Capacitive Power Transfer for Contactless Charging

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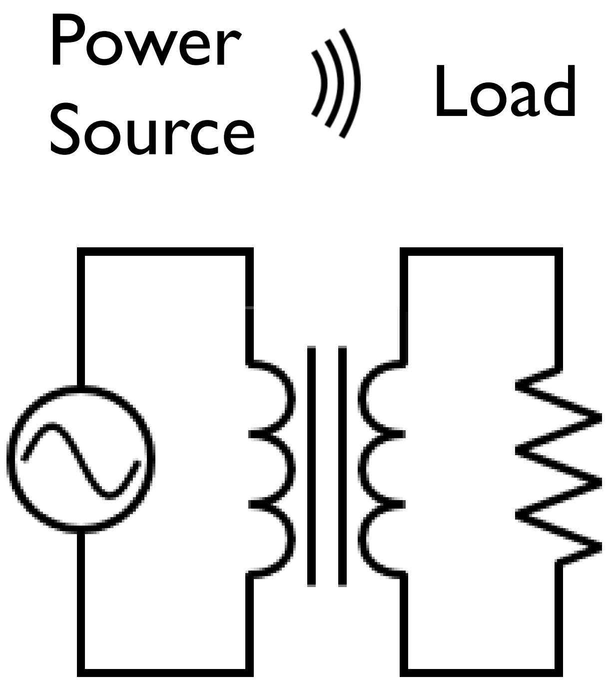
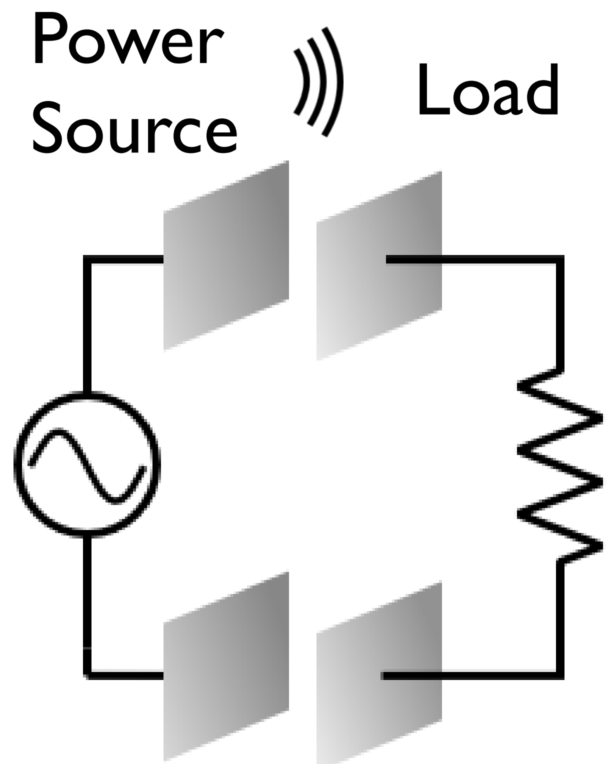
Why Wireless Power?

Wireless Power Technology

Close-coupled wireless power transfer



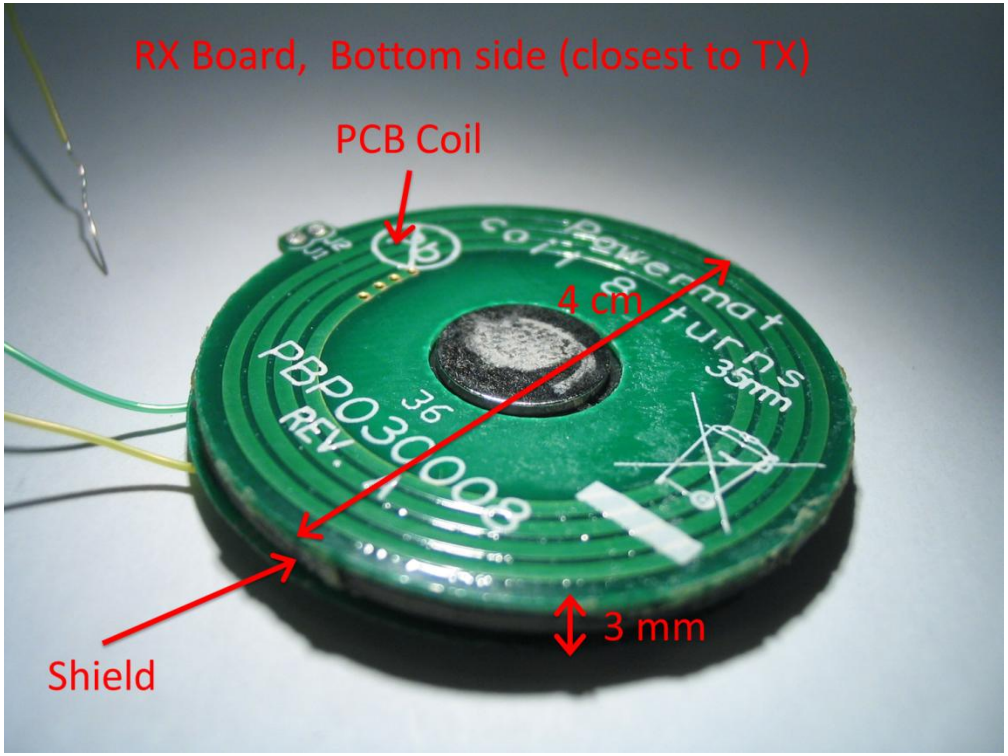
1. Inductive



2. Capacitive

Wireless Power Technology

Close-coupled wireless power transfer



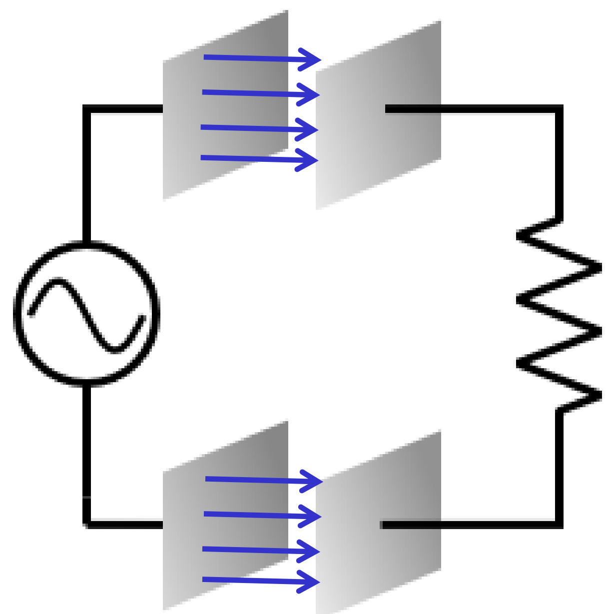
1. Inductive

- ✓ Compact Area
- ✓ Moderate distances
- ✓ High perm. materials common
- ○ Good alignment required
- X Flux shielding required

Wireless Power Technology

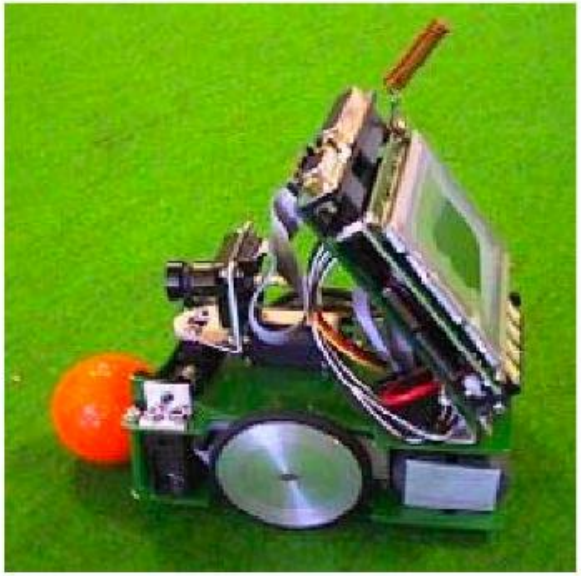
Close-coupled wireless power transfer

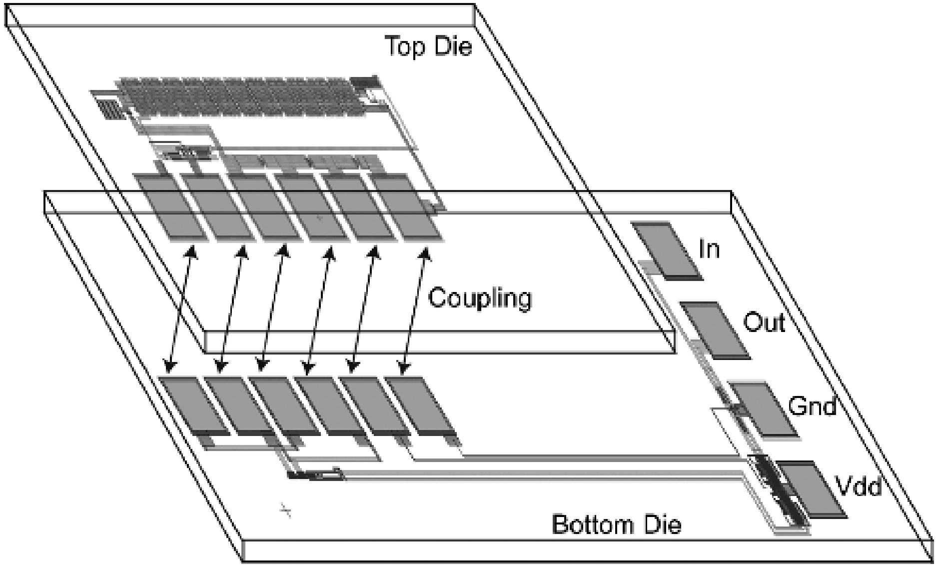
- ✓ Very thin
- ✓ Electric field confined
- ✓ Tolerant of misalignment
- X Limited distance
- X High-k materials less common



2. Capacitive

Prior Art

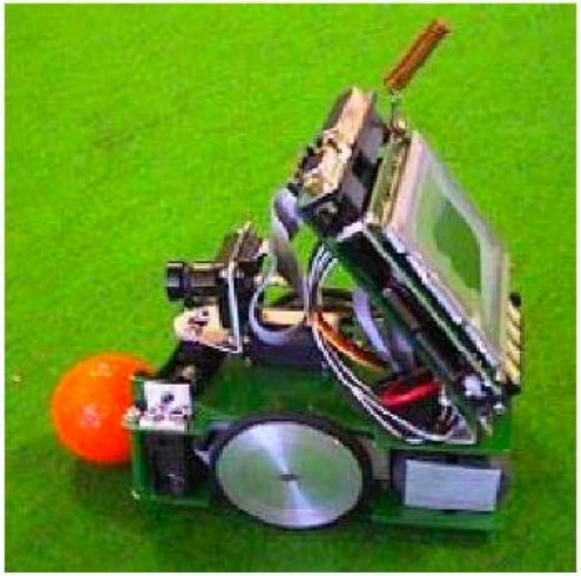




A. Hu. 2008.
Soccer Playing Robot
13.9 nF
217 kHz
~40 W
44% efficient

E. Culurciello. 2008.
Inter-chip power transfer
10 fF
15 MHz
~100 uW
~1% efficient

Why isn't the efficiency higher?

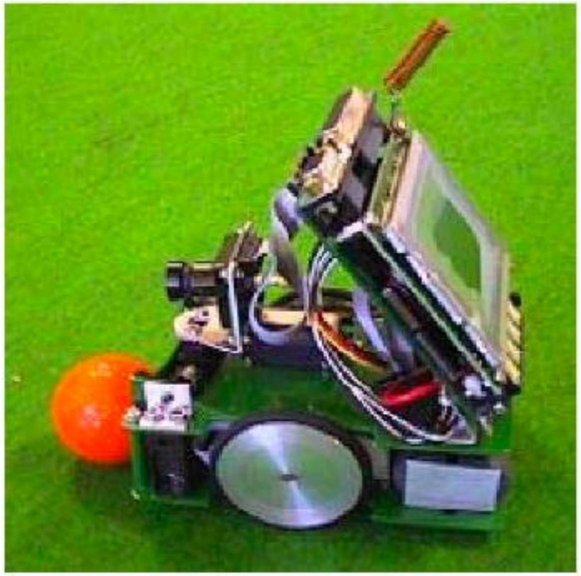


1. Fairly weak coupling
   : 13.9 nF = 50 Ω at 200 kHz

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?



