

The technology behind the world's smallest 12V, 10A voltage regulator

Reduced size with increased switching frequency and efficiency

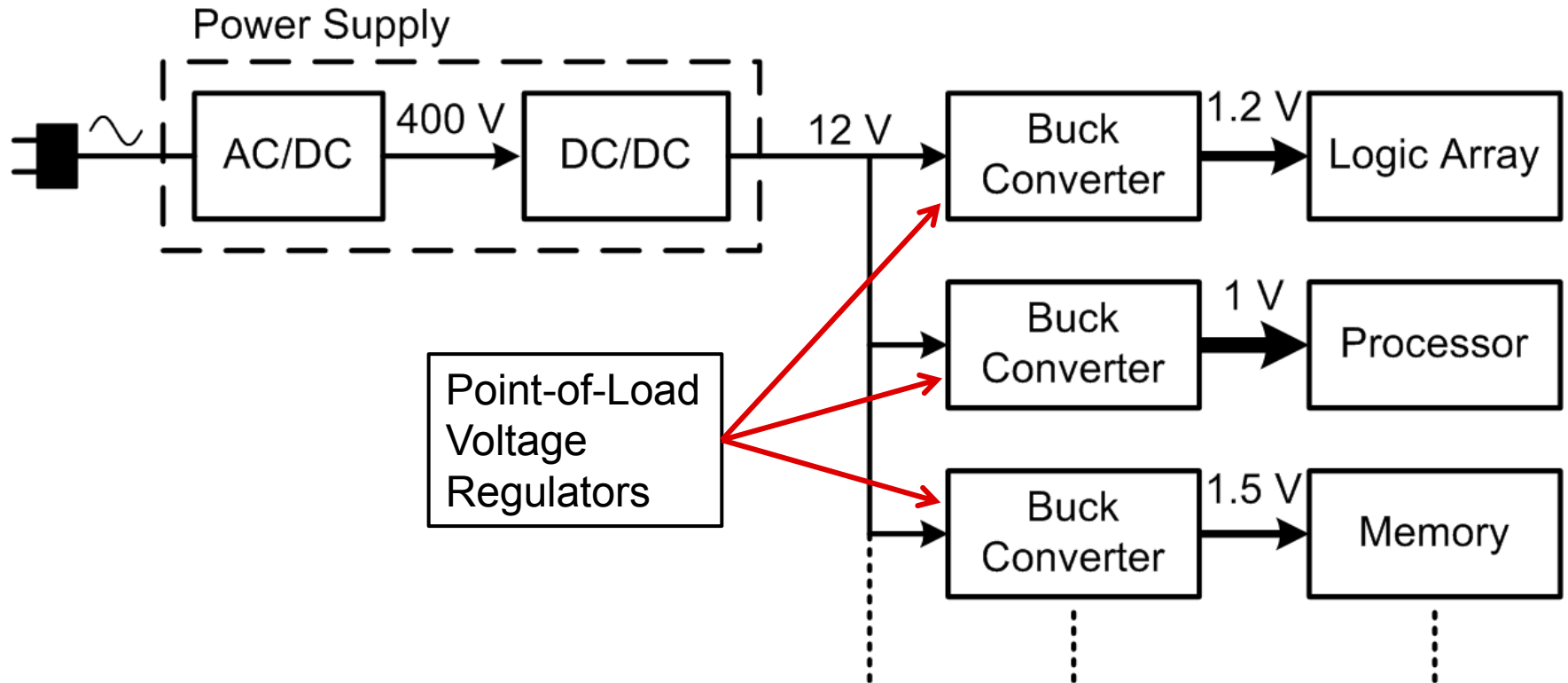
Pradeep Shenoy, Ph.D.

Systems Engineer, Texas Instruments

Applied Power Electronics Conference, March 17, 2016

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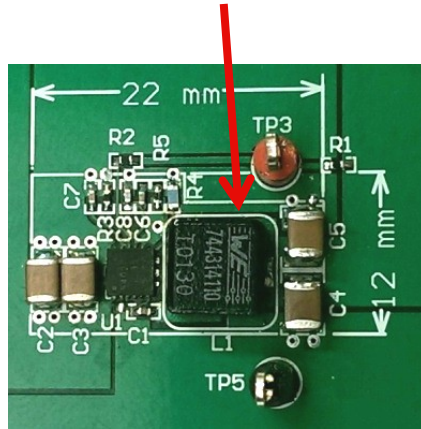
Power delivery system



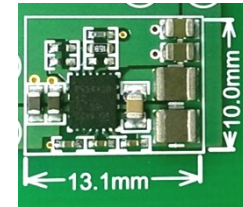
Point-of-load converters often have high voltage conversion ratios (10:1)

Why increase switching frequency?

Inductors are usually the largest component.



