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Laboratory Performance and Safety Test Results of the Hyundai / Mojo Mobility 7.0 kW WPT System

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Abstract

In recent years, as electric vehicles have become more popular and manifest in the market, charging systems have become an important aspect of electric vehicle utilization and adoption. Currently, it takes at least 4 hours to fully charge the Kia Soul EV using level 2 (6.6kW) charging[1]. Wireless charging makes the charging process automated, which enables a vision where chargers are commonplace and the driver does not have to be concerned with plugging in for routine driving. For example, wireless chargers may be in public parking lots or even embedded in the roadway, so the driver does not have to stop for hours merely to recharge the vehicle. In this view, wireless charging is a key enabling technology for the widespread adoption of electric vehicles.

In this manuscript, an overview of the prototype wireless power transfer (WPT) system design is provided as well as detailed laboratory test methodology and test results of the aforementioned WPT system. The WPT system design, development, fabrication, and calibration were executed by the Hyundai Motor Company in partnership with Mojo Mobility Inc. under the U.S. DOE FOA-667. Testing of the WPT system as integrated into a Kia Soul EV was conducted at Idaho National Laboratory's (INL) Electric Vehicle Infrastructure (EVI) lab to quantify the performance and safety capabilities of the WPT system. Testing was conducted across a wide range of coil misalignment, coil gap, and power transfer levels. This manuscript details the test results and findings from the Hyundai / Mojo mobility WPT system which includes measured values of overall system efficiency (AC to DC), sub-system efficiencies, power quality metrics, and electromagnetic field (EM-field) emissions measurements around the vehicle.

Keywords: Wireless Charging, Inductive Charger, Testing Processes, Safety, Efficiency

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1 Introduction

With the increasing need for electrified transportation, automated charging solutions are quickly becoming a necessity for increased EV adoption as well as a charging functionality for fully autonomous vehicles. To that end, a prototype 85 kHz wireless charging system designed to be capable of 19.2 kW output is developed, fabricated, and installed into a Kia Soul EV. The WPT system is designed to be capable of operating over a 200 mm coil-to-coil gap, with more than 90% system efficiency. This wireless power transfer (WPT) system is created by Hyundai Motor Group in partnership with Mojo Mobility Inc. under the U.S. Department of Energy FOA-667.

In this manuscript an overview is provided of the prototype WPT system design as well as detailed laboratory test methodology and test results of the aforementioned WPT system. Testing of the prototype WPT system is conducted at Idaho National Laboratory's (INL) Electric Vehicle Infrastructure (EVI) lab to quantify the efficiency, power quality, and safety capabilities of the WPT system. Testing is conducted across a wide range of coil to coil misalignment, coil to coil gap, and power transfer level. The test results include overall system efficiency (AC to DC), sub-system efficiency, power quality, and EM-field emissions measurements around the vehicle.

2 WPT System Design and Specification

A prototype 85 kHz wireless charging system is designed and developed to be capable of up to 19.2 kW output over a 200 mm coil-to-coil gap, with more than 90% system efficiency. All aspects of the WPT system are designed by the Hyundai Motor Group along with a partner company, Mojo Mobility. Figure 1 shows the WPT system electrical schematic overview which includes the input power AC/DC converter (power factor correction device), high-frequency inverter, resonant circuit, primary coil ground transmitter assembly and secondary coil vehicle receiver assembly, output rectifier with smoothing circuit, and closed loop current control algorithm via Wi-Fi communications. The ground transmitter coil assembly, which is located on the ground surface under the vehicle during charging, is 1,180 mm long x 920 mm wide and contains the primary coil and resonant tuning circuit. The vehicle receiver assembly which is mounted on the underside of the front of the vehicle is 740 mm long x 800 mm wide and contains the secondary coil assembly, the resonant tuning circuit and the output rectifier with smoothing circuit. The WPT system is designed for a nominal coil-to-coil magnetic gap of 200 mm and capable of a range of 150 mm to 210 mm. The construction of the coil windings inside the assembly enclosures of the ground assembly and vehicle assembly results the ground clearance distance being equal to the coil to coil gap distance. Therefore the designed nominal ground clearance distance is also 200 mm.

