Capacitive Power Transfer for Contactless Charging

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Why Wireless Power?

The Powermat

"…I started to wonder if the magnet on the iPhone case was safe in my pocket where I also keep my credit cards…

I was told that I should remove my iPhone from the case after charging because [it] was not intended for daily use. "

Thomas Scholle

1 star amazon review

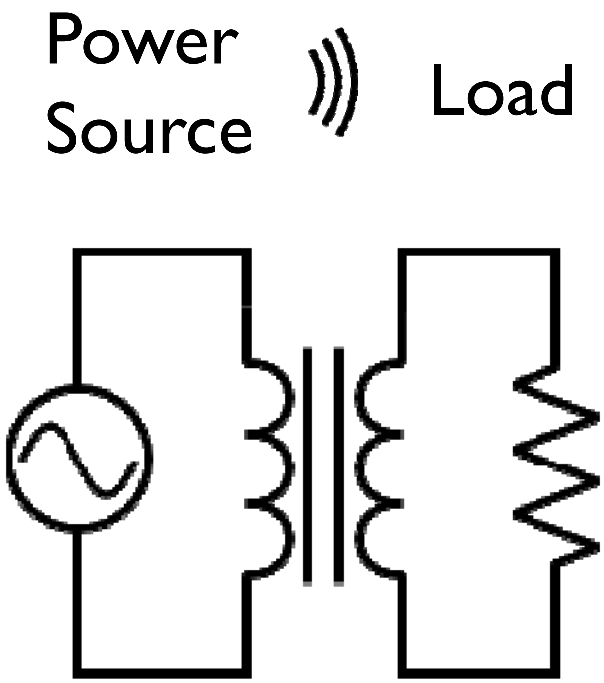
“you'll need to invest another $40 per device to get the full functionality as you see it advertised. Too pricey for me!”

