Capacitive Power Transfer for Contactless Charging

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Why Wireless Power?
Wireless Power Technology

Close-coupled wireless power transfer

1. Inductive

2. Capacitive
Wireless Power Technology

Close-coupled wireless power transfer

I. Inductive

- Compact Area
- Moderate distances
- High perm. materials common
  - Good alignment required
- Flux shielding required
Wireless Power Technology

Close-coupled wireless power transfer

✓ Very thin
✓ Electric field confined
✓ Tolerant of misalignment
✗ Limited distance
✗ High-k materials less common

2. Capacitive
Soccer Playing Robot
13.9 nF
217 kHz
~40 W
44% efficient

Inter-chip power transfer
10 fF
15 MHz
~100 uW
~1% efficient
Why isn’t the efficiency higher?

1. Fairly weak coupling
   → 13.9 nF = 50 Ω at 200 kHz

2. Need for high Q components
   → If Q = 25, efficiency is 50%

13.9 nF
217 kHz
~40 W
44% efficient
2 Ω load
4 A current
Why isn’t the efficiency higher?

1. Fairly weak coupling
   : $13.9 \text{ nF} = 50 \text{ }\Omega\text{ at } 200 \text{ kHz}$

2. Need for high Q components
   : If $Q = 25$, efficiency is 50%

Solution

- Push to $\sim 10X$ higher frequencies
- ZVS to mitigate switching losses
- Higher voltages / lower currents

13.9 nF
217 kHz
~40 W
44% efficient
2 $\Omega$ load
4 A, 8V output
Optimization Approach

Given \( P_{\text{out}} \) and \( C \), how do we maximize the efficiency?

or

What is the minimum required \( C \) to achieve a particular \( P_{\text{out}} \) and efficiency?
Requirements

• $3.5 \text{ pF/cm}^2$ (¼ mm air gap) with $\sim 50 \text{ cm}^2$ gives 150 pF

• Need $>2.5 \text{ W}$ (USB spec.)
Resonance Motivation

C = 150 pF
I = 500 mA
I = C \frac{dV}{dt} = 2 \pi f CV
V = 5 V \Rightarrow f = 100 MHz
Power Available from Source

\[ R = \frac{1}{2\pi fC} \]

Available Power vs Frequency for 50 pF Source Impedance

- \( V_S = 100 \text{ V} \)
- \( V_S = 35 \text{ V} \)
- \( V_S = 25 \text{ V} \)
- \( V_S = 15 \text{ V} \)
- \( V_S = 5 \text{ V} \)
But not high (loaded) $Q$}

Ex.

$Q_L = 10$

Need 90% efficiency

$\Rightarrow Q_{\text{ind}} > 100$

No free lunch! High loaded $Q$ puts stress on inductor.
Capacitive Power Transfer System

1. Powertrain optimization

2. Alignment and load sensitivity
Powertrain Architecture
Efficiency Expression

Minimize:
- Increase voltage

Maximize:
- Fixed

Minimize:
- Large switch
- Small inductor

\[ \eta = 1 - \frac{1}{2} \frac{\| i_t \|^2 R_S}{P_{out}} \]

Does not consider switching losses => Eliminate with ZVS
Approximate ZVS Analysis

\[ \phi = \angle \left( \frac{i_t}{v_s} \right) = -\arccos \left( \frac{V_D}{V_S} \right) \]
Approximate ZVS Analysis

Initial charge

\[ q_{sw} = 2 C_{oss} V_S \]

\[ q_t = \text{Charge removed by inductor} \]
ZVS Condition

From integration:

\[ q_t = \frac{\|i_t\|}{\omega} (1 - \cos \phi) \]

ZVS requires:

\[ q_t \geq q_{sw} \]

Refactored as:

\[ \omega \leq \frac{P_{out}}{0.64V_D V_S 2C_{oss}} \left( 1 - \frac{V_D}{V_S} \right) \]

\[ q_t = \text{Charge removed by inductor} \]
Example Design

$P_{\text{out}} = 4 \, \text{W}$, $V_S = 35 \, \text{V}$, and $R_{\text{on}}C_{\text{oss}} = 44 \, \text{ps}$
**Example Design**