The coil size depends on the maximum power transfer level requirement. This WPT system is designed for up to 19.2 kW output. For a lower power target, the coil size would be reduced accordingly. Both the transmitter and receiver coils use Litz wire and have a 2 mm layer of ferrite (N95 material) covering the complete coil area as a magnetic flux guide to improve efficiency and reduce radiated EM-field emissions. A 2015 Kia Soul EV is used as a surrogate vehicle in which the prototype WPT system is installed. All components of the WPT system are designed to be capable of 19.2 kW output, however, the WPT system has been demonstrated up to 10 kW output when aligned and at nominal ground clearance. Charging at 19.2 kW may be pursued in future projects, however for the testing and evaluation, as detailed in this manuscript, the WPT system is operated up to a charge power level of 7.0 kW output which is more closely aligned with industry standard levels[2].

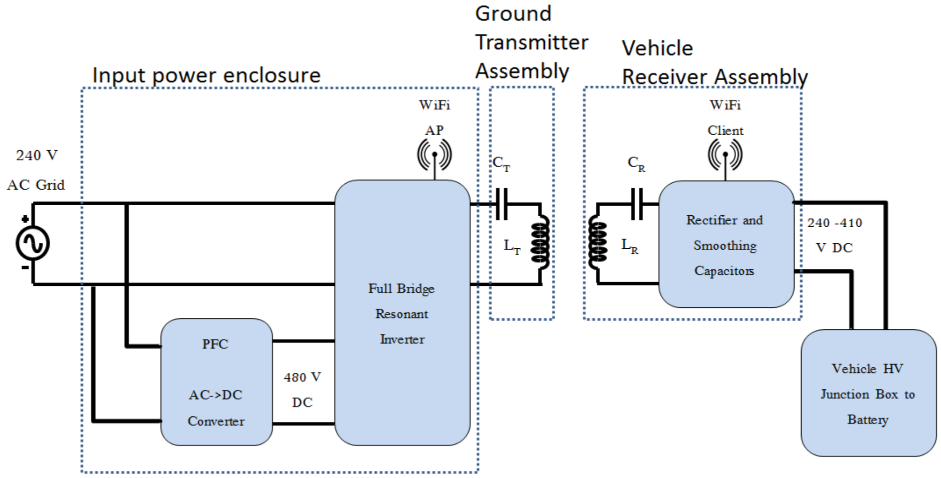

Figure 1. Hyundai / Mojo Mobility WPT System Electrical Schematic Overview

3 Laboratory Test Setup

The Hyundai / Mojo Mobility WPT system, as installed on a Kia Soul EV, is tested in the EVI lab at INL using a specific test setup specifically intended to test and evaluate the performance and safety of WPT systems including efficiency, power quality, and EM-field emissions. The EVI lab test setup includes specific laboratory equipment for accurate positioning of the WPT coil assemblies. This includes coil to coil gap, coil alignment, as well as coil rotation and tilt. The EVI lab testing capabilities also include high accuracy data acquisition system to measure and record the electrical power flow, power quality, and EM-field emissions during testing. Figure 2 shows the Hyundai / Mojo Mobility WPT system during testing in the EVI lab.

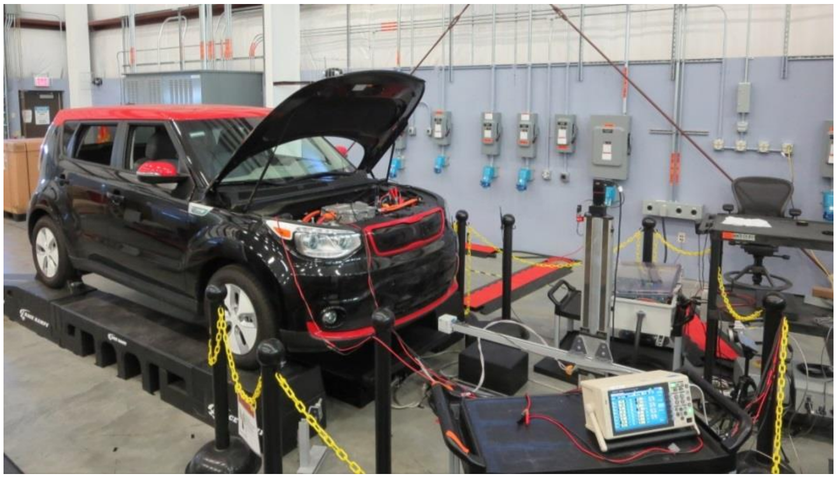

Figure 2. Hyundai / Mojo Mobility WPT system on Kia Soul EV during testing at INL's EVI lab

