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

Reduced size with increased switching frequency and efficiency

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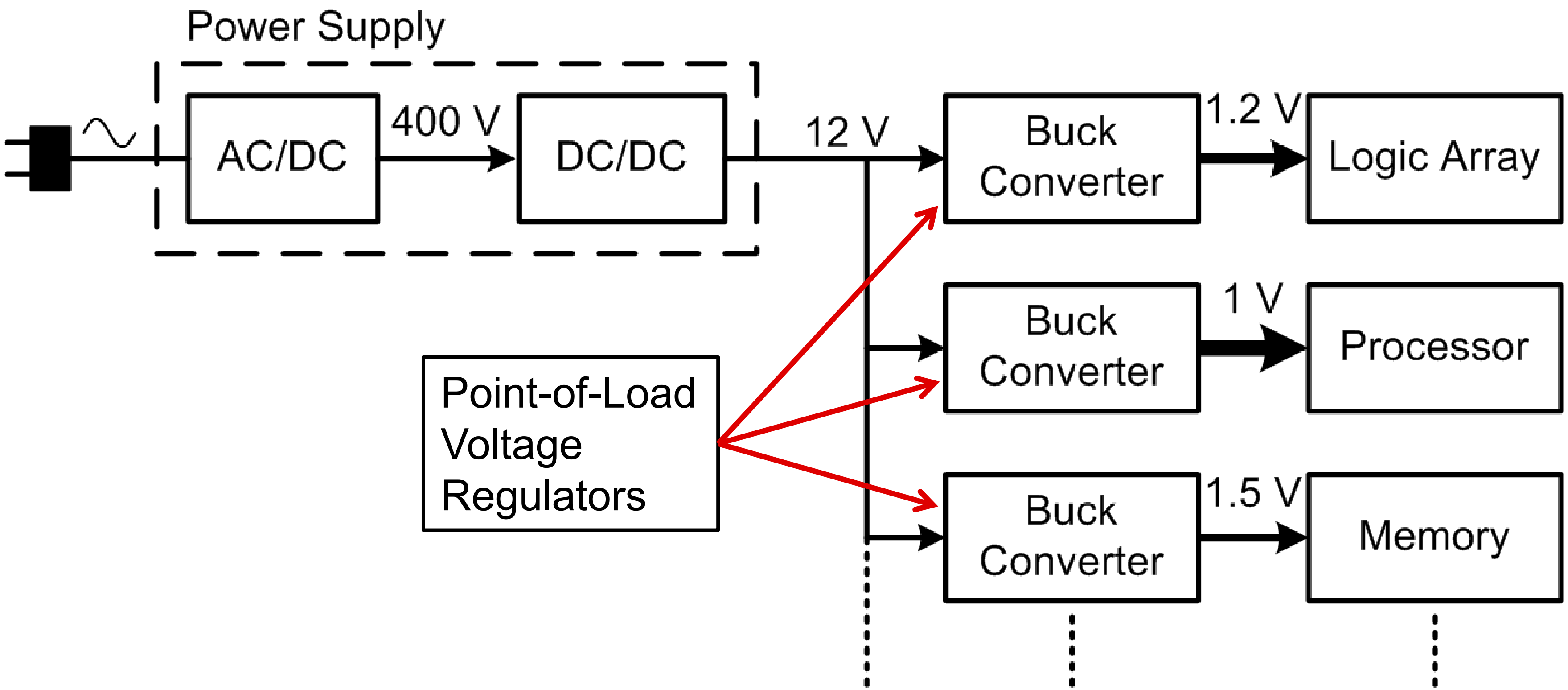
SLYY088

Texas Instruments

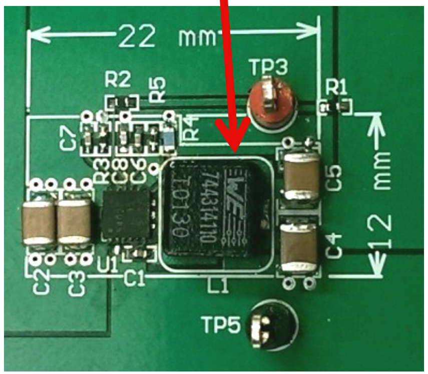
Power delivery system



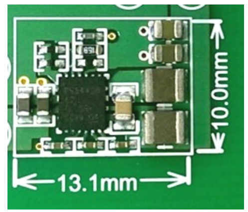
Point-of-load converters often have high voltage conversion ratios (10:1)

Why increase switching frequency?