J. Lincoln

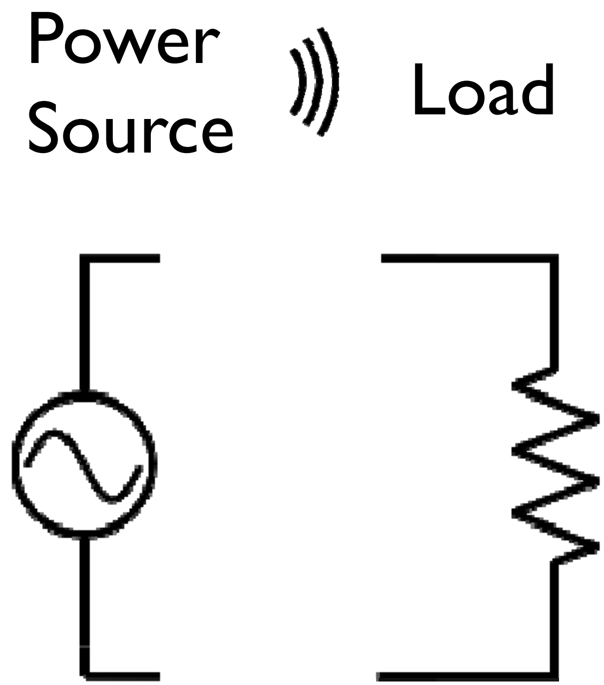
2star amazon review

Wireless Power Technology

Close-coupled wireless power transfer



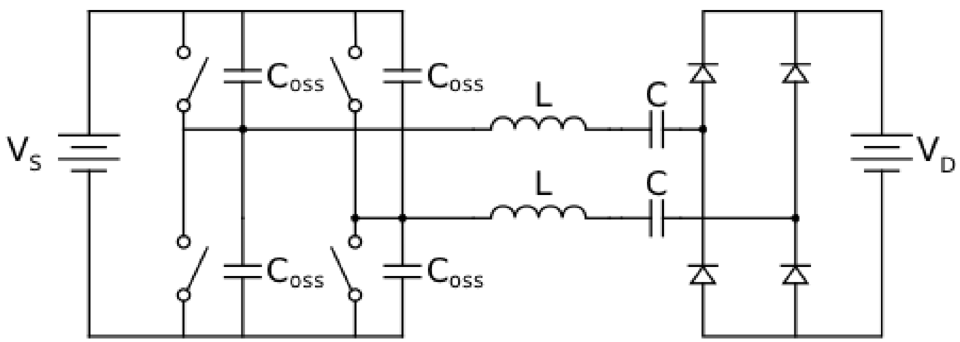
1. Inductive



2. Capacitive

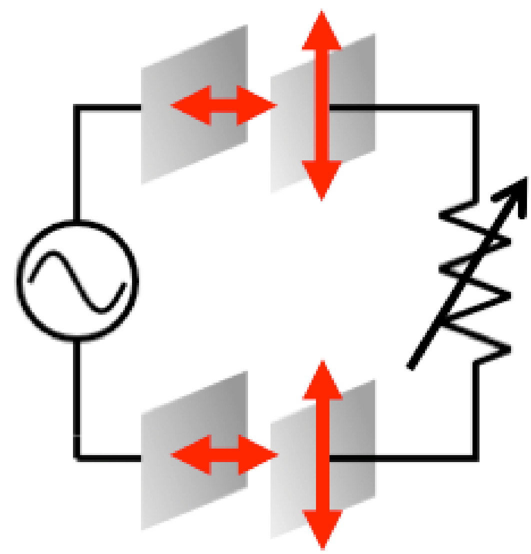
Capacitive Power Transfer System

1



Powertrain optimization

2

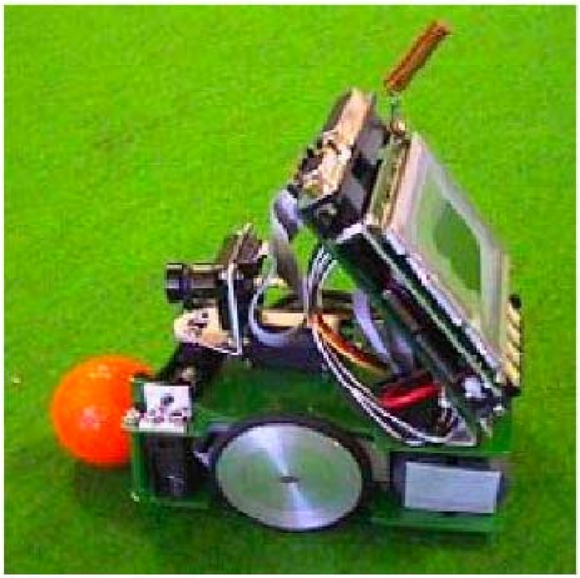


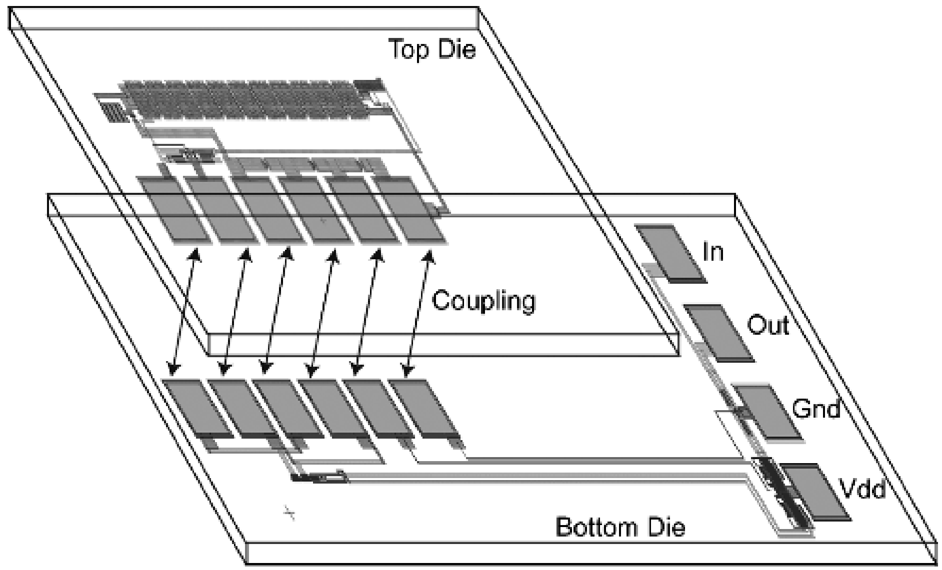
Alignment and load sensitivity

Requirements

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

Prior Art

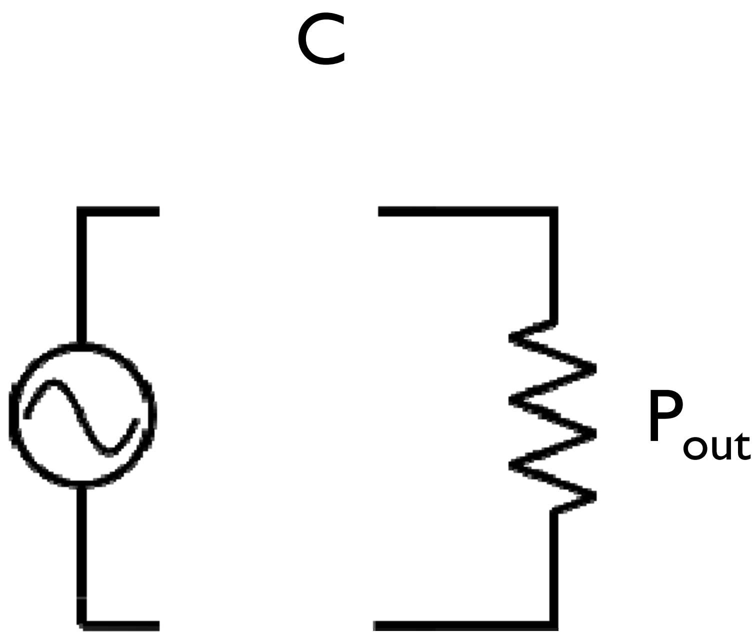




A. Hu. 2008.
Soccer Playing Robot
13.9 nF
217 kHz
~40 W?
44% efficient

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

Optimization Approach

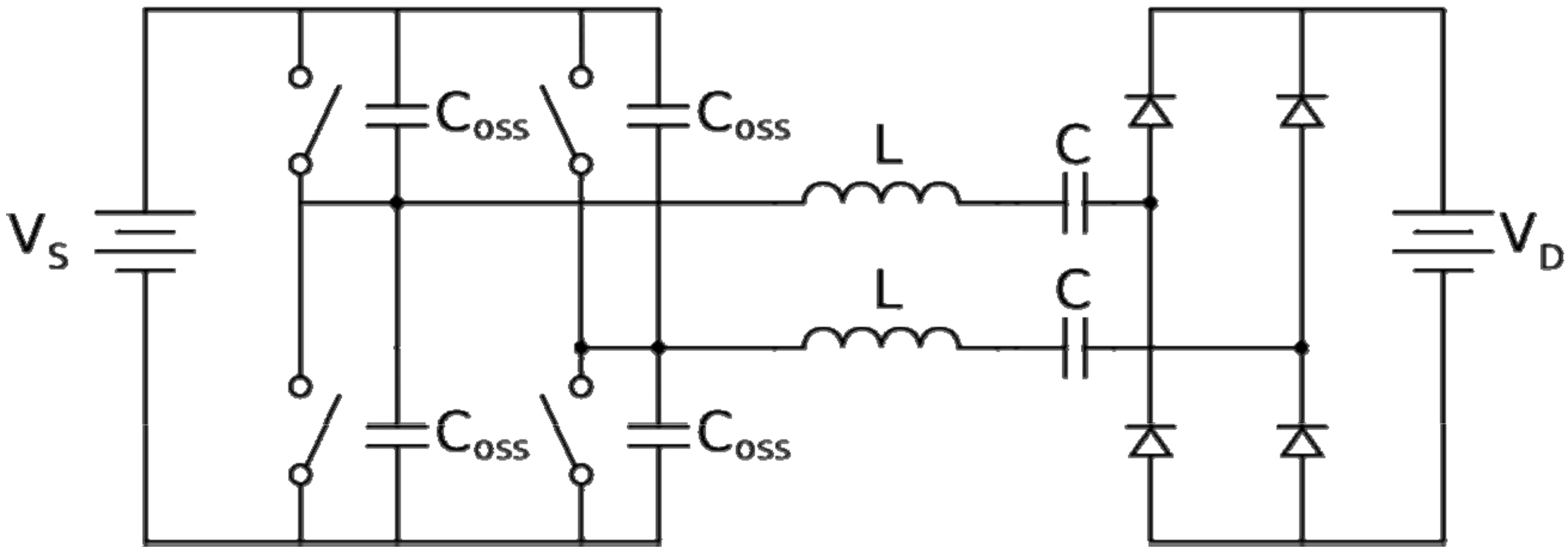


Given P_{out} and C, how do we maximize the efficiency?

or

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

Powertrain Architecture



Efficiency Expression

Minimize:
Increase voltage

Minimize:
Large switch
Small inductor

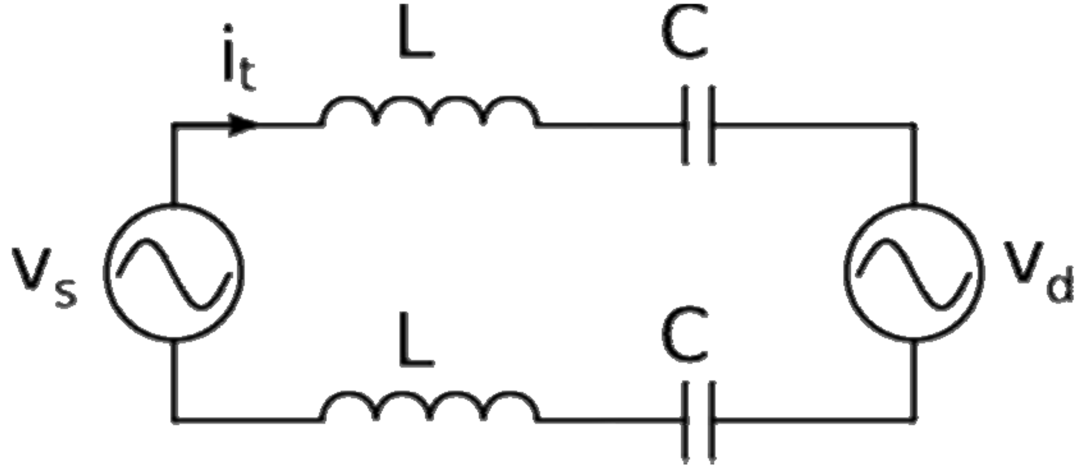
$$\eta = 1 - \frac{1}{2}\frac{\left\| i_t \right\|^2 R_S}{P_{out}}$$

Maximize

Fixed

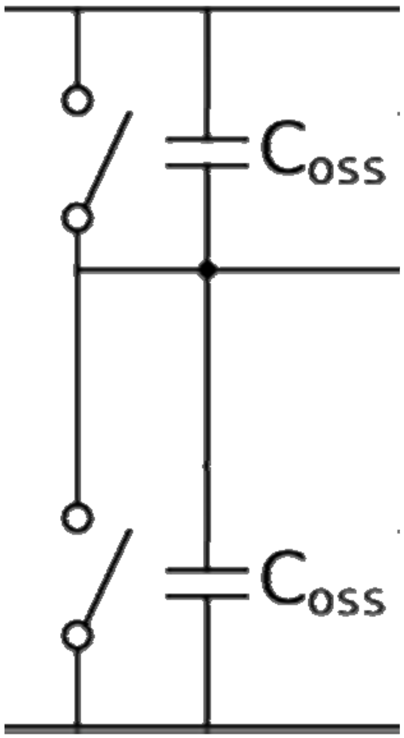
Does not consider switching losses => Eliminate with ZVS

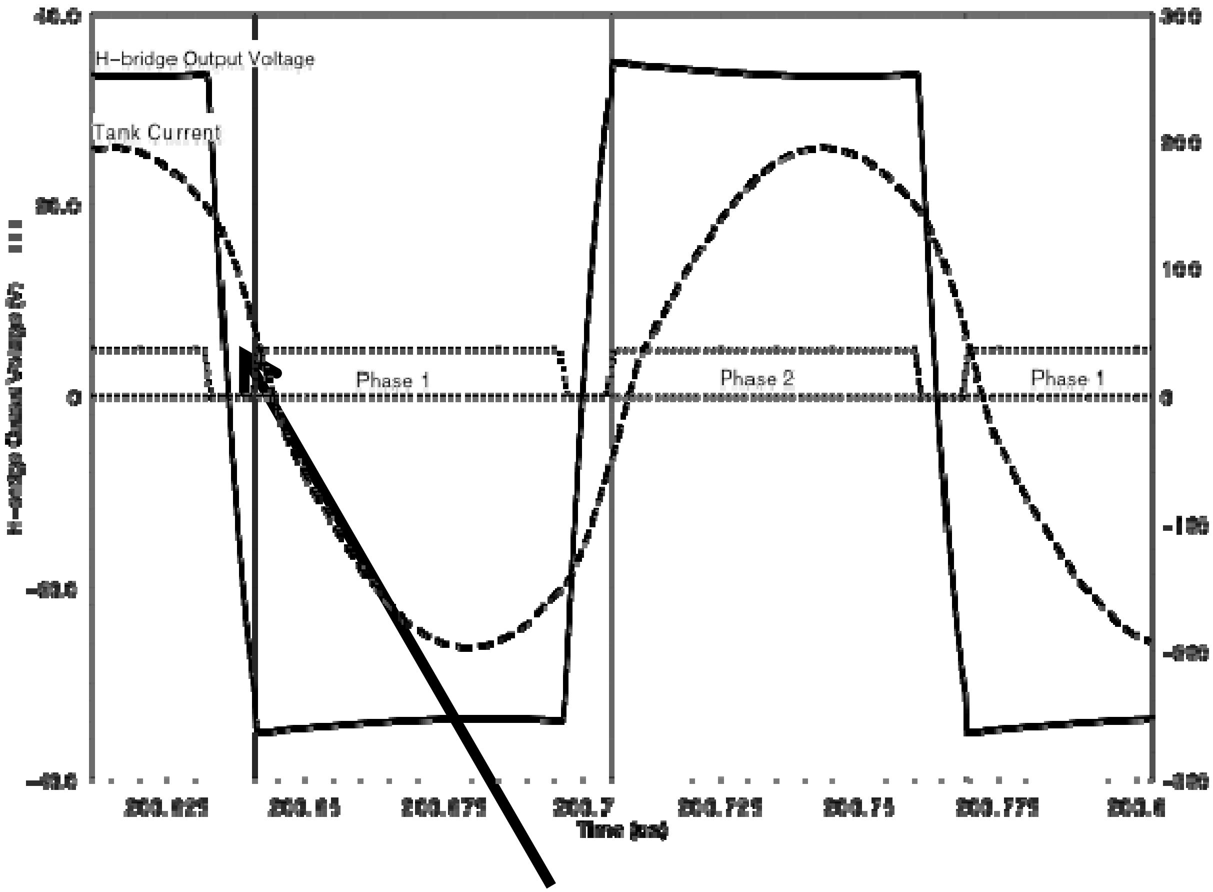
Approximate ZVS Analysis



$$\phi = \angle\left(\frac{i_t}{v_s}\right) = \arctan\left(-\sqrt{\frac{V_S^2}{V_D^2} - 1}\right)$$