13.9 nF
217 kHz
~40 W
44% efficient
2 Ω load
4 A, 8V output

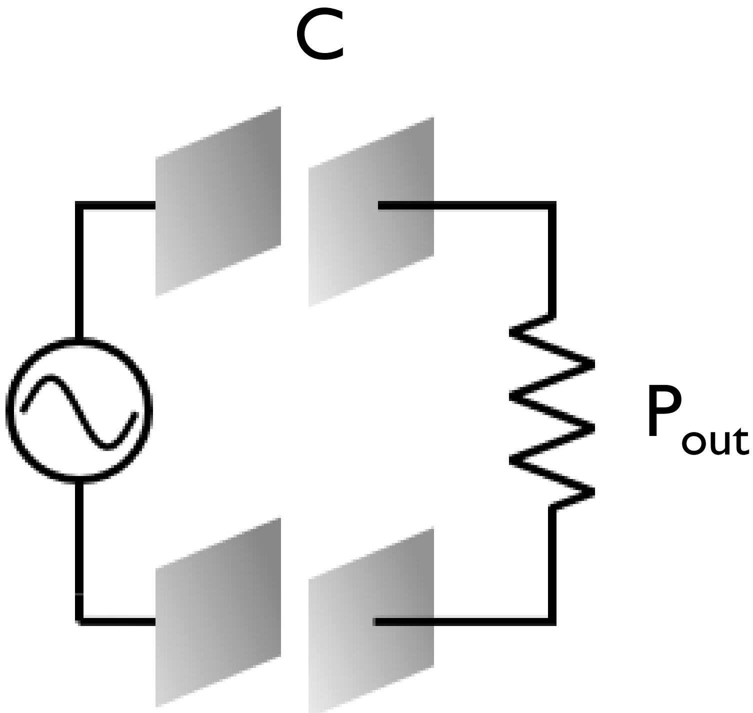
1. Fairly weak coupling
   : 13.9 nF = 50 Ω at 200 kHz

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

Solution

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

Optimization Approach



Given P_{out} and C, how do we maximize the efficiency?

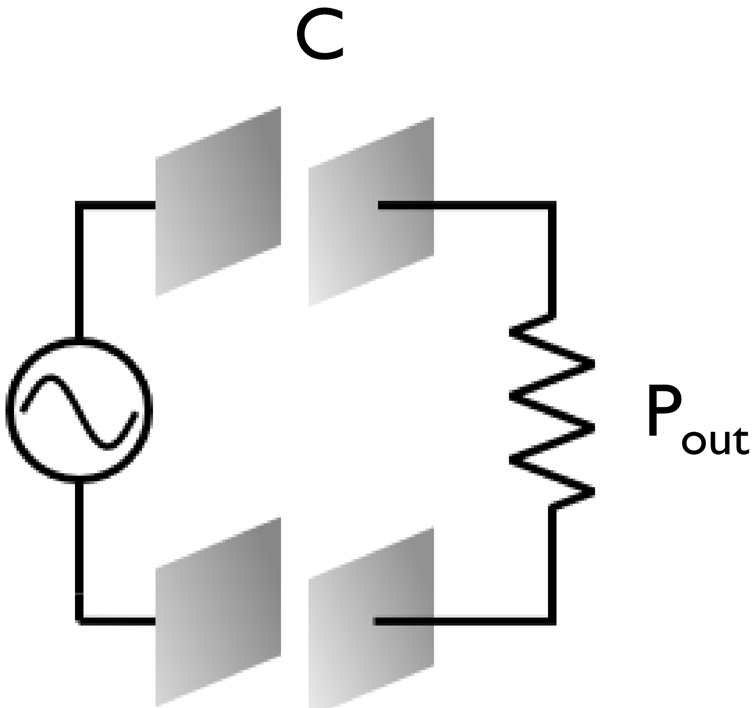
or

What is the minimum required C to achieve a particular P_{out} and efficiency?

Requirements

- 3.5 pF/cm^2(¼ mm air gap) with ~50 cm^2 gives 150 pF
- Need >2.5 W (USB spec.)

Resonance Motivation



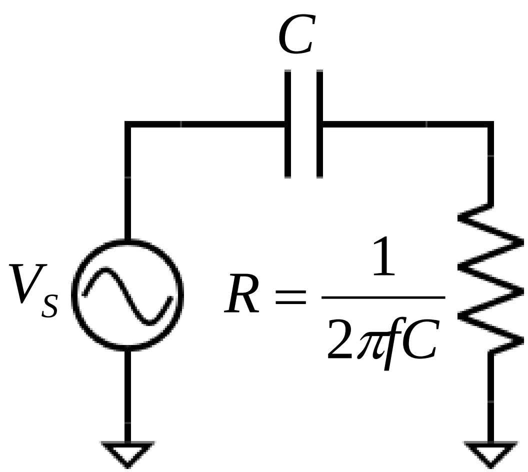
C = 150 pF

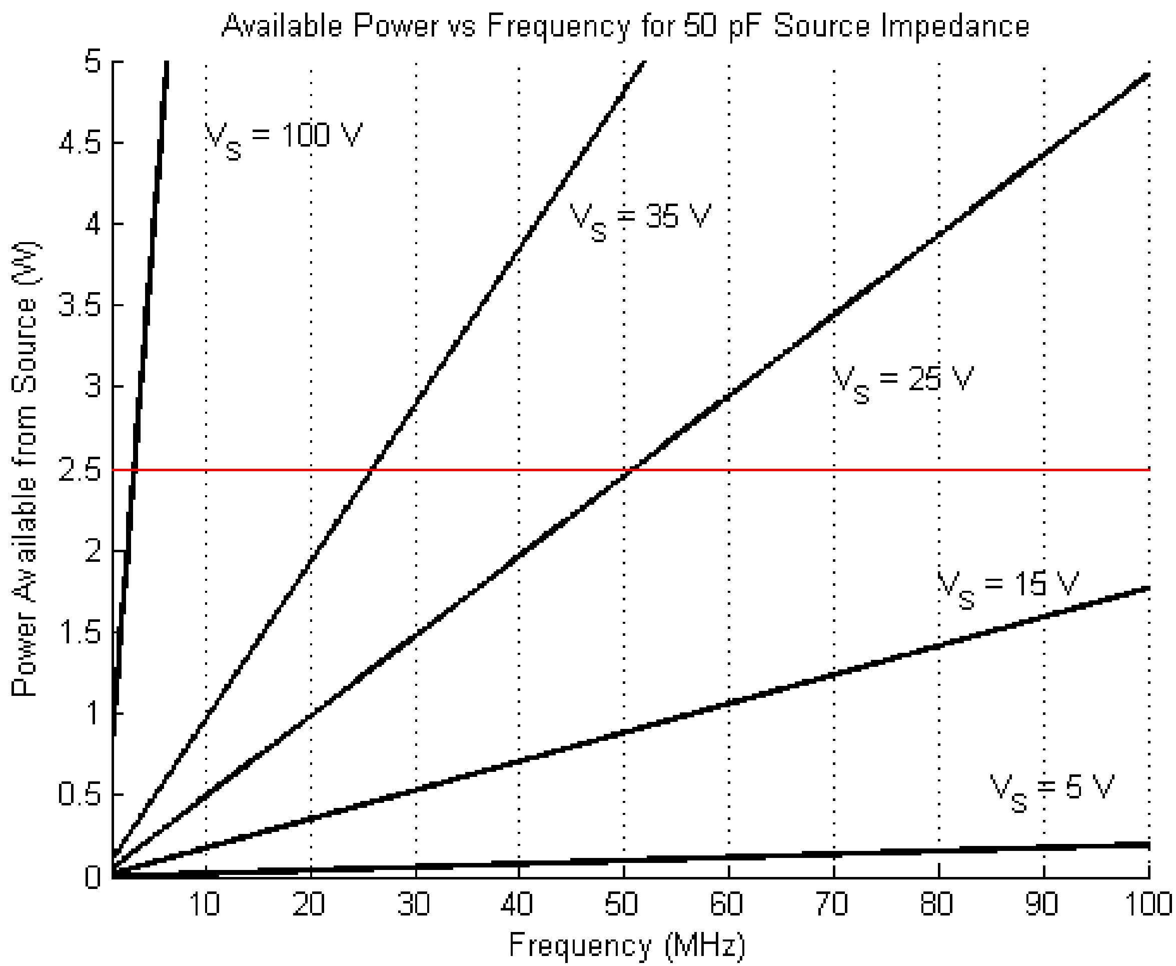
I = 500 mA

I = C dV/dt = 2 π f C V

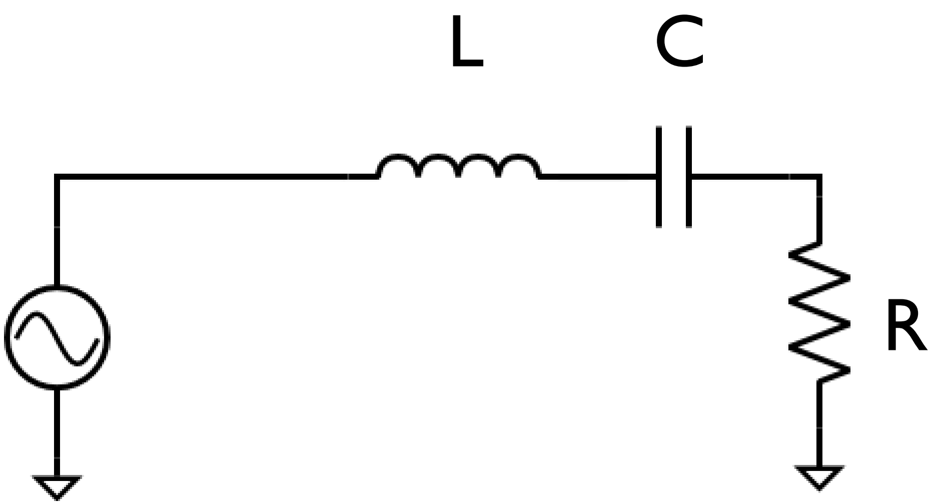
V = 5 V => f = 100 MHz

Power Available from Source





But not high (loaded) Q



Ex.

Q_L=10

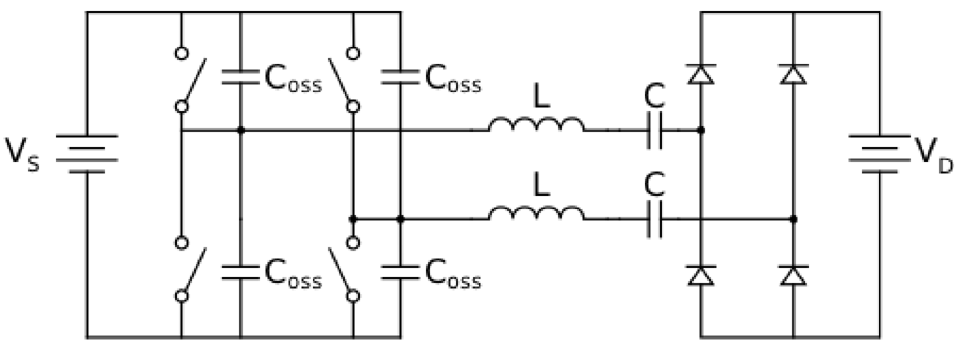
Need 90% efficiency

=> Q_{ind} > 100

No free lunch! High loaded Q puts stress on inductor.

