Standardization of Wireless Power Transfer for PH-EV – Technology Validated through Testing, SAE J2954

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Abstract

Wireless Power Transfer (WPT) is presently being applied to consumer electronics in the low power range and is being commercialized in the high power range for plug-in and electric vehicles starting in 2018. There are many advantages to WPT using magnetic resonance used in high power transfer such as high efficiency over an air gap. There are however many technology challenges remaining before the widespread implementation of this technology. The SAE Vehicle Wireless Power and Alignment Taskforce published the Technical Information Report J2954 in 2016 to assist in the harmonization in the first phase of this technology. SAE J2954 is a performance-based approach for WPT by specifying ground and assembly coils to be used in a test stand (per Z-height) to validate performance, interoperability and safety. Though there were two types of topologies used for the WPT coils in SAE J2954, they are both interoperable with one-another. The main goal of this SAE J2954 bench testing campaign was to validate interoperability for SAE TIR J2954. The main challenge is that this type of testing had not been done before on such a scale with real automaker and supplier systems. A number of Automakers, suppliers and government employees worked together to create this test plan and results. In order to validate the interoperability, performance, and EMC & EMF of this technology, a bench test was created based on the SAE J2954 TIR, supported by the SAE WPT Taskforce along with the US Department of Energy's Idaho National Lab and TDK North America. The tests are conducted across two different power classes (between 3.7 kW to 7.7kW) and the two different topologies (circular and double-D). This report describes the testing and gives the results for these different WPT systems. This testing validates the first stage of SAE J2954 standardization and proves that WPT is not only possible over an air gap of 250mm but also interoperable over both power classes and topologies with high efficiencies (many tests were above 90% AC to DC efficiency).

Introduction

As light duty passenger vehicle transportation systems progress towards fully autonomous, zero emission solutions, electric vehicles are one solution for reaching this goal. With autonomous vehicles, the charging system will also need to be fully autonomous to enable convenient, hands-free charging both in parking locations. Wireless power transfer (WPT) is a technology that fulfills the requirements for the fully automatic charging solution for autonomous and electric vehicles in general.

The path towards commercializing safe and interoperable wireless power transfer is enabled by robust industry codes and standards to guide and align the wide range of WPT applications. The SAE J2954 standardization is currently under development for light duty and heavy duty wireless power transfer. The goal of this standardization is to specify minimum criteria and recommendations to enable safe and efficient wireless power transfer.

This manuscript details the testing and validation of eight WPT systems which demonstrated the interoperable power transfer capability validating the first level of standardization of SAE J2954. The eight WPT systems cover two SAE of the J2954 power classes: WPT 1 and WPT 2 (3.7kW and 7.7kW) using three ground clearance classes, Z1-Z3 (ranging from 100mm to 250mm). The validation bench testing is conducted off-board the vehicle by use of a SAE J2954-specified test fixture that enables highly accurate testing of a range of operating conditions such as coil to coil misalignment, ground clearance, system output voltage, and requested power transfer level. Throughout testing, the system efficiency, power quality, and electromagnetic field emissions are measured. The test results are used by the SAE J2954 committee to enable a results-based decision process in developing the SAE J2954 Recommended Practice, the next phase of standardization.

Objectives Overview

The bench testing was conducted on eight WPT systems from three vehicle OEM and supplier / manufacturer teams in an effort to validate SAE J2954 WPT design interoperability, power transfer capability, and efficiency. The WPT systems of various power class, Z class (ground clearance) and coil topology are tested off-board the vehicle, using a bench test fixture that is detailed in the SAE J2954 TIR[1]. The testing focused on validating the WPT designs for matched and interoperable:

- Power transfer capability
- System efficiency
- Power quality
- Electromagnetic (EM) field emissions

The WPT systems are tested across various operating conditions including:

- Ground clearance from 100 mm to 250 mm
- Coil to coil misalignment up to 75 mm in the fore / aft direction and 100 mm side to side
- Battery voltage from 280 V to 420 V DC
- Full power and half power

The test results were used by the SAE J2954 Taskforce to enable the results-based decision process in developing the recommended practice.