The test setup is comprised of a servo-motor driven, coil positioning system that accurately positions the ground coil assembly with respect to the vehicle coil assembly to within an accuracy of +/- 0.2 mm. 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. To accommodate the overall height of the coil positioning system under the WPT vehicle coil assembly, non-metallic ramps of 350 mm in height are used to elevate the vehicle for testing thus eliminating the need to dig a pit or modify the building floor structure in order to recess the coil positioning equipment below the vehicle. Additionally the vehicle ramps contain no metallic or conductive components and therefore have no impact or interaction with the electromagnetic field created by the WPT system during operation.

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 four channel power meter with current and voltage measurement capabilities is utilized to measure the electrical power at multiple nodes throughout the WPT system in order to determine the overall system efficiency (AC to DC) as well as sub-system efficiencies. The power meter is also utilized to quantify the power quality of the WPT system (specifically the power factor and the input current total harmonic distortion (THD)) with respect to the input grid supply during operation. The EM-field measurement probe is utilized to quantify the magnetic field and electric field around the vehicle 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 for subsequent in-depth analysis and visualization of the performance and safety metric across the wide range of operating conditions during testing.

4 Performance and Safety Test Results

The WPT system is tested across a wide range of operating conditions including coil misalignment, coil to coil gap, and power transfer level. Nominal operating conditions are defined as 7.0 kW DC output with the coils in alignment and a coil to coil gap of 200 mm. Table 1 details the performance and safety results as measured during nominal operation. The measured 88.4% total system efficiency is defined as the total DC output power provided to the vehicle's high voltage DC bus (in which the vehicle's battery system is connected) divided by the total grid AC input power drawn by the WPT system. Two sub-system efficiencies are also detailed in Table 1. The sub-system efficiency, front end power electronics efficiency, is defined as the DC output power from the power factor correction circuit divided by the total grid AC input power drawn by the WPT system. This sub-system efficiency includes power factor correction circuit as well as the ancillary loads such as fans, lights, and communications controls devices. The sub-system efficiency, DC to DC efficiency, is defined as the DC output power provided to the vehicle's high voltage DC bus divided by the DC output from the power factor correction circuit. This sub-system efficiency includes the full bridge resonant inverter, the resonant tuning circuit, the coil to coil coupling, and the output rectifier with smoothing circuit. As shown in Table 1, the front end power electronics efficiency is 96.5% and the DC to DC efficiency is 91.7%. Additionally Table 1 shows, the magnetic and electric field of 18.3 A/m and 278 V/m respectively. These measurements are recorded at nominal WPT operating conditions measured with the center of the EM-field probe at a distance of 200 mm from the front surface of the vehicle, along the center line of the vehicle, and vertically centered within the coil gap. The measured power quality of the WPT is 9.5% input current THD and a power factor of 0.995. Additionally, it is notable that the operating fundamental frequency of the WPT system is 88.3 kHz.

Table 1: Measured Safety and Performance Metrics at 7.0 kW DC output power

Ground Clearance (coil gap)	**200 mm**
Total System Efficiency (AC to DC)	88.4%
Front End Pwr. Elec. Efficiency	96.5%
DC to DC Efficiency	91.7%
Magnetic field at front of vehicle	18.3 A/m
Electric field at front of vehicle	278 V/m
Input Current THD	9.5%
Power Factor	0.995
Operating Frequency	88.3 kHz