1) Smaller size



Converter volume: 1,270 mm³

Inductor volume: 232 mm³

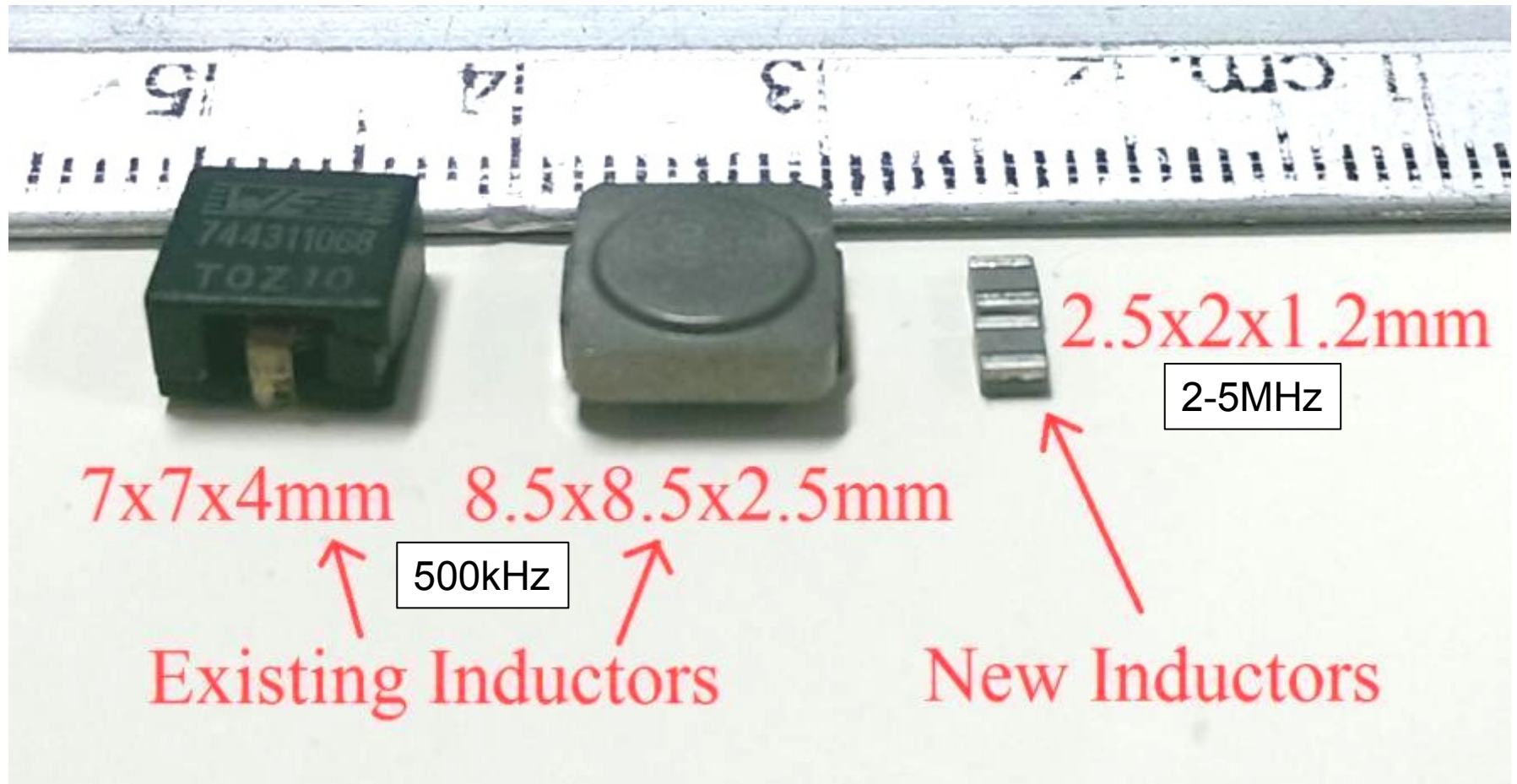
Converter volume: 157 mm³

Inductor volume: 19.2 mm³

2) Faster response

3) Lower BOM cost

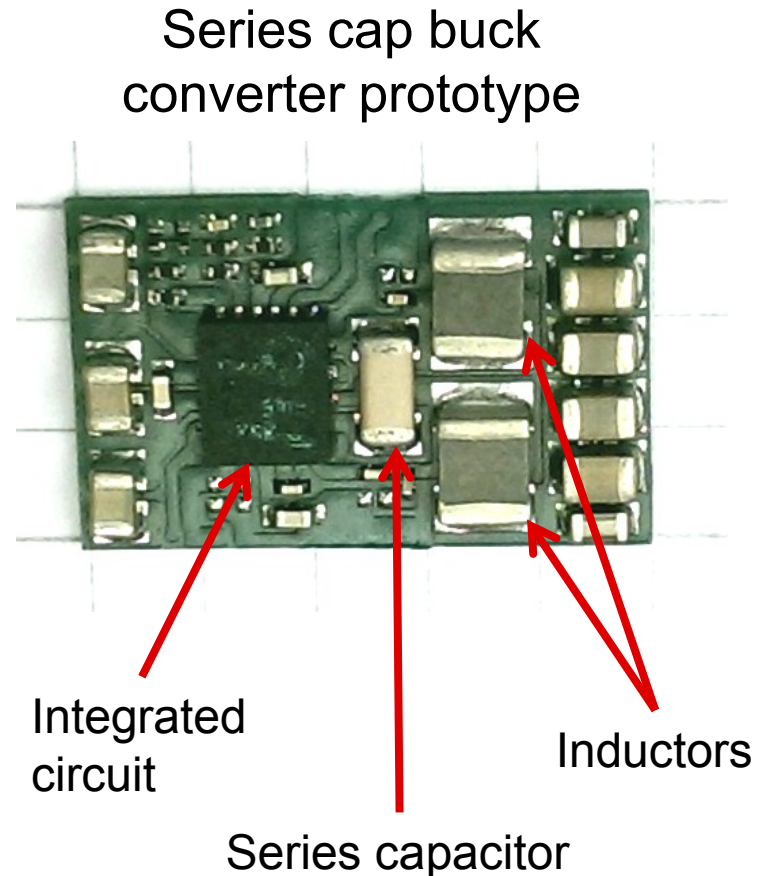
Inductor size reduction



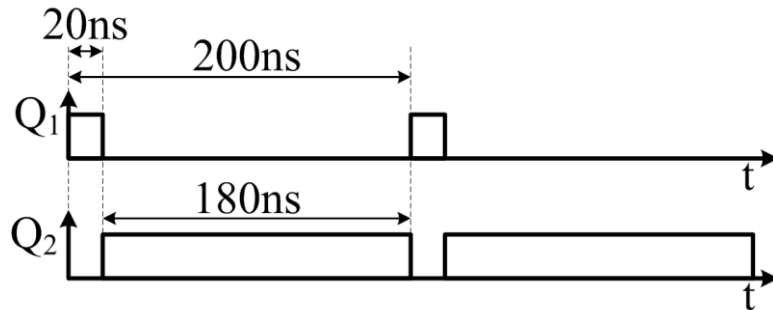
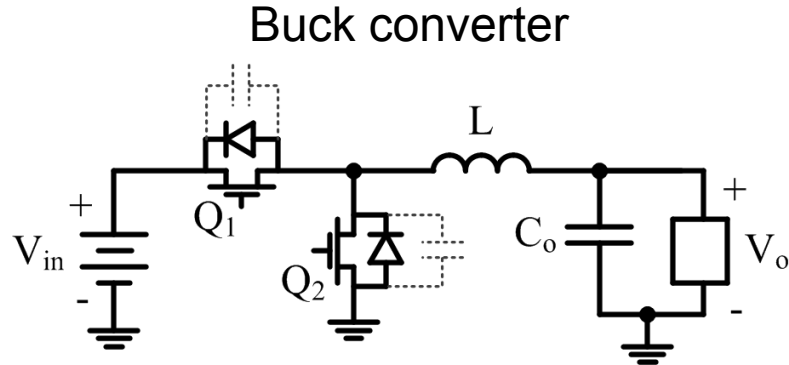
High frequency operation → 15 times smaller inductors!

Agenda

- High frequency buck converter limitations
- Series capacitor buck converter
- Example results
 - 12V in, 10A out application
- Size comparison



High frequency (HF) buck converter limitations



Switch timing diagram

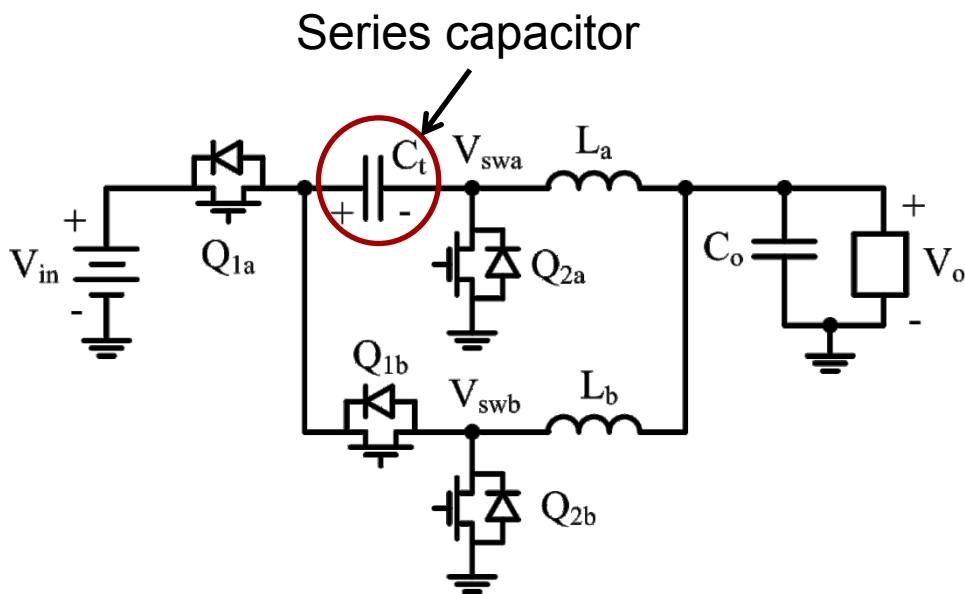
- High switching loss

$$P_{loss} \propto f_{sw}$$

- High side switch (Q_1) on-time is very short at HF
 - 5 MHz \rightarrow 200ns period
 - 10-to-1 voltage ratio
 \rightarrow 20ns high side on-time

HF converters on the market today have low conversion ratios (<5-to-1) and low current (<1A)

