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Test Results of the PLUGLESS™ Inductive Charging System from Evatran Group, Inc.

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ABSTRACT

Laboratory testing is conducted on a wireless charging system by the Idaho National Laboratory in support of the U.S. Department of Energy's Advanced Vehicle Testing Activity. System efficiency and magnetic and electric field strength are measured during wireless charger operation over a wide range of conditions, including coil gap, offset alignment, and power transfer rate. Component surface temperatures are monitored at a full-power charge rate. The PLUGLESS™ inductive charging system from the Evatran Group, Inc. is tested in a laboratory setting and results are detailed.

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INTRODUCTION

A wireless charging system enables automated charging of electric vehicles without the need for an operator to plug-in the vehicle. Wireless charging systems are comprised of power electronics that convert grid power (i.e., 60 Hz in the United States) to a higher frequency power that is delivered to an electrical coil located on or below the ground under the vehicle. This coil is referred to as the primary coil. On the vehicle, a second electrical coil is attached to the underside of the vehicle; this is referred to as the secondary coil. Power is transferred from the primary coil (ground side) to the secondary coil (vehicle side) when the two coils are relatively close to being concentric, with an appropriate distance or gap between the two coils. The output power from the secondary coil is rectified from the higher frequency power to DC power, which is used to charge the onboard energy storage system (i.e., battery).

Wireless charging for grid-connected vehicles (i.e., plug-in electric vehicles) is an emerging technology, with the added driver convenience of hands free automated charging. This convenience may increase the acceptance of grid-connected vehicles. It is important to quantify the system characteristics of wireless charging technologies through in-depth testing to gain a full understanding of the system performance characteristics of the technology.

The Idaho National Laboratory (INL) conducts laboratory and vehicle level testing of a wide range of plug-in electric vehicle charging infrastructure in support of the U.S. Department of Energy Advance Vehicle Testing Activity. With the emergence of wireless charging technology, INL is a leader in the testing of wireless charging systems both in a laboratory and for vehicle level testing. This paper will detail the laboratory testing and results from the PLUGLESS™ inductive charging system, which is the first available inductive charging system intended for plug-in electric vehicles.

TESTING OVERVIEW

The INL conducts testing of wireless charging systems to benchmark system efficiency and the electric and magnetic (EM) field strength in close proximity to the system. Specialized equipment is used to operate the wireless charging system outside of a vehicle and measure and record the data used to quantify the system performance.

For wireless charging system testing, it is important to define the coordinate system and origin utilized for testing and presentation of results. The origin is defined to be at the geometric center of the secondary coil and at the bottom plane of the enclosure housing the secondary coil. This geometric center of the secondary coil is not necessarily in the center of the housing that encloses the secondary coil. From this origin, the positive X direction is toward the front of the vehicle, the positive Y direction is toward the left side (driver's side) of the vehicle, and the positive Z direction is up vertically toward the roof of the vehicle. Figure 1 shows a drawing of the coordinate system with respect to a vehicle.

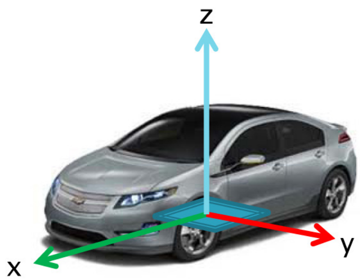

Figure 1. Coordinate system for testing wireless charging *(image provided by SAE J2954).*

The origin of this coordinate system was chosen because it is consistent with the consumer's frame of reference, which is the vehicle when standing next to the vehicle. Therefore, the secondary coil also is chosen as the frame of reference for testing when compared to the primary coil. This is important when evaluating the EM field strength at a location in which a fixed distance from the secondary coil; therefore, it is an appropriate origin for the coordinate system test measurements and reporting. Conversely, if the primary coil is used as the origin for the coordinate system, the distance from the primary coil origin to the location in which a person could be standing next to the vehicle will vary with varying coil alignment. This would make EM field strength measurements more difficult to analyze and interpret due to the varying distance to the location of the person standing next to the vehicle.

Several parameters, which are shown in Table 1, potentially impact the wireless charging system efficiency and EM field strength. These parameters are tested and analyzed to determine the extent of their impact on system efficiency and EM field strength.

Table 1. Parameters investigated and the extent of impact on system efficiency and electric and magnetic field strength.