Choose $\eta = 0.9, \ Q = 40$

- Minimum $C$ is 147 pF
- Optimum $V_D/V_S$ is 0.8
- Optimum switch size $C_{oss} = 13$ pF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega$</td>
<td>$\frac{P_{out}}{0.64AVV_S^2}\frac{1}{2C_{oss}}(1 - AV)$</td>
<td>$2\pi 7.8 \text{ Mrad/s}$</td>
</tr>
<tr>
<td>$L$</td>
<td>$\frac{1}{\omega^2 C} \left( \frac{0.64}{2} \frac{\omega CAV V_S^2}{P_{out}} \sqrt{1 - A_V^2} + 1 \right)$</td>
<td>$3.8 \mu\text{H}$</td>
</tr>
<tr>
<td>$R_{on}$</td>
<td>$\frac{\tau_{sw}}{C_{oss}}$</td>
<td>$3.4 \Omega$</td>
</tr>
<tr>
<td>$V_D$</td>
<td>$AVV_S$</td>
<td>$28 \text{ V}$</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>$\frac{1}{\sqrt{LC}}$</td>
<td>$2\pi 6.7 \text{ Mrad/s}$</td>
</tr>
<tr>
<td>$R_L$</td>
<td>$\frac{2 \times 0.64^2 V_D^2}{P_{out}}$</td>
<td>$161 \Omega$</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>$\frac{2}{R_L \sqrt{\frac{L}{C}}}$</td>
<td>$1.9$</td>
</tr>
<tr>
<td>$</td>
<td></td>
<td>i_t</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$\arctan \left( -\sqrt{\frac{1}{A_V^2} - 1} \right)$</td>
<td>$-37^\circ$</td>
</tr>
<tr>
<td>$I_{out}$</td>
<td>$\frac{P_{out}}{V_D}$</td>
<td>$143 \text{ mA}$</td>
</tr>
</tbody>
</table>
Simulation Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{out}$</td>
<td>4 W</td>
<td>4 W</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.8</td>
<td>0.81</td>
</tr>
<tr>
<td>$</td>
<td></td>
<td>i_t</td>
</tr>
<tr>
<td>$I_{out}$</td>
<td>143 mA</td>
<td>142 mA</td>
</tr>
<tr>
<td>$\angle(v_d/v_s)$</td>
<td>$-37^\circ$</td>
<td>$-32^\circ$</td>
</tr>
</tbody>
</table>
Prototype Powertrain Circuit

Siliconix Si1029X

35 V

C_{oss}

C_{oss}

3.5 Ω

C_{oss}

C_{oss}

8 pF

125 pF

12 uH

Q = 42

Coilcraft 1812LS

NXP Schottky PMEG6002EJ

28 V

V_D
Experimental Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Simulation</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{out}$</td>
<td>4 W</td>
<td>4 W</td>
<td>3.72 W</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.8</td>
<td>0.81</td>
<td>0.77</td>
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<tr>
<td>$|i_t|$</td>
<td>223 mA</td>
<td>222 mA</td>
<td>—</td>
</tr>
<tr>
<td>$I_{out}$</td>
<td>143 mA</td>
<td>142 mA</td>
<td>133 mA</td>
</tr>
<tr>
<td>$\angle(v_d/v_s)$</td>
<td>-37°</td>
<td>-32°</td>
<td>-48°</td>
</tr>
</tbody>
</table>

![Graph](image)
Extension to Inductive Transfer

Resonate out leakage inductance.
Capacitive Power Transfer System

Powertrain optimization

Alignment and load sensitivity
Automatic Frequency Tuning
Automatic Frequency Tuning

Phase Contribution of Tank [°]

Phase Shift
Around the Loop = 0

$\Delta f$

$\varphi$

$f / f_0$
Automatic Duty Cycle Control

Light-load condition: not enough current in tank to get Zero Voltage Switching (ZVS)
Automatic Duty Cycle Control

SHUTDOWN

Supply Current

DC Output Voltage
Capacitive Power Transfer System

Current Sense
Power Input
On/Off Control
Enable
Gate Driver
Phase Shift

Transmitter
Receiver
Capacitive Interface
Load
Capacitive Charger Demonstration
With 6 by 10 cm$^2$, we transfer 3.8 W at 83% efficiency over a 0.5 mm air gap.
Conclusion

Power transfer over small capacitors is enabled by

1. Zero Voltage Switching
   Enable moderate voltage, high frequency operation
2. Automatic Tuning
   Robust to changes in coupling capacitance
3. Duty cycle adjustment without RX feedback
   Preserve efficiency at light loads
Future Work

1. Extension to galvanic isolation
2. Pixelation
Thank You!

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