Series capacitor buck topology



Two-phase, series cap buck topology

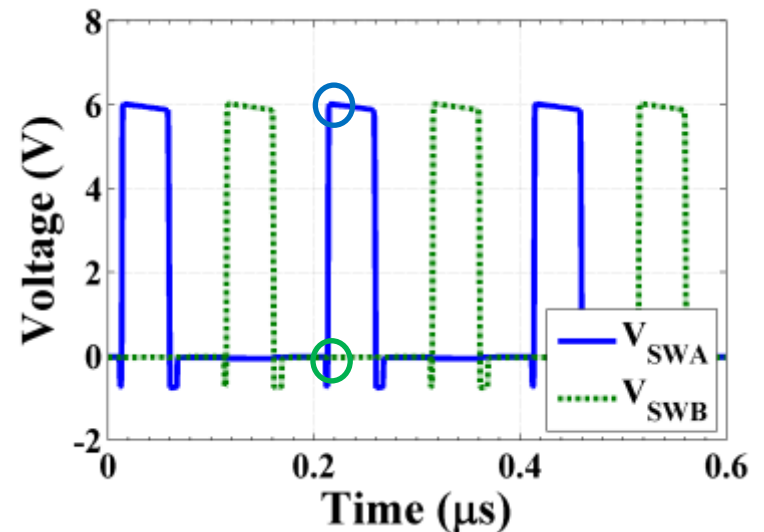
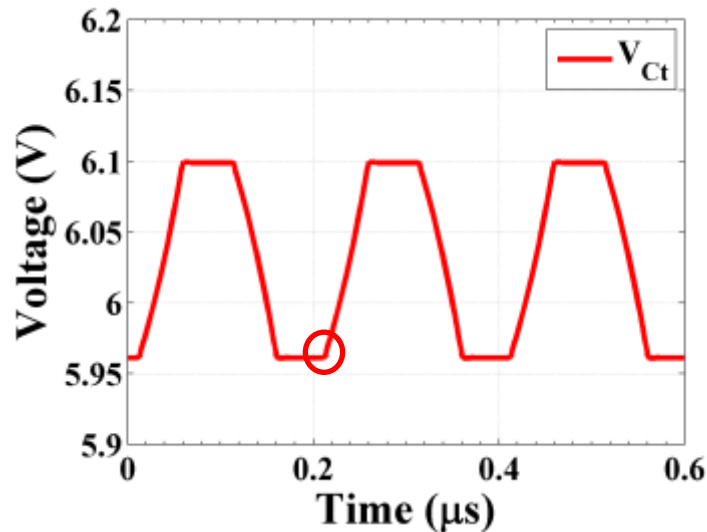
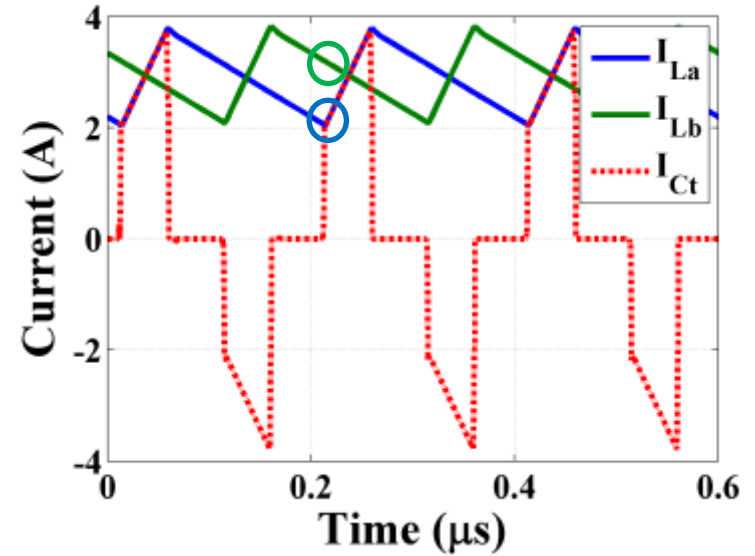
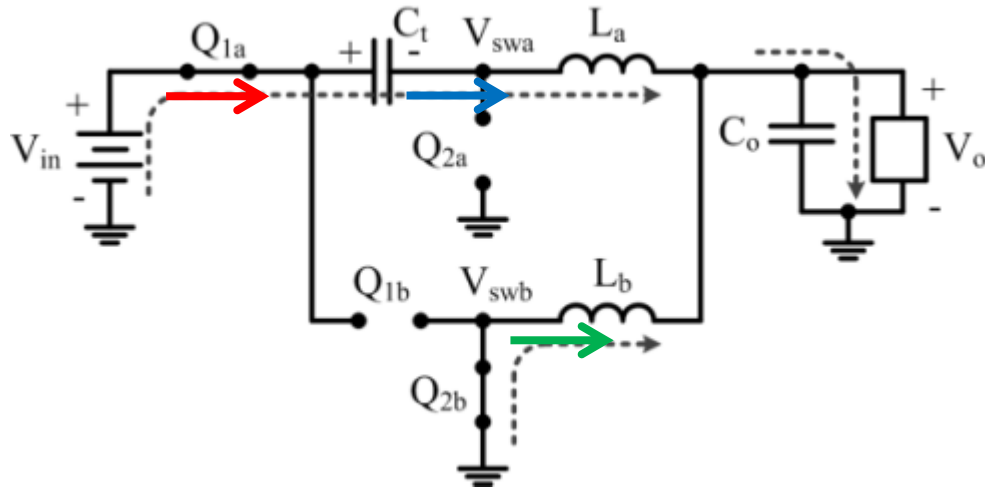
✓ Benefits

- ✓ Single conversion stage
- ✓ Lower switching loss
- ✓ Cap soft charge/discharge
- ✓ Auto current balancing
- ✓ On-time doubled

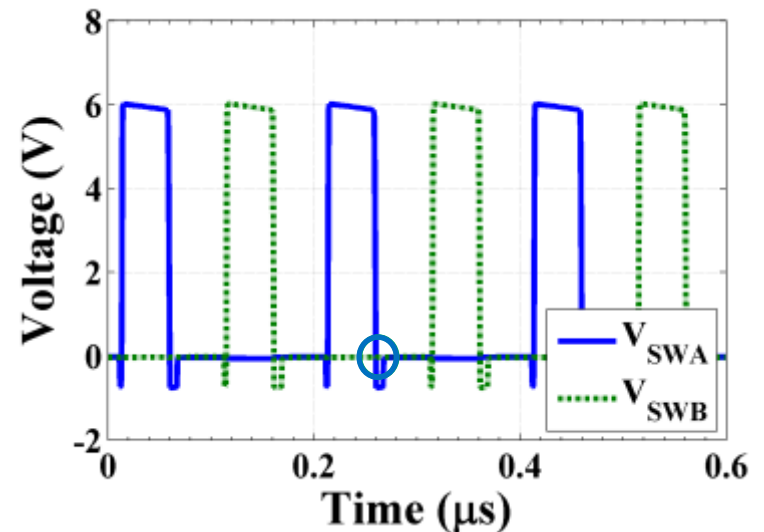
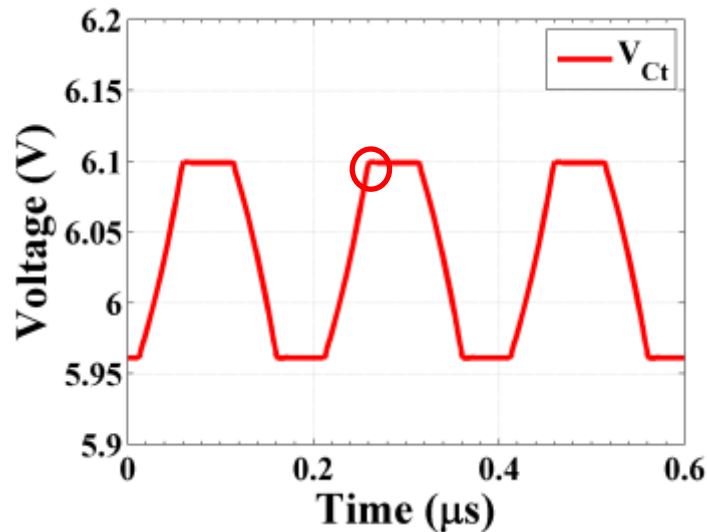
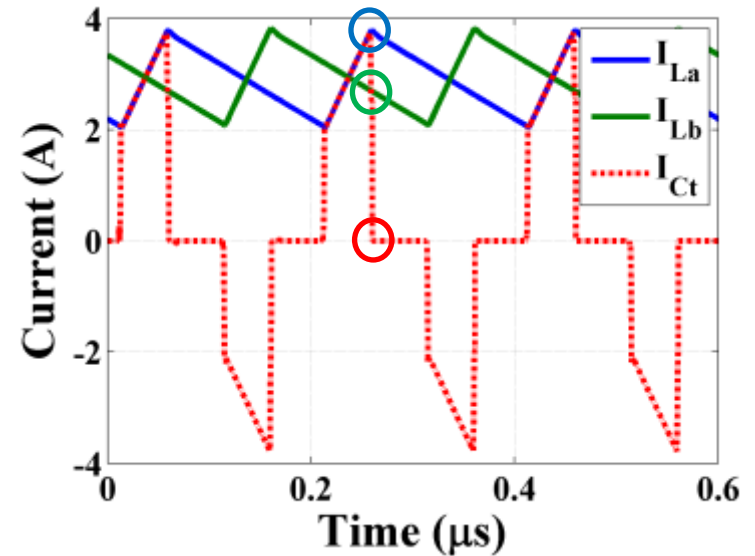
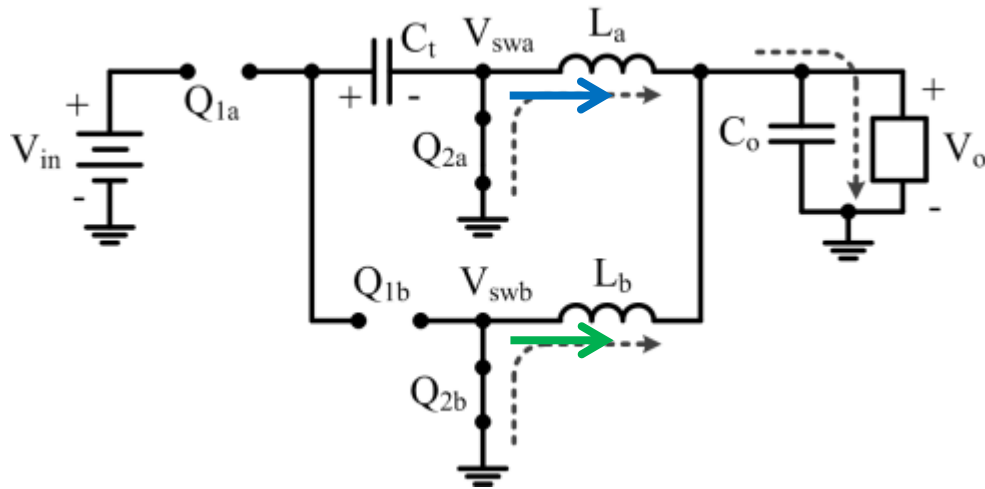
• Drawbacks