Coil to coil position
Gap (Z direction)
In X direction (front to back of vehicle)
In Y direction (side to side of vehicle)
Coil to coil rotation
Tilt or angle between coils
Output power
Temperature (warm-up impact)

The laboratory wireless charging testing at INL is conducted in harmony to the draft test procedures of the SAE J2954 document, specifically for testing full systems (matched primary and secondary coils). INL test procedures include additional testing for system efficiency and the EM field across a matrix of coil alignments for various coil to coil gaps and output power levels. Overall the test setup configuration, test plan, and results analysis are in accordance with SAE J2954.

THE PLUGLESS™ INDUCTIVE CHARGING SYSTEM BY EVATRAN GROUP, INC.1

The PLUGLESS™ inductive charging system is intended for use with plug-in electric vehicles. The PLUGLESS™ inductive charging system provides visual alignment guidance to the driver via illuminated arrows on the control panel to ensure the charging coils are aligned between the vehicle adapter and parking pad. Once a minimum threshold alignment is achieved, the system changes the operational state to wait for the driver to turn off the vehicle and release the brake. The PLUGLESS™ inductive charging system then engages an interlock system to prevent voltage from being present at the conductive charge receptacle. Finally, the PLUGLESSTM inductive charging system uses the SAE J1772 protocol with the onboard charge module to initiate and complete charging. Table 2 shows the manufacturer's specifications for the PLUGLESS™ inductive charging system.

Table 2. Manufacturer's specifications for the PLUGLESS™ inductive charging system.1

Manufacturer's Specifications	
Input Voltage	208 to 240 VAC
Recommended Circuit Breaker	30-A circuit breaker
Maximum Continuous Output Power to Vehicle	3.3 kW
Gap Between Enclosures	4 in. (100 mm)

The DC power output of the PLUGLESS™ inductive charging system is designed to provide power to the onboard charge module of the vehicle, which, in turn, charges the energy storage system. This means it is connected, in parallel, with the conductive SAE J1772 port. This design allows for ease of integration into vehicles that are SAE J1772 compliant. A safety interlock system in the PLUGLESS™ system prevents simultaneous operation of the conductive and inductive charging systems. It also prevents the wireless system from energizing the terminals on the charge port used for plug-in charging.

The PLUGLESS™ inductive charging system is comprised of three main components (Figure 2): the control panel, the ground pad, and the vehicle adapter. The control panel is the wall-mounted power electronic module that supplies power to the parking pad, visually provides charging status, and provides parking alignment guidance to the driver via flashing LED lights. The parking pad is installed on the garage floor or the surface of the parking spot under the vehicle. It contains the primary coil and other electronics necessary for wireless power transfer to the secondary coil. The vehicle adapter attaches to the underside of the vehicle and contains the secondary coil and other electronics that are necessary for wireless power transfer and to provide the DC power output.

Figure 2. PLUGLESS™ inductive charging system components (from left to right): control panel, ground pad, and vehicle adapter.

The PLUGLESS™ inductive charging system contains radio modules in the control panel and vehicle adapter to communicate vehicle-measured system quantities and to control interlocks in the vehicle adapter.

LABORATORY TEST SETUP

Laboratory testing is conducted at INL on wireless charging systems to benchmark system efficiency and the EM-field levels near the wireless charging system. The wireless charging system is operated in a laboratory test fixture to enable proper functionality outside of the vehicle. Measurement equipment and data acquisition are utilized to measure and record electrical data from electrical nodes located at the input of the control panel and output from the vehicle adapter, EM field strength from an EM field analyzer, thermal images using an infrared camera, and test conditions and other additional information as needed. All of these components are controlled by a custom LabVIEW Test Control Program, which utilizes multiple methods of communication, including GPIB, Serial, and Ethernet to control and communicate with multiple devices. The LabVIEW Test Control Program controls test timing, the laboratory coil positioning system, the programmable DC load, and all data acquisition components. The Test Control Program also shows the real-time feedback of the measured parameters to allow the test operator to monitor the test conditions.

Laboratory Wireless Charger Test Fixture

The laboratory test fixture enables proper operation of the wireless charging system outside a vehicle for the sole purpose of testing. This test fixture includes a servo motor controlled positioning table to locate the primary coil with respect to the secondary coil, a fiberglass support frame that suspends the secondary coil over the primary coil at the required gap, a communications module to emulate the required J1772 protocol for proper functionality, and a programmable DC load to control and sink the output power from the wireless charging system. Figure 3 shows the positioning table and the fiberglass support frame for the testing wireless charging systems.