4.1 System Efficiency

Coil to coil misalignment and coil to coil gap are primary factors influencing the efficiency of WPT systems. To quantify impact of coil to coil misalignment along the X-axis (fore to aft of the vehicle) and Y-axis (side to side) on the total system efficiency of the Hyundai / Mojo Mobility WPT, a full range of testing is conducted to detail the total system efficiency. Figure 3 shows the total system efficiency (AC to DC) when operating at 7.0 kW output power and a coil to coil gap of 200 mm across a range of X and Y coil to coil misalignment. As expected, the peak efficiency of 88.4% occurs where the coils are in magnetic alignment and misalignment in either the X or Y direction results in a decrease of total system efficiency. Note the mostly symmetrical system efficiency results with respect to coil misalignment as well as the difference in magnitude of misalignment impact on system efficiency along the X-axis and Y-axis. The reduction in system efficiency is greater in the Y-axis for a given coil to coil misalignment. This is primarily due to the non-square coil assembly design of the WPT system. Recall the dimensions along the Y-axis of the ground assembly and the vehicle assembly are 920 mm and 800 mm respectively whereas the dimensions along the X-axis are 1,180 mm and 740 mm respectively. This results in a ground coil assembly to vehicle coil assembly overlap of +/-60 mm along the Y-axis and +/-220 mm along X-axis.

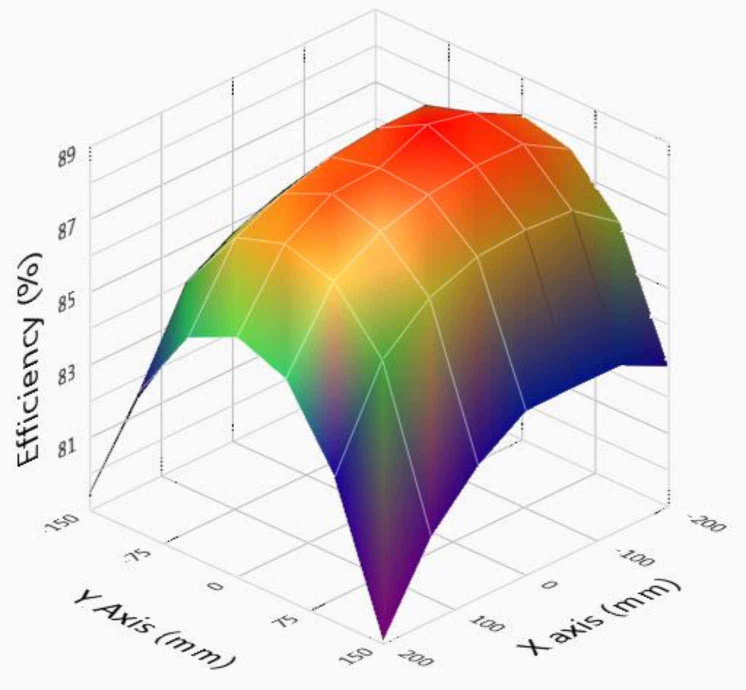

Figure 3. – WPT Total System Efficiency variation due to coil misalignment at 7.0kW and 200mm coil gap

4.2 Sub-system Efficiency

During the testing of the Hyundai / Mojo Mobility WPT, the power was measured at multiple nodes along the path of power flow. This enables the analysis of sub-system efficiencies of various components within the WPT as well as quantifying the total system efficiency. Two sub-system efficiencies were analyzed for this testing, which are the front end power electronics efficiency and the DC to DC efficiency. Analyzing these sub-system efficiencies provides insight as to the mechanisms of power loss within the WPT system.

Testing was conducted across a range of coil to coil misalignment along the X-axis at three coil gaps (150, 175, 200 mm) in order to quantify the impact of change in coil to coil gap and the impact of X-axis misalignment on total system efficiency and sub-system efficiencies. Figure 4 shows the results for three coil to coil gaps tested. Note the front end power electronics sub-system efficiency is nearly constant across the range X-axis misalignment, but does have a small increase in efficiency with decreasing coil gap from 200 mm to 150 mm. In contrast, the DC to DC sub-system efficiency is negatively impacted by misalignment as well as shows a non-symmetrical trend from the positive to negative misalignment. A misalignment of + 200 mm, where the ground coil assembly is farther under the vehicle results in a 1.0% to 1.5% lower DC to DC sub-system efficiency than a misalignment of -200 mm, where the ground coil assembly is less under the vehicle. Additionally, as seen in Figure 4, the change in coil to coil gap from 200 mm to 150 mm has a significant impact on the DC to DC sub-system efficiency with a variation of greater than 2% change in efficiency. These results show that the DC to DC power transfer accounts for the majority of the loss during charging. Additionally the DC to DC efficiency shows the greatest impact from both misalignment as well as coil to coil gap. This indicates that the change in the magnetic coil to coil coupling is significantly contributing to the change in efficiency. The total system efficiency includes the two sub-system efficiencies previously discussed and shows a similar trend of non-symmetrical efficiency with positive and negative misalignment along the X-axis. Overall the total system efficiency ranges from 86% to over 90% across the range of misalignment and coil to coil gap tested.