WPT System Descriptions

Eight WPT systems are tested to validate the matched and interoperable design requirements detailed in SAE J2954 TIR[1] for power transfer capability, system efficiency, power quality, and electromagnetic field emissions. The designs included circular and double-D coil topologies, across two power classes, WPT1 and WPT2 (input Volt-Amps of 3.7kVA and 7.7kVA respectively), and across three ground clearance classes.

The WPT systems are comprised of three primary sub-systems which include the input power electronics, the ground assembly (GA), and the vehicle assembly (VA). The input power electronics contains the power electronics and controls hardware to convert the 60 Hz grid input power into the 85 kHz AC power for the GA. The GA contains the primary coil, ferrite, and tuning components to enable efficient, high power transfer. The VA contains the secondary coil, ferrite, tuning components, a rectifier circuit, and shielding to ensure efficient and safe operation on a vehicle.

Inductive couplers can 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 can be operated in either mode if required.

WPT 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 pole in the magnetic center of the assembly and the opposite pole around the outer assembly. This causes flux to exit the assembly magnetic center and return to all outer edges of the assembly. When used as a VA Coil it is predominately sensitive to vertical fields in space.

Multi-coil assemblies typically combine both structures, and use decoupled coils to enable polarized or non-polarized fields to be created when set as a primary, and, as a secondary, naturally capture both the vertical and horizontal fields entering the assemblies.

The two types of assemblies used in the TIR SAE J2954 are the “circular”/ square non-polarized for both WPT 1 and WPT 2 (See Figure 0a) as well as Multi-coil, DDQ (or so-called “D-D Coils, see Figure 0b) for WPT 2. Note, the WPT 3 coils are described in the upcoming Recommended Practice SAE J2954

Two examples of VA and GA assemblies are shown below in Figures 0a and 0b with these two topologies (from SAE J2954).

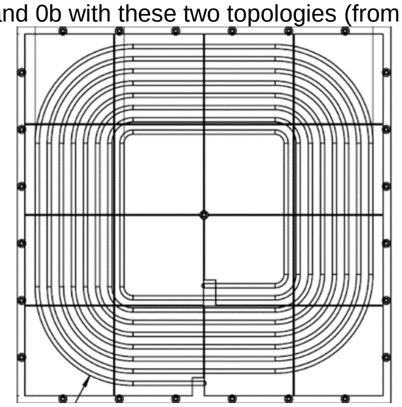

Figure 0a.VA-WPT 2/Z3 Example with circular topology (without shield)

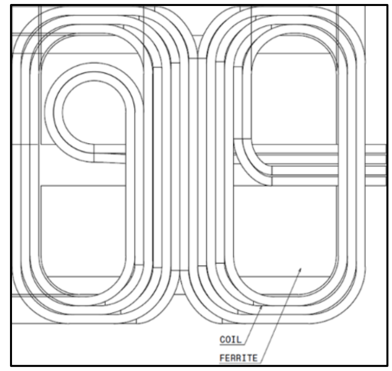

Figure 0b.VA-WPT 2/Z3 Example with circular topology (without shield)

WPT Systems for bench testing were provided from Nissan-Witricity, Toyota and Daimler-Jaguar-Qualcomm. However, there were multiple other automakers supporting the creation of testing and feedback of results from the SAE J2954 Taskforce.

Testing Methodology

Testing of the eight WPT systems is conducted at Idaho National Laboratory’s (INL) Electric Vehicle Infrastructure (EVI) lab which has proven expertise in the testing and evaluation of advanced vehicle charging infrastructure. During the WPT testing in this project, representatives from each WPT team are present at INL, as shown in Figure 1, to ensure WPT system proper functionality, interoperable controls tuning, and overall engineering support. This multi-team collaboration is essential to the successful completion of the testing effort to produce high accuracy data and findings.

Figure 1. WPT interoperability testing

Matched and Interoperable Test Plan

Testing is conducted for all matched and interoperable WPT combinations across a range test conditions. The eight matched WPT systems test results provide a baseline for which the fourteen interoperable WPT test results can be compared.