Inductors are usually the largest component.



1) Smaller size



Converter volume: 1,270 mm^3

Inductor volume: 232 mm^3

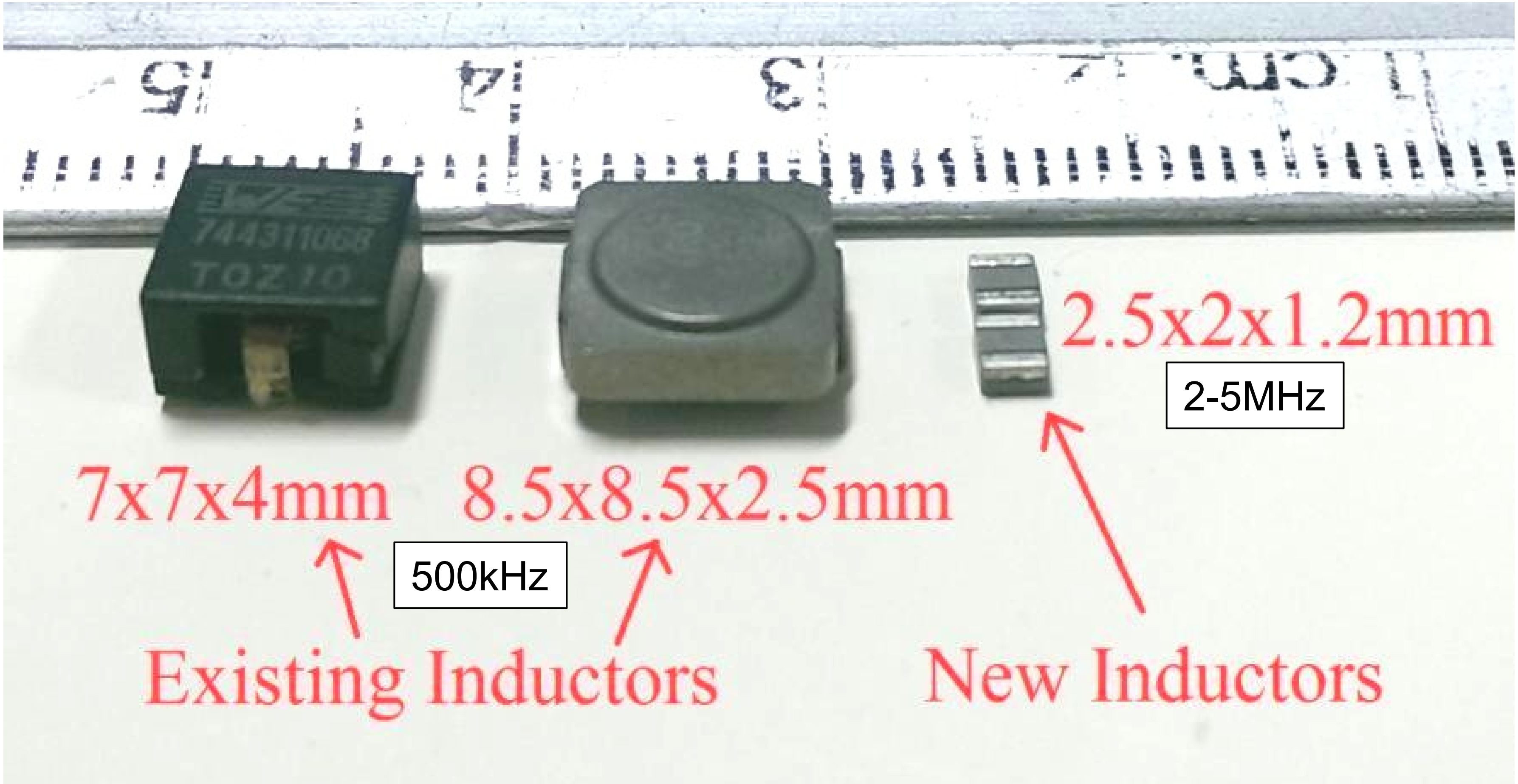
Converter volume: 157 mm^3

Inductor volume: 19.2 mm^3

2) Faster response

3) Lower BOM cost

Inductor size reduction

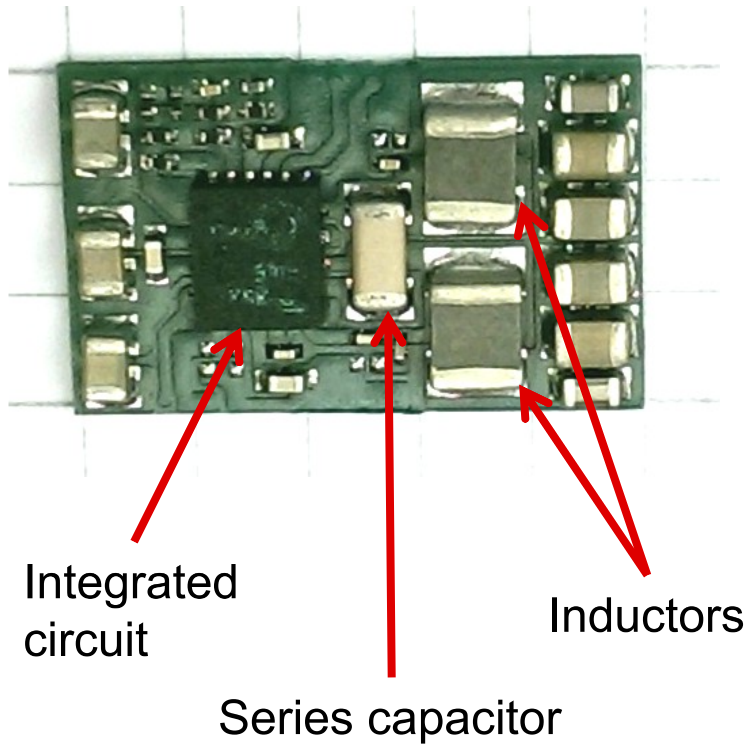


High frequency operation → 15 times smaller inductors!

