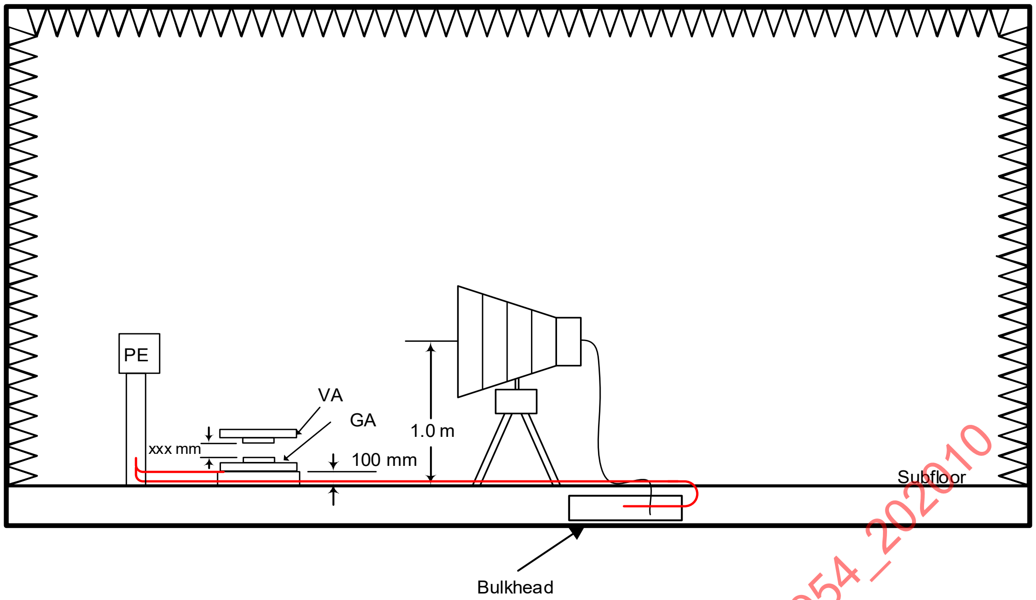


Figure 8 - RI ALSE test setup for component-level wireless charging system for vehicle components side view

The component-level wireless charging system should be tested to the requirements of RF CDN (coupling/decoupling network) injection 150 kHz to 80 MHz IEC 61000-4-6, using a 30 Vrms EMF test severity level.

9.1.2 Radiated Emissions

The wireless charging system shall be tested to the requirements for radiated emissions; refer to FCC Part 18. Measurement at antenna distances of either 3 m or 10 m is allowed. It is recommended to use an antenna distance of 10 m. Measurement at other antenna distances is allowed; reference ANSI C63.30 for the proper scaling factors. The recommended limit for the frequency range of 79.00 to 90.00 kHz is 82.8 dBµA/m (limits shall be reduced by 15 dB to 67.8 dBµA/m for EV WPT installations within a distance of 10 m from known sensitive equipment in public spaces), as indicated in Figure 10. The recommended setup is shown in Figure 9, which illustrates an SAE J2954 test station system on a turntable.

The emission of the fundamental is to be scanned at a maximum turntable angle step size of 22.5 degrees. Once the maximum emission is found using a maximum step size of 22.5 degrees, more precise measurement of the maximum emission may be determined by reducing the turntable angle increment.

Testing shall be done over a metal ground plane at an open area test site (OATS). Testing in an absorber-lined shielded enclosure (ALSE) may be utilized if it can be shown to have correlation to OATS. If testing over an outdoor test site (OTS), the limits should be adjusted accordingly based on the correlation to the OATS.

Limits and test methods for EV WPT are presently under review globally by various regulatory bodies. Presently, there are efforts on-going to develop this assessment, showing that ALSE results correlate with results from OATS. These are only recommended limits based on classifying the WPT function as FCC part 18 below 30 MHz. The test station system measurement setup and limits are presently under development with CISPR 11, CISPR 25, and ANSI C63.30.

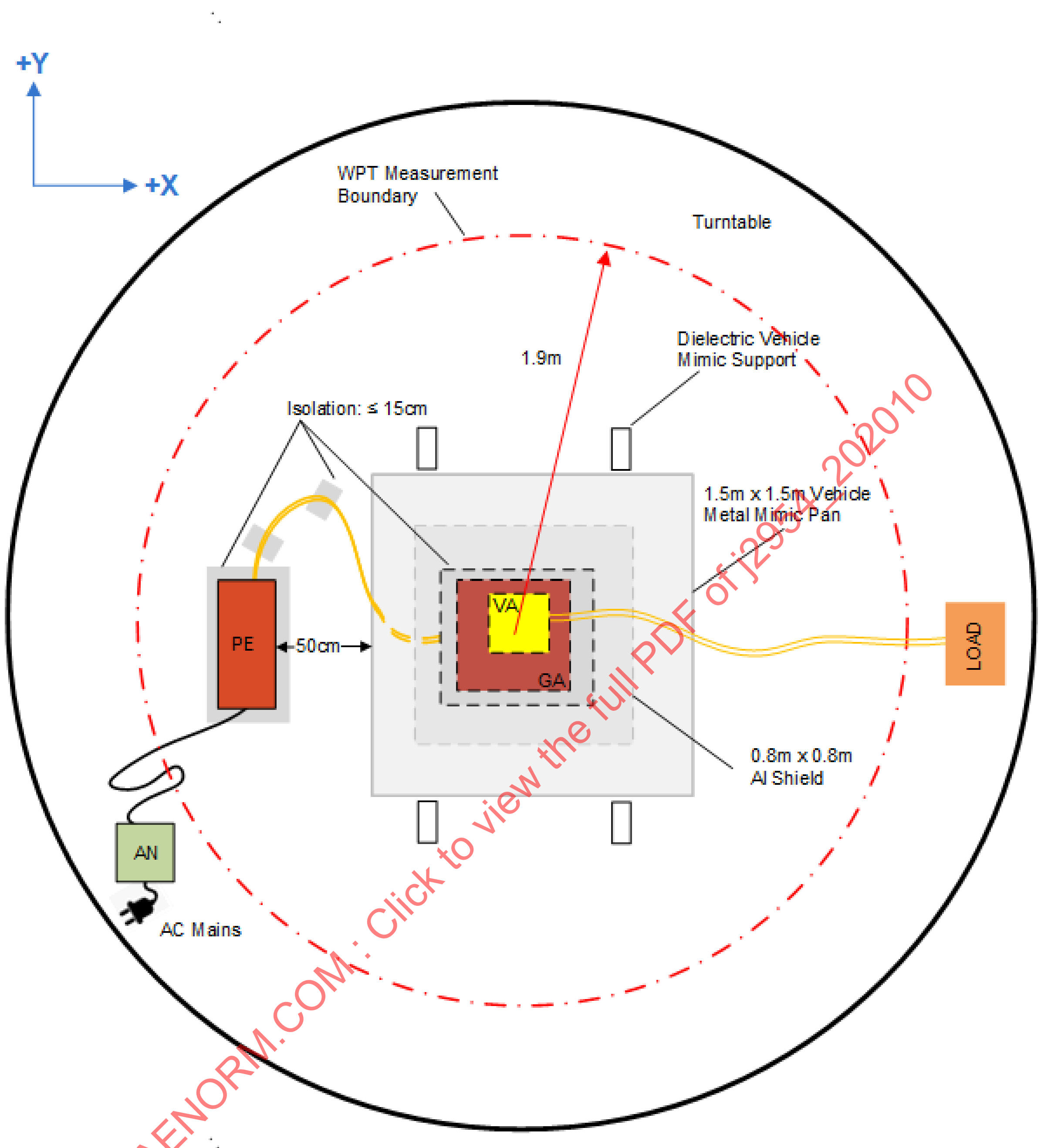


Figure 9A - Recommended test setup, top view, for radiated emissions testing of SAE J2954 test station system with power electronics in the front position

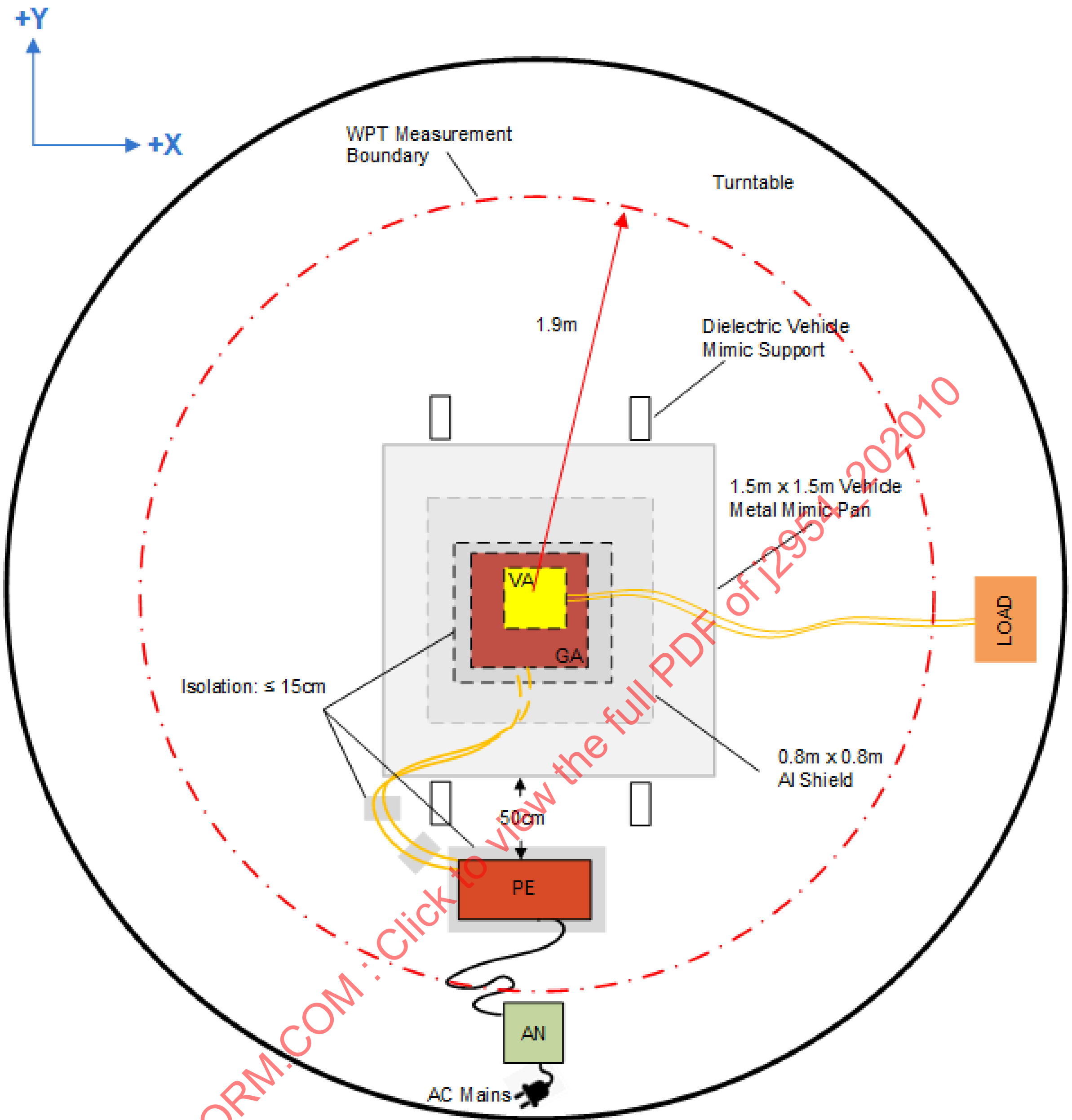


Figure 9B - Recommended test setup, top view, for radiated emissions testing of SAE J2954 test station system with power electronics in the side position

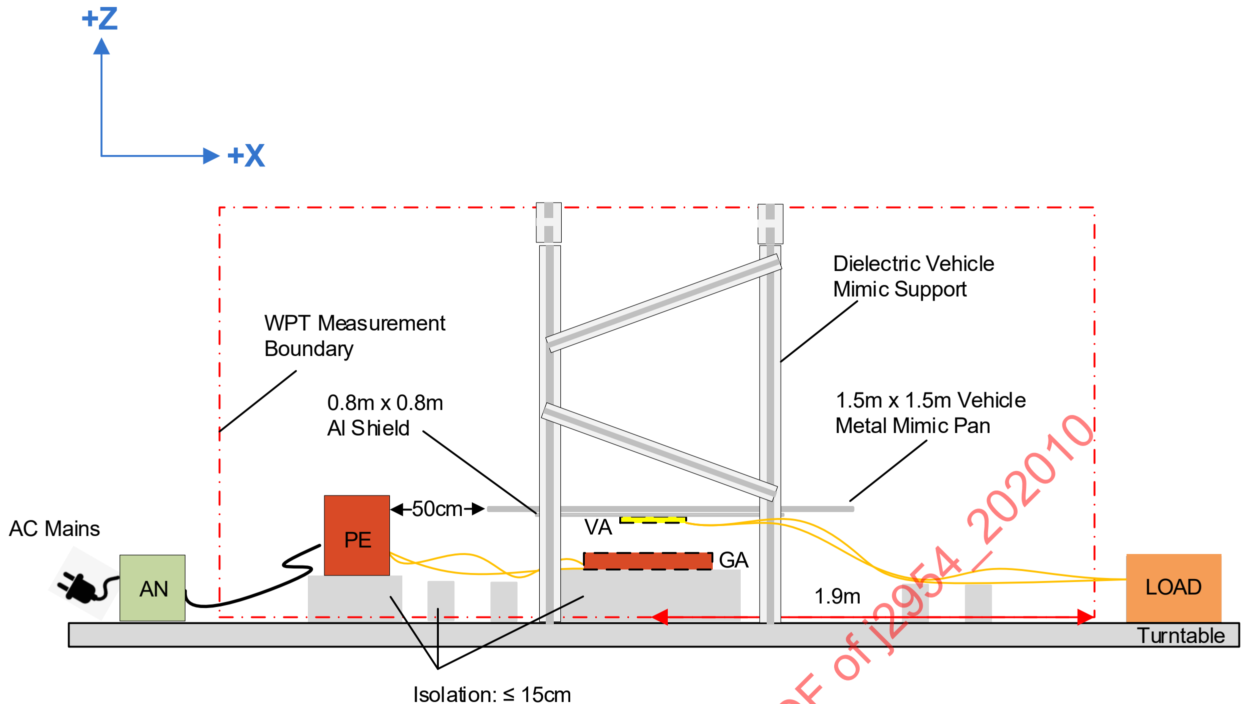


Figure 9C - Recommended test setup, side view, for radiated emissions testing of SAE J2954 test station system with power electronics in the front position

Notes for recommended test setup of radiated emissions testing of SAE J2954 test station system:

- Distance is measured from antenna to 1.9 m fixed radius ring centered on the GA.
- VA and vehicle mimic assembly are shifted by [dX, dY] relative to the GA to achieve offset conditions.
- The GA and the VA are raised above the ground plane using a spacer up to 15 cm. The GA coil package can have a large area which can inadvertently be capacitively coupled with the ground plane. Given this, the GA coil package needs to be raised up near 15 cm. All spacers need to be non-magnetic and non-metallic materials. The vehicle spacer cannot have direct metallic contact with the ground plane.
- Figures 9A to 9C show the typical position of the PE relative to the WPT system. For testing of the specific system, placement of PE is as specified by the manufacturer of the WPT system.
- Use of Artificial Mains Network (AN) and/or a Common Mode Absorption Device (CMAD) is recommended on the AC mains feed to the GA for radiated emissions testing only.
- Note that the z-height is to be measured from the surface of the VA facing down to the bottom side of the GA. This is known as the VA coil ground clearance.

Unintentional Radiators: The emissions from electronic devices within the vehicle-level wireless charging system not related to the power transfer function shall meet FCC Part 15, Subpart B, radiated limits for unintentional radiators. In countries outside the USA, other radiated emission limits may apply. The emissions from electronic devices within the component-level wireless charging system not related to the power transfer function should meet FCC Part 15, Subpart B, radiated limits for unintentional radiators. In countries outside the USA, other radiated emission limits may apply.

Intentional Radiators: The emissions from RF communications devices within the vehicle-level wireless charging system shall meet FCC Part 15, Subpart C, requirements for intentional radiators. The emissions from RF communications devices within the component-level wireless charging system should meet FCC Part 15, Subpart C, requirements for intentional radiators (e.g., Wi-Fi, Bluetooth, LTE, etc.).

9.1.3 Conducted Emissions

The conducted emissions for the WPT function (not wireless communication devices) within the system should meet FCC Part 18 requirements on a vehicle level.

The emissions from electronic devices (not related to the power transfer function) within the component-level wireless charging system should meet FCC Part 15, Subpart B, conducted limits for unintentional radiators.

Conducted emissions from intentional radiators (i.e., communication devices) shall meet the requirements of FCC Part 15, Subpart C.

9.1.4 Electrostatic Discharge (ESD)

The component-level wireless charging system should be tested to the requirements for ESD; refer to IEC 61000-4-2.

9.1.5 Harmonic Distortion Immunity

The component-level wireless charging system should be tested to the requirements for harmonic distortion immunity; refer to IEC 60204-1.

9.1.6 Electrical Fast Transients

The component-level wireless charging system should be tested to the requirements for electrical fast transient immunity; refer to IEC 61000-6-2.

9.1.7 Voltage Dips, Short Interruptions, and Voltage Variations Immunity

The component-level wireless charging system should be tested to the voltage dips, short interruptions, and voltage variations immunity; refer to IEC 61000-4-11.

9.1.8 Magnetic Field Immunity

The component-level wireless charging system should be tested for magnetic field immunity; refer to IEC 61000-4-8.

9.1.9 EMC Tests - On-Board Vehicle Electronic Components

On-vehicle electronic modules intended for sale to a vehicle Original Equipment Manufacturer (OEM) shall be validated per OEM-specific EMC requirements. If the vehicle OEM is not known, at a minimum, the following automotive component EMC tests are required for on-board electronics during normal operation of vehicle (but not necessarily when the WPT system is active). The intention of this chapter is to ensure EMC of on-board electronics under normal vehicle operation.

The following standards apply to the above-mentioned measurements: CISPR 25 Chapters 6.2 and 6.4, ISO 11452-2, ISO 11452-4, ISO 7637-2, ISO 7637-3, and ISO 10605.

9.2 Vehicle-Level EMC Tests

9.2.1 Radiated Emissions Due to Wireless Power Transfer

The fundamental frequency for WPT is the operating frequency within the tuning band (79.00 to 90 kHz). The compliance of the product is dependent on testing the system installed on the intended vehicle and having radiated emissions below regulatory limits set by the specific country of intended use. The vehicle measurement procedure is presently under development with CISPR 11, CISPR 12, and ANSI C63.30.

The SAE J2954 recommended limits are shown in Figure 10. The recommended limit for the operating frequency range of 79.00 to 90.00 kHz is 82.8 dBµA/m (limits shall be reduced by 15 dB to 67.8 dBµA/m for EV WPT installations within a distance of 10 m from known sensitive equipment in public spaces). The recommended setup is shown in Figure 11. The figure illustrates the vehicle on turntable.

The measurement method and test environment are according to the test described in 9.1.2. When the system is not in WPT mode and vehicle is not present, systems not on vehicle shall meet all applicable regulations and systems on vehicle shall meet the requirements set forth by the specific vehicle OEM. Please note that the ANSI C63.30 standard includes procedures for compliance testing of several different types of WPT products with applicable electromagnetic compatibility (EMC) and radio regulatory requirements. The test procedures in ANSI C63.30 focus on radiated field and conducted measurements and refers to established standards. Consideration is also given to appropriate testing distances and test locations (such as semi-anechoic chambers, OATs, ground plane, and earth sites). Related national and international standards (e.g., CISPR, SAE, etc.) are used to the extent possible. Laboratory EMF and CIED management guidelines are given in 10.9.

9.2.1.1 Unintentional Radiation

The emissions from electronic devices not related to the wireless power system shall meet FCC Title 47, Part 15, Subpart B, radiated limits for unintentional radiators. In countries outside the USA, other radiated emission limits may apply.

9.2.1.2 Intentional Radiation

The emissions from all RF communications devices that are classified as intentional radiators according to FCC within WPT systems shall meet FCC Part 15, Subpart C, requirements for intentional radiators (e.g., Wi-Fi, Bluetooth, LTE, etc.).

The emissions from the WPT system are classified as Industrial Scientific and Medical (ISM) and shall meet FCC Title 47, Part 18 requirements with modifications for the fundamental frequency in the range of 79 to 90 kHz as shown in Figure 10.

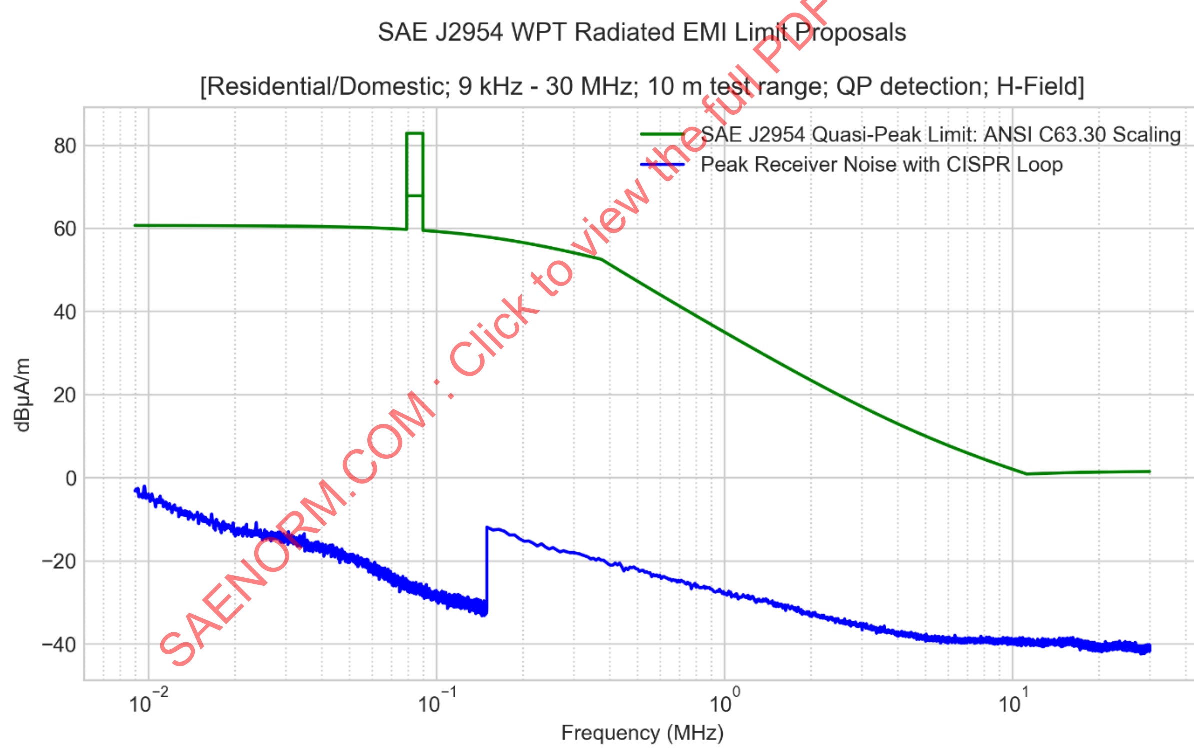


Figure 10 - Recommended limits

The recommended limit for the frequency range of 79.00 to 90.00 kHz for WPT is 82.8 dBuA/m. The recommended limits are for a 10 m antenna distance.

NOTE: Limits may be reduced based on regional regulatory requirements. For example, limits may be reduced by 15 dB to 67.8 dBµA/m for EV WPT installations within a distance of 10m from known sensitive equipment in public spaces.

NOTE: Additional regulatory limits specific to applicable regions shall be met.

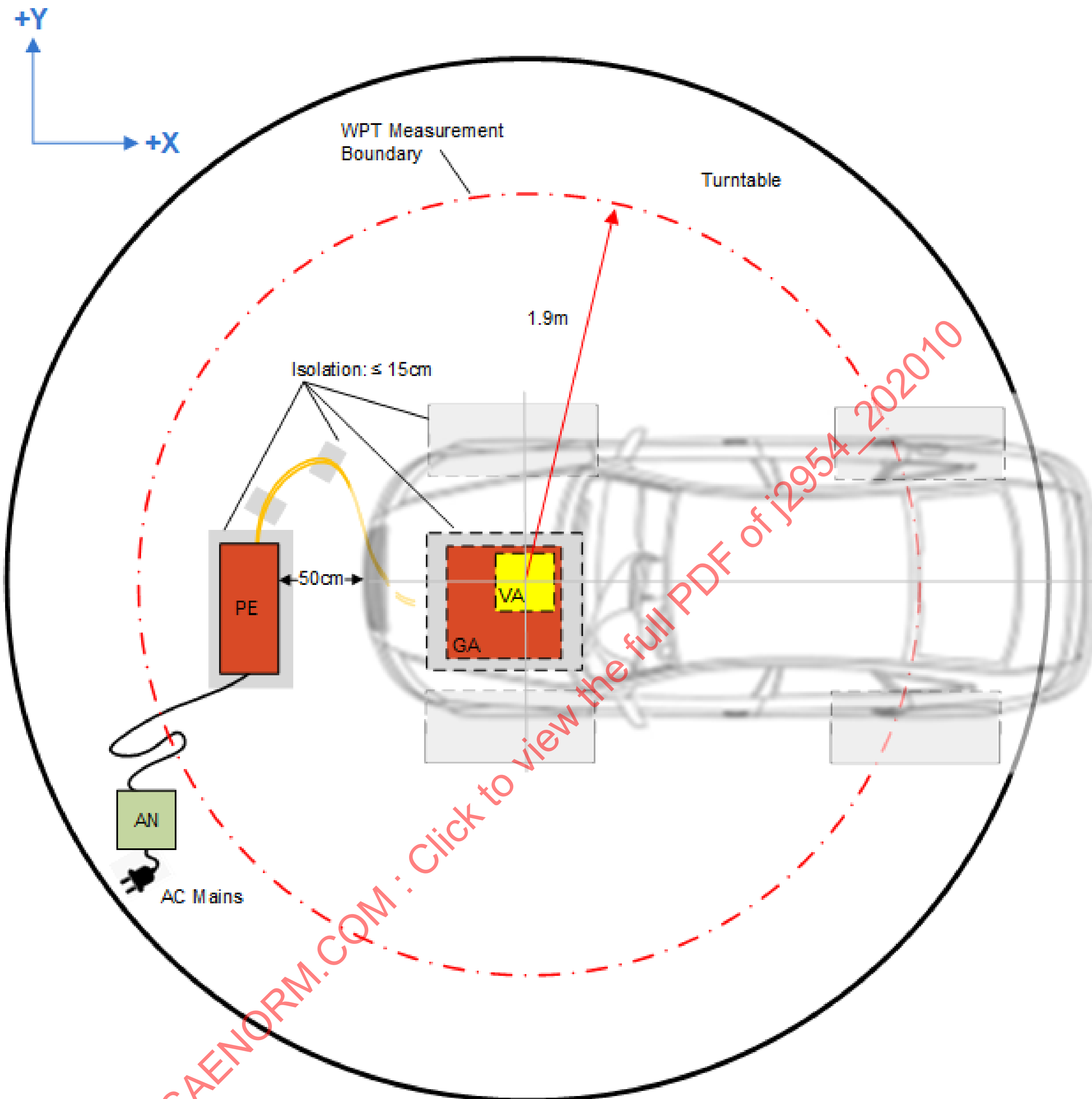


Figure 11A - Recommended setup, top view, for vehicle radiated emissions testing with power electronics in the front position

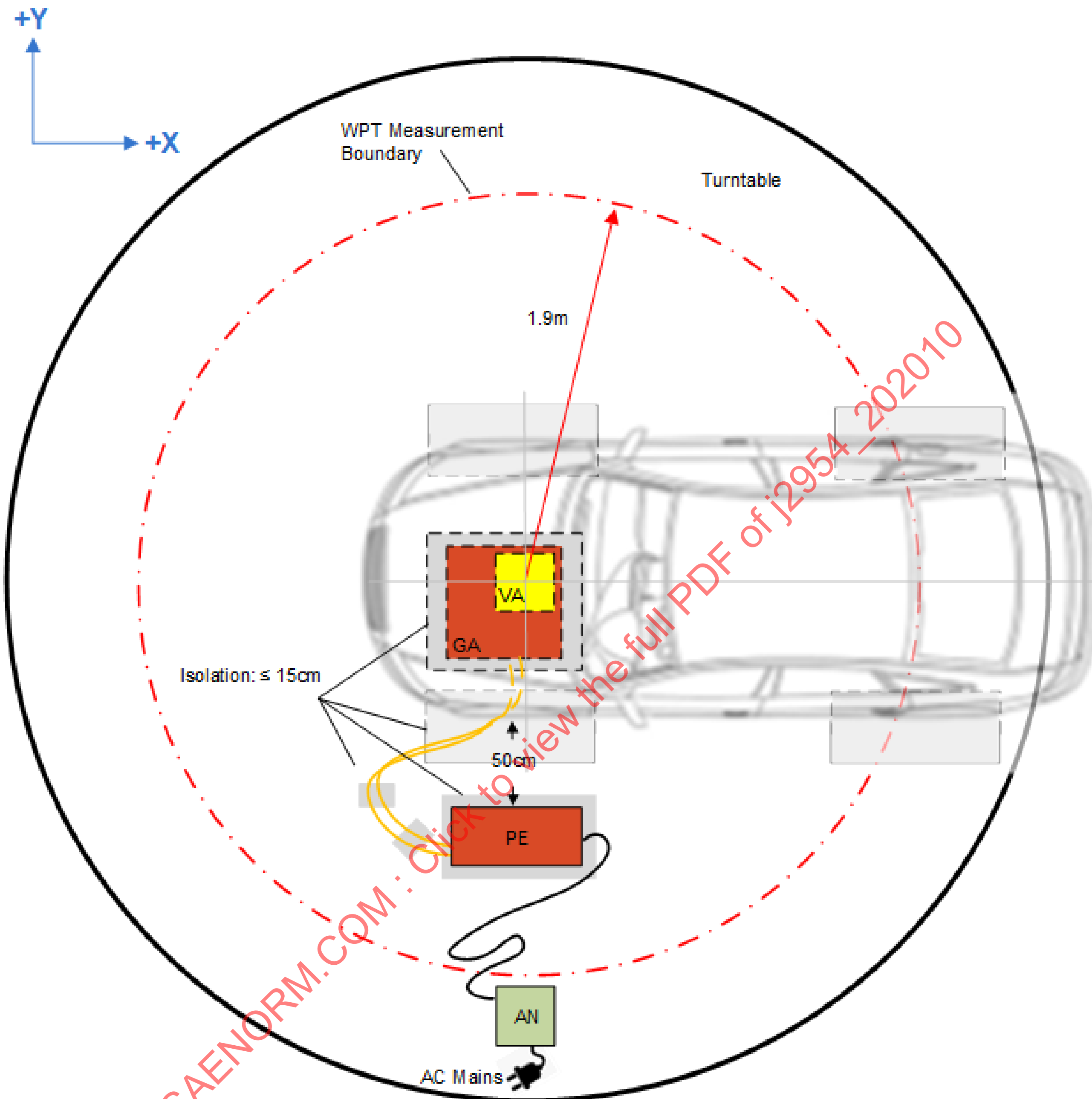


Figure 11B - Recommended setup, top view, for vehicle radiated emissions testing with power electronics in the side position

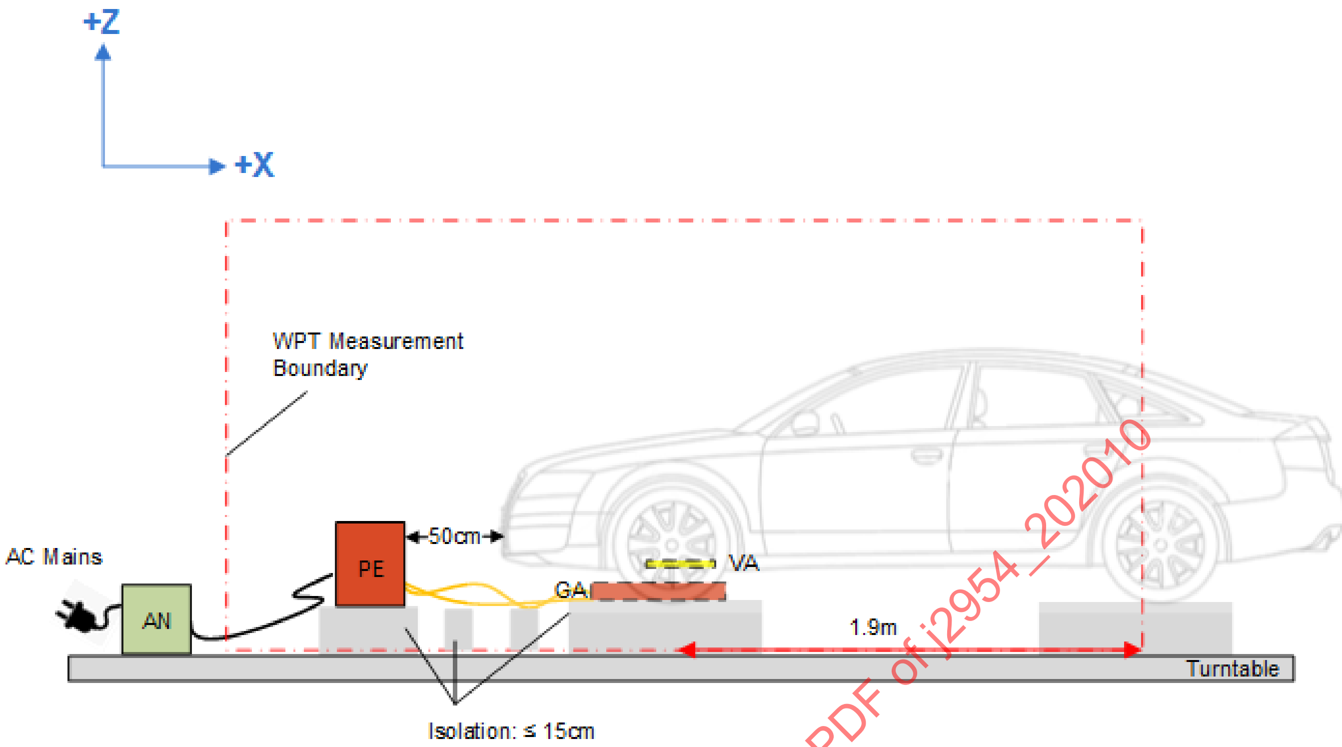


Figure 11C - Recommended setup, side view, for vehicle radiated emissions testing with power electronics in the front position

Notes for recommended setup of vehicle radiated emissions testing:

- Distance is measured from antenna to 1.9 m fixed radius ring centered on the VA.
- GA is shifted by [-dX, -dY] to achieve same relative offset conditions as in mimic testing.
- Clearance between vehicle and power electronics is recommended to be 50 cm.
- In case of vehicle testing on a turntable, etc., the VA should be the center of the rotation due to weight, etc.
- The GA and the vehicle are raised above the ground plane using a spacer up to 15 cm. The GA coil package can have a large area which can inadvertently be capacitively coupled with the ground plane. Given this, the GA coil package needs to be raised up near 15 cm. All spacers need to be non-magnetic and non-metallic materials. The vehicle spacer cannot have direct metallic contact with the ground plane.
- Figures 11A to 11C show the typical position of the PE relative to the WPT system. For testing of the specific system, the PE is placed as specified by the manufacturer.
- Use of an Artificial Mains Network (AN) and/or a Common Mode Absorption Device (CMAD) on the AC mains feed to the GA is recommended for radiated emissions testing only.
- Note that the z-height is to be measured from the surface of the VA facing down to the bottom side of the GA. This is known as the VA coil ground clearance.

9.2.2 Conducted Emissions, System Level

The conducted emissions for the WPT function (not wireless communication devices) within the system shall meet FCC Part 18 requirements.

The emissions from electronic devices not related to the wireless power system shall meet FCC Title 47, Part 15, Subpart B, conducted limits for unintentional radiators.

Conducted emissions from intentional radiators (i.e., communication devices) shall meet the requirements of FCC Part 15, Subpart C.

The system shall meet all applicable in-country requirements for each country in which it is planned to be used; e.g., in certain countries, CISPR 11 requirements apply.

9.2.3 Radiated Immunity

Vehicle-level radiated immunity testing is to be conducted by the vehicle OEM according to their internal requirements and test methods.

The system shall meet all applicable in-country requirements for each country in which it is planned to be used; e.g., ECE REG 10 EMC requirements may apply in EC.

9.2.4 Conducted Immunity

Vehicle-level conducted immunity testing is to be conducted by the vehicle OEM according to their internal requirements and test methods.

The system shall meet all applicable in-country requirements for each country in which it is planned to be used; e.g., ECE REG 10 EMC requirements may apply in EC.

9.2.5 Electrostatic Discharge (ESD)

Vehicle-level ESD testing is to be conducted by the vehicle OEM according to their internal requirements and test methods.

The system shall meet all applicable in-country requirements for each country in which it is planned to be used; e.g., ECE REG 10 EMC requirements may apply in EC.

10. EMF EXPOSURE TO HUMANS AND CARDIAC IMPLANTABLE ELECTRONIC DEVICES (CIED)

10.1 General

Section 10 applies to all Product GAs and Product VAs. Human EMF exposure limits are based upon ICNIRP 2010 guidelines. Limits for implanted medical devices (IMD) other than cardiac implantable electronic devices (CIED) are under consideration, but CIEDs are considered worst case in terms of combined criticality, prevalence, and susceptibility potential. CIEDs are therefore the basis for CIED EMF limits in this standard. CIED WPT magnetic interoperability assessment limits are defined herein by setting CIED EMF reference levels in a manner analogous to ICNIRP limits.

EMF and related measurements in this Section 10 should NOT be made over a metallic ground plane, unless otherwise stated.

Three physical regions are defined to facilitate EMF safety management of the wireless charging system:

- Region 1 is the entire area underneath the vehicle, including and surrounding the wireless power assemblies. Region 1 shall not extend beyond lower body structure edges (e.g., rocker panels or lower edge of bumpers).

- Region 2 is the region outside the periphery of the vehicle. The boundary between Regions 1 and 2 extends downward from the lower periphery of the vehicle body sides. When the vehicle is not covering the GA, Region 2 includes the entire area over and around the GA.

- Region 3 is the vehicle interior.

The EMF management regions are illustrated in Figures 12 and 13. The following EMF safety management principles shall be adhered to for each respective region:

Region 1: The manufacturer shall take reasonable measures to prevent exposure of human beings in Region 1 to EMF levels exceeding the limits listed in Tables 11 or 12. Such exposures may be prevented in Region 1 by any of various means, including any of the following:

a. Active or passive access control; i.e., preventing or barring a human being from entering that area when WPT is active.

b. Detection and shutdown before ingress into areas where such exposure could occur.

c. By meeting the human EMF exposure limits specified in Tables 11 or 12.

Regions 2 and 3: Magnetic fields shall meet the CIED EMF reference levels listed in Table 13 for any realistic CIED lead loop position associated with a reasonably foreseeable human body torso position in Regions 2 or 3. For all locations in Regions 2 and 3, the EMF shall also meet the EMF reference levels listed in Table 11, or the induced internal electric field basic restrictions listed in Table 12.

Regions 2 and 3: Touch currents shall meet the limits listed in Table 14.

The EMF management strategy shall be applicable for all operational conditions; e.g., coupler offset or other system variations which may affect the worst-case exposure.

In addition to the CIED and human EMF requirements, touch current requirements are given to prevent the possibility of startle-reaction for a person touching the vehicle and/or charging system during operation.

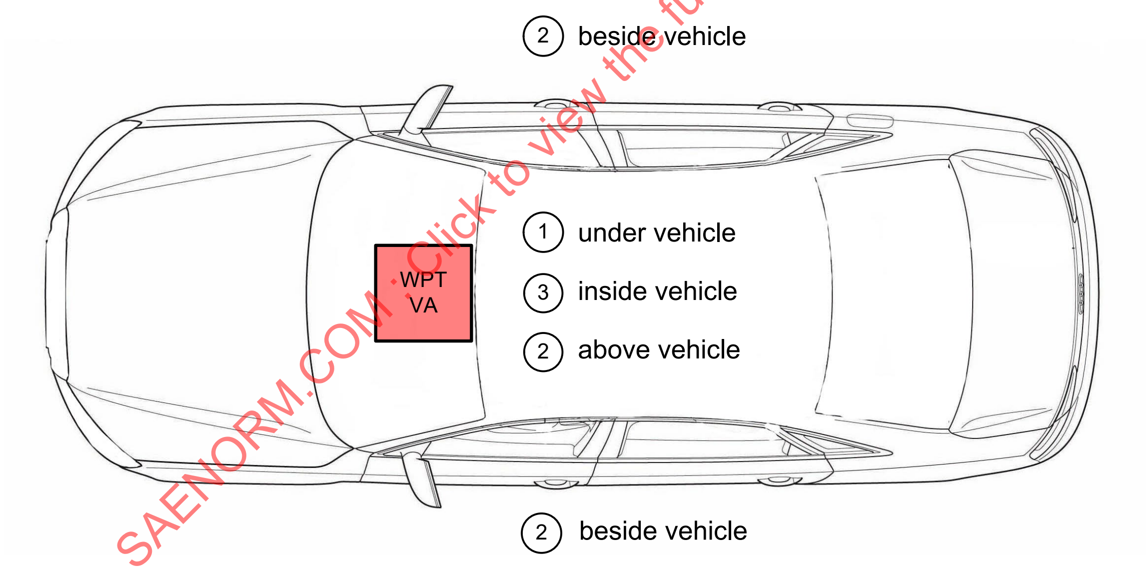


Figure 12 - EMF regions, top view

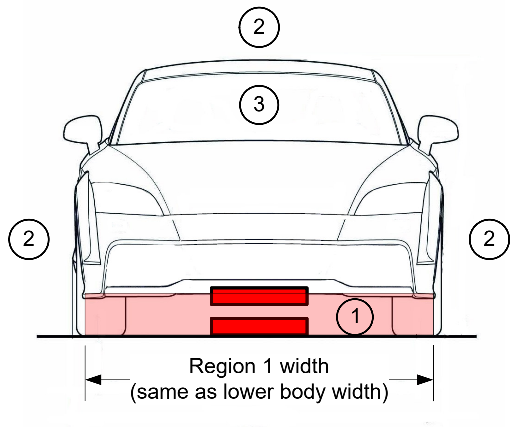


Figure 13 - EMF regions, front view

10.2 Vehicle-Level EMF Requirements

For any realistic location in Region 2 and 3, the CIED EMF Reference Limits are typically the most stringent. Measurements for CIED EMF reference levels in Region 2 shall be based on reasonable human body torso positions and so shall be made at most 20 cm from the vehicle. In Region 3, CIED EMF reference level measurements shall be based on reasonable human body torso positions.

For all locations in Regions 2 and 3, electric and magnetic fields shall comply with the guidelines for general public EMF exposure referenced in ICNIRP 2010. Compliance with the reference levels listed in Table 11 ensures compliance with the basic restrictions of the guideline, which are listed in Table 12. Recommended procedures for performing an EMF assessment using the basic restrictions are given in Appendix K.

NOTE: Additional regulatory restrictions on EMF may exist in some markets or regions.

The general public human EMF reference levels given in Table 11 are applicable from 3 kHz to 10 MHz, including the standard operating frequency of band of 79 to 90 kHz, and significant harmonics thereof.

Table 11 - Human EMF exposure standard, reference levels

Quantity	ICNIRP 2010 General Public Reference Level (rms Field Strength for 79-90 kHz)
Magnetic Field	27 μT or 21.5 A/m[1]
Electric Field	83 V/m

[1] When using 100 cm^2 three-axis standard field probe for magnetic field measurements.

Table 12 - Human EMF exposure standard, basic restriction levels

Quantity	ICNIRP 2010 General Public Basic Restriction Level (rms Field Strength for 79-90 kHz)
Internal Electric Field	1.35×10^{-4} * f(Hz) = 10.475 V/m at 85 kHz

NOTE: It is recognized that the ICNIRP 2010 guidelines recommend that the restrictions on internal electric fields induced by electric or magnetic fields, including transient or very short-term peak fields, be regarded as instantaneous values which should not be time averaged. The use of rms measurements and limits for EMF exposure assessment is predicated on the assumption that the WPT fields are continuous and sinusoidal during the rms averaging period, and do not contain transient overshoot. If the WPT fields are modulated, substantially non-sinusoidal, or include overshoot during amplitude transitions, the EMF assessments should be performed using peak limits equal to the rms limits times 1.41.

The use of spatial averaging (of multiple field probe positions) for human EMF exposure is not recommended until guidance is provided by EMF exposure standardization bodies, based on correlation analysis of wireless charger spatially averaged reference level versus spatial peak Basic Restriction dosimetry.

The CIED and human EMF exposure limits shall be met in Regions 2 and 3 under all normal (non-faulted) operating conditions of the wireless charging system, including coupler offset.

10.2.1 Cardiac Implantable Electronic Device (CIED) EMF Requirements

CIED WPT magnetic interoperability assessment limits are defined herein by setting CIED EMF reference levels in a manner analogous to ICNIRP limits. Based on the ISO 14117 Appendix M, it is expected that CIEDs operate as designed when 79 to 90 kHz magnetically induced lead voltages, in a 225 cm² loop area, are less than the levels defined as $V_{MAX\_INDUCED\_RMS} = \frac{3\sqrt{2}}{2}$ mV × Frequency (kHz) (e.g., 180.31 mVrms at 85 kHz). These voltages are the basis for the field limits in the SAE J2954 CIED EMF reference levels shown in Table 13, which shall not be exceeded for any realistic CIED lead loop position associated with a reasonably foreseeable human body torso position in Regions 2 or 3. Under the CIED EMF reference level measurement distance constraints described in 10.4, the Table 13 levels provide an alternative, but conservative, assessment of CIED WPT magnetic interoperability, utilizing the same 100 cm² field probe used for human EMF assessment. All field measurement limits are conservatively expressed as the magnitude (root sum squared) of the X, Y, and Z components of the magnetic field (e.g., $|B_{FIELD}| = \sqrt{B_X^2 + B_Y^2 + B_Z^2}$).

NOTE: If the WPT fields are modulated, substantially non-sinusoidal, or include overshoot during amplitude transitions, the CIED EMF assessments should be performed using peak limits equal to the rms limits times 1.41.

NOTE: The limits and precautionary measures for CIEDs may be revisited in the future based on data as per the ISO 14117 Committee. Additional limits for other IMDs are under consideration.

Table 13 - CIED EMF reference level

Quantity	Magnetic Field Limit Regions 2 and 3 (rms)
Magnetic Field Strength	15.0 μT or 11.9 A/m[1] (for 79 to 90 kHz)

[1] These limits apply when using 100 cm² standard field probe, perform four measurements in a 2 x 2 grid and spaced at 7.5 cm (probe centered at each point) centered around the location of each reading above 15.0 μT. Average these four measurements.

10.3 Touch Current Requirements

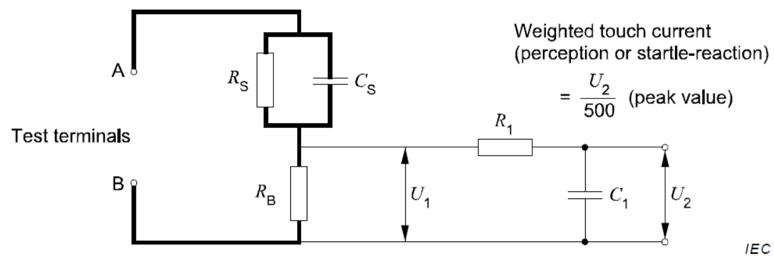
The requirement for touch currents is given in Table 14. The requirement is specified in terms of the output voltage U_2 of the IEC 60990 touch current measuring circuit weighted for perception or startle-reaction. This requirement level is chosen to correspond to the ICNIRP general public touch current reference level in the frequency range of 2.5 to 100 kHz.

The touch current limit applies to the current which can occur when a person comes in simultaneous contact with any two accessible conductive portions of the vehicle or charging system, or an accessible conductive portion of the vehicle or charging system, and ground. The magnitude of the touch current will depend on situational factors.

Table 14 - Touch current limits

Touch Current Limit	
Touch Current (ICNIRP units) (mA, rms) (Information Only)	IEC 60990 Measuring Circuit Output U_2 (mV, rms) (Normative)
0.2 * f(kHz) (e.g., 15.8 mA at 79 kHz)	75

NOTE: If the WPT touch current measuring circuit output voltage U_2 is modulated, substantially non-sinusoidal, or includes overshoot during amplitude transitions, the touch current assessment should be performed using peak limits equal to the rms limits times 1.41.



R_S	1 500 Ω	R_1	10 000 Ω
R_B	500 Ω	C_1	0,022 µF
C_S	0,22 µF		

Figure 14 - IEC 60990 touch current measuring circuit

10.4 Vehicle Human/CIED EMF Assessment - General Considerations

Procedures for EMF assessment of vehicles with wireless chargers should be based on standardized EMF measurement procedures, to the degree they apply. Table 15 lists several applicable or related EMF measurement standards.

The objective of the following procedure is to determine compliance of the maximum magnetic and electric fields in Regions 2 and 3, for their respective worst-case gap and alignment (maximum offset) operating conditions and power levels. Although system controls may reduce power under misaligned or large gap conditions, maximum EMF may still occur under such conditions. Worst-case EMF may be associated with conditions producing maximum GA and/or VA coil current.

Probe movement during EMF measurements may be subject to an appropriate minimum distance(s) between the probe and nearby metallic surfaces or the Region 1 boundary or the GA when the vehicle is not present. The purpose of such probe distance restrictions is to improve reproducibility and avoid excessive overestimation of exposure, while maintaining correlation to the fundamental exposure metrics:

- For human EMF reference level assessments, the minimum probe distance shall be chosen such that compliance with the reference levels (Table 11) ensures compliance with the basic restrictions (Table 12).

- For CIED EMF reference level assessments, the minimum probe distance shall be chosen such that compliance with the CIED EMF reference levels (Table 13) conveys compliance with the ISO 14117 lead voltage test limits for uninfluenced device operation (based on an assumed 225 cm^2 lead loop area). The reference field level of 15 µT using a 100 cm^2 probe and averaging four points is conservatively chosen to ensure this limit is met.

For human EMF assessment, the probe tip shall be placed as close to the vehicle body as possible (e.g., less than 1 cm) in Region 2, and in the designated locations of Region 3. At the bottom edge of the vehicle, the plane of measurement (boundary of Region 1) shall extend directly downward from the lower edge of the vehicle as shown in Figure 13. For CIED EMF assessment, it is recommended that the minimum probe distance (to sensor perimeter) should be less than or equal to the minimum expected effective distance from a patient's implanted lead loop, to the metallic surface or boundary in question. A conservative approach for human EMF assessment is to use no minimum distance; i.e., to allow the probe to touch all objects and boundaries. For human EMF assessment near non-metallic objects (e.g., seat cushions), no minimum distance shall be applied.