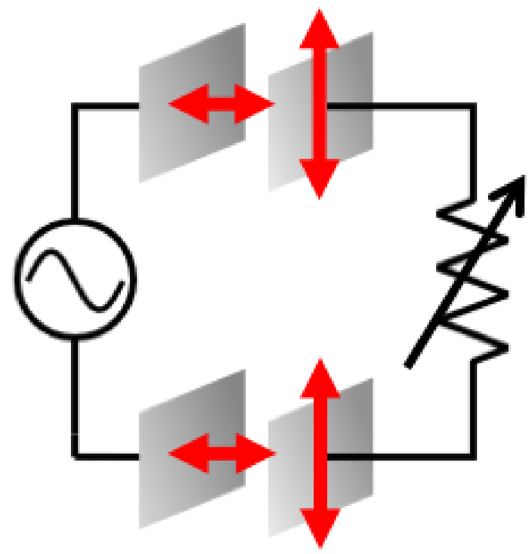
Capacitive Power Transfer System

1



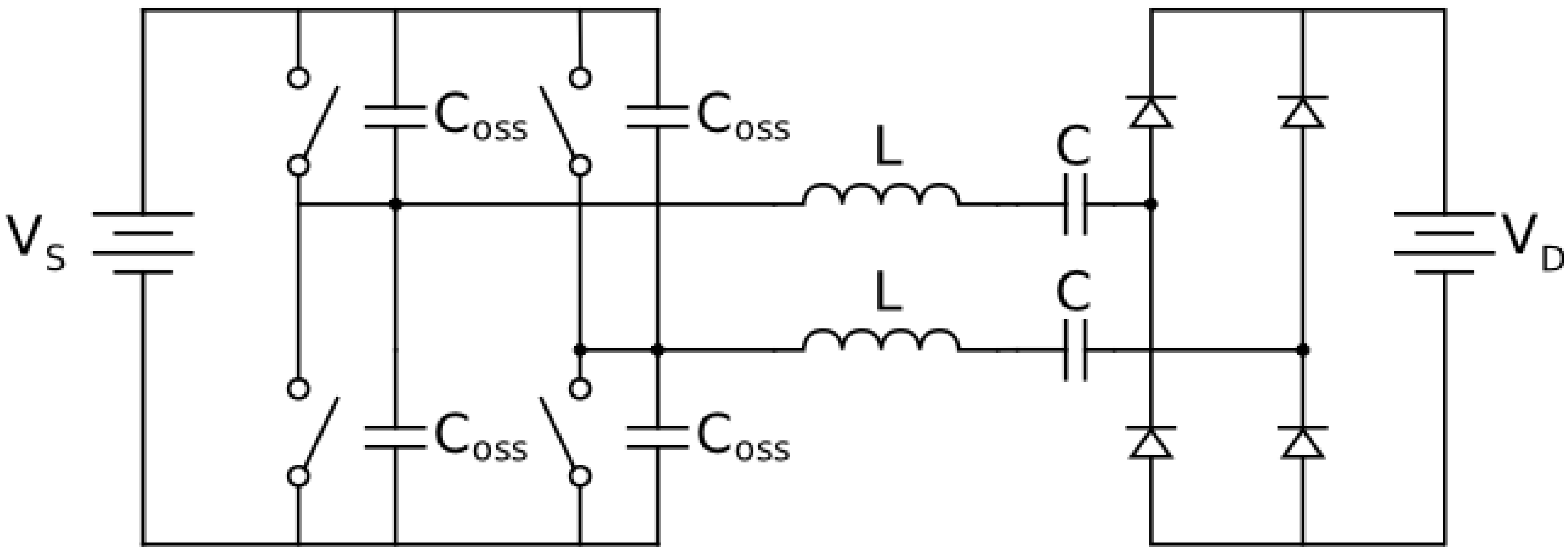
Powertrain optimization

2



Alignment and load sensitivity

Powertrain Architecture



Efficiency Expression

Minimize:
Increase voltage

Minimize:
Large switch
Small inductor

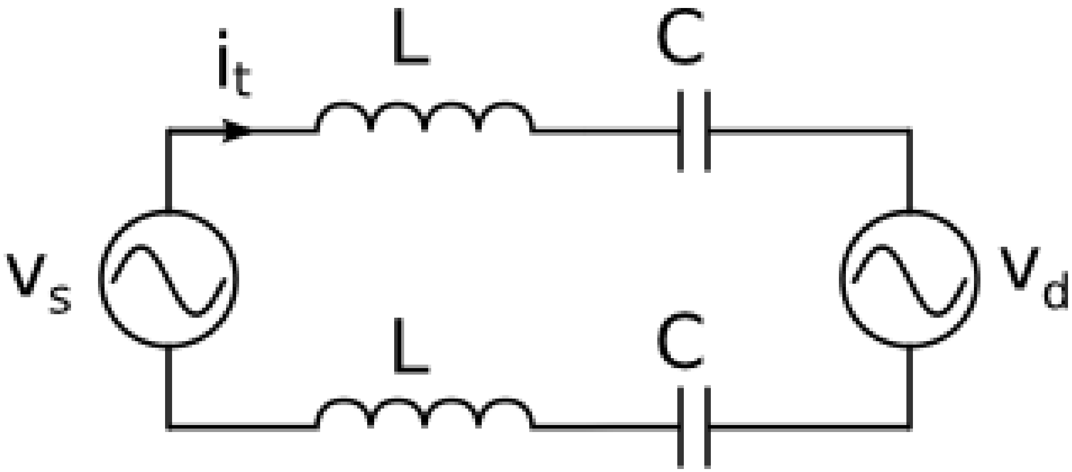
$$\eta = 1 - \frac{1}{2}\frac{\|i_t\|^2 R_S}{P_{out}}$$

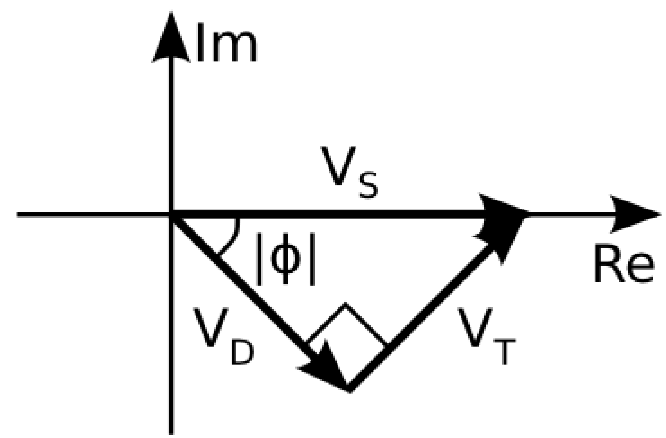
Maximize

Fixed

Does not consider switching losses => Eliminate with ZVS

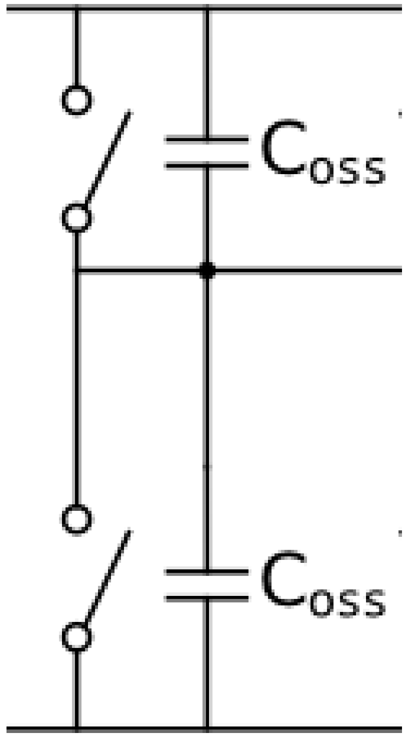
Approximate ZVS Analysis

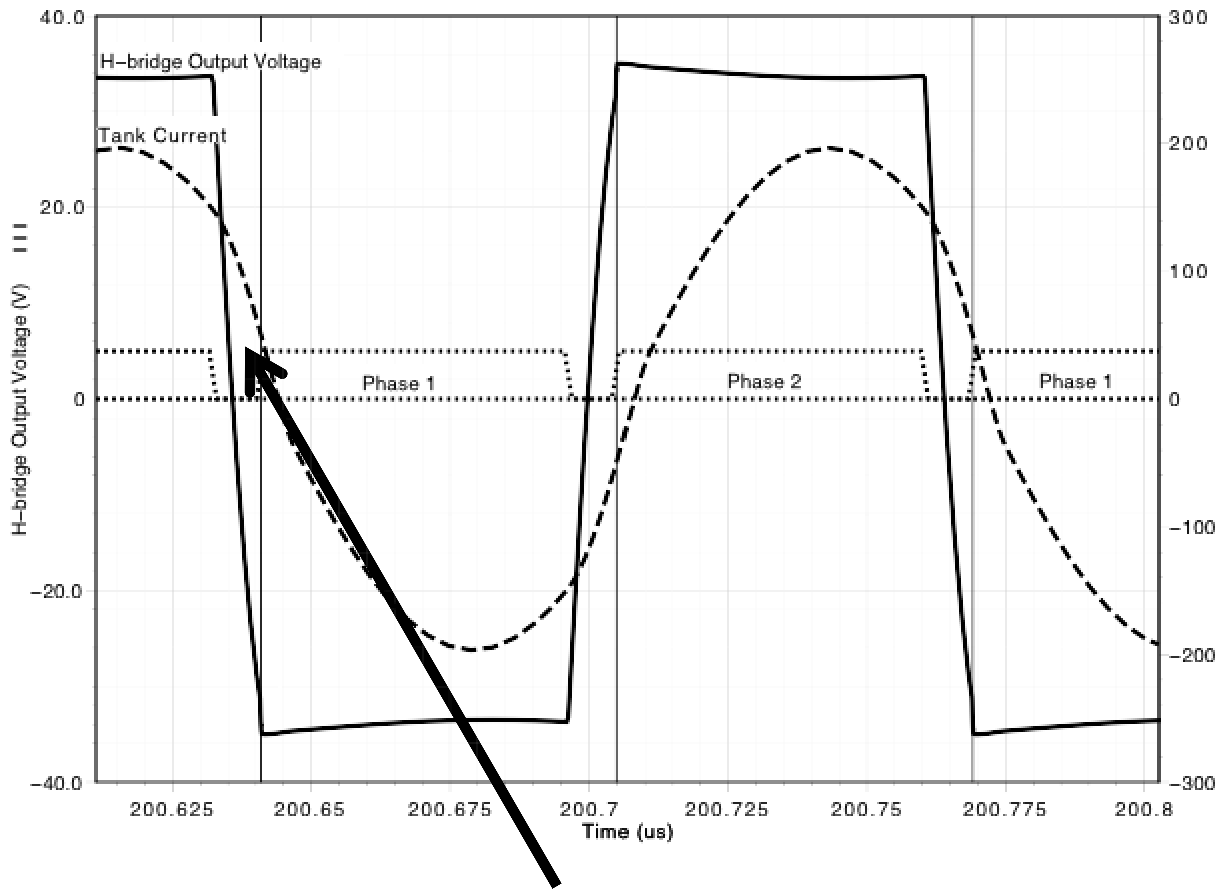




$$\phi = \angle\left(\frac{i_t}{v_s}\right) = -\arccos\left(\frac{V_D}{V_S}\right)$$

Approximate ZVS Analysis





Initial charge

$$q_{sw} = 2C_{oss}V_S$$

q_t = Charge removed by inductor

ZVS Condition

From integration:

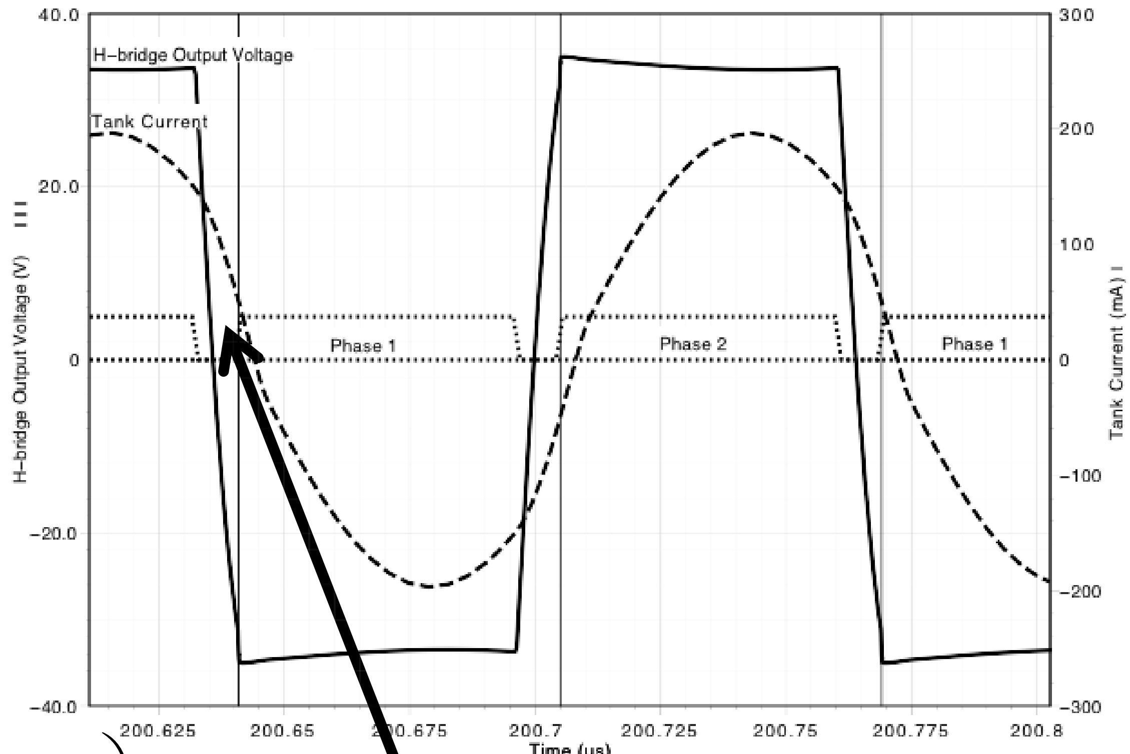
$$q_t = \frac{\|i_t\|}{\omega}(1 - \cos\phi)$$

ZVS requires:

$$q_t \ge q_{sw}$$

Refactored as:

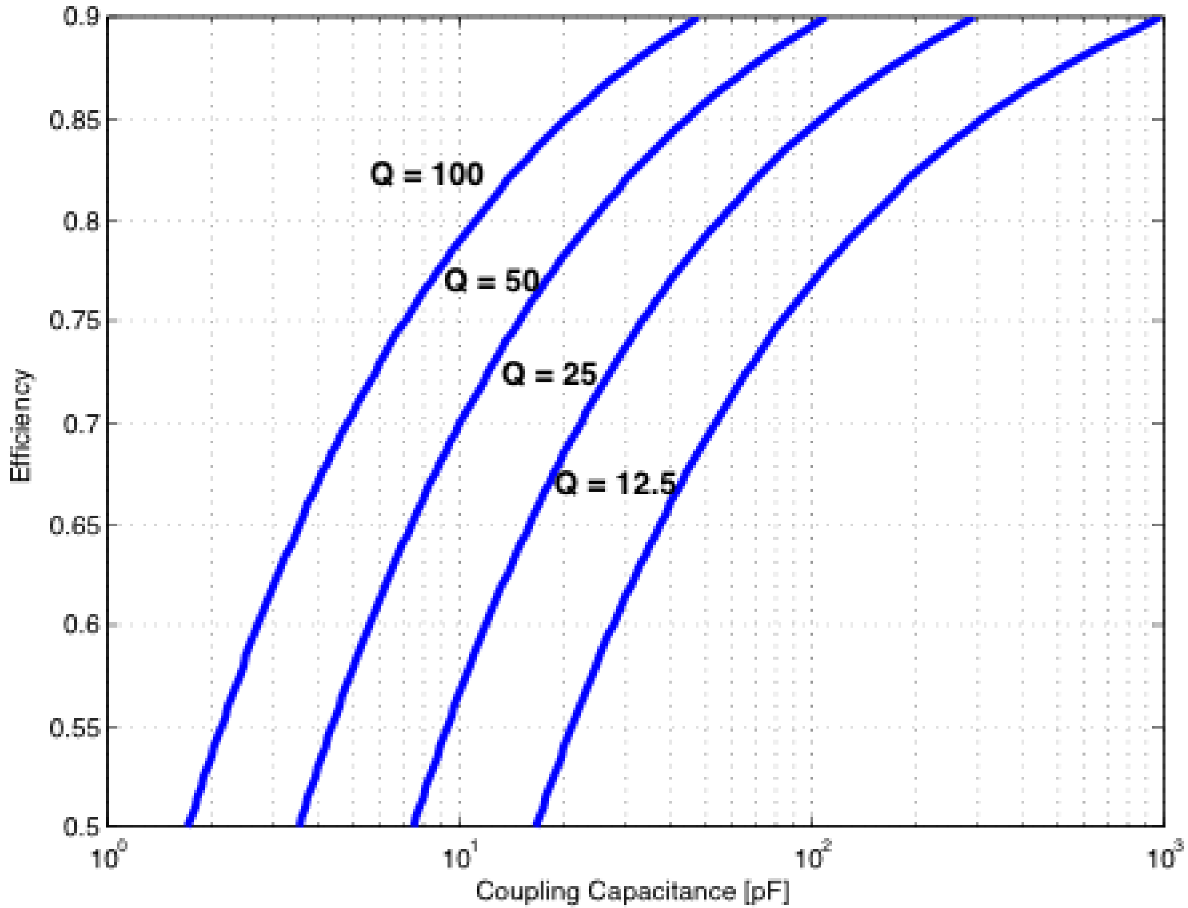
$$\omega \le \frac{P_{out}}{0.64 V_D V_S 2C_{oss}}\left(1 - \frac{V_D}{V_S}\right)$$



q_t = Charge removed by inductor

Example Design

Pout = 4 W, V_S = 35 V, and $R_{on}C_{oss}$ = 44 ps



Example Design

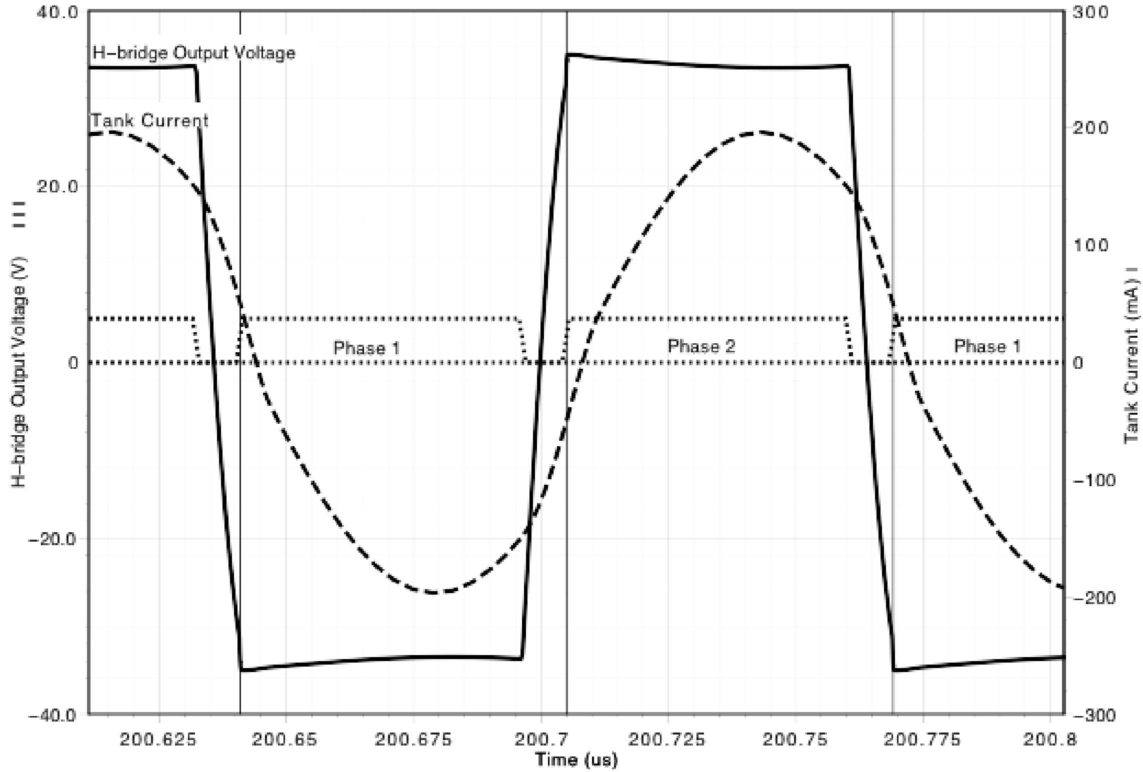
Choose
$\eta = 0.9, Q = 40$

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

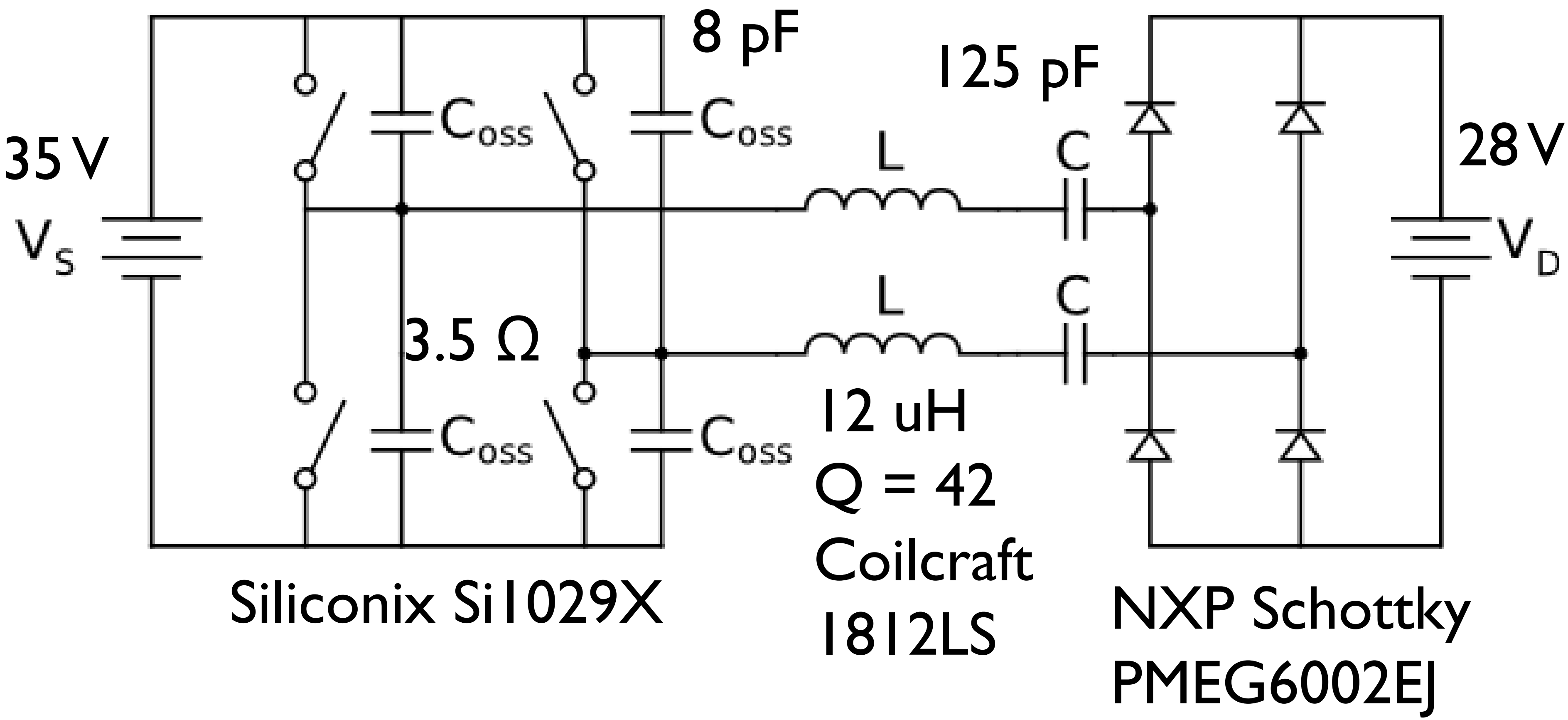
Parameter	Expression	Value
ω	$\frac{P_{out}}{0.64 A_V V_S^2 2C_{oss}}(1 - A_V)$	$2\pi 7.8\,\mathrm{Mrad/s}$
L	$\frac{1}{\omega^2 C}\left(\frac{0.64}{2}\frac{\omega C A_V V_S^2 \sqrt{1-A_V^2}}{P_{out}} + 1\right)$	$3.8\,\mu\mathrm{H}$
R_{on}	$\frac{\tau_{sw}}{C_{oss}}$	$3.4\,\Omega$
V_D	$A_V V_S$	$28\,\mathrm{V}$
ω_0	$\frac{1}{\sqrt{LC}}$	$2\pi 6.7\,\mathrm{Mrad/s}$
R_L	$\frac{2 \times 0.64^2 V_D^2}{P_{out}}$	$161\,\Omega$
Q_L	$\frac{2}{R_L}\sqrt{\frac{L}{C}}$	1.9
$\lVert i_t \rVert$	$\frac{P_{out}}{(0.64 V_D)}$	$223\,\mathrm{mA}$
ϕ	$\arctan\left(-\sqrt{\frac{1}{A_V^2} - 1}\right)$	$-37°$
I_{out}	$\frac{P_{out}}{V_D}$	$143\,\mathrm{mA}$