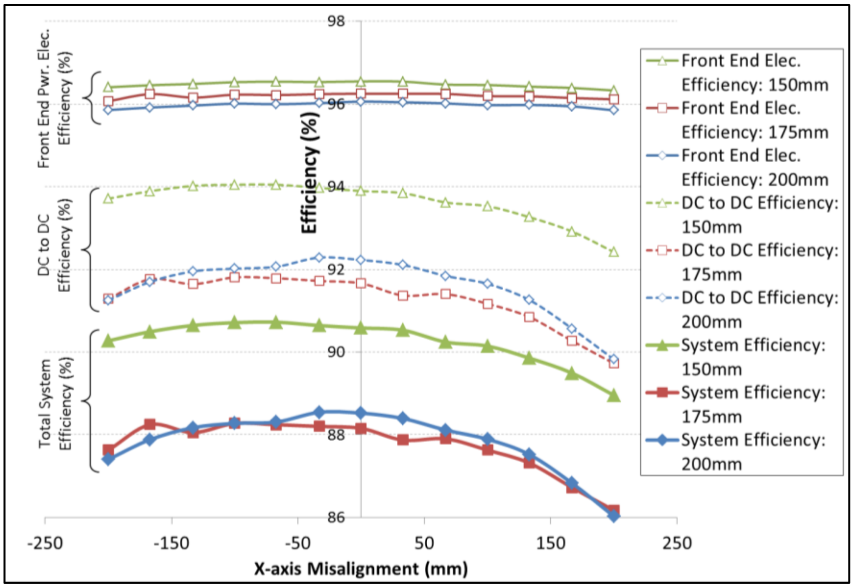

Figure 4. – Efficiency as impacted by X-axis misalignment and coil to coil gap

Additionally testing was conducted across a range of coil to coil misalignment along the Y-axis (vehicle side to side) at three coil gaps (150, 175, 200 mm) in order to quantify the impact of change in coil gap and Y-axis misalignment on efficiency. Figure 5 shows the total system efficiency and sub-system efficiencies for three coil to coil gaps tested. Similar to previous testing, the front end power electronics sub-system efficiency is nearly constant across the Y-axis misalignment, but does have a small increase in efficiency with decreasing coil gap. In contrast, the DC to DC sub-system efficiency is significantly impacted by misalignment along the Y-axis and shows a nearly symmetrical trend. The difference in efficiency is 4% reduction at +/-150 mm misalignment when compared to efficiency when aligned. This is a significantly greater impact in the Y-axis misalignment as compared to the X-axis misalignment of +200 mm which resulted in a 1.5% reduction. Additionally, as seen in Figure 5, the coil to coil gap also has impact on the DC to DC sub-system efficiency with a variation of greater than 2% change in efficiency. The total system efficiency is comprised of the two sub-system efficiencies and shows a symmetrical trend for efficiency across misalignment along the Y-axis. Overall the total system efficiency ranges from less than 84% to greater than 90% across the range of misalignment and coil to coil gap.