Approximate ZVS Analysis





Initial charge

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

q_t = Charge removed by inductor

ZVS Condition

From integration:

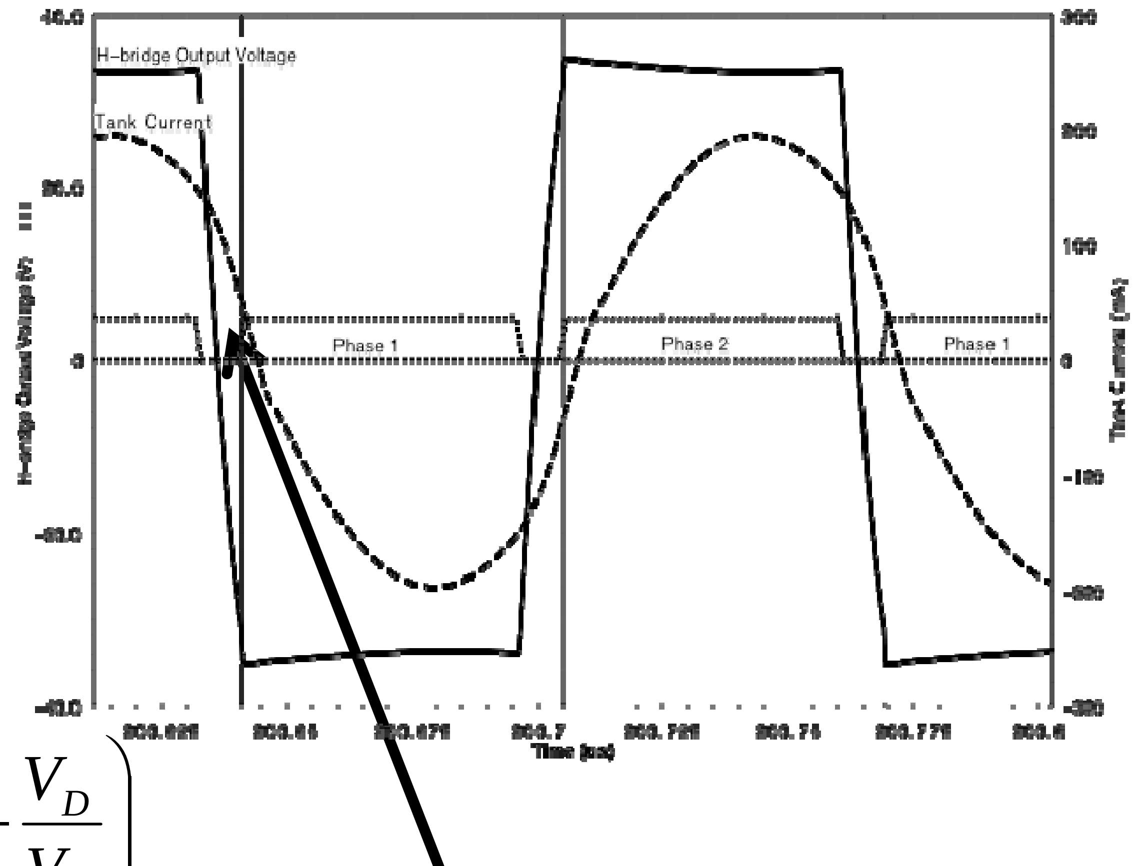
$$q_t = \frac{\left\| i_t \right\|}{\omega}\left(1 - \cos\phi\right)$$

ZVS requires:

$$q_t \geq q_{sw}$$

Refactored as:

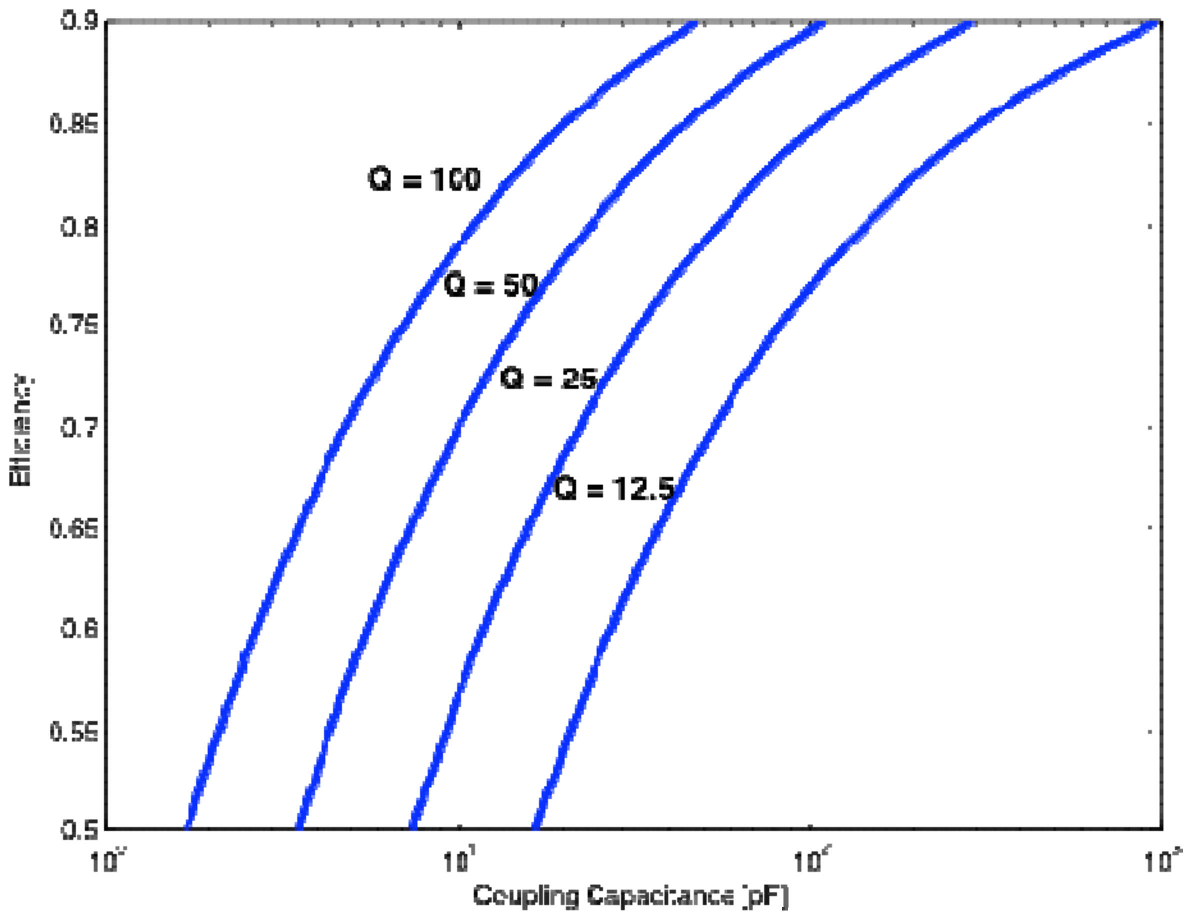
$$\omega \leq \frac{P_{out}}{0.64 V_D V_S \, 2C_{oss}}\left(1 - \frac{V_D}{V_S}\right)$$