Matched WPT operation involves power transfer from a GA to a VA produced by the same manufacturer, whereas interoperable operation involves power transfer from of a GA to a VA produced from differing manufacturers. The interoperable combinations may have differing power classes, ground clearance classes, or even fundamental coil topologies. Validating the safe and efficiency functionality of the matched and interoperable WPT combinations is the primary motivation of the testing and evaluation project described in this manuscript.

The test plan details the test condition requirements which include a range of ground clearance, coil to coil misalignment, output voltage and requested power transfer as shown in Table 1. For each test condition, the WPT transfers power until it is deemed to be in steady state operation. After steady state of power transfer is reached, data is then collected and certain real-time calculations are performed to provide instant feedback as to the performance and safety of the WPT system.

Table 1. Range of test conditions of the various operating conditions

Operating condition	Z1	Z2	Z3
Ground Clearance	100 - 150mm	140 - 210mm	170 - 250mm
Coil to coil misalignment	From aligned (0,0) to misaligned (±75,±100)		
WPT output voltage	280V, 350V, 420V DC		
Power transfer	100% power and 50% power transfer		

Test Setup and Test Equipment

The bench test setup utilized at INL is shown in Figure 2. It is comprised of a servo-motor driven, coil positioning system that accurately positions the ground coil assembly (GA) with respect to the vehicle coil assembly (VA) to within less than 1mm of accuracy. This coil positioning system is capable of misalignment up to +/- 300 mm in both the X and Y direction as well as change in coil to coil gap Z of up to 275 mm. A fiberglass channel strut frame is utilized to support all of the vehicle components including the VA, rectifier and tuning circuits, aluminum shielding, and a standardized steel mimic plate intended to physically represent the floor pan of a vehicle chassis. A DC load bank is utilized to absorb the output power from the WPT system and it is controlled to emulate a vehicle's high voltage battery including internal resistance.

For measuring the EM-field safety, power quality, and efficiency performance capabilities of the WPT system, a data acquisition system utilizes a high accuracy power meter and an EM-field measurement probe. The power meter with current and voltage measurement capabilities is utilized to measure the input and output power of the WPT system in order to determine the overall system efficiency (AC to DC efficiency). The power meter is also utilized to quantify the power quality of the WPT system, specifically the power factor at the input grid supply during operation. The EM-field measurement probe is utilized to measure the magnetic field and electric field near the WPT system during operation as well as measure the operating fundamental frequency of the WPT system. All of the measured data during testing is recorded and time aligned via the data acquisition system for subsequent, in-depth analysis and visualization of the performance and safety metric across the wide range of operating conditions during testing.

Figure 2. INL's SAE J2954 WPT bench test fixture and test equipment

WPT Test Results and Analysis

The data are collected and analyzed during WPT bench testing to enable the SAE J2954 results-based decision processes for developing the recommended practice and the standard. The main results and outcomes from the testing efforts are described in the following section including system efficiency, power quality, and electromagnetic field emissions near the WPT system during steady state operation.

System Efficiency

A primary scope of the WPT validation testing is to quantify the system efficiency of the matched and interoperable WPT system combinations. The system efficiency is calculated from the concurrent, steady state measurements of DC output power from the VA and input power from the 60 Hz AC grid power source. For reference, the SAE J2954 TIR[1] specifies minimum efficiency criteria for both matched and interoperable WPT operation when the coils are in alignment (≥85%) and when operating at any coil misalignment (≥80%)[1]. The test results from matched and interoperable WPT operation across a range of aligned and misaligned conditions is detailed in this section of the manuscript.

The resulting efficiencies in the SAE J2954 bench Tests are shown in detail in Appendix A and a summary chart is shown below in Table 2 related to output voltages.