A fiberglass channel strut frame suspends the secondary coil over the primary coil at the required test position. Because the wireless charging system creates magnetic fields that can cause localized heating due to eddy currents in conductive objects near the coils, fiberglass was chosen for the channel strut frame and all fasteners due to its insulating electrical properties. Channel strut framing was also chosen due to its adjustability. The gap between the secondary coil and the primary coil can be adjusted by loosening the channel strut fasteners, sliding the secondary coil in the Z direction to the new required gap position, and then retightening the fasteners. This method can accommodate a small amount of tilt by utilizing unsymmetrical positioning of the channel strut frame adjustment in the Z direction.

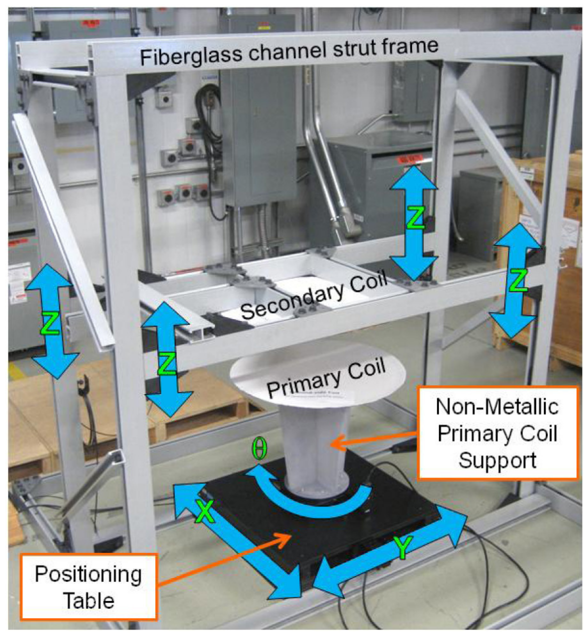

Figure 3. Laboratory Test fixture for wireless charger coils alignment positioning.

The servo motor-controlled positioning table is used to reposition the primary coil offset with respect to the secondary coil for each test point. This positioning table controls the primary coil position along the X axis, Y axis, and rotational axis as commanded from the LabVIEW Test Control Program in accordance with the test plan. The positioning table utilizes precision-crossed roller ways and large diameter lead screws driven by servo motors for position control. The extent of table positioning is ±300 mm along the X and Y axis with an accuracy of ±0.030 mm. The rotational axis extent is 360 degrees and is only limited by the wiring cord management of the primary coil. Because the positioning table contains several metallic components, a non-conductive stand-off is used to attach and elevate the primary coil 18 in. above the positioning table. At this distance, the EM field strength at the positioning table is fairly low, which will reduce the eddy currents induced in the metal components of the positioning table, thereby reducing any unintentional temperature rise.

In order to operate the wireless charging system outside of its intended vehicle, vehicle communications with the wireless charging system must be emulated for proper functionality. To accomplish this, a SAE J1772 compatible emulation module was implemented to command the control pilot state of the charger, as well as other vehicle communication signals required by the system to control charging states or other required functionality.

For laboratory testing of wireless charging systems, a programmable DC load was utilized in place of an energy storage system. This allowed for greater control, precision, and more time for testing, because there was no need to discharge the energy storage system after testing. The DC programmable load used is a Chroma 63210 that is capable of 14.5 kW, with an input voltage capability up to 500 VDC.

Laboratory Testing Measurement Equipment

For electrical measurements, a Hioki power meter 3390 is used to measure currents and voltages for both DC and AC signals at multiple nodes throughout the system. The Hioki power meter2 is able to calculate real-time power, harmonics, power factor, and efficiency. Additionally, an integration feature allows energy measurement through integration of power over the duration of the test. All of the data measured from the Hioki power meter is recorded and stored to a computer via the LabVIEW test control software.

EM fields are created near the wireless charging coils during operation. A Narda EHP-200a Field Analyzer3 is used to measure these EM fields and is capable of measuring magnetic field strength from 0.0006 to 300 A/m (0.00075 to 375 μT) and electric field strength from 0.02 to 1,000 V/m. The meter is capable of EM field measurements from 9 kHz to 30 MHz, which completely covers the range of frequencies for wireless charging and harmonics.