- 50% duty cycle limitation
 - Theoretical: $V_{in,min} = 4 \times V_{out}$
 - Practical: $V_{in,min} = 5 \times V_{out}$

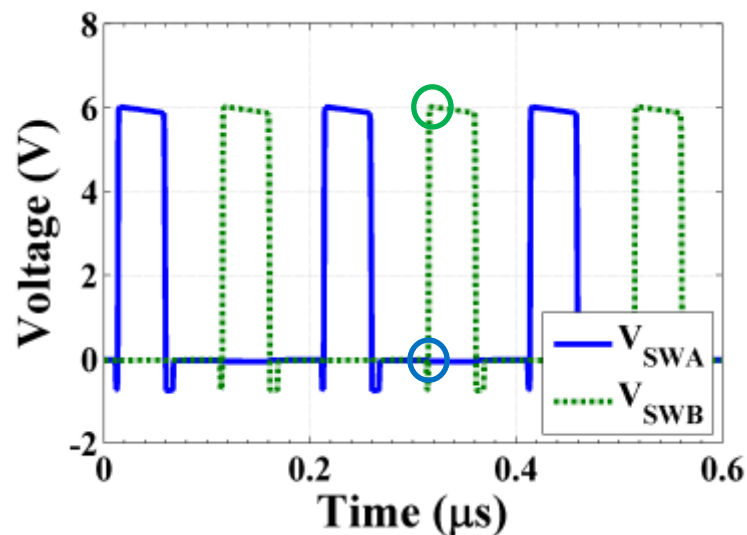
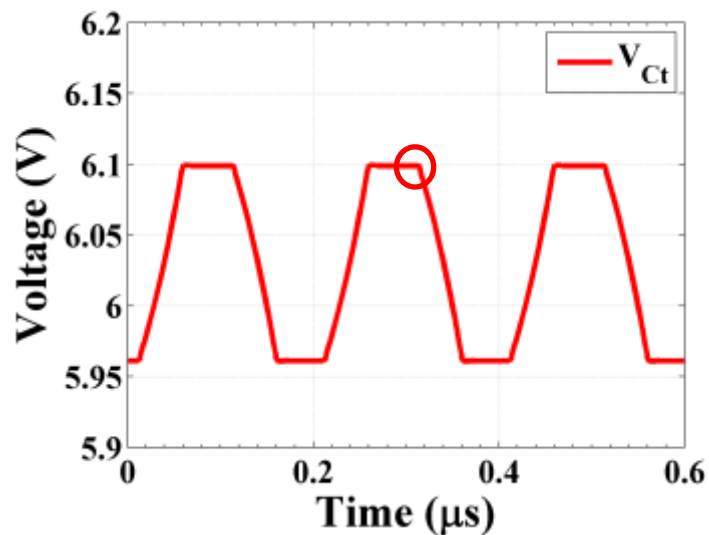
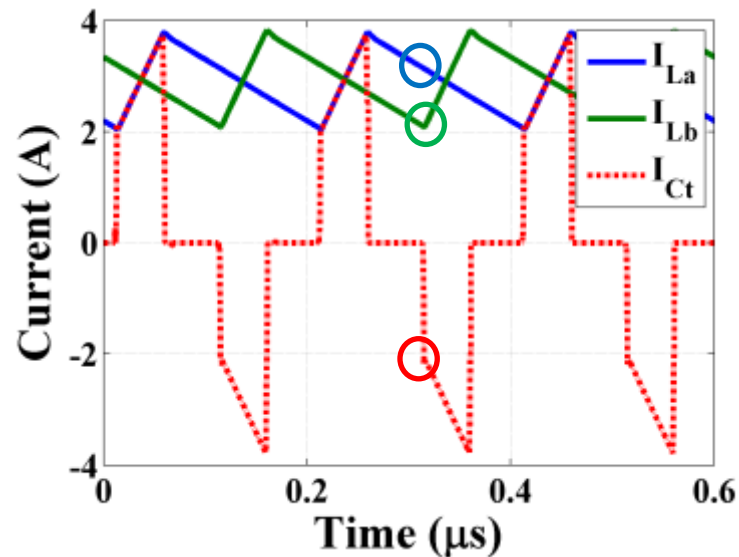
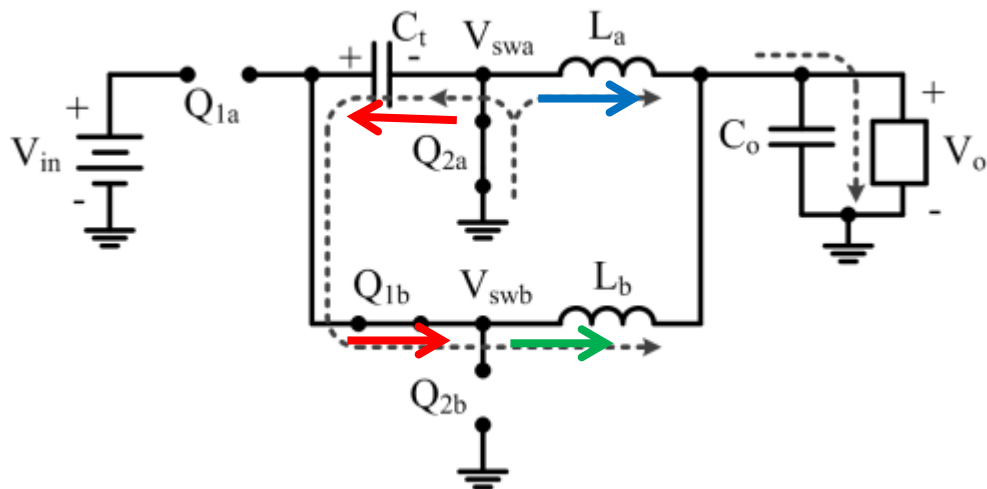
Steady-state operation: Step 1