Simulation Results

Parameter	Design	Simulation
P_{out}	4 W	4 W
η	0.8	0.81
$\|\|i_t\|\|$	223 mA	222 mA
I_{out}	143 mA	142 mA
$\angle(v_d/v_s)$	$-37°$	$-32°$

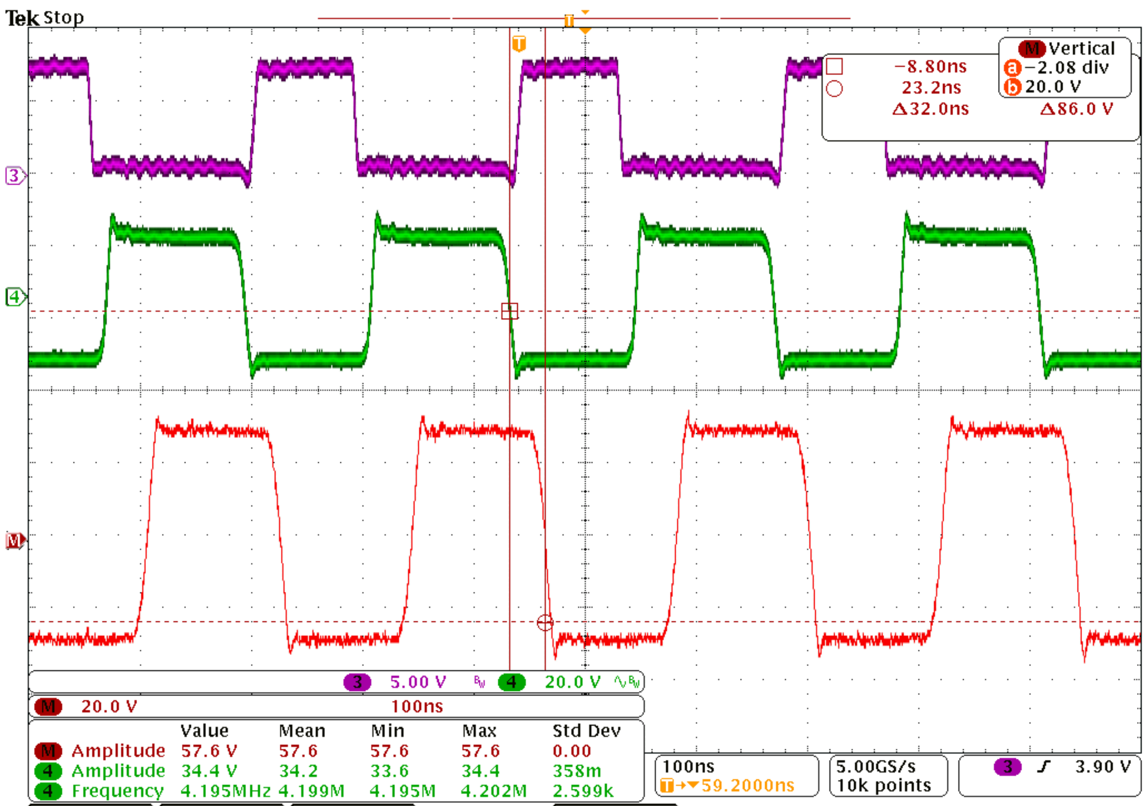


Prototype Powertrain Circuit

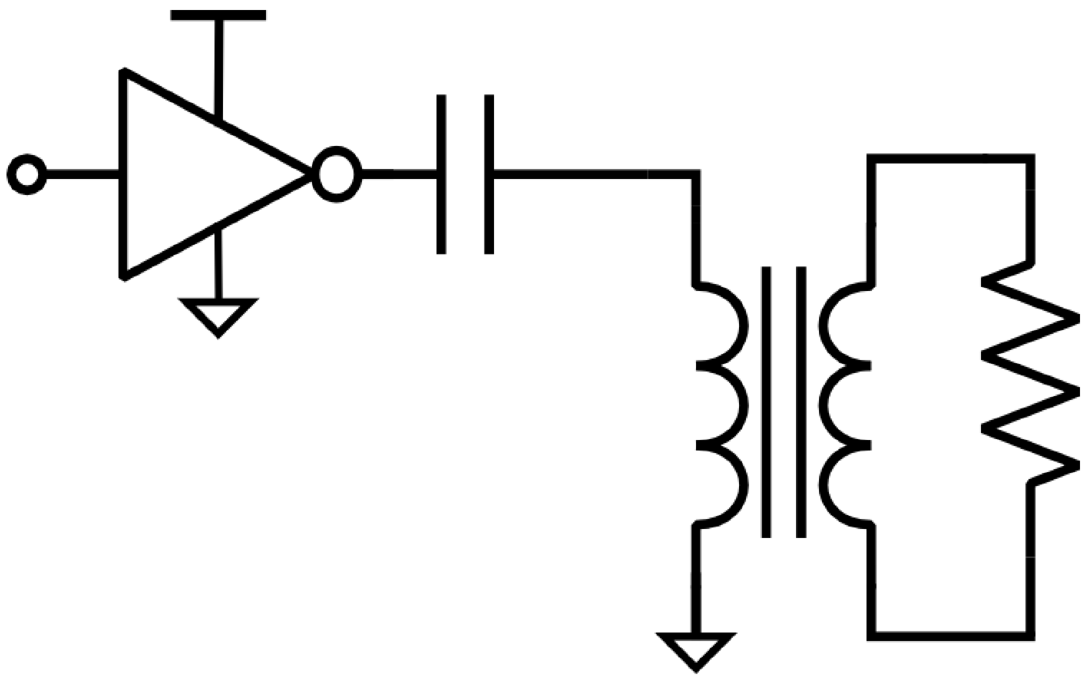


Experimental Results

Parameter	Design	Simulation	Experimental
P_{out}	4 W	4 W	3.72 W
η	0.8	0.81	0.77
$\|\|i_t\|\|$	223 mA	222 mA	—
I_{out}	143 mA	142 mA	133 mA
$\angle(v_d/v_s)$	$-37°$	$-32°$	$-48°$



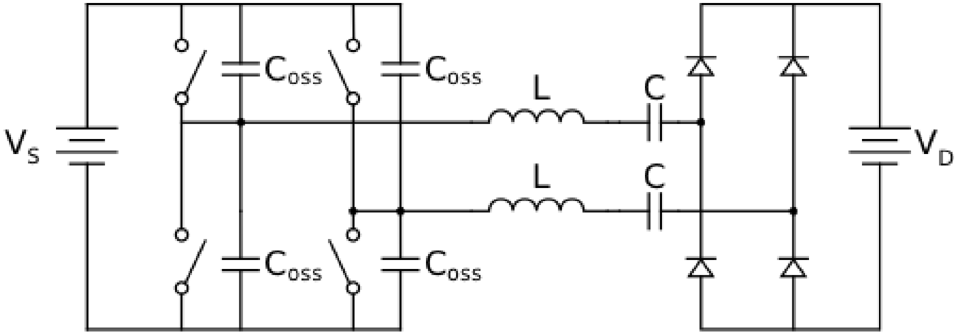
Extension to Inductive Transfer



Resonate out leakage inductance.