Monitoring the temperature of the wireless charging system during operation is important because objects in close proximity to the coils may increase in temperature if they are conductive and couple with the magnetic field created by the wireless power transfer. During testing, thermal imaging was continuously monitored using an infrared camera. This quantified the surface temperature of all accessible components and monitored the temperature of any foreign object that happens to be in proximity to the testing.

Quasi-static testing is conducted for each test point, which is a specific test condition distinctly characterized by output power, coil to coil relative position, and EM field measurement location. At each test point, the wireless charging system is operated for between 30 seconds and 10 minutes at the fixed condition, while measurements are recorded. Test points are grouped together into a test sequence that is timed and controlled by the LabVIEW Test Control Program. This test sequencing allows for efficient and repeatable testing that enables thousands of test points to be conducted over a relatively short period of time.

Test Setup Specific to the PLUGLESS™ Inductive Charging System

For laboratory testing, the input voltage was 208-VAC, single-phase from a 30-A circuit breaker. The nominal test condition included a coil to coil gap of 100 mm (4.0 in.) and a DC output power of 3.3 kW. The DC output power is controlled by the programmable DC load to an allowable lower voltage limit of 165 VDC. Below this lower voltage limit, no power is drawn from the inductive charging system. This lower voltage limit is chosen to ensure the manufacture's maximum current output limit of 20 Amp is adhered to for all power levels up to and including 3.3 kW. In-vehicle operation may have a different voltage limit requirement. This may impact the range of operation of the inductive charging system, but this impact can only be realized with vehicle-specific testing.

System efficiency is a primary output metric from this testing. It is defined as the DC power output from the vehicle adapter (input to the on-board charge module) divided by the power input from the 208 VAC. Figure 4 shows a schematic of the power flow from electricity generation to the vehicle propulsion system. The green arrows indicate the portion of this flow path that is the PLUGLESS™ inductive charging system; therefore, they show the system's interaction with the entire well to wheels path.

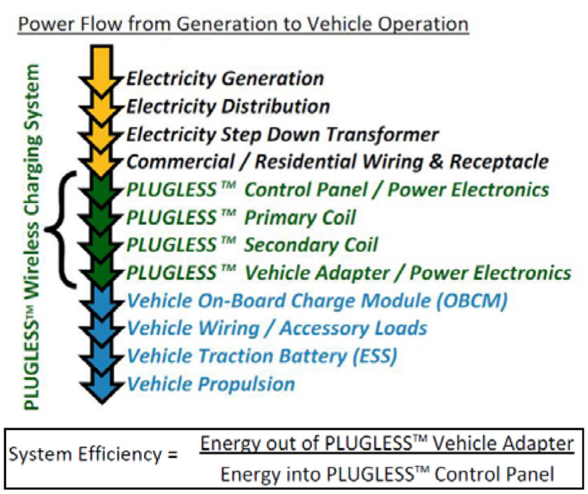

Figure 4. Definition of system efficiency.

TEST RESULTS - PLUGLESS™ INDUCTIVE CHARGER BY EVATRAN GROUP, INC.

Measured System Efficiency

The PLUGLESS™ inductive charging system is tested at several coil to coil gaps over an array of alignment test points. This array of test points is the X and Y position of the primary coil with respect to the secondary coil. The test array is comprised of test points at 30-mm intervals in the X and Y direction, up to 120 mm of alignment offset. At each test point, the inductive charging system is operated at a steady-state condition, while measurements are collected and then analyzed for system efficiency. Figure 5 shows the system efficiency of the PLUGLESS™ system when operating at 3.3-kW output power at a coil to coil gap of 100 mm for various coil offset alignments.

