Design of A Zero-Voltage-Switching Large-Air-Gap Wireless Charger for Plug-in Hybrid Electric Vehicles

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Outline

• Project Background

• Topologies for Wireless Power Transfer System

• Simulation and Design

• Experimental Validation

• Conclusion and Future works
Wireless Power Transfer

(a) by sprayed form  
(b) by point to point

Wireless Power Transfer
Wireless Power Transfer

• The potential of wireless technology has emerged in the higher-power applications, e.g., battery charger for Plug-in Hybrid Electric Vehicle (PHEV) or Electric Vehicle (EV) where removing the cable between a power source and a load is of importance for safety since the exposed power cable is subject to the sparkles when plugged in or unplugged and mechanical deterioration caused by outdoor environment and users.

• Right now the wireless power transfer (WPT) system with air-gap greater than ten centimeters at ~kWatt rating exhibits the wide popularization.
Wireless Power Transfer

• Point-point Resonant

>> Spray Form

MIT Design (2m, 60W10MHz)

Wisconsin Design (220W, 30cm, 3.6MHz)

Excellent and inspiring design with high efficiency!
No chance for power electronics!
Too high switching frequency!

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Wireless Power Transfer

• WPT system for vehicle charging design should target low operating frequency (<100kHz) because

1) the current high-power electronics devices (IGBTs and MOSFETs) feel difficult to work in ~MHz domain (high switching loss, high reverse recovery loss, and low switching speed)

2) the magnetic field generated by coils operated at high frequency would create electromagnetic interference (EMI) issues with other electronics devices on board.

ORNL Design (2.5kW, 25.4cm, 23kHz)
Wireless Power Transfer

Series-Series Topology

Series-Parallel Topology

Parallel-Series Topology

Parallel-Parallel Topology

(a) Large air-gap WPT system
(b) Equivalent circuit model
APEL Solutions

Equivalent Circuit

Actual Coils
Proposed Reactive-power Compensated Parallel-Parallel topology and its equivalent circuit model
Maxwell Model

\[
L_m = 5.72 \mu H \\
L_s = 12.53 \mu H \\
C_p = 0.86 \mu F \\
C_s = 0.86 \mu F \\
\]

Switches: CoolMOS
Control Algorithm: LLC Resonant

1. For resonant WPT, effectiveness of transferring the power is more critical than efficiency;
2. Low \(L_m\) will induce high excitation current thereby more reactive power to burden the power electronics system and coils.
Maxwell Model

Air Gap
Sedans: 100mm ~ 150mm;
SUV: 200mm ~ 250mm;
Truck: >250mm.

Sliding
Maxwell Model

- Mutual Inductance (uH)
- Leakage Inductance (uH)

- Coil Slide (mm)
- Coil Gap (mm)
Maxwell Model
Maxwell Model

Simulation Results for SP and PP Topology

<table>
<thead>
<tr>
<th></th>
<th>PP</th>
<th>SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum $C_p$ voltage</td>
<td>165V</td>
<td>172V</td>
</tr>
<tr>
<td>Bridge Current Peak</td>
<td>22A</td>
<td>41A</td>
</tr>
<tr>
<td>DC Bus Input Voltage</td>
<td>150V</td>
<td>70V</td>
</tr>
<tr>
<td>Output Power</td>
<td>1.5kW</td>
<td>1.5kW</td>
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</table>
System Impedance
Soft Switching

ZVS

![Diagram of power electronics circuit with labels: Q1, Q2, Q3, Q4, Lr, Cr, Lm, T, Co, Lf.](attachment:image.png)
Test Bench

Soft Switching is needed for the H-bridge.

High frequency is not required. Either CoolMOS or IGBT will be fine;

For CoolMOS, Zero Voltage Switching;

For IGBT, Zero Current Switching.

11kW CoolMOS based Inverter/PFC
Test Bench

400W output demonstration (efficiency ~72%)

Test Bench

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Experimental Validations

Waveforms@87W (Purple is the bridge output voltage, green is the bridge output current, and the left two are the load voltage and current)

Waveforms@400W (red is the bridge output voltage, purple is the bridge output current, and the left two are the load voltage and current)
Experimental Validations

Waveforms@1.5kW, Vb=230V, Vin=200V

Waveforms @ 2kW, Vb=230V, Vin=200V
Experimental Validations

Experimental Efficiency at different battery voltage (1.5kW)
Experimental Validations (Air Gap)

Experimental Efficiency @ (1.3kW, 200V)
Experimental Validations (Sliding)

![Experimental Setup Image]

**Experimental Efficiency @ (1.3kW, 200V)**

- Overall Efficiency (%)
  - Winding Slide (mm): 0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200
  - Winding Distance: 100mm, 110mm, 120mm, 130mm, 140mm, 150mm

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Experimental Validations (Air Gap & Sliding)
Conclusions

1. WPT with PE requires lower operating frequency in Vehicle charging system;

2. Extraction of the Coil Parameters needs the assistance of FEA software, etc, Maxwell;

3. Soft-switching technique is highly demanded in WPT system.

4. Future development will be focusing on higher power capability (6.6kW). PFC part will be the focus.
Acknowledgement

1. Ansys/Maxwell;

2. APEL team;

Thank you!

Questions?