Depending on the relative values of minimum probe distances for human and CIED EMF measurements, and whether the basic restrictions are used for human EMF assessment, the human and CIED EMF assessments may be combined for efficiency. Figure 15 provides a recommended flowchart for combined human and CIED EMF assessments.

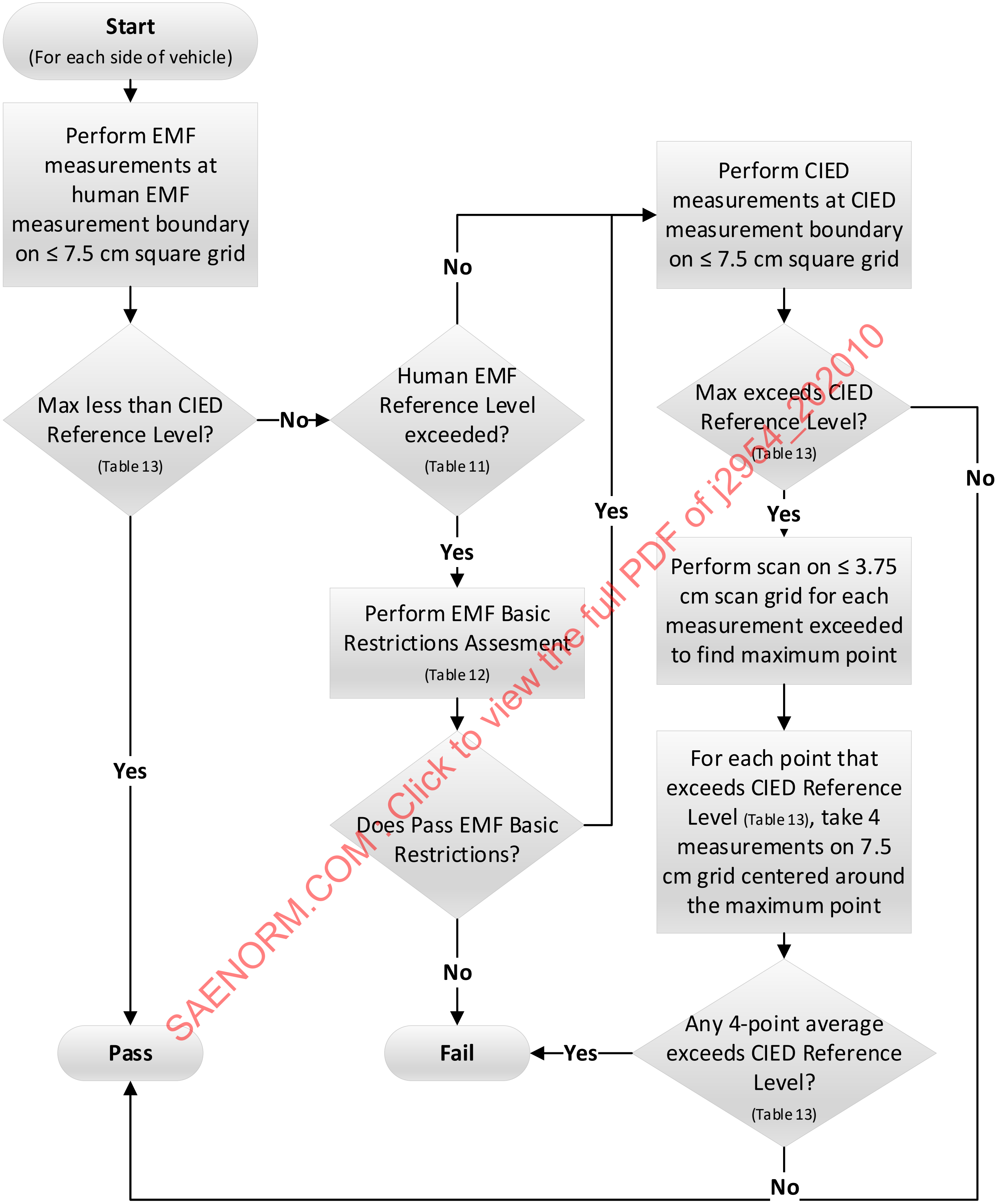


Figure 15 - Flowchart for combined EMF and CIED assessment

Table 15 - Reference EMF exposure measurement standards

Related Exposure Measurement Procedures (Informative)
IEC 60990: Methods of measurement of touch current and protective conductor current.
IEC 61786-2: Measurement of DC magnetic fields, AC magnetic and electric fields from 1 Hz to 100 kHz with regard to exposure of human beings. Part 2: Basic standard for measurements.
IEC TS 62764-1: Measurement procedures of magnetic field levels generated by electronic and electrical equipment in the automotive environment with respect to human exposure.
IEEE Std. C95.3: Recommended practice for measurements and computations of electric, magnetic, and electromagnetic fields with respect to human exposure to such fields, 0 Hz to 100 kHz.

10.5 Instrumentation

For magnetic and electric field EMF measurement using reference levels, and for CIED EMF reference level measurement, the following specifications apply:

- The instrument should utilize rms or peak detection, based on the considerations described in 10.2.
- An isotropic three-axis sensor should be used.
- The three sensors should be centered at the same point.
- The sensor shell should be spherical in shape, with a maximum external diameter of 12.5 cm.
- For magnetic field measurement, the three sensors should be circular with an area of 100 cm^2.
- A coarse resolution of 7.5 cm or less should be used when sweeping for peak values.

If the CIED reference level is exceeded during measurement, then an average at four designated points may be applied. The following method for determining a field average for the CIED reference level applies:

a. Using a minimum resolution of 3.75 cm, sweep each region where the CIED reference level (15 µT) is exceeded in Regions 2 or 3. Find and record (or mark) the location of highest reading.

b. Designate an equally spaced 2 x 2 grid of 4 measurement points centered around the highest recorded point. The resolution of the grid should be 7.5 cm. The plane of the grid should be chosen to maximize the average reading in Regions 2 or 3.

c. At each of the four grid points, record the field value (magnitude of all probe axes).

d. Average all four points. The averaged result shall be less than the CIED reference level.

NOTE: If the field probe interferes with the ground (due to the peak occurring at or near the ground) then the 2 x 2 grid of four measurements can be moved up so that the field probe is touching the ground for the lower two measurements.

In general, to facilitate the search for the spatial maximum fields within Region 2, it is recommended that appropriate means be devised and constructed to constrain the range of probe movement so that it does not enter Region 1 during testing. For example, a short vertical plastic barrier "wall" under the edge of the vehicle, enclosing Region 1, is suggested. The height of the wall should be at least equal to the vehicle ground clearance minus the radius of the probe.

A graphical representation of an example CIED reference scan is shown below. Note that it is possible the maximum point be off the original 7.5 cm grid so care should be taken to find the actual maximum before performing the averaging.

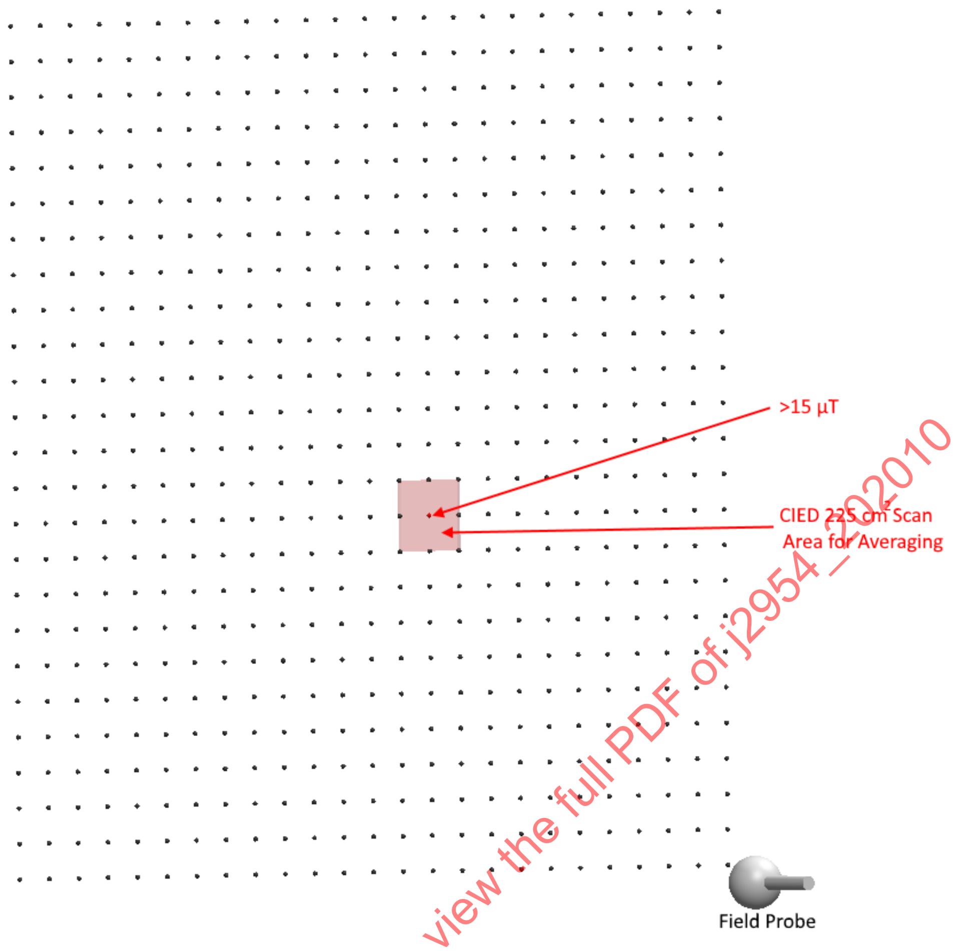


Figure 16 - Reference scan example with measurement above reference level

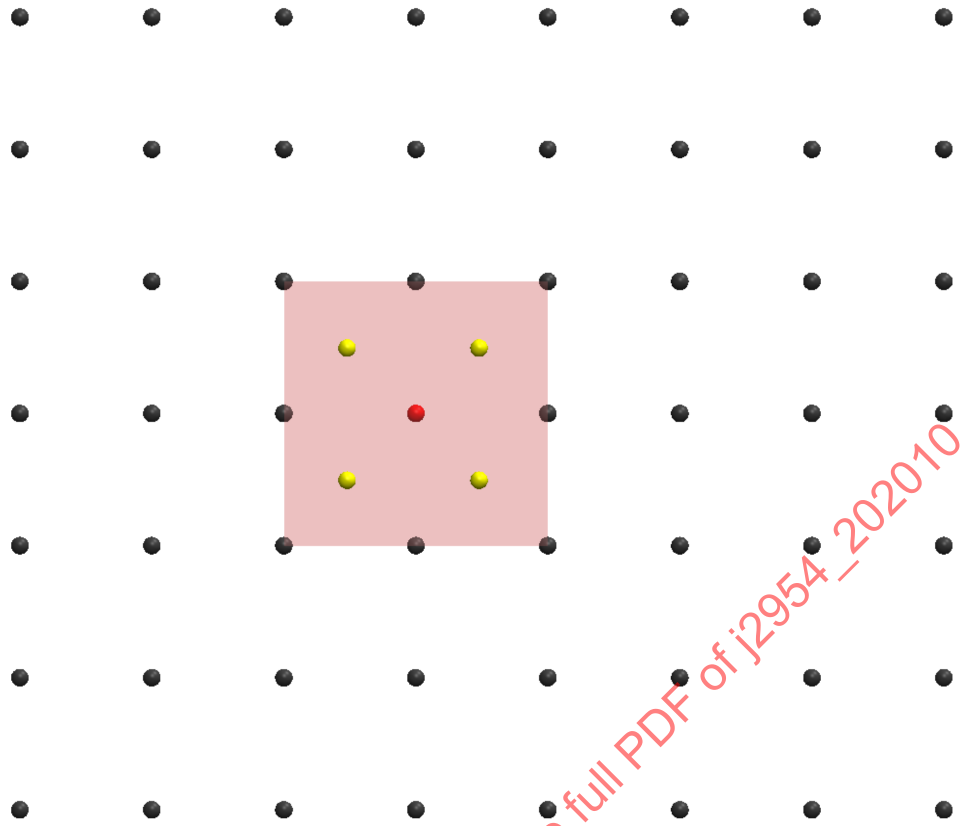


Figure 17 - Region for reference level average measurement - 2 x 2 grid with light color points indicate points of measurement centered around peak

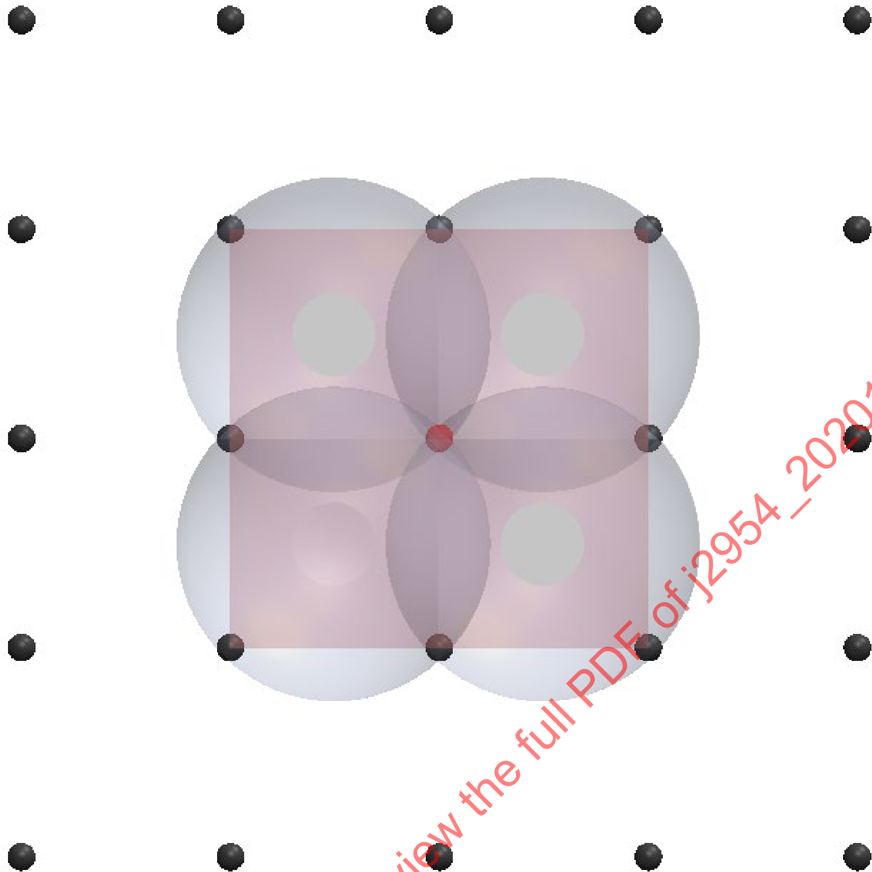


Figure 18 - Locations for standard field probe averages around peak - 2 x 2 grid separated equidistantly by 7.5 cm center-to-center

10.6 Facility for EMF/CIED Exposure Assessment

Vehicle WPT human and CIED EMF exposure measurements shall be performed over a ground surface which is representative of the actual system usage. Usually, this means that testing shall be performed on a concrete or asphalt paved surface.

10.7 Vehicle Regions 2 and 3 Exposure Assessment

The following experimental procedure for reference level assessment is recommended to find the maximum fields in Regions 2 and 3, among several combinations of misalignment and gap:

a. Set up the system offset and gap conditions.

b. Sweep the magnetic field probe horizontally around the Region 1/Region 2 boundary (e.g., at one half of the height of the floor pan), to find the maximum boundary field. Maintain a sufficiently slow rate of motion to avoid motion-induced magnetic reading errors. Scan vertically and outward from the Region 1 boundary as necessary to determine the location of the spatial maximum field. Record the maximum Region 2 magnetic field location and value.

c. Repeat Step b. for the electric field EMF measurement.

d. At each seating position in Region 3, sweep the magnetic field probe throughout the occupant area to find the maximum field. Maintain a sufficiently slow rate of motion to avoid motion-induced magnetic reading errors. Record the maximum magnetic field location and value for each seating position. Additionally, at each seating position, record the fields measured at points A (head), B (chest), C (seat cushion), and D (foot), illustrated in Figure 19.

e. If the vehicle floorpan is non-metallic, repeat Step d. for the electric field EMF measurement. For vehicles with metallic floor pans, an electric field assessment is not required in Region 3, except in the vicinity of floor openings.

f. Repeat for each combination of offset and gap conditions.

An example worksheet (Table 16) is provided with a minimum set of offset and gap combinations to be tested. This is intended as a starting point because fields may vary rapidly with offset or gap, especially at large offsets and gaps. Additional offset and gap combinations should be considered as appropriate to determine the worst-case conditions for magnetic and electric fields, if results obtained from the initial measurements exceed 50% of the exposure limit.

Table 16 - Example worksheet for worst-case operating condition search

Coupler Offset and Gap			Max Magnetic Field		Max Electric Field	
dX	**dY**	**dZ**	**Location**	**B(uT)**	**Location**	**E(V/m)**
+max	+max	Max				
+max	-max	Max				
-max	+max	Max				
-max	-max	Max				

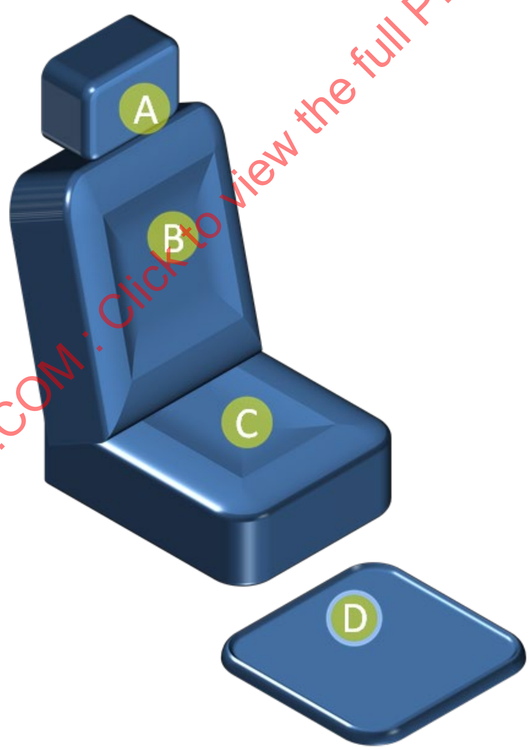


Figure 19 - Region 3 EMF data points

10.8 Touch Current Assessment Procedure

Measurements of touch current shall be performed in accordance with IEC 60990, utilizing the measurement network weighted for perception or startle-reaction. Measurements shall be performed over a metallic ground plane, with the charging system (and vehicle, if applicable) elevated by a nominal minimum amount necessary to reduce the effect of the ground plane on WPT operation and achieve normal operating conditions; e.g., 10 cm. Measurements shall be performed between the combinations of accessible parts listed in Table 17.

Table 17 - Touch current measurement points

Measurement	IEC 60990 Figure 4 Touch Current Measurement Network Connection Points	
	Test Terminal A	**Test Terminal B**
1	Vehicle body (e.g., door latch)	Ground plane directly under Terminal A
2	Metallic enclosure of charging system control/display	Ground plane directly under Terminal A
3	Vehicle body (e.g., door latch)	Metallic enclosure of charging system control/display
4	Additional exposed metallic charging system components	Additional metallic charging system components

All combinations of metallic charging system components, the vehicle body, and ground, which are simultaneously accessible and reachable by a person during charging, shall be added to the Table 17 list of measurements to be performed. For any measurements where Test Terminal B is not connected to the ground plane, it is necessary that the measuring instrument (connected to U_2 of the IEC 60990 Figure 4 measurement network) shall utilize a differential amplifier input.

Measurements should be performed for the coupler configurations listed in Table 18.

Table 18 - Coupler configurations for touch current measurement

Coupler Offset and Gap		
dX	dY	dZ
0	0	min
+max	+max	min
-max	+max	min

NOTE: Vehicle body (or mimic)-to-ground touch current will usually be dependent on the body or mimic capacitance to ground. Elevating the vehicle or using a mimic with less area than the vehicle underbody will tend to decrease capacitance and increase touch current. It may be necessary to add body or mimic capacitance to restore a value representative of the minimum capacitance which may occur in actual usage conditions (representing the smallest applicable vehicle on the ground).

10.9 Laboratory EMF and CIED Exposure Management

At the time of publication of this standard, the use of vehicle WPT systems will still be a new technology, and as such it is anticipated that many laboratories may initially lack policies addressing the operation of such systems. To aid in the creation or expansion of such policies, the following practices are suggested. The purpose of this section is not to impose requirements or to modify existing policies, but rather to educate.

During the testing process, steps should be taken to ensure that personnel are not exposed to hazardous RF electromagnetic fields or voltages. Special care should be taken when working with component-level systems which may have less shielding than their vehicle integrated counterparts, and which may not include automatic protection systems.

For the prevention of exposure to excessive electromagnetic fields, a marked safety perimeter should be established around the wireless power transfer system, and personnel should not enter the safety perimeter when wireless power transfer fields are active. It is recommended that magnetic and electric field limits of Table 19 be used, to provide combined protection for persons with CIEDs, and for the general public.

Table 19 - Combined EMF limits for laboratory use

Quantity	Laboratory EMF Limit (rms)
Magnetic Field	15 µT or 11.9 A/m
Electric Field	83 V/m
Touch Current	15.8 mA

NOTE: If the fields or currents are substantially non-sinusoidal, or include overshoot during amplitude transitions, the assessments should be performed using peak limits equal to the rms limits times 1.41.

It is recommended that the perimeter be first established at a distance greater than 3.0 m around the system being tested and that initial power up be done at lowest power transfer level possible. Controls for operating the wireless charging system and any safety apparatus should be located outside the EMF perimeter. The power level will then be gradually increased to rated power, while the electrical and magnetic fields are carefully monitored by the laboratory field sensor(s) set up at the perimeter. If the sensor readings exceed the EMF threshold during the perimeter exercise, power transfer should be stopped immediately, and the perimeter should be increased to a safe distance. Misalignment also shall be considered when attempting to introduce the conditions of maximum field strength/intensity leakage. Once the worst-case EMF conditions are understood and established, the perimeter can be moved inward until fields at the perimeter are at the recommended limit levels.

Careful attention shall be paid to the grounding of equipment, to prevent the possibility of RF shock or burn from touching equipment having RF potential. In some laboratory measurement setups, it may be necessary to operate the VA (possibly including the rectifier and load) in a “floating” or ungrounded condition (e.g., to mimic vehicle conditions). In such cases, it is important to consider whether inadvertent grounding through a human could occur.

If metallic WPT equipment is isolated from ground and accessible to personnel, the maximum human body grounding current should not exceed 15.8 mA. Particular attention should be paid to ungrounded objects which are in close proximity to the WPT couplers (e.g., a floor pan mimic plate), and which are directly accessible from the perimeter or have attached conducting elements extending to or beyond the perimeter (e.g., instrumentation leads).

As component level systems may not have sufficient shielding, precautions should be made to protect any equipment sensitive to high intensity magnetic and electric fields, so long as the countermeasures do not alter the performance of the wireless power transfer system.

10.9.1 ICNIRP Safety Compliance

Measure the magnetic and electric field levels at the perimeter of the boundary surrounding charging coils (0.8 m from the center point of VA coil, vehicle: 0 mm from vehicle edges) for ICNIRP compliance for safety of the test operator.

Evaluate the EM field at nominal Z-gap (manufacturer recommended) for both the aligned condition and maximum (worst case) misalignment in X and Y at full rated power. From these results, set a perimeter boundary around the test setup to ensure the test operator safety.

Repeat this evaluation of the EM field at the maximum Z-gap and the worst-case X and Y misalignment and roll and yaw to verify that the worst-case EM field conditions have been identified. Set the perimeter boundary in accordance with the maximum measured EM field of any test condition.

Table 20 - Measurements of fields

		Performance Metrics	Safety Notes
ICNIRP	ICNIRP Gen.Pub. Distance X-Axis		
	ICNIRP Gen.Pub. Distance Y-Axis		

11. ADDITIONAL SAFETY REQUIREMENTS

UL is writing a UL standard (UL 2750, in development) to cover the safety aspects of the off-vehicle components and operation of WPT. SAE J2954 is working collaboratively with UL on this project with the intent that the documents are compatible, not overlapping, and, together, cover the subject adequately.

The NFPA National Electric Code (NEC), Article 625, has provisions covering the installation of wireless charging systems. The NEC is used by most U.S. local electrical inspection services to determine approval of electrical installations.

12. COMMUNICATIONS AND ALIGNMENT

12.1 Introduction

Wireless charging of PEVs adds a number of communication requirements to those required to support conductive charging. Foremost among these is the need to be able to communicate between the VA and the GA over a wireless physical medium.

This results in the need to positively and securely identify the PEV presently being charged by the WPT system. SAE J2954 Product GAs and Product VAs rely on the work of SAE J2836/6, SAE J2847/6, and SAE J2931/6 to support communications needed for WPT.

Wireless charging is convenient due to its contactless nature. One of the benefits of wireless charging is the flexibility provided in alignment between the charging infrastructure and a vehicle. While fairly large tolerances may be allowed, some level of vehicle alignment is required to ensure safe and efficient charging. It is primarily the responsibility of the vehicle's on-board capability to guide or otherwise assist the driver in aligning the VA to the GA. There is a need, however, for a standardized method to allow for any vehicle with a SAE J2954 Product VA to align with any SAE J2954 Interoperability Class I GA.

The SAE J2954 alignment sub-team has surveyed vehicle OEMs and wireless charging suppliers to determine the minimum common method for alignment (fine alignment, pairing, and alignment check) to be standardized. A list of potential common alignment technologies is given in Appendices M, N, O, and P. The goals of these three informative alignment technologies are to communicate methodologies for triangulation alignment to assist in manual and automated vehicles.

As described in other parts of this standard, communications are used to support a variety of functions, along with alignment, that are of utility to the user as well as necessary to ensure efficient and safe transfer of power while complying with applicable regulations. The sections below give a high-level description of the functions supported; details can be found in the above referenced communications standards.

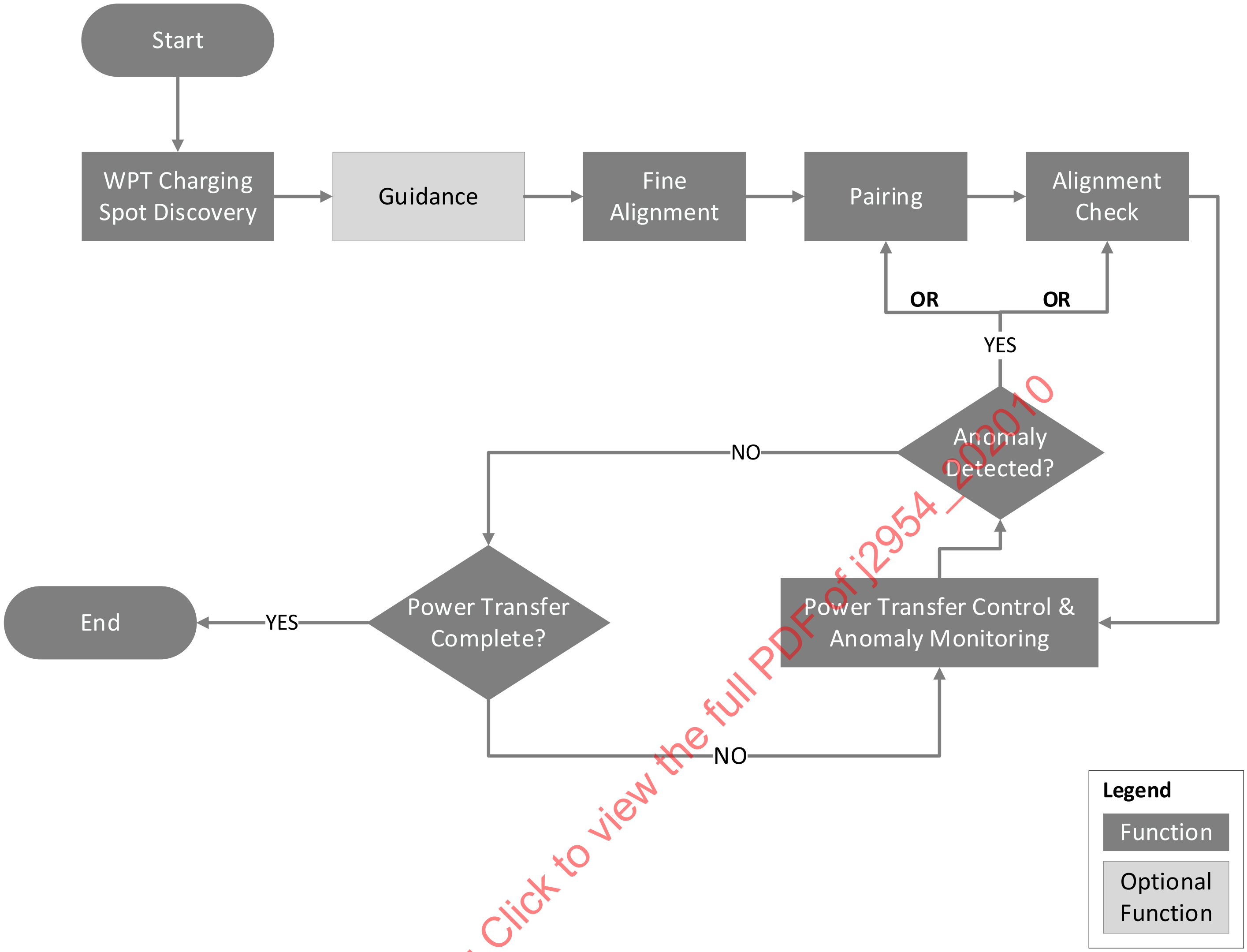


Figure 20 - Wireless charging process flow diagram

12.2 WPT Charging Spot Discovery

WPT charging spot discovery allows a user to locate a WPT location, its capabilities, compatibilities, and availability. Communication supporting this functionality is independent of the charging technology and may reuse general Internet technologies and capabilities. It is not covered by this specification.

12.3 Guidance

Supporting communication capabilities are defined in SAE J2847/6 to facilitate manual or automated positioning of a PEV for optimal power transfer.

Guidance consists of an optional method of providing assistance to the vehicle or driver when farther than 1.5 m to the charging location for navigation into the parking bay/slot.

For guidance, the recommendations are as follows:

a. If guidance is used at distances greater than 1.5 m, it is recommended that such guidance occur at a minimum of 6 m.

b. The accuracy for guidance should be such that the kinematics of the vehicle allow for parking within the alignment tolerance on first approach.

12.4 Fine Alignment

A fine alignment mechanism provides assistance to the vehicle or driver when closer than 1.5 m from the charging location to facilitate centered alignment between the VA coil and the GA coil. When aligned, the VA coil should be within the defined allowed offsets for the WPT system as defined in 8.2.2.

The following are the current minimum requirements for fine alignment:

a. The same minimum common fine alignment method shall be used for all Interoperability Class I GA infrastructure.

b. The GA and VA shall attempt to begin the fine alignment process somewhere between 0.5 to 1.5 m from the centered position of the VA coil and GA coil, or alternatively, when the VA and GA have initiated communication.

c. The final alignment position check shall ensure the VA is within positioning tolerance to a reasonable confidence level (see 8.2.2).

It is possible that the VA may choose to utilize one or more fine alignment methods in conjunction with or instead of the common alignment method. It is not the intention of SAE J2954 to limit vehicle fine alignment methods but rather provide a minimum means for interoperability. For this reason, only the Interoperability Class I GA shall be required to implement a single standardized method of fine alignment as a minimum requirement, but the VA shall be able to either use the common method or another method that will function with installed Interoperability Class I GAs.

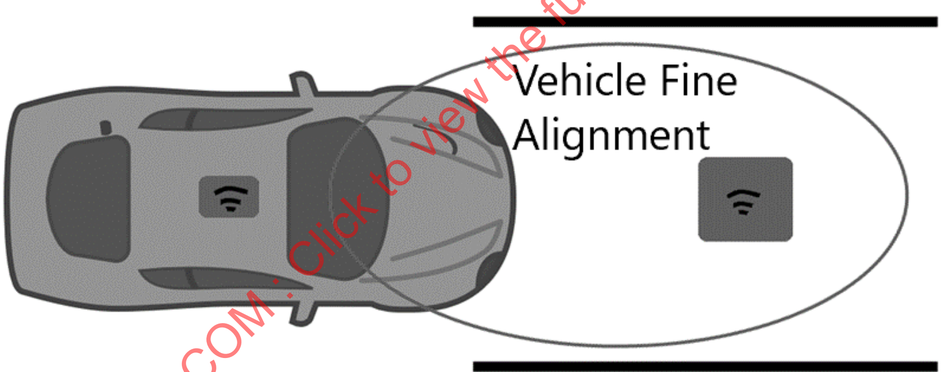


Figure 21 - SAE J2954 vehicle alignment concept

12.4.1 Details of Interoperability for Fine Alignment Method

Prior to fine alignment of the GA and VA coils, vehicle guidance may have optionally been used to assist the driver in finding the appropriate SAE J2954 parking space. By this point in time, appropriate communication information has been exchanged between the VA and GA (including vectors for calculating the natural offset described in 12.4.2).

12.4.1.1 Generalized Fine Alignment Process

- The VA requests the fine alignment method from the GA.
- The driver (or vehicle, if automated) positions the vehicle into the parking spot while the VA monitors positioning conditions.
- The driver puts the vehicle into park. If this position does not appear favorable (see 8.2.2 for position tolerance requirements) from the initial VA position measurements, the driver is notified to reposition the vehicle before power transfer can begin.
- The VA requests the GA to terminate the fine alignment.

12.4.2 Alignment Natural Offset Between Circular- and DD-Topologies

When a circular-topology VA as described in Appendix A is used over a DD-topology GA as described in Appendix H, or a DD-topology VA as described in Appendix G is used over a circular-topology GA as described in Appendix B, a "natural offset" (x_0) has to be set between the VA and GA, as shown in Figure 22. This offset between circular and DD-topology is needed for correct coupling and power transfer. It is unrealistic to have a table of every possible natural offset for every VA and GA; therefore, appropriate vector information is required for the VA to determine the "natural offset" during the guidance and fine alignment processes. To facilitate, it is anticipated that the VA and GA will exchange vector information prior to guidance or fine alignment to determine the natural offset.

The GA shall define one vector (X, Y, Distance) that gives the distance and direction from the GA coil geometric center to the designated axis in which the centered position is achieved with a circular reference VA coil's center point. If the GA coil has multiple possible vectors (such as is the case for the DD-topology) then a single axis is chosen for the designated vector to achieve centered position with a circular reference VA coil. Note that if the GA coil has no natural offset with a reference circular VA coil, then the vector will have zero direction and distance.

The VA shall define two vectors (X, Y, Distance) that gives the distance and direction from the VA coil geometric center to the designated axis in which the centered position is achieved with a circular reference GA coil's center point. One vector is defined for forward movement of the VA and one vector is defined for backward movement of the VA (and they could be the same). Only one of the VA's vectors is transmitted depending on the direction of movement determined by the VA. Note that if the VA coil has no natural offset with a reference circular GA coil, then the vector will have zero direction and distance.

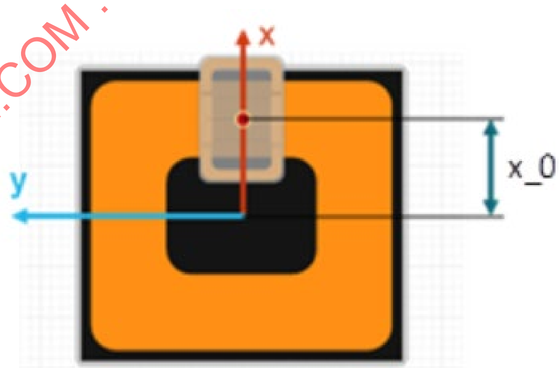


Figure 22 - Example for the "natural offset" definition x_0 for a DD-topology VA over a circular-topology GA

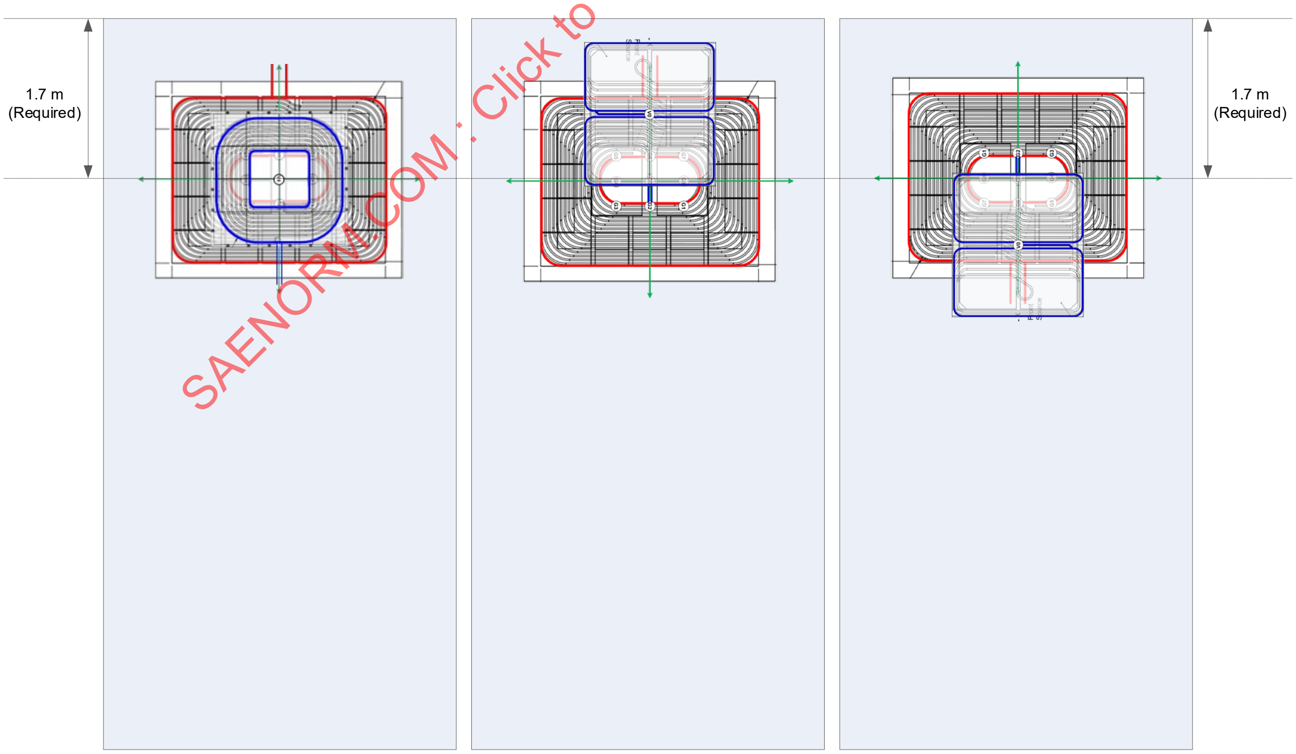
The following values as shown in Table 21 are examples for the systems described in the appendices of this standard.

Table 21 - "Natural offset" (x_0) for the systems as described in the appendices of this standard

Appendix		F	B	H.1	H.2
		WPT1 CR	WPT1-3 CR	WPT2 DD	WPT3 DD
AA.1	WPT1/Z1 CR	X_0 = 0 mm	X_0 = 0 mm		
AA.2	WPT1/Z2 CR	X_0 = 0 mm	X_0 = 0 mm		
AA.3	WPT1/Z3 CR	X_0 = 0 mm	X_0 = 0 mm		
AA.4	WPT2/Z1 CR	X_0 = 0 mm	X_0 = 0 mm	X_0 = 170 mm	
AA.5	WPT2/Z2 CR	X_0 = 0 mm	X_0 = 0 mm	X_0 = 170 mm	
AA.6	WPT2/Z3 CR	X_0 = 0 mm	X_0 = 0 mm		
AA.7	WPT3/Z1 CR	X_0 = 0 mm	X_0 = 0 mm		
AA.8	WPT3/Z2 CR	X_0 = 0 mm	X_0 = 0 mm		
AA.9	WPT3/Z3 CR	X_0 = 0 mm	X_0 = 0 mm		
BG.1	WPT2/Z1 DD	X_0 = 155 mm	X_0 = 190 mm	X_0 = 0 mm	X_0 = 0 mm
BG.2	WPT2/Z2 DD	X_0 = 155 mm	X_0 = 190 mm	X_0 = 0 mm	X_0 = 0 mm
BG.3	WPT2/Z3 DD			X_0 = 0 mm	X_0 = 0 mm
BG.4	WPT3/Z1 DD			X_0 = 0 mm	X_0 = 0 mm
GG.5	WPT3/Z2 DD			X_0 = 0 mm	X_0 = 0 mm
G.6	WPT3/Z3 DD			X_0 = 0 mm	X_0 = 0 mm

NOTE: The above natural offsets are specific examples of known values at the time of issuance of this standard. Blank items above are to be determined and entered in a future version.

The values given in Table 21 are examples based on magnetics only. The "natural offset" which needs to be used in practice may be different because of further consideration of variable frequency and tuning circuit aspects. That means the values as shown in Table 21 may need further fine tuning to achieve power and/or efficiency maximum.



Important: Consider EMF exposure when determining appropriate natural offset!

Figure 23 - Examples of DD and circular coil natural offset conditions

12.4.3 WPT Alignment and Vehicle Automated Driving Systems

SAE J3016 includes taxonomy and definitions for terms related to on-road motor vehicle automated driving systems and refers to levels of automation 1 through 5. The alignment methods and techniques referenced in this standard are recommended for use in assisting with automation of parking, alignment, and charging of on-road automated driving systems for assistance in wireless power transfer.

12.5 Pairing

Pairing aims to validate that the VA coil is positioned above the GA coil intended for power transfer and confirm that the VA is communicating with the same GA it is parked over. If no automated common pairing method is available between the GA and the VA, then the VA shall perform one of two actions:

a. If the VA or GA is capable of automatically identifying the physical pairing uniquely on its own (e.g., unique SSID, automated optical recognition in parking space or vehicle, etc.), then the pairing confirmation shall occur automatically.

b. If no other option is available, at a minimum, the VA (by means of a user interface) shall request "external confirmation." External confirmation is provided when the operator is capable of uniquely identifying the GA over which the vehicle is parked (e.g., by means of signage, SSID, or other unique aspects such as a single parking space).

12.5.1 Generalized Pairing Process

- The VA requests pairing to begin and waits for the modulated signal from the GA.
- The VA and GA perform whatever measurements are deemed necessary during the transmission of the modulated signal to determine correct pairing.
- Based on the measurements during the transmission of the pairing signal, the VA reports the pairing code to the GA and the GA determines if they are appropriately paired. If so, the alignment check process begins.
- If an automated pairing method is unavailable, the VA requests external confirmation from the operator in order to correctly pair the VA with the GA over which the vehicle is parked.

12.6 Alignment Check

Alignment check aims to validate that the VA coil is ready to receive power from the GA coil.

In the case that the GA and the VA do not have another compatible means for alignment check by using external signaling and sensors, the GA and VA shall perform a power check. The power check method assumes that appropriate compatibility parameters have already been exchanged through the SAE J2847/6 communication channel, including the VA coil ground clearance range. Using this information, combined with the power transfer compatibility parameters, the GA and VA can determine if alignment is sufficient to begin full power transfer. During the power check, anomaly monitoring shall also occur to ensure no anomalous behavior which can be associated with misalignment. Power check shall only be used once pairing has been confirmed.

The process for power check is as follows:

- The VA requests the minimum power/current that the GA is capable of delivering (using the previously exchanged compatibility parameters). The VA load (battery) is available to transfer power.
- The GA ramps its GA coil current to its minimum capable level.
- The GA and VA perform measurements to ensure the power level is appropriate based on the compatibility parameters (including VA coil ground clearance).
- The GA and VA perform anomaly monitoring to ensure no anomalous behavior which would indicate misalignment.

- If all initial measurements are within the bounds expected by the GA and the VA, then the VA continues to make appropriate power/current requests to the GA to ramp up power. When the VA is satisfied that the GA is appropriately coupled, then alignment check is confirmed, and power transfer begins from that point.

- If at any point during power ramp up the GA or the VA determines there are anomalous measurements, then the alignment check is reported as a failure.

12.6.1 Generalized Alignment Check Process

- The VA requests the alignment check to begin and provides the necessary information.

- The GA provides the appropriate signaling or measurements and informs the VA of its appropriate parameters and/or their measurements.

- The VA performs appropriate signaling or measurements to determine if the alignment is satisfactory to begin full power transfer.

- The VA reports to the GA whether alignment is satisfactory to begin full power transfer.

13. CONTROL STABILITY AND MONITORING

13.1 Control States of Operation

The following states are considered separately for control stability:

- Pre-negotiation

- Power start-up

- Power shutdown

- Power transfer and optimization

- Error conditions

13.2 Power Transfer Cycle Control

If the alignment is satisfactory, the VA requests power transfer at which point the GA may optionally ramp the current down first or may start from present state of current to reach currents required for power transfer. A key functionality required for efficient power transfer is the capability for the PEV to control the power transfer process. To support this, SAE J2847/6 defines messages that provide the following capabilities:

- Verification of compatibility

- Initiation of a charging cycle

- Control of the GA current/voltage/energy to match the vehicle’s requests

- Modification of the power transfer process in response to external and internal events

- Termination of the charging cycle

13.2.1 Anomaly Monitoring During Power Transfer

During power transfer, the delivered power is coordinated and not expected to change sharply except in the case where the VA or Vehicle removes the load for safety reasons. Unexpected changes in power, current, voltage, efficiency, or other measurements within the GA or VA are considered anomalies.

The VA and GA may independently determine their own definition of a measurement anomaly based upon expected system operation. If the GA or the VA detects an anomaly or a series of anomalies, the GA shall shutdown power transfer immediately and proceed to either the alignment check or pairing states to verify appropriate alignment and/or pairing. If the anomaly is a large and sharp drop in input power detected by the GA, then the GA shall consider that the VA has removed the load for safety reasons and shall immediately terminate power transfer and negotiate next steps over out-of-band SAE J2847/6-compliant communications.

13.2.2 Monitoring of the Charging Process

To ensure that power transfer operates within specified operation and regulatory limits, the PEV may be equipped with various sensors and detectors for critical events. SAE J2847/6 defines messages that allow for the communication of these events so that appropriate action can be taken.

The GA shall have a means to prevent power transmission continuing when the power control program has malfunctioned. This may be accomplished by using a watchdog timer or having a supervisor program for the power control program.

13.2.3 Control Bandwidth/Update Rates and Stability

The GA shall have the means to increase and decrease the delivered power to the VA during power transfer. The GA makes these adjustments by changing the GA coil current to meet the needs of the system. The VA may have its own mechanism of control to optimize power delivery to the vehicle battery system. In the case that the VA has the ability to make changes that affect the power delivery or impedance seen at the GA coil, special considerations shall be made to ensure the control loop on the GA and the control loop on the VA operate in a way that guarantees control criteria for stability.

The GA and VA together form a closed-loop control system. In addition, separate but interacting closed or open-loop control systems may exist on the GA and VA.

To ensure stability during pre-negotiation, the following criteria shall be met:

- The GA and VA shall follow the pre-negotiation protocol defined in J2847/6 to ensure operational compatibility of the GA and VA as well as to negotiate power transfer parameters.

The VA sets the power ramp conditions by communicating the desired power from the GA. To ensure stability during power start-up, the following criteria shall be met:

- The power shall ramp at a rate no less than 0.25 kW/s and no greater than 2 kW/s.

- If the VA is capable of making adjustments on its own that affect power delivery or the impedance seen at the GA coil, the changes shall not result in power delivery changes that exceed the above ramp-up and ramp-down rates. The VA shall only request changes in power delivery during start-up once its own control adjustments are complete.

To ensure stability during power transfer, the following criteria shall be met:

- The GA shall ramp power at a rate no less than 0.25 kW/s and no greater than 2 kW/s when a change in power is requested by the VA.

- The GA shall update its power control parameters that are capable of changing the GA coil current at a rate of at least 500 Hz or greater to ensure power delivery is constant when the impedance at the GA coil changes due to changes caused by the VA electronics.

- If the VA is capable of adjusting power or impedance seen at the GA coil, the VA shall update its power control or impedance control parameters at a rate less than or equal to 50 Hz to ensure the GA can appropriately compensate for the resultant impedance changes before further VA impedance changes occur.

- All changes in GA coil current shall result in a condition that guarantees no more than 10% overshoot. Whenever possible, the GA coil current changes should result in an overdamped condition.

- Under constant loading conditions, all changes by the VA shall result in a condition that guarantees no more than 10% overshoot of power delivery to the vehicle battery system.

During power shutdown, the following criteria shall be met:

- The power shall ramp down at a rate of 2.5 kW/s or more during power shutdown (i.e., power request to 0 kW).

During Error Conditions, the following criteria shall be met:

- The VA shall protect itself from damage and may operate at any update rate necessary to do so.
- The GA shall be capable of decreasing its GA coil current to stop power transfer and shall meet the criteria for 13.2.1.
- In the event that the VA communication is lost for more than 2 seconds, the GA shall ramp down its GA coil current to stop power transfer within 4 seconds from the loss of communication.
- An emergency shutdown shall occur when a system anomaly is detected or a critical system malfunction has occurred. The GA shall ramp down its GA coil current and stop power transfer within 1 second of an emergency shutdown.
- In all error cases, the GA coil current shall remain low enough to meet EMF limits specified in Section 10, directly above the GA coil (as if no VA were present) when no power transfer is occurring.

13.2.4 Frequency Modification During Charge Cycle/Power Transfer

See 6.4.2 for frequency adjustment requirements.

14. SAE J2954 PARKING SPACE

14.1 Location of GA coil Center Point in SAE J2954 Parking Space

This Section 14 applies specifically for Interoperability Class I GAs and may be used as a reference for the location of Class II GAs as well. SAE J2954 specifies a single position for the geometric center of the GA coil in a parking space; however, it is recognized that these recommendations cannot be enforced. See Figure 24.

The reference datum point (0,0) used for measurements is at the inner edge of the parking lot line in the front of the parking space on the Y-axis center line.

The geometric center of the GA coil is shown in Figure 24. There shall be visible marks on the GA to indicate the X and Y axis of the geometric center of the coil for installation. The X and Y position GA markings shall be located on each edge.

The geometric center of the GA coil shall be 1.7 m from the datum point (front of parking space) and shall be located on the centerline in the parking space.

The geometric center of the GA coil shall have an installation tolerance of ±0.01 m in the X axis.

The geometric center of the GA coil shall have an installation tolerance of ±0.01 m in the Y axis.

The recommended length of an SAE J2954 parking space is 6 m.