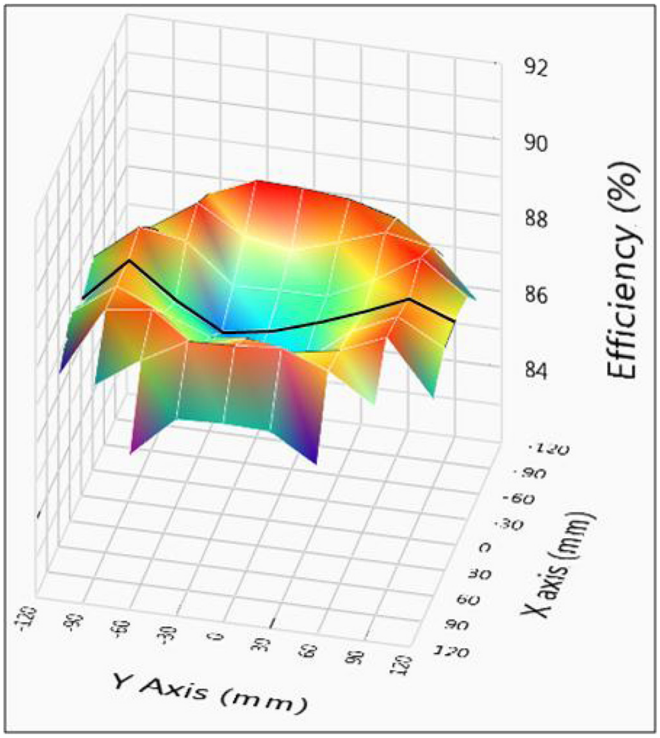

Figure 5. System efficiency at 3.3-kW output and 100-mm gap at various coil to coil offset alignments.

Note that the maximum efficiency for this operation condition of a 100-mm gap at 3.3 kW is 88.8% at X = −90 mm and Y = −30 mm. The system efficiency can be seen as slightly lower when the coils are aligned (i.e., X = 0, Y = 0). Also note that at the outer extent of the operating envelope, where the offset alignment is greater than 90 mm, the system efficiency is reduced.

In Figure 5, the black line highlights the cross section of the system efficiency surface plot along the Y axis. Since the system efficiency surface plot is relatively symmetric around the zero offset test point, the cross section (black line) will be used for comparison of system efficiency at other operating conditions.

Similar to the results shown in Figure 5, a range of tests were conducted over the array of coil alignment test points at 3.3 kW output power for a range of coil gaps. Figure 6 shows the cross sections of the system efficiency surface plots along the Y-axis for each of the coil gap operating conditions. Note the 100mm gap condition is the same as the black line highlighted in surface plot on Figure 5.

Figure 6 shows that coil gap has an impact on system efficiency over the range of XY alignment tested. At a larger than nominal coil gap (i.e., greater than 100 mm), the system efficiency is greater when the coils are in alignment (0,0); however, the system efficiency is reduced at the outer extent of the operating alignment envelope. At the largest gap tested (i.e., 130-mm gap), the extent of operation for 3.3 kW decreased. With the coil gap of 130 mm and an offset alignment of 120 mm (0,120), the system was unable to output 3.3 kW given the output current limitation of the system. For coil gaps smaller than the nominal gap (i.e., less than 100 mm), the system efficiency is lower when the coils are in alignment (0,0); however, the system efficiency is higher near the outer extent of the operating alignment envelope. Overall, this shows that system efficiency changes by up to 4% with a coil gap variation of 50 mm (120 to 70 mm). This extent of operation was tested in the laboratory setup, off-board the vehicle, using a lower voltage limit of 165-VDC output. This extent of alignment operation may be different for operation onboard a vehicle, dependent on the vehicle specific operational requirements.

Testing is conducted at various output power levels to determine the impact on system efficiency. For ease of comparison, the system efficiency results along the Y-axis are shown in Figure 7. The 3.3-kW output power curve is identical to the 100-mm curve shown in Figure 6. This is the same nominal test condition. Output power shows a moderate trend of increasing efficiency at 2.75 and 2.2 kW compared to 3.3-kW output power. Additionally, a system efficiency of greater than 90% was measured at mid power levels and moderate coil misalignment (Figure 7). At significantly reduced power (1.1 kW), the efficiency is significantly less.

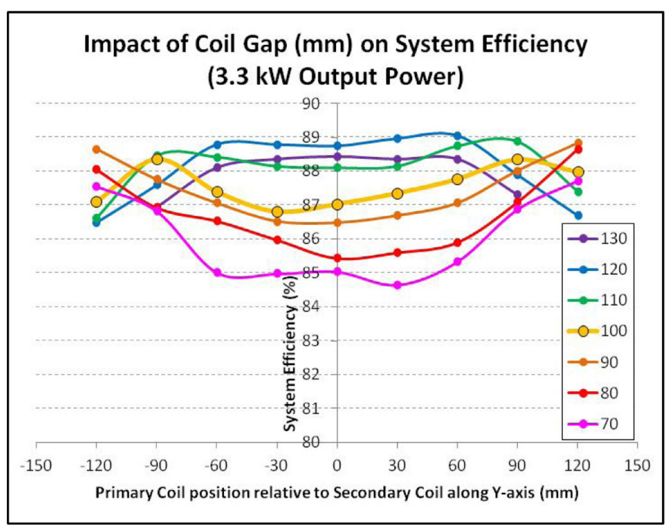

Figure 6. The impact of the coil to coil gap on system efficiency.