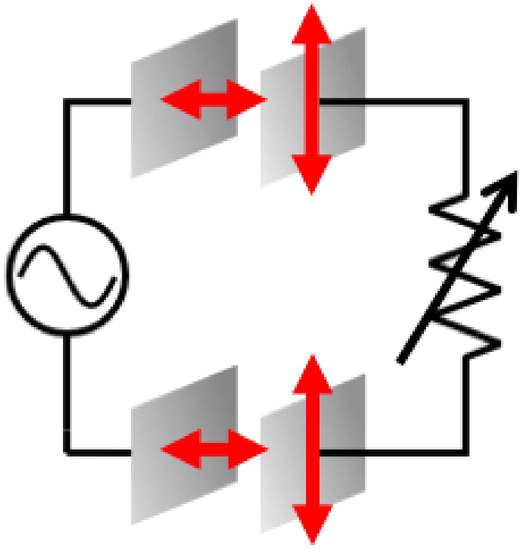
Capacitive Power Transfer System

1



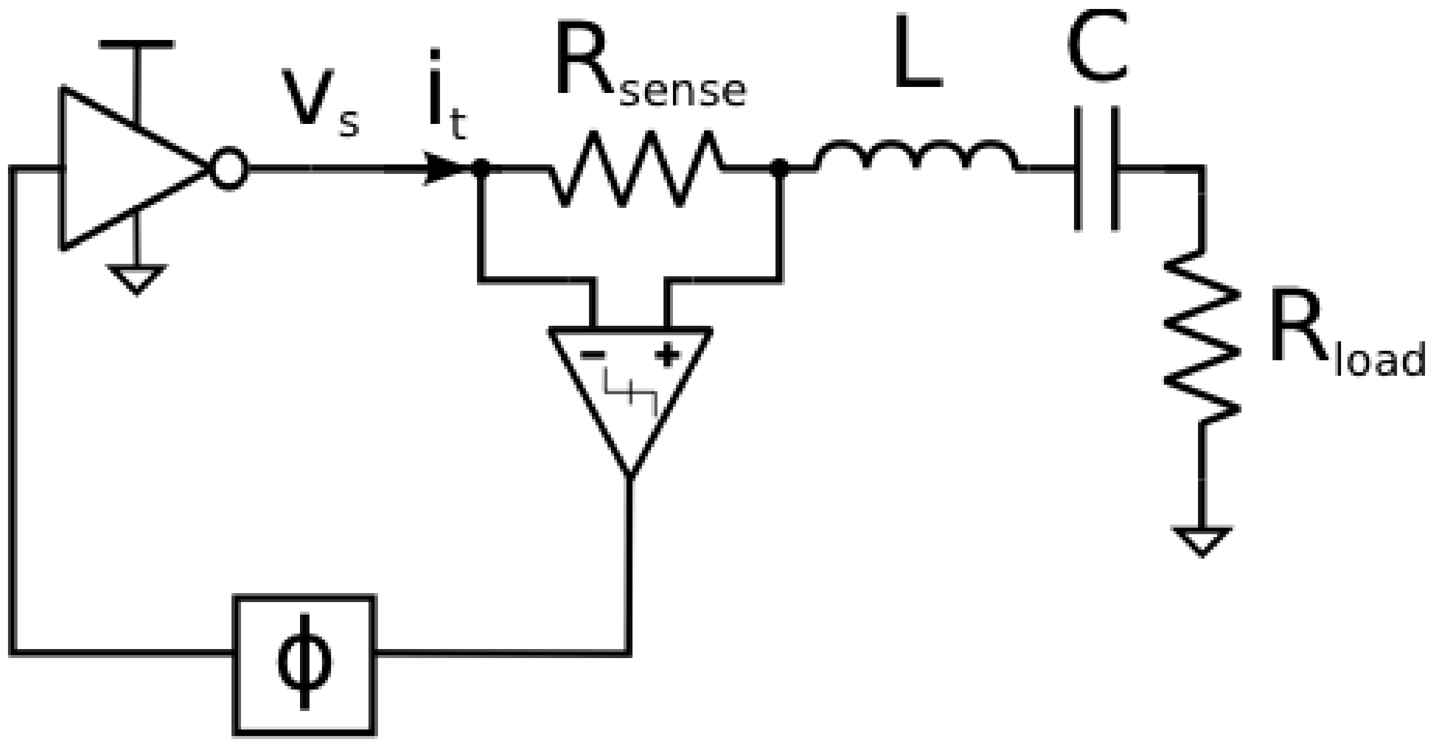
Powertrain optimization

2

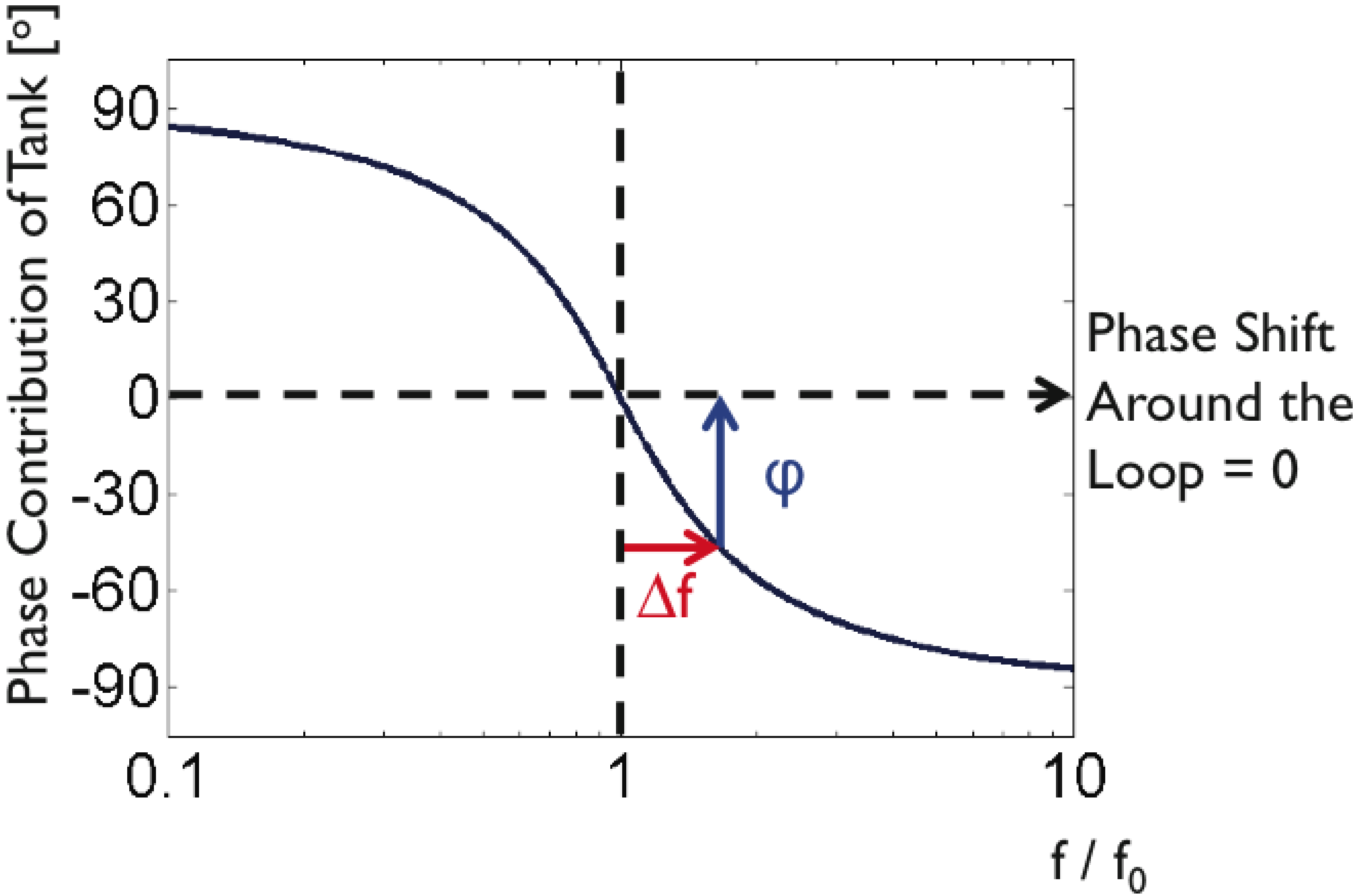


Alignment and load sensitivity

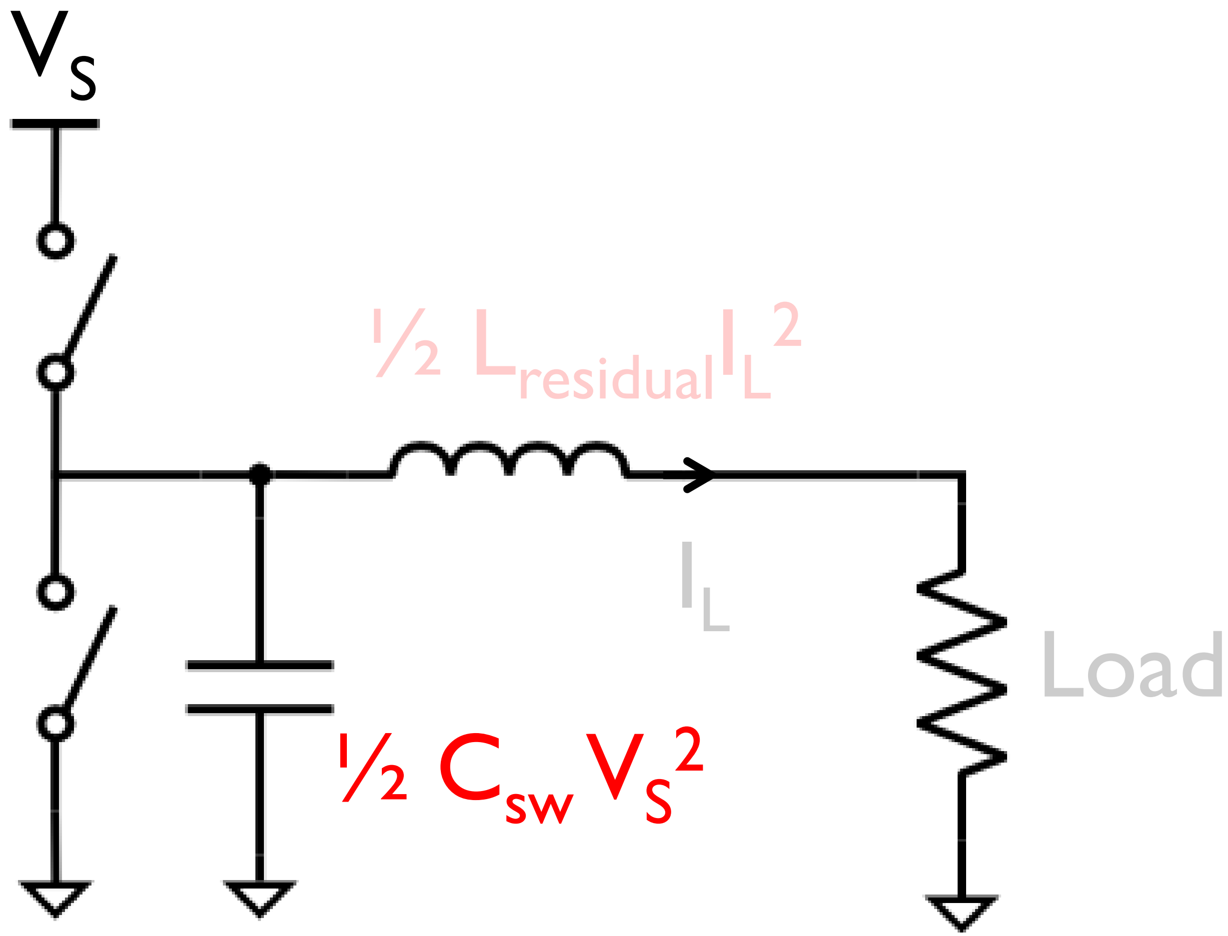
Automatic Frequency Tuning



Automatic Frequency Tuning



Automatic Duty Cycle Control



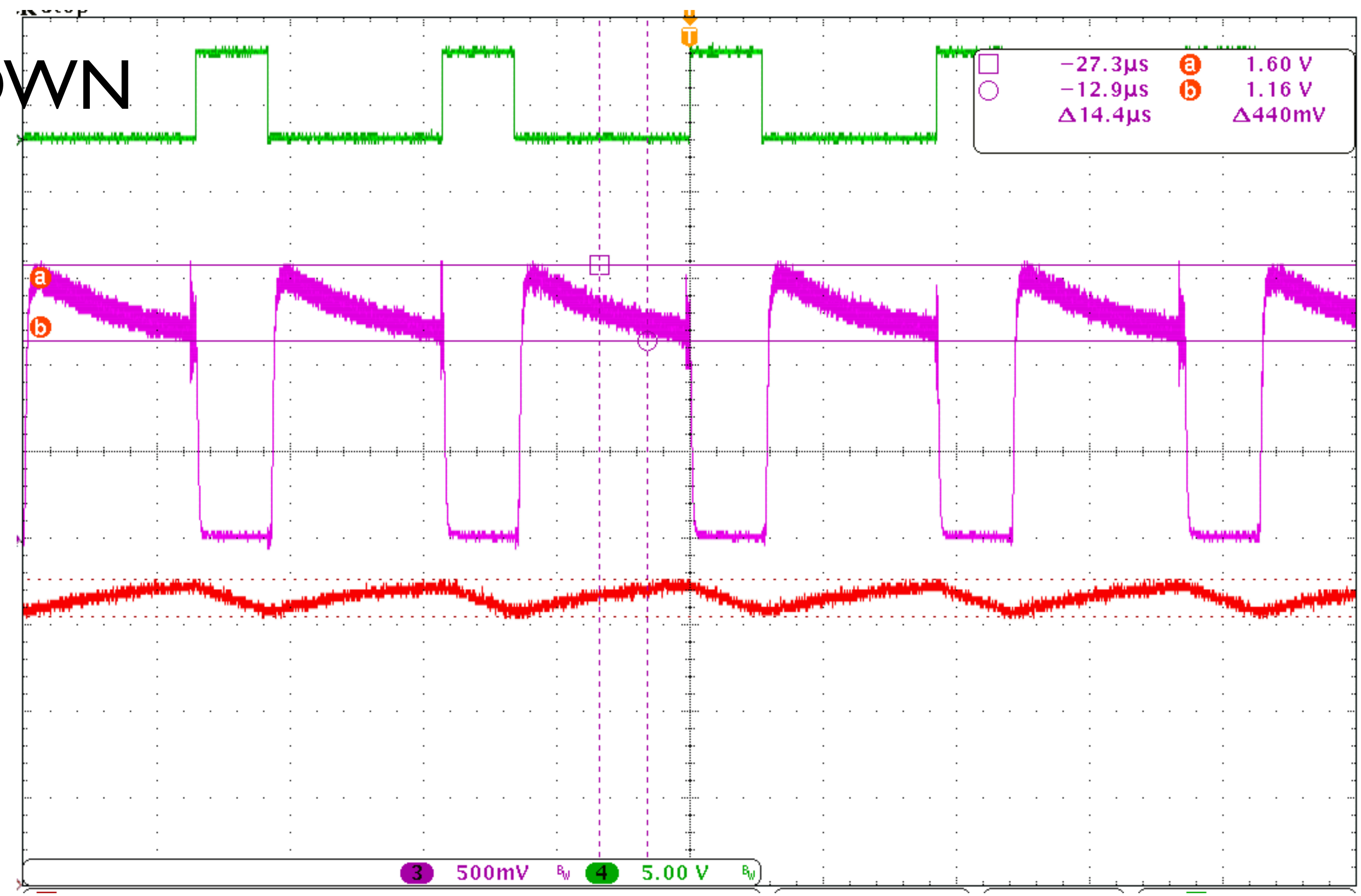
Light-load condition: not enough current in tank to get Zero Voltage Switching (ZVS)