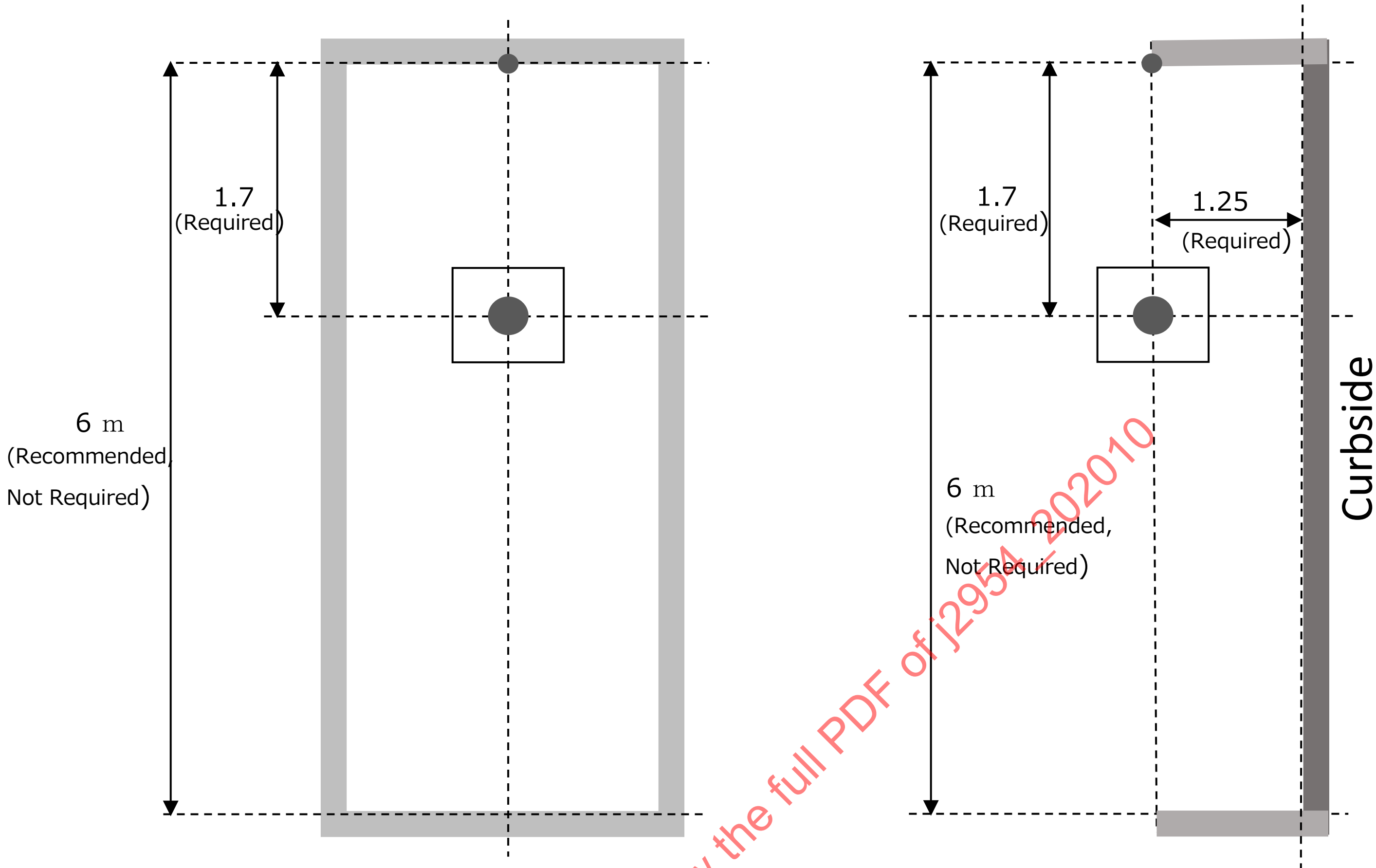


Figure 24 - SAE J2954 GA geometric center location diagram

NOTE: The centerline for handicapped parking spaces is based on the actual parking stall and not the extra space available for entry/exit around the vehicle.

14.2 SAE J2954 Parking Space Parking Direction and Visual Cues

The SAE J2954 parking space shall allow a vehicle to drive forward into the space unless the requirements of the parking space dictate otherwise. The SAE J2954 parking space shall also facilitate additional visual alignment cues where possible.

14.3 SAE J2954 Parking Space Markings

It is helpful to designate SAE J2954 parking spaces for interoperable charging. The following figures show the recommended signage to be used for designating an SAE J2954 parking space. See Figure 25.

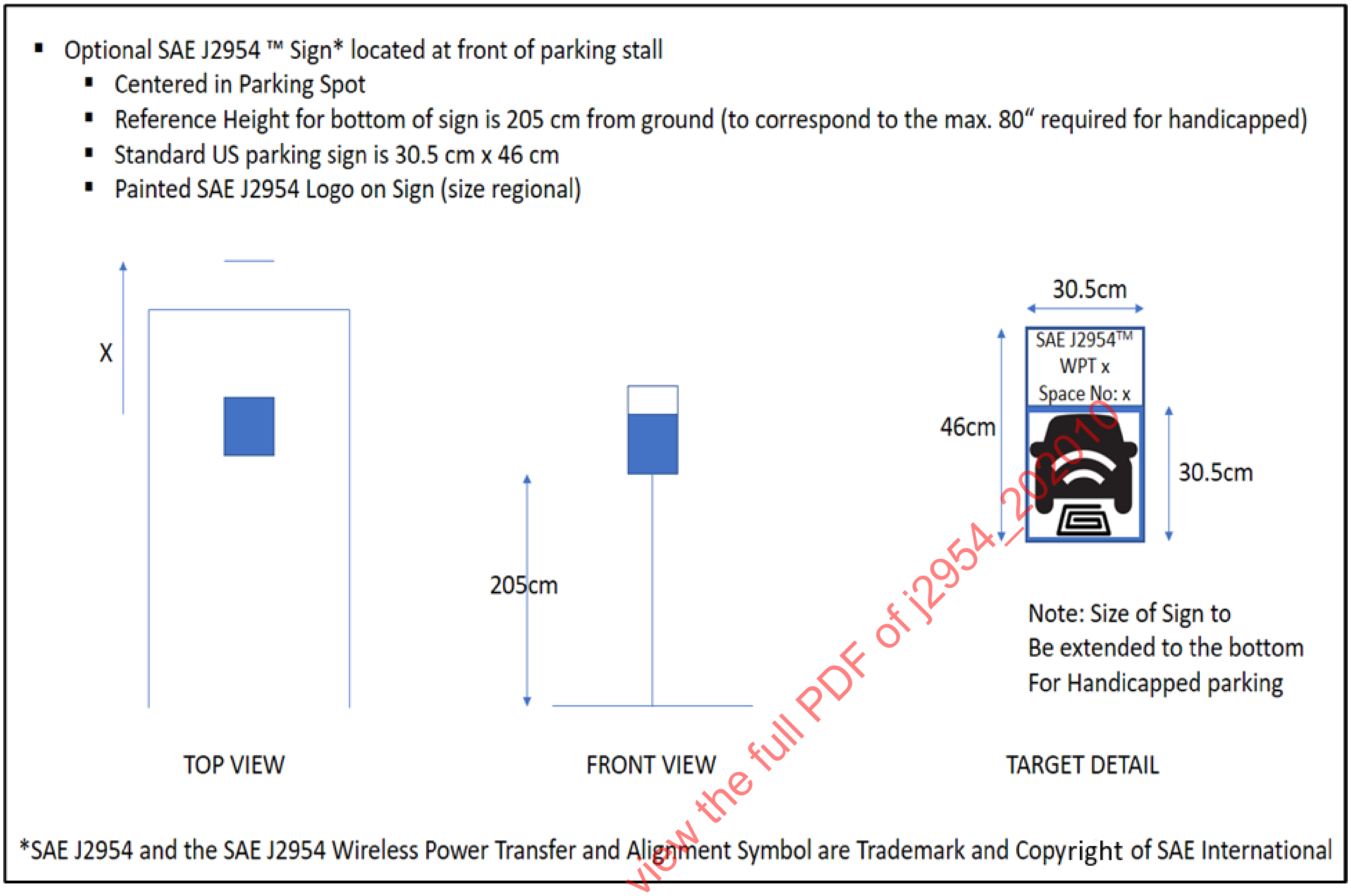


Figure 25 - SAE J2954 wireless charging identification markers

15. PERFORMANCE TESTING

Performance testing appears in various sections of this standard:

- Requirements for specific performance related to power transfer are given in Section 8
- EMC testing appears in Section 9
- EMF testing appears in Section 10
- Power transfer testing is covered in 15.1
- Performance relative to safety is covered in Section 16

As listed in 8.2, testing for Product GAs and Product VAs is performed against SAE J2954 Test Station devices. Because of the need to change relative positions of the GA and VA and to change other test conditions during these tests, they are most conveniently done at a component level on a test station.

Testing of other functions such as some aspects of communication and alignment (Section 12) and live object protection (Section 16) are performed at a vehicle/system level.

15.1 Power Transfer Testing

The procedures in Section 15.1 are intended to support the requirement that the vehicle side components of any SAE J2954-compliant system be interoperable with the infrastructure side components of any SAE J2954-compliant system. This section addresses both component-level testing for power transfer and vehicle-level testing with regards to power transfer.

SAE J2954 has established normative Test Station VAs for WPT1, WPT2, and WPT3 (Appendix A) and a normative Test Station GA (Appendix B) against which Product GAs and Product VAs shall meet the power transfer performance requirements established in Section 8. All such Product VAs and GAs shall be tested for performance and safety with Test Station devices as described in Section 8, even if they are presented as a system from the same manufacturer.

During testing, whether at the component or vehicle level, consideration should be given to electromagnetic safety, as described in 10.9.

15.1.1 SAE J2954 WPT Test Station

The SAE J2954 Test Station enables X and Y offsets and Z-gap variations for power transfer performance testing. It can also be used for EMC and EMF testing. The ideal test station has an X, Y, and Z positioning mechanism which is capable of 1 mm precision, as well as provision for testing roll, pitch, and yaw. Any of the above offset positions may be achieved by moving the GA or the VA. Since process efficiency during test is important, the positioning mechanism should be automated, but that is not required.

The materials for the test station frame, including any supporting mechanisms, shall be non-metallic except for the devices being tested and the shield and vehicle mimic. All other metallic materials should be kept below the plane of the base of the GA coil or above the mimic plate.

If the test station is being used for EMC testing, it should be on a metal turntable.

Figure 26 shows an example of an SAE J2954 WPT Test Station.

The WPT Test Station GA consists of GA electronics driving a GA coil and a GA Communications Module. The GA electronics and the GA coil are represented as the power transfer functions within boxes 12 and 11 of Figure 1; the GA communications module is represented by the communication functions within boxes 12 and 13.

The WPT Test Station VA consists of a VA coil connected to VA electronics and a VA communication module. The VA coil and the VA electronics are represented as the power transfer functions within boxes 21 and 22 of Figure 1; the VA communication module is represented by the communication functions within boxes 22 and 23 along with a vehicle CAN bus simulator.

A Product GA or a Product VA would comprise these same elements, including the communication function.

The shield is used to protect ferrous materials (such as a steel underbody) from the heating effects of the magnetic fields that are not captured by the VA resonator. Since the fields are generated by the GA resonator, the design and size of the GA resonator is a principal determining factor in the optimal shield size. However, the vehicle may not be able to accommodate the optimal shield size, and a specific vehicle application may require a shield that is smaller.

For GA testing using the normative Test Station VAs, the aluminum shield to be used is specified in the appendix for that specific VA. The shield to be used when using the test station with a Product VA shall be specified by the manufacturer and should be the size and contour (if possible) of the shield that will be used when mounting the VA to the vehicle.

Because it is possible that the shield size may not capture the stray fields from the GA, either because of the GA size or shape or because the shield size possible for a given Product VA is small, heating of the steel mimic plate might occur. Therefore, when testing, the mimic plate in the test station shall be monitored for excess heating while testing.

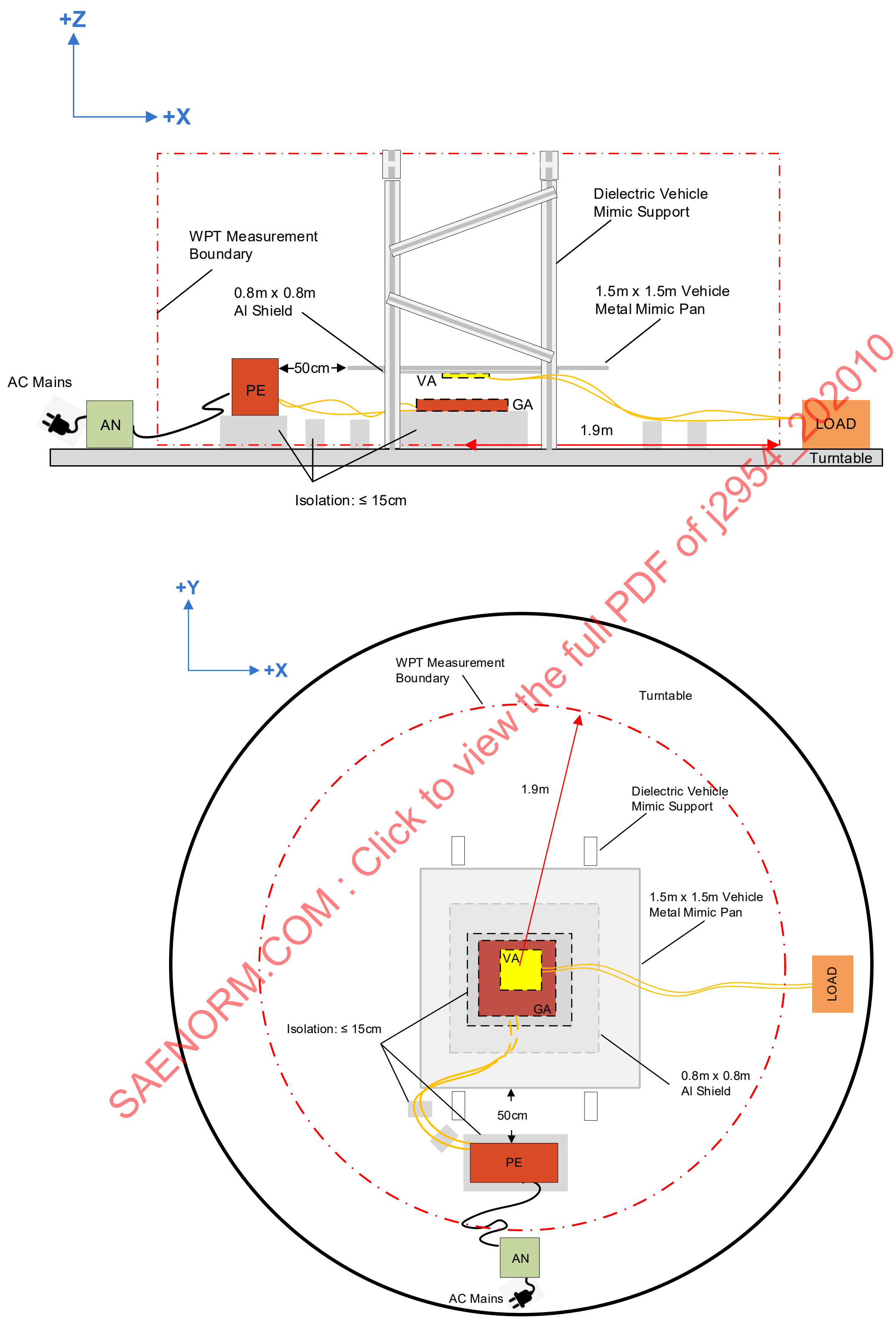


Figure 26 - SAE J2954 WPT Test Station

15.1.2 Component Power Transfer Test for Product VA

As described in 8.2.1.1, the Product VA is tested against the normative GA from Appendix B in conjunction with the GA communication module. The manufacturer of the Product VA specifies the aluminum shield size and shape; for most accurate results, the shield specified should be as close to the size and shape of the actual shield to be used when installed on the vehicle.

The VA output goes to a DC load as a replacement for the battery system of the actual vehicle. Communication shall be active, and enablement of the conditions that would otherwise be available from the vehicle (CAN signals, for example) shall be possible. Testing which simulates the various critical steps in the control sequence described in Figure 20, including charging control, shall occur to ensure safe and proper operation and to confirm non-operation in those cases when the compatibility check is not valid.

On the GA side, communication shall be active and able to simulate the handshake and the various critical steps in the control sequence described in Figure 20, including charging control, to ensure safe and proper operation/non-operation. Power transfer system efficiency tests shall be made at nominal input voltage as described in 8.2.8.1.

15.1.3 Vehicle Test for Product VA

While component test is more convenient, a vehicle test can instead be performed to determine conformance of a Product VA. A vehicle test would give more accurate power transfer results, but control of the test conditions will be more difficult: the state of charge (SOC) of the battery will be constantly changing and while the actual CAN signals will be available, they might not be easily controllable to simulate the necessary test conditions. A mechanism for rapid restoration of the SOC to a low level (low output voltage) should be provided for test efficiency.

The Product VA being tested should be installed as intended as a product, using the intended shield. Temperature monitoring of the vehicle underbody should be considered by the manufacturer.

The positioning offsets in X, Y, and Z can be accomplished with movement of the GA for X and Y and spacers under the wheels and/or the GA for Z adjustments.

15.1.4 Test for Product GA

As described in 8.2.1.2 and 8.2.1.3:

An Interoperability Class I GA is tested against each of the normative VAs in Appendix A using the VA communication module for control.

An Interoperability Class II GA is tested against normative VAs within the specified GA ground clearance range in Appendix A along with the VA communication module, as well as the specific VAs it is meant to work with.

15.1.4.1 Interoperability Class I Product GA

Testing a Product GA is to be done using a test station. Communication shall be active and enablement of the conditions that would otherwise be available from the vehicle (CAN signals, for example) shall be possible. Testing which simulates the various critical steps in the control sequence described in Figure 20, including charging control, shall occur to ensure safe and proper operation and non-operation.

Power transfer system efficiency tests shall be made at nominal, low and high input voltage, as described in 8.2.8.2.

15.1.4.2 Interoperability Class II Product GA

Testing a Product GA is to be done using a test station. Communication shall be active and enablement of the conditions that would otherwise be available from the vehicle (CAN signals, for example) shall be possible. Testing which simulates the various critical steps in the control sequence described in Figure 20, including charging control, shall occur to ensure safe and proper operation or non-operation.

Power transfer system efficiency tests shall be made at nominal, low and high input voltage, as described in 8.2.8.3.

15.1.5 Coordinate System

The coordinate system used for definition and testing should utilize the three-dimensional reference system as defined by ISO 4130.

where:

X = positive in the reverse direction

Y = positive to the right side

Z = positive in the upward direction

X, Y = 0,0 is defined by the centered position of the GA coil

Z = 0 is defined by the surface of the ground

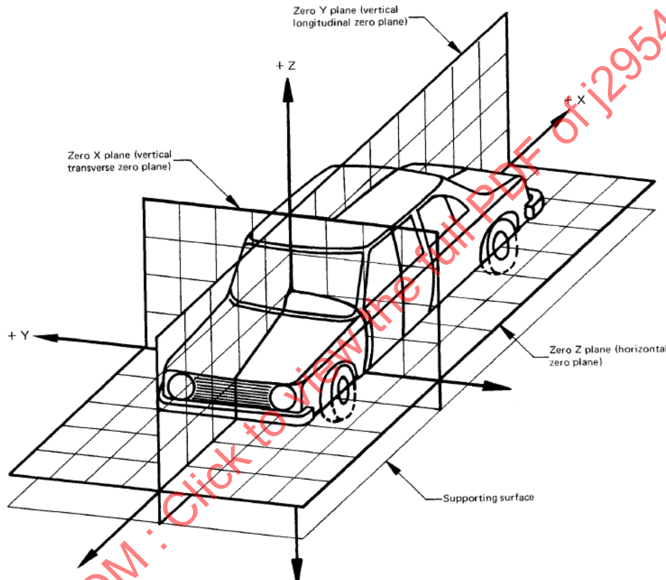


Figure 27 - ISO 4130 three-dimensional reference system vehicle coordinate system

15.1.6 Test Environment

Test station and vehicle-level testing shall, for the purpose of 15.1, be conducted at an ambient temperature of 20 °C ± 5 °C throughout the set up and testing process (environmental tests are not covered in this section at this time). The air speed of the room shall not exceed 0.5 m/s near the test sample, and no additional cooling or ventilation shall be provided for the test sample unless specified by the manufacturer or required for safety.

The grounding of equipment shall be set up to prevent the possibility of RF shock or burn caused by touching equipment having RF potential. If metallic WPT equipment is isolated from ground and accessible to personnel, the maximum human body grounding current shall be assessed. The line frequency and RF currents shall be within the limits in UL 2594, and shall be verified accordingly.

15.1.7 System Efficiency Test Procedure

System efficiency shall be determined by measuring the power from the AC grid into the GA electronics and measuring the DC power out of the VA electronics, which feeds the battery system and essential auxiliary loads. Non-essential auxiliary loads should not be considered. System efficiency is the ratio of output power to input power, expressed as a percentage.

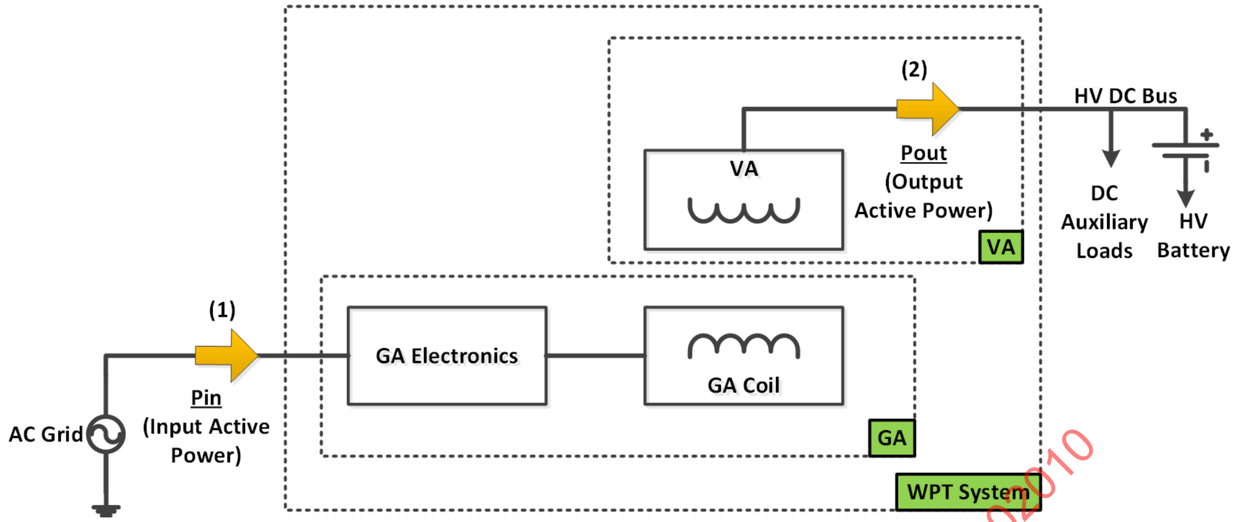


Figure 28 - Block diagram of a WPT system (including VA and GA) illustrating the efficiency points (1) and (2)

15.1.7.1 SAE J2954 System Efficiency Test Conditions

The specific test requirements are dependent on the device being tested, and in the case of a Product VA, on manufacturer specifications. AC grid power shall be provided as listed by the GA specification. The GA might be either a Product GA or a Test Station GA.

Input power shall be measured at the input to the GA electronics with appropriate test equipment. Refer to IEC 61000-3-7.

Output load voltage and power shall be specified as appropriate for the specific test configuration.

An Interoperability Class I GA shall be tested with all of the VAs from Appendix A (SAE WPT Test Station VAs), over the full Z range as specified in Table 2 and the three reference battery voltages of 280 V, 350 V, and 420 V, with an equivalent series load resistance of 0.15 Ω.

An Interoperability Class II GA shall be tested over the specified Z range of that GA with the VAs from Appendix A (SAE WPT Test Station VAs) which cover that Z range at the three reference battery voltages of 280 V, 350 V, and 420 V, with an equivalent series load resistance of 0.15 Ω.

When testing Product VAs, the Z range and the output voltage range shall be specified by the VA manufacturer.

Coil alignment shall include all required offsets in X and Y, in increments of no more than 50% of the maximum offset in that direction. Z offsets shall be at the minimum, the maximum, and the midpoint, as specified by the manufacturer if a Product VA is being tested, or as specified in Table 2 for the Z class of the Appendix A VA being used.

In addition to the offset limits in X, Y, and Z, system efficiency tests shall include testing for rotational misalignment. Roll is the rotation of the vehicle around the X axis, pitch is the rotation of the vehicle around the Y axis, and yaw is the rotation of the vehicle around the Z axis. Testing of roll, pitch, and yaw shall be performed at the centered alignment position (X and Y) at maximum roll, pitch, and yaw as specified. If the test is a test-station test, Z should be at the mid-range position; if the test is a vehicle test, Z should be as the vehicle presents.

Position tolerance is ±1.0 mm for linear dimensions and less than ±0.5 degree for angular dimensions.

System efficiency tests shall be run only after the system has warmed up (a minimum of 5 minutes at full power) and the system temperature is stable. Ambient temperature shall be 20 °C ± 5 °C. Temperature stability should be determined by measuring the surface temperature of the GA using a thermocouple or another contact method, or by an IR camera; the accuracy of the thermal camera should be confirmed using a thermocouple or other contact method.

15.1.7.2 System Efficiency Requirement

For all conditions of X, Y, Z, and rotational offsets:

- For Product Vas, the requirements in 8.2.8.1 apply.
- For Class I Product Gas, the requirements in Table 8 apply.
- For Class II Product Gas, the requirements in Table 9 apply.

Table 22 - Sample system efficiency test form

Test No.	Z POS	X POS	Y POS	Roll/Pitch/Yaw	PWR Factor	P In	P Out	EFF	Mimic Temp

15.1.7.3 Surface Temperature

During all the test station and vehicle tests, the temperature of accessible surfaces of the functional units shall be monitored to ensure that they are compliant with UL 2750 maximum surface temperature levels.

16. SAFETY VERIFICATION

Performance testing is designed to measure how well units work. Safety testing is meant to ensure units do not transfer power if it is unsafe to do so. Safety verification must occur prior to the start of power transfer and also during power transfer.

16.1 Safety Verification Prior to Power Transfer

Communication, as described in Section 12, shall be verified to work, and those systems which are not designed to be compatible or fail the compatibility check state, cannot move to the next state nor eventually to power transfer.

After compatibility has been confirmed, the system must also pass the alignment check to ensure that the vehicle is positioned within the alignment tolerance zone.

Resultant behavior of the WPT system shall be checked to ensure that actions, including safety verification, are consistent with SAE J2847/6 messages.

16.2 Safety Verification During Power Transfer

In the event that power transfer is interrupted, the system shall not automatically restart unless it is manually restarted, or the safety systems associated with WPT verify that it is safe to restart automatically.

16.2.1 Safe Operation with Respect to Metallic Foreign Objects

Safe operation with respect to metallic foreign objects is primarily the responsibility of the infrastructure side components of the system. Therefore, this testing is done using a candidate Product GA and either a Test Station VA or an SAE J2954 Product VA.

The potential hazards with metallic foreign objects fall into three areas:

- Metallic object becomes hot enough to damage the surface with which it is in contact and, as a result, creates an electrical thermal issue. For example, an object on the GA surface might get hot enough to damage the surface and expose components which could be dangerous.

- Metallic object is heated to a temperature that is dangerous to touch at the time that the object becomes accessible. Accessibility could happen after the vehicle leaves the charging spot or if someone reaches under the vehicle. The maximum temperature that an object reaches is not a sufficient test criteria; if the heat capacity of the object is small enough, by the time the object becomes accessible it may have cooled to a temperature below the touch threshold.

- Metallic object in contact with a flammable item becomes hot enough and contains enough thermal energy to cause ignition of the flammable item.

One approach is to control the characteristics of the magnetic fields through the GA coil design such that dangerous temperatures cannot occur.

Another approach is to use a FOD system to detect objects and cause the system to take action, such as shutting down power transfer if already running, or preventing the system from starting power transfer if detection occurs before power transfer has started.

16.2.1.1 Test Requirements and Considerations

Whether GA coil design or a FOD system is used, the following are the requirements:

- Objects shall not be above touch hazard temperature when a person is able to touch that object.

- Any damage to the GA surface shall not create a safety hazard.

- Objects shall not cause ignition.

16.2.1.2 Test Objects

Table 23 lists the required objects that shall be used to verify the safety of the system against heating of foreign objects.

Due to the fact, a list of possible objects is infinite in length, a set of test objects is provided which will ensure a minimum FOD capability. Additional test objects can be tested but are not required in order to certify the Product GA as safe under this standard. These test objects have been selected because they are appropriate to prevent the hazards mentioned above, are readily available and allow repeatability of results independent of what facility is performing the tests while keeping the number of objects at a reasonable level.

This list was developed through an SAE risk analysis which considered likelihood of occurrence and severity of failure to detect.

Table 23 - Table of test objects

Item	Sample Objects	Temp Rise	Ignition Test	Alignment of test object at H_{max}	Notes
1	Paper stack with paper clip		X	Largest parallel field	Five sheets 20lb paper at least 2 inches square attached to a steel wire paper clip approximately 1.25 inches long. Location and orientation should refer to the paper clip. Stack is assumed to be lying flat on the surface.
2	Foil with paper backing		X	Largest perpendicular field	2 x 4 inches, similar to chocolate bar wrapper or cigarette foil material. Lying flat on the surface.
3	Coins	X		Largest perpendicular field	U.S. 5¢ coin.
4	Nail	X		Largest parallel field	10d common steel, uncoated.
5	Aluminum foil	X		Largest perpendicular field	2 to 3 inch square or circular piece 0.002 to 0.010 inch thick.
6	Steel bar	X		Largest perpendicular field and largest parallel field	4 x 2.75 x 0.4 inches lying flat on the surface.

16.2.1.3 Test Procedure without a FOD System

The actual procedure for a given implementation is highly dependent on the specific implementation of the GA coil. The manufacturer of the GA coil must specify and mark the location and orientation of the strongest magnetic field component parallel to the surface of the GA coil package or perpendicular to the GA coil package with a VA which produces that largest magnetic field component. This location and orientation are to be noted as "H_{Max}."

The GA and the VA shall be arranged such that the Z height and the X/Y offset are those that create H_{Max}. If there are multiple positions which create H_{Max}, choose the position which gives the greatest accessibility to the GA coil package surface so that test objects may be placed most easily and accurately.

16.2.1.3.1 Test Object in Place Before Power Transfer

Place the first ignition test object on the GA coil package surface at the H_{Max} location with the longest dimension of the metallic portion of the test object along the H_{Max} orientation. Turn on power transfer to full power and maintain that level for 10 minutes. Repeat with the other ignition test object. If ignition does not occur this test is passed.

16.2.1.3.2 Test Object Introduced During Power Transfer

This test will use the four temperature rise test objects.

Turn on power transfer to full power and maintain that level during each of the tests. With full power being transferred, place the test object in the H_{Max} position and orientation (longest dimension of the test object aligned with H_{Max}). Let power transfer continue for 5 minutes, at which time quickly remove the test object and measure its temperature.

If less than 80 °C, that object at that position has passed. If greater than 80 °C, measure the temperature at 30 seconds after removal and 60 seconds after removal. If the temperature of the test object 60 seconds after removal is less than 80 °C, the test is passed.

If the test object is more than 80 °C at 60 seconds or if there was damage to the GA surface, the test is failed.

Rotate through test objects to give the heated object time to cool back to ambient before using it again. Repeat with the test object placed at a random position.

16.2.1.4 Test Procedure with a FOD System

The actual procedure for a given implementation is highly dependent on the specific implementation of the GA coil and the FOD system. The manufacturer of the GA coil must specify and mark the location and orientation of the strongest magnetic field parallel to or perpendicular to the surface of the GA coil package with a VA which produces that largest magnetic field component. This location and orientation are to be noted as "H_{Max}."

The manufacturer shall specify the location on the surface of the GA coil package where the probability of non-detection of the test object is the greatest. If there is more than one such location, the three with the highest probability of non-detection shall be specified and notated as D_{Min1}, D_{Min2}, and D_{Min3}. If there is a directional component to the detection sensitivity, that shall also be specified.

The GA and the VA shall be arranged such that the Z height and the X/Y offset are those that create H_{Max}. If there are multiple positions which create H_{Max}, choose the position which gives the greatest accessibility to the GA coil package surface so that test objects can be placed most easily and accurately.

16.2.1.4.1 Test Object in Place Before Power Transfer

a. Place the first ignition test object on the GA coil package surface object at the H_{Max} location with the longest dimension of the metallic portion of the test along the H_{Max} orientation. If power does turn on, increase to full power, and maintain that level for 10 minutes unless object is detected. Repeat with the other ignition test object. If the test object was detected or if ignition does not occur, this test is passed.

b. Place the first temperature rise test object at D_{Min1}; if an orientation sensitivity was specified, align the test object longest dimension in the orientation which will be most difficult to detect.

   Turn on power. If FOD system is activated and prevents the start of power transfer, this test with this object is passed. Repeat with the next test object.

   If power does turn on, increase it to full power. Let it run at full power for 5 minutes or until the FOD system is activated and turns off power. Remove the test object and measure its temperature; if less than 80 °C, that object at that position has passed.

   If greater than 80 °C, measure the temperature at 30 seconds after removal and 60 seconds after removal. If the temperature at of the test object 60 seconds after removal is less than 80 °C, the test is passed.

   Repeat with the other temperature rise test objects.

16.2.1.4.2 Test Object Introduced During Power Transfer

If there is a test mode which indicates FOD without actually initiating power shutdown, that mode may be used to make testing more efficient, except that the first two FOD detection tests must be performed such that power is actually shut down.

This test will use the four temperature rise test objects.

a. Turn on power transfer to full power and maintain that level during each of the tests. With full power being transferred, place the test object in the H_{Max} position and orientation (longest dimension of the test object aligned with H_{Max}). Let power transfer continue for 5 minutes or until the FOD system is activated, at which time quickly remove the test object and measure its temperature.

   If less than 80 °C, that object at that position has passed. If greater than 80 °C, measure the temperature at 30 seconds after removal and 60 seconds after removal. If the temperature of the test object 60 seconds after removal is less than 80 °C, the test is passed.

   If the test object is more than 80 °C at 60 seconds or if there is damage to the GA coil package surface, the test is failed.

   Rotate through test objects to give the heated object time to cool back to ambient before using it again

b. With full power being transferred, place the first test object in a random position and orientation. Let power transfer continue for 5 minutes or until the FOD system is activated, at which time quickly remove the test object and measure its temperature.

If less than 80 °C, that object at that position has passed. If greater than 80 °C, measure the temperature at 30 seconds after removal and 60 seconds after removal. If the temperature of the test object 60 seconds after removal is less than 80 °C, the test is passed.

If the test object is more than 80 °C at 60 seconds or if there is damage to the GA coil package surface, the test is failed.

Rotate through test objects to give the heated object time to cool back to ambient before using it again.

c. With full power being transferred, place the first test object at D_{Min1} with orientation for highest probability of non-detection. Let power transfer continue for 5 minutes or until the FOD system is activated, at which time quickly remove the test object and measure its temperature.

If less than 80°C, that object at that position has passed. If greater than 80 °C, measure the temperature at 30 seconds after removal and 60 seconds after removal. If the temperature of the test object 60 seconds after removal is less than 80 °C, the test is passed.

If the test object is more than 80 °C at 60 seconds or if there is damage to the GA coil package surface, the test is failed.

Rotate through test objects to give the heated object time to cool back to ambient before using it again.

d. With full power being transferred, place the first test object at D_{Min2} with orientation for highest probability of non-detection. Let power transfer continue for 5 minutes or until the FOD system is activated, at which time quickly remove the test object and measure its temperature.

If less than 80 °C, that object at that position has passed. If greater than 80 °C, measure the temperature at 30 seconds after removal and 60 seconds after removal. If the temperature of the test object 60 seconds after removal is less than 80 °C, the test is passed.

If the test object is more than 80 °C at 60 seconds or if there is damage to the GA coil package surface, the test is failed.

16.2.2 Live Object Protection

Informative Appendix C details a guideline regarding a possible testing approach for live object protection.

17. DURABILITY

Component and vehicle system durability shall comply with the most recent, applicable UL 2750, as well as SAE J1211 specification, which applies specifically to the vehicle and its on-vehicle components. SAE J1211 describes the durability of the components based on dynamic testing.

During test station and vehicle testing, the GA and VA coil packages shall be compliant with SAE J2954 and UL 2750 definitions of allowable surface temperature levels in order to promote operator safety.

18. NOTES

18.1 Revision Indicator

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this standard. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY THE SAE HYBRID - EV COMMITTEE

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APPENDIX A - TEST STATION VA SPECIFICATIONS (NORMATIVE)

A.1 TEST STATION VA WPT1/Z1

This appendix provides the mechanical and electrical design specifications of the Test Station VA for power class WPT1 and gap class Z1 (VA WPT1/Z1).

NOTE: Specifications designed for optimal operation with the Test Station GA WPT1 specified in Appendix F.

A.1.1 MECHANICAL SPECIFICATION

Figures A1, A2, A3, and A4 show the mechanical dimensions of the Test Station VA WPT1/Z1.

The ferrite tiles are made using PC95 (TDK).

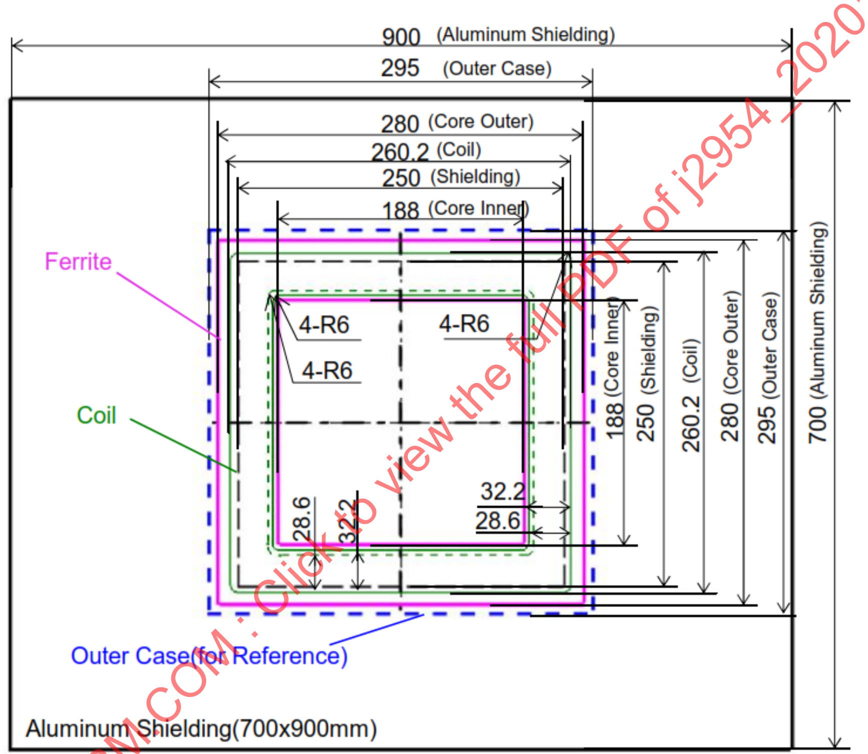


Figure A1 - Mechanical dimensions of the Test Station VA WPT1/Z1

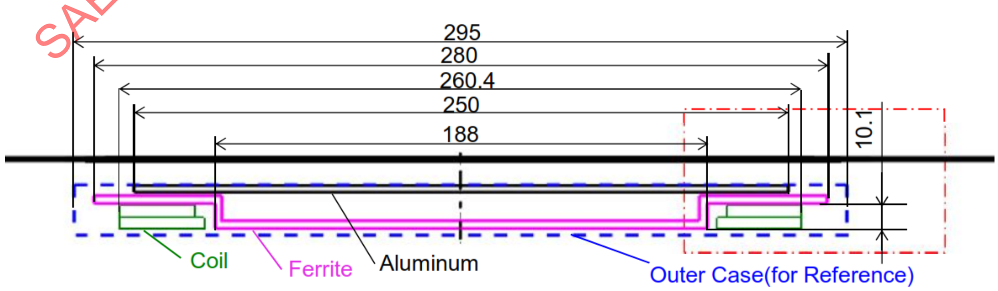


Figure A2 - Mechanical dimensions of the Test Station VA WPT1/Z1

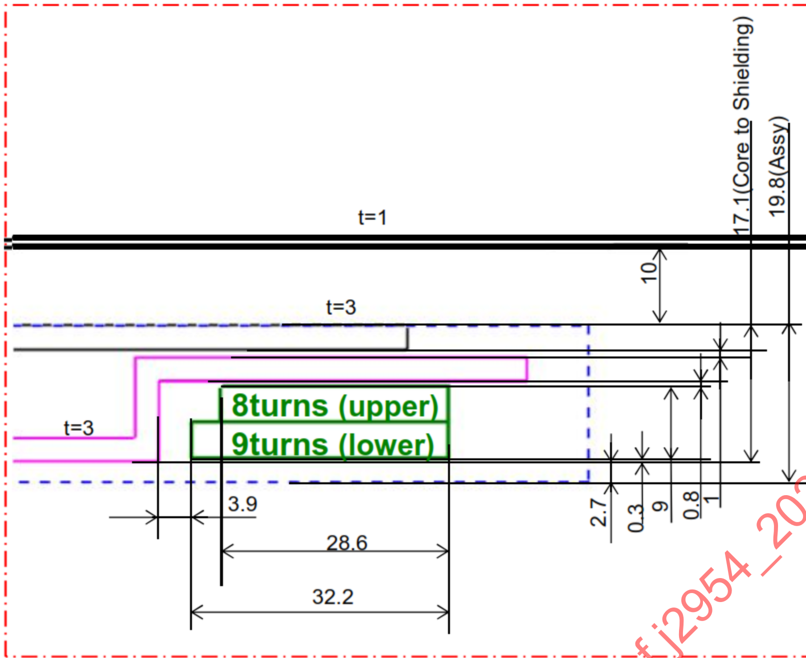


Figure A3 - Detailed cross section view

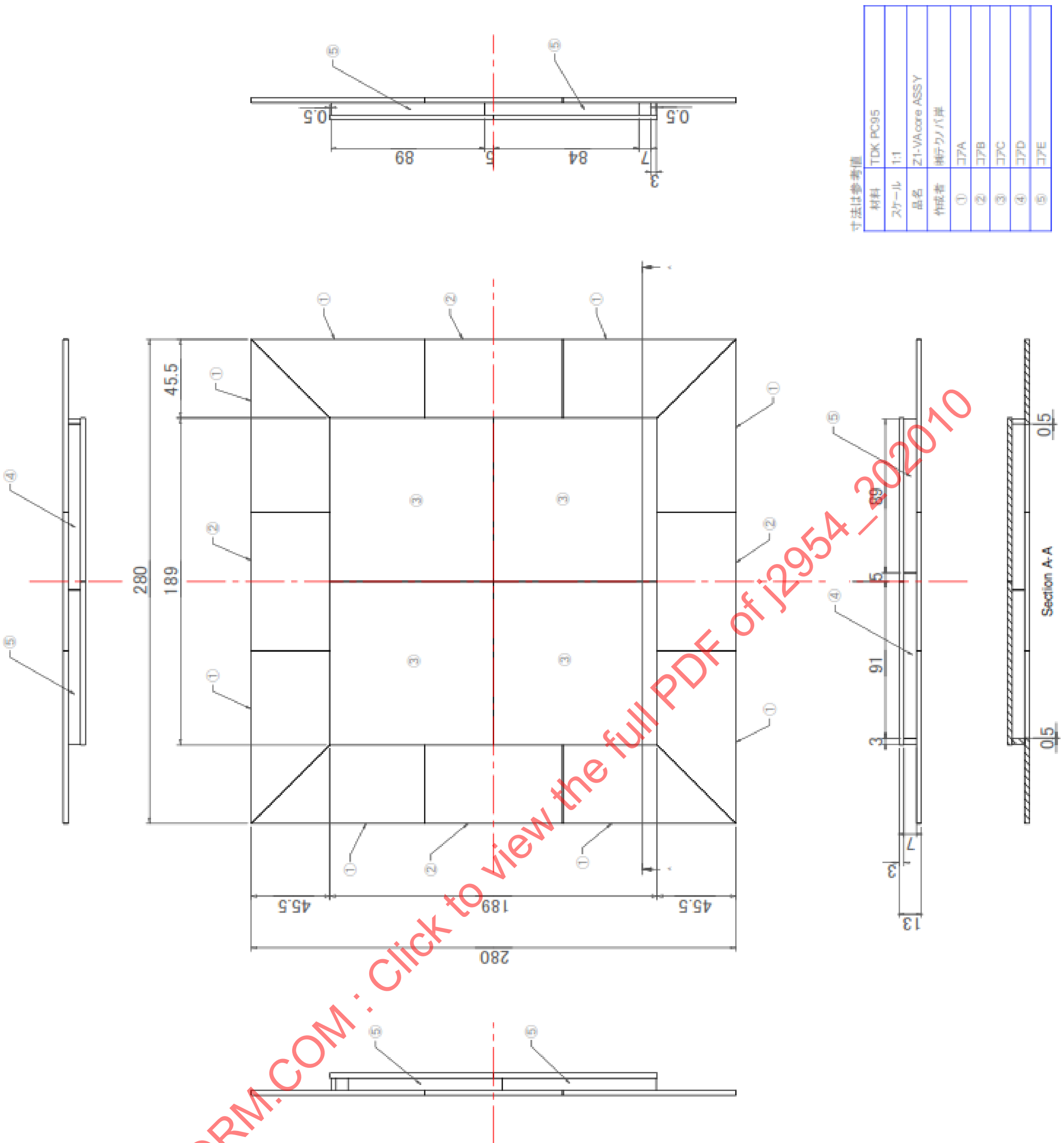


Figure A4 - Detail of the ferrite core construction

A.1.2 ELECTRICAL SPECIFICATION

Figure A5 shows the electrical specification of the of the Test Station VA WPT1/Z1.

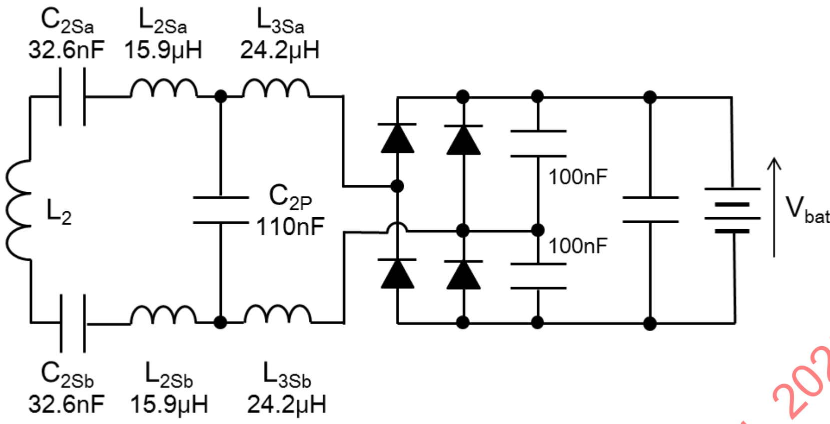


Figure A5 - Electrical specification of the Test Station VA-WPT1/Z1

The minimum and maximum inductance are given in Table A1.

Table A1 - Inductance

L_2 min	214 µH
L_2 max	232 µH

A.2 TEST STATION VA WPT1/Z2

This appendix provides the mechanical and electrical design specifications of the VA for power class WPT1 and gap class Z2 (VA WPT1/Z2).

NOTE: Specifications designed for optimal operation with the Test Station GA WPT1 specified in Appendix F.

A.2.1 MECHANICAL SPECIFICATION

Figures A6, A7, A8, and A9 show the mechanical dimensions of the Test Station VA WPT1/Z2.

The ferrite tiles are made using PC95 (TDK).