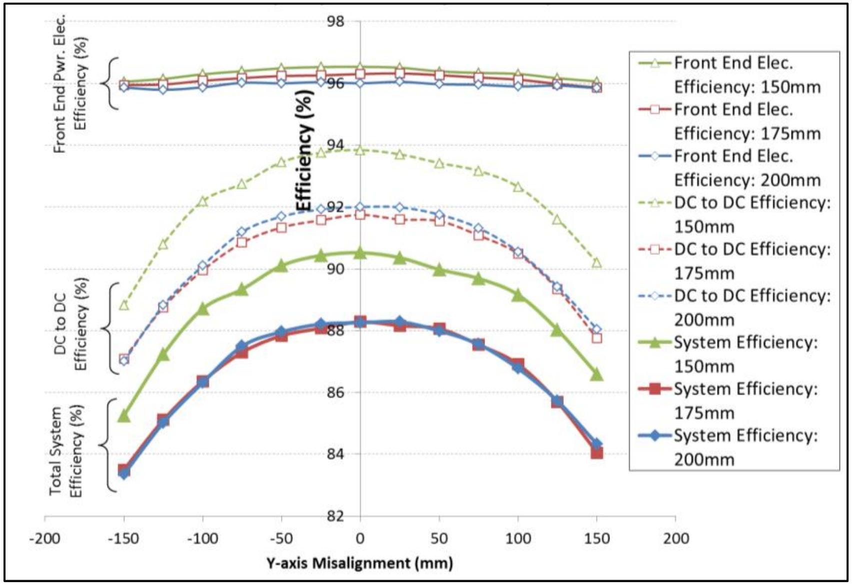

Figure 5. – Efficiency as impacted by Y-axis misalignment and coil to coil gap

The testing showed the impact of misalignment and coil to coil gap is significant with impact over 4% from misalignment of -150 mm along the Y-axis and coil to coil gap impact of slightly greater than 2% with as little as 25 mm increase in coil to coil gap. This confirms the importance of accurate vehicle alignment during parking as well as properly designed coil to coil gap dimensions in regards to WPT system vehicle integration.

4.3 Power Quality

Throughout all phases of testing, the power quality of the WPT system input power was measured using the power meter to determine the interaction and influence of the WPT system onto the electric gird supplied power. These measurements specifically quantified the power factor and the input current total harmonic distortion (THD) of the WPT system. Across the various test conditions such as coil to coil gap and misalignment, the power factor and input current THD are very consistent. However, when operating at reduced power levels there was measureable change in both the power factor and input current THD. Figure 6 shows the power factor and the input current THD of the WPT system across a wide range of output power. Note the best power factor and input current THD occurs at full power transfer, and are measured to be 0.995 and 9.5% respectively. With decreasing power transfer, the power factor decreases and the input current THD increases. Additionally the results show no significant influence of coil to coil gap on power factor or input current THD. Overall the test results show the power factor is above the industry minimum limit of 0.95[3].

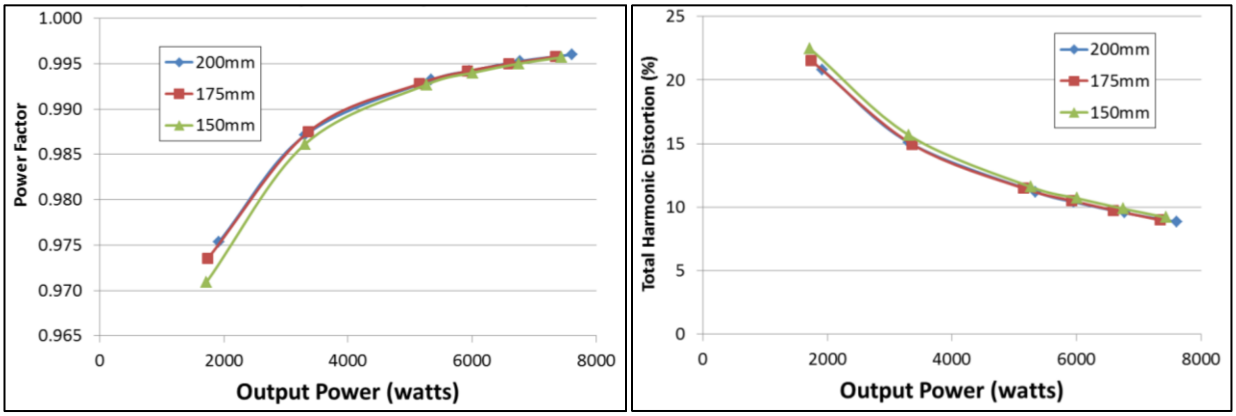

Figure 6. – Power Factor and Current THD variation across a range of Output Power for three coil gaps