System		280V Out				350 V Out				420V out Std Test Shield				420V out OEM Test shield			
	Z Pos	# Pos Full Power	Max Eff.	Min Eff.	Avg Eff.	# Pos Full Power	Max Eff.	Min Eff.	Avg Eff.	# Pos Full Power	Max Eff.	Min Eff.	Avg Eff.	# Pos Full Power	Max Eff.	Min Eff.	Avg Eff.
OVERALL - MATCHED	High	13	92.65%	91.67%	92.12%		93.20%	92.74%	93.04%		93.23%	92.48%	92.86%				
ALL 13 POSITIONS	Low	13	85.08%	80.33%	82.76%		85.51%	83.06%	82.11%		85.79%	82.76%	82.22%				
OVERALL - INTEROPERABLE	High	13	91.94%	91.51%	91.64%		92.16%	91.46%	92.07%		92.41%	91.78%	92.09%		92.09%	89.80%	91.24%
ALL 13 POSITIONS	Low	13	83.72%	77.17%	82.63%		83.10%	79.54%	81.97%		80.73%	49.54%	74.00%		79.75%	11.57%	57.79%
OVERALL - MATCHED	High	13	92.65%	91.67%	92.12%		93.20%	92.74%	93.04%		93.23%	92.48%	92.86%				
ONLY FULL POWER POSITIONS	Low	12	85.08%	80.33%	83.56%		85.51%	83.06%	84.41%		85.79%	82.76%	84.62%				
OVERALL - INTEROPERABLE	High	13	91.94%	91.51%	91.64%		92.16%	91.46%	92.07%		92.41%	91.78%	92.09%		92.09%	89.80%	91.24%
ONLY FULL POWER POSITIONS	Low	0	83.72%	80.42%	82.63%		83.10%	80.35%	81.97%		80.73%	74.63%	77.24%		79.75%	73.09%	75.76%

Values in RED are outside the limits specified in the TIR

Table 2. Summary of High/Low Efficiency Bench Test Results

The test results have been separated into three misalignment ranges to detail the impact of coil-to-coil misalignment. The three categories are with the GA and VA are *Aligned* (0,0), *Maximum Misalignment* (+/-75,+/-100), and *Moderated Misalignment* (which ranges between the aligned and maximum misalignment cases). The test results from each of the three misalignment categories include the full range of evaluated ground clearances and output voltages as detailed by the test plan. Figure 3 shows a histogram of all full power system efficiency measurements for matched WPT results across the range of ground clearance, coil to coil misalignment, and output battery voltage. A majority of the system efficiency results are greater than 89% and a few test results show matched system efficiency exceeding 93%. Conversely a few test conditions resulted in system efficiency between 80% and 89% but no aligned test conditions resulted in system efficiency less than 85%.

Figure 4 shows a histogram of all full power system efficiency measurements for interoperable WPT results across the range of ground clearance, coil to coil misalignment, and output battery voltage. A majority of the system efficiency results are greater than 87% with a few test results showing efficiency exceeding 93%. Some test conditions resulted in system efficiency between 79% and 87% and very few were below the SAE J2954 TIR[1] minimum efficiency criteria.