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

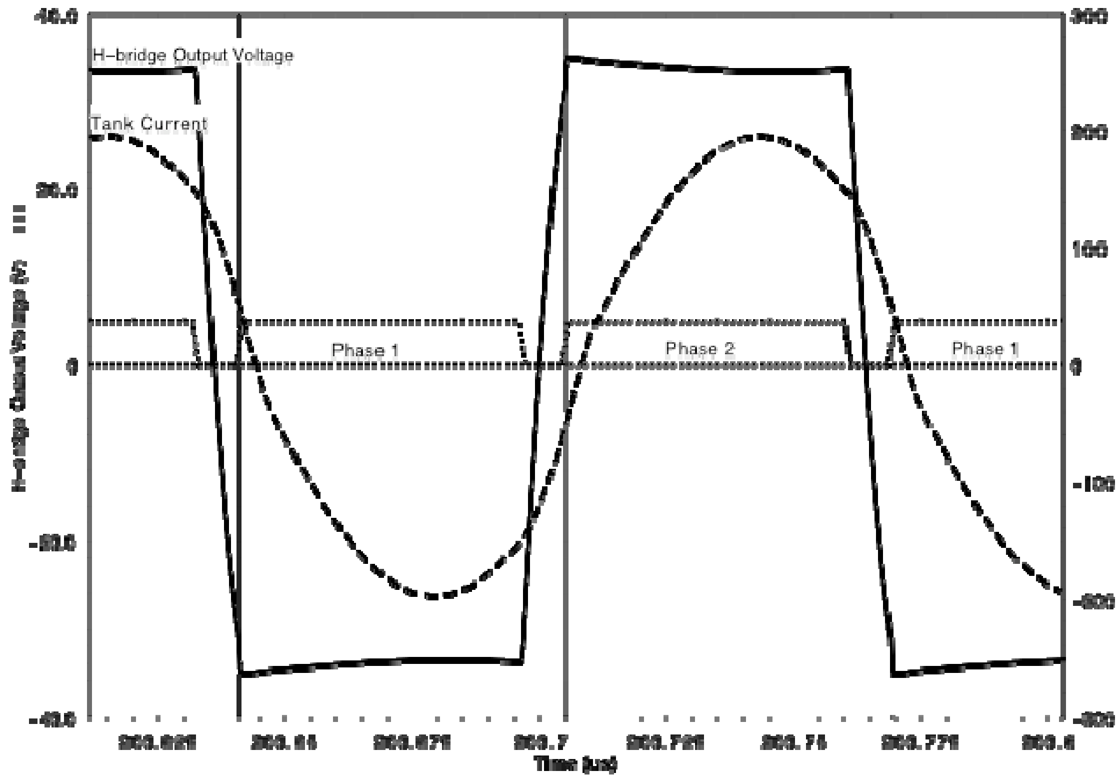
η = 0.9, Q = 40

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

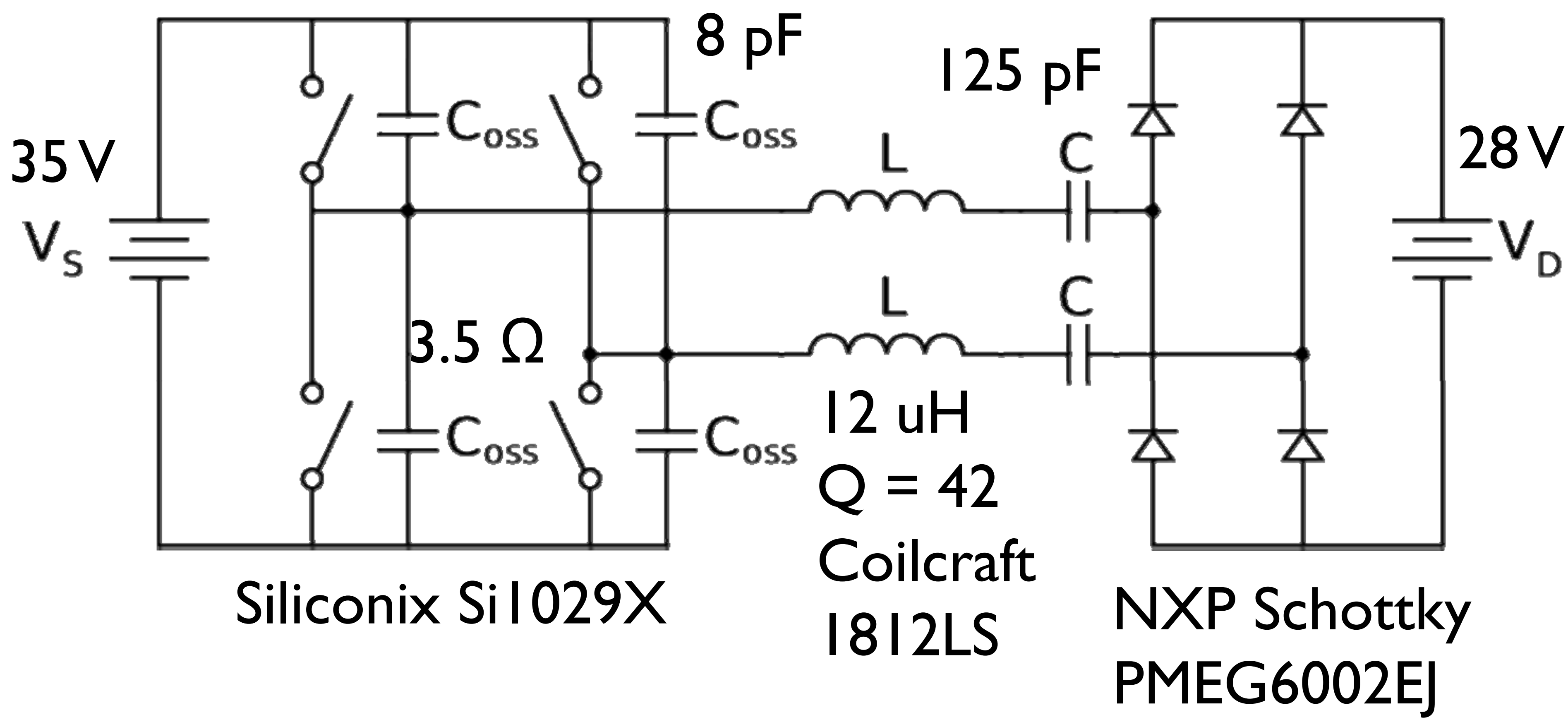
Parameter	Expression	Value
ω	$\frac{P_{out}}{0.64 A_V V_S^2 2C_{oss}}(1 - A_V)$	$2\pi 7.8$ Mrad/s
L	$\frac{1}{\omega^2 C}\left(\frac{0.64}{2}\frac{\omega C A_V V_S^2 \sqrt{1-A_V^2}}{P_{out}} + 1\right)$	3.8 μH
R_{on}	$\frac{\tau_{sw}}{C_{oss}}$	3.4 Ω
V_D	$A_V V_S$	28 V
ω_0	$\frac{1}{\sqrt{LC}}$	$2\pi 6.7$ Mrad/s
R_L	$\frac{2\times 0.64^2 V_D^2}{P_{out}}$	161 Ω
Q_L	$\frac{2}{R_L}\sqrt{\frac{L}{C}}$	1.9
$\|\|i_t\|\|$	$\frac{P_{out}}{(0.64 V_D)}$	223 mA
ϕ	$\arctan\left(-\sqrt{\frac{1}{A_V^2} - 1}\right)$	$-37°$
I_{out}	$\frac{P_{out}}{V_D}$	143 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
$\angle(v_d/v_s)$	$-37°$	$-32°$

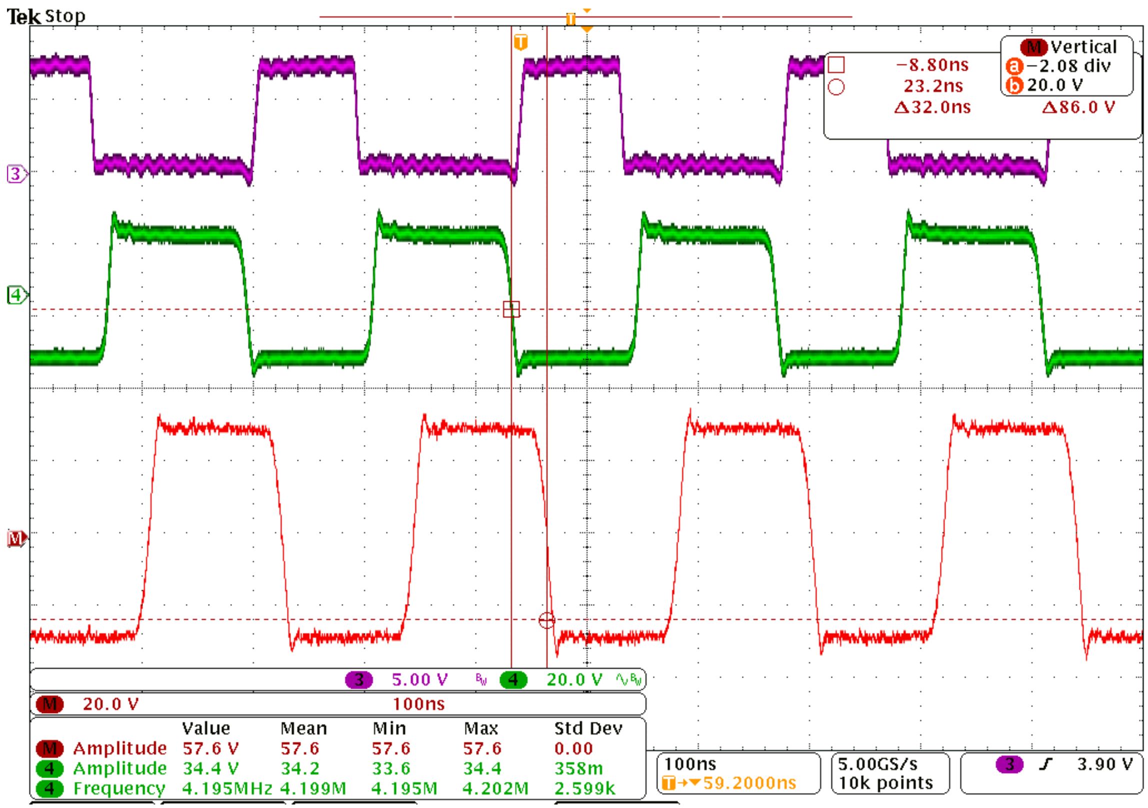


Prototype Powertrain Circuit



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
$\angle(v_d/v_s)$	$-37°$	$-32°$	$-48°$



