Idaho National Laboratory

Testing Results: PLUGLESS™ Wireless Charging System by Evatran Group Inc.

Jim Francfort
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What is Wireless Charging for Plug-In Vehicles?

• Wireless Power Transfer (WPT) across an air gap
  – Power Electronics convert grid power (60Hz) to higher frequency power
    • Typical operating frequency: 20 kHz to 150 kHz
      – 85 kHz is emerging as the selected frequency by OEM’s
    – Coil to Coil coupling via magnetic resonance enables high efficiency power transfer across the air gap
  – Higher frequency power rectified is into DC power to charge the battery
INL Wireless Charging Testing

• **Scope:** Provide Results from Testing
  – System Efficiency
  – Electric and Magnetic (EM) Field Strength
  – Impact on Grid (power quality, harmonics, etc.)
  – Support SAE J2954 committee

• Factors that impact System Efficiency and EM Field
  – Coil to Coil Position
    • Alignment (X, Y, θ, Tilt)
    • Gap between coils
  – Output Power
  – Temperature (warm-up effects)

• Testing is conducted in conjunction with SAE J2954 guidelines
INL Wireless Charging Test Equipment

- Programmable Loads
  - AC Loads (9.0 kW) Chroma 63804
  - DC loads (58 kW) Chroma 63210
- Hioki 3390 Power Meter
  - 4 channel AC and DC current and voltage
  - Real-time integration for power & energy
- NARDA EHP-200a
  - Electric Field
  - Magnetic Field
- FLIR SC640 Thermal Camera
- Fiberglass channel strut frame with multi-axis positioning table
- CAN communications (as required)
- Custom LabVIEW test control program for data acquisition and test host function to synchronize all test operations
INL Wireless Charging Laboratory Testing

- Grid Power: 480 & 208 VAC
- Hioki Power Meter 3390
- Chroma AC Load
- Chroma DC Load
- Custom LabVIEW Host and Data Acquisition
- FLIR IR Camera
- Fiberglass Channel Strut Supports Secondary Coil
- Narda EM Field Meter (EHP-200a)
- Polycarbonate Primary Coil Stand-off
- Multi-Axis Positioning System
**INL Wireless Charger Coil Positioning**

- **Primary Coil**
  - Software position control
    - Ball-screw positioning table with servo motors
      - X, Y, θ
  - Supported by polycarbonate stand-off
    - Increase distance to the metallic positioning table

- **Secondary Coil**
  - Suspended from fiberglass channel strut frame
  - Manually adjusted
    - Z position (coil to coil Gap)
    - Tilt by differential Z
**PLUGLESS™ Wireless Charging System from Evatran Group Inc.**

- Rated power: 3.3 kW output (208 VAC input as tested)
- 30 A circuit breaker
- Nominal Gap between coils: 100mm (4.0”)
- Vehicle application: Chevrolet Volt (as tested)
- Dimensions:
  - Primary Coil (circular) above ground installation
    - Approx. Circular: 559mm dia. x 470mm long
  - Secondary Coil (oval) attaches under rear of vehicle
    - Rectangular: 464mm long x 525mm wide

INL Laboratory Test Setup: PLUGLESS™ by Evatran

- Three Measurement Nodes
  - AC Grid Input (60 Hz)
  - Control Panel output to Primary Coil (parking pad)
  - DC Vehicle Adaptor output to On-Board Charge Module (OBCM)

- Secondary coil output was unable to be measured due to sealed vehicle-side enclosure
INL Laboratory Test Setup

- Measurement orientation
  - Origin:
    - Bottom face the Vehicle Adapter enclosure
    - Center of the Secondary Coil (inside Vehicle Adapter)
  - X: towards front of vehicle
  - Y: towards drivers side
  - Z: up through roof
**PLUGLESS™: Driver’s Parking Alignment Guide System**

- Green arrows on the Control Panel direct driver towards best alignment
- Numbers on control panel indicates alignment “score” (0-99)
- INL’s X and Y positioning system origin is very close to the “best alignment” of the PLUGLESS™ Alignment Guide
  - A few iterations to get to this origin positioning
  - Perhaps markings on case enclosures to aid test labs

![Graphs showing alignment guide indicator values for X-axis and Y-axis positions](image-provided-by-sae-j2954)
**EM Field Frequency Scan 10kHz – 100kHz**