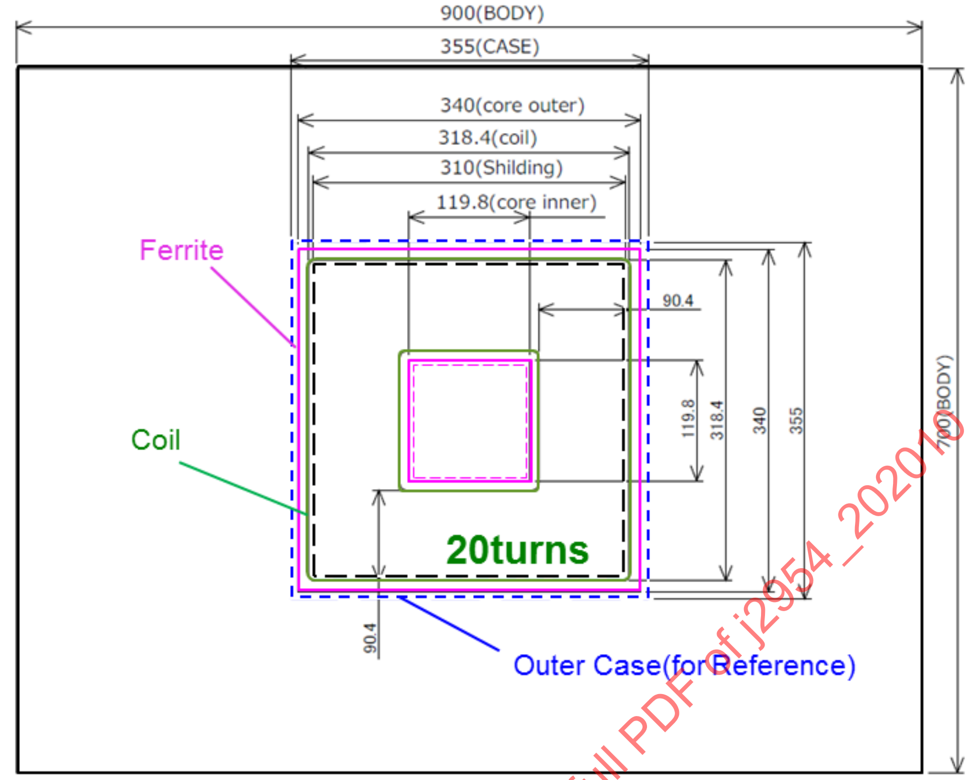


Figure A6 - Mechanical dimensions of the Test Station VA WPT1/Z2

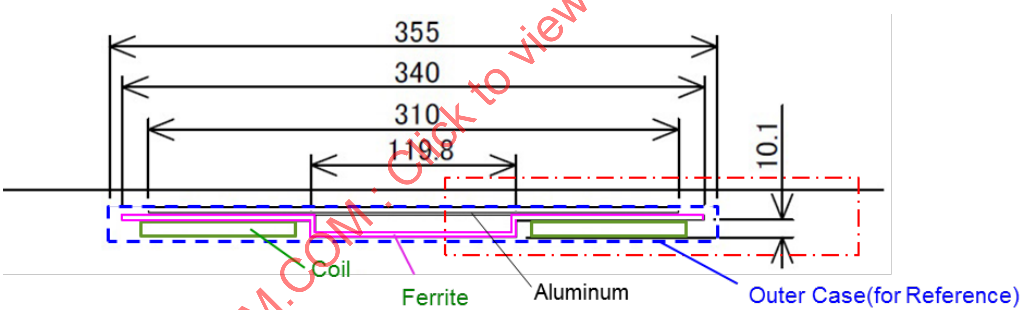


Figure A7 - Mechanical dimensions of the Test Station VA WPT1/Z2

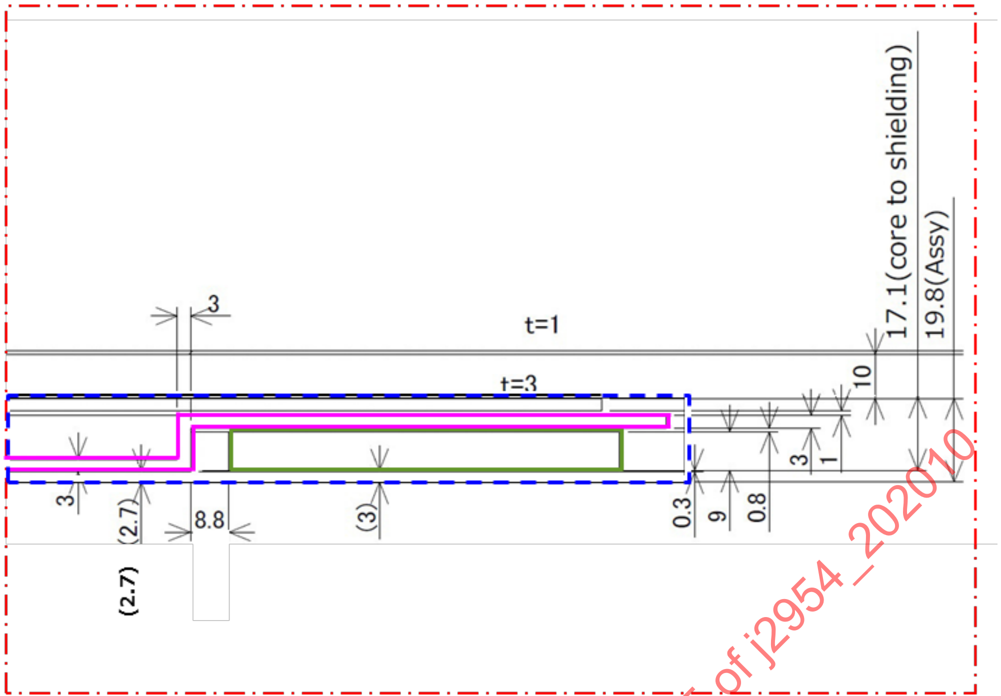


Figure A8 - Detailed cross section view

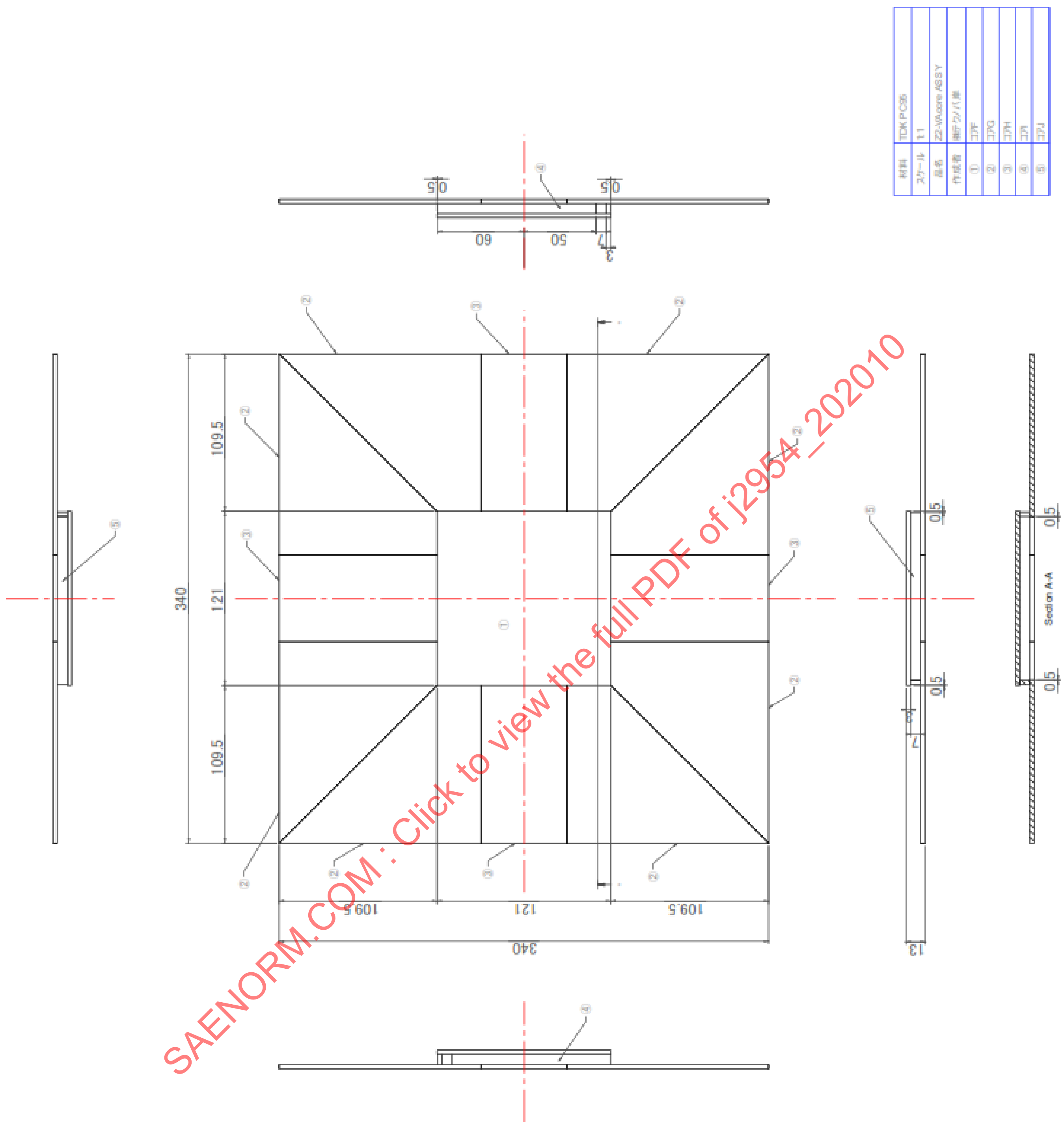


Figure A9 - Detail of the ferrite core construction

A.2.2 ELECTRICAL SPECIFICATION

Figure A10 shows the electrical specification of the Test Station VA WPT1/Z2.

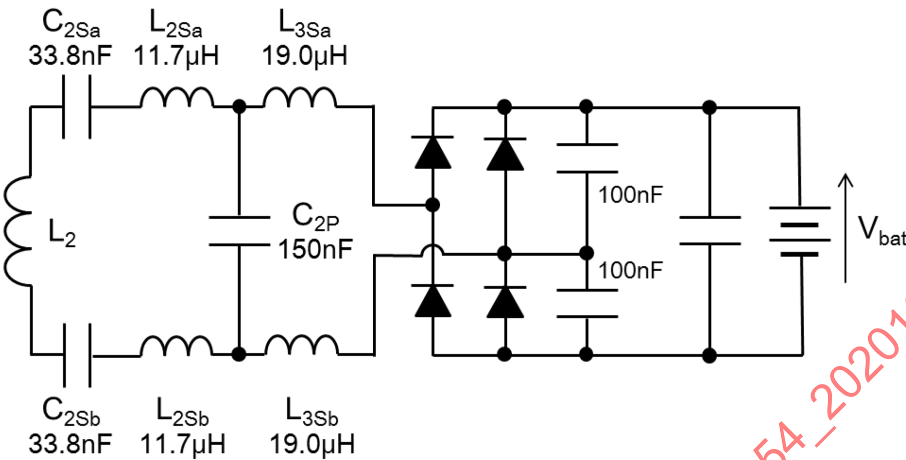


Figure A10 - Electrical specification of the Test Station VA-WPT1/Z2

The minimum and maximum inductance are given in Table A2.

Table A2 - Inductance

L_2 min	207 µH
L_2 max	214 µH

A.3 TEST STATION VA WPT1/Z3

This appendix provides the mechanical and electrical design specifications of the VA for power class WPT1 and gap class Z3 (VA WPT1/Z3).

NOTE: Specifications designed for optimal operation with the Test Station GA WPT1 specified in Appendix F.

A.3.1 Mechanical Specification

Figures A11, A12, A13, and A14 show the mechanical dimensions of the Test Station VA WPT1/Z3.

The ferrite tiles are made using N96 (TDK).

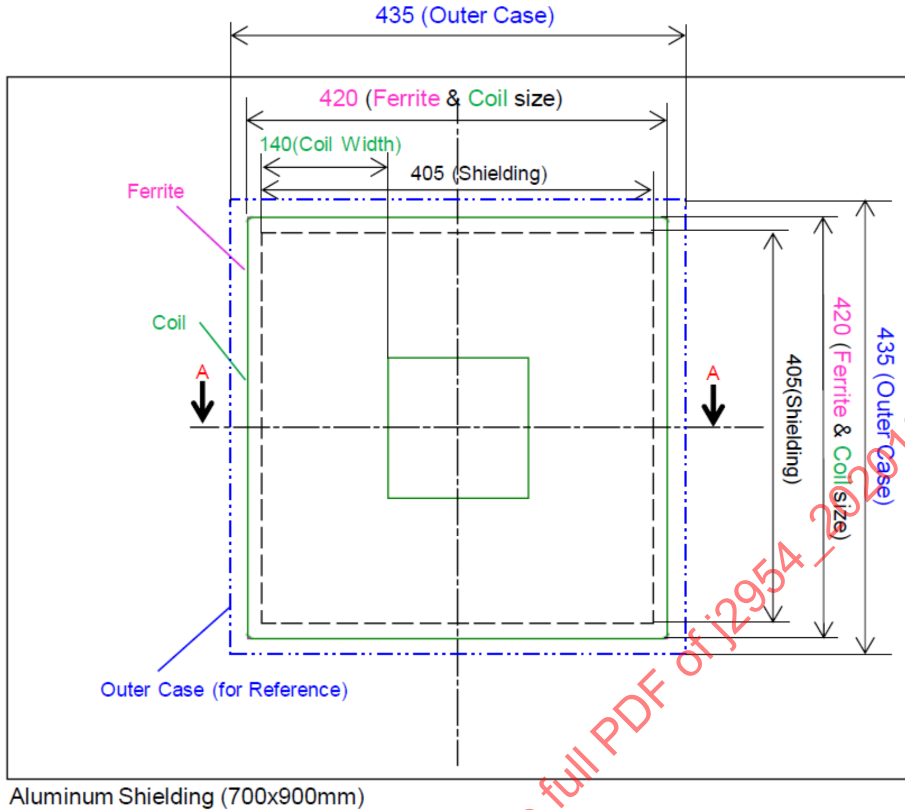


Figure A11 - Mechanical dimensions of the Test Station VA WPT1/Z3

Figure A12 - Mechanical dimensions of the Test Station VA WPT1/Z3

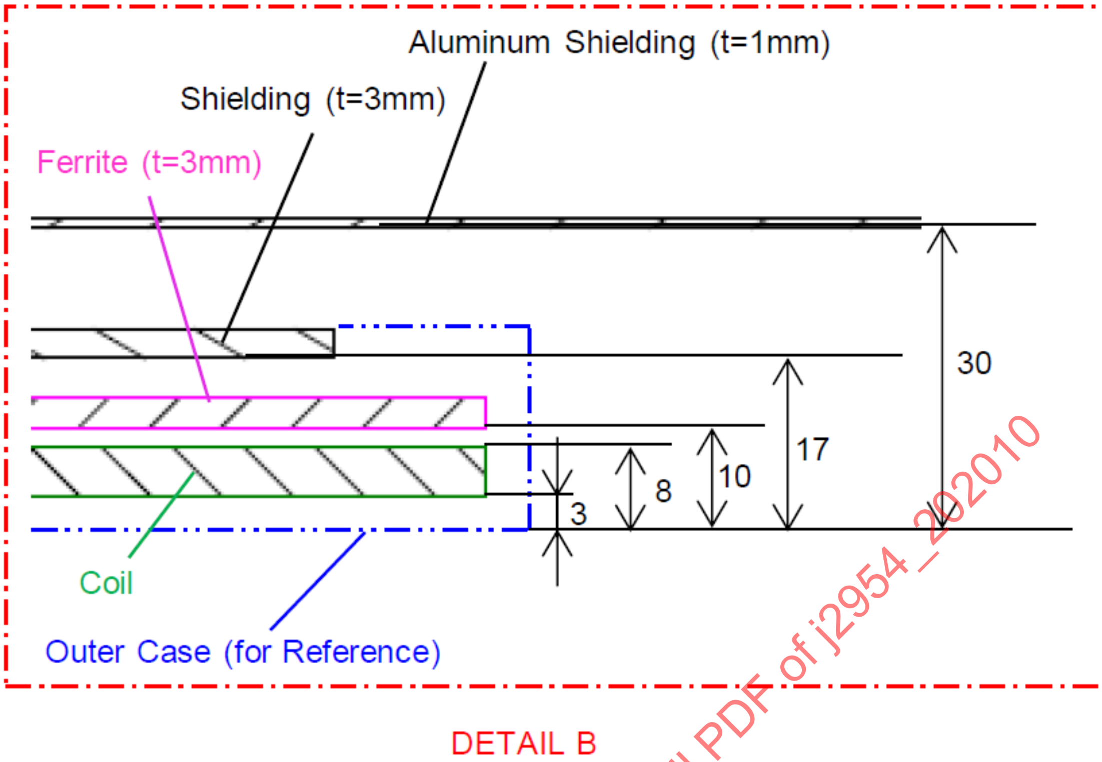


Figure A13 - Detailed cross section view

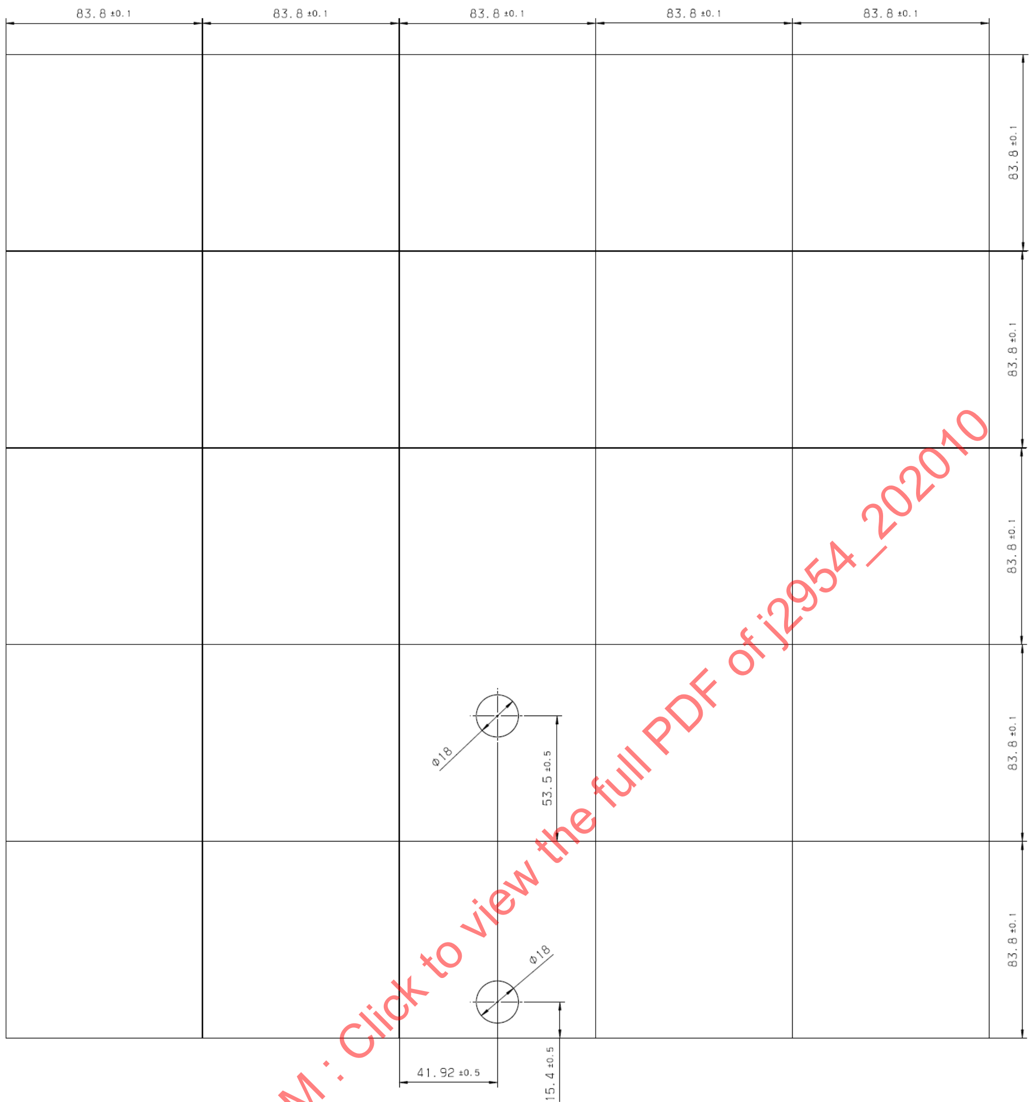


Figure A14 - Detail of the ferrite core construction

A.3.2 Electrical Specification

Figure A15 shows the electrical specification of the Test Station VA WPT1/Z3.

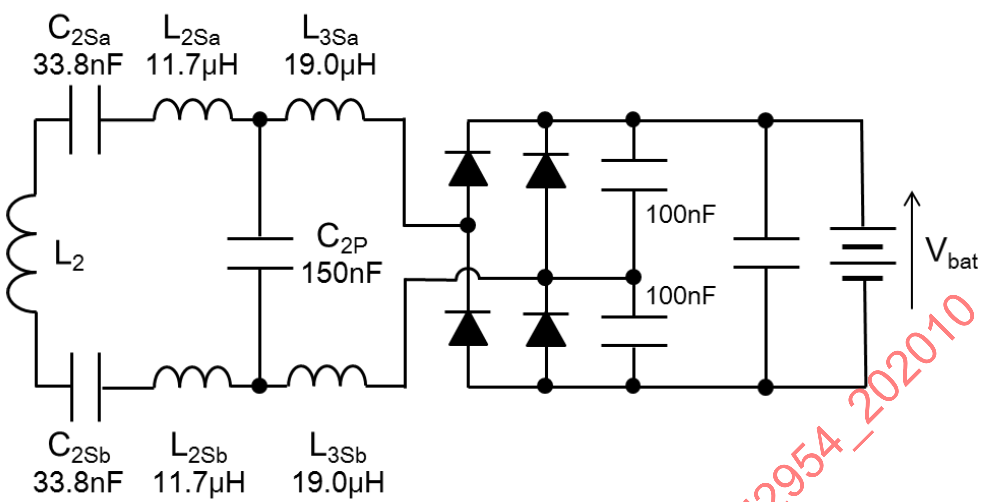


Figure A15 - Electrical specification of the Test Station VA-WPT1/Z3

The minimum and maximum inductance are given in Table A3.

Table A3 - Inductance

L_2 min	198 µH
L_2 max	203 µH

A.4 TEST STATION VA WPT2/Z1

This appendix provides the mechanical and electrical design specifications of the VA for power class WPT2 and gap class Z1 (VA WPT2/Z1).

NOTE: Specifications are designed for optimal operation with the Test Station Universal GA specified in Appendix B.

A.4.1 MECHANICAL SPECIFICATION

Figures A16 and A17 show the mechanical dimensions of the Test Station VA WPT2/Z1.

Typical properties of the ferrite material used in the VA are shown in Table A4.

Table A4 - Typical ferrite properties

Material	MnZn
Initial Permeability (25 °C)	>1000
Flux Density, B_S (100 °C) (H = 1200 A/m, 10 kHz)	>400 mT
Core Loss, P_V (100 kHz, 200 mT, 100 °C)	<350 kW/m^3

The lateral dimensions of the aluminum shield shown in Figure A17 are 800 x 800 mm, and the thickness should be 0.7 mm or larger.

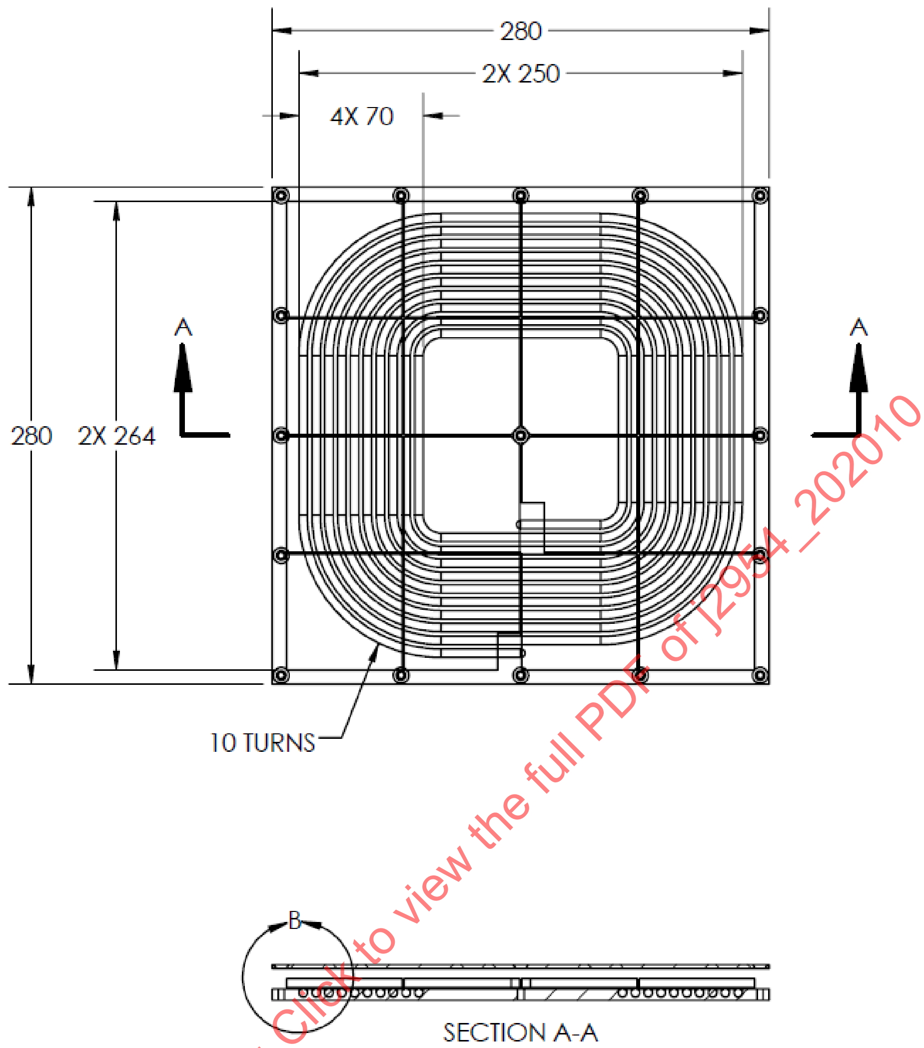


Figure A16 - Mechanical dimensions of the Test Station VA WPT2/Z1

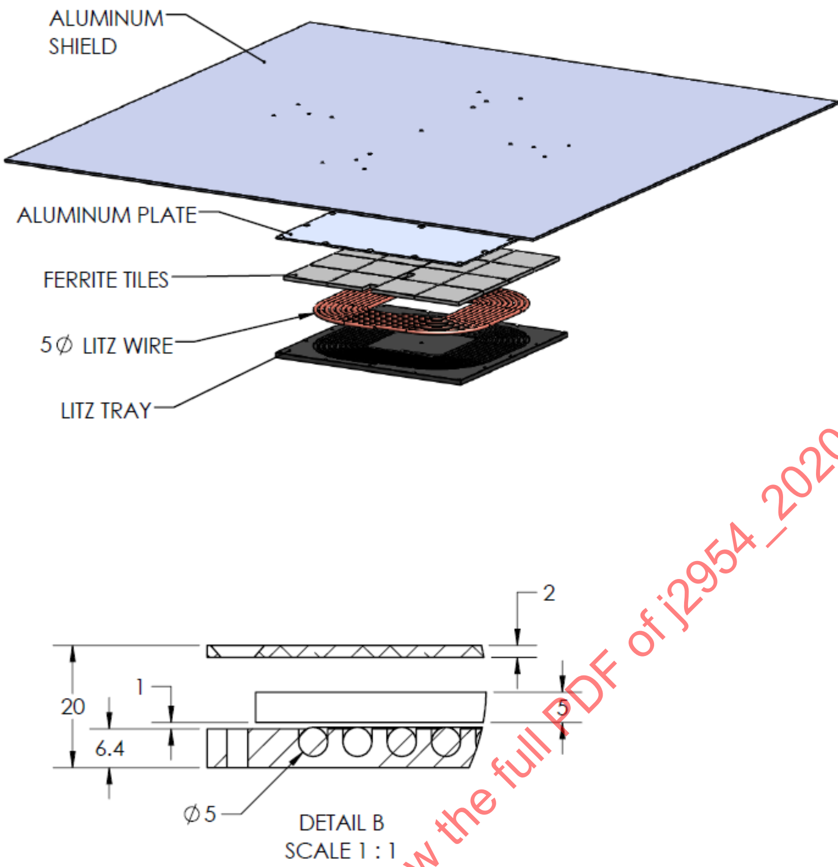


Figure A17 - Exploded view of the Test Station VA WPT2/Z1

A.4.2 Electrical Specification

Figure A18 shows the electrical specification of the Test Station VA WPT2/Z1.

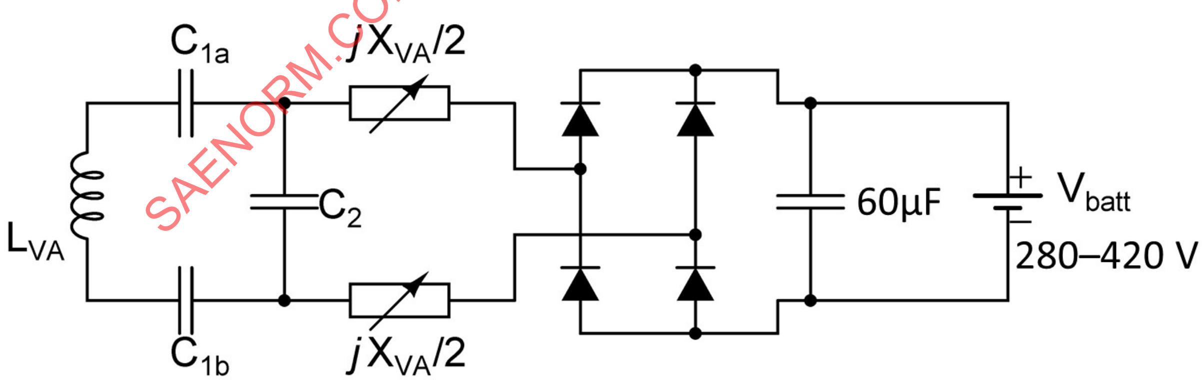


Figure A18 - Electrical specification of the Test Station VA WPT2/Z1

Minimum and maximum values of secondary coil inductance L_{VA} and the impedance matching values are given in Table A5.

Table A5 - Secondary coil inductance L_{VA} and impedance matching values

L_{VA}_min [μH]	37.2
L_{VA}_max [μH]	38.7
C1a [nF]	290
C1b [nF]	290
C2 [nF]	170
X_{VA}/2 min [Ω]	-8
X_{VA}/2 max [Ω]	5

A.5 TEST STATION VA WPT2/Z2

This appendix provides the mechanical and electrical design specifications of the VA for power class WPT2 and gap class Z2 (VA WPT2/Z2).

NOTE: Specifications are designed for optimal operation with the Test Station Universal GA specified in Appendix B.

A.5.1 MECHANICAL SPECIFICATION

Figures A19 and A20 show the mechanical dimensions of the Test Station VA WPT2/Z2.

Typical properties of the ferrite material used in the VA are shown in Table A6.

Table A6 - Typical ferrite properties

Material	MnZn
Initial Permeability (25 °C)	>1000
Flux Density, B_S (100 °C) (H = 1200 A/m, 10 kHz)	>400 mT
Core Loss, P_V (100 kHz, 200 mT, 100 °C)	<350 kW/m^3

The lateral dimensions of the aluminum shield shown in Figure A20 are 800 x 800 mm, and the thickness should be 0.7 mm or larger.

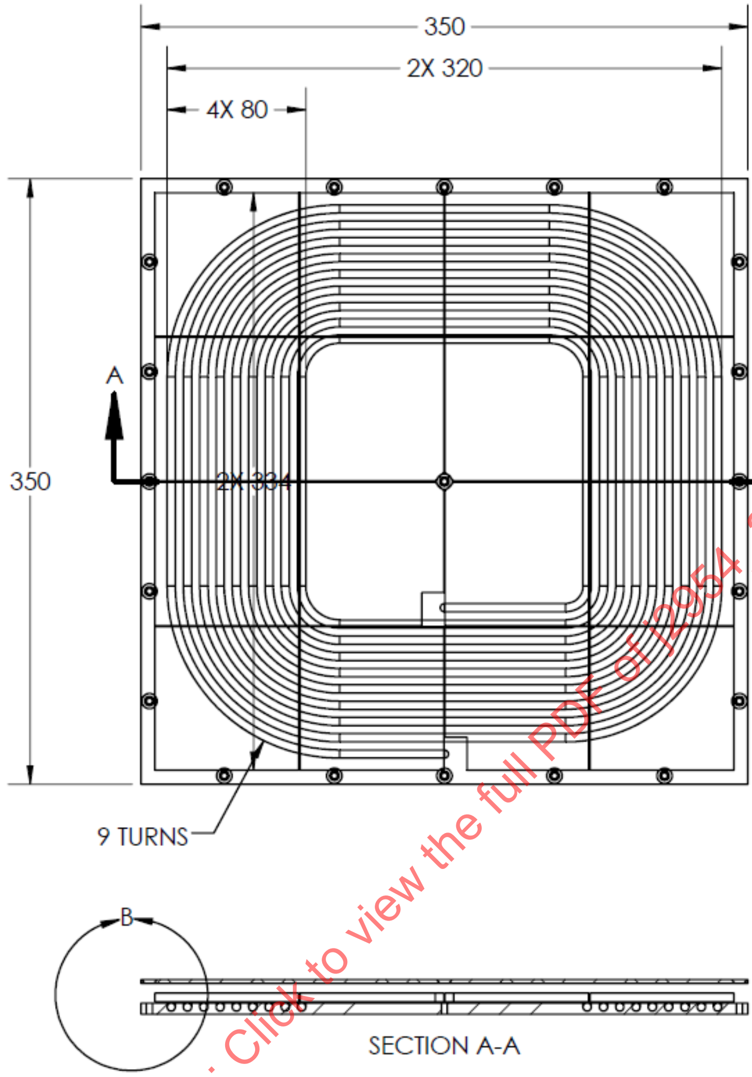


Figure A19 - Mechanical dimensions of the Test Station VA WPT2/Z2

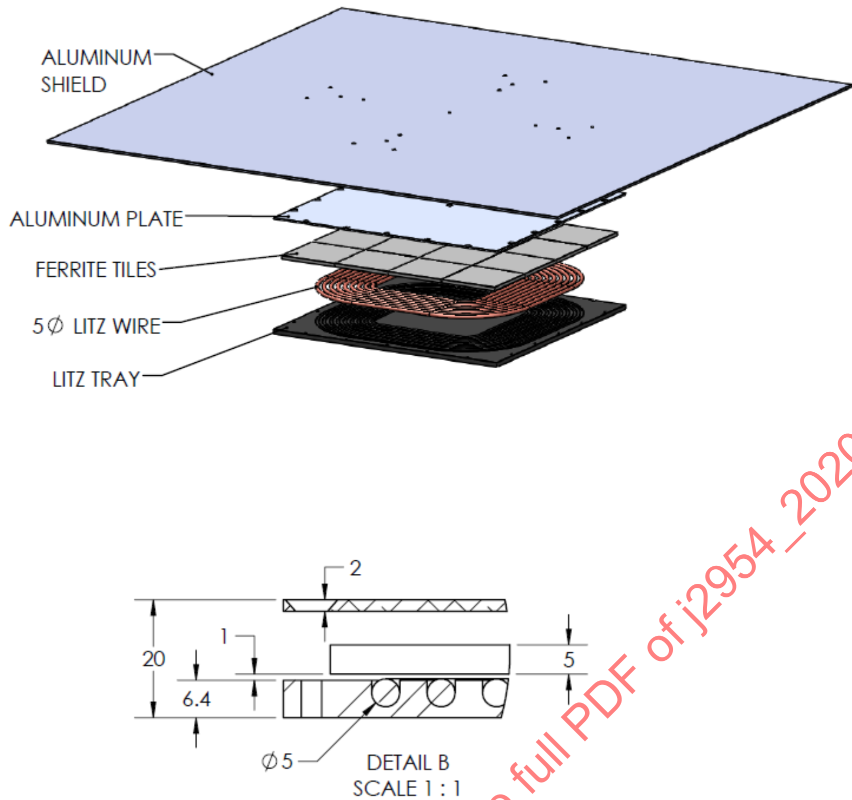


Figure A20 - Exploded view of the Test Station VA WPT2/Z2

A.5.2 Electrical Specification

Figure A21 shows the electrical specification of the Test Station VA WPT2/Z2.

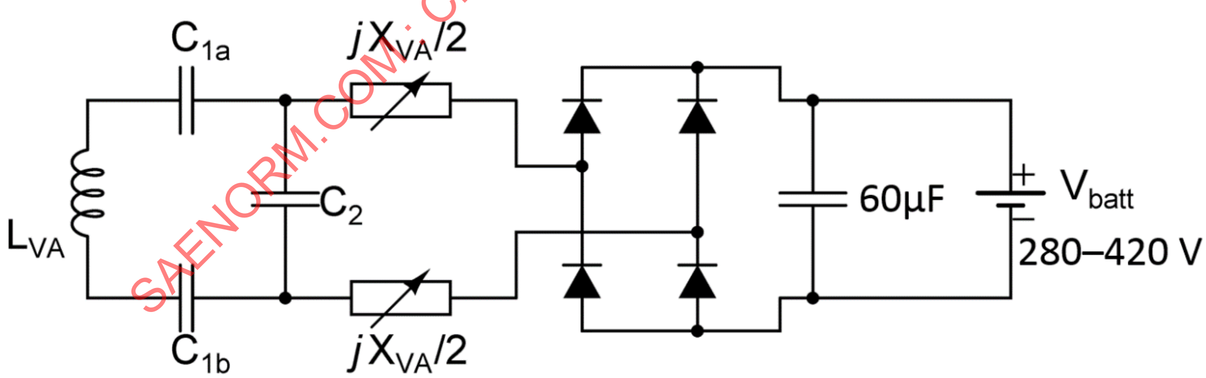


Figure A21 - Electrical specification of the Test Station VA WPT2/Z2.

Minimum and maximum values of secondary coil inductance L_{VA} and impedance matching values are given in Table A7.

Table A7 - Secondary coil inductance L_{VA} and impedance matching values

L_{VA}_min [μH]	43.1
L_{VA}_max [μH]	44.0
C1a [nF]	250
C1b [nF]	250
C2 [nF]	170
X_{VA}/2 min [Ω]	-6
X_{VA}/2 max [Ω]	7

A.6 TEST STATION VA WPT2/Z3

This appendix provides the mechanical and electrical design specifications of the VA for power class WPT2 and gap class Z3 (VA WPT2/Z3).

NOTE: Specifications are designed for optimal operation with the Test Station Universal GA specified in Appendix B.

A.6.1 Mechanical Specification

Figures A22 and A23 show the mechanical dimensions of the Test Station VA WPT2/Z3.

Typical properties of the ferrite material used in the VA are shown in Table A8.

Table A8 - Typical ferrite properties

Material	MnZn
Initial Permeability (25 °C)	>1000
Flux Density, B_S (100 °C) (H = 1200 A/m, 10 kHz)	>400 mT
Core Loss, P_V (100 kHz, 200 mT, 100 °C)	<350 kW/m^3

The lateral dimensions of the aluminum shield shown in Figure A23 are 800 x 800 mm, and the thickness should be 0.7 mm or larger.

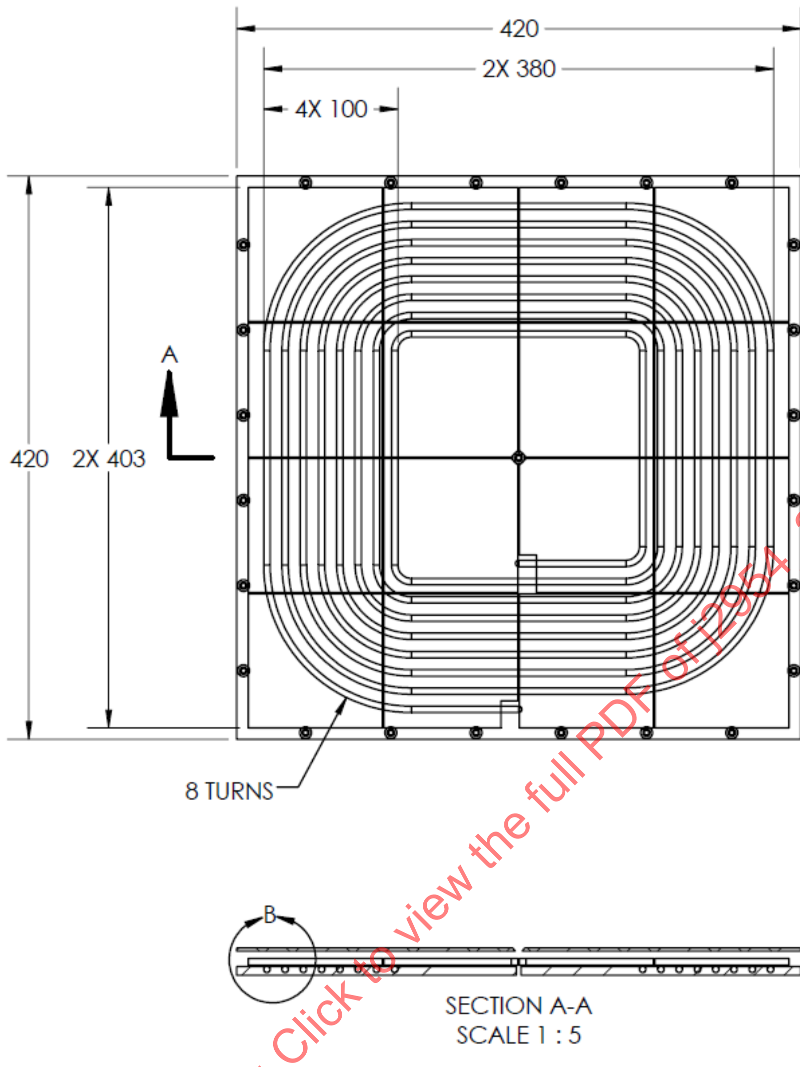


Figure A22 - Mechanical dimensions of the Test Station VA WPT2/Z3

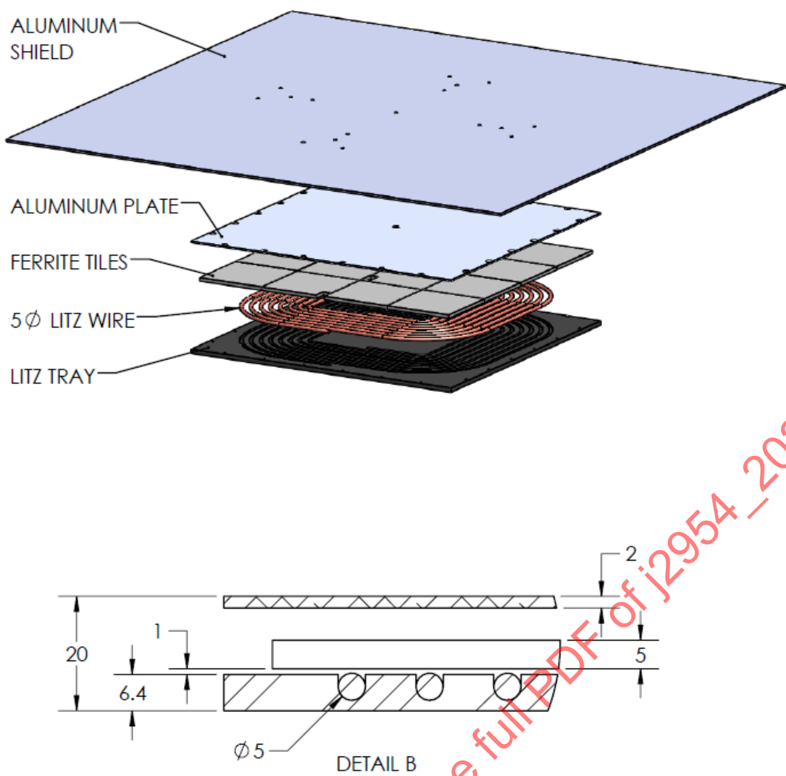


Figure A23 - Exploded view of the Test Station VA WPT2/Z3

A.6.2 Electrical Specification

Figure A24 shows the electrical specification of the Test Station VA WPT2/Z3.

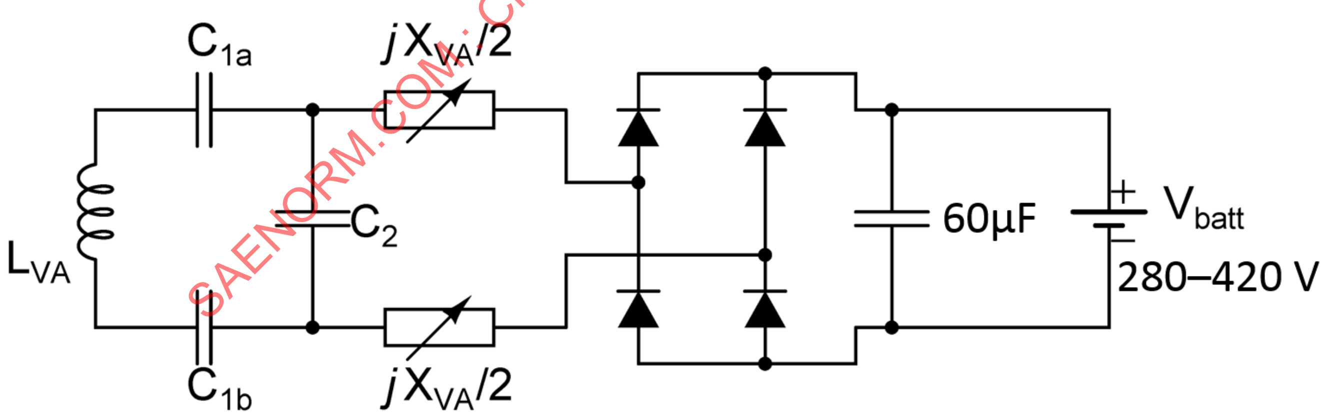


Figure A24 - Electrical specification of the Test Station VA WPT2/Z3

Minimum and maximum values of secondary coil inductance L_{VA} and impedance matching values are given in Table A9.

Table A9 - Secondary coil inductance L_{VA} and impedance matching values

L_{VA}_min [µH]	39.3
L_{VA}_max [µH]	40.0
C1a [nF]	310
C1b [nF]	310
C2 [nF]	170
X_{VA}/2 min [Ω]	-8
X_{VA}/2 max [Ω]	5

A.7 TEST STATION VA WPT3/Z1

This appendix provides the mechanical and electrical design specifications of the VA for power class WPT3 and gap class Z1 (VA WPT3/Z1).

NOTE: Specifications are designed for optimal operation with the Test Station GA specified in Appendix B.

A.7.1 Mechanical Specification

Figures A25 and A26 show the mechanical dimensions of the ferrite and the coil of the VA WPT3/Z1.

Typical properties of the ferrite material used in the VA are shown in Table A10.

Table A10 - Typical ferrite properties

Material	MnZn
Initial Permeability (25 °C)	>1000
Flux Density, B_S (100 °C) (H = 1200 A/m, 10 kHz)	>400 mT
Core Loss, P_V (100 kHz, 200 mT, 100 °C)	<350 kW/m^3

The lateral dimensions of the aluminum shield shown in Figure A26 are 800 x 800 mm, and the thickness should be 0.7 mm or larger.

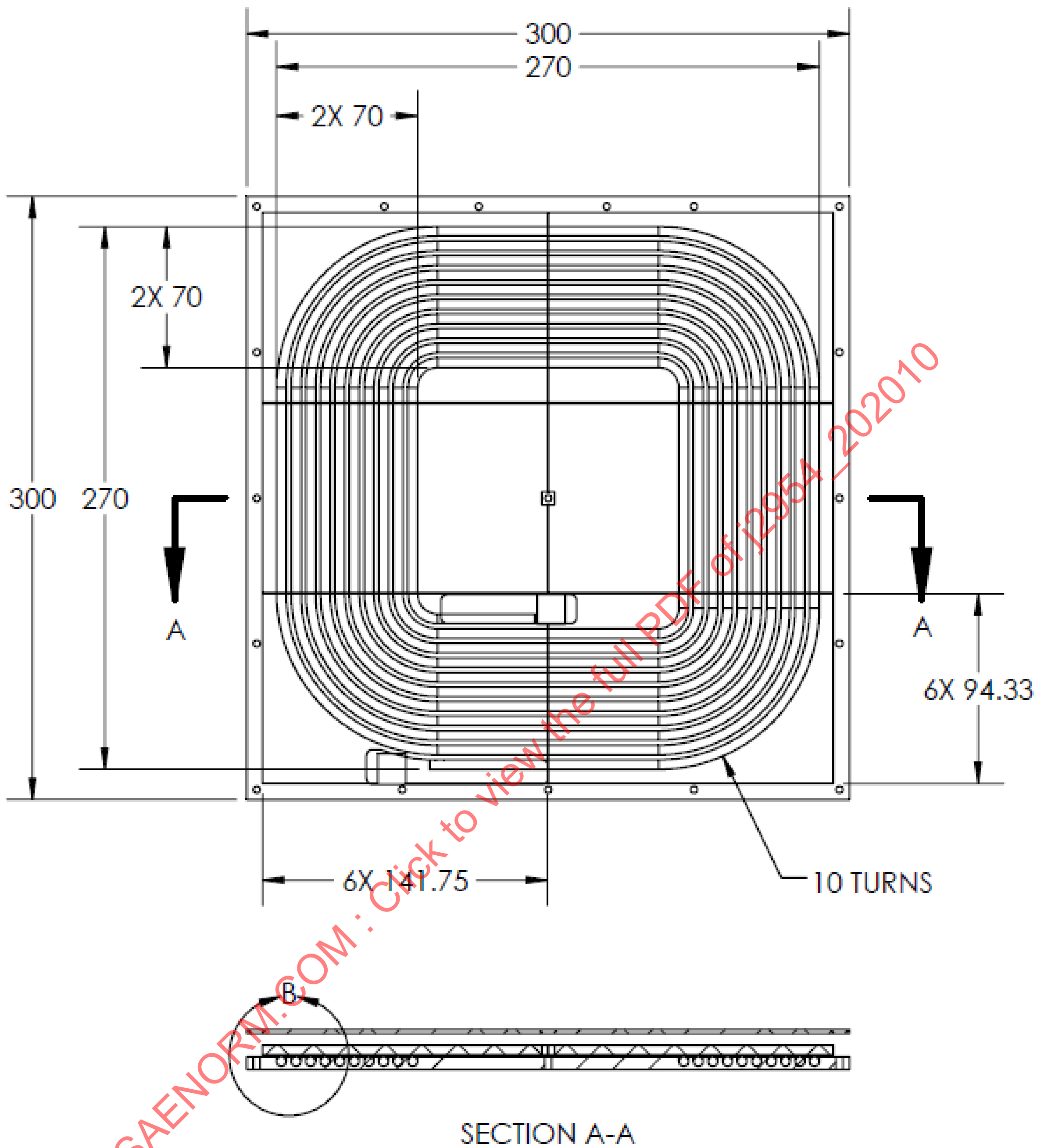


Figure A25 - Mechanical dimensions of the Test Station VA WPT3/Z1

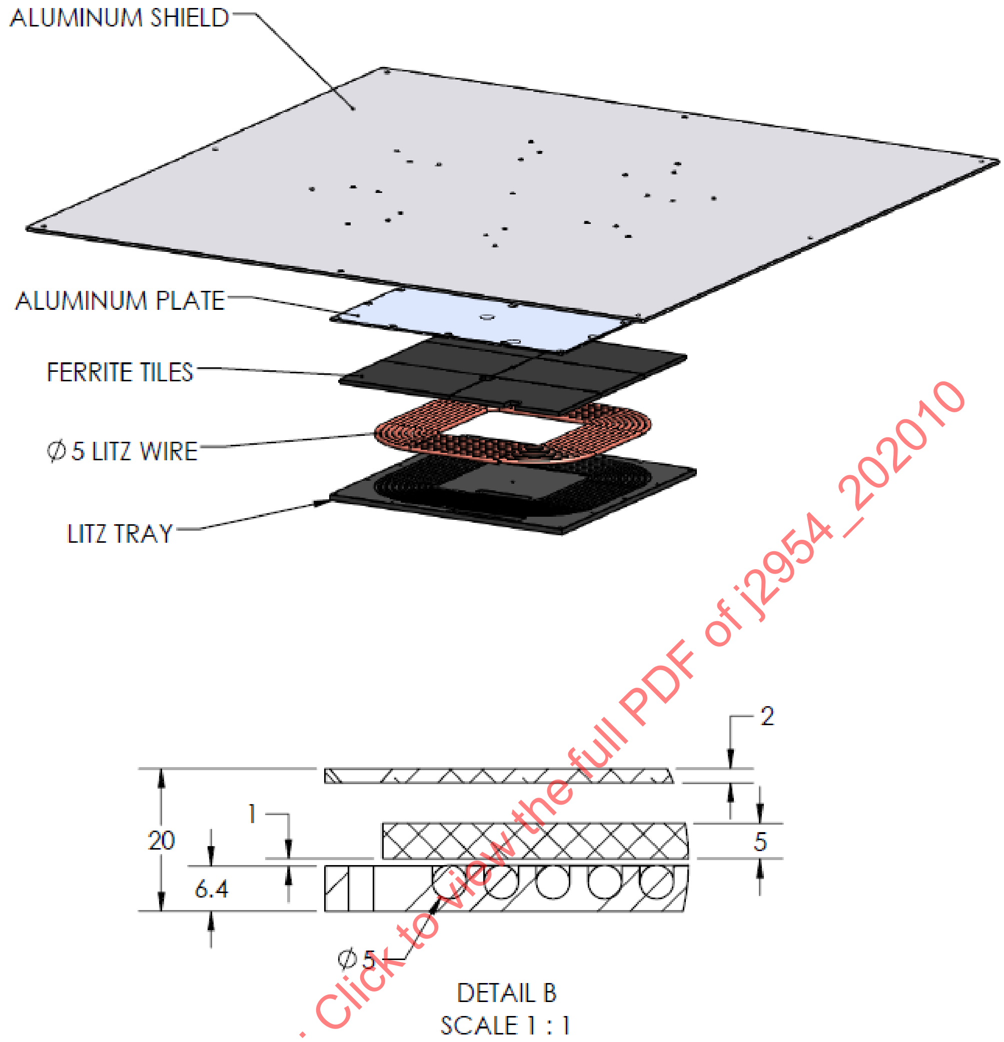


Figure A26 - Exploded view of the Test Station VA WPT3/Z1

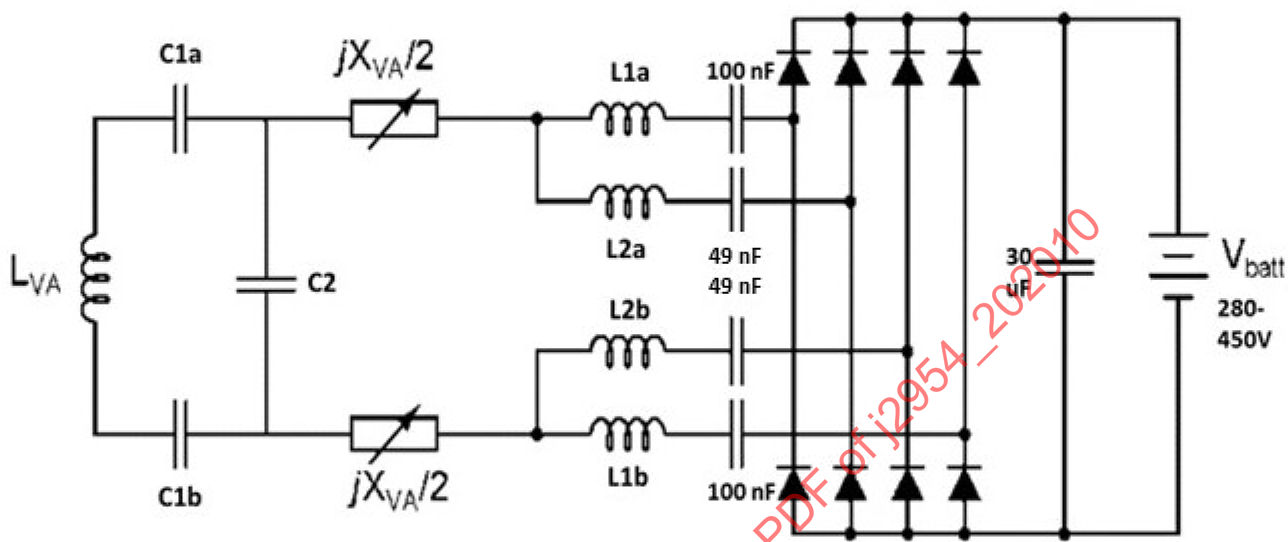
Table A11 shows the mechanical dimensions of the VA WPT3/Z1 and nominal vehicle shield.