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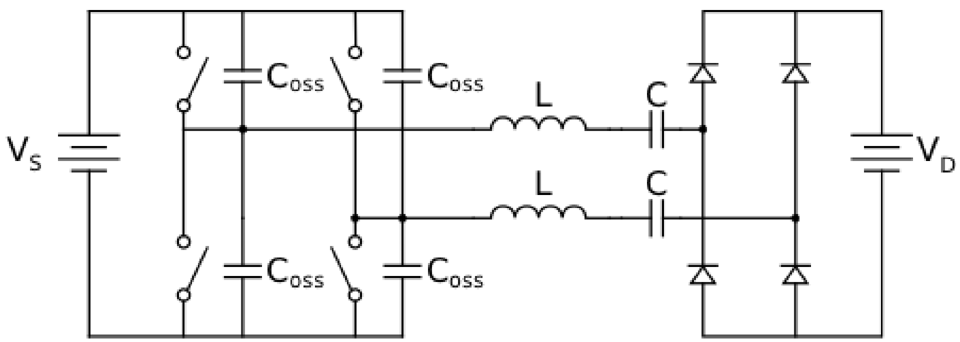
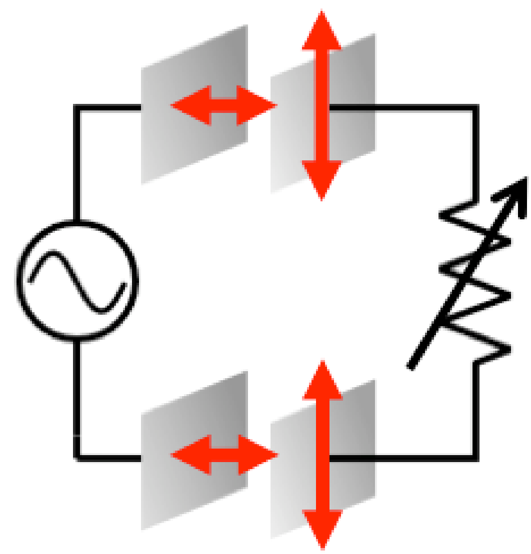