4.4 Electromagnetic Field

Electromagnetic field (EM-field) measurements are conducted at the front of the vehicle in a precise grid pattern to characterize and visualize the magnitude of the EM-field adjacent to the front bumper of the vehicle. This was accomplished by using an EM-field measurement probe to measure the magnetic and electric field during steady state operation of the WPT system during full power transfer. The center of the EM-field probe is positioned by a 2-axis, servo-motor controlled positioning apparatus at the pre-determined measurement grid locations that range from -200 mm to +650 mm in the Z direction and from -450 mm to +450 mm in the Y direction. For all of the measurements, the center of the EM-field probe was positioned as a distance of 200 mm from the forward most surface of the vehicle front bumper. Figure 7 shows a photo of the front of the vehicle with the Y and Z axis overlaid for reference. The vertical center line of the vehicle, which is the Z-axis, is indicated by the dashed yellow line on Figure 7, 8, and 9. For reference the lower surface of the vehicle coil assembly is at Z-axis = 0.0 mm. The ground surface is Z-axis = -200 mm since testing is conducted at the nominal condition of 200 mm ground clearance.

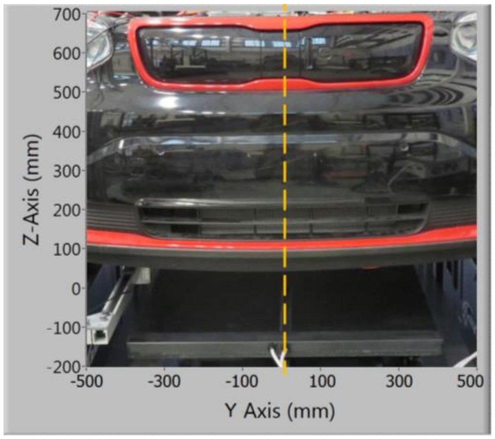

Figure 7. – Area of EM-field measurement at front of the vehicle

The EM-field measurements are conducted during 7.0 kW steady state operation, at a coil to coil gap of 200 mm, with the coils in alignment. Figure 8 shows the magnetic field measurements in A/m at the front of the vehicle. The muted color regions are below the ICNIRP 2010 general public exposure limit of 21 A/m, whereas the brightly colored region (lower center) is greater than the ICNIRP 2010 limit[4]. Note the H-field symmetrical characteristic across the Y-axis. The maximum measured H-field strength is 21.7 A/m. This measurement is closest to the ground coil assemble and along the vehicle's center axis. Overall the H-field measurement results at the front of the vehicle, verify that nearly the entire region next to the vehicle is within the industry public exposure limit during 7.0 kW power transfer.

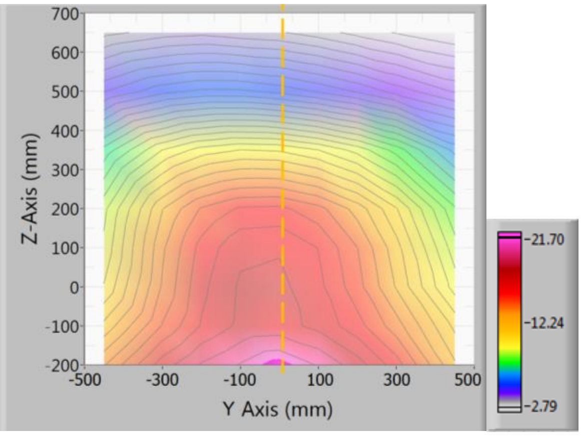

Figure 8. – H-field (A/m) measurement at 200 mm from the front of the vehicle

Electric field measurements are concurrently conducted with the magnetic field measurements discussed previously at the pre-described measurement locations at front of the vehicle. Figure 9 shows the electric field measurements in V/m. The muted color section is below the ICNIRP 2010 general public exposure limit of 83 V/m, whereas the brightly colored region (below Z=500 mm) is greater than the ICNIRP 2010 limit. Note the non-symmetrical E-field characteristic in the Y direction which shows a larger E-field on the passenger side of the vehicle (negative Y direction). The maximum measured E-field strength is 425 V/m which occurs at two locations. One maximum location is closest to the passenger side of the ground coil assemble and the second maximum location is near the Litz wires connection to the ground coil assembly from the inverter power electronics. Overall the E-field measurement results indicate a majority of the area 200 mm in front of the vehicle, exceeds the general public exposure limit, by up to five times, during 7.0 kW output WPT operation.