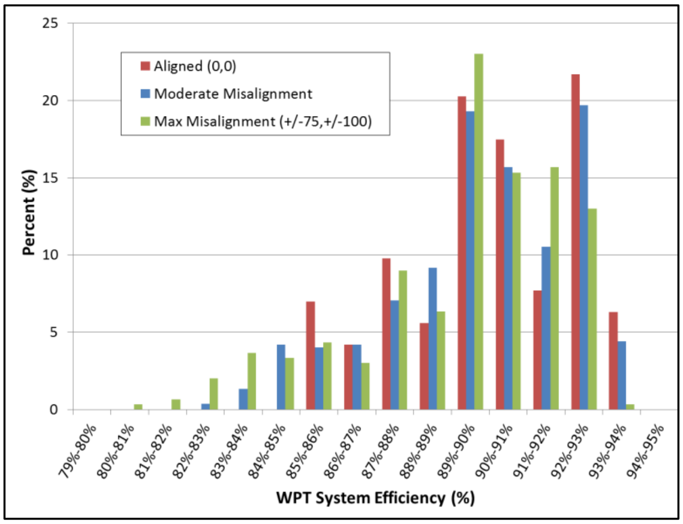

Figure 3. Histogram of Matched WPT system efficiency results

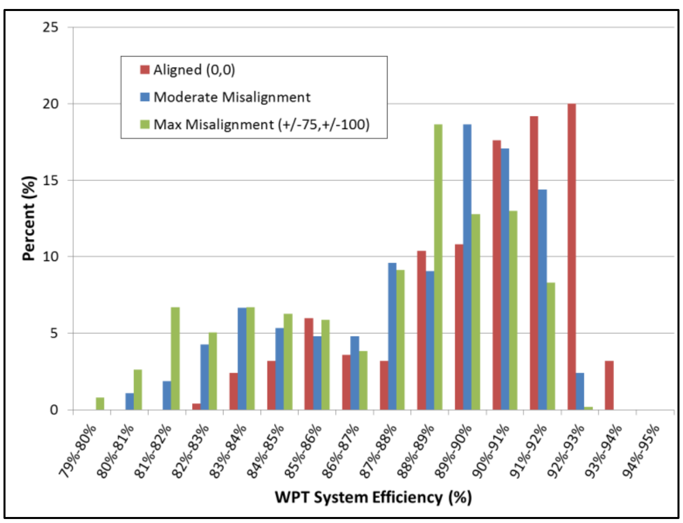

Figure 4. Histogram of Interoperable WPT system efficiency results

Overall, the system efficiency results show high efficiency for the WPT systems during matched and interoperable operation across a wide range of conditions. Generally, the interoperable efficiency results are only 2% less than the matched WPT results which show the WPT system designs are robust.

Power Quality

Power quality is measured during all phases of testing across the various operating conditions of ground clearance, coil misalignment and DC output voltage. The power factor is measured at the system input power connection during all test conditions and all results are ≥0.95 for all WPT systems tested. This is within the industry standard limits[2] for charging system power quality.

Electromagnetic Field Emissions

The electromagnetic (EM) field strength is measured during all test conditions while the WPT system is operating at steady state power transfer to ensure the EM-field strength is within public safety limits. For reference, the industry public exposure limit is 21 A/m (27 □T) and 83 V/m as defined by ICNIRP 2010[2]. These EM-field limits are guidelines to ensure the safety of persons near devises with operating frequencies up to 100kHz.

For the WPT testing detailed in this manuscript, the EM-field was measured at a fixed location near the WPT system that is analogous to the area below the front bumper of the vehicle. An EM-field measurement probe is used that is capable of measuring both the magnetic and electric field strength in three axis (X, Y, and Z). The vector sum of the three measurements is presented in this section of the manuscript. The center of the measurement probe is positioned 50mm from the edge of the steel mimic plate (800mm from the VA center) and vertically positioned between the GA and VA. This measurement location is representative of the area in front of the vehicle were the EM-field strength local maxima is expected to occur and where people may interact with the EM-field radiated from the WPT system.

The EM-field test results have been separated into three misalignment ranges to detail the impact of coil-to-coil misalignment on EM-field strength. The three categories are with the GA and VA are *Aligned* (0,0), *Maximum Misalignment with the GA farther away from the EMF probe* (+75,+/-100), and *Maximum Misalignment with the GA nearer to the EMF probe* (-75,+/-100). The test results from each of the three misalignment categories include the full range of evaluated ground clearances and output voltages as detailed by the test plan.

EMC Measurement Testing

Both EMC and EMF bench testing was conducted at TDK RF Solutions facilities in Cedar Park, TX. There were two sites which were tested at TDK to measure the relative results for EMC: The Open Area Test Site as well as the Open Field Test sites.

Open Area Test Site (OATS) Testing

The WPT systems are evaluated for EMC on an Open Area Test Site or perfect electrical conductor (PEC) plane test site shown in Figure 9 below. Figures 10a and 10b show OATS results under aligned conditions for both circular and D-D topologies.