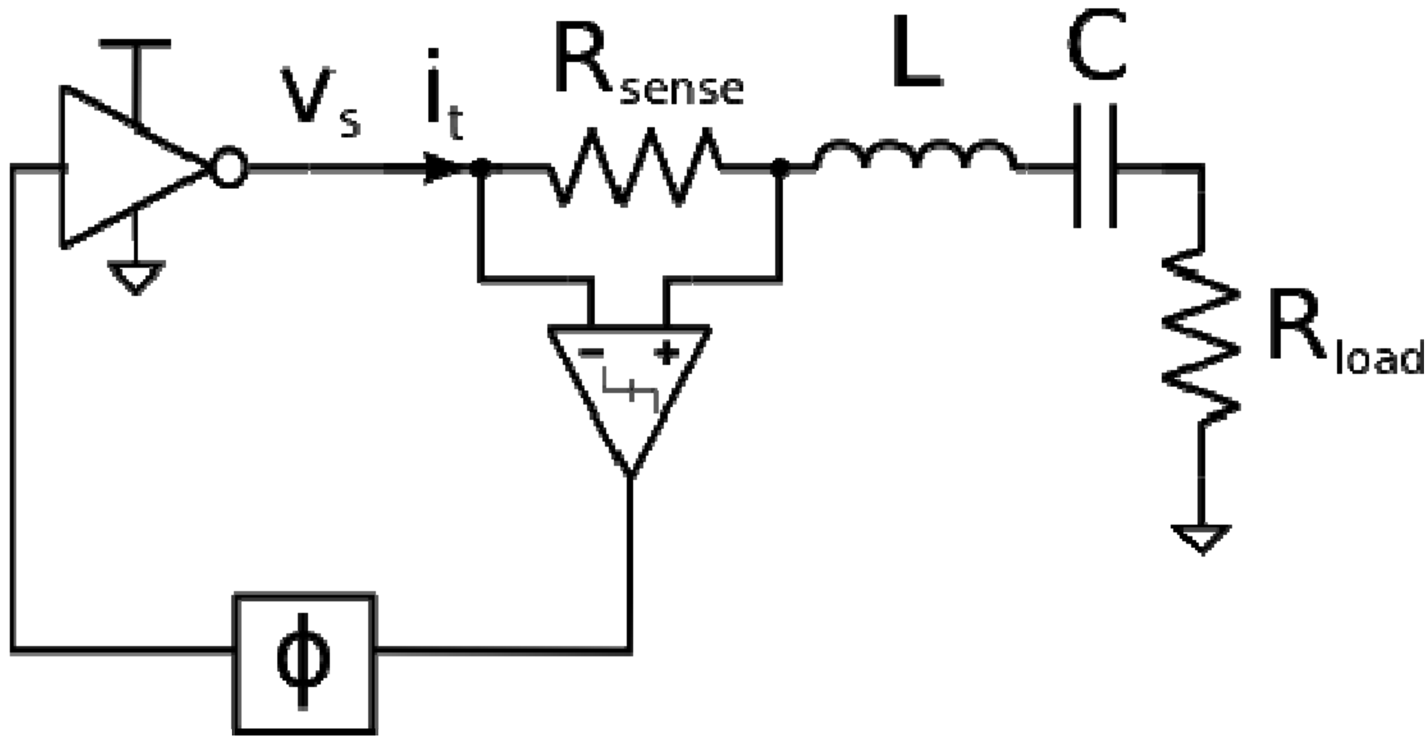
Powertrain optimization

2

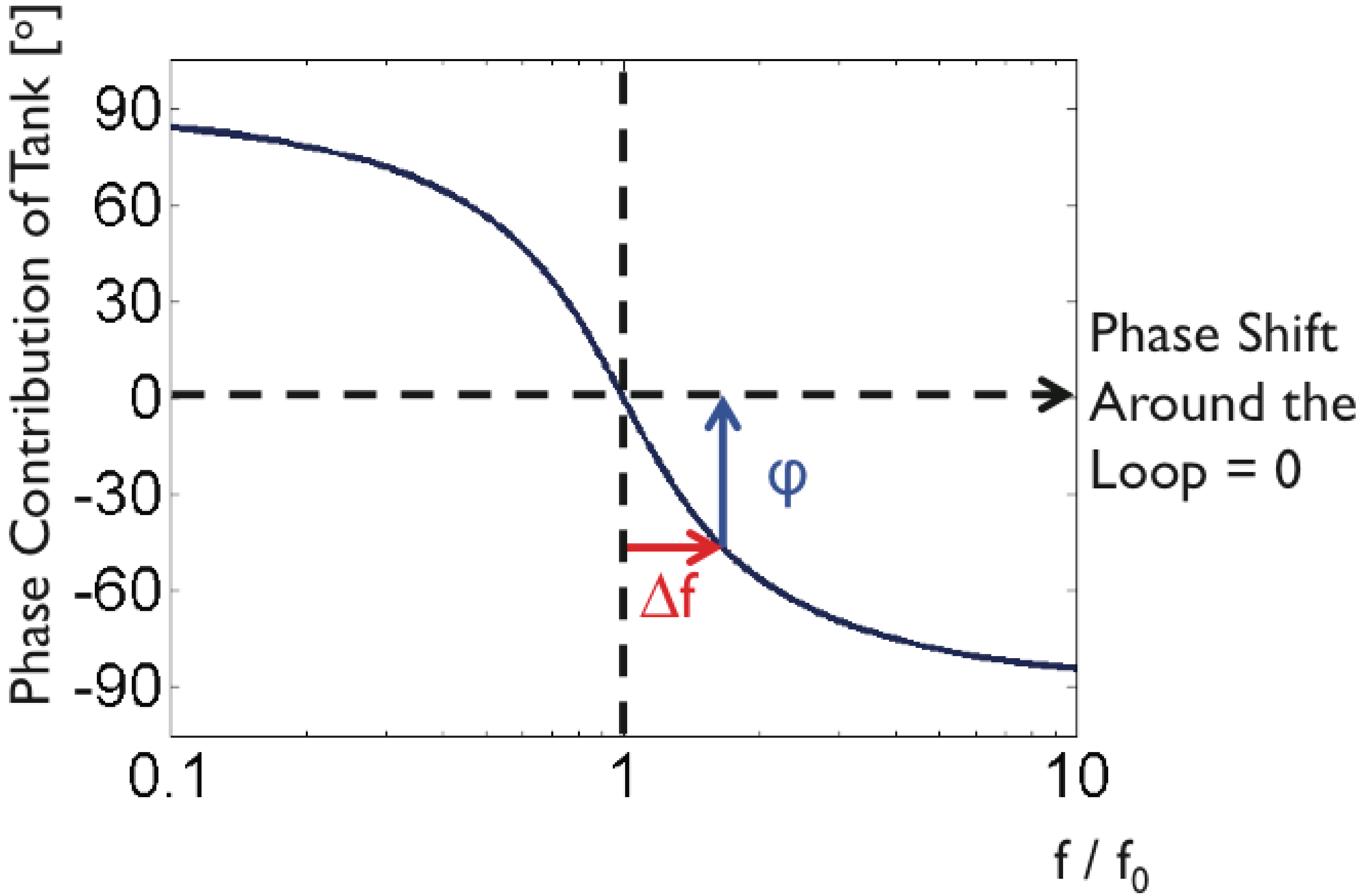


Alignment and load sensitivity

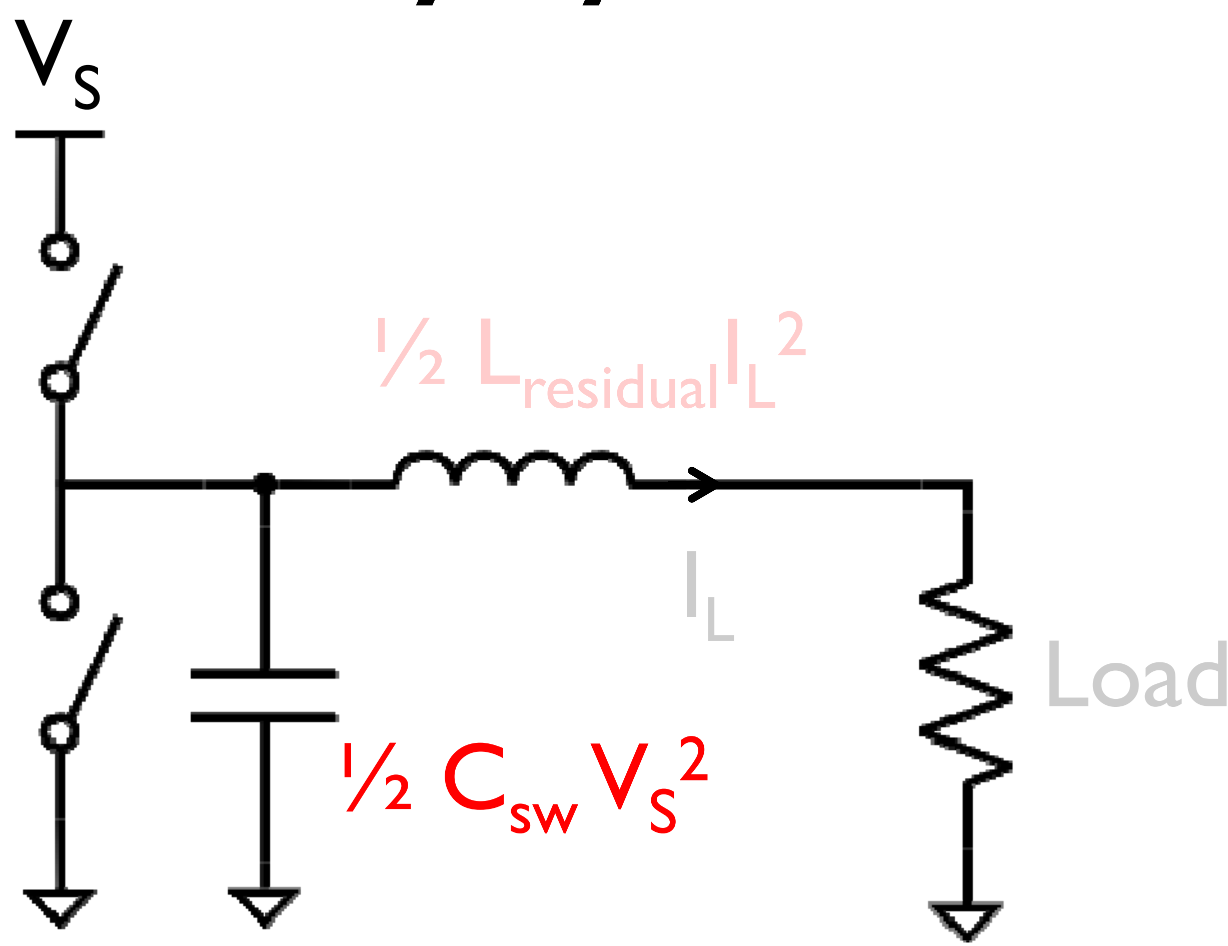
Automatic Frequency Tuning



Automatic Frequency Tuning



Automatic Duty Cycle Control



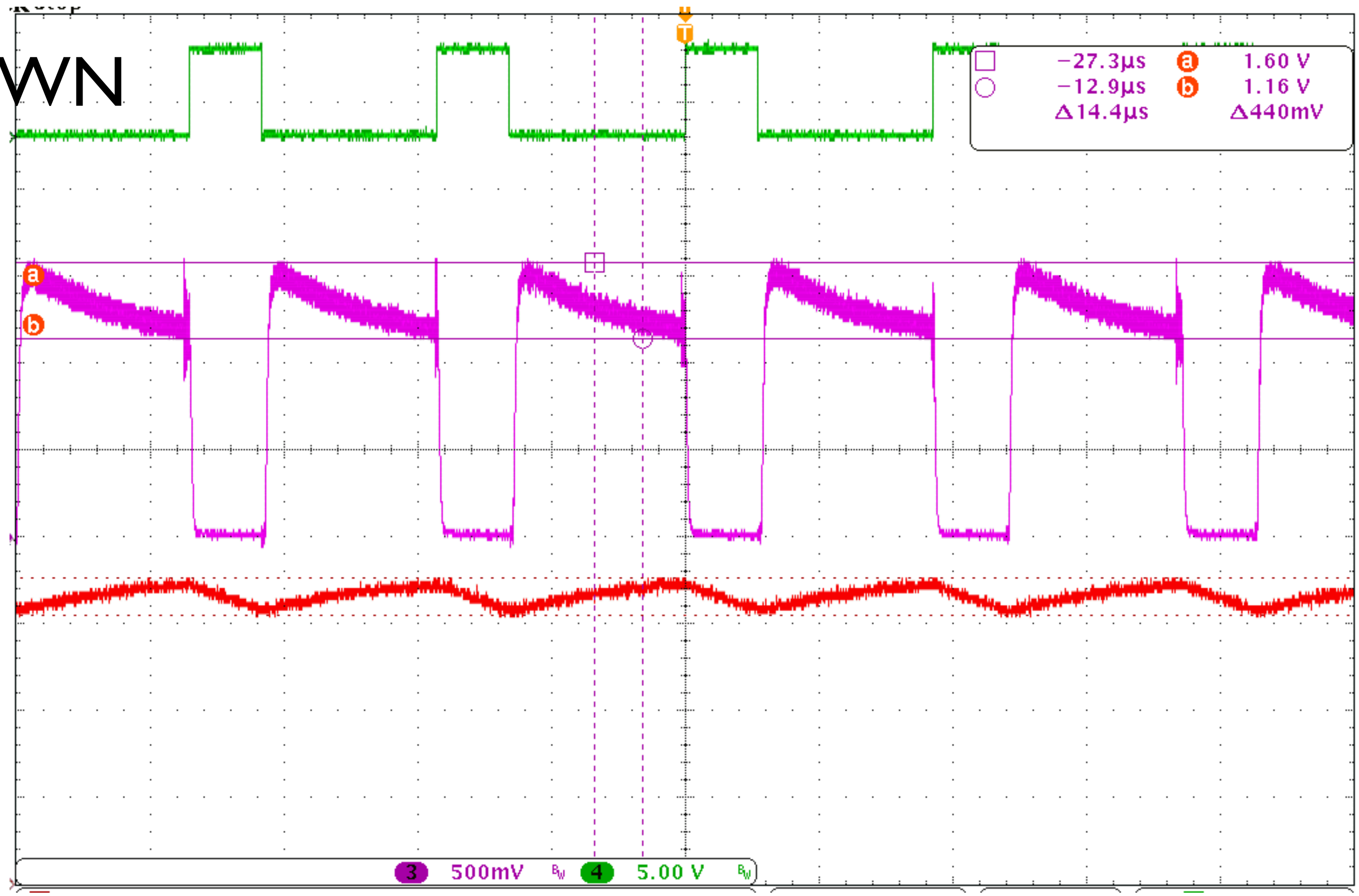
Light-load condition: not enough current in tank to get Zero Voltage Switching (ZVS)