Table A11 - Mechanical dimensions of the Test Station VA WPT3/Z1

	Coil + Ferrite Only	Housing	Vehicle Shield Size
L x W x H [mm]	284 x 284 x 12.6	300 x 300 x 20	800 x 800 x 1

A.7.2 Electrical Specification

Figure A27 shows the electrical specification of the VA WPT3/Z1.



C1a, C1b [nF]	223
C2 [nF]	143
$jX_{VA}/2$ [ohms]	-15 to 0
L1a, L1b [uH]	54
L2a, L2b [uH]	54

Figure A27 - Electrical specification of the Test Station VA WPT3/Z1

Minimum and maximum values of secondary coil inductance L_{VA} are given in Table A12.

Table A12 - Secondary coil inductance L_{VA}

L_Min [µH]	45.0
L_Max [µH]	47.0

A.8 TEST STATION VA WPT3/Z2

This appendix provides the mechanical and electrical design specifications of the VA for power class WPT3 and gap class Z2 (VA WPT3/Z2).

NOTE: Specifications are designed for optimal operation with the Test Station GA specified in Appendix B.

A.8.1 MECHANICAL SPECIFICATION OF THE VA WPT3/Z2

Figures A28 and A29 show the mechanical dimensions of the ferrite and the coil of the VA WPT3/Z2.

Typical properties of the ferrite material used in the VA are shown in Table A13.

Table A13 - Typical ferrite properties

Material	MnZn
Initial Permeability (25 °C)	>1000
Flux Density, B_S (100 °C) (H = 1200 A/m, 10 kHz)	>400 mT
Core Loss, P_V (100 kHz, 200 mT, 100 °C)	<350 kW/m^3

The lateral dimensions of the aluminum shield shown in Figure A29 are 800 x 800 mm, and the thickness should be 0.7 mm or larger.

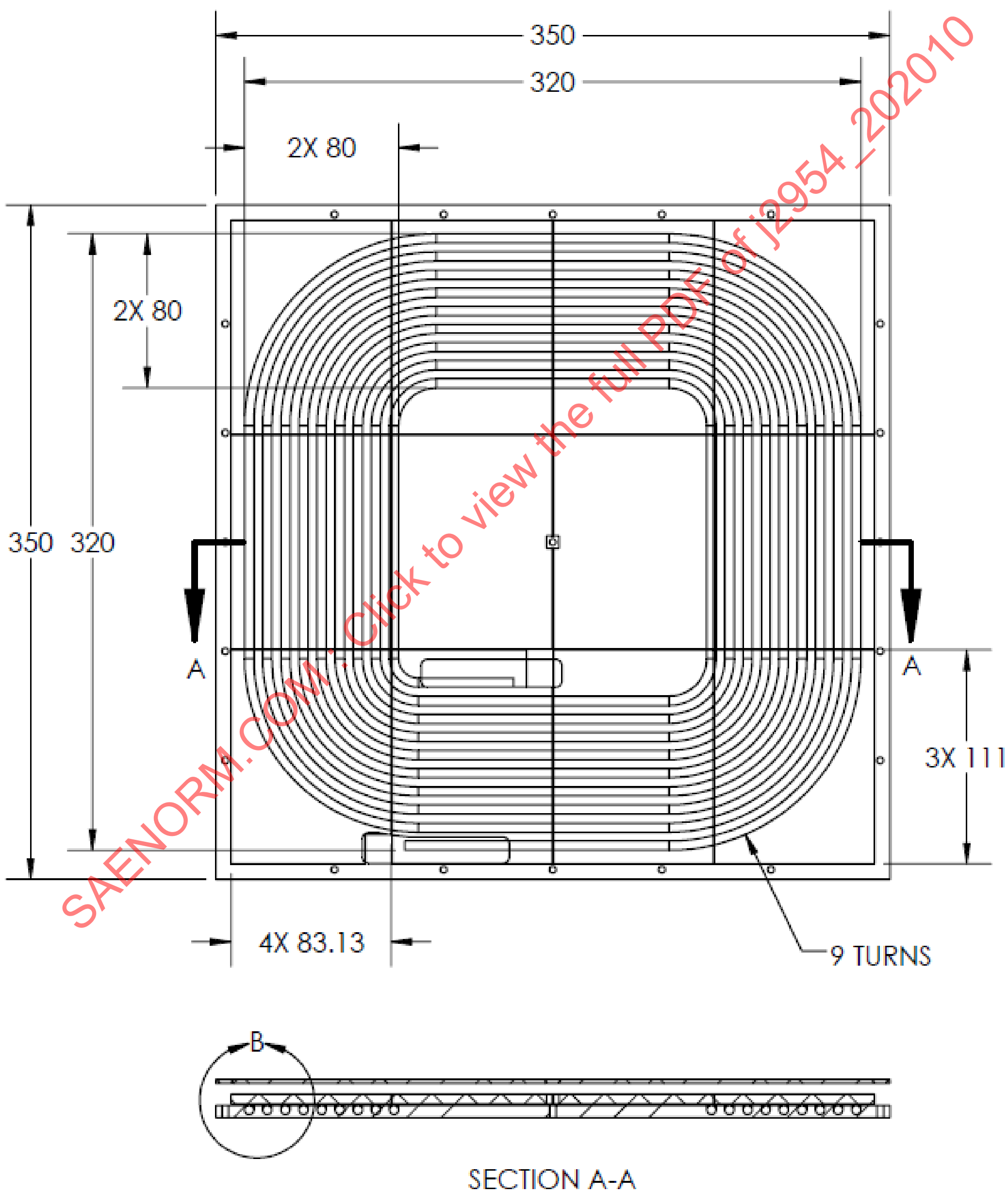


Figure A28 - Mechanical dimensions of the Test Station VA WPT3/Z2

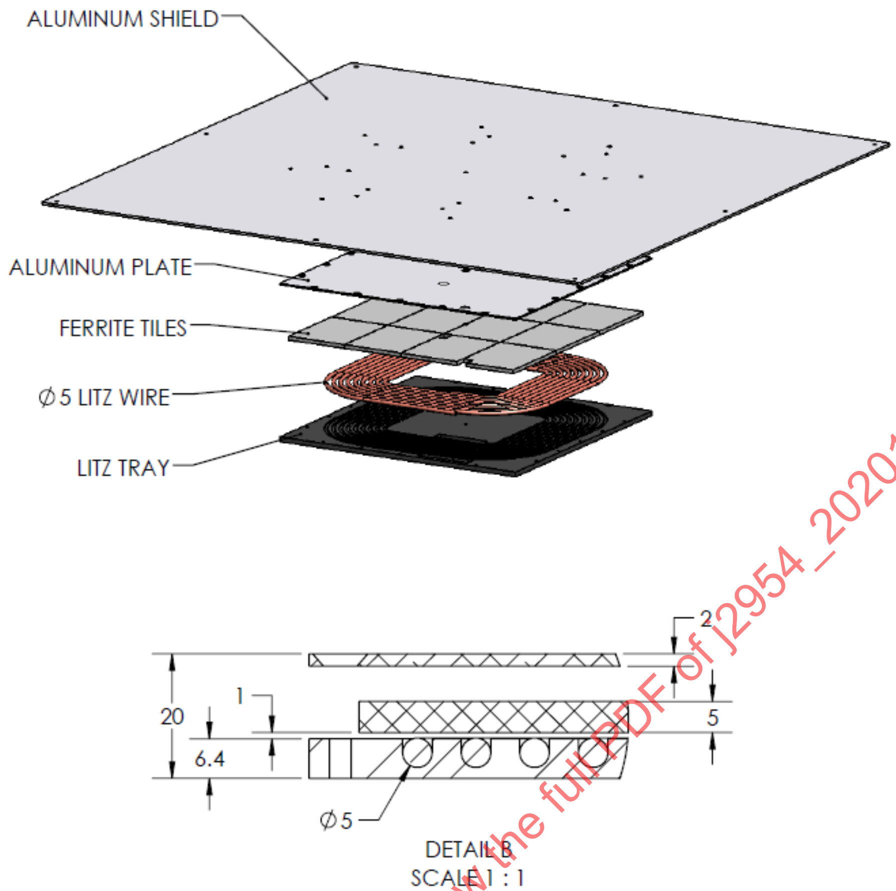


Figure A29 - Exploded view of the Test Station VA WPT3/Z2

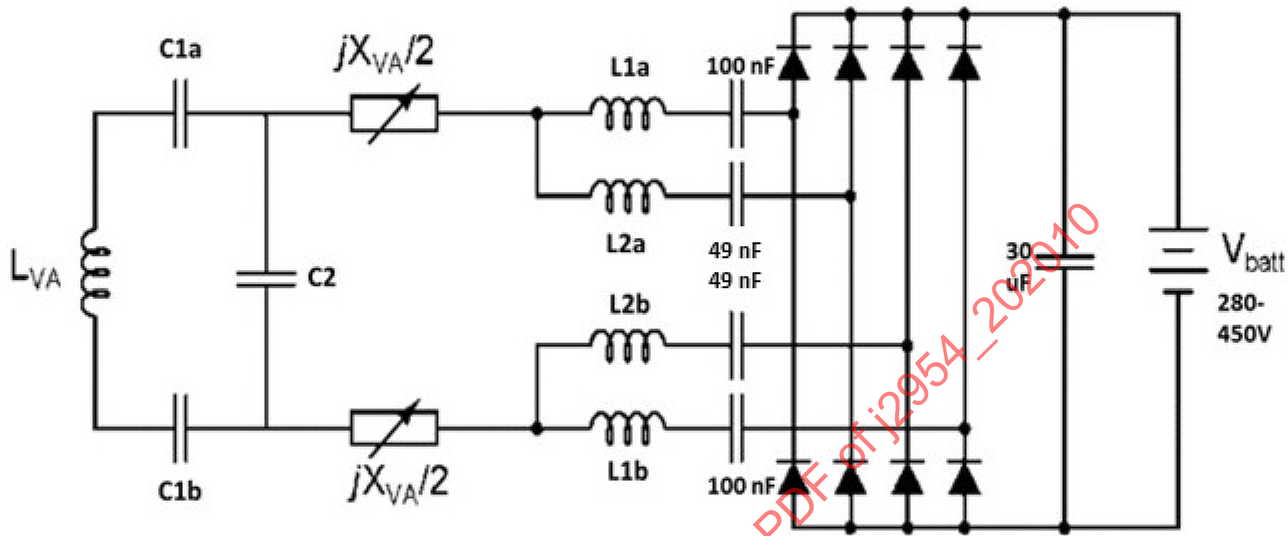
Table A14 shows the mechanical dimensions of the VA WPT3/Z2 and nominal vehicle shield.

Table A14 - Mechanical dimensions of the Test Station VA WPT3/Z2

	Coil + Ferrite Only	Housing	Vehicle Shield Size
L x W x H [mm]	334 x 334 x 12.6	350 x 350 x 20	800 x 800 x 1

A.8.2 Electrical Specification

Figure A30 shows the electrical specification of the VA WPT3/Z2.



C1a, C1b [nF]	270
C2 [nF]	145
$jX_{VA}/2$ [ohms]	-15 to 0
L1a, L1b [uH]	54
L2a, L2b [uH]	54

Figure A30 - Electrical specification of the Test Station VA WPT3/Z2

Minimum and maximum values of secondary coil inductance L_{VA} are given in Table A15.

Table A15 - Secondary coil inductance L_{VA}

L_Min [μH]	43.1
L_Max [μH]	44.0

A.9 TEST STATION VA WPT3/Z3

This appendix provides the mechanical and electrical design specifications of the VA for power class WPT3 and gap class Z3 (VA WPT3/Z3).

NOTE: Specifications are designed for optimal operation with the Test Station GA specified in Appendix B.

A.9.1 Mechanical Specification

Figures A31 and A32 show the mechanical dimensions of the ferrite and the coil of the VA WPT3/Z3.

Typical properties of the ferrite material used in the VA are shown in Table A16.

Table A16 - Typical ferrite properties

Material	MnZn
Initial Permeability (25 °C)	>1000
Flux Density, B_S (100 °C) (H = 1200 A/m, 10 kHz)	>400 mT
Core Loss, P_V (100 kHz, 200 mT, 100 °C)	<350 kW/m³

The lateral dimensions of the aluminum shield shown in Figure A32 are 800 x 800 mm, and the thickness should be 0.7 mm or larger.

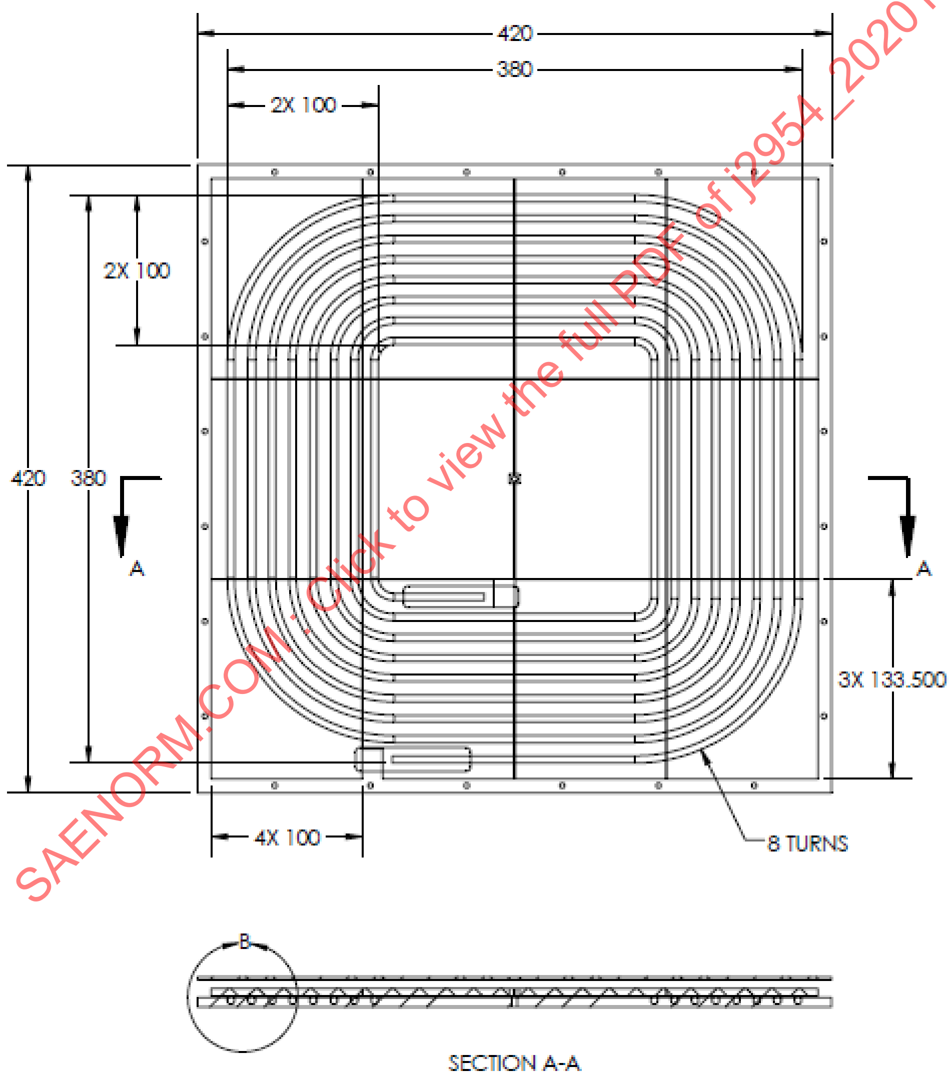


Figure A31 - Mechanical dimensions of the Test Station VA WPT3/Z3

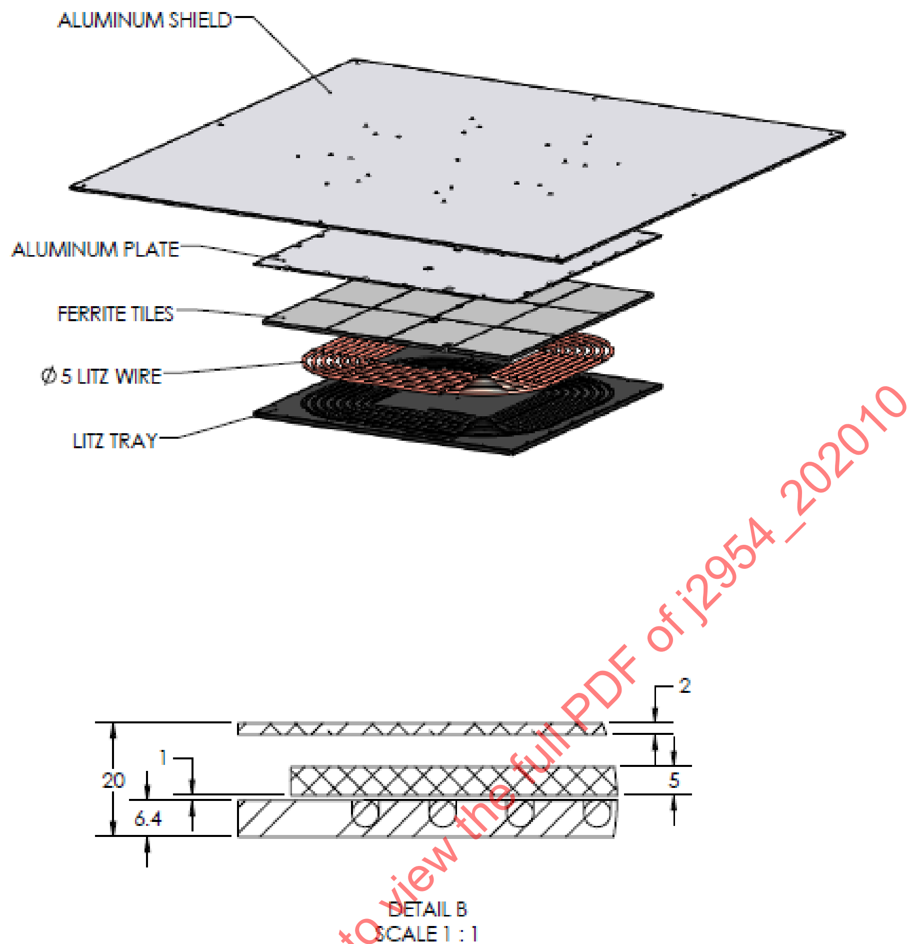


Figure A32 - Exploded view of the Test Station VA WPT3/Z3

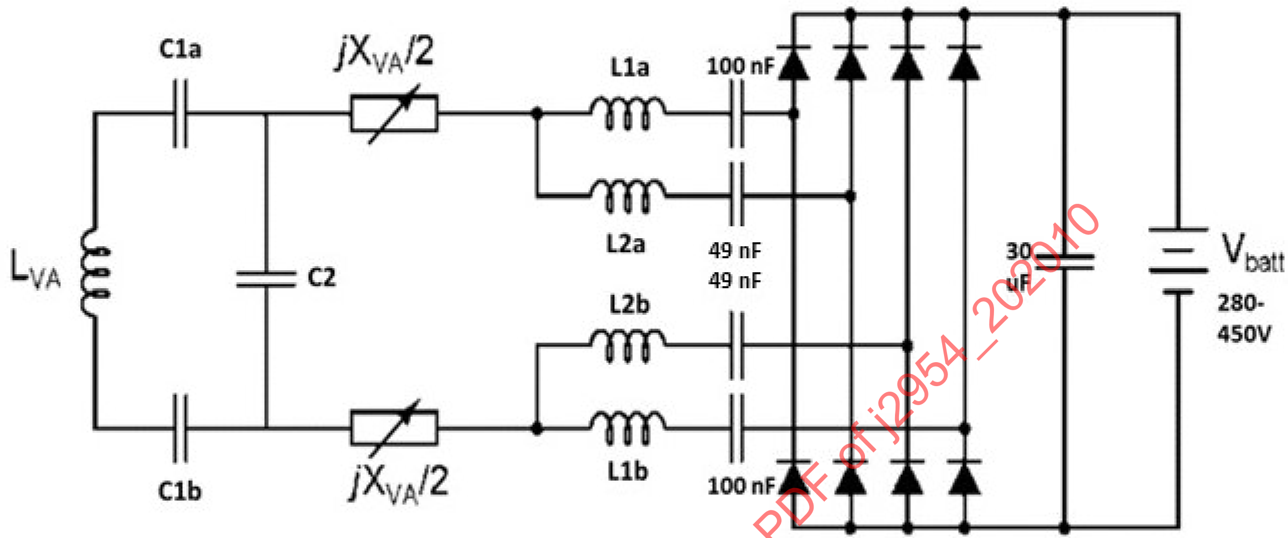
Table A17 shows the mechanical dimensions of the VA WPT3/Z3 and nominal vehicle shield.

Table A17 - Mechanical dimensions of the Test Station VA WPT3/Z3

	Coil + Ferrite Only	Housing	Vehicle Shield Size
L x W x H [mm]	401.5 x 401.5 x 12.6	420x 420 x 20	800 x 800 x 1

A.9.2 Electrical Specification

Figure A33 shows the electrical specification of the VA WPT3/Z3.



C1a, C1b [nF]	325
C2 [nF]	150
$jX_{VA}/2$ [ohms]	-15 to 0
L1a, L1b [uH]	54
L2a, L2b [uH]	54

Figure A33 - Electrical specification of the Test Station VA WPT3/Z3

Minimum and maximum values of secondary coil inductance L_{VA} are given in Table A18.

Table A18 - Secondary coil inductance L_{VA}

L_Min [µH]	39.3
L_Max [µH]	40.0

APPENDIX B - TEST STATION UNIVERSAL GA (WPT1, WPT2, WPT3) (NORMATIVE)

This appendix provides the mechanical and electrical design specifications of the Test Station Universal GA.

NOTE: Specifications designed for optimal operation with the Test Station VA WPT2/Z1 (Appendix A.4), the Test Station VA WPT2/Z2 (Appendix A.5), the Test Station VA WPT2/Z3 (Appendix A.6), the Test Station VA WPT3/Z1 (Appendix A.7), the Test Station VA WPT3/Z2 (Appendix A.8), and the Test Station VA WPT3/Z3 (Appendix A.9).

B.1 MECHANICAL SPECIFICATION

Figures B1 and B2 show the mechanical dimensions of the Test Station Universal GA. Figure B3 shows an exploded view of the mechanical construction of the GA with the aluminum plate towards the ground. The ferrite layers in the GA are constructed of ferrite tiles of dimensions 100 x 150 x 5 mm and 100 x 100 x 5 mm. Typical properties of the ferrite material used in the GA are shown in Table B1.

Table B1 - Typical Ferrite Properties

Material	MnZn
Initial Permeability (25 °C)	>1000
Flux Density, B_S (100 °C) (H = 1200 A/m, 10 kHz)	>400 mT
Core Loss, P_V (100 kHz, 200 mT, 100 °C)	<350 kW/m^3

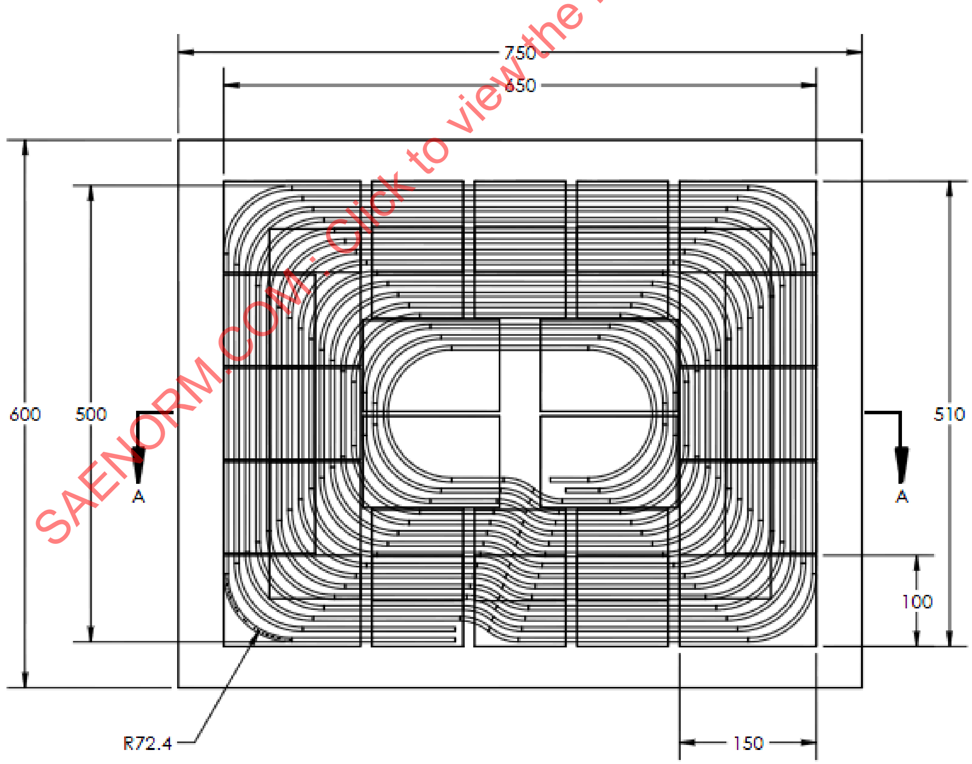


Figure B1 - Mechanical dimensions of the Test Station Universal GA

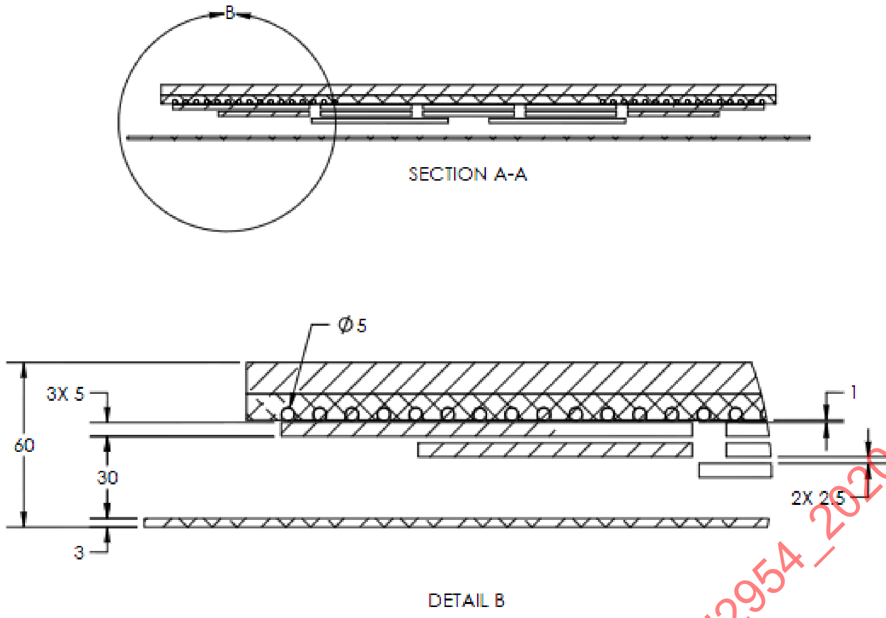


Figure B2 - Detailed cross section view of the Test Station Universal GA

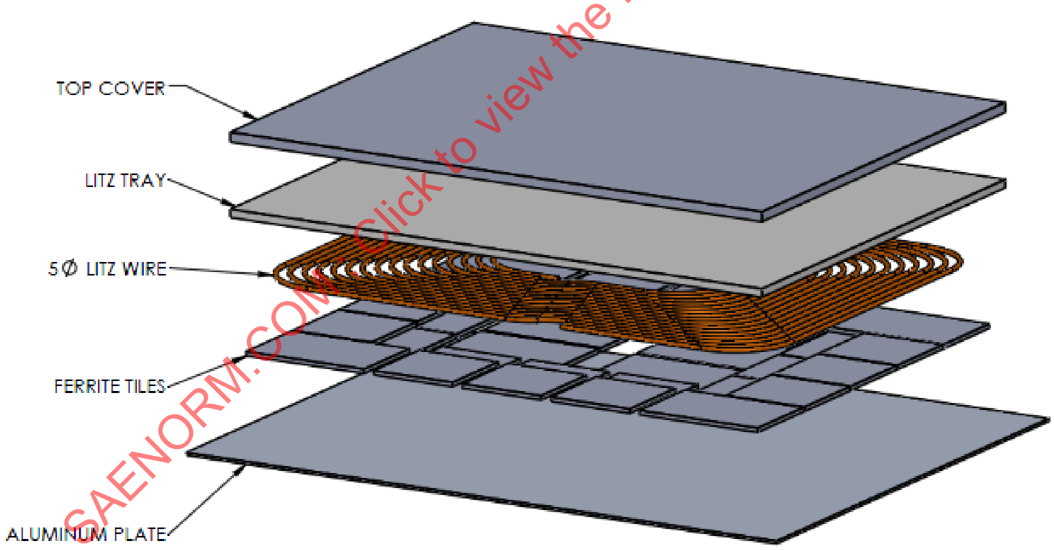


Figure B3 - Exploded view of the Test Station Universal GA

NOTE: Ferrite placed on a single plane rather than at three levels can also be used but will result in a slight change of inductance and coupling values.

B.2 ELECTRICAL SPECIFICATION

Figure B4 and the values in Table B2 show the electrical specification of the Test Station Universal GA.

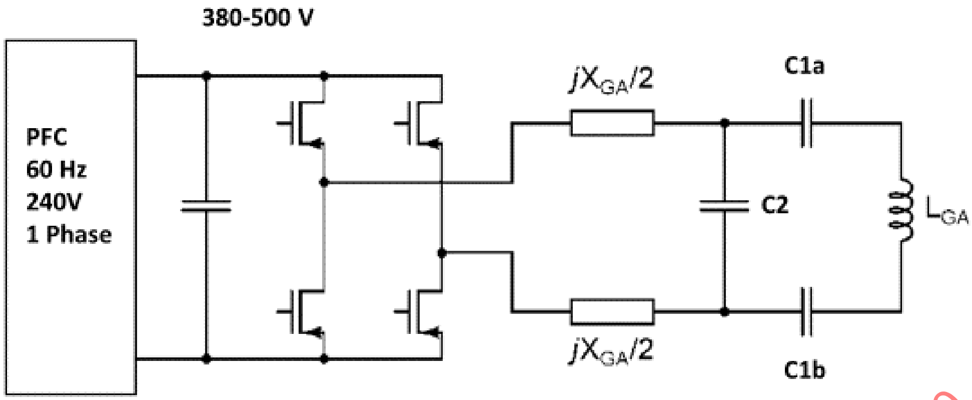


Figure B4 - Electrical schematic of the Test Station Universal GA

Table B2 - Table of values

C1a, C1b [nF]	320
C2 [nF]	270
$jX_{GA}/2$ [ohms]	4 to 16

Minimum and maximum values of L_{GA} when simulated with an 800 x 800 mm aluminum shield are given in Table B3.

Table B3 - Primary coil inductance L_{GA} depending on the Z-class

Z-Class	VA	L_{GA}_Min [µH]	L_{GA}_Max [µH]
WPT2/Z1	Appendix A.4	29.6	35.8
WPT2/Z2	Appendix A.5	35.1	38.1
WPT2/Z3	Appendix A.6	37.4	38.7
WPT3/Z1	Appendix A.7	30.0	36.2
WPT3/Z2	Appendix A.8	35.1	38.1
WPT3/Z3	Appendix A.9	37.4	38.7

Table B4 - Maximum currents in the Test Station Universal GA

Maximum PFC Output Current	29 ADC
Maximum GA Inverter Output Current	40 A rms
Maximum GA Coil Current	75 A rms

Minimum and maximum values of k when simulated with an 800 x 800 mm aluminum shield are given in Table B5.

Table B5 - Coupling k between primary and secondary coil depending on the Z-class

Z-Class	VA	k_Min	k_Max
WPT2/Z1	Appendix A.4	0.109	0.238
WPT2/Z2	Appendix A.5	0.090	0.221
WPT2/Z3	Appendix A.6	0.087	0.229
WPT3/Z1	Appendix A.7	0.119	0.246
WPT3/Z2	Appendix A.8	0.090	0.221
WPT3/Z3	Appendix A.9	0.087	0.229

APPENDIX C - LIVE OBJECT PROTECTION (INFORMATIVE)

This appendix gives suggested guidelines for the test procedure that should be undertaken to ensure humans are protected from being exposed to EMF in excess of the ICNIRP basic restrictions. It is intended for testing and verification of live object protection (LOP) systems integrated in a Product GA.

First, the borderline where the ICNIRP limits are met when transferring power under worst case field conditions has to be determined. Then the speed of decay from turn-off of the system (detection) down to 27 uT or less is determined.

Based on informal investigations, we shall use an encroachment speed of 1000 mm/s. Therefore, the LOP safety line is the above borderline, extended by the product of the decay time in seconds and 1000 mm/s.

This border (the LOP border) is the line where detection of a mimic should happen.

C.1 SPEED OF SHUTDOWN TEST

This part of the test measures the system shutdown speed from trigger to the ICNIRP limit (27uT).

The test is undertaken under worst-case conditions; i.e., it shall take place with the system delivering full rated power to the VA on the vehicle, when the VA is under worst-case alignment as described below:

The test is undertaken with an integrated VA coil (or VA coil and vehicle mimic) positioned over the Product GA which incorporates the LOP system as submitted for validation. The vehicle or vehicle mimic is parked over the Product GA's base-pad (or "pad") while the vehicle is located at the maximum X and Y offset as shown in Figure C1. A magnetic field probe is placed over the base pad resting on the surface in a location that is expected to be a strong magnetic field.

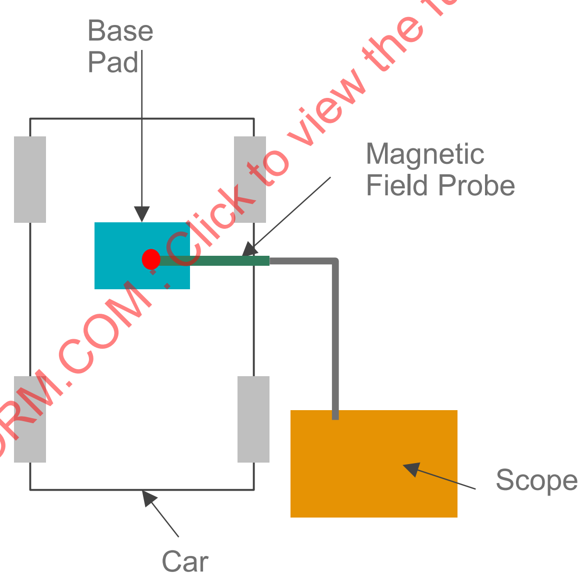


Figure C1 - Test measurement set-up for LOP

The probe is connected to a scope which is triggered by the shutdown event and which records the field decay over time. The shutdown shall be initiated without the risk of human exposure, therefore requiring a repeatable manual trigger which initiates this timing. The time signal at which the LOP system triggers is captured on the same scope as the magnetic field strength, allowing the decay of the field to be plotted and evaluated with time.

The time it takes for the field to be less than the ICNIRP limit is the decay time, used later in the process.

This test may be run several times at different GA surface locations to ensure that the decay time determined is the longest that is expected.

C.2 DETERMINING THE LOP BORDERS

Using the same setup, with the GA transferring maximum power, determine the line around the periphery of the GA where the fields, while transferring maximum power, are at the ICNIRP 27uT limit. This line is the LOP border.

Once the above tests are completed, using an encroachment speed, informally experimentally determined, of 1000 mm/s and the decay time determined above, determine the product of the decay time and 1000 mm/s to arrive at the distance outside the LOP border, determined above, that a live object shall be detected. This is the detection line.

C.3 HUMAN MIMIC

It would be dangerous to use a human to trigger the system for these tests. Therefore, a mimic is needed, something that will reasonably represent a not-so-easy-to-detect human limb.

A 5 cm diameter sphere, filled with water, has been selected as a reasonable mimic of a child's hand, based on size, yet reasonably easy to replicate.

C.4 LOP TEST

The purpose of this test is to verify, based on the above determinations, that the mimic is detected before it reaches the detection line. This test can be done without power being transferred.

Using the mimic, verify that the LOP system triggers before the test object goes over the detection line at several locations around the periphery of the GA. If detection triggering occurs reliably, the LOP system could be considered reliable.

APPENDIX D - PARKING SPACE DEFINITION GUIDELINE (INFORMATIVE)

D.1 SAE J2954 PARKING SPACE GLOBAL SURVEY

The following diagram shows the results of the SAE J2954 parking space global survey.

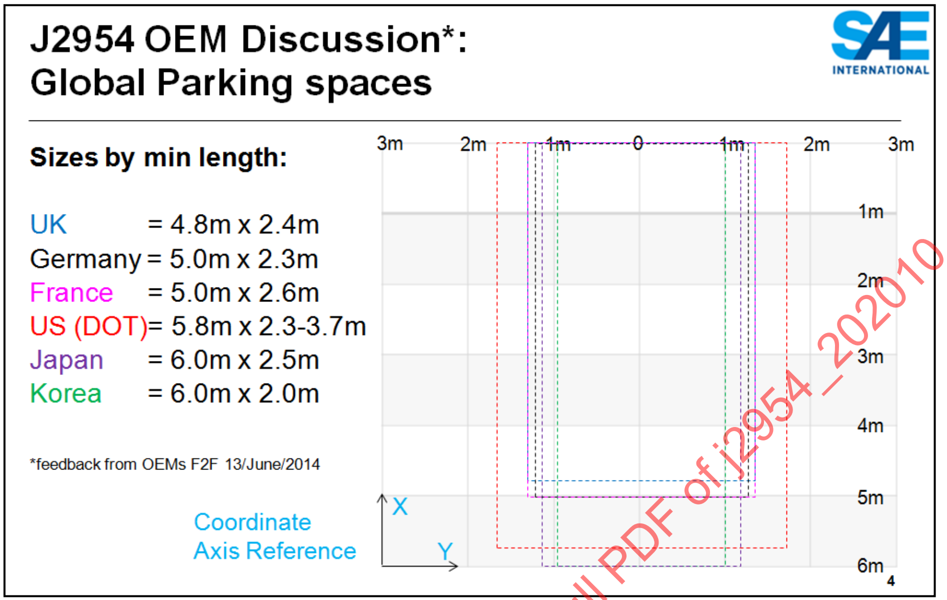


Figure D1 - SAE J2954 OEM survey for GA location in parking space

The following diagram shows the effects of the GA center point in the X-axis.

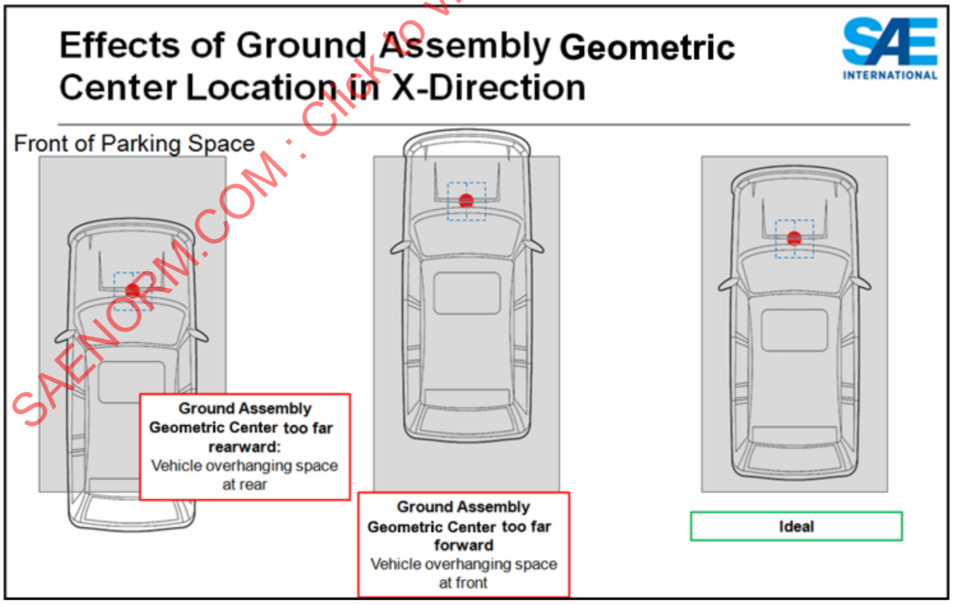


Figure D2 - Effect of incorrect GA location in parking space

APPENDIX E - UL REFERENCE STANDARDS FOR GROUND ASSEMBLY TESTING (INFORMATIVE)

Test Name	Description	Standard Reference
Input Test	Verification of nameplate ratings.	UL 2202, Section 49 UL 2594, Section 48
Leakage Current	Measurement of currents available to the user on accessible surfaces (applied to cord connected devices).	UL 2202, Section 47 UL 2594, Section 46
Leakage Current after Humidity	Measurement of currents available to the user on accessible surfaces after humidity conditioning (applied to cord connected devices).	UL 2202, Section 48 UL 2594, Section 47
Temperature	Verification that rated temperatures or components and materials are not exceeded during normal operation.	UL 2202, Section 50 UL 2594, Section 49
Capacitor Discharge	Verification that GA input capacitors due not retain a charge sufficient to shock the user (applied to cord connected devices).	UL 2594, Section 50
Dielectric Strength	Verification that insulation and physical spacing are sufficient to prevent a dielectric breakdown between specific parts.	UL 2202, Section 51 UL 2594, Section 51
Transformer Burnout	As an abnormal condition, transformers (not previously tested) are caused to go into burnout condition to verify there is no shock or fire hazard caused by the condition.	UL 2202, Section 53.2 UL 2594, Section 52.2
Transformer Overload	As an abnormal condition, transformers (not previously tested) are intentionally overloaded to verify there is no shock or fire hazard caused by the condition.	UL 2202, Section 53.3 UL 2594, Section 52.3
Forced Ventilation	Equipment with ventilation openings are allowed to operate with ventilation blocked to verify that no fire or shock will occur if used in this manner.	UL 2202, Section 53.7 UL 2594, Section 52.6
Component Faults	Verification that short circuit or open circuit at various components will not cause a fire or shock hazard.	UL 2202, Section 53.8 UL 2594, Section 52.7
Strain Relief	Verification that the means to secure a cord or cable to a device will withstand a pull force without causing any strain on internal connections.	UL 2202, Section 55 UL 2594, Section 54
Grounding Impedance	Verifies that the grounding path, from any exposed metal part to the main earth terminal of the equipment, has a resistance of less than 0.1 Ω.	UL 2202, Section 57 UL 2594, Section 56.1
Ground Continuity	Verifies that all parts that are intended to be grounded have a continuous path to ground without interruption.	UL 2594, Section 56.2
Impact Test	A test performed on materials to verify that a dropped object will not impact the enclosure and dent, break, or crack the enclosure material to the point that spacings are reduced to below acceptable levels or that exposure to live parts is allowed.	UL 2594, Section 57
Vehicle Drive Over	A test performed on materials used in the GA coil package to verify that the enclosure will not crack or break to the point that exposure to live parts is allowed, or to the point where water can enter the enclosure and wet live parts, when a vehicle drives over the GA coil package.	UL 2594, Section 58
Drop Test	For any portion of the device that is considered moveable and is intended to be carried by hand, the device is dropped and there can be no fire or shock hazard that develops from damage or other deterioration associated with the drop.	UL 2594, Section 59
Mounting Means	For any device that is intended to mount on a wall, post, or ceiling, a test is performed to verify that the device will not fall from its supporting/mounting means, and that the wall itself is not damaged to the point where the mounting is compromised.	UL 2594, Section 64
Bonding Conductor Test	If conductors used in the device to provide bonding of accessible metal parts are sized smaller than the main earth conductor, then this test verifies that a fault current will not open a bonding conductor and leave accessible metal parts isolated from earth.	UL 2202, Section 60
Mold Stress	For plastic enclosures, this test verifies that an oven aging will not deteriorate or damage the enclosure to the point that live parts are accessible or that ingress of water protection is affected.	UL 2594, Section 66
Chemical Exposure	For GA coil packages, the material has the potential of being subjected to automotive chemicals. This test verifies that the enclosure material is not deteriorated or damaged due to exposure to the chemicals.	UL 2594, Section 67.4
Rain Test	This test is used to verify that the power source is acceptable for outdoor use (indoor use only enclosures need not be tested). A simulated rain falls on the device and no water can wet live parts.	UL 2202, Section 83.1

APPENDIX F - WPT1 INTEROPERABILITY CLASS II TEST STATION GA (INFORMATIVE)

F.1 EXAMPLE GA WPT1 (INFORMATIVE)

This appendix provides the mechanical and electrical design specifications of the GA WPT1.

NOTE: Specifications designed for optimal operation with the Test Station VA WPT1/Z1 (Appendix A.1), the Test Station VA WPT1/Z2 (Appendix A.2), and the Test Station VA WPT1/Z3 (Appendix A.3).

F.1.1 Mechanical Specification

Figures F1, F2, F3, F4, and F5 show the mechanical dimensions of the GA WPT1.

The ferrite tiles are made using N96 (TDK).