Figure 9. TDK OATS site with WPT and measuring equipment

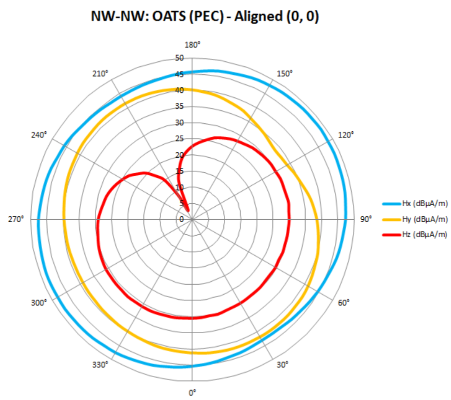

Figure 10a. Circular Topology, WPT2 OATS EMC measuring results

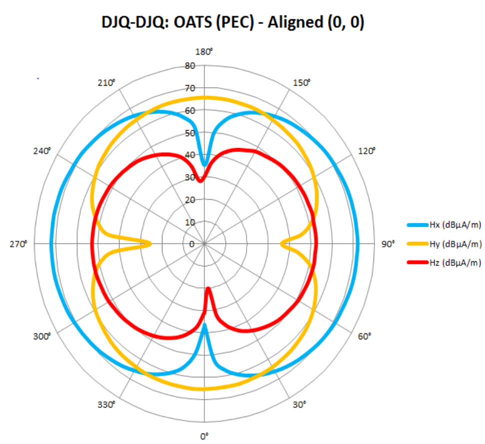

Figure 10b. DD Topology, WPT2 OATS EMC measuring results

Open Field Test Site (OFTS) Testing

The WPT systems are evaluated for EMC on an open field test site (OFTS) using real earth shown in Figure 11 below. Figures 12a and 12b show OFTS results under aligned conditions for both circular and D-D topologies. Table 3 shows the EMC results summarized between the OATS and PEC under interoperable conditions.

Figure 11. TDK RETS site with WPT and measuring equipment

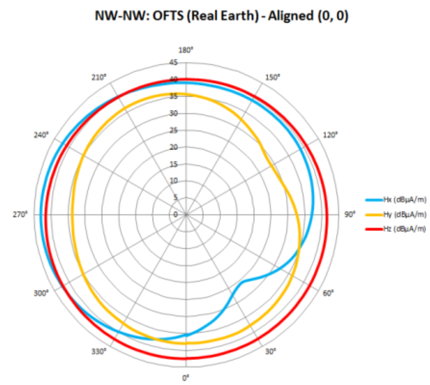

Figure 12a. Circular Topology, WPT2 OFTS EMC measuring results

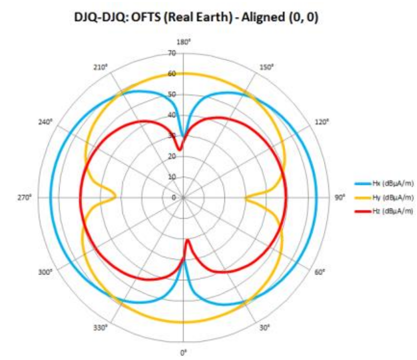

Figure 12b. DD Topology, WPT2 OFTS EMC measuring results

Two major influencing parameters on the H-field emissions have been identified: the type of the ground (PEC – perfectly electrically conductive vs. „real earth“, i.e. soil/grass) the offset between BP and VP (0/0 or 75/100). Below, in Table 3, the WPT2 EMC results from the SAE J2954 Testing between the circular (NW) and DD (DJQ) are summarized in relation to the testing sites.

	GA	VA	Input Power (W)	Alignment (x,y,z) mm	Hx (dBµA/m) @ Angle (deg)	Hy (dBµA/m) @ Angle (deg)	Hz (dBµA/m) @ Angle (deg)
OATS (PEC)	DD	Circular	4210	(-75,100,250)	73.03	66.34	55.34
					270°	175°	270°
OATS (PEC)	Circular	DD	7230	(-75,100,250)	68.83	61.94	49.84
					270°	185°	250°