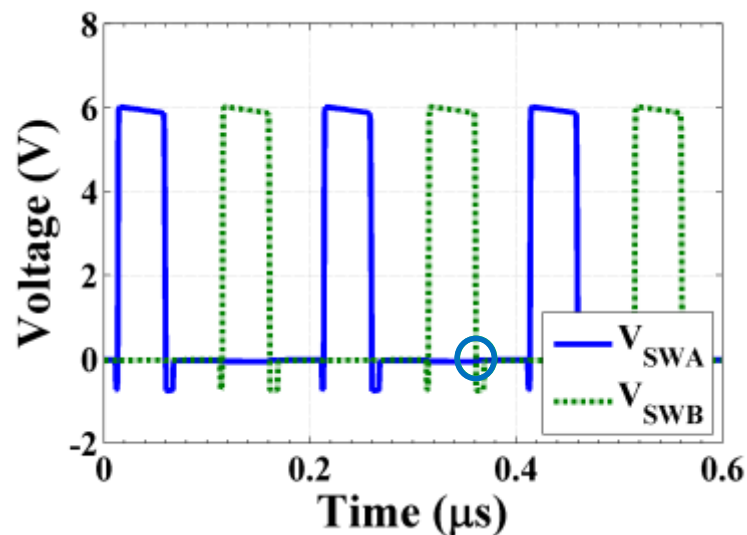
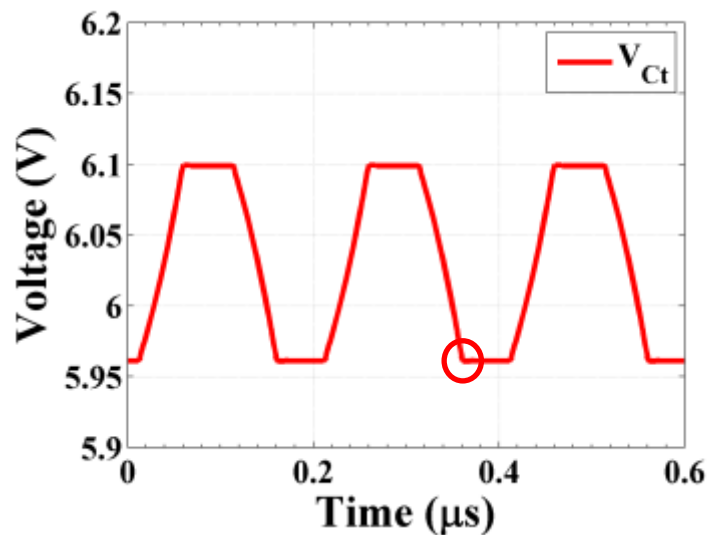
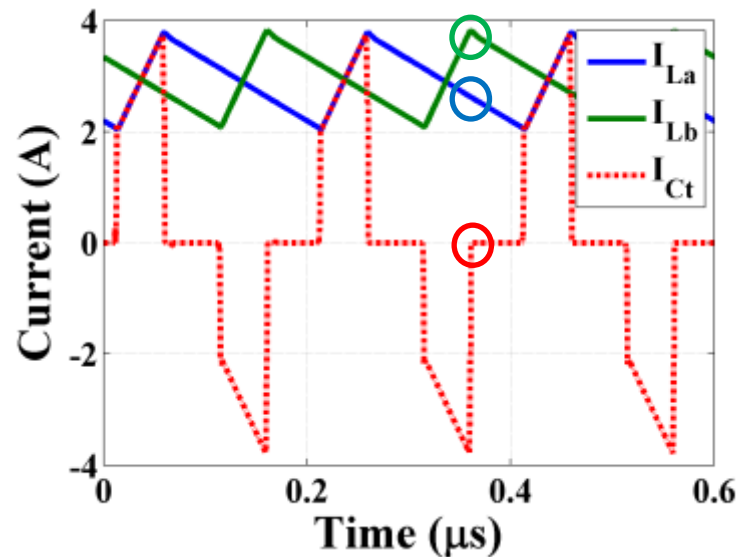
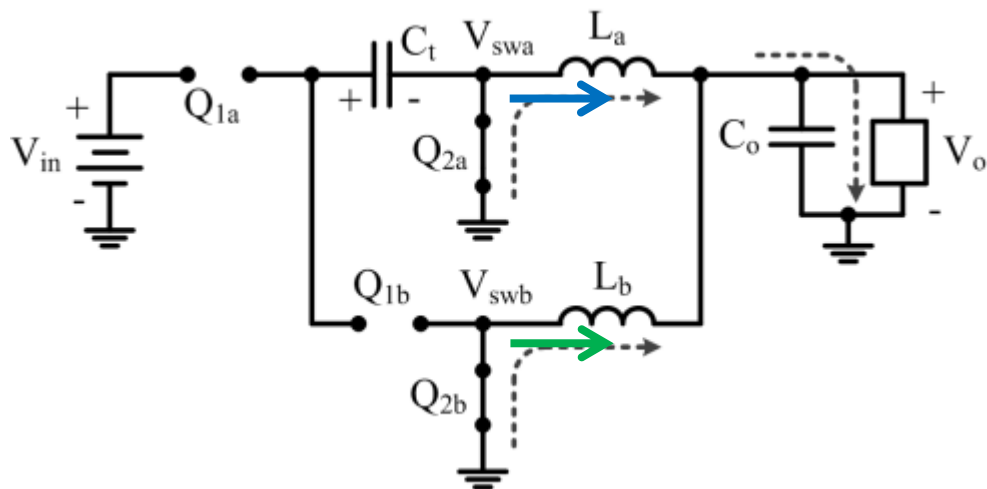
Steady-state operation: Step 2



Steady-state operation: Step 3

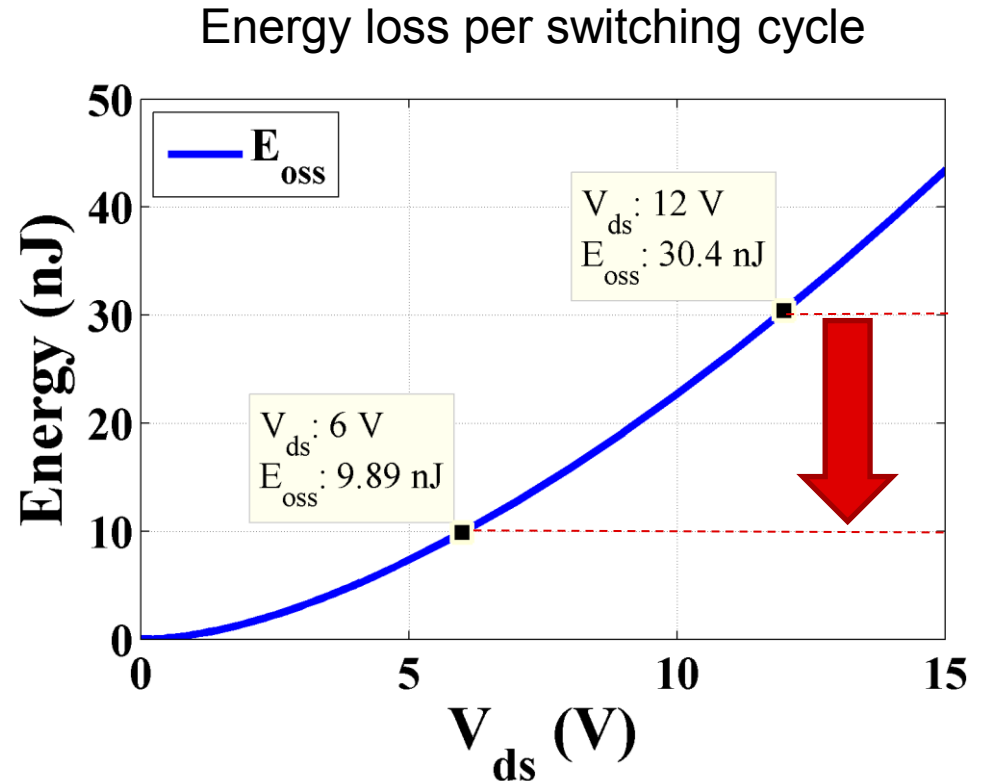


Steady-state operation: Step 4



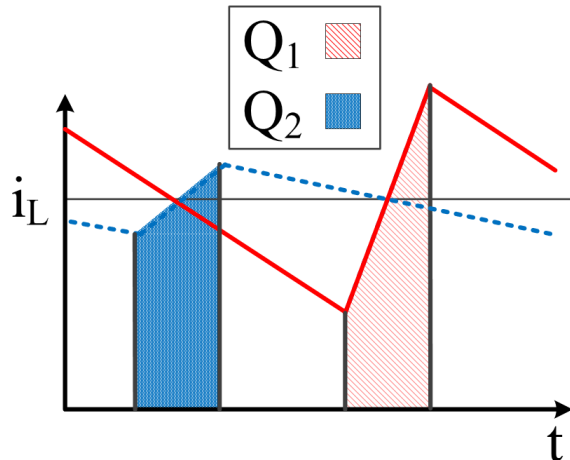
Reduced switching loss

- Reduced switch voltage/current overlap loss
- Loss due to switch output capacitance reduced by 67%
- Enables higher frequency operation