Automatic Duty Cycle Control

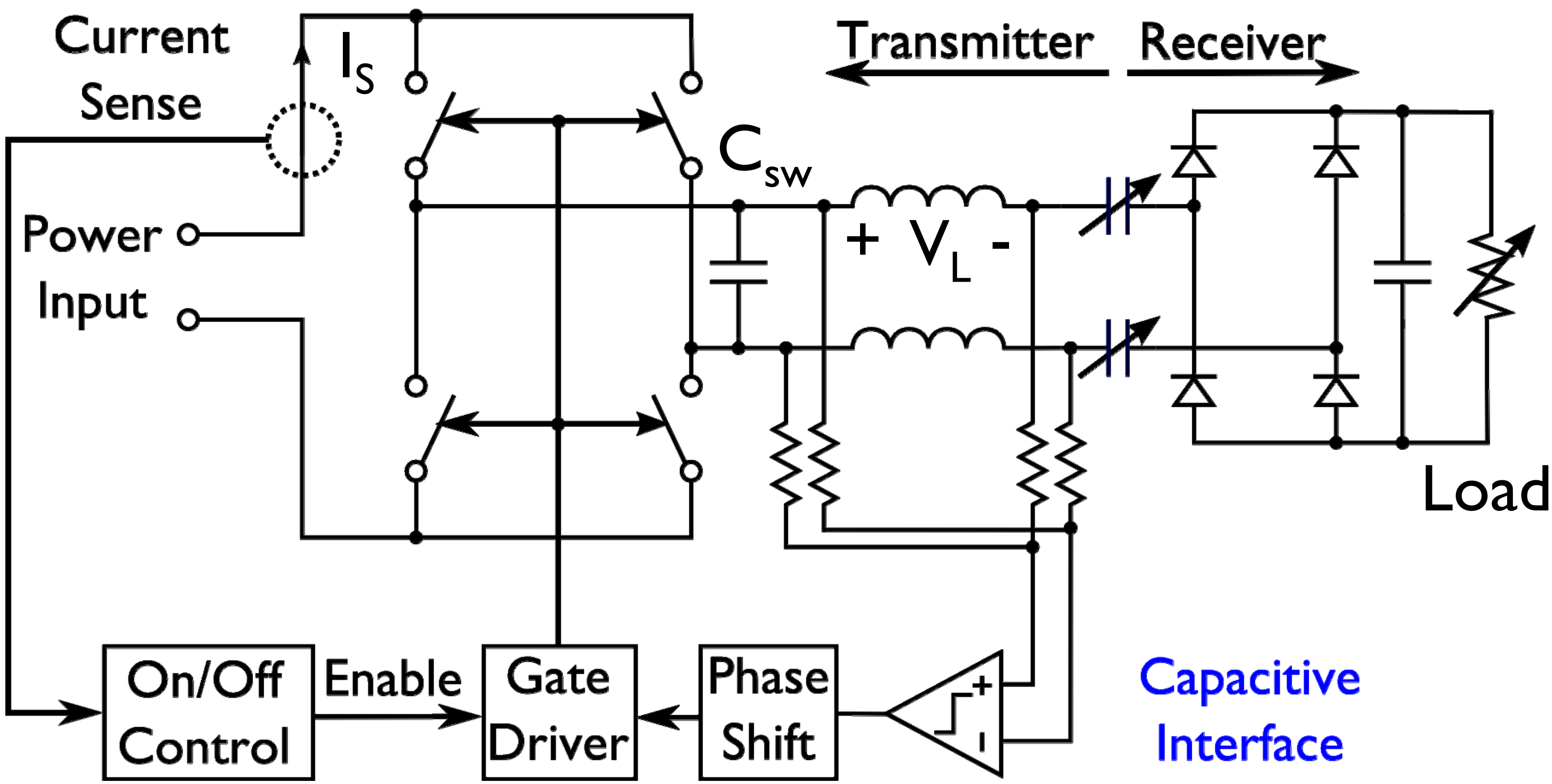
SHUTDOWN

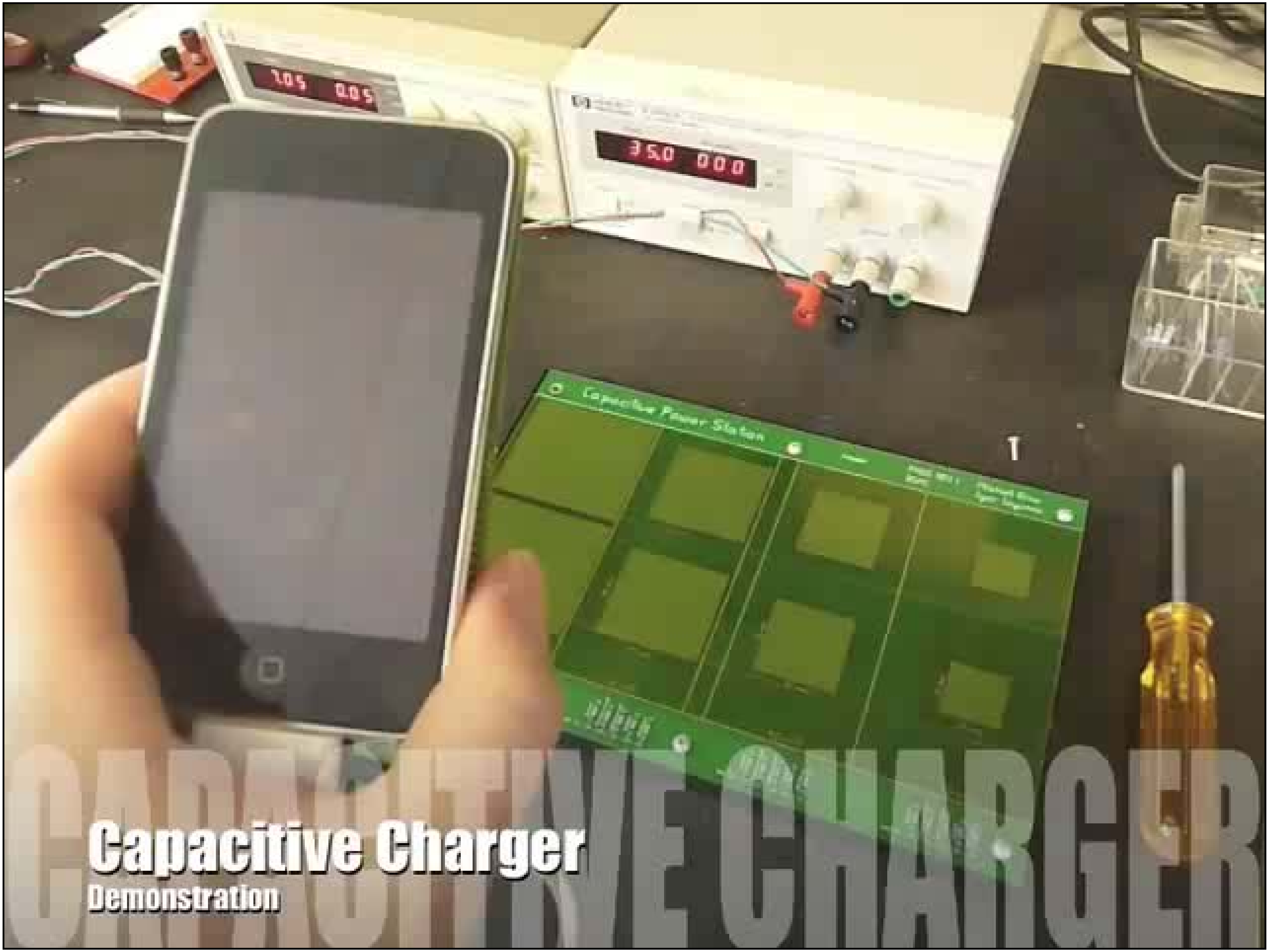
Supply Current

DC Output Voltage

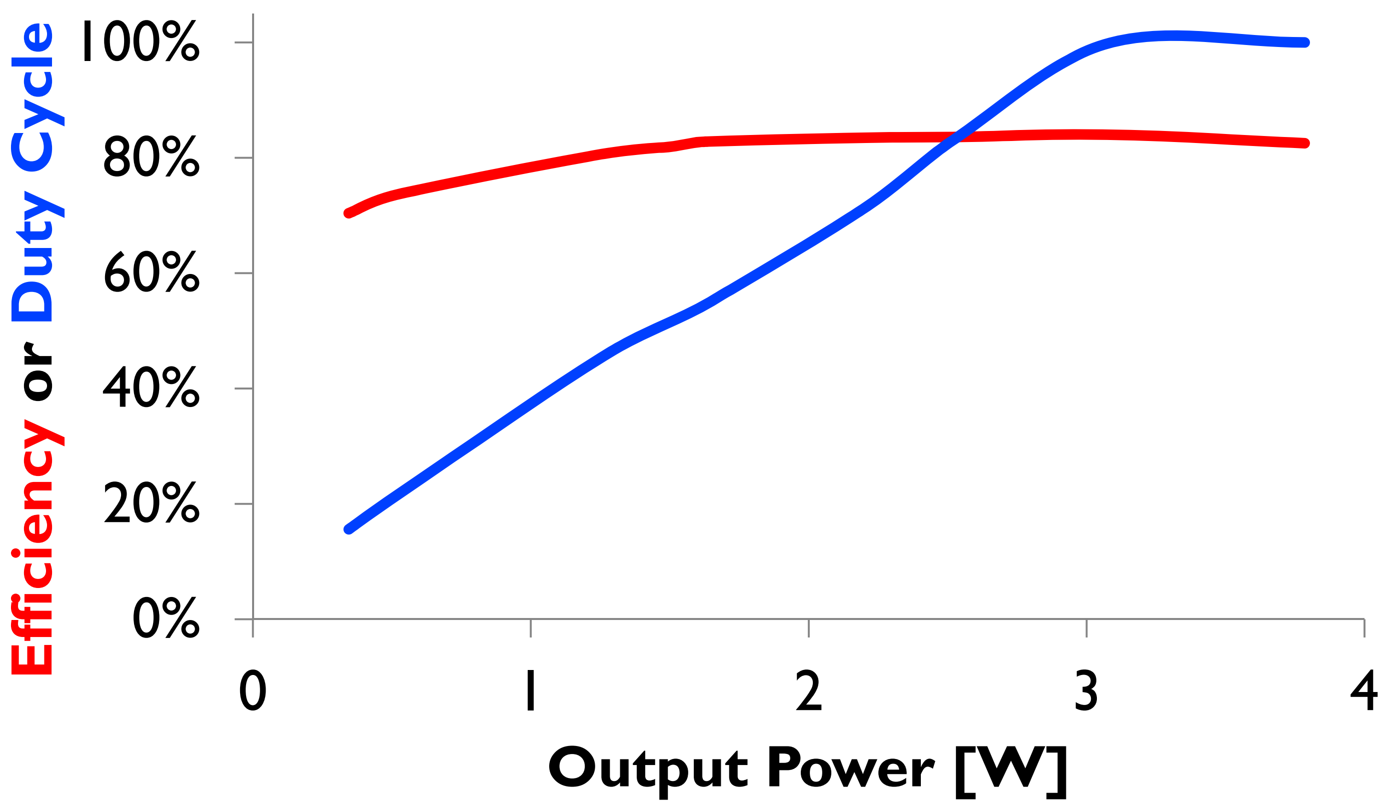


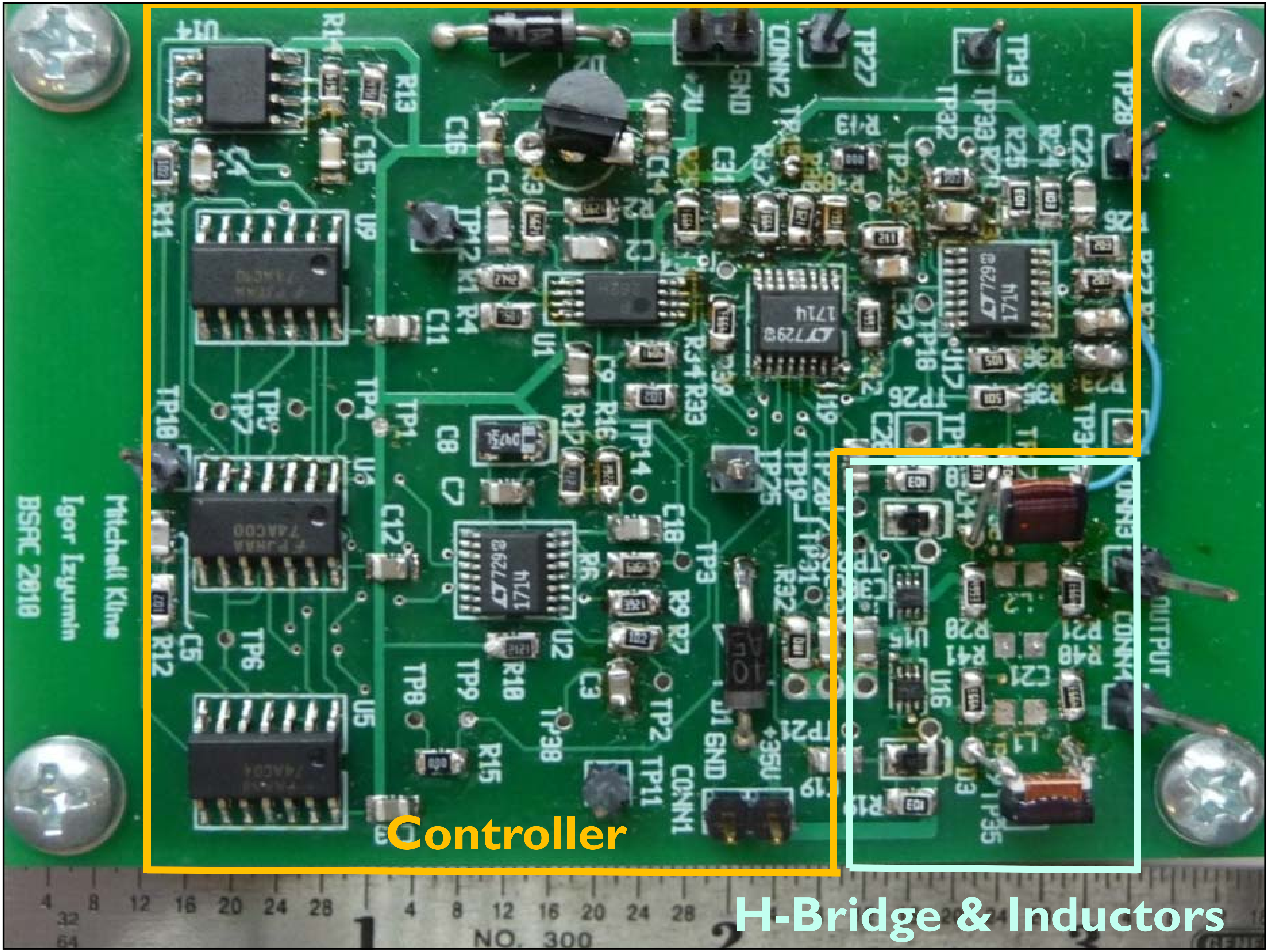
Capacitive Power Transfer System