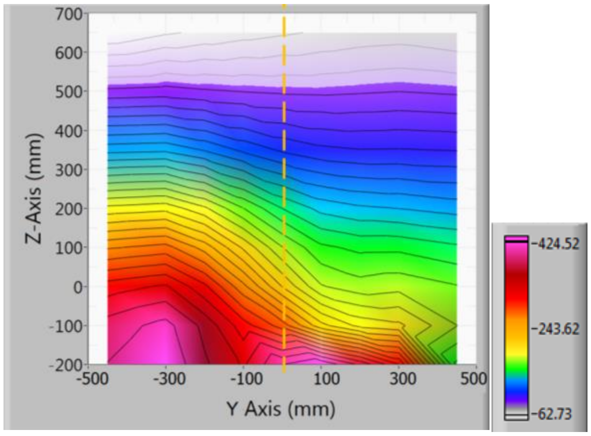

Figure 9. – E-field (V/m) measurement at 200mm from the front of the vehicle

The EM-field emissions measurements around the WPT system at front of the vehicle exceeded the ICNIRP 2010 public exposure limit. The highest magnetic field measured is 21.7 A/m which is only slightly higher than the public exposure limit of 21.0 A/m. However the highest electric field measured is 425 V/m is more than five times above the public exposure limit of 83 V/m. The E-field emissions in excess of the public exposure limit will require further development and modification to the WPT system to reduce the E-field emissions to acceptable levels.

5 Summary

A prototype 7.0 kW WPT system is designed, developed, constructed, and calibrated under the U.S. Department of Energy FOA-667 by the Hyundai Motor Group in partnership with Mojo Mobility. The WPT system is integrated into a 2015 Kia Soul EV and delivered to Idaho National Laboratory for performance, power quality, and safety testing and evaluation at INL's EVI lab. The testing and evaluation at INL measured the total system efficiency, sub-system efficiencies, electrical power quality, and EM-field emissions of the WPT system during 7.0 kW power transfer. These measurements are accomplished through utilizing laboratory testing equipment and fixtures specific for the evaluation of WPT systems.

The Hyundai / Mojo Mobility WPT system operates at a constant fundamental frequency of 88.3 kHz across all test conditions including misalignment, variation in coil to coil gap, and reduced power levels. The WPT system demonstrated high efficiency, high power quality, and low magnetic field emissions across a wide range of coil misalignment and coil to coil gap. The total AC to DC system efficiency at the nominal coil to coil gap of 200 mm ranged from 80% to a peak efficiency of 88.4% when aligned. With a decreased coil to coil gap of 150 mm, the total system efficiency exceeded 90%. Throughout the range of testing, the power factor is measured to be 0.995 and the input current THD is 9.5%. The magnetic field measured in front of the vehicle was generally below the public exposure limit except for the highest value of 21.7 A/m. However the electric field emissions measured in front of the vehicle were generally above the public exposure limit, with the highest measured value of 425 V/m which is more than five times the public exposure limit. The E-field emissions in excess of the public exposure limit will require further development and modification to the WPT system in order to reduce the E-field emissions to acceptable levels.

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Authors

Richard "Barney" Carlson is currently the principal researcher at INL's Electric Vehicle Infrastructure (EVI) laboratory where he leads the testing and evaluation efforts to characterize the performance and safety of advanced EV charging systems in support of the U.S. Department of Energy. He has a bachelors and masters in mechanical engineering from the University of California, Davis. He has over twenty year experience in the research, design, development, and testing of plug-in electric vehicles and charging infrastructure.

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Shawn Salisbury is an advanced vehicle research engineer at Idaho National Laboratory where he is involved with laboratory testing of advanced EV charging systems and analysis of real-world EV infrastructure usage in support of several U.S. Department of Energy projects. He received his BS and MS in mechanical engineering from Colorado State University, and has been working at INL since his graduation in 2014.

Bilal Javaid completed his Bachelor degree from University of Michigan Ann Arbor in 2013 with a major in Biomedical Engineering and a minor in Electrical Engineering. Bilal has worked at Hyundai America Technical Center since graduating. He has worked on the EV wireless charging project from the perspective of vehicle CAN bus communications, software & control logic, and test & measurement. He also worked on vehicle-to-vehicle communication system by assisting in RF-related installation aspects, software, and test & measurement.