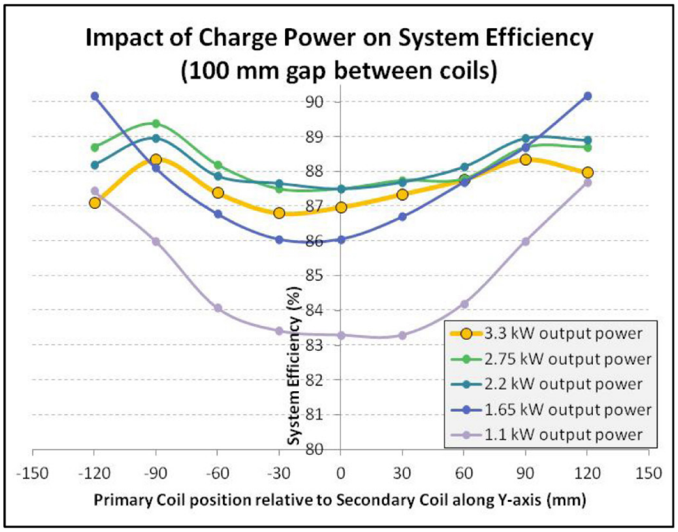

Figure 7. The impact of the output power on system efficiency.

Measured Magnetic and Electric Field Strength

The EM field strengths are measured during all test operating conditions. The field strength measurement magnitude is dependent on the distance from the source and the magnitude of the generated field strength. A field measurement taken closer to the source results in a larger measurement value or, if the source is producing a higher magnitude field, the measurement value at a fixed distance will also be larger. For this laboratory testing, a distance of 0.8 m from the center of the secondary coil is chosen as the nominal distance for EM field strength measurements. This distance is representative of the consumer accessible area under the edge of a vehicle. For instance, the Chevrolet Volt is 1.79-m wide, excluding the side mirrors.4 Assuming that a wireless charger's secondary coil is centered under the vehicle, the edge of the vehicle is 0.895 m from the center of the secondary coil. If a person were to kneel beside the vehicle and reach under the edge of the vehicle, it is reasonable to estimate that the person's hand would be 0.8 m from the center of the secondary coil. Therefore, the measurement distance chosen for the laboratory EM field measurement is 0.8 m from the center of the secondary coil.

There are several EM field industry guidelines for human exposure limits, including ICNIRP 19985 and 2010,6 IEC 62233,7 and ARPANSA RPS No.3 guidelines. This paper will present the measurements and results from the laboratory testing of the PLUGLESS™ system. At the reader's discretion, the multiple reference guidelines can be reviewed for comparison to the presented EM field measurement results.

The EM field measurement is comprised of multiple measurements for both EM field levels over a wide range of frequencies. Figure 8 shows the EM field measurement, 0.8 m from the center of the secondary coil, over a frequency sweep from 10 to 100 kHz, with the inductive charging system operating at 3.3-kW output power, the coils aligned (0,0), and a 100-mm coil to coil gap. This measurement is conducted with a step size of 250 Hz (i.e., measurements conducted at 10.00, 10.25, and 10.50 kHz).

The system operating frequency of 19.5 kHz can be seen in Figure 8 as the fundamental frequency in both EM field measurements. The magnetic field's third harmonic can be seen at 58.5 kHz; however, the second, fourth, and fifth harmonics are below measureable levels (i.e., 39, 78, and 97.5 kHz). For the electric field measurement, four harmonics are seen on Figure 8, with the fifth harmonic showing the largest magnitude.