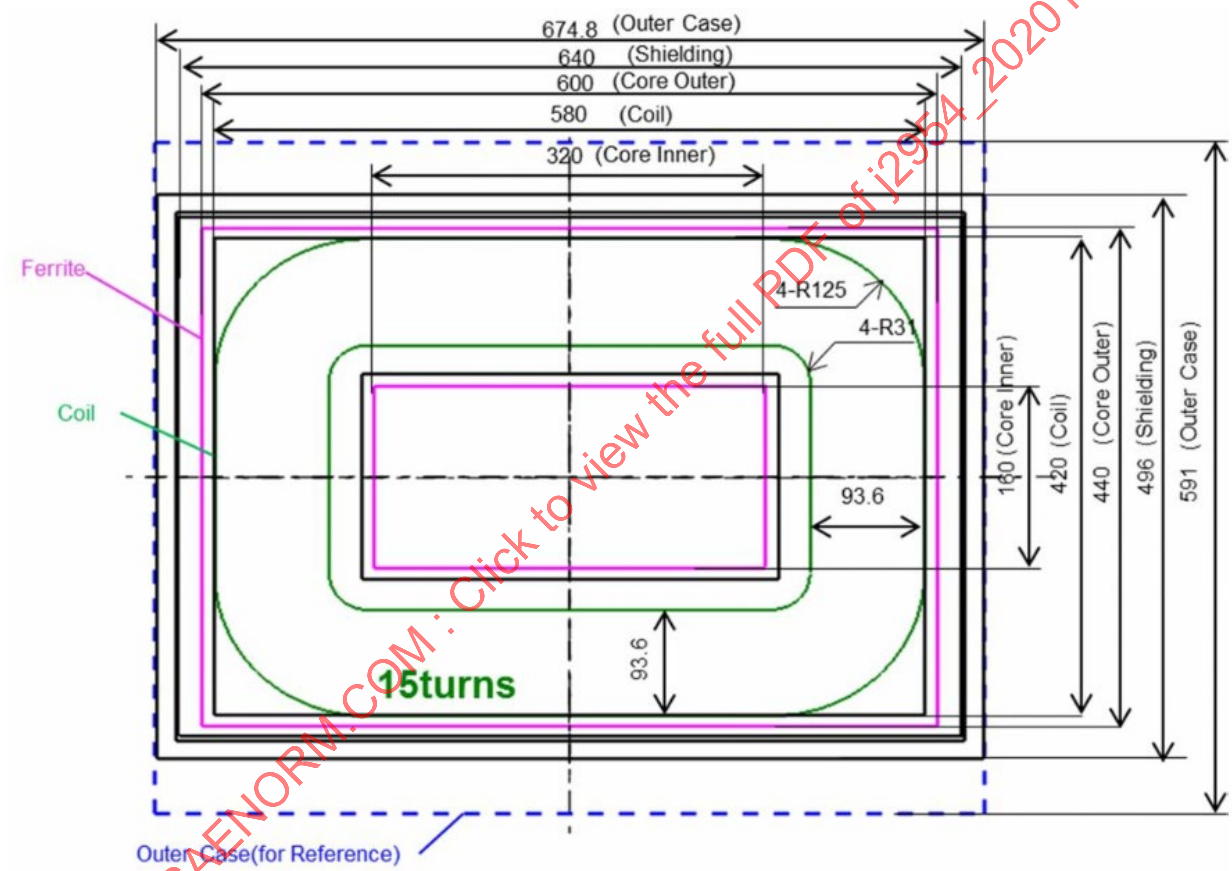


Figure F1 - Mechanical dimensions of the GA WPT1

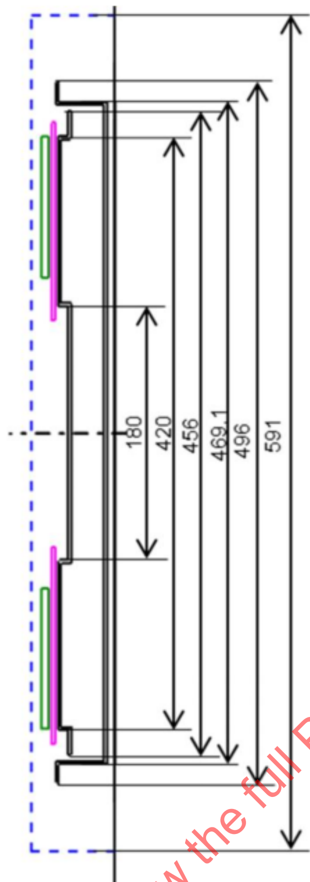


Figure F2 - Mechanical dimensions of the GA WPT1

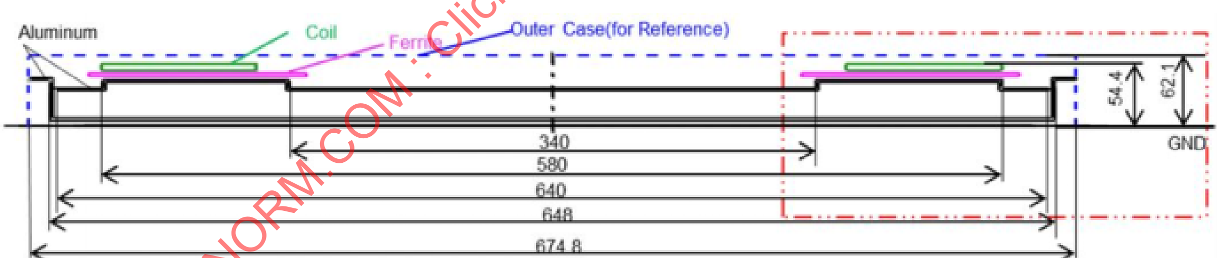


Figure F3 - Mechanical dimensions of the GA WPT1

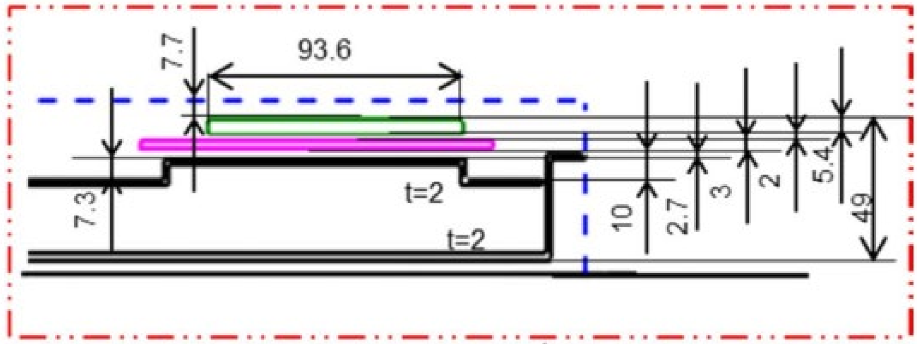


Figure F4 - Detailed cross-section view

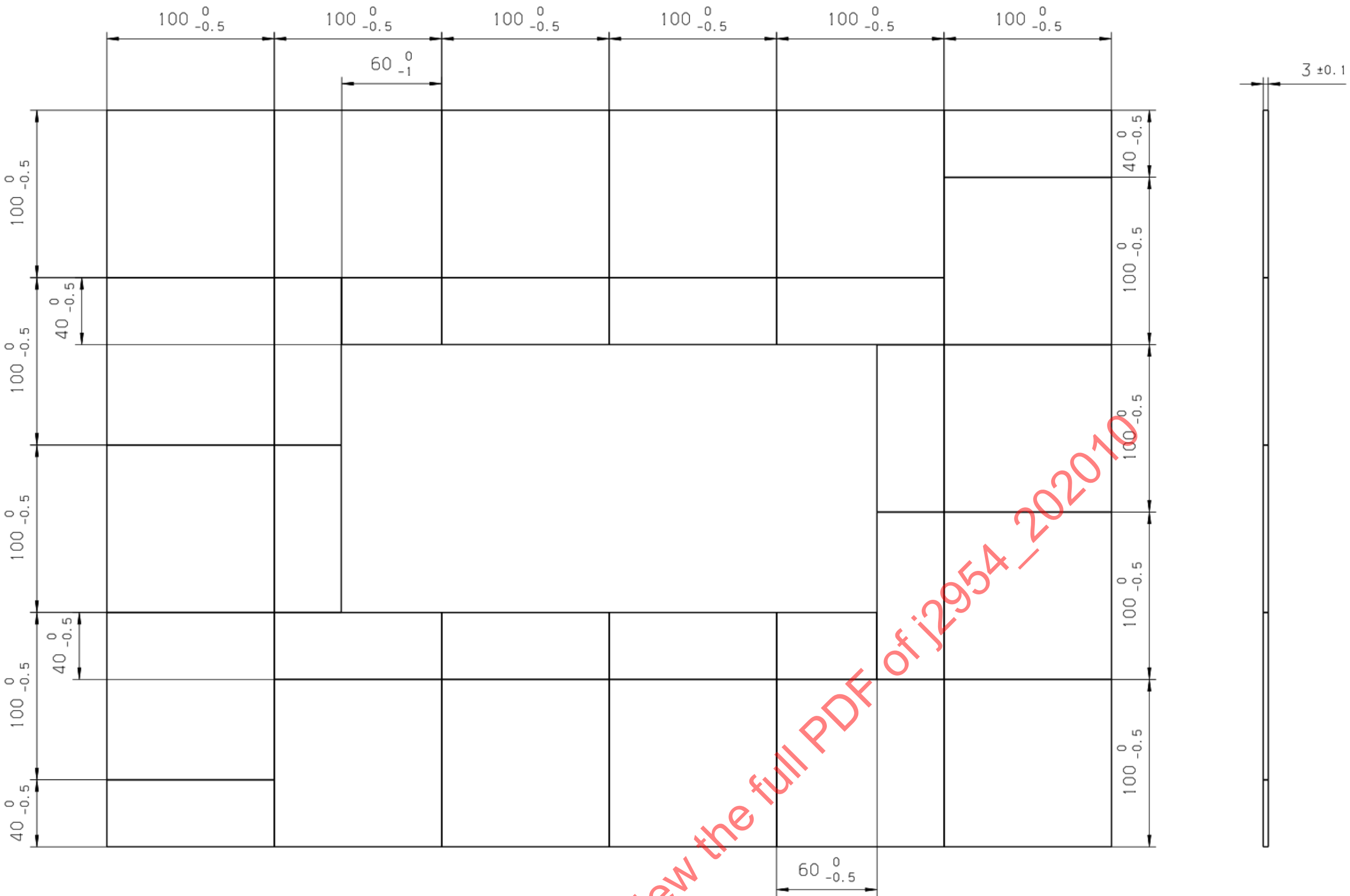


Figure F5 - Detail of the ferrite core construction

F.1.2 Electrical Specification

Figure F6 shows the electrical specification of the GA WPT1.

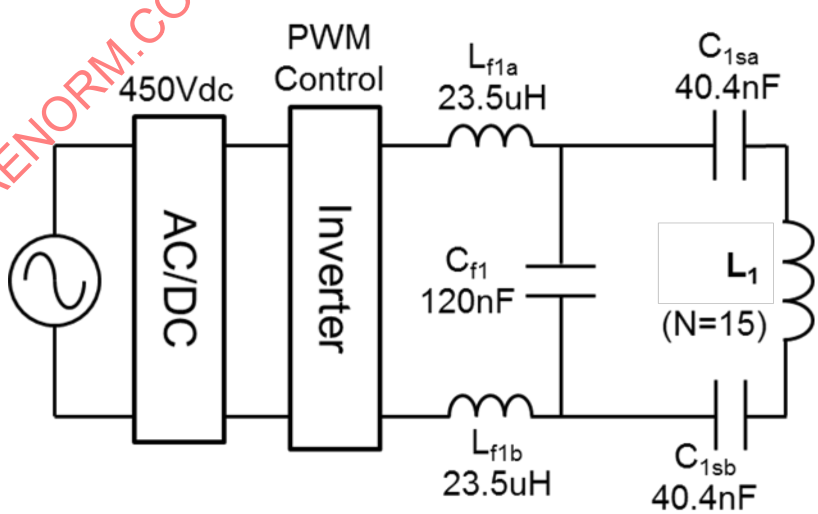


Figure F6 - Electrical specification of the GA WPT1

Table F1 - Maximum values of currents

Maximum PFC Output Current	9 ADC
Maximum GA Inverter Output Current	30 A rms
Maximum GA Coil Current	30 A rms

Minimum and maximum values of L1 are given in Table F2.

Table F2 - Primary coil inductance L1 depending on the Z-class

Z-Class	VA	L_1 Min [μH]	L_1 Max [μH]
Z1	Appendix A.1	185	217
Z2	Appendix A.2	212	223
Z3	Appendix A.3	224	227

Minimum and maximum values of k are given in Table F3.

Table F3 - Coupling k between primary and secondary coil depending on the Z-class

Z-Class	VA	k Min	k Max
Z1	Appendix A.1	0.100	0.249
Z2	Appendix A.2	0.085	0.221
Z3	Appendix A.3	0.084	0.243

APPENDIX G - EXAMPLE PRODUCT VA SPECIFICATIONS (INFORMATIVE)

G.1 PRODUCT VA WPT2/Z1

This appendix provides the mechanical and electrical design specifications of a Product VA for power class WPT2 and gap class Z1 (VA WPT2/Z1).

NOTE: The specifications are designed for optimal operation with the example Product GA WPT2 specified in Appendix H.1.

G.1.1 MECHANICAL SPECIFICATION

Figure G1 shows the mechanical dimensions of the Product VA WPT2/Z1. For clarity, the housing is not shown. The VA orientation on the vehicle is indicated by the icon on the left.

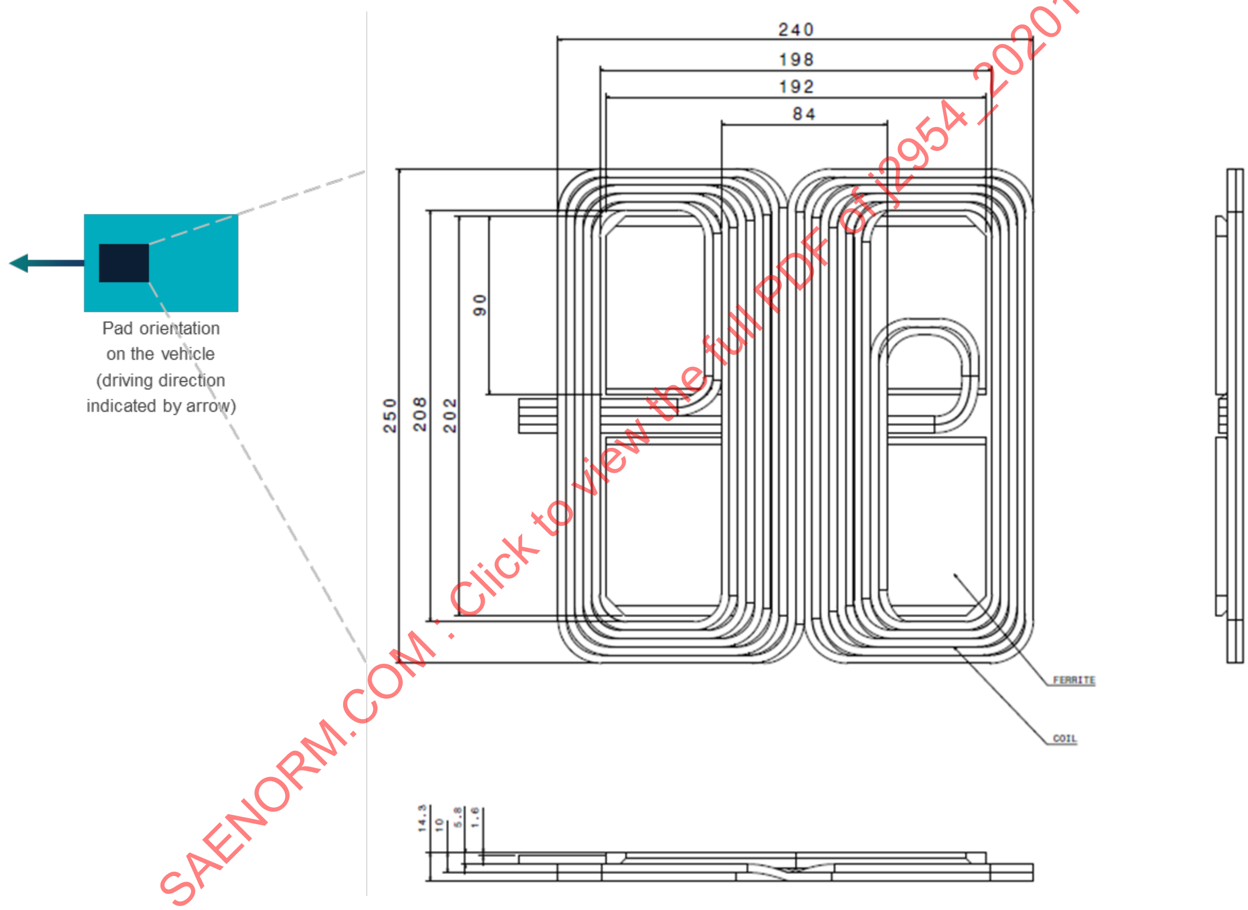


Figure G1 - Mechanical dimensions of the Product VA WPT2/Z1

Figure G2 shows a detailed cross-section view (including housing and an assumed vehicle shield thickness of 2 mm).

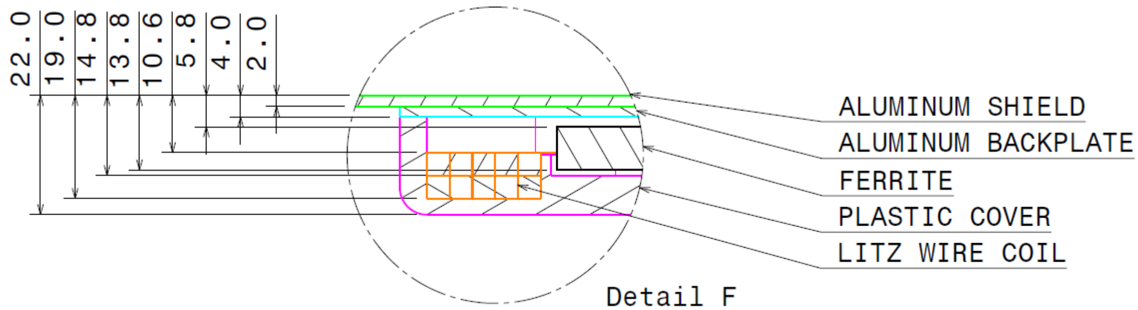


Figure G2 - Detailed cross-section view of the Product VA WPT2/Z1

Table G1 shows the mechanical dimensions of the Product VA WPT2/Z1.

Table G1 - Mechanical dimensions of the Product VA WPT2/Z1

	Coil + Ferrite Only	**Housing (w/o Vehicle Shield)**
L x W x H [mm]	240 x 250 x 13.3	250 x 260 x 20

G.1.2 Electrical Specification

The VA is made using ferrite tiles of N96 or similar. Coupling and inductances listed are achieved when an aluminum shield of 1.1 m x 1.1 m x 0.76 mm to 1 mm thick is used per the drawing.

The system is tuned for a fixed frequency operation at f = 85 kHz. Frequency tuning to compensate, e.g., for height and alignment variation, is not required.

Figure G3 shows the electrical specification of this VA. Typical currents and voltages for the WPT2 power class are indicated in the block diagram.

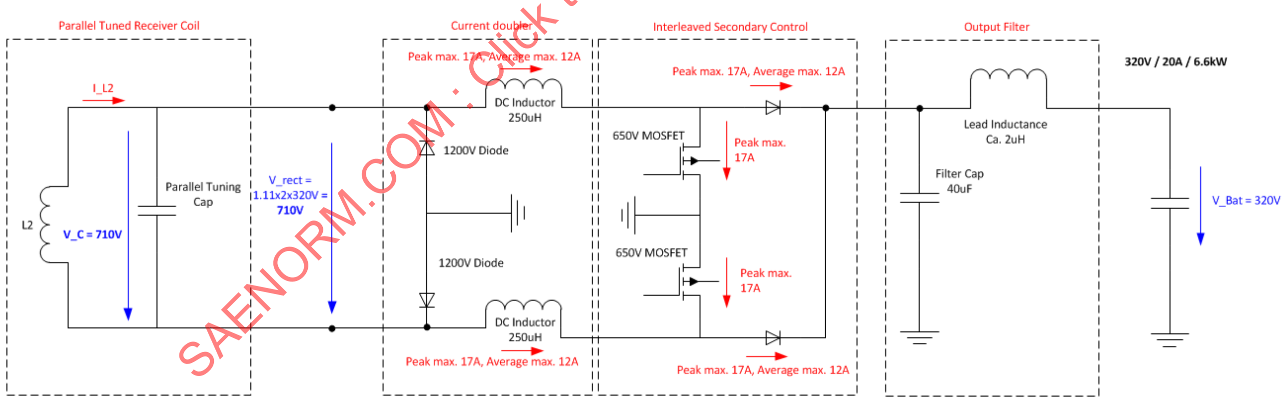


Figure G3 - Electrical specification of the Product VA WPT2/Z1

Values of secondary tuning capacitor C and minimum and maximum values of secondary coil inductance L2 are given in Table G2.

Table G2 - Secondary coil inductance L2 and secondary tuning capacitor C

L_Min [µH]	24.2
L_Max [µH]	26.2
C [nF]	145

G.2 PRODUCT VA WPT2/Z2

This appendix provides the mechanical and electrical design specifications of a Product VA for power class WPT2 and gap class Z2 (VA WPT2/Z2).

NOTE: The specifications are designed for optimal operation with the example Product GA WPT2 specified in Appendix H.1.

G.2.1 MECHANICAL SPECIFICATION

Figure G4 shows the mechanical dimensions of the Product VA WPT2/Z2. For clarity, the housing is not shown. The VA orientation on the vehicle is indicated by the icon on the left.

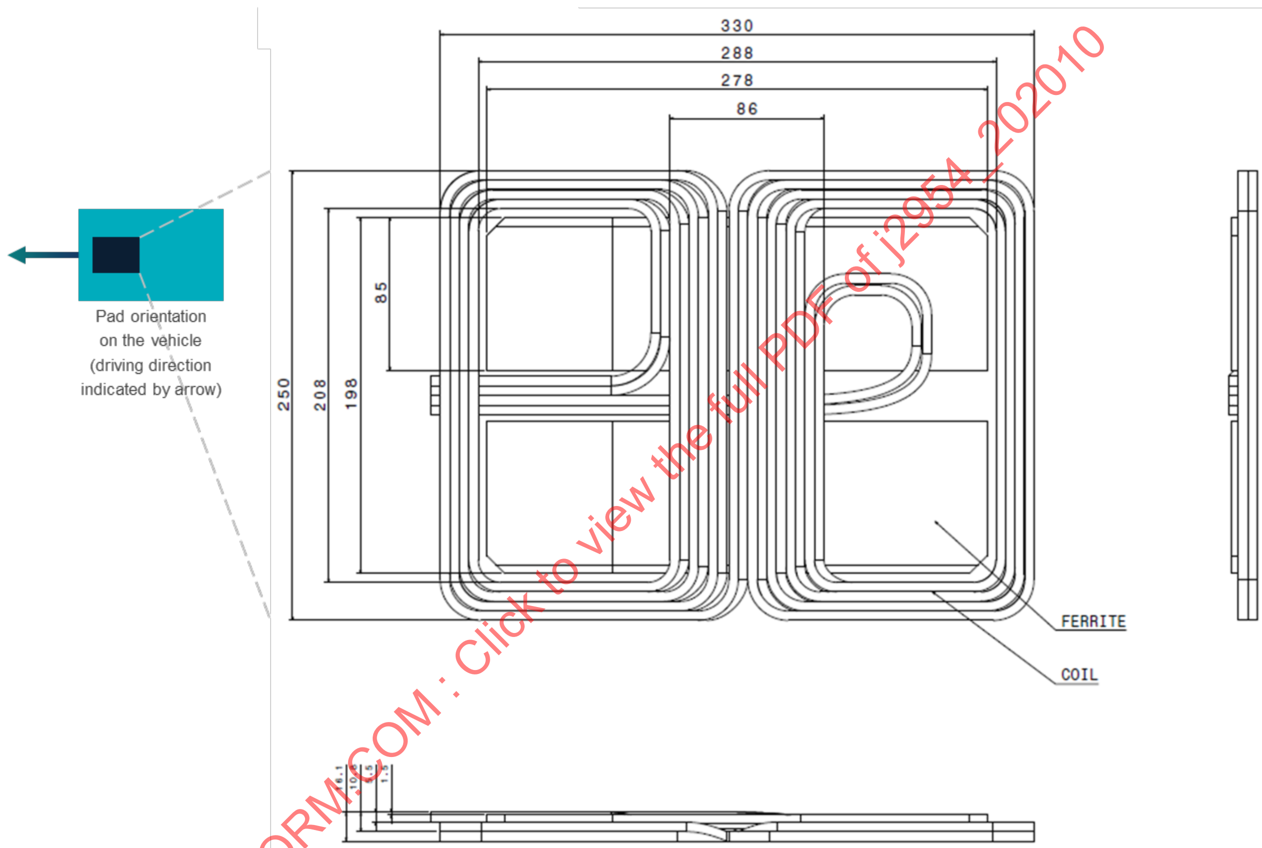


Figure G4 - Mechanical dimensions of the Product VA WPT2/Z2

Figure G5 shows a detailed cross-section view of the Product VA WPT2/Z2 (including housing and an assumed vehicle shield thickness of 2 mm).

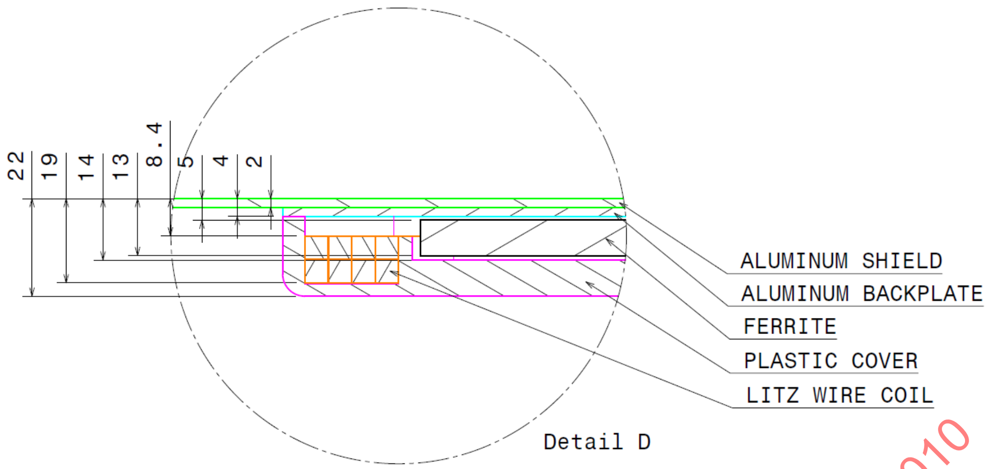


Figure G5 - Detailed cross-section view of the Product VA WPT2/Z2

Table G3 shows the mechanical dimensions of the Product VA WPT2/Z2.

Table G3 - Mechanical dimensions of the Product VA WPT2/Z2

	Coil + Ferrite Only	**Housing (w/o Vehicle Shield)**
L x W x H [mm]	330 x 250 x 16	340 x 260 x 20

G.2.2 Electrical Specification

The VA is made using ferrite tiles of N96 or similar. Coupling and inductances listed are achieved when an aluminum shield of 1.1 m x 1.1 m x 0.76 mm to 1 mm thick is used per the drawing.

The system is tuned for a fixed frequency operation at f = 85 kHz. Frequency tuning to compensate, e.g., for height and alignment variation, is not required.

Figure G6 shows the electrical specification of the Product VA WPT2/Z2. Typical currents and voltages for the WPT2 power class are indicated in the block diagram.

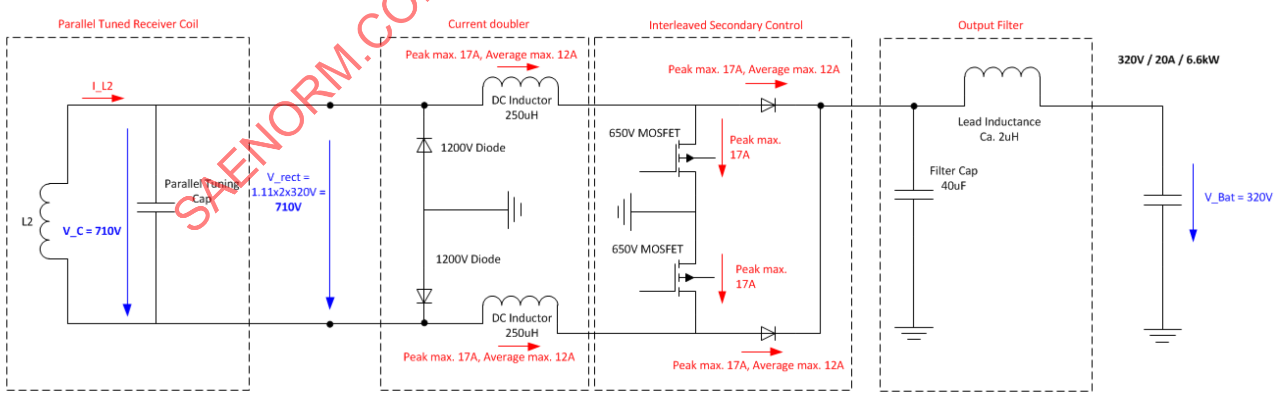


Figure G6 - Electrical specification of the Product VA WPT2/Z2.
Values of secondary tuning capacitor C and minimum and maximum values of secondary coil inductance L2 are given in Table G4.

Table G4 - Secondary coil inductance L2 and secondary tuning capacitor C

L_Min [µH]	19.5
L_Max [µH]	20.5
C [nF]	181

G.3 PRODUCT VA WPT2/Z3

This appendix provides the mechanical and electrical design specifications of a Product VA for power class WPT2 and gap class Z3 (VA WPT2/Z3).

NOTE: The specifications are designed for optimal operation with the example Product GA WPT2 specified in Appendix H.1.

G.3.1 MECHANICAL SPECIFICATION

Figure G7 shows the mechanical dimensions of the Product VA WPT2/Z3. For clarity, the housing is not shown. The VA orientation on the vehicle is indicated by the icon on the left.

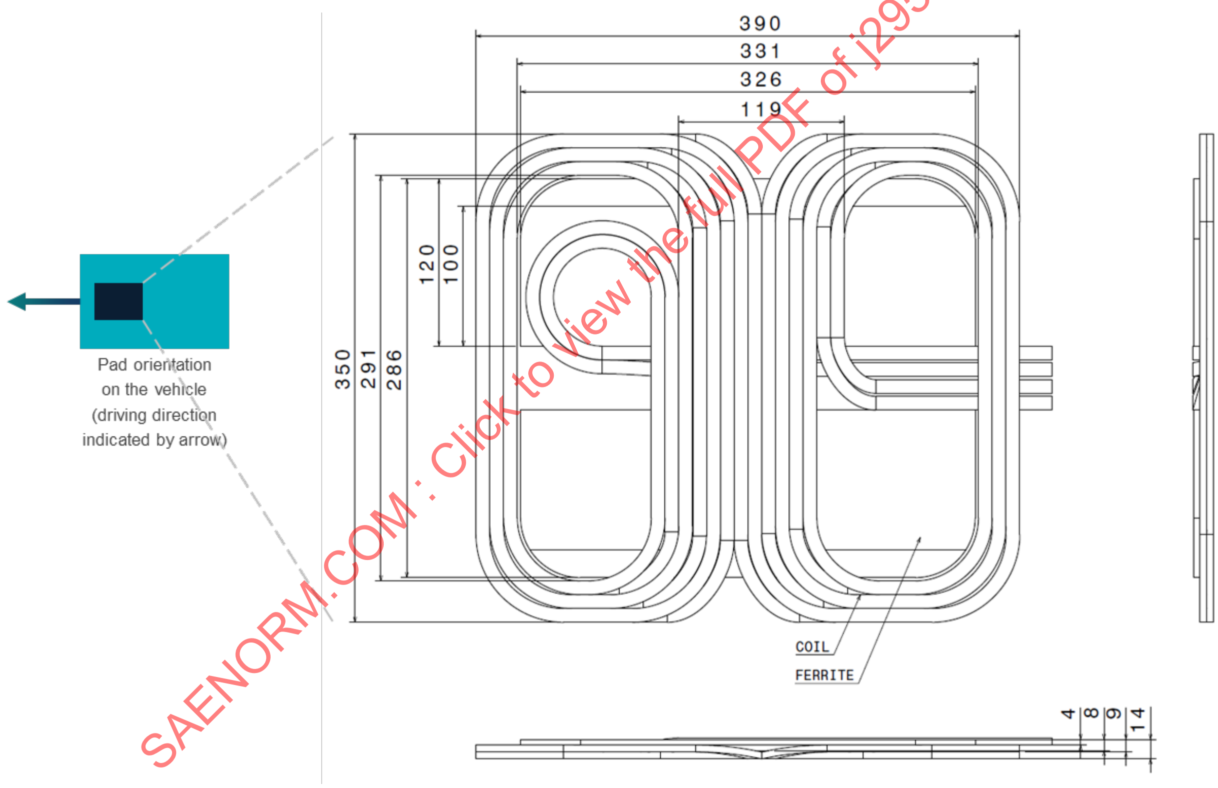


Figure G7 - Mechanical dimensions of the Product VA WPT2/Z3

Figure G8 shows a detailed cross-section view of the Product VA WPT2/Z3 (including housing and an assumed vehicle shield thickness of 2 mm).

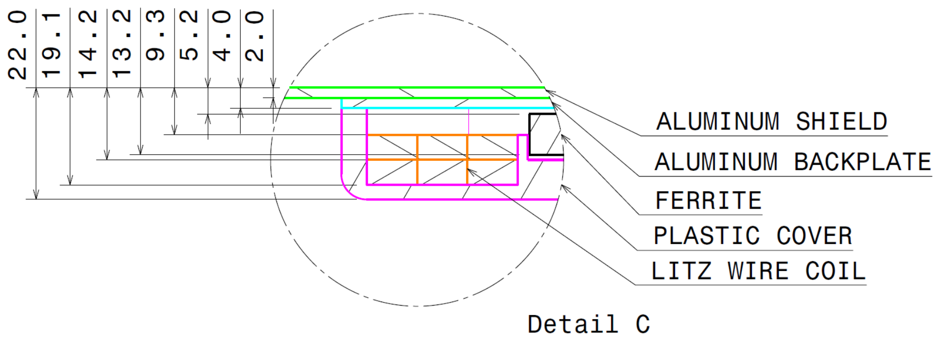


Figure G8 - Detailed cross-section view of the Product VA WPT2/Z3

Table G5 shows the mechanical dimensions of the Product VA WPT2/Z3.

Table G5 - Mechanical dimensions of the Product VA WPT2/Z3

	Coil + Ferrite Only	**Housing (w/o Vehicle Shield)**
L x W x H [mm]	390 x 350 x 14	400 x 360 x 20

G.3.2 Electrical Specification

The VA is made using ferrite tiles of N96 or similar. Coupling and inductances listed are achieved when an aluminum shield of 1.1 m x 1.1 m x 0.76 mm to 1 mm thick is used per the drawing.

The system is tuned for a fixed frequency operation at f = 85 kHz. Frequency tuning to compensate, e.g., for height and alignment variation, is not required.

Figure G9 shows the electrical specification of the Product VA WPT2/Z3. Typical currents and voltages for the WPT2 power class are indicated in the block diagram.

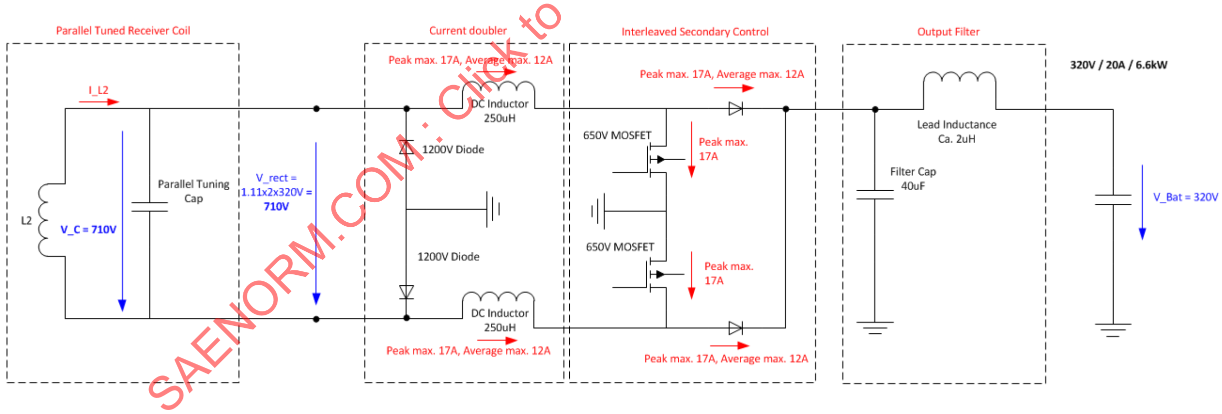


Figure G9 - Electrical specification of the Product VA WPT2/Z3

Values of the secondary tuning capacitor C and minimum and maximum values of secondary coil inductance L2 are given in Table G6.

Table G6 - Secondary coil inductance L2 and secondary tuning capacitor C

L_Min [µH]	13.5
L_Max [µH]	14.2
C [nF]	250

G.4 PRODUCT VA WPT3/Z1

This appendix provides the mechanical and electrical design specifications of a Product VA for power class WPT3 and gap class Z1 (VA WPT3/Z1).

NOTE: The specifications are designed for optimal operation with the example Product GA WPT3 specified in Appendix H.2.

G.4.1 MECHANICAL SPECIFICATION

Figure G10 shows the mechanical dimensions of the ferrite and the coil for the VA WPT3/Z1. For clarity, the housing is not shown. The VA orientation on the vehicle is indicated by the icon on the left.

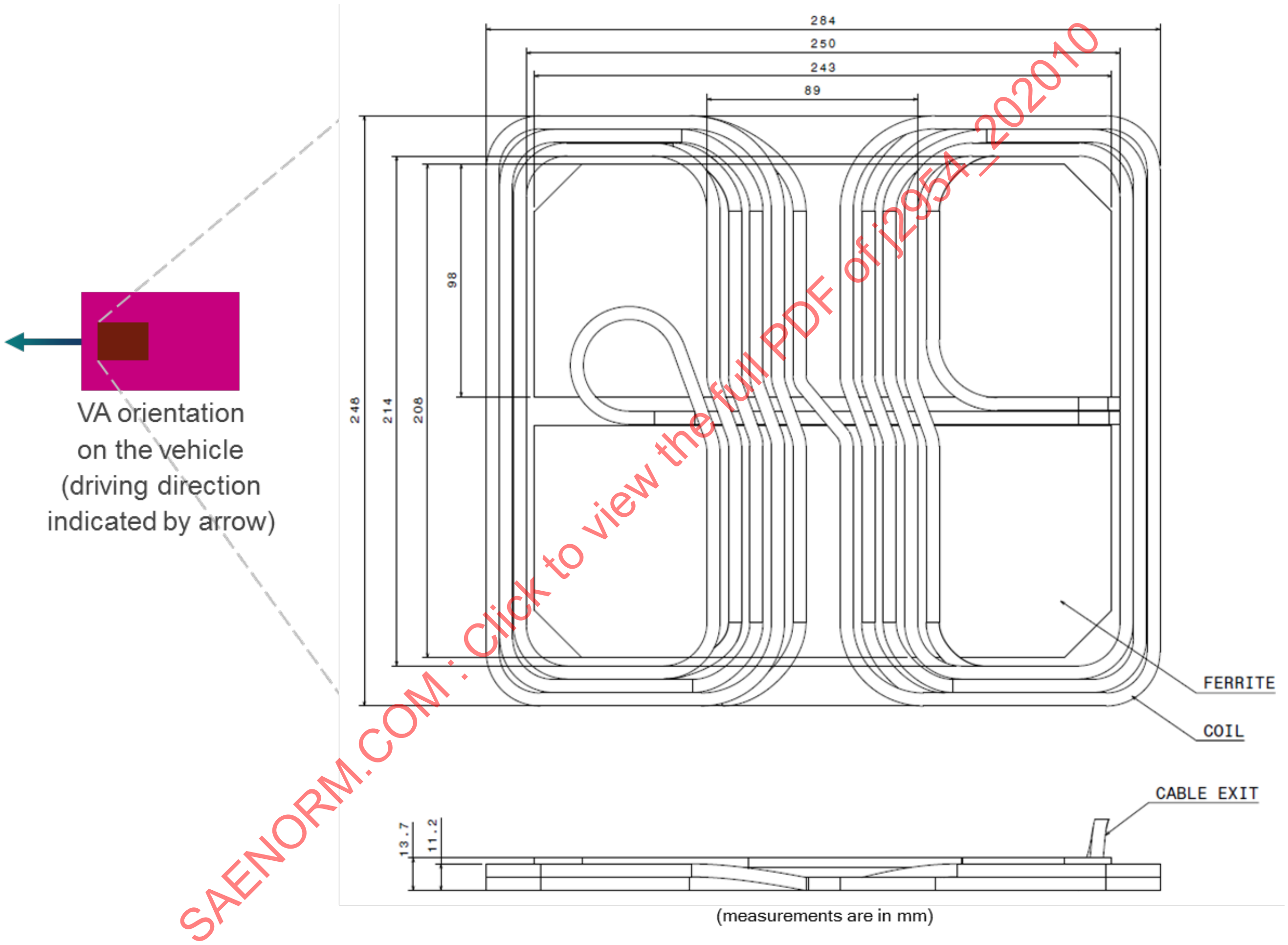


Figure G10 - Mechanical dimensions of the Product VA WPT3/Z1

Figure G11 shows a detailed cross-section view of the Product VA WPT3/Z1 (including housing and an assumed vehicle shield thickness of 2 mm). The Product VA WPT3/Z1 has four turns (bifilar).

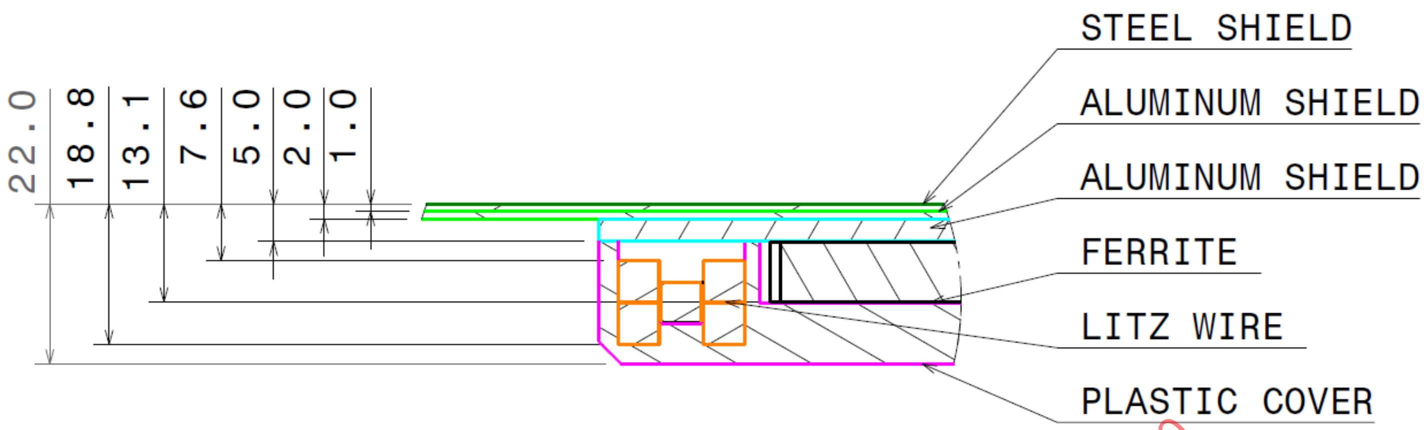


Figure G11 - Detailed cross-section view of the Product VA WPT3/Z1

Table G7 shows the mechanical dimensions of the VA WPT3/Z1.

Table G7 - Mechanical dimensions of the VA WPT3/Z1

	Coil + Ferrite Only	Housing (w/o Vehicle Shield)
L x W x H [mm]	284 x 248 x 13.7	302 x 302 x 20

G.4.2 Electrical Specification

The VA is made using ferrite tiles of N96 or similar. Coupling and inductances listed are achieved when an aluminum shield of 1.1 m x 1.1 m x 0.76 mm to 1 mm thick is used per the drawing.

The system is tuned for a fixed frequency operation at f = 85 kHz. Frequency tuning to compensate, e.g., for height and alignment variation, is not required.

Figure G12 shows the electrical specification of this VA. Typical currents and voltages for the WPT3 power class are indicated in the block diagram.

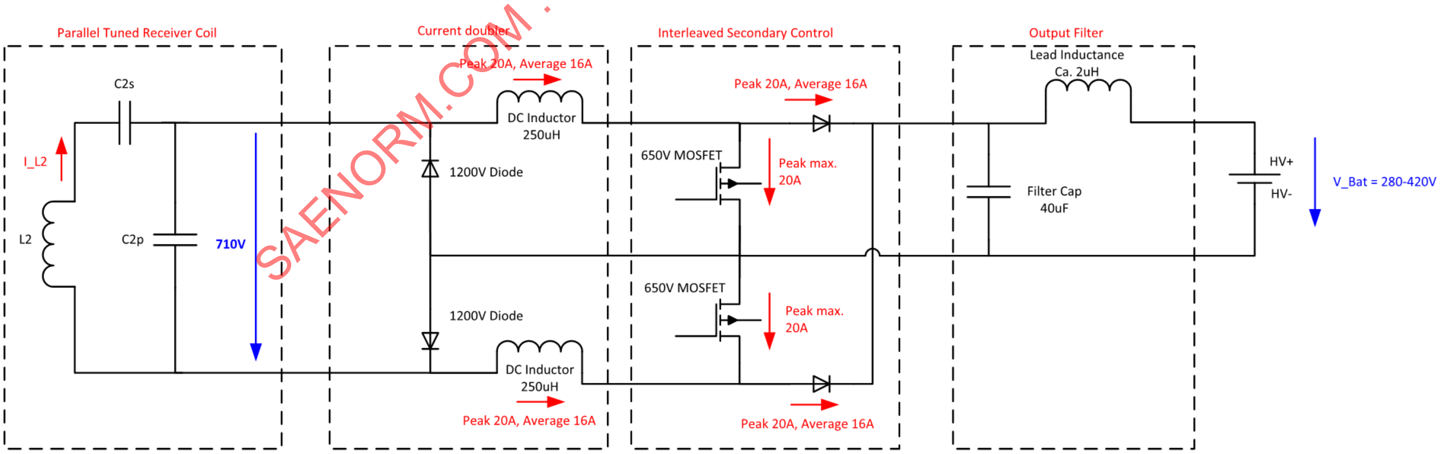


Figure G12 - Electrical specification of the Product VA WPT3/Z1

Values of secondary tuning capacitor C and minimum and maximum values of secondary coil inductance L2 are given in Table G8.

Table G8 - Secondary coil inductance L2 and secondary tuning capacitor C

L_Min [µH]	27.1
L_Max [µH]	29.4
C2s/C2p [nF]	517/169

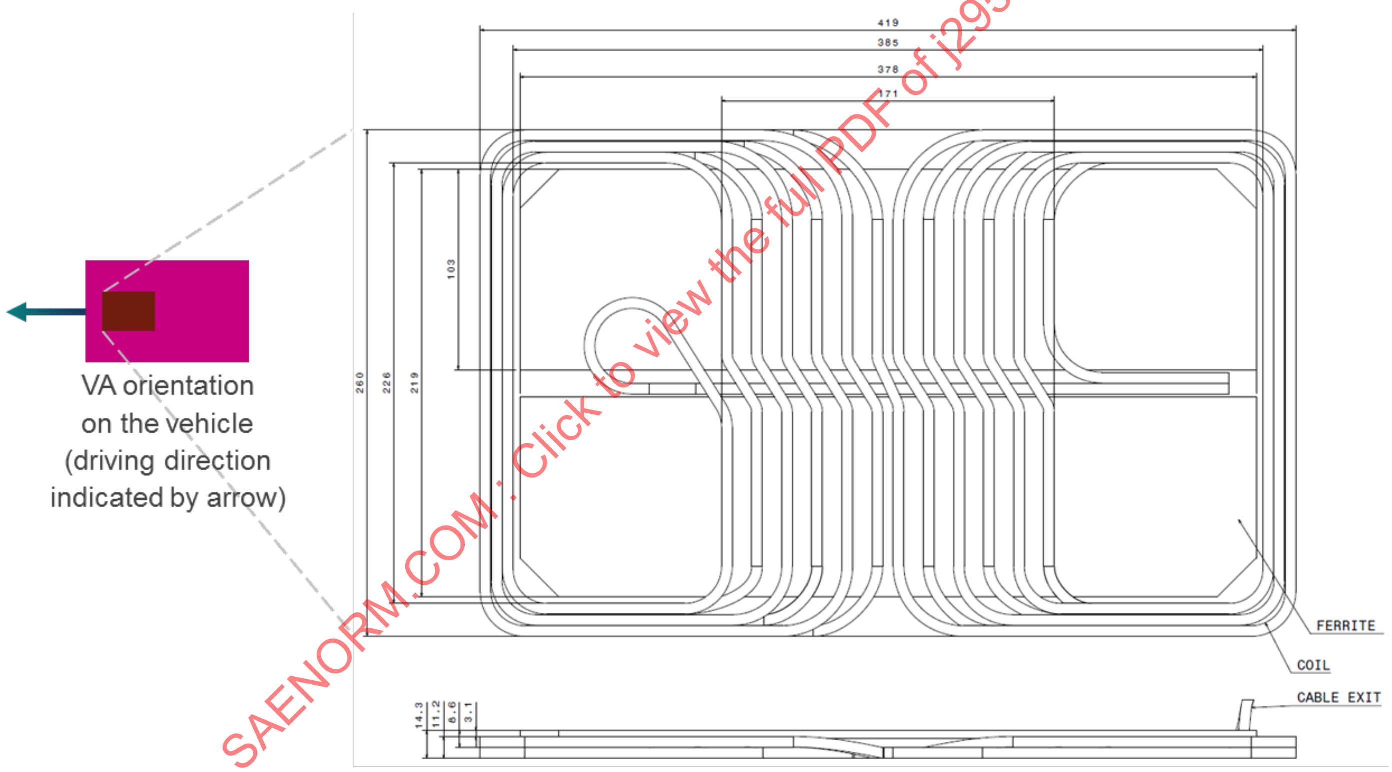
G.5 PRODUCT VA WPT3/Z2

This appendix provides the mechanical and electrical design specifications of a Product VA for power class WPT3 and gap class Z2 (VA WPT3/Z2).

NOTE: The specifications are designed for optimal operation with the example Product GA WPT3 specified in Appendix H.2.

G.5.1 MECHANICAL SPECIFICATION

Figure G13 shows the mechanical dimensions of the ferrite and the coil for the Product VA WPT3/Z2. For clarity, the housing is not shown. The VA orientation on the vehicle is indicated by the icon on the left.



(measurements are in mm)

Figure G13 - Mechanical dimensions of the Product VA WPT3/Z2

Figure G14 shows a detailed cross-section view of the Product VA WPT3/Z2 (including housing and an assumed vehicle shield thickness of 2 mm). The Product VA WPT3/Z2 has three turns (bifilar).

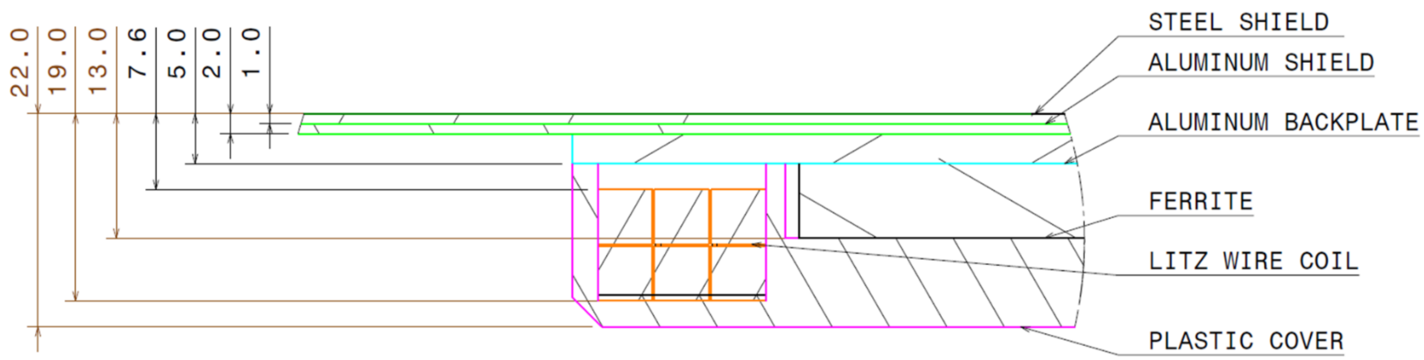


Figure G14 - Detailed cross-section view of the Product VA WPT3/Z2

Table G9 shows the mechanical dimensions of the Product VA WPT3/Z2.

Table G9 - Mechanical dimensions of the Product VA WPT3/Z2

	Coil + Ferrite Only	Housing (w/o Vehicle Shield)
L x W x H [mm]	419 x 260 x 14.3	438 x 302 x 20

G.5.2 Electrical Specification

The VA is made using ferrite tiles of N96 or similar. Coupling and inductances listed are achieved when an aluminum shield of 1.1 m x 1.1 m x 0.76 mm to 1 mm thick is used per the drawing.

The system is tuned for a fixed frequency operation at f = 85 kHz. Frequency tuning to compensate, e.g., for height and alignment variation, is not required.

Figure G15 shows the electrical specification of the Product VA WPT3/Z2. Typical currents and voltages for the WPT3 power class are indicated in the block diagram.