- 100mm coil to coil gap, 3.3kW output power (nominal case)
- EM field measurement position (baseline test position)
  - X=0mm
  - Y=800mm (from the center of Secondary coil)
  - Z=-50mm (centered vertically in gap)

- Operating frequency
  - 19.5 kHz

- Peak Magnetic Field (H-field)
  - 12.9 A/m
  - (16.2 µT)

- Peak Electric Field (E-field)
  - 22.1 V/m
Definition: System Efficiency

System Efficiency = \( \frac{\text{Energy out of PLUGLESS™ Vehicle Adapter}}{\text{Energy into PLUGLESS™ Control Panel}} \)

Power Flow from Generation to Vehicle Operation

PLUGLESS™ Wireless Charging System

- Electricity Generation
- Electricity Distribution
- Electricity Step Down Transformer
- Commercial / Residential Wiring & Receptacle
- PLUGLESS™ Control Panel / Power Electronics
- PLUGLESS™ Primary Coil
- PLUGLESS™ Secondary Coil
- PLUGLESS™ Vehicle Adapter / Power Electronics
- Vehicle On-Board Charge Module (OBCM)
- Vehicle Wiring / Accessory Loads
- Vehicle Traction Battery (ESS)
- Vehicle Propulsion
System Efficiency Variation with Coil Position

- 3.3 kW output power
- 100mm gap between coils
- X-axis and Y-axis show Primary Coil position relative to Secondary Coil

### Efficiency Results (at 3.3 kW output with 100mm gap)

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Efficiency</td>
<td>88.8%</td>
</tr>
<tr>
<td>Nominal Efficiency</td>
<td>87.0%</td>
</tr>
<tr>
<td>Minimum Efficiency</td>
<td>86.1%</td>
</tr>
</tbody>
</table>

Primary Coil position relative to Secondary Coil (mm)

- (-90, -30)
- (0, 0)
- (120, -60)
**EM Field Variation with Coil Position**

- 3.3 kW output power
- 100mm gap between coils
- X-axis and Y-axis show Primary Coil position relative to Secondary Coil

**EM Field Results (at 3.3 kW output with 100mm gap)**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum H-field (A/m)</td>
<td>21.9</td>
</tr>
<tr>
<td>Nominal H-field (A/m)</td>
<td>12.9</td>
</tr>
<tr>
<td>Maximum E-field (V/m)</td>
<td>35.2</td>
</tr>
<tr>
<td>Nominal E-field (V/m)</td>
<td>22.1</td>
</tr>
</tbody>
</table>

**Primary Coil position relative to Secondary Coil (mm)**

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,120)</td>
<td></td>
</tr>
<tr>
<td>(0,0)</td>
<td></td>
</tr>
<tr>
<td>(60,120)</td>
<td></td>
</tr>
<tr>
<td>(0,0)</td>
<td></td>
</tr>
</tbody>
</table>
Gap Variation (Z direction)

- 3.3 kW output
- 100mm gap (nominal case)
Gap Variation (Z direction)

- 3.3 kW output
- 70mm gap
Gap Variation (Z direction)

- 3.3 kW output
- 80mm gap
Gap Variation (Z direction)

- 3.3 kW output
- 90mm gap
Gap Variation (Z direction)

- 3.3 kW output
- 100mm gap (nominal case)
Gap Variation (Z direction)

- 3.3 kW output
- 110mm gap
Gap Variation (Z direction)

- 3.3 kW output
- 120mm gap
Gap Variation (Z direction)

- 3.3 kW output
- 130mm gap
Coil to Coil Gap Impact on System Efficiency and EM Field

- 3.3 kW output
- EM field measured at
  - X=0.0m Y=0.8m
  - Centered vertically in gap (Z=-50mm)

Impact of Coil Gap (mm) on System Efficiency (3.3 kW Output Power)
Output Power Impact on System Efficiency and EM Field

- 100mm coil to coil gap
- EM field measured at
  - X=0.0m Y=0.8m
  - Centered vertically in gap (Z=-50mm)

Impact of Charge Power on System Efficiency (100 mm gap between coils)
Warm-up (at nominal conditions)

- Does Temperature have an Impact?
- Nominal (3.3 kW, 100 mm gap), Aligned (0,0)
- Test starts (3.3 kW) immediately after 208 VAC connected to control panel
AC Input Waveform: Power Factor & Total Harmonic Distortion (THD)

- 0.65 Power Factor (consistent across power, position, and gap variation)
- Input Current THD = 112% (at 3.3 kW output)
- Input Voltage THD = 4% (at 3.3 kW output)
Fact Sheet

PLUGLESS™ Level 2 EV Charging System (3.3 kW) by Evatran Group Inc.