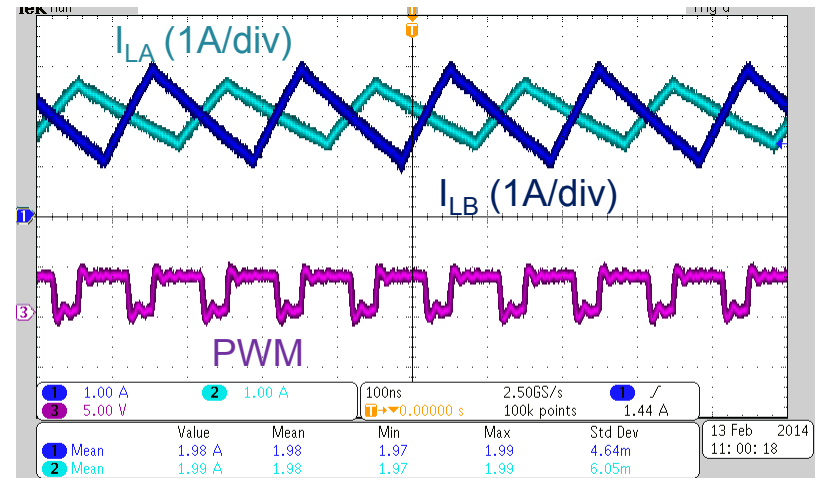
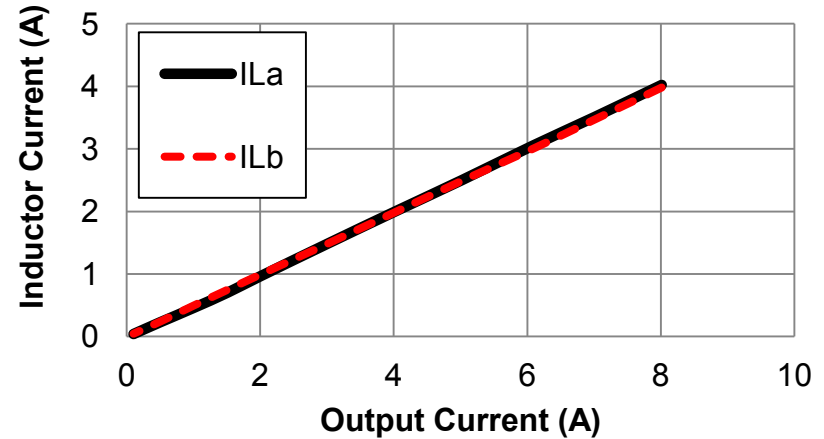


Auto current sharing

- Series capacitor forms current feedback mechanism
- Robust to variations in L , DCR
- No sensing/control loops



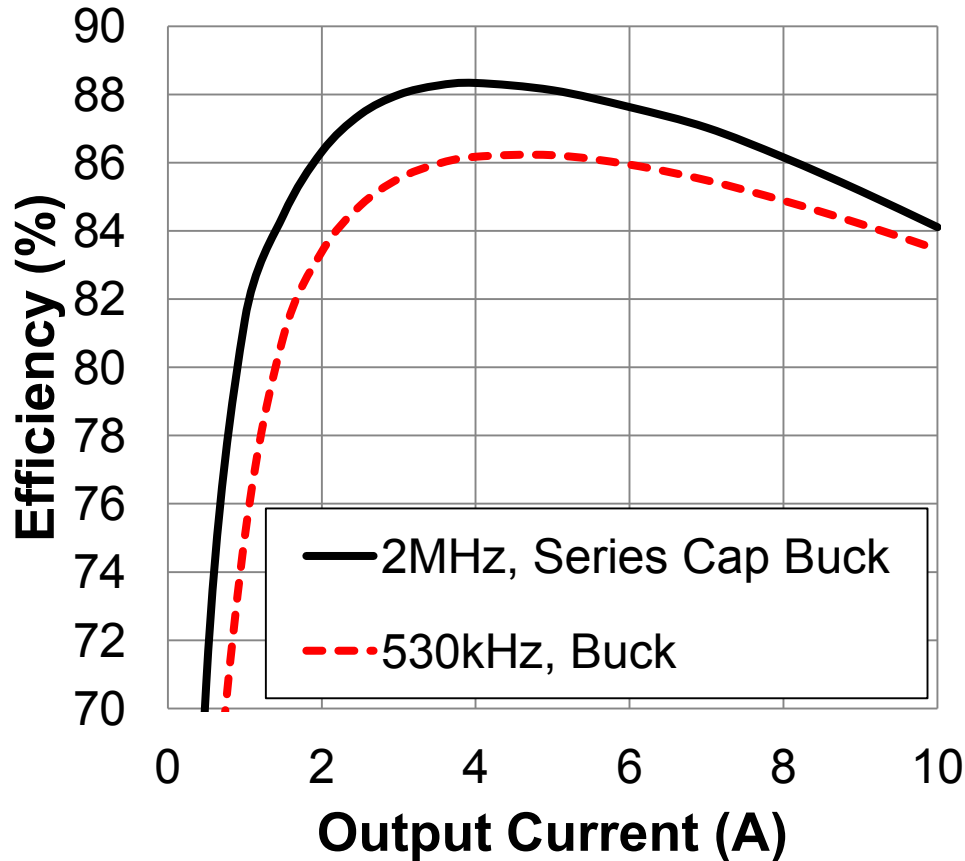
Current sharing: $L_a \approx 100\text{nH}$, $L_b \approx 200\text{nH}$



1) I_{LB} , 2) I_{LA} , 3) PWM, $V_o=1.8\text{V}$, $I_o=4.0\text{A}$

P.S. Shenoy, et al., "Automatic current sharing mechanism in the series capacitor buck converter," in *Proc. IEEE Energy Conversion Conf. Expo.*, Sept. 2015.

Measured efficiency comparison

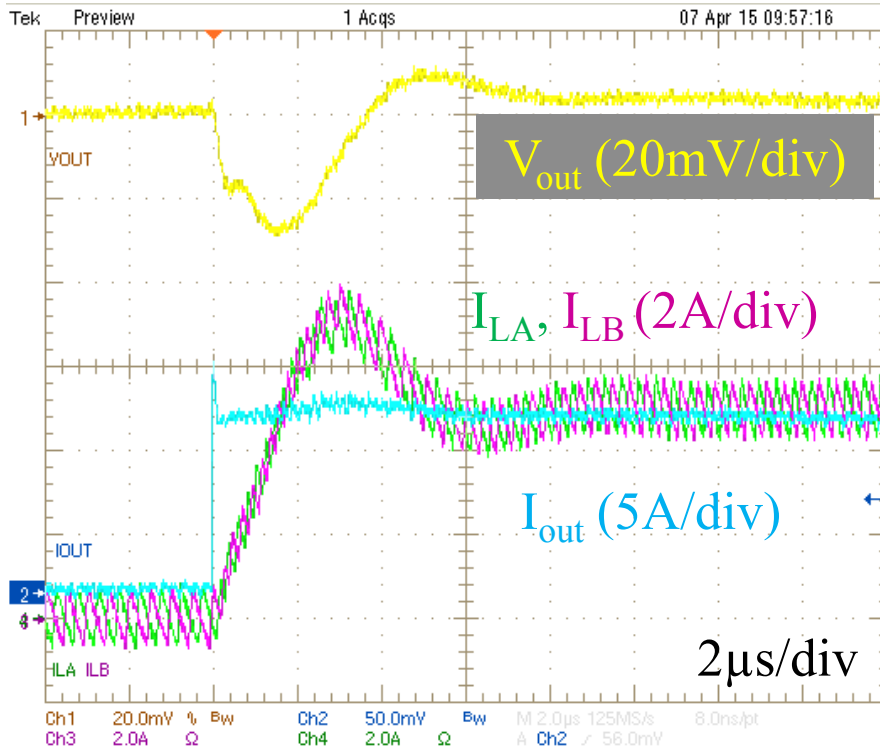


- Conditions:
 - 12V in, 1.2V out
 - Room temperature, no air flow
- Higher efficiency over the load range
- Inductors selected for equivalent DCR