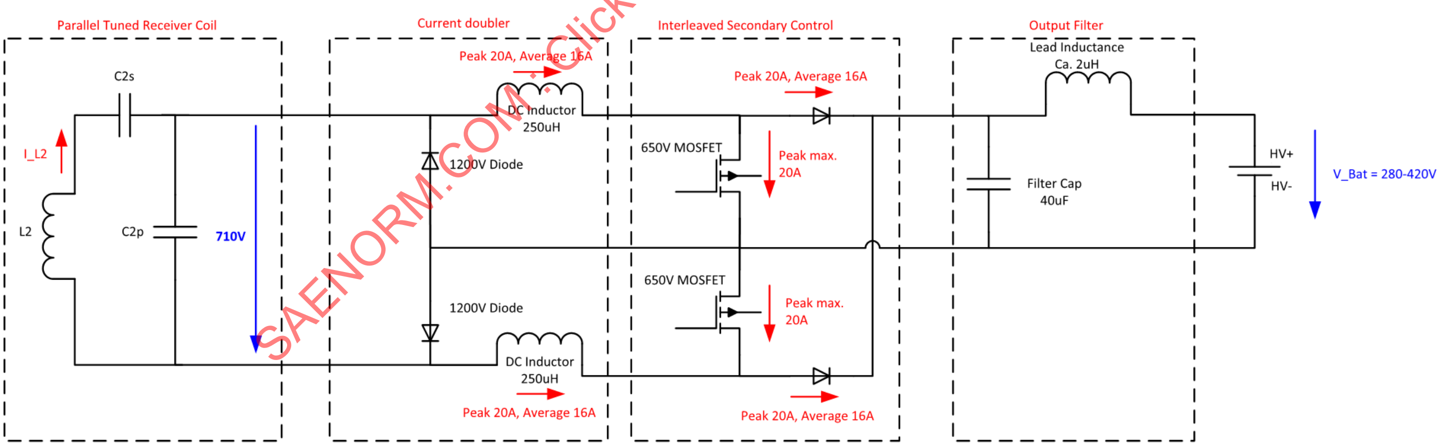


Figure G15 - Electrical specification of the Product VA WPT3/Z2.

Values of secondary tuning capacitor C and minimum and maximum values of secondary coil inductance L2 are given in Table G10.

Table G10 - Secondary coil inductance L2 and secondary tuning capacitor C

L_Min [µH]	44.7
L_Max [µH]	48.2
C2s/C2p [nF]	165/146

G.6 PRODUCT VA WPT3/Z3

This appendix provides the mechanical and electrical design specifications of a Product VA for power class WPT3 and gap class Z3 (VA WPT3/Z3).

NOTE: The specifications are designed for optimal operation with the example Product GA WPT3 specified in Appendix H.2.

G.6.1 MECHANICAL SPECIFICATION

Figure G16 shows the mechanical dimensions of the ferrite and the coil for the Product VA WPT3/Z3. For clarity, the housing is not shown. The VA orientation on the vehicle is indicated by the icon on the left.

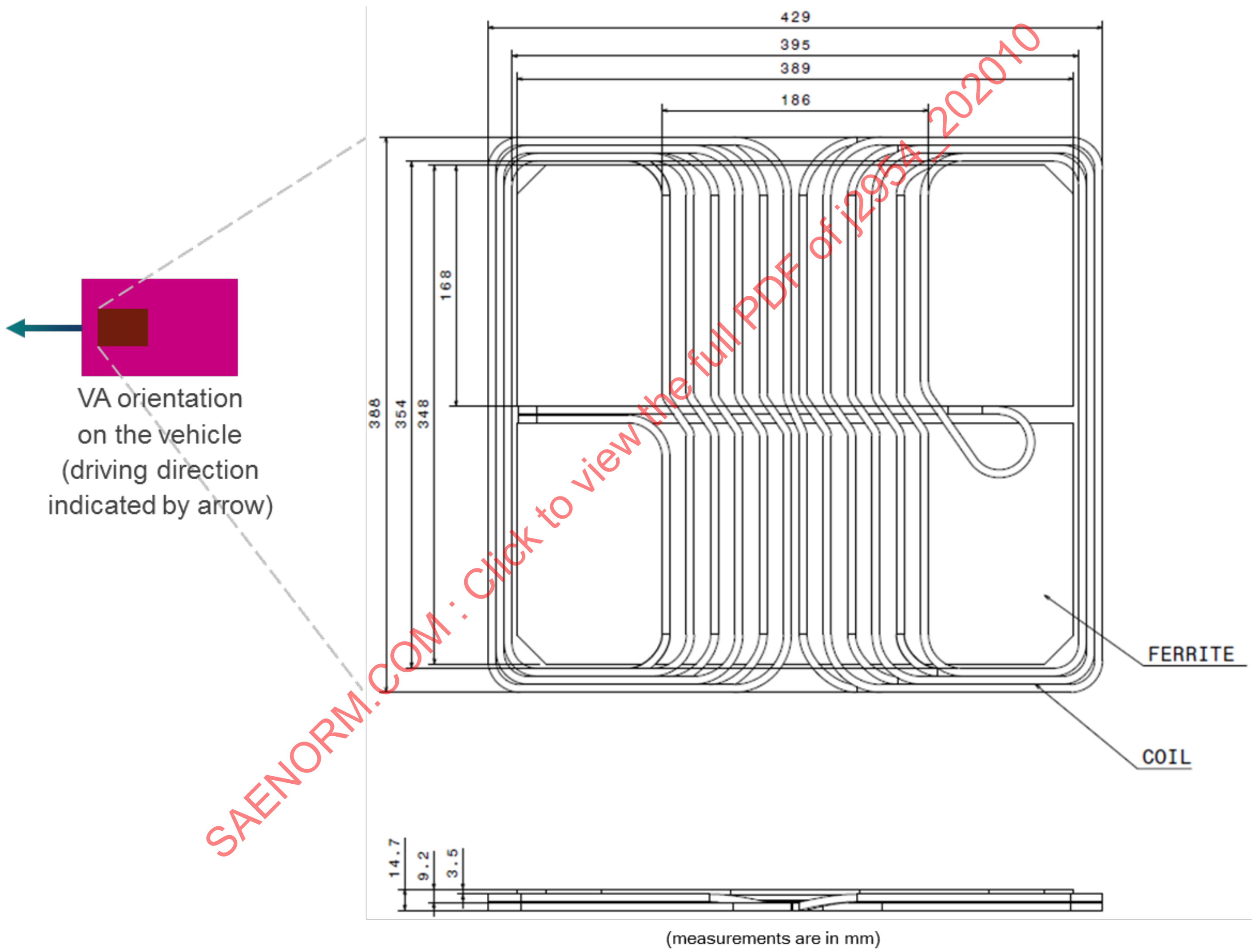


Figure G16 - Mechanical dimensions of the Product VA WPT3/Z3

Figure G17 shows a detailed cross-section view of the Product VA WPT3/Z3 (including housing and an assumed vehicle shield thickness of 2 mm). The Product VA WPT3/Z3 has three turns (bifilar).

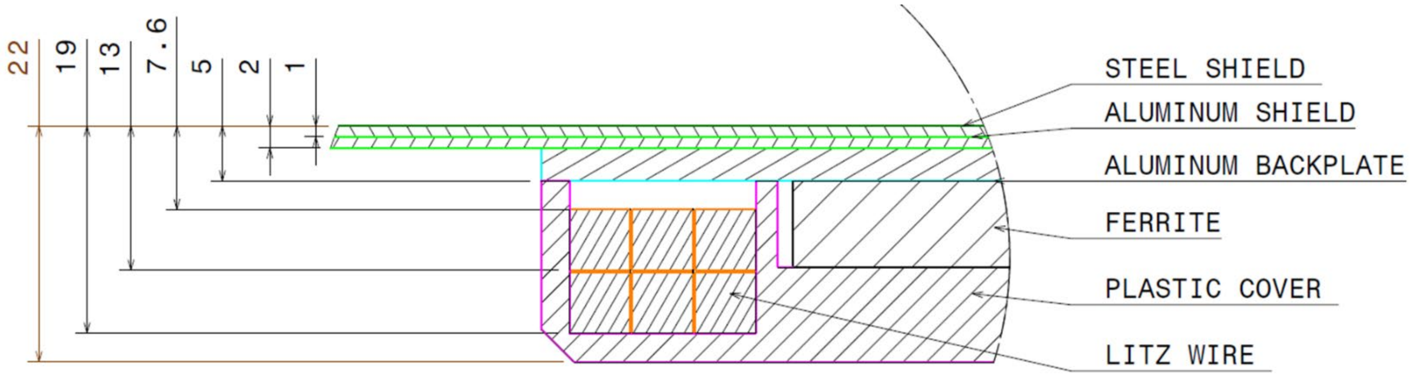


Figure G17 - Detailed cross-section view of the Product VA WPT3/Z3

Table G11 shows the mechanical dimensions of the VA WPT3/Z3.

Table G11 - Mechanical dimensions of the Product VA WPT3/Z3

	Coil + Ferrite Only	Housing (w/o Vehicle Shield)
L x W x H [mm]	429 x 388 x 14.7	449 x 442 x 20

G.6.2 Electrical Specification

The VA is made using ferrite tiles of N96 or similar. Coupling and inductances listed are achieved when an aluminum shield of 1.1 m x 1.1 m x 0.76 mm to 1 mm thick is used per the drawing.

The system is tuned for a fixed frequency operation at f = 85 kHz. Frequency tuning to compensate, e.g., for height and alignment variation, is not required.

Figure G18 shows the electrical specification of the Product VA WPT3/Z3. Typical currents and voltages for the WPT3 power class are indicated in the block diagram.

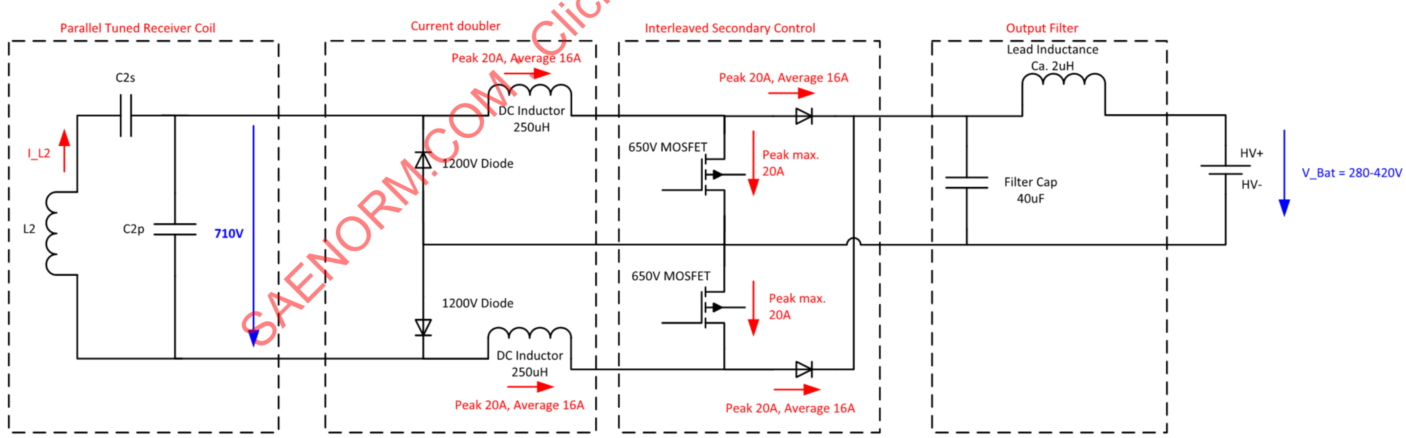


Figure G18 - Electrical specification of the Product VA WPT3/Z3

Values of the secondary tuning capacitor C and minimum and maximum values of secondary coil inductance L2 are given in Table G12.

Table G12 - Secondary coil inductance L2 and secondary tuning capacitor C

L_Min [µH]	61.1
L_Max [µH]	64.7
C2s/C2p [nF]	94/142

APPENDIX H - EXAMPLE OF AN ABOVE GROUND PRODUCT GA SPECIFICATION (INFORMATIVE)

H.1 EXAMPLE PRODUCT GA WPT2

This appendix provides the mechanical and electrical design specifications of an example Product GA for power class WPT2.

NOTE: Specifications designed for optimal operation with the Product VAs specified in Appendices G.1, G.2, and G.3.

H.1.1 Mechanical Specification

Figure H1 shows the mechanical dimensions of the Product GA WPT2. For clarity, the housing is not shown. The GA orientation in the parking space is indicated by the icon on the left.

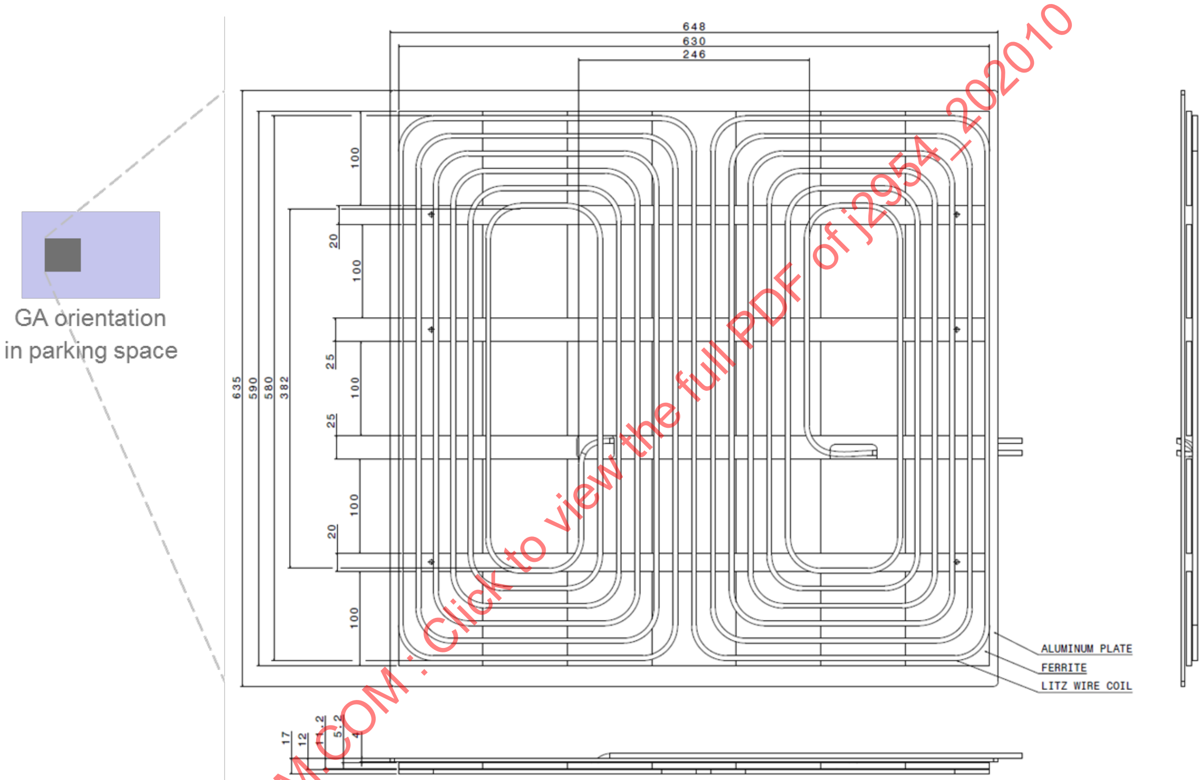


Figure H1 - Mechanical dimensions of the Product GA WPT2

Figure H2 shows a detailed cross-section view of the Product GA WPT2 (including housing).

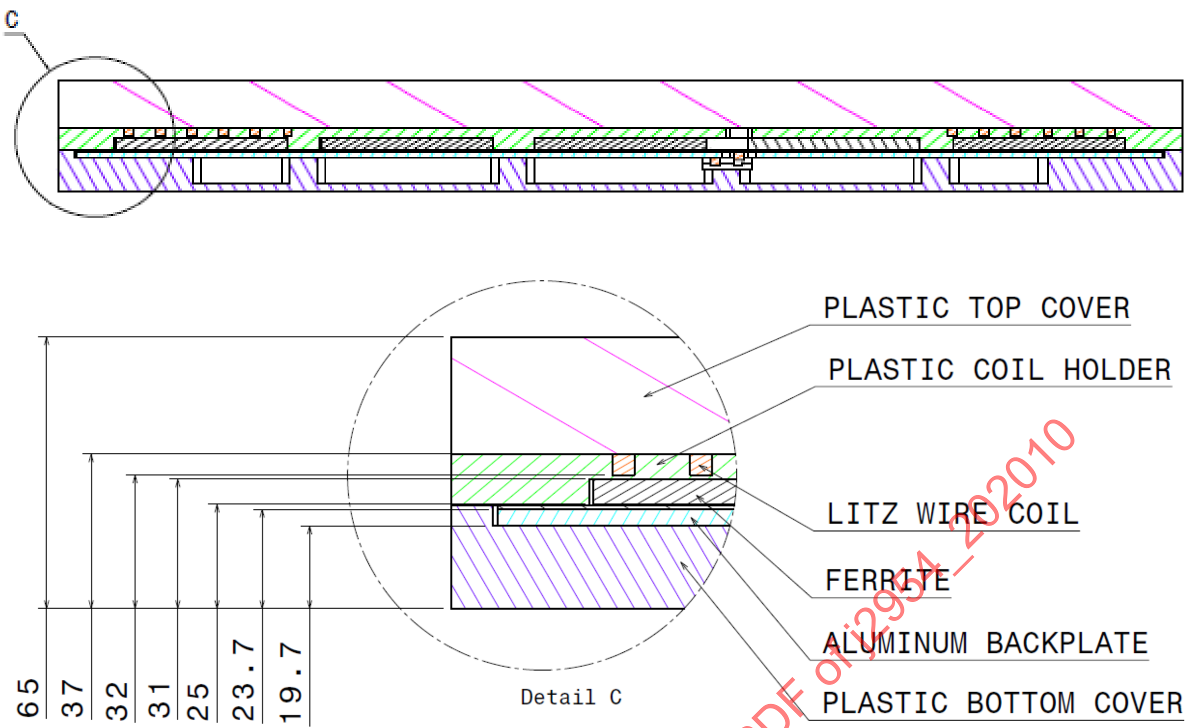


Figure H2 - Detailed cross-section view of the Product GA WPT2

Table H1 shows the mechanical dimensions of the of the Product GA WPT2.

Table H1 - Mechanical dimensions of the Product GA WPT2

	Coil + Ferrite Only	Housing
L x W x H [mm]	630 x 590 x 22	657 x 670 x 65

H.1.2 Electrical Specification

The system is tuned for a fixed frequency operation at f = 85 kHz. Frequency tuning to compensate, e.g., for height and alignment variation, is not required.

Figure H3 shows the electrical specification of the Product GA WPT2. Typical currents and voltages for the WPT2 power class are indicated in the block diagram.

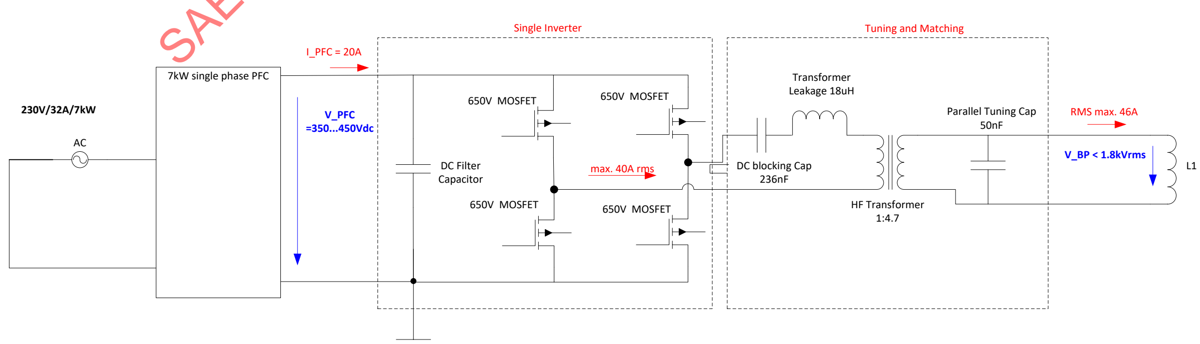


Figure H3 - Electrical specification of the Product GA WPT2

The value of the primary coil inductance L1 varies depending on the air gap class. Minimum and maximum values of L1 are given in Table H2.

Table H2 - Primary coil inductance L1 depending on the Z-class

Z-Class	VA	L_Min [µH]	L_Max [µH]
Z1	Appendix G.1	54.9	62.5
Z2	Appendix G.2	62.5	65.8
Z3	Appendix G.3	65.6	68.5

The coupling k between the primary and the secondary coil also varies depending on the air gap class. Minimum and maximum values of k are given in Table H3.

Table H3 - Coupling k between primary and secondary coil depending on the Z-class

Z-Class	VA	k_Min	k_Max
Z1	Appendix G.1	0.162	0.344
Z2	Appendix G.2	0.134	0.318
Z3	Appendix G.3	0.126	0.314

H.2 EXAMPLE PRODUCT GA WPT3

This appendix provides the mechanical and electrical design specifications of an example Product GA for power class WPT3.

NOTE: Specifications designed for optimal operation with the Product VAs specified in Appendices G.4, G.5, and G.6.

H.2.1 Mechanical Specification

Figure H4 shows the mechanical dimensions of the ferrite and the coil for the Product GA WPT3. For clarity, the housing is not shown. The GA orientation in the parking space is indicated by the icon on the left.

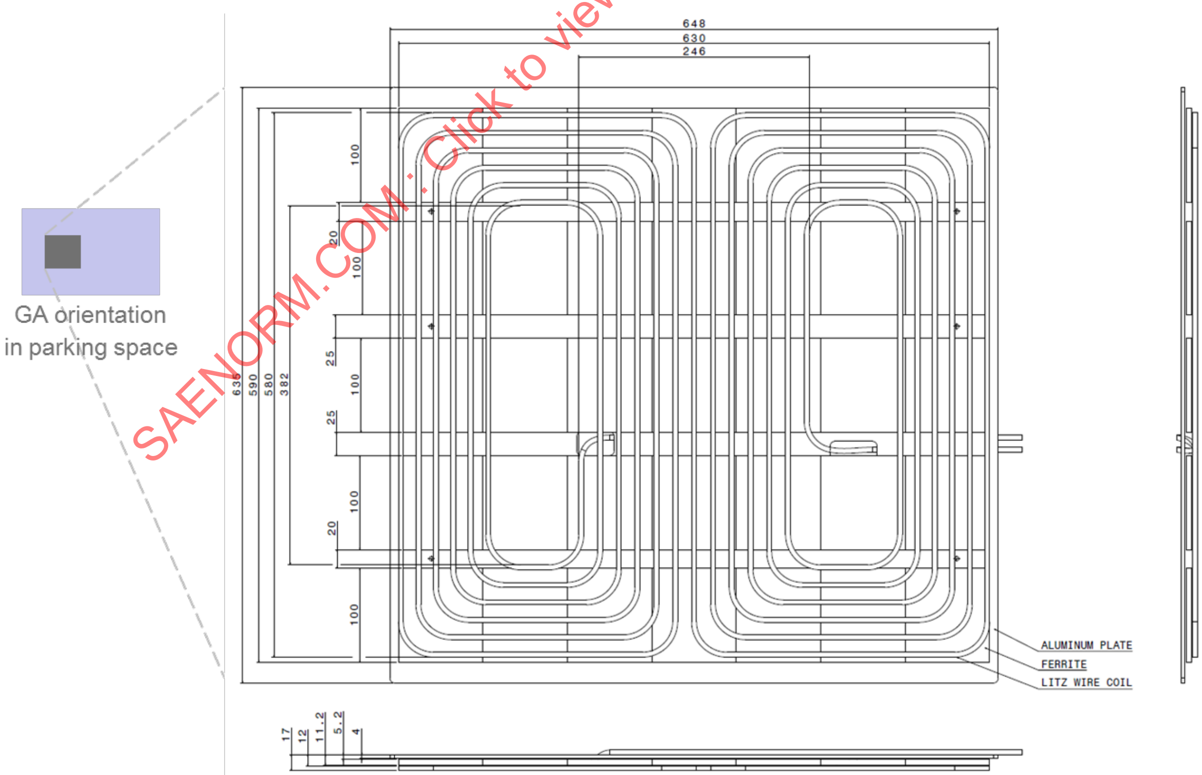


Figure H4 - Mechanical dimensions of the Product GA WPT3

Figure H5 shows a detailed cross-section view of the Product GA WPT3 (including housing).

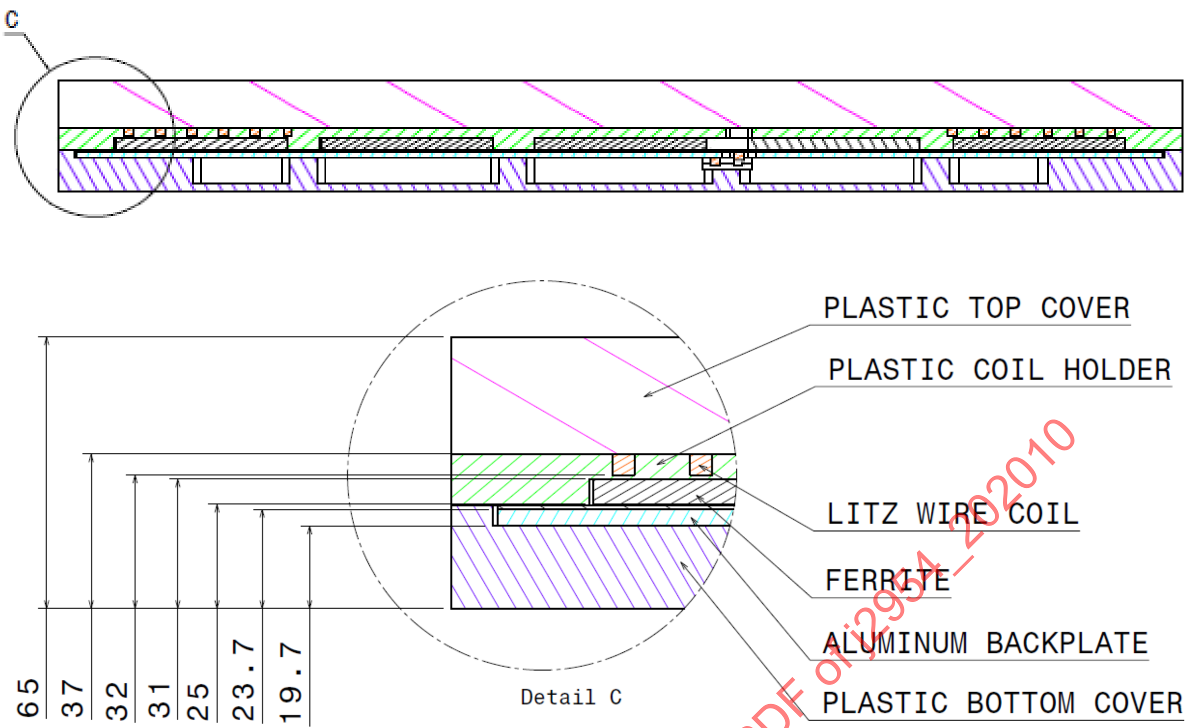


Figure H5 - Detailed cross-section view of the Product GA WPT3

Table H4 shows the mechanical dimensions of the Product GA WPT3.

Table H4 - Mechanical dimensions of the Product GA WPT3

	Coil + Ferrite Only	Housing
L x W x H [mm]	630 x 590 x 22	657 x 670 x 65

H.2.2 Electrical Specification

The system is tuned for a fixed frequency operation at f = 85 kHz. Frequency tuning to compensate, e.g., for height and alignment variation, is not required.

Figure H6 shows the electrical specification of the Product GA WPT3. Typical currents and voltages for the WPT3 power class are indicated in the block diagram.

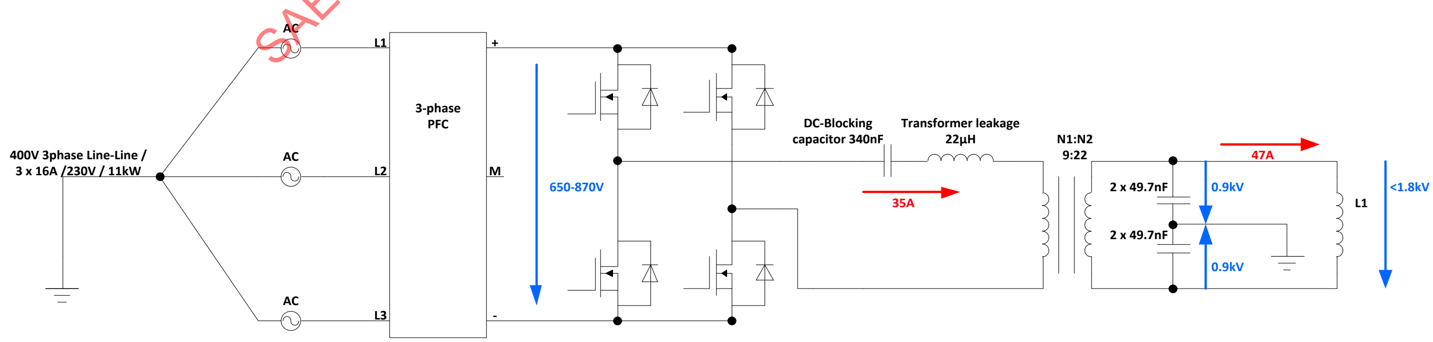


Figure H6 - Electrical specification of the Product GA WPT3

The value of the primary coil inductance L1 varies depending on the air gap class. Minimum and maximum values of L1 are given in Table H5.

Table H5 - Primary coil inductance L1 depending on the Z-class

Z-Class	VA	L_Min [µH]	L_Max [µH]
Z1	Appendix G.4	56.9	64.3
Z2	Appendix G.5	68.3	72.3
Z3	Appendix G.6	67.9	71.7

The coupling k between the primary and the secondary coil also varies depending on the air gap class. Minimum and maximum values of k are given in Table H6.

Table H6 - Coupling k between primary and secondary coil depending on the Z-class

Z-Class	VA	k_Min	k_Max
Z1	Appendix G.4	0.170	0.388
Z2	Appendix G.5	0.160	0.385
Z3	Appendix G.6	0.140	0.344

APPENDIX I - GENERAL DESCRIPTION OF INTEROPERABILITY (INFORMATIVE)

Inductive couplers may be designed in a number of topologies and can be described by their magnetics, either polarized or non-polarized; or, in the case of multi-coil topologies, as both, given they may be operated in either mode if required. Examples of common assembly topologies are shown schematically in Figure I1.

All assemblies are built to ensure flux-only exists on one side of the assembly by ensuring appropriate use of ferrite or aluminum backing. Non-polarized topologies have a magnetic pole in the center of the assembly and the opposite magnetic pole around the outer assembly. This causes flux to exit the assembly center and return to all outer edges of the assembly. An example of such an assembly is shown in Figure I1(a). When used as a VA coil, it is predominately sensitive to vertical fields in space.

Polarized assemblies have north and south poles at either end of the assembly structure. This causes the flux to be shaped based on the orientation of the pad (polarized). Examples of such assemblies are shown in Figures I1(b) and I1(c). When used as VA coil, these assemblies are predominantly sensitive to horizontal fields.

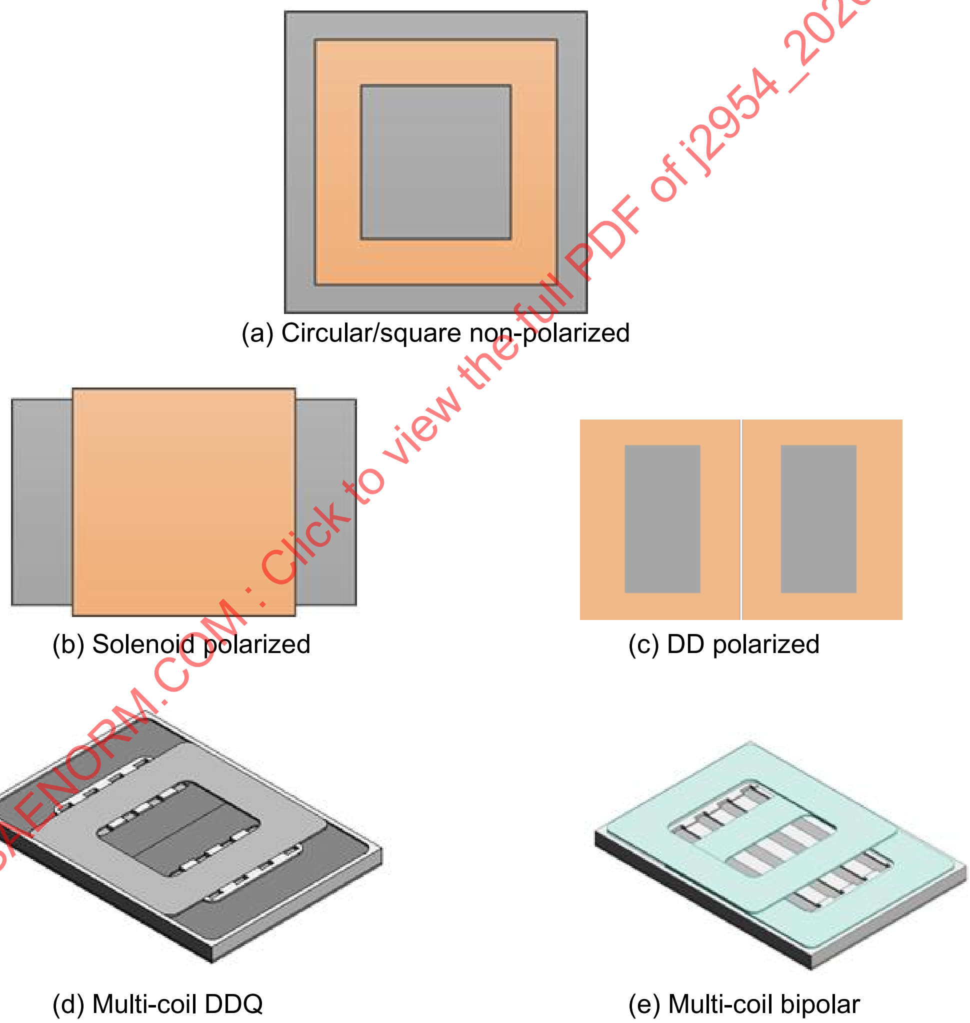


Figure I1 - Common assembly topologies

Multi-coil assemblies typically combine both topologies and use decoupled coils to enable polarized or non-polarized fields to be created when set as a GA coil, and, when set as a VA coil, naturally capture both the vertical and horizontal fields entering the assemblies.

The GA and VA of a WPT system may or may not be produced by the same manufacturer. To ensure interoperability, the GA and VA manufacturer need to know the mechanical and electrical characteristics of the VA and GA, respectively.

APPENDIX J - DESCRIPTION FOR SYSTEM INTEROPERABILITY (INFORMATIVE)

J.1 TERMS AND DEFINITIONS

DUT: Device under test

FUNDAMENTAL MUTUAL INDUCTANCE: The mutual inductance M describes the magnetic interaction and characteristic between the GA and the VA coil system. The fundamental mutual inductance M_0 is defined as the mutual inductance M divided by the GA number of coil turns and divided by the VA number of coil turns. The value for the fundamental mutual inductance is defined by the geometric coil and ferrite design and the positioning parameters x, y, z describing the position from the VA coil system against the GA coil system. A specific value of the fundamental mutual inductance is valid for a specific position x, y, z.

GAUGE DEVICE: Test devices which are intended to be used for development and testing of product GA coils in order to prove that a GA coil meets magnetic interoperability requirements in accordance to this appendix.

I_1 : GA coil current.

I_2 : VA coil current.

$I_1 \times N_1$: GA coil specific ampere turns.

$I_1 \times N_2$: VA coil specific ampere turns.

L_1 : Inductance of the GA device.

L_2 : Inductance of the VA device.

M : Mutual inductance.

M_0 : Fundamental mutual inductance with M= M_0 x N_1 x N_2.

$P_{b,out}$: Output power of VA device measured at the RESS (e.g., traction battery or adjustable load).

PRODUCT GA: Any GA device intending to prove standard conformance. As an example, as described in the Appendix H of SAE J2954.

PRODUCT VA: Any VA device intending to prove standard conformance. As an example, as described in the Appendix G of SAE J2954.

TEST STATION GA: As described in the normative Appendix B of SAE J2954.

TEST STATION VA: As described in the normative Appendix A of SAE J2954.

GA: Either a Test Station GA or a product GA.

VA: Either a Test Station VA or a product VA.

$U_{b,out}$: Output voltage of VA device measured at the load (e.g., traction battery or adjustable load).

Φ : Magnetic flux.

N_1 : Number of turns of a GA coil.

N_2 : Number of turns of a VA coil.

This appendix describes parameters of GA and VA coils to ensure interoperability between GA and VA coils from different manufacturers, Z-classes, power classes, and different coil topologies. Besides a description of necessary parameters, it also provides possible test setups that can be applied to approve GA and VA coil interoperability.

This appendix is applicable to product GA devices and product VA devices, but also for reference GA and reference VA devices. It is intended to be a generic approach that is not dependent on any coil topology or any specific electronic configuration and to provide flexibility for product implementation.

Both coils and electronics are interdependent at the system level, as the electronics shall be designed in a manner to cover for variations of the coil system parameters, which in turn vary with displacement of GA to VA coil. Rather than specify details of the electronics, magnetic and electric interoperability parameters are described. These parameters refer to the electrical interface between the electronics and the terminals of the coils.

J.2 MAGNETIC AND ELECTRIC INTEROPERABILITY

J.2.1 General Requirements

A wireless power transfer system contains several fundamental types of functional blocks (see also Figure J1):

- The coil system, which serves as the magnetic transformer and is characterized by the mutual inductance M. M may vary with coil position.
- The VA electronics connected to the VA coil, which ensure that all EV operation points (e.g., $P_{b,out}$, $U_{b,out}$) will lead to a VA side generated range of magnetic flux (amp turns) which is, in combination with the GA side generated range of magnetic flux (amp turns), required for the amount of power to be transferred.
- The GA electronics connected to the GA coil, which ensure that a GA side range of magnetic flux (amp turns) is generated such that, in combination with the range of magnetic flux (amp turns) generated by the EV's VA electronics and coil, the required amount of power is transferable.

NOTE: The power electronics have to accommodate ranges of magnetic fluxes in order to overcome variances of the power transfer behavior of the coil system due to the variation of M.

To ensure overall GA or VA interoperability, it is necessary to prove both magnetic and electrical interoperability.

Magnetic interoperability is ensured if GA coils and VA coils provide sufficient magnetic coupling over the designated range of coil positions. The coupling is described in this appendix by means of fundamental mutual inductance values. Fundamental mutual inductance values can be determined with VA reference coils or with VA gauge devices as described herein.

Electrical interoperability is ensured if GA and VA coils present sufficient ranges of magnetic flux. Magnetic flux ranges are represented in this appendix by means of ampere turns. The ranges of magnetic flux (amp turns) to be generated by the coils and associated electronics are specified in this appendix as part of the electrical interoperability description.

The following parameters are defined to describe the magnetic transformer interoperability.

- Magnetic interoperability parameters:
  - For each alignment point one value of fundamental mutual inductance M_0, covering the range of coil positions expected.
- Electric interoperability parameters:
  - For each power class a range of magnetic flux (amp turns), to be provided by a GA coil and its associated power electronics.
  - For each power class a range of magnetic flux (amp turns), to be provided by a VA coil and its associated power electronics.

The following parameters are defined to describe the system interoperability:

a. For each alignment point, there exists one set of values for the magnetic parameters (M,L1,L2) → F(x,y,z) = {M,L1,L2}. This leads to a defined range of values for the magnetic parameters covering the full range of coils positions expected.

b. Z_{VA}: Impedance presented by the VA electronics for all possible EV operation points ($P_{b,out}$, $U_{b,out}$). Defined from the terminals of the VA coil looking toward the load.

c. Z_{GA}: Impedance seen at the terminals of the GA coil looking toward the load (a function of Z_{VA} and the magnetic parameters).

d. Tolerance factor: A factor applied to the magnetic and impedance parameters to account for variations in construction, component values, and vehicle integration. This factor is necessary to guarantee interoperability across the range of systems expected in the field (covering different power and Z-classes).

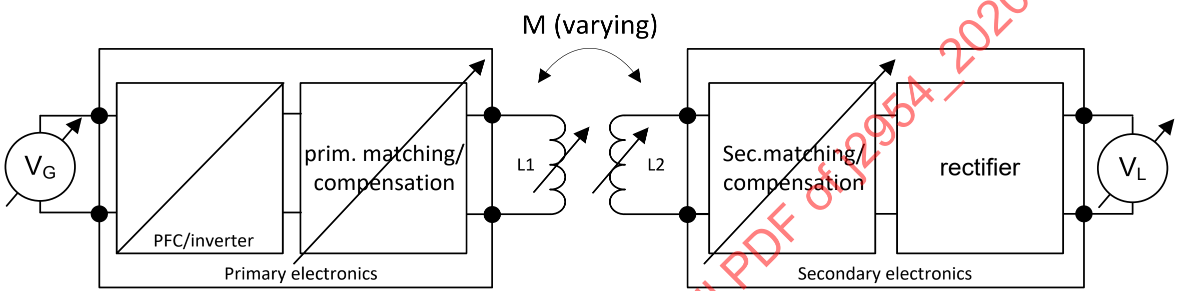


Figure J1 - General schematic of the concept showing the coils with their ports to the power electronics and the varying parameters

Key	Description
VG	Grid with voltage variations.
PFC/inverter	Front-end and power conversion (variable operating is optional).
Prim. matching/compensation	GA impedance matching and compensation (variable impedance matching, and variable tuning is optional).
L1	GA coil with self-inductance L1, whereas L1 does not affect power transfer behavior if compensated properly.
M	Mutual inductance variations due to alignment offset and z-height variations.
L2	VA coil with self-inductance L2, whereas L2 does not affect power transfer behavior if compensated properly.
Sec. matching/compensation	VA impedance matching and compensation (variable impedance matching, and variable tuning is optional).
Rectifier	AC to DC power conversion.
VL	Load (with battery voltage variations).

J.2.2 Center Alignment Point Requirements

Coil designs generating a coaxial magnetic field are intended to be used as well as coil designs with a transversal characteristic.

Coaxial and transversal GA devices both create a magnetic field distribution, which allows energy transfer to both, coaxial and transversal VA devices.

NOTE: Depending on application-specific product constraints—e.g., package space, weight, mounting position—a product decision for a coaxial or transversal coil design can be made.

As interoperability between coaxial and transversal coil designs is technically feasible, the following configurations can occur:

- Coaxial GA device operated with coaxial VA device
- Coaxial GA device operated with transversal VA device
- Transversal GA device operated with transversal VA device
- Transversal GA device operated with coaxial VA device

A GA device shall provide at least one center Alignment Point for coaxial magnetic field power transfer for usage by coaxial VA devices.

A GA device shall provide at least one center Alignment Point for transversal magnetic field power transfer for usage by transversal VA devices.

The bipole at the center alignment point for transversal magnetic field power transfer shall be orientated along the x-direction.

The positions of the center alignment points shall be exchanged between SECC and EVCC via communication.

The positions of the center alignment points shall have the same y-coordinate position.

The distance of the center alignment positions shall be maximum of 30 cm.

J.2.3 Magnetic Interoperability

J.2.3.1 Introduction

To define the characteristics of the magnetic field without requiring full reference VA device or product VA device and without the need of power transfer over the devices, a simple gauge device is defined (see J.3.4).These gauge devices are used to characterize the magnetic flux which is generated by a GA coil by measuring open circuit voltages, induced in the windings of the VA gauge devices.

The relation between the voltage U_{i2} measured with a gauge device in open circuit condition and the effective magnetic flux Φ generated by an exciting GA coil can be expressed as follows:

$$\Phi_{1\rightarrow 2} = C_{TD}\frac{U_{i2}}{\omega \times N_2} \quad \text{(Eq. J1)}$$

where:

C_{TD} = calibration factor of the gauge device as provided by the gauge device manufacturer

U_{i2} = induced voltage in gauge device, generated by the GA excitation I_1 x N_1

ω = 2πf; f = 85 kHz (nominal operating frequency)

N_2 = number of turns of the gauge device

$\Phi 1\rightarrow 2$ = magnetic flux the gauge device is exposed to, excited GA coil

A GA coil specific ampere turns $I_1 \times N_1$ value is required to generate a GA coil magnetic flux. To create a metric that can be more generally applied, the magnetic flux Φ is normalized by the GA coil current I_1. The resulting metric characterizes the magnetic coupling for a specific combination of GA and VA coils as follows:

$$\frac{\Phi_{1\rightarrow 2}}{I_1} = C_{TD}\frac{U_{i2}}{\omega \times N_2 \times I_1} = M_0 \times N_1 \quad \text{(Eq. J2)}$$

where:

M_0 = fundamental mutual inductance with $N_1 = 1$, $N_2 = 1$

N_1 = number of turns of the test stand or product GA device

I_1 = primary coil current

The values for the fundamental mutual inductance M_0 given in this appendix relate to the combination of:

- A reference GA device being tested with a reference VA device.
- A reference GA device being tested with a gauge device.

A gauge device is intended to serve as representation of a reference VA device or as representation of a product VA device. Any product GA device will produce the same magnetic flux at the gauge device as a reference GA device if the following equation is fulfilled:

$$M_{0,P} \times N_{1P} \times I_{1P} \overset{!}{=} M_{0,R} \times N_{1R} \times I_{1R} = \Phi_{1\rightarrow 2} = C_{TD}\frac{U_{i2}}{\omega \times N_2} \quad \text{(Eq. J3)}$$

Subscript P does refer to product GA device, whereas Subscript R refers to reference GA device, respectively.

Equation J3 requires that product GA device and reference GA device produce the same magnetic flux on the gauge device, that is, $\Phi_{1\rightarrow 2}$ and U_{i2} are the same for both. This shall be true for all offset positions. If the product GA device and the reference device have the same fundamental mutual inductance, the ampere-turns on the two coils shall be equal:

$$N_{1P} \times I_{1P} = N_{1R} \times I_{1R} \quad \text{(Eq. J4)}$$

Any reference and product GA device which shows the values of fundamental inductance M_0 either with reference VA devices or with gauge devices given in this appendix is compliant with respect to magnetic interoperability.

J.2.3.2 Mutual Inductance Requirements

In.2.3.2.1 to J.2.3.2.3, the fundamental mutual inductance values as measured with reference GA devices and as determined with the gauge devices according to the procedures in J.3.4.1 and J.3.4.2 are listed. The intended use of these tables is to verify that a reference GA device has the proper magnetic flux characteristics. The tables may also be used by system developers to compare the magnetic flux characteristics measured with product GA devices with the magnetic flux characteristics to that of reference GA device. A product GA device with equivalent magnetic flux characteristics as listed in these tables shall be considered to have proper magnetic characteristics, i.e. being magnetically interoperable.

Magnetic interoperability shall be confirmed by testing in accordance with J.3.2.2

Since the mutual inductance changes for different coil positions, the requirements are separately given for different X- and Y-positions and according to the Z-classes.

J.2.3.2.1 Fundamental Mutual Inductance Values for Z1 Class

A reference GA device shall provide fundamental mutual inductance values as given in Table J1. Magnetic interoperability is achieved, if the measured mutual inductance values are within a tolerance band of ±10% around the values given in Table J1.

Table J1 - Fundamental mutual inductance values M_0 for Z1 (in µH)

Z-Position	(X, Y) Position	Coaxial Sec. Gauge Device "CC325" Coupled with:		Transversal Sec. Gauge Device "DD275" Coupled With:	
		Coaxial GA Device	Transversal GA Device with Center Alignment Point of (170, 0)	Coaxial GA Device with Center Alignment Point of (160, 0)	Transversal GA Device
$Z1_{min}$ = 100 mm	Nominal position (0, 0)	(inner 0, 0997) (middle 0, 217) (outer 0, 264) 0.124	(inner 0, 165) (middle 0, 313) (outer 0, 342)	(0, 241)	(0, 554)
$Z1_{max}$ = 150 mm	Nominal position (0, 0)	(inner 0, 0667) (middle 0, 142) (outer 0, 172) 0.084	(inner 0, 098) (middle 0, 189) (outer 0, 215)	(0, 136)	(0, 319)
$Z1_{min}$ = 100 mm	Offset position (100, 75)	(inner 0, 0955) (middle 0, 192) (outer 0, 21) 0.116	(inner 0, 059) (middle 0, 142) (outer 0, 202)	(0, 159)	(0, 346)
$Z1_{max}$ = 150 mm	Offset position (100, 75)	(inner 0, 0586) (middle 0, 119) (outer 0, 188) 0.073	(inner 0, 050) (middle 0, 109) (outer 0, 145)	(0, 097)	(0, 201)
$Z1_{min}$ = 100 mm	Offset position (-100, -75)	(inner 0, 0867) (middle 0, 173) (outer 0, 191) 0.105	(inner 0, 114) (middle 0, 222) (outer 0, 240)	(0, 132)	(0, 309)
$Z1_{max}$ = 150 mm	Offset position (-100, -75)	(inner 0, 0518) (middle 0, 106) (outer 0, 124) 0.065	(inner 0, 066) (middle 0, 125) (outer 0, 136)	(0, 078)	(0, 181)

NOTE: Values without brackets are derived from reference VA device measurements and values with brackets are derived from gauge device measurements

J.2.3.2.2 Fundamental Mutual Inductance Values for Z2 Class

A reference GA device shall provide fundamental mutual inductance values as given in Table J2. Magnetic interoperability is achieved, if the measured mutual inductance values are within a tolerance band of ±10% around the values given in Table J2.

Table J2 - Fundamental mutual inductance values M_0 for Z2 (in µH)

Z-Position	(X, Y) Position	Coaxial Sec. Gauge Device “CC325” Coupled with:		Transversal Sec. Gauge Device “DD275” Coupled with:	
		Coaxial GA Device	Transversal GA Device with Center Alignment Point of (170, 0)	Coaxial GA Device with Center Alignment Point of (170, 0)	Transversal GA Device
$Z2_{min}$ = 140 mm	Nominal position (0, 0)	(inner 0, 0724) (middle 0, 154) (outer 0, 187) 0.131	(inner 0, 108) (middle 0, 207) (outer 0, 236)	(0, 151)	(0, 354)
$Z2_{max}$ = 210 mm	Nominal position (0, 0)	(inner 0, 0565) (middle 0, 120) (outer 0, 145) 0.073	(inner 0, 056) (middle 0, 109) (outer 0, 126)	(0, 074)	(0, 179)
$Z2_{min}$ = 140 mm	Offset position (100, 75)	(inner 0, 0641) (middle 0, 130) (outer 0, 147) 0.109	(inner 0, 052) (middle 0, 116) (outer 0, 155)	(0, 097)	(0, 222)
$Z2_{max}$ = 210 mm	Offset position (100, 75)	(inner 0, 0343) (middle 0, 0709) (outer 0, 0837) 0.059	(inner 0, 035) (middle 0, 075) (outer 0, 097)	(0, 053)	(0, 118)
$Z2_{min}$ = 140 mm	Offset position (-100, -75)	(inner 0, 0571) (middle 0, 0116) (outer 0, 0134) 0.101	(inner 0, 072) (middle 0, 138) (outer 0, 150)	(0, 097)	(0, 198)
$Z2_{max}$ = 210 mm	Offset position (-100, -75)	(inner 0, 0302) (middle 0, 0632) (outer 0, 0769) 0.055	(inner 0, 034) (middle 0, 066) (outer 0, 074)	(0, 049)	(0, 108)

NOTE: Values without brackets are derived from reference VA device measurements and values with brackets are derived from gauge device measurements

J.2.3.2.3 Fundamental Mutual Inductance Values for Z3 Class

A reference GA device shall provide fundamental mutual inductance values as given in Table J3. Magnetic interoperability is achieved, if the measured mutual inductance values are within a tolerance band of ±10% around the values given in Table J3.