Results from Full System Testing in a Laboratory Environment

Description / Specifications

- System Input Voltage operating Voltage: 208 to 240 VAC
- Circuit Breaker Rating: 30 A
- Nominal gap between coils: 100 mm
- Rated maximum power output: 3300 watts

- Parking Pad (Primary Coil) System
  - Shape: Approximately Circular
  - Size: 559 dia. x 470 long mm

- Vehicle Adapter (Secondary Coil) System
  - Shape: Rectangular
  - Size: 464 long x 525 wide mm

Measured System Parameters during Laboratory Testing

- Input Power Measurements (at 3.3 kW output, 100mm gap)
  - Input Voltage: 208 VAC
  - Input Current RMS: 28 Amps RMS
  - Power Factor: 0.95
  - Voltage Total Harmonic Distortion (THD): 4.7%
  - Current Total Harmonic Distortion (THD): 11.2%

- Wireless Power Transfer Operation
  - Operating Frequency: 19.5 kHz

- DC Output Measurements (at 3.3 kW output, 100mm gap)
  - Output Voltage: 214 VDC
  - Output Current: 15.4 Amps
  - Voltage Ripple Factor: 0.75%

- Operating Temperatures at 3.3 kW output
  - Parking Pad: Max observed surface temperature: 51 °C
  - Vehicle Adapter: Max observed surface temperature: 47 °C

Laboratory Test Measurement Coordinate System


Test Coordinates System Origin: Center of the Secondary Coil at the Bottom Surface of the Enclosure

Efficiency (%)

- Primary Coil position relative to Secondary Coil (mm)
  - 100 mm gap: 92.9%, (0,0), 92.9%, (0,0)
  - 110 mm gap: 90.2%, (-50,30), 86.1%, (-50,30)
  - 120 mm gap: 87.0%, (-60,60), 86.1%, (-60,60)

Impact of Charge Power on System Efficiency (100 mm gap between coils)

- E-field vector sum (V/m)
- E-field X-axis (V/m)
- E-field Y-axis (V/m)
- H-field Z-axis (A/m)
- H-field Y-axis (A/m)
- H-field X-axis (A/m)
- H-field vector sum (A/m)

Measurement (Primary Coil at 0.8m from Center of the Secondary Coil, Gap, 3.3kW Output Power)

- Primary Coil position relative to Secondary Coil (mm)
  - 0.8m from Center of the Secondary Coil:
    - 21.9, (0,120)
    - 12.9, (0,0)
    - 35.2, (60,120)
    - 22.1, (0,0)

Electric Field

- Primary Coil position relative to Secondary Coil (mm)
  - 21.9, (0,120)
  - 12.9, (0,0)
  - 35.2, (60,120)
  - 22.1, (0,0)
Next Steps

- Vehicle level testing completed (not yet published)
  - PLUGLESS system
    - Installed on Chevy Volt
    - Outdoor testing (asphalt parking lot)
    - Same measurement equipment as in lab (Hioki, NARDA, etc.)
  - Correlate to specific test points conducted in laboratory

- Conduct debris testing (in progress)
  - After INL safety review approval (since debris will get hot = potential for fire)
  - Empty soda can, paper clips, CD, rebar, coins, paper clip, etc.
  - At various distance from wireless charger operating at nominal condition (3.3 kW, 100mm gap, various coil misalignment)
Summary / Comments:

• INL’s laboratory testing of the PLUGLESS™ Wireless Charging system by Evatran Group Inc. is complete
  – System Efficiency and EM field measurement impact from
    • Coil to Coil Position
      – Gap
      – Alignment Offset
    • Output Power
    • EM field meter measurement location

• Fact Sheet has been published
Acknowledgement

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More Information

http://avt.inl.gov