Automatic Duty Cycle Control

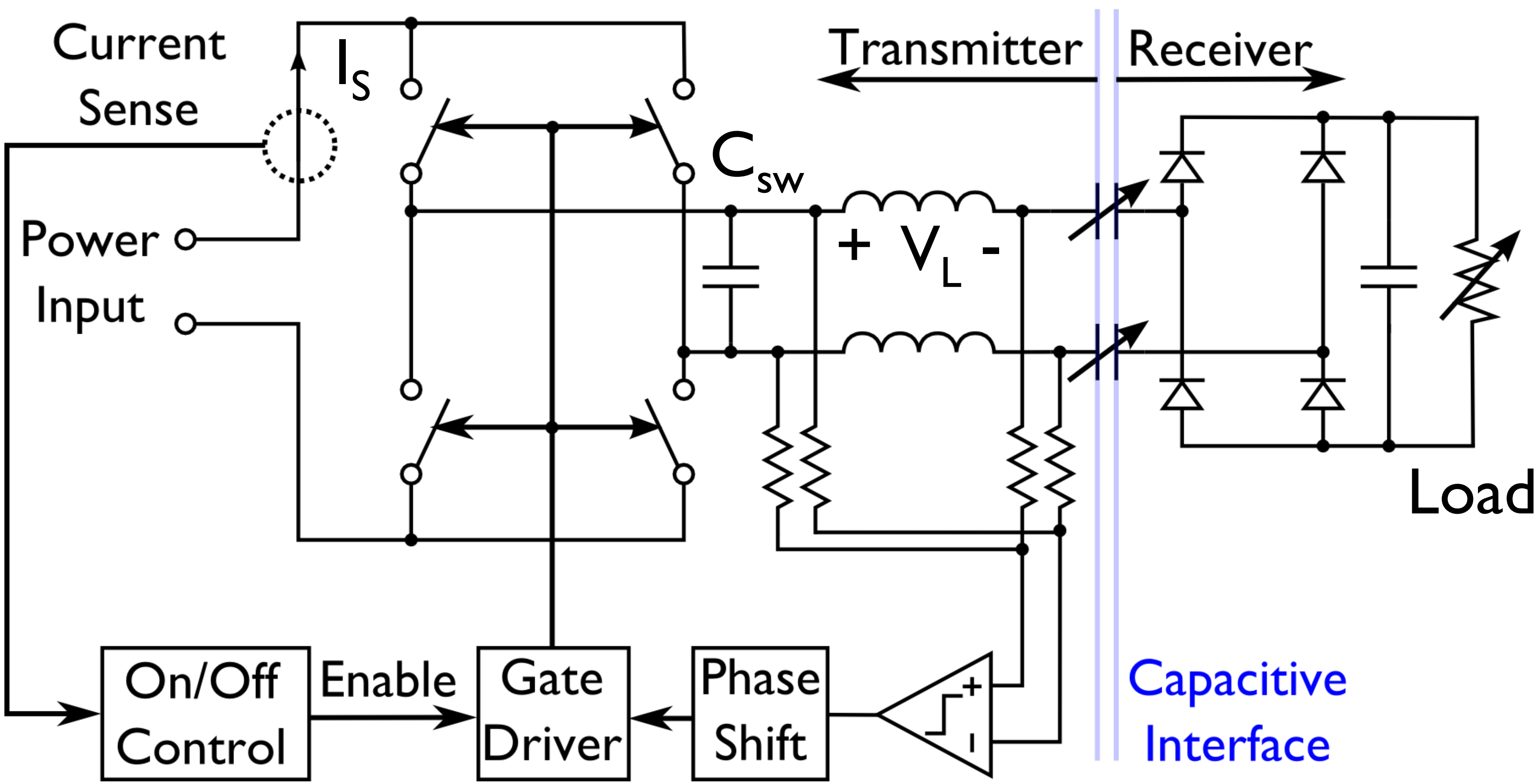
SHUTDOWN

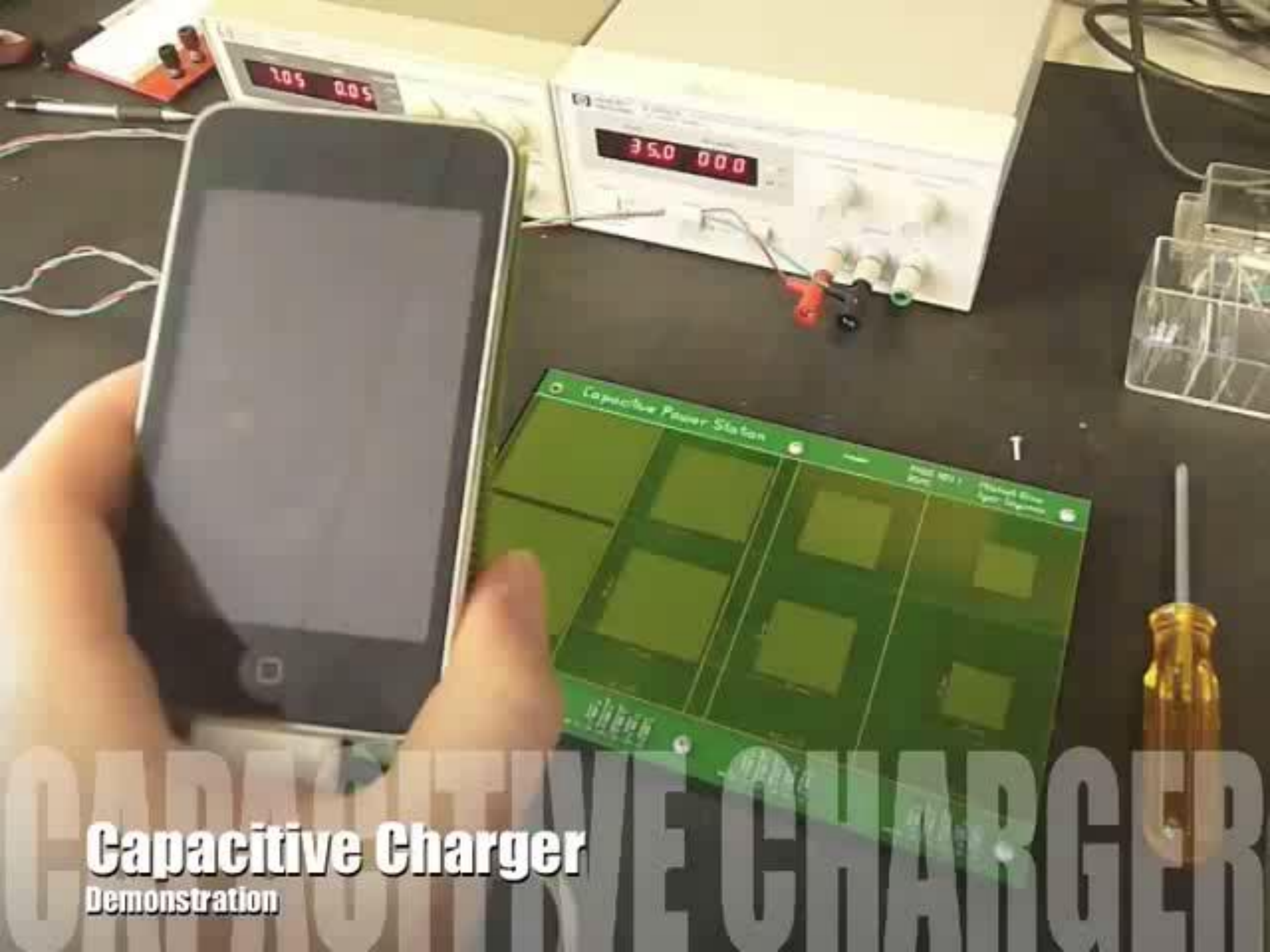
Supply
Current

DC
Output
Voltage

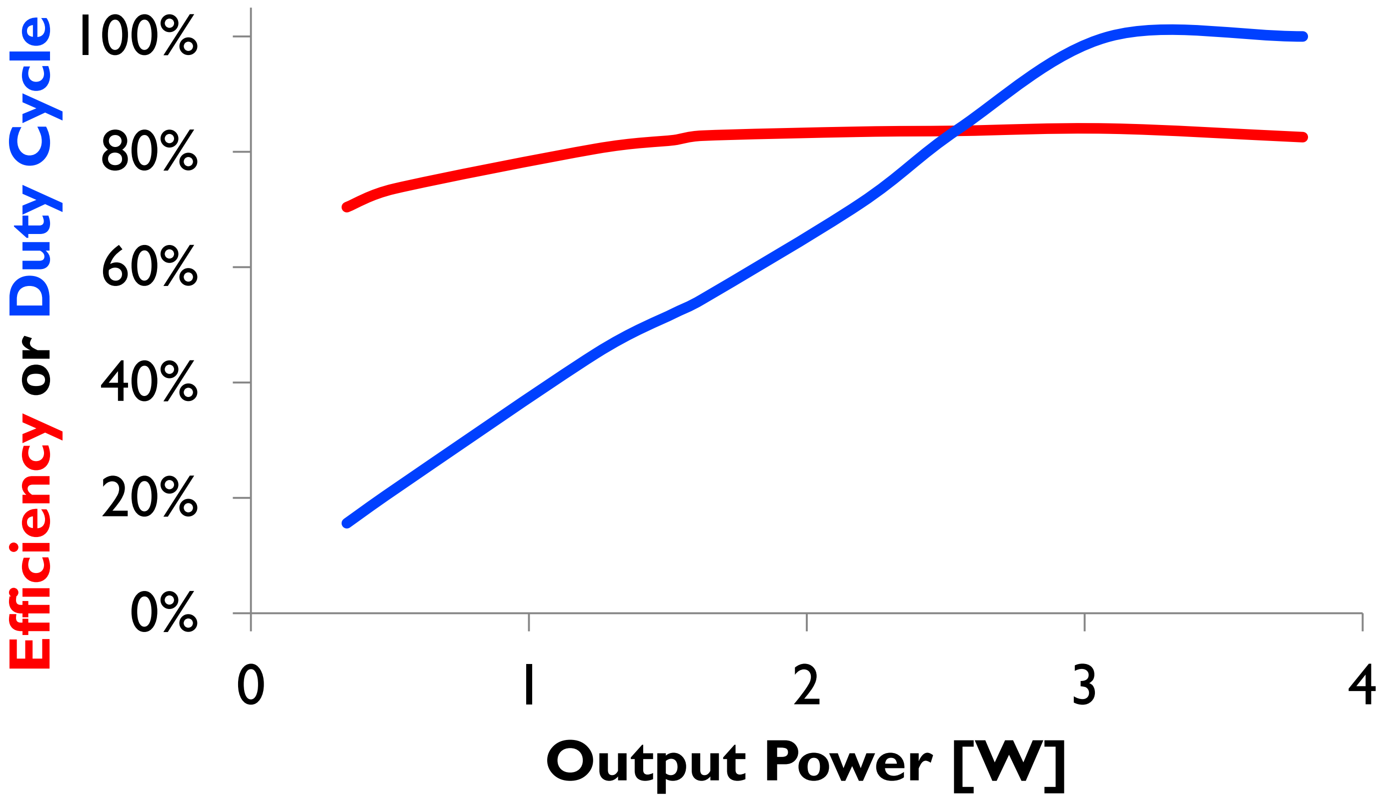


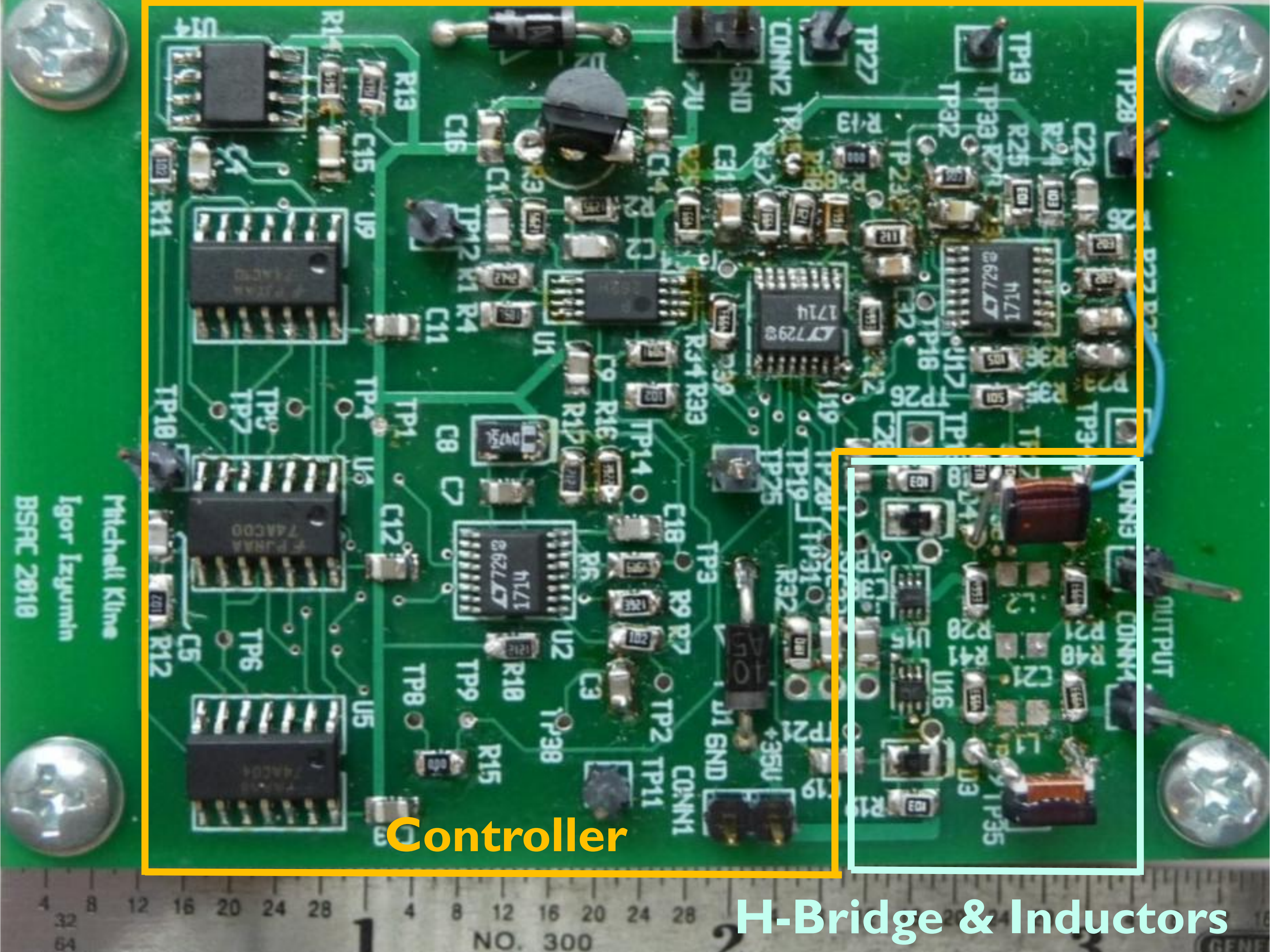
Capacitive Power Transfer System

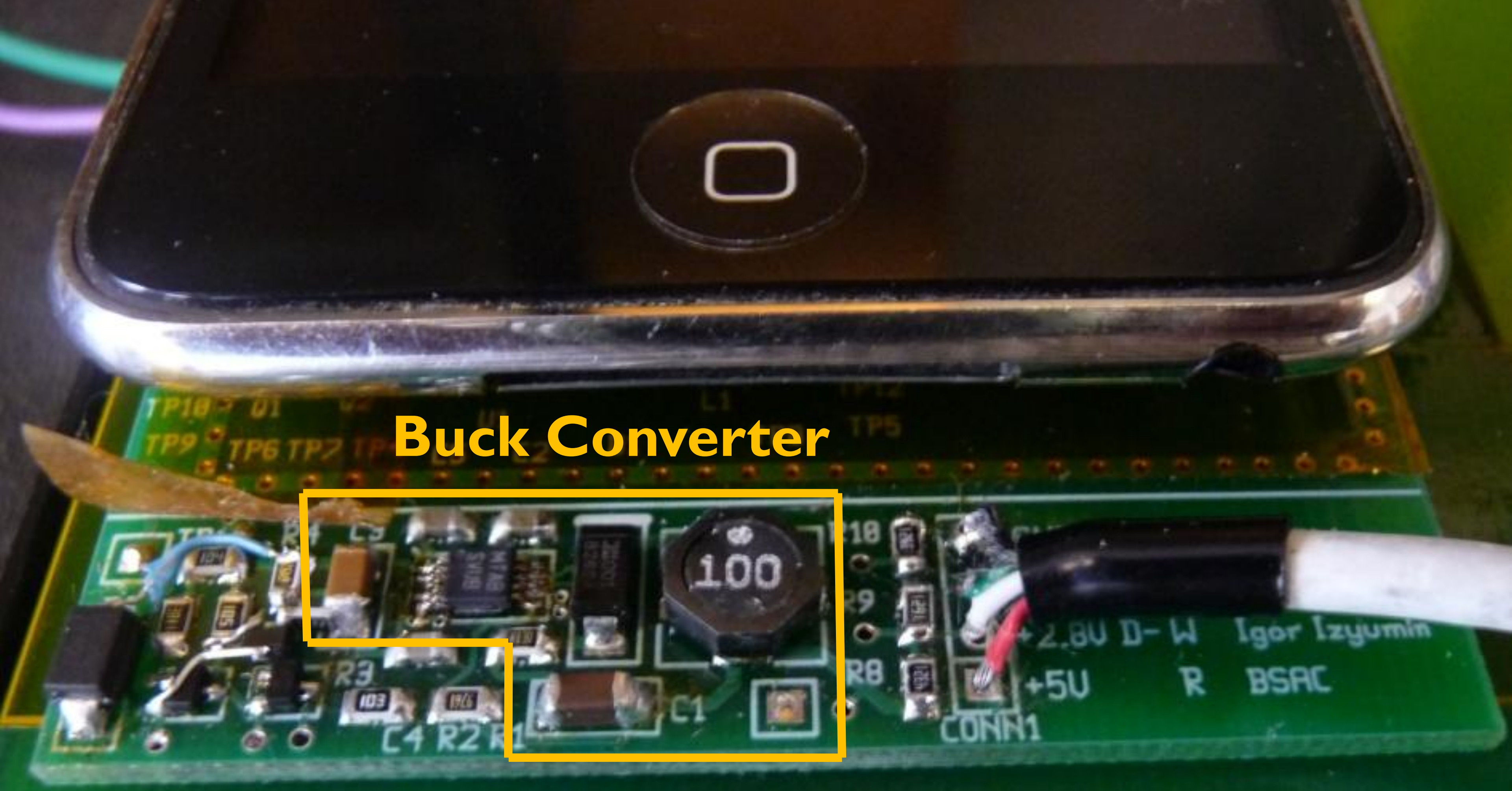
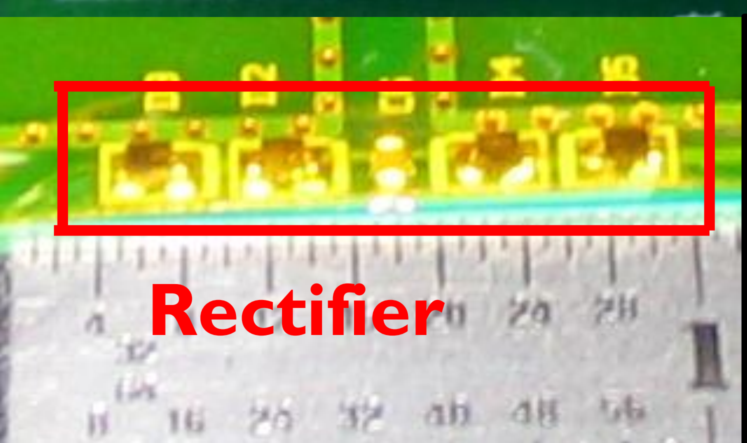



CAPACITIVE CHARGER
Capacitive Charger
Demonstration
Capacitive Power Station
7.05 0.05
35.0 00.0

With 6 by 10 cm^2, we transfer 3.8 W at 83% efficiency over a 0.5 mm air gap.




Controller
H-Bridge & Inductors
Mitchell Kline
Igor Izyumin