Table J3 - Fundamental mutual inductance values M_0 for Z3 (in μH)

Z-Position	(X, Y) Position	Coaxial Sec. Gauge Device "CC325" Coupled with:		Transversal Sec. Gauge Device "DD275" Coupled with:	
		Coaxial GA Device	Transversal GA Device with Center Alignment Point of (170, 0)	Coaxial GA Device with Center Alignment Point of (170, 0)	Transversal GA Device
$Z3_{min}$ = 170 mm	Nominal position (0, 0)	(inner 0, 0565) (middle 0, 120) (outer 0, 145) 0.143	(inner 0, 080) (middle 0, 156) (outer 0, 179)	(0, 109)	(0, 262)
$Z3_{max}$ = 250 mm	Nominal position (0, 0)	(inner 0, 0296) (middle 0, 0627) (outer 0, 0765) 0.074	(inner 0, 039) (middle 0, 076) (outer 0, 090)	(0, 051)	(0, 125)
$Z3_{min}$ = 170 mm	Offset position (100, 75)	(inner 0, 0488) (middle 0, 0999) (outer 0, 115) 0.115	(inner 0, 045) (middle 0, 097) (outer 0, 126)	(0, 073)	(0, 168)
$Z3_{max}$ = 250 mm	Offset position (100, 75)	(inner 0, 0247) (middle 0, 0515) (outer 0, 0620) 0.060	(inner 0, 027) (middle 0, 058) (outer 0, 075)	(0, 040)	(0, 087)
$Z3_{min}$ = 170 mm	Offset position (-100, -75)	(inner 0, 0430) (middle 0, 0887) (outer 0, 106) 0.104	(inner 0, 052) (middle 0, 100) (outer 0, 110)	(0, 075)	(0, 151)
$Z3_{max}$ = 250 mm	Offset position (-100, -75)	(inner 0, 0218) (middle 0, 0462) (outer 0, 0575) 0.055	(inner 0, 023) (middle 0, 045) (outer 0, 051)	(0, 034)	(0, 080)

NOTE: Values without brackets are derived from reference VA device measurements and values with brackets are derived from gauge device measurements

J.2.4 Electrical Interoperability

J.2.4.1 Introduction

The coil system of the WPT system serves as a magnetic transformer that maps the impedance of the VA side Z_2 to the GA side Z_1.

The relation between these parameters is given by Equation J5:

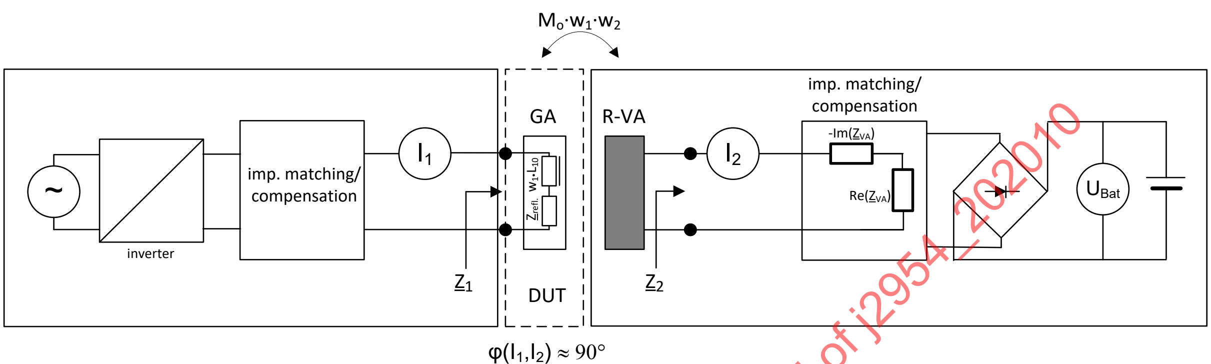
$$\underline{Z}_1 = j(\omega \times L_1) + \frac{\omega^2 \times M^2}{j(\omega \times L_2) + \underline{Z}_2} \quad \text{(Eq. J5)}$$

The second term on the right side of Equation J5 is the reflected impedance from the VA device to the GA device.

The self-inductances L_1 and L_2 are mainly governed by product specific characteristics like coil size, number of windings, coil, and winding geometry, which should be open for product development. If not properly compensated, remaining parts of the self-inductances L_1 and L_2 will contribute to reactive power rather to the transfer of active power between GA and VA device. Therefore, with the design of the GA and VA device, adequate compensation shall be considered.

Before detailed explanations to the different steps for the achievement or validation of coils electric interoperability are given, some theoretical background is provided to prepare the explanations as follows:

Figure J2 shows a schematic to explain the impedance approach.



Key	Description
Z1: GA complex impedance	X20 = ω ▪ L20: reactance of VA coil per winding
X10 = ω ▪ L10: reactance of GA coil per winding	$\underline{Z}_2 = \mathrm{Re}(\underline{Z}_2) + j \cdot \mathrm{Im}(\underline{Z}_2)$: VA complex impedance (incl. compensation, load)
N1: GA number of turns	ZRefl.: VA complex load impedance reflected on GA side
N2: VA number of turns	

Figure J2 - Schematic to explain impedance

The impedance Z_1 is given by Equation J5 which can be rewritten:

$$\underline{Z}_1 = jX_{10} \times N_1^2 + \underline{Z}_{Refl} \quad \text{(Eq. J6)}$$

The reflected impedance $\underline{Z}_{Refl}$ is given as:

$$\underline{Z}_{Refl} = \frac{\omega^2 \times M_0^2 \times N_1^2 \times N_2^2}{j(X_{20} \times N_2^2) + \mathrm{Re}\{\underline{Z}_2\} + j\mathrm{Im}\{\underline{Z}_2\}} =$$

$$\frac{\omega^2 \times M_0^2 \times N_1^2 \times N_2^2}{\mathrm{Re}\{\underline{Z}_2\} \times \left\{1 + j\frac{\mathrm{Im}\{\underline{Z}_2\} + X_{20} \times N_2^2}{\mathrm{Re}\{\underline{Z}_2\}}\right\}} \quad \text{(Eq. J7)}$$

With:

$$\Delta = \frac{\mathrm{Im}\{\underline{Z}_2\} + X_{20} \times N_2^2}{\mathrm{Re}\{\underline{Z}_2\}} \quad \text{(Eq. J8)}$$

The reflected impedance becomes:

$$\underline{Z}_{Refl} = \frac{\omega^2 \times M_0^2 \times N_1^2 \times N_2^2}{\mathrm{Re}\{\underline{Z}_2\}} \times \frac{1}{(1 + j\Delta)} =$$

$$\frac{\omega^2 \times M_0^2 \times N_1^2 \times N_2^2}{\mathrm{Re}\{\underline{Z}_2\} \times (1 + \Delta^2)} \times (1 - j\Delta) \quad \text{(Eq. J9)}$$

The separation of the real and imaginary part of the reflected impedance leads to:

$$\mathrm{Re}\{\underline{Z}_{\mathrm{Refl}}\} = \frac{\omega^2 \times M_0^2 \times N_1^2 \times N_2^2}{\mathrm{Re}\{\underline{Z}_2\} \times (1+\Delta^2)} \quad \text{(Eq. J10)}$$

$$\mathrm{Im}\{\underline{Z}_{\mathrm{Refl}}\} = -\Delta \times \mathrm{Re}\{\underline{Z}_{\mathrm{Refl}}\} \quad \text{(Eq. J11)}$$

$$|\underline{Z}_{\mathrm{Refl}}| = \mathrm{Re}\{\underline{Z}_{\mathrm{Refl}}\} \times \sqrt{1+\Delta^2} \quad \text{(Eq. J12)}$$

$$\varphi(\underline{Z}_{\mathrm{Refl}}) = \arctan(-\Delta) \quad \text{(Eq. J13)}$$

The general behavior of Z_{refl} is shown in Figure J3.

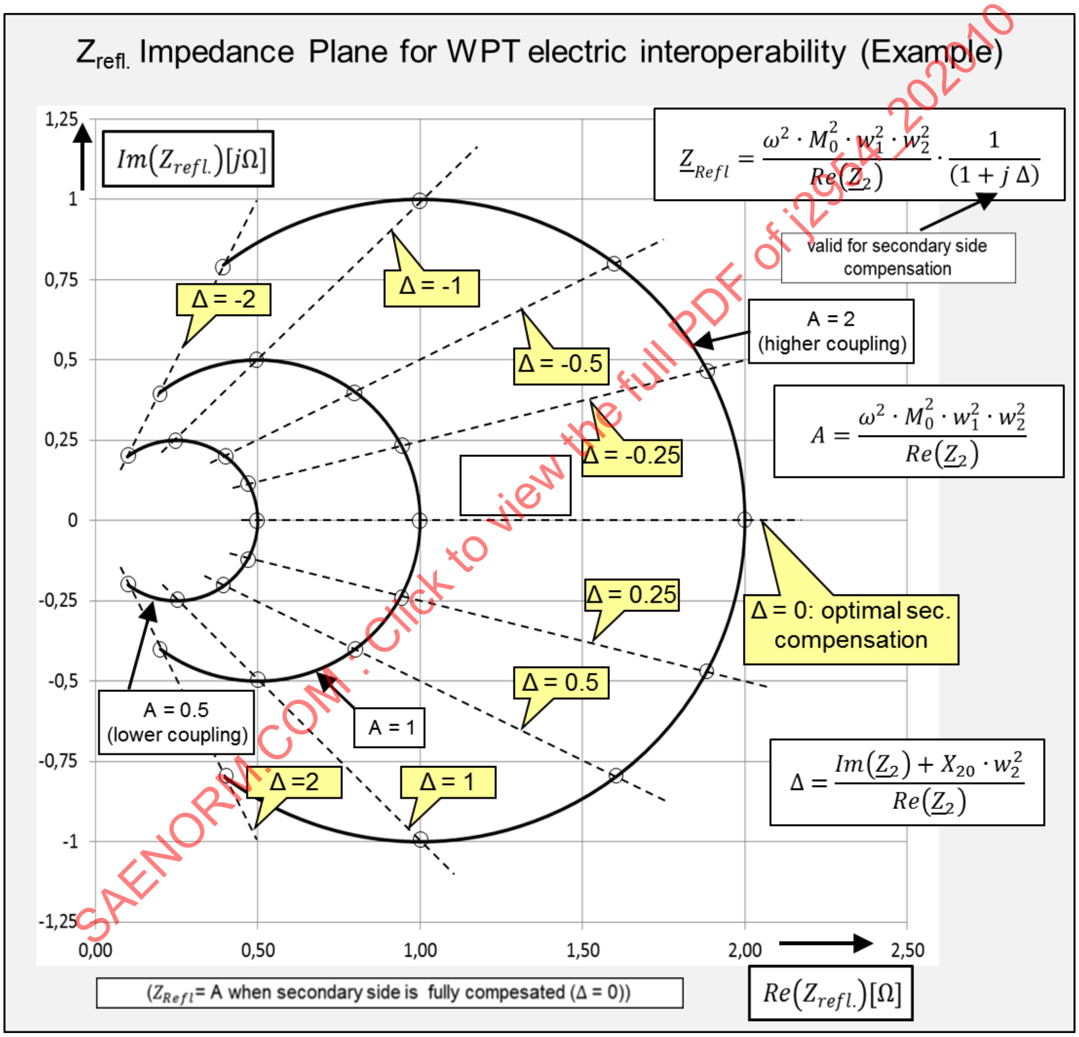


Figure J3 - General behavior of the reflected impedance (example)

Normalized impedances are defined as:

$$\underline{Z}_{\mathrm{Refl,norm}} = \frac{\underline{Z}_{\mathrm{Refl}}}{N_1^2} \quad \text{(Eq. J14)}$$

And:

$$\underline{Z}_{2,\mathrm{norm}} = \frac{\underline{Z}_2}{N_2^2} \quad \text{(Eq. J15)}$$

So that (compare to Equation J9):

$$\underline{Z}_{\text{Refl,norm}} = \frac{\omega^2 \times M_0^2}{\text{Re}(\underline{Z}_{2,\text{norm}})} \times \frac{1}{(1+j\,\Delta)} =$$

$$\frac{\omega^2 \times M_0^2}{\text{Re}(\underline{Z}_{2,\text{norm}}) \times (1+\Delta^2)} \times (1 - j\Delta) \quad \text{(Eq. J16)}$$

The normalized impedances may be used to establish ranges that are common to all product systems since ranges for the normalized mutual inductance M_0 are established.

The GA real power can be described as:

$$P_{\text{prim}} = |I_1 \times N_1|^2 \times \text{Re}(\underline{Z}_{\text{Refl,norm}}) \quad \text{(Eq. J17)}$$

The VA real power can be described as:

$$P_{\text{sec}} = |I_2 \times N_2|^2 \times \text{Re}(\underline{Z}_{2,\text{norm}}) \quad \text{(Eq. J18)}$$

Neglecting the transformer losses, the current ratio can be described with:

$$P_{\text{prim}} = P_{\text{sec}} : \frac{|I_1 \times N_1|}{|I_2 \times N_2|} = \sqrt{\frac{\text{Re}(\underline{Z}_{2,\text{norm}})}{\text{Re}(\underline{Z}_{\text{Refl,norm}})}} \quad \text{(Eq. J19)}$$

Or:

$$\frac{|I_1 \times N_1|}{|I_2 \times N_2|} = \frac{\text{Re}(\underline{Z}_{2,\text{norm}})}{\omega \times M_0} \times \sqrt{(1+\Delta^2)} \quad \text{(Eq. J20)}$$

Rearranging, the induced voltage per turn on the VA coil is given by:

$$\frac{U_{i2}}{N_2} = \omega \times M_0 \times |I_1 \cdot N_1| = \text{Re}(\underline{Z}_{2,\text{norm}}) \times \sqrt{(1+\Delta^2)} \times |I_2 \times N_2| \quad \text{(Eq. J21)}$$

And the required amp-turns on the GA coil is:

$$|I_1 \times N_1| = \frac{\text{Re}(Z_{2,\text{norm}}) \times \sqrt{1+\Delta^2}}{\omega \times M_0} \times |I_2 \times N_2| \quad \text{(Eq. J22)}$$

Or equivalently:

$$|I_1 \times N_1| = \frac{P_{\text{sec}}}{|I_2 \times N_2|} \times \frac{\sqrt{(1+\Delta^2)}}{\omega \times M_0} \quad \text{(Eq. J23)}$$

Equation J21 specifies the necessary induced voltage per turn on the VA coil as a function of the VA current and impedance parameters, while Equations J22 and J23 express the necessary amp turns on the GA coil in equivalent forms. Equation J23 shows why it is important to restrict the phase of the VA impedance to small values (i.e., keep *Δ* small) to limit unnecessary increases in coil currents.

By re-arranging Equation J23, the dependency of P_{sec} on the product of GA coil current I_1 and VA coil current I_2 can be clearly revealed:

$$|I_1 \times N_1||I_2 \times N_2| = \frac{\sqrt{(1+\Delta^2)}}{\omega \times M_0} \times P_{\text{sec}} \quad \text{(Eq. J24)}$$

J.2.4.2 Electric Interoperability Requirements

The driving factor for the GA electronics design is the impedance $\underline{Z}_1$, presented by the GA device to the GA electronics and therefore constituting the electrical load for the GA side. $\underline{Z}_1$ is composed of:

- The inductance value L_1 of the GA coil at operating frequency
- The AC-resistance of the GA device copper winding (for simplification also representing losses in ferrites and shielding)
- The reflected impedance $\underline{Z}_{\mathrm{Refl}}$ as being transformed from the impedance $\underline{Z}_2$ presented to the VA device coil by the VA device compensation network, power electronics and the load

L_1 does vary depending on the VA device position over the GA device. Proper compensation of that varying reactance is the responsibility of the manufacturer. Being suitable compensated, L_1 $d$oes not significantly influence the power transfer performance of the GA subsystem. Keeping the AC-resistance of the GA copper winding adequately low is also the responsibility of the manufacturer. For the impedance $\underline{Z}_{Refl}$, the VA device relevant parameter is the impedance $\underline{Z}_2$ presented to the VA device coil by the VA device electronics and the load. $\underline{Z}_2$ is transformed to the GA device and appears as reflected impedance $\underline{Z}_{Refl}$. Any amount of (residual) $\underline{Z}_2$-reactance, expressed by the value of Δ (see also Equation J8) becomes part of $\underline{Z}_{Refl}$, whereas the sign of $\underline{Z}_2$-reactance appears negated (see also Figure J3) at the GA device terminals. The relevant transformation parameter (from $\underline{Z}_2$ to $\underline{Z}_{Refl}$) is the mutual inductance M or the fundamental mutual inductance M_0, respectively. M_0 is varying as indicated in Tables J1 to J3.

Equations J6 to J24 cover all effects of impedance transformation, variety of M_0, and remaining reactive parts as expressed in the parameter Δ. Only variance of L_1 is not included here.

Equation J24 shows that a product of GA and VA ampere turns is required to transfer a specified amount of power P_{sec}. That product of ampere turns is dependent on the mutual inductance M, the operating frequency ω and the parameter Δ as being defined in Equation J8. In accordance with Equation J21, that product of ampere turns leads to a voltage, which is required to be induced by the GA device in a VA device coil for the specified amount of power P_{sec} as follows:

$$U_{i2} = \omega \times M_0 \times N_1 \times N_2 \times |I_1| \quad \text{(Eq. J25)}$$

Declaration of interoperability requires that a reference or product GA devices (DUT) does induce a voltage V_2 in a corresponding reference VA device under worst condition (i.e., at the outer X-, Y- and Z-displacement between the coils), at the maximum sustainable coil current $I_{1,max}$ as specified by the coil manufacturer and while nominal power is transferred.

Electric interoperability tests aim to demonstrate, that this induce a voltage requirement is met by the DUT.

Manufacturers of reference GA devices and product GA devices shall ensure that the DUT is capable to induce the voltages as given in Table J4 for the desired power class. These values already include a reservation for VA side possible detuning in the range of Δ = ±0.3.

Table J4 - Voltages (rms) required to be induced in circular reference VA devices

Power Class	VA position over GA device [mm]	U_{i2} at $\lvert I_{1,max} \rvert$ [V] (rms)
MF-WPT 1		Not yet specified
MF-WPT 2		Not yet specified
MF-WPT 3-Z1	X = 75, Y = 100, Z = 150	180 ± 3%
MF-WPT 3-Z2	X = 75, Y = 100, Z = 210	150 ± 3%
MF-WPT 3-Z3	X = 75, Y = 100, Z = 250	150 ± 3%
MF-WPT 4		To be determined in future version
MF-WPT 5		To be determined in future version

Reference GA devices shall induce the voltages according to Table J4 with:

- M-values confirmed during magnetic interoperability testing in accordance to this appendix
- At $|I_{1,max}|$ = 75 A ± 1.5% (rms)
- At the operating frequency of 85 kHz ± 0.5%

The induced voltage requirement criterion as specified herein is intended to leave space for magnetic and electric design optimization to product device manufacturers.

Product GA devices shall induce the voltages according to Table J4 with:

- M_0-values confirmed during magnetic interoperability testing in accordance to this appendix
- At the maximum device coil current for which the coil has been designed
- At the lowest intended operating frequency ±0.5%

J.2.5 Impedance Equivalents

Requirements on the GA electronics including compensation can be expressed in terms of the range of impedance at the GA coil, $\underline{Z}_1$, over which the target power, P_{PRIM}, is to be delivered. The maximum GA coil current translates directly into the minimum real impedance requirement at the GA coil. Given a power transfer level P_{PRIM}, the corresponding $Re(\underline{Z}_1)$ is given by (see J.17)

$$\mathrm{Re}(\underline{Z}_1) = \frac{P_{PRIM}}{I_1^2} \quad \text{(Eq. J26)}$$

Or, in normalized terms:

$$\mathrm{Re}(\underline{Z}_{1,norm}) = \frac{P_{PRIM}}{|I_1 \times N_1|^2} \quad \text{(Eq. J27)}$$

This impedance becomes the minimum real impedance seen at the GA coil when delivering P_{PRIM} and the GA coil current is $|I_{1,max}|$.

The imaginary part of the impedance is determined by the reactance of the GA coil inductance and the imaginary part of the reflected impedance from the VA coil. This is a function of the relative position of the coils and the VA tuning. The maximum detuning of the GA coil inductance caused by the presence of the VA coil is defined as

$$\delta_{\max} = \frac{L_{1,\max} - L_{1,\min}}{L_{1,\max}} \quad \text{(Eq. J28)}$$

With a detuning range of ±*Δ* on the VA, the range of $Im(\underline{Z}_{1,norm})$ for any position is:

$$\frac{\omega L_{1,max}}{N_1^2} + |\Delta| \times \mathrm{Re}(\underline{Z}_{refl}) \leq \mathrm{Im}(\underline{Z}_{refl}) \leq \frac{\omega L_{1,max}}{N_1^2} \times (1 - \delta_{\max}) - |\Delta| \times \mathrm{Re}(\underline{Z}_{refl}) \quad \text{(Eq. J29)}$$

Equation J29 holds for the range of reflected impedance $Re(\underline{Z}_{refl})$ assuming the detuning caused by an arbitrary VA is allowed to be up to δ_{max} at any coil position. This is a very conservative assumption since the amount of GA coil detuning varies with relative coil position and is generally largest at the strongest coupling positions. With this assumption, the resulting impedance space at the GA coil is then as shown in Figure J4. Again, we neglect the small contribution of the coil losses to $Re(\underline{Z}_1)$.

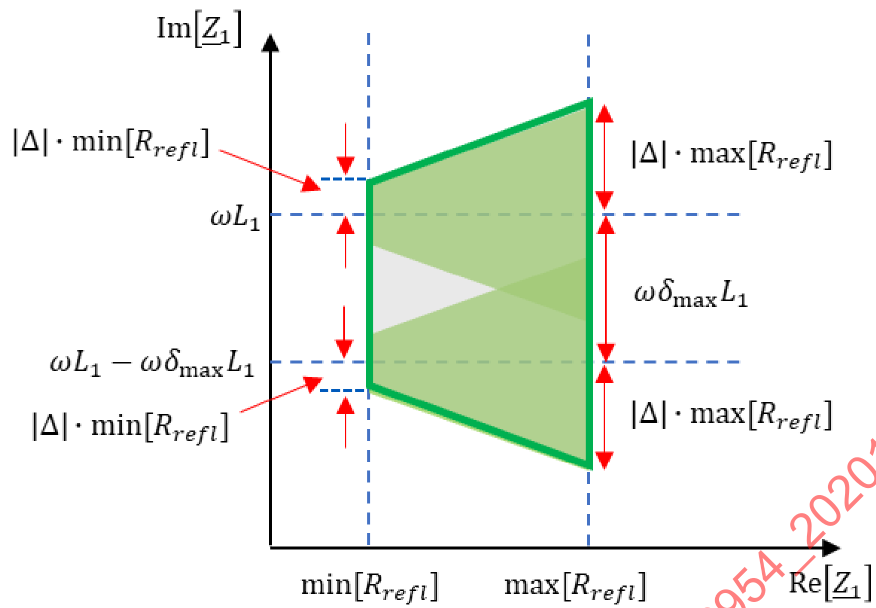


Figure J4 - Impedance space at the GA coil (example)

Figure J4 shows that the range of reactance depends on the real part because of the VA detuning parameter Δ (see J.11) and on the detuning of the GA coil inductance δ_{max}. The range of real impedance at which P_{PRIM} can be delivered is bounded on the low side by the maximum GA coil current, and on the high side by the capability of the GA side power electronics (inverter). The ratio of the maximum to minimum $Re(\underline{Z}_1)$ is a key parameter that drives volt-amp requirements on the GA side power electronics.

The VA electronics on the reference systems provide for tuning of the VA impedance, $Re(\underline{Z}_2)$, allowing the range of reflected impedance to vary less than $M_{0,max}^2/M_{0,min}^2$ (see J.10). This reduces the requirements of the GA side electronics. For the reference GA systems, the ratio of real impedance over which full power can be delivered is:

$$\frac{\max[Re(\underline{Z}_1)]}{\min[Re(\underline{Z}_1)]} \approx 3.0 \quad \text{(Eq. J30)}$$

Without tuning on the VA side, the GA electronics would have to drive a much wider range of impedances, with a max to min ratio of real impedances of approximately 10.0. This dramatically increases the size of the impedance space that must be driven.

To cover an equivalent impedance space as the reference GA systems, product GA electronics should cover an impedance space defined by Table J5.

Table J5 - Recommended parameters for GA coil impedance space

Parameter	Value
Maximum primary coil detuning $\delta_{\max}$	Z1: 20% Z2 and Z3: 10%
Maximum secondary detuning Δ	±0.3
$\frac{\max[Re(\underline{Z}_1)]}{\min[Re(\underline{Z}_1)]}$	≥3

Figure J5 shows a comparison of an impedance space derived using the approach outlined above (green) with impedance spaces computed for the circular WPT3 reference GA coil and reference electronics (black) and an alternative set of electronics (yellow). Since the circular reference GA coil and electronics have demonstrated interoperability with all reference VA coils, its impedance space serves as the minimum needed for interoperability. The derived impedance space uses the parameters in Table J5 along with the GA coil inductance of the reference coil. The resulting impedance space covers most of the reference impedance space, but also includes areas outside of it that may be difficult to realize with actual electronics. The alternative electronics, consisting of an inverter with a maximum input DC voltage of 900 V and a maximum output current of 34 A rms with an LCL compensation network, also provides an impedance space that completely encloses the reference region. As a result, this set of electronics driving the reference GA coil should be expected to interoperate fully with all reference VA coils and other VA coils that work with the reference GA.

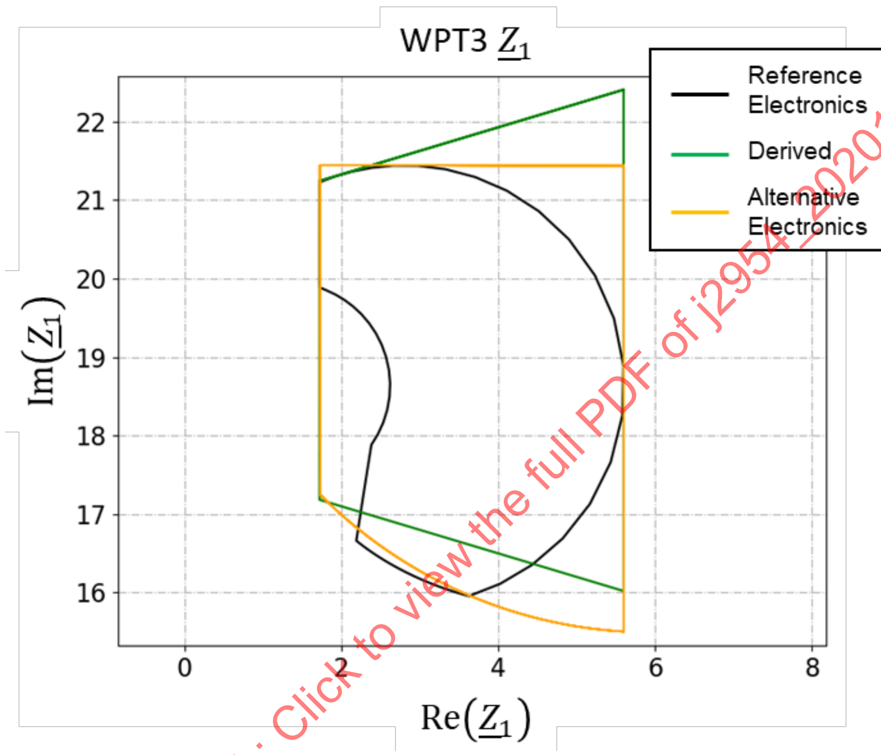


Figure J5 - Impedance spaces of the reference GA and alternate electronics

This example illustrates how the impedance at the GA coil may be used as a guide to creating interoperable GA systems. It also shows that the impedance space derived using the maximum coil current and parameters in Table J5 is a good starting point for design, although some adjustment of parameters may be needed to prevent overdesign and better match what standard electronics can provide.

J.3 COMPLIANCE TEST AND MEASUREMENT SPECIFICATIONS

J.3.1 Requirements to be Tested

The following requirements shall be confirmed by testing:

- Primary devices shall proof magnetic interoperability in accordance to requirements in J.2.3.2 and according to the conformance test procedure in J.3.2.2
- Primary devices shall proof electric interoperability in accordance to requirements in J.2.4.2 and according to the conformance test procedure in J.3.3.2

J.3.2 Magnetic Interoperability Testing

J.3.2.1 General Requirements

Proof of magnetic interoperability is to be done by means of fundamental mutual inductance conformance testing. It may be applied either to reference GA devices or product GA device to declare magnetic interoperability.

The GA devices are tested to confirm they provide the fundamental mutual inductance values given in J.2.3.2. For rebuilding reference GA devices, the specific values in Tables J1 to J3 are applicable for the proof of magnetic interoperability. For product GA devices, the specific values in Tables J1 to J3 are recommended for the proof of magnetic interoperability.

Fundamental mutual inductance conformance tests have to be performed with the coaxial gauge device according to J.3.4, if a reference GA device or a product GA device has to prove magnetic interoperability with VA circular reference or product devices.

Fundamental mutual inductance conformance tests have to be performed with the transversal gauge device according to J.3.4.2, if a reference GA device or a product GA device has to prove magnetic interoperability with VA transversal reference or product devices.

Primary reference devices or GA product devices have to be tested against all settings (alignment points and Z-ranges) and all coil combinations, as referred to in Table J1 to Table J3 to the extent of seeking magnetic interoperability.

The measurements can be performed by low voltage measurements. However, the GA ampere turns for $I_1 \times w_1$ should exceed 10 A rms for more accurate results.

J.3.2.2 Measurement Procedure

a. Place the gauge device at the specific test position.

b. Taking into account the number of turns of the GA device (DUT), set the GA current at the coil terminals to an rms-value such that an adequate ampere turn value I_1×w_1 is achieved. Take care that the current has sinusoidal shape at 85 kHz.

c. Measure and record the open circuit voltage of the windings of the gauge device (rms-values) and the applied coil current (rms-value).

d. Calculate the fundamental mutual inductance according to the equations given in J.3.4.1 and J.3.4.2, respectively.

J.3.3 Electric Interoperability Testing

J.3.3.1 General Requirements

Electric interoperability conformance testing requires the knowledge of magnetic behavior of the device to be tested. Therefore, magnetic interoperability conformance testing has to be done prior to electric interoperability testing; i.e., the results gathered during magnetic conformance tests, namely the fundamental mutual inductance M_0, is required to be known and to be taken into account while assessing the results of electric interoperability conformance tests.

Declaration of GA device electric interoperability based on electric interoperability tests in accordance with this appendix:

- Is applicable to reference GA devices or product GA devices.

- Have to be done with the reference VA device(s), which represent the power- and Z-gap class for which interoperability of the reference or product GA device is intended to be declared.

- If a GA device is intended for operation in a certain frequency range or at different frequency points, tests shall be done with the lowest intended operating frequency.

The following success criteria are to be met/to be confirmed during the electric interoperability conformance test:

- The desired power level is transferable with GA device electrical test parameters and at coil positions shown in Table J4.
- No mechanical, electrical or thermal degradation to the device under test while applying the electrical test parameters and at coil positions shown in Table J4. The definition of suitable mechanical, electrical and thermal evaluation criteria is under device manufacturer responsibility. The manufacturer has also to define how long a test at maximum power transfer rate has to last and whether or not load cycling has to be applied during the test. If applicable, the load cycling profile(s) are to be provided by the device manufacturer.

The electric interoperability conformance tests as described in this appendix are exclusively meant to confirm electric interoperability of GA devices (coils). These tests are not meant to confirm other requirements; e.g., concerning system efficiency, EMF, EMC. Such requirements need system level testing (product conformance testing).

J.3.3.2 Measurement Procedures for Reference and Product GA Devices Electric Interoperability Testing

The test set-up for reference or product GA device electric interoperability conformance tests is shown in Figure J6.

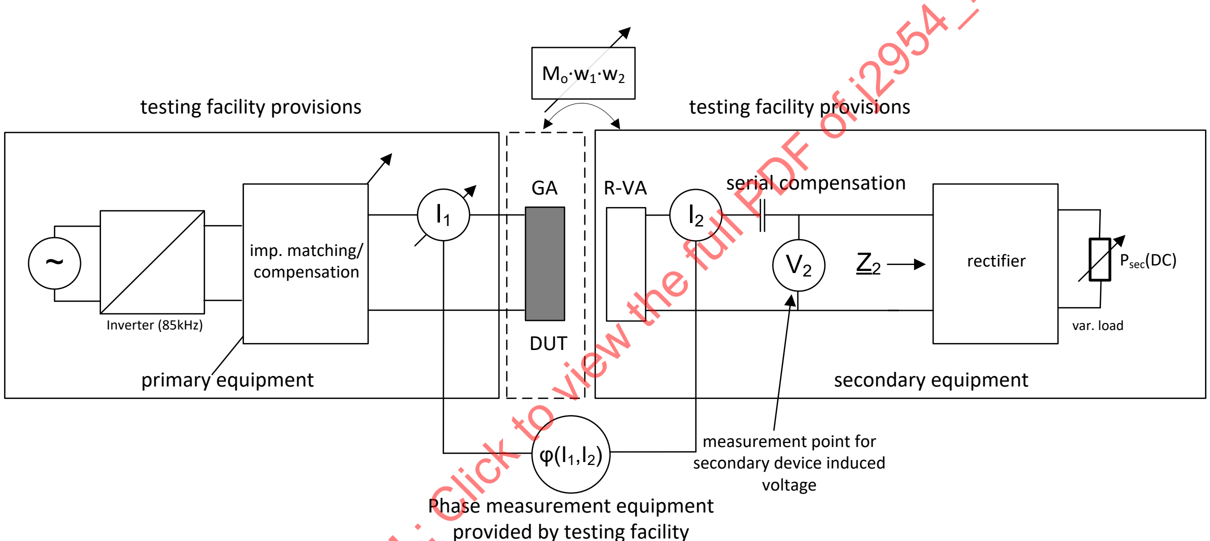


Figure J6 - Test set-up for reference or product GA device electric interoperability conformance tests

The VA load, as well as GA and the VA compensation networks, do not have to be product representative. Usually this equipment is provided by the test house. It is recommended to apply simple serial compensation at the VA side.

The VA variable load shall be set up such, that the VA device sees the following resistive impedance:

$$Z_2 = \frac{P_{sec}}{|I_2|^2} \tag{Eq. J31}$$

To ensure that the nominal power is transferred while voltages according to Table J4, are induced in the VA device, the following applies for the current I_2 and for Z_2 subsequently:

$$|I_2|(RMS) = \frac{1}{\omega \times M_0 \times N_1 \times N_2 \times |I_{1,max}|} \times P_{sec} \tag{Eq. J32}$$

When Equation J32 is applied for the setting of the current I_2 (Z_2 subsequently) and having ensured, that the VA inductance is fully compensated by the serial capacitor, the VA device induced voltage U_{i2} can be measured at the point indicated in Figure J6.

J.3.3.2.1 Primary Device Electric Interoperability Conformance Testing Procedure

a. Place the reference VA device over the GA device (DUT) at the geometrical location which represents the lowest value of magnetic coupling to be conformance tested; i.e., lowest expected value of M_0.

b. Adjust the variable load in accordance to Equations J31 and J32. This pre-setting of the variable load aims at the achievement of power level $P_{sec}(DC)$ while the VA device induced voltage U_{i2} settles at the corresponding value in Table J4.

c. Adjust the capacitance of the VA serial compensation capacitor to a value which suits full compensation of VA device inductance L_2.

d. Set the GA impedance matching and compensation network such that the GA impedance can be accommodated by the inverter.

e. Set the inverter's frequency to the desired operating frequency of the device under test and start increasing the current I_1 through the windings of the GA device (DUT). While increasing I_1, observe the phase between I_1 and I_2 and, if necessary, retune the phase to 90 degrees ± 3 degrees by changing the operating frequency of the inverter. If the inverter operating frequency becomes different than the desired operating frequency ±3%, stop the test, readjust the capacitance of the serial capacitor accordingly, and resume the test.

f. While increasing the current I_1, continue to observe that the current I_2 and the power P_{sec} fulfil requirements as per Equation J32. If necessary, readjust the variable load. Make sure that the current I_1 never exceeds its maximum allowable value (design limit).

g. When arriving at desired power level P_{sec}, stop increasing the current I_1.

h. Check again that the phase between I_1 and I_2 is in the range of 90 degrees ± 3 degrees, that the ratio between the current I_2 and the power P_{sec} fulfill requirements as per Equation J32 and that the frequency is within the allowed range. If necessary, re-adjust all settings until arriving at desired values.

i. Under this test condition, confirm that the GA device coil current does not exceed the maximum allowed current (design limit). If so, the electric interoperability of the GA device has passed the electric interoperability conformance test.

J.3.4 Gauge Devices for Fundamental Mutual Inductance Tests

The gauge devices described in J.3.4.1 and J.3.4.2 are meant to be used for magnetic interoperability tests of GA reference devices or GA product devices.

J.3.4.1 Coaxial VA Gauge Device

This section describes the dimensions of the coaxial VA gauge device to be used for magnetic interoperability conformation of GA reference devices or GA product devices. Calibration of the gauge device is done by the gauge device manufacturer.

The gauge device carries three windings, each of them existing of two turns. Open circuit voltage measurement is to be performed on all three windings by means of a voltage measurement device, which provides an input impedance of 10 kΩ or higher.

For all three windings, the values for the mutual inductances are given in Tables J1, J2, and J3.

They are derived by measuring the voltages of the three windings an calculating the fundamental mutual inductance according to Equation J33.

$$M_{oi} = \frac{U_i}{N_2 \times N_1 \times I_1 \times \omega} \quad \text{(Eq. J33)}$$

where:

ω = angular frequency applied for the test $(\omega = 2 \times \pi \ \times 85\ kHz)$

N_1 = number of turns of the GA reference device or the GA product device

N_2 = number of turns per gauge device winding ($N_2 = 2$)

I_1 = the GA current (RMS value) under the condition, that I_1 remains with constant amplitude during voltage measurements

The index *i* indicates the values for the inner, middle, and outer winding.

The fundamental mutual inductances M_{0i} may be used to derive an averaged fundamental mutual inductance. As an example, an average with equal weighting of the values is given in Equation J29.

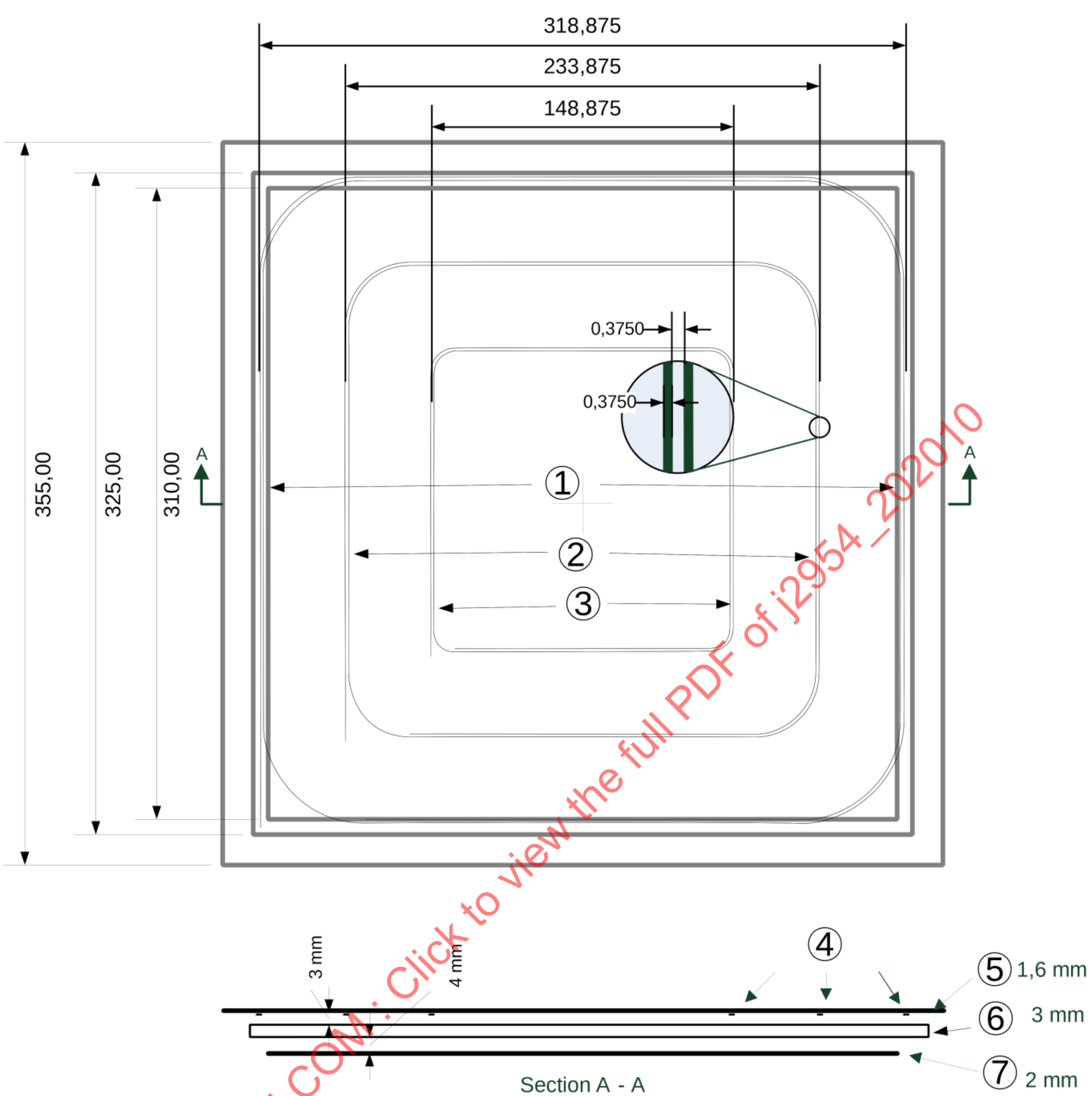
$$\overline{M_0} = \frac{1}{3}(M_{0inner} + M_{0middle} + \ M_{0outer}) \quad \text{(Eq. J34)}$$

Other weightings might be appropriate for comparison with different dimensions of the product VA device.

If appropriate the calibration factor C_{TD} represents the relation between the fundamental mutual inductance of the gauge device and the mutual inductance measured with the VA reference device.

$$M_0 = C_{TD} \times \overline{M_0} \quad \text{(Eq. J35)}$$

The size and structure of the coaxial VA gauge device is shown in Figure J7.



KEY			
1	Outer copper winding	5	PCB GFK
2	Middle copper winding	6	Ferrite
3	Inner copper winding	7	Aluminum
4	PCB copper		

Figure J7 - Coaxial gauge device "CC325"

J.3.4.2 Transversal VA Gauge Device

This section describes the dimensions of the transversal VA gauge device to be used for magnetic interoperability conformation of GA reference devices or GA product devices. Calibration of the gauge device is done by the gauge device manufacturer.

The gauge device carries an eight-shaped winding consisting of one winding with opposite winding direction with two turns each. Open circuit voltage measurement is to be performed by means of a voltage measurement device, which provides an input impedance of 10 kΩ or higher.

The fundamental mutual inductance is to be calculated in accordance with the following formula:

$$M_o = C_{TD} \frac{\overline{Ui}}{N_2 \times N_1 \times I_1 \times \omega} \quad \text{(Eq. J36)}$$

where:

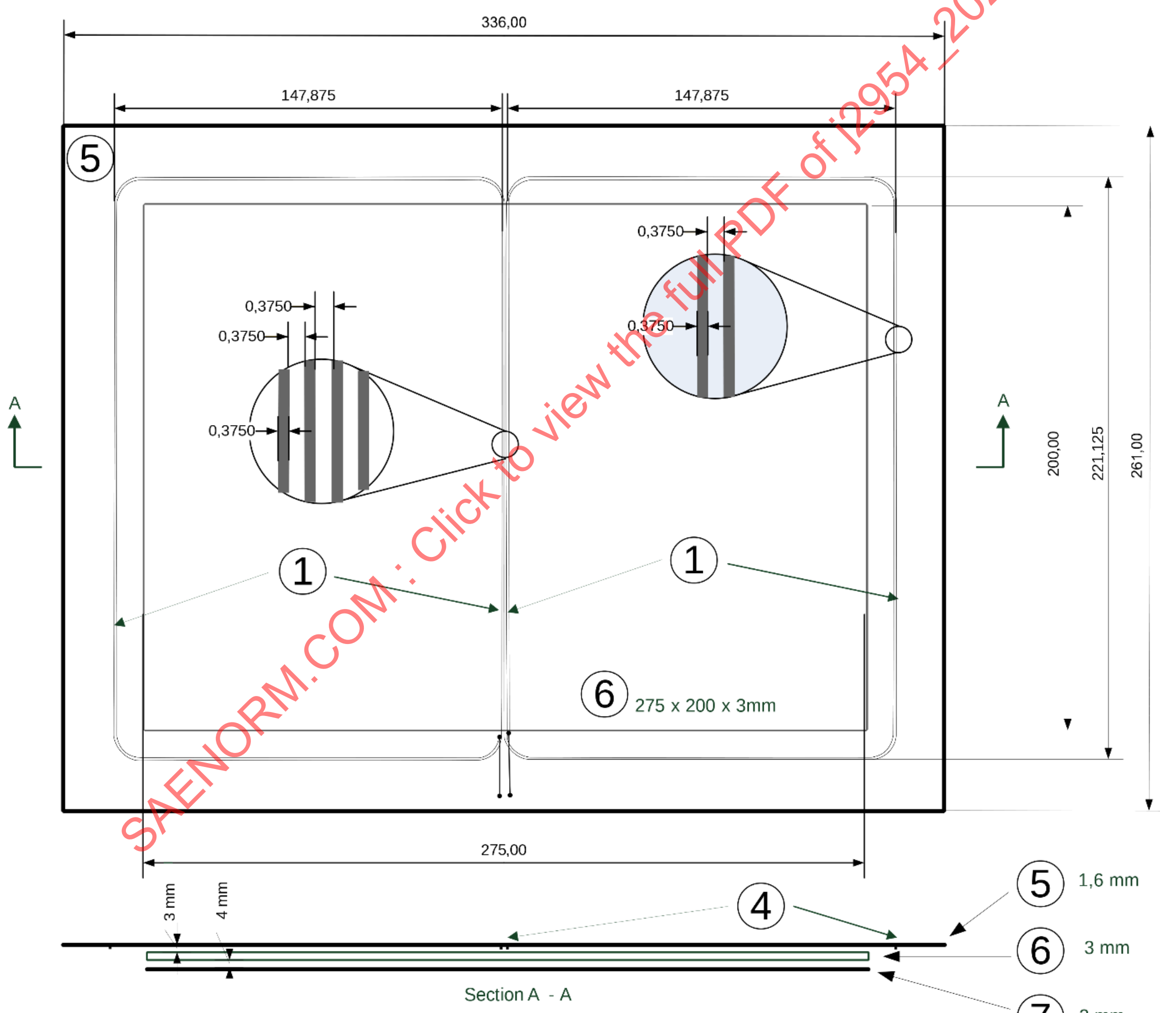
ω = angular frequency applied for the test ($\omega = 2 \times \pi \times 85kHz$)

N_1 = number of turns of the GA reference device or the GA product device

N_2 = number of turns per gauge device winding ($N_2 = 2$)

I_1 = GA current (RMS value) under the condition, that I_1 remains with constant amplitude during voltage measurements

The size and structure of the transversal VA gauge device is shown in Figure J8.



KEY			
1	Outer copper winding	5	PCB GFK
2	Middle copper winding	6	Ferrite
3	Inner copper winding	7	Aluminum
4	PCB copper		

Figure J8 - Transversal gauge device "DD275"

APPENDIX K - GUIDELINES FOR ASSESSMENT OF EMF COMPLIANCE WITH THE GENERAL PUBLIC BASIC RESTRICTION LEVELS (ALL REGIONS) (INFORMATIVE)

The basic restrictions given in Table K1 represent the maximum localized electric field induced in the body tissue due to externally impressed electric or magnetic fields. These induced fields cannot be directly measured, and therefore, the following procedure is provided for a consistent evaluation with SAE J2954 devices when a basic restrictions assessment is used.

The reference levels of Table K2 are exposure guidelines for whole body exposures provided in a directly measurable format. The modelling of the induced EMF inside a live object is a complicated process and is recommended only if EMF hazards cannot be ruled out through direct testing against the reference levels. It should be noted that the margin between reference levels and basic restrictions is highly dependent upon the orientation of the live object within the defined Regions; although the simulation method will allow a more exact determination of the presence of a hazard, it will not result in a system with excessive EMF becoming acceptable. When the impressed field is substantially non-uniform, the reference level assessment may be more conservative, and compliance with the reference levels is not required if the basic restrictions are met.

Table K1 - EMF exposure standard, basic restriction levels

Field	ICNIRP 2010 General Public Restriction Level (rms Field Strength)
Internal Electric Field	$1.35 \times 10^{-4} * f(Hz) = 10.7$ V/m at 79 kHz

Table K2 - EMF exposure standard, reference levels

Field	ICNIRP 2010 General Public reference level (rms Field Strength)
Magnetic Field	27 µT or 21.5 A/m
Electric Field	83 V/m

It is not required that the same method of assessment be used for the impressed electric and magnetic fields of the WPT system. For example, the impressed electric fields may be assessed against the reference levels, while the impressed magnetic fields may be assessed against the basic restrictions. This appendix addresses the assessment of impressed magnetic fields by basic restrictions. The assessment of impressed electric fields by basic restrictions is under study.

K.1 METHODOLOGY/PROCESSES

For the WPT operating frequency band specified in 6.4.2, the human body constitutive parameters are such that the “scattered” magnetic fields created by induced tissue conduction and displacement currents are much less that the impressed magnetic field. Therefore, it is acceptable to partition the problem into two successive calculations whereby the impressed WPT magnetic field is calculated in the first solver and the induced human body tissue electric field is calculated in the second solver. This process is often used because different solvers may be more suited for the two calculations. However, it is also acceptable to perform the entire calculation in one solver if the solver is capable.

K.1.1 Calculation and Validation Process

Figures K1 and K2 outline the validation processes for the two-solver and one-solver calculation processes, respectively.