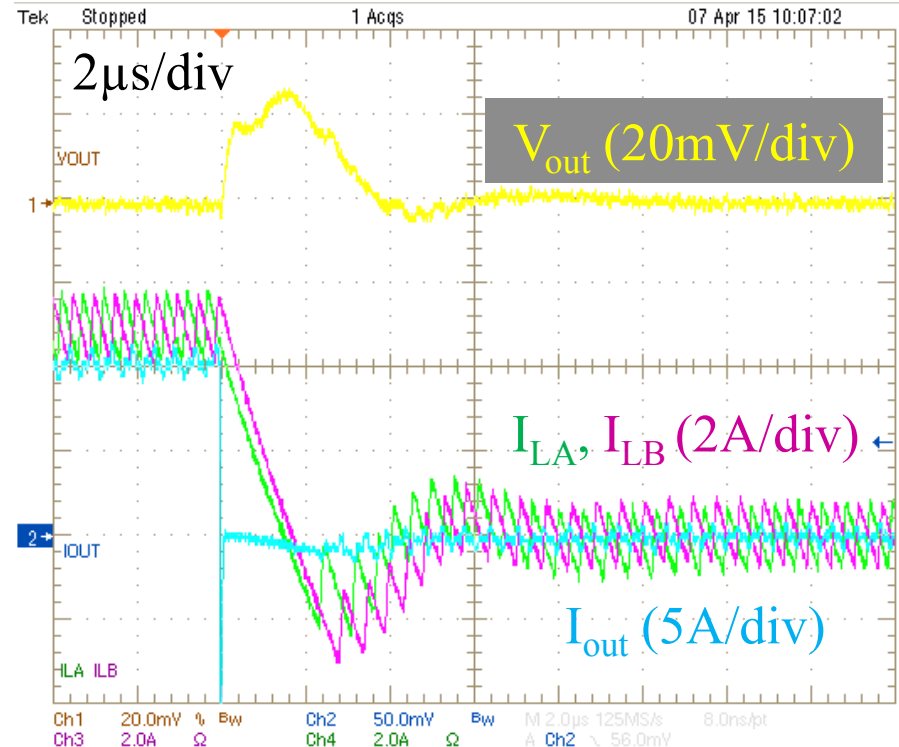
Higher efficiency at ~4 times the switching frequency

Fast load transient response

Load step up



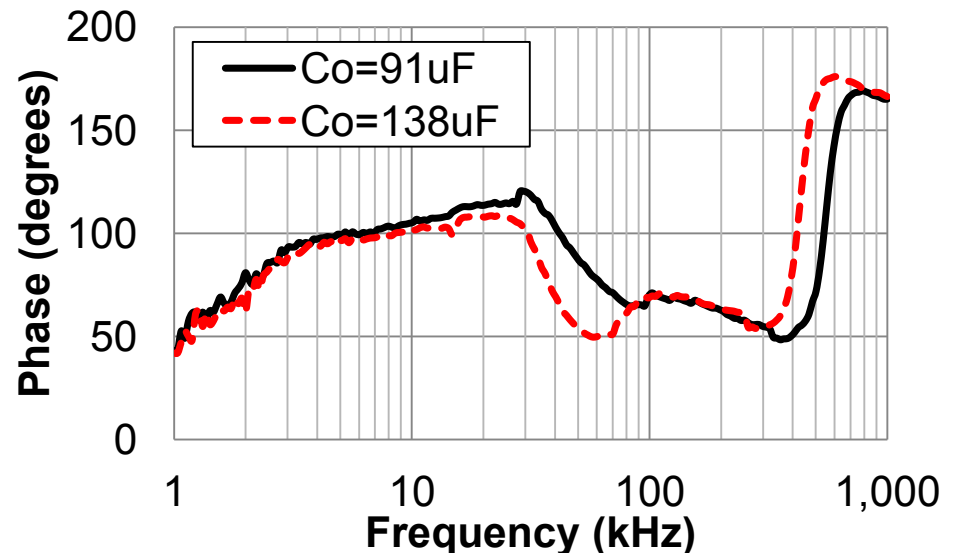
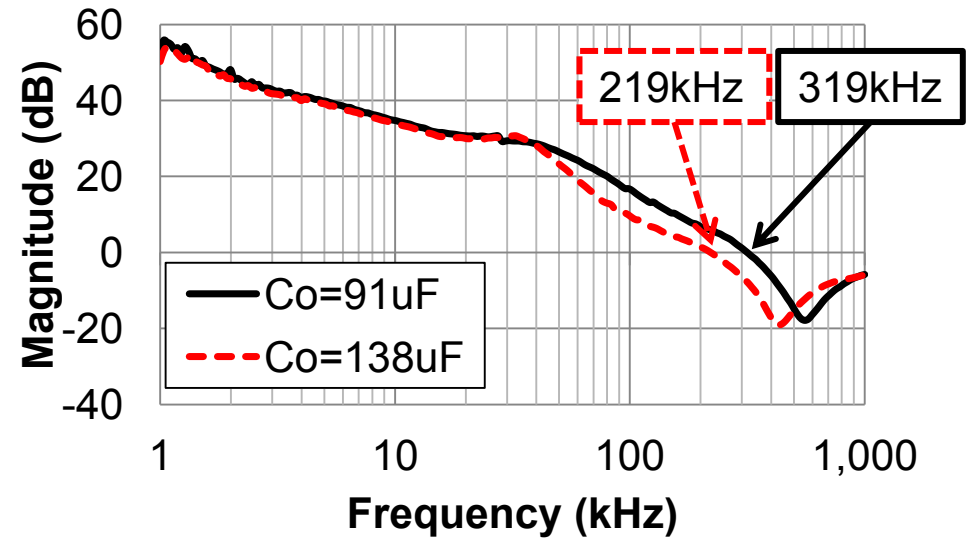
Load step down



- 12V in, 1.0V out; 500A/μs full load steps; 2MHz per phase
- Deviation in V_{out} < 25mV; Settling time < 4μs
- Excellent dynamic current sharing

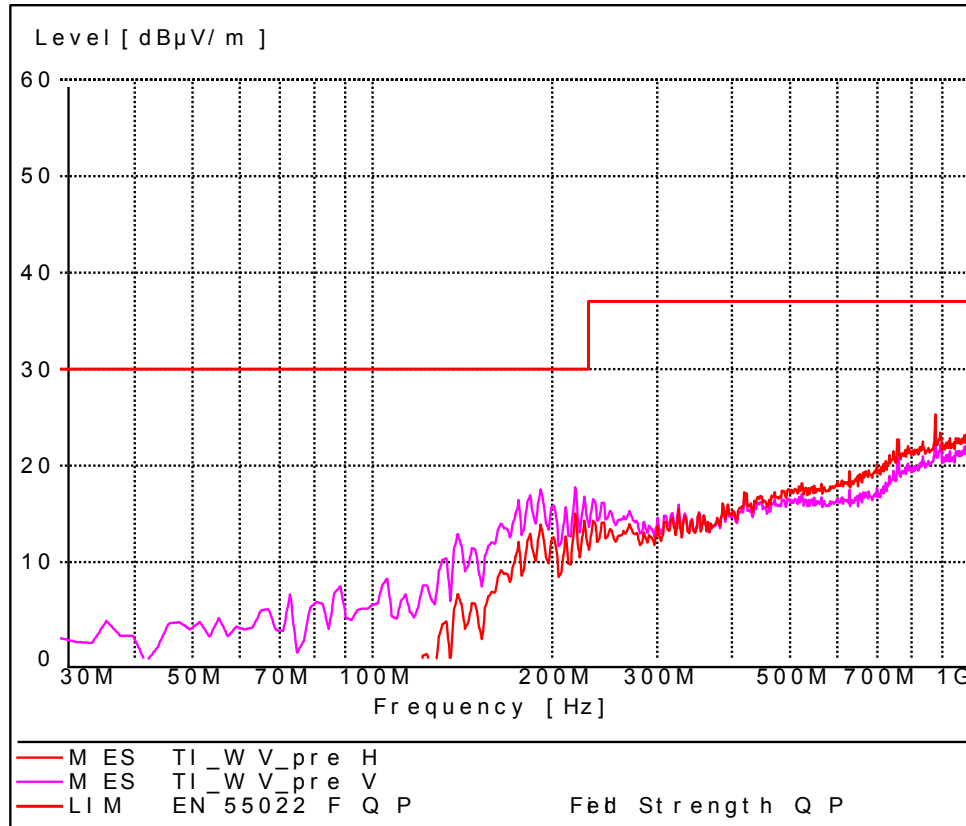
Closed loop performance

- Conditions:
 - 12V in, 1.2V out
 - 2.5A load
 - Room temperature
- High bandwidth
 - Over 200kHz crossover frequency
- Stable
 - Over 45 degrees phase margin