BSAC 2010


Buck Converter
100
C1
+2.8V D- W
+5V R
Igor Izyumin
BSAC
CONN1

Rectifier

Conclusion

Power transfer over small capacitors is enabled by

1. Zero Voltage Switching

   Enable moderate voltage, high frequency operation

2. Automatic Tuning

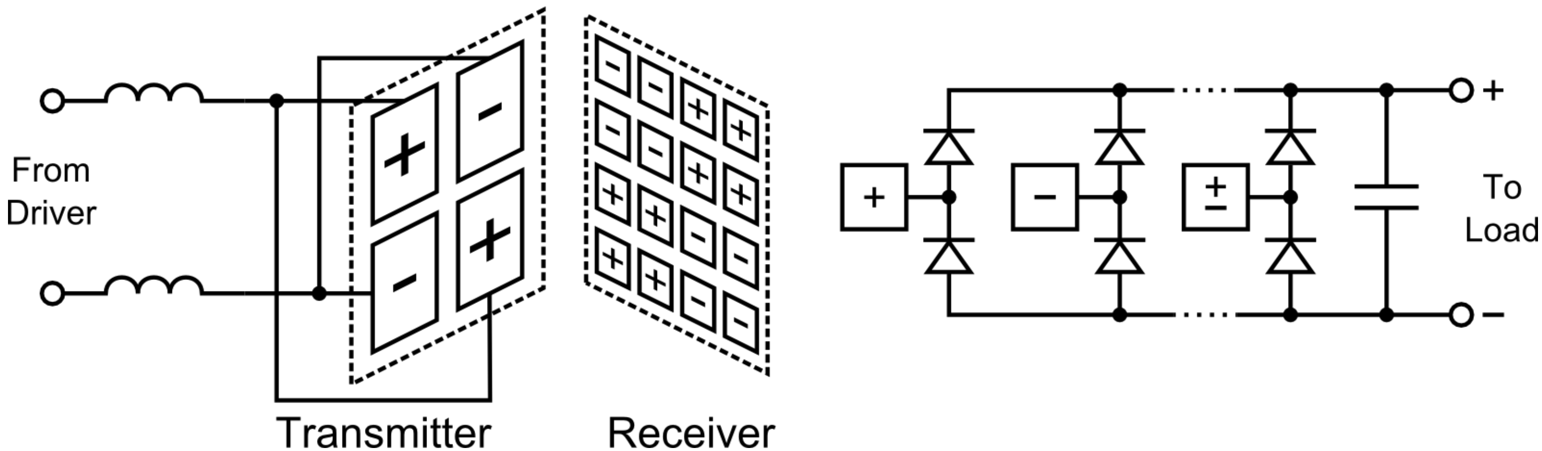
   Robust to changes in coupling capacitance

3. Duty cycle adjustment without RX feedback

   Preserve efficiency at light loads

Future Work

1. Extension to galvanic isolation
2. Pixelation



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Kun Wang
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