From Figure 8, it is noteworthy to observe that the largest measured magnitudes at the fundamental frequency for both EM fields are in the Z-axis direction. This indicates that the field is toroidal in shape (i.e., donut shaped). Conversely, the electric field harmonic's predominant field strength is in the Y-axis direction. This is the linear direction between the wireless charger coils and the EM field meter. EM field measurements are conducted during operation of the PLUGLESS™ inductive charging system over the standardized array of alignment test points. For each test point, a maximum magnetic field (H- field) and electric field (E- field) strength is determined. The maximum E and H field strengths are shown in Figures 9 and 10 as measured 0.8 m from the center of the secondary coil in the Y-axis during operation at 3.3-kW output power and a 100-mm coil gap. All of the measured maximums occurred at 19.5 kHz, because this is the system operating frequency. In Figures 9 and 10, the black "x" indicates the test point at which the coils are aligned (0,0). At this test point, the H-field strength maximum is measured to be 12.9 A/m (16.1 μT) and the E-field strength maximum is 22.1 V/m. The E and H-field strengths increase as the primary coil moves in the positive Y direction. This is the direction in which the primary coil is moving closer to the EM field meter. It is located 0.8 m (800 mm) from the secondary coil along the Y-axis and centrally located vertically in the Z-axis between the coils (i.e., 50mm below the secondary coil for a coil gap of 100 mm).

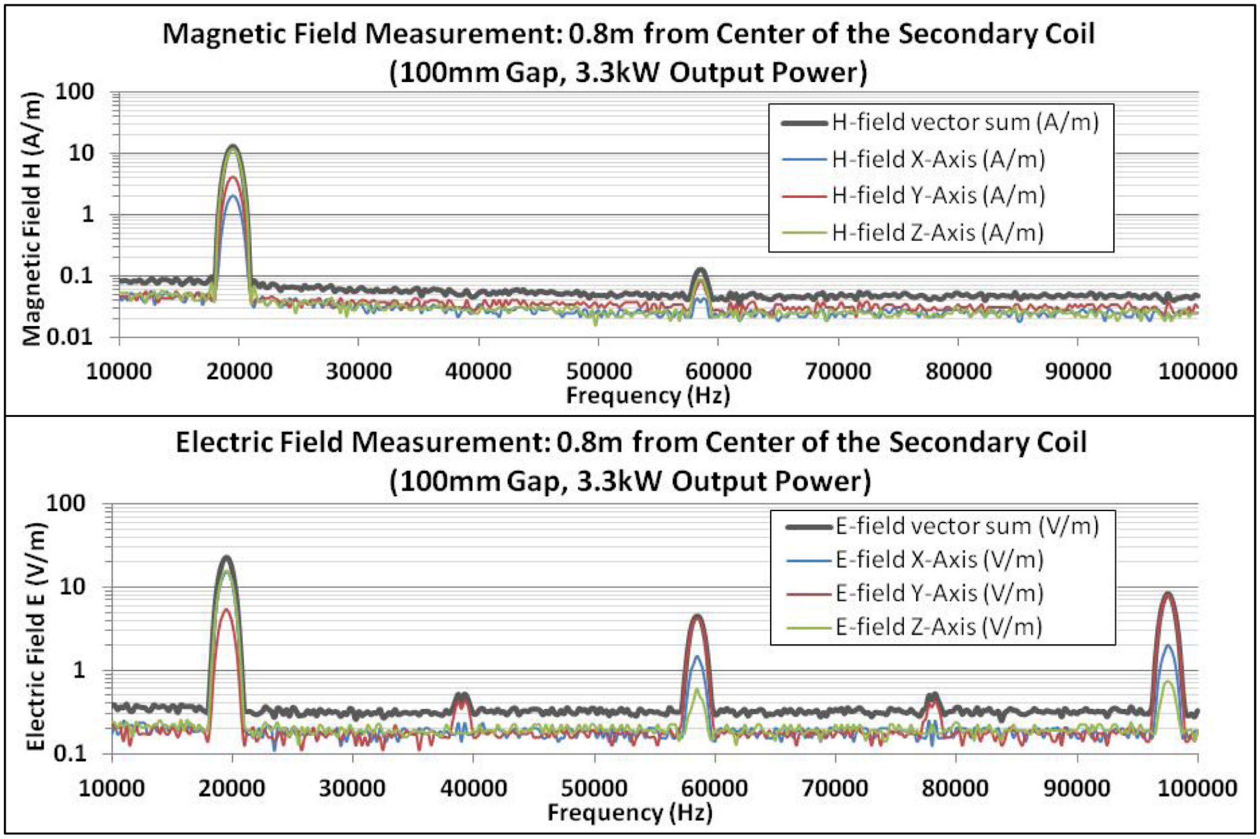

Figure 8. Scan of magnetic and electric fields for coil to coil alignment (0,0) at 100-mm gap and 3.3 kW.