Table 3. EMC measuring results under interoperable conditions

EMF Measurement Testing

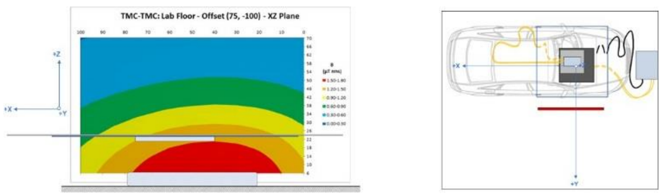

Figure 13a. Circular Topology, WPT1 EMF measuring results (1.88µT)

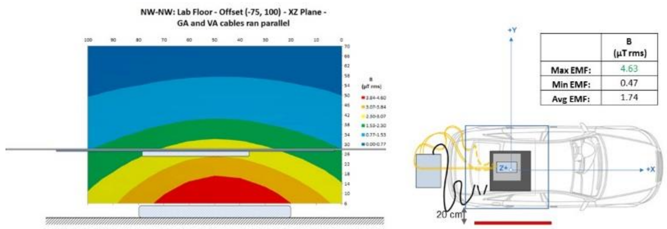

Figure 13b. Circular Topology, WPT2 EMF measuring results (4.63µT)

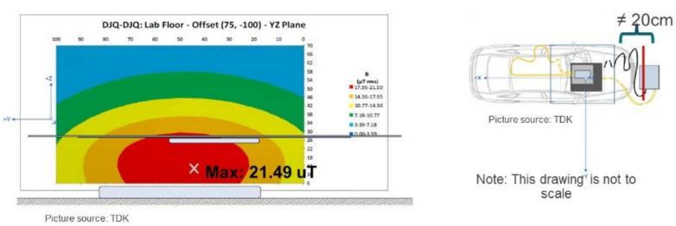

Figure 13c. DD Topology, WPT2 EMF measuring results (21.49µT)

Next Steps towards Standardization

The Recommended Practice (RP) SAE J2954 is to be published at the end of 2017 based on the findings in this technical report. The RP J2954 includes higher power classes to WPT 3 (11kW) as well as object detection, alignment systems.

Starting at the end of 2017, as a first phase in the *SAE Wireless Power Transfer, Cooperative Research Project* further performance, interoperability and EMC/EMF testing on the WPT 3 bench systems is planned in a laboratory environment. In addition, in 2018, testing will be done with real vehicle and ground assemblies planned utilizing all three power levels (WPT 1-3) within the SAE WPT Cooperative Research Project. The objective of this project is to generate additional data on the bench and vehicle for use in finalizing the SAE J2954 standard in 2018.

Summary/Conclusions

Bench testing of eight WPT systems at Idaho National Lab validated the power transfer capability, system efficiency, power quality, and EM-field safety across a wide range of operating conditions. The results show that interoperable WPT operation is not only possible, but also quite efficient.

A majority of matched system WPT test results showed AC to DC system efficiency greater than 89% with a few efficiency results exceeding 93%. Additionally for interoperable system WPT operation, the majority of results were greater than 87% efficiency with a few efficiency results exceeding 93%. Throughout testing the power factor is measured to be greater than 0.95 across all evaluated operating conditions.

The EM-field strength was measured during all steady state operating conditions. The EMF Test Bench Measurements (directional) results from TDK were as follows
WPT 1 – 2.88µT (circular) peak
WPT 2 – 4.63µT (circular) & 21.49µT (DD) peaks

Through this bench-testing project, the SAE J2954 WPT testing and design requirements were validated to be both interoperable between the two topologies (circular-DD) and power levels (WPT 1-2) with high efficiency, while within EMF limits. This validated the content of the TIR J2954.

The next steps are to complete the SAE J2954 bench testing up to WPT 3 (11kW) and finally vehicle testing WPT 1-3 for the Recommended Practice and Standard phases respectively.

References

1. SAE J2954 TIR, "*Wireless Power Transfer for Light-Duty Plug-In / Electric Vehicles and Automated Charging and Alignment Methodology"*, 2016.
2. SAE J2894/1, "*Power Quality Requirements for Plug-In Electric Vehicle Chargers*", 2011.
3. ICNIRP 2010, "*Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz to 100 kHz)"*, 2010.

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