Electromagnetic Interference (EMI)

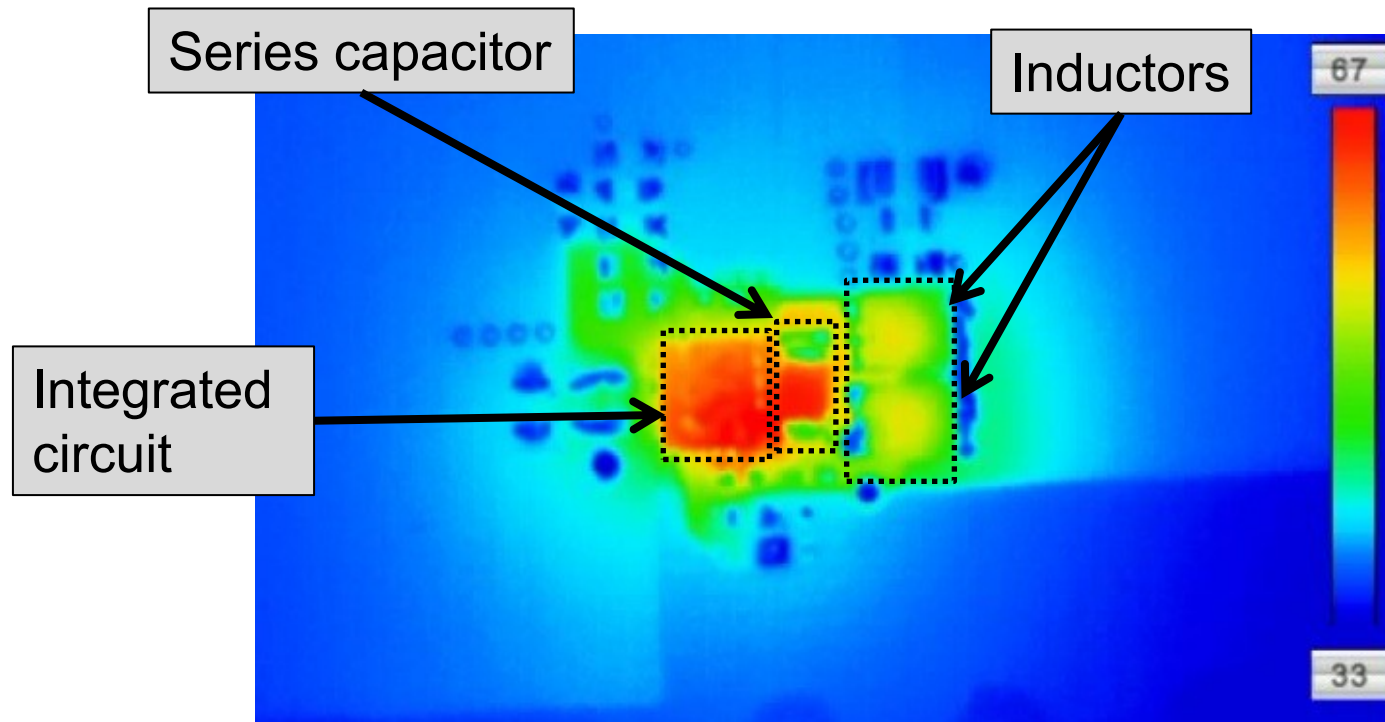
12V in, 1.2V out, 10A load, no snubber



Passes CISPR Class B Standard

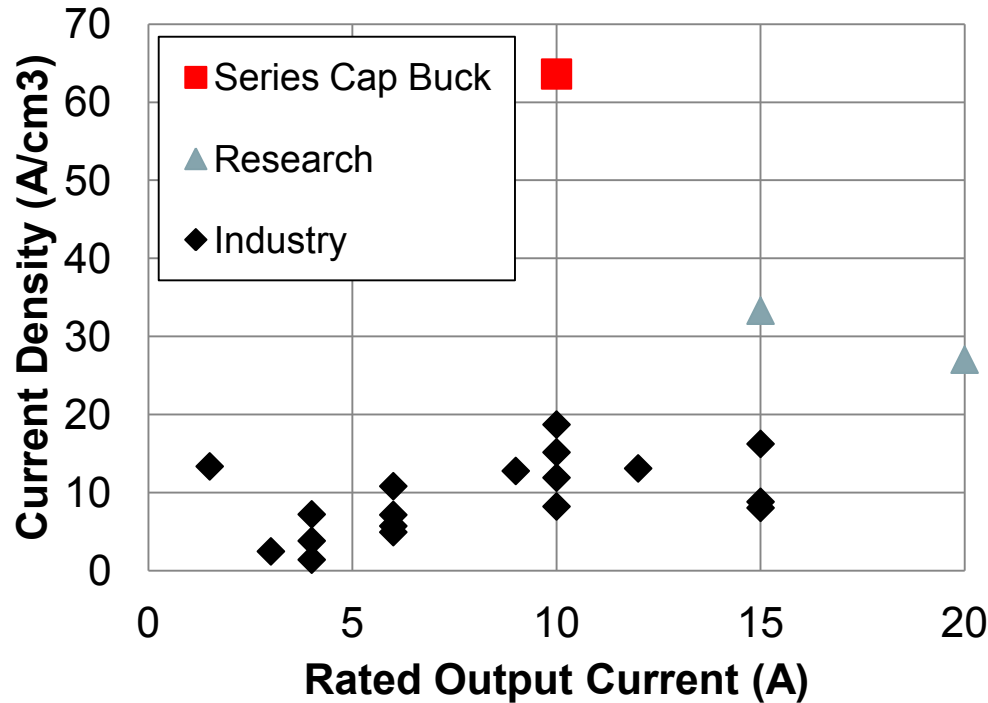
Where's the heat?

12V in, 1.2V out, 10A, room temperature, no air flow



The inductors are (still) not the thermal bottleneck

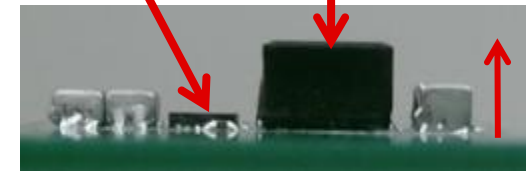
Current density comparison



Series cap buck: 1.2mm height



IC Inductors



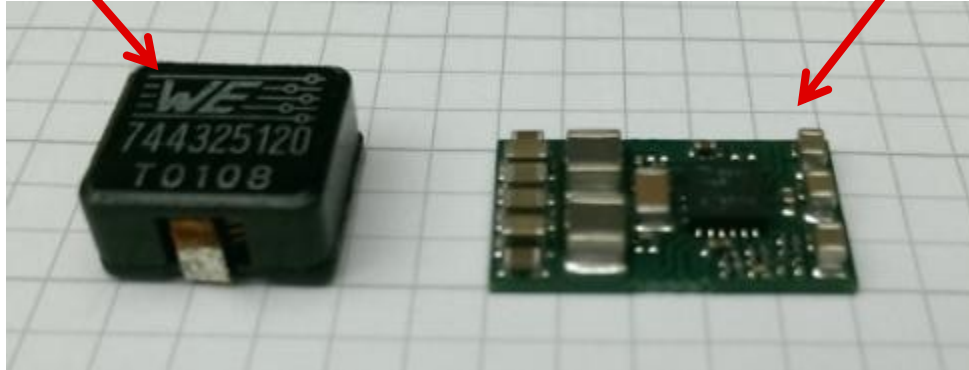
Buck: 4.8mm height

A 3x to 7x improvement in total solution current density

Series capacitor buck total solution size

10A inductor for a regular buck
 $10.2 \times 10.2 \times 4.7 \text{mm} = 489 \text{mm}^3$

10A series cap buck prototype
 $16 \times 10 \times 1.85 \text{mm}^* = 296 \text{mm}^3$



*Includes
PCB
thickness

The series capacitor buck converter is 40% smaller than the inductor alone on a 10A buck evaluation board!

Summary

- Buck converters have fundamental limitations.
- An HF **series capacitor buck converter** has been demonstrated for a 12V in, 10A out application.
 - High efficiency, fast transient response, low EMI
 - Inductor size is **15 times smaller**
 - Current density **over 50A/cm³**
 - Power density at 1.2V out is **1.25kW/in³**
- No compound semiconductors (GaN, GaAs, etc.) or special magnetics are needed!

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