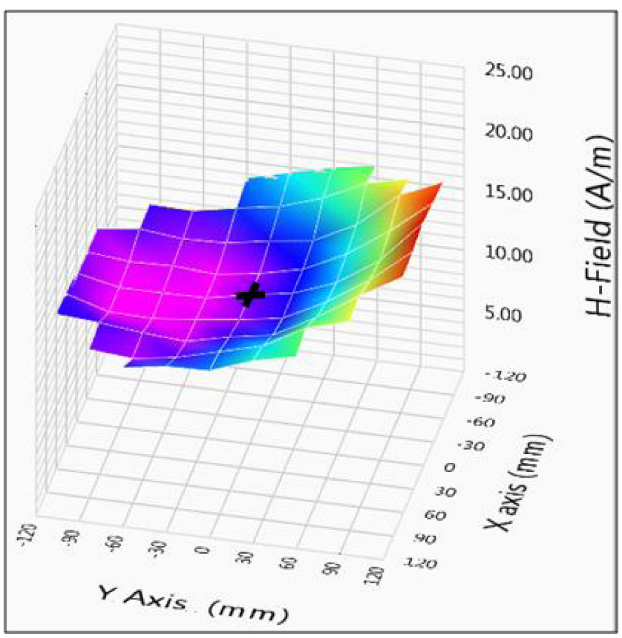

Figure 9. Maximum magnetic field strength at the 100-mm gap and 3.3-kW output power for various coil offset alignments.

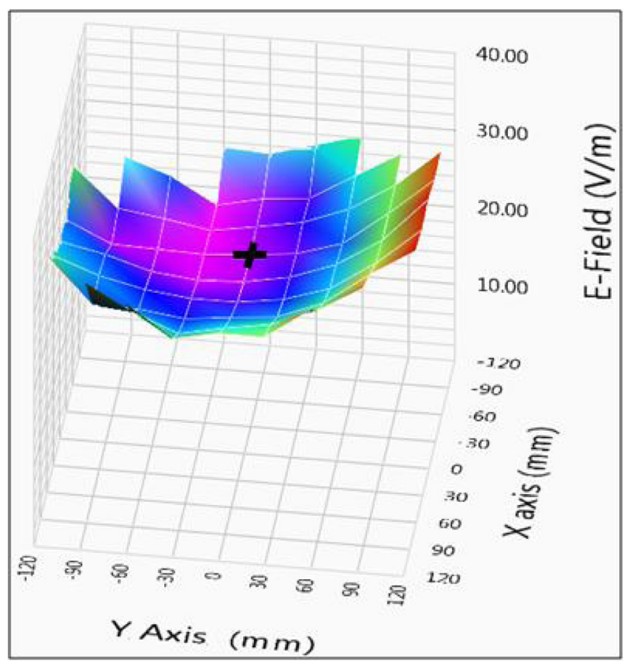

Figure 10. Maximum electric field strength at the 100-mm gap and 3.3-kW output power for various coil offset alignments.

Within the operating extent of the PLUGLESS™ inductive charging system during laboratory testing at this 100-mm gap and 3.3*kW output power, the maximum H-field measured is 21.9 A/m (27.4 μT) when the primary coil is at an offset alignment of 0,120 mm with respect to the secondary coil, and the maximum electric field is 35.2 V/m when the primary coil is at an offset alignment of 60,120 mm with respect to the secondary coil.

SUMMARY

The system efficiency and EM field strength results from testing of the PLUGLESS™ inductive charging system are presented in this paper for multiple test conditions. The impact of coil to coil gap, offset alignment, and power transfer level are investigated.

EM field strengths were measured to be 12.9 A/m (16.1 μT) and 22.1 V/m, respectively, when the coils are aligned (0,0) and operating with a coil to coil gap of 100 mm and at a rated output power of 3.3 kW. The EM field strength varied with offset alignment in relation to the relative position of the primary coil to EM field measurement location.

The maximum system efficiency of 88.8% was measured when operating at a coil to coil gap of 100 mm and a rated output power of 3.3 kW. Additionally, system efficiencies over 90% were measured at reduced output power levels when operating at a coil to coil gap of 100 mm.

Throughout this testing, system efficiency results varied by up to 7%, dependent on coil to coil gap, offset alignment, and output power. The overall extent of operation, as installed in a vehicle, may differ from these laboratory results due to different operational requirements during vehicle operation. However, these laboratory results demonstrate the system performance characteristics in standardized and repeatable laboratory conditions.

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