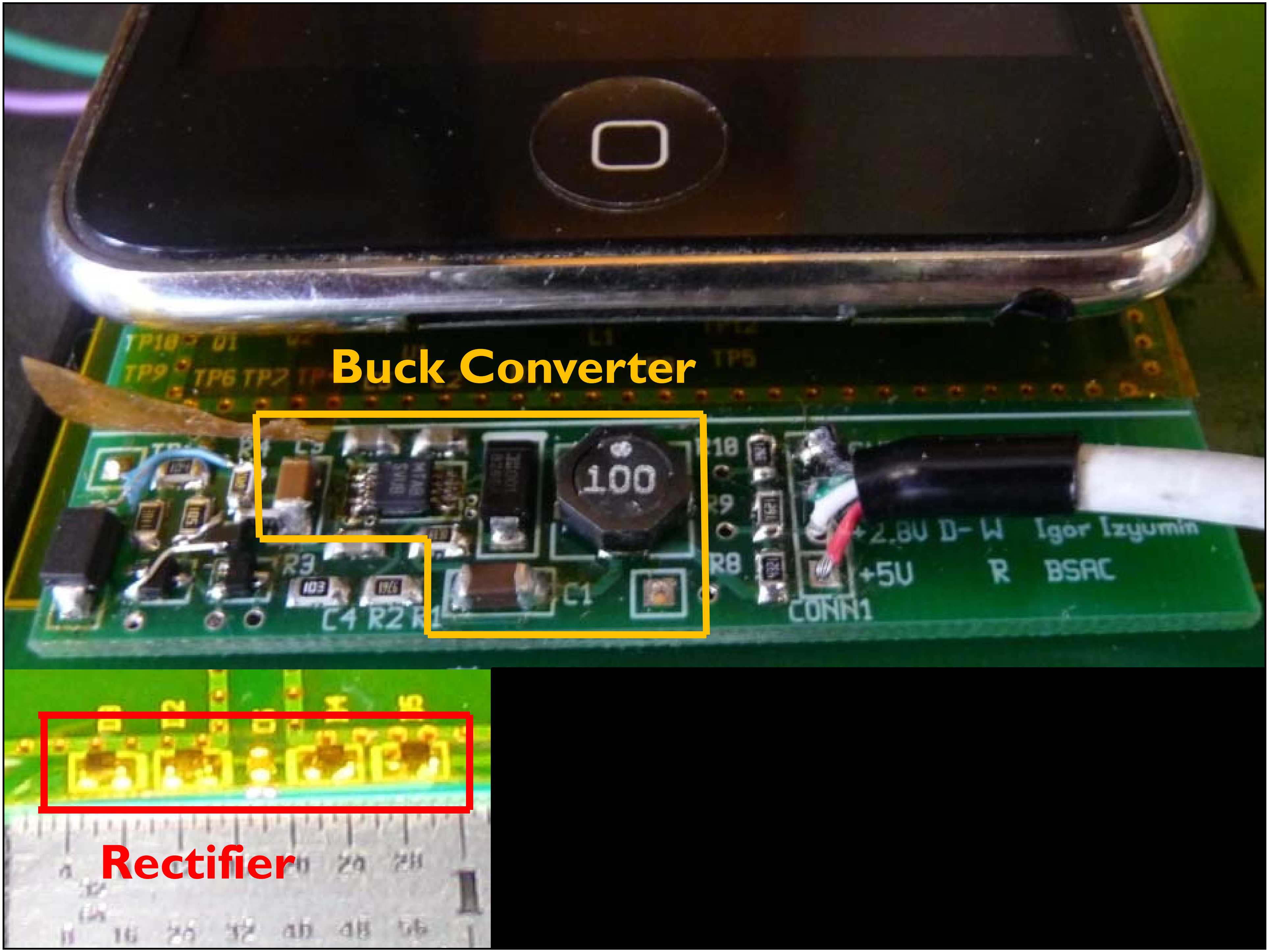



Capacitive Power Station
Capacitive Charger
Demonstration

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


Buck Converter
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

Thank You!

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