Agenda

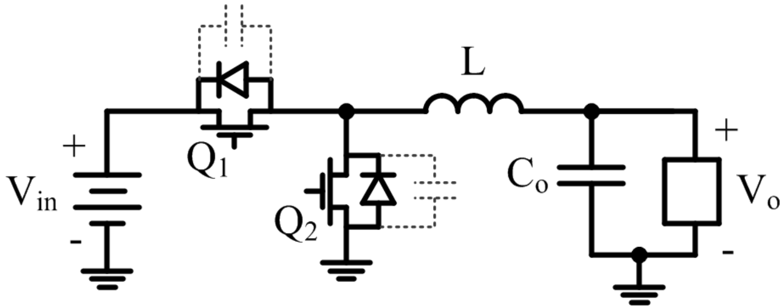
- High frequency buck converter limitations
- Series capacitor buck converter
- Example results
  - 12V in, 10A out application
- Size comparison

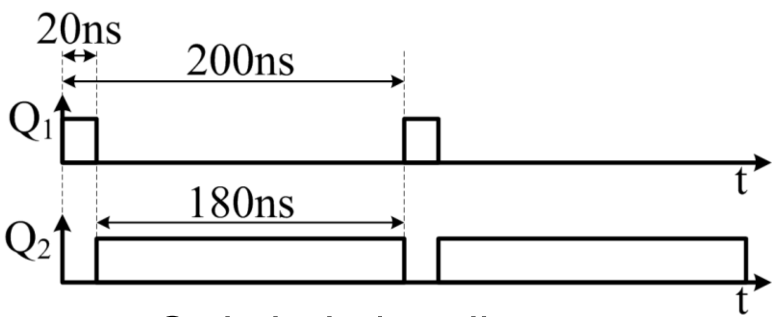
Series cap buck converter prototype



High frequency (HF) buck converter limitations

Buck converter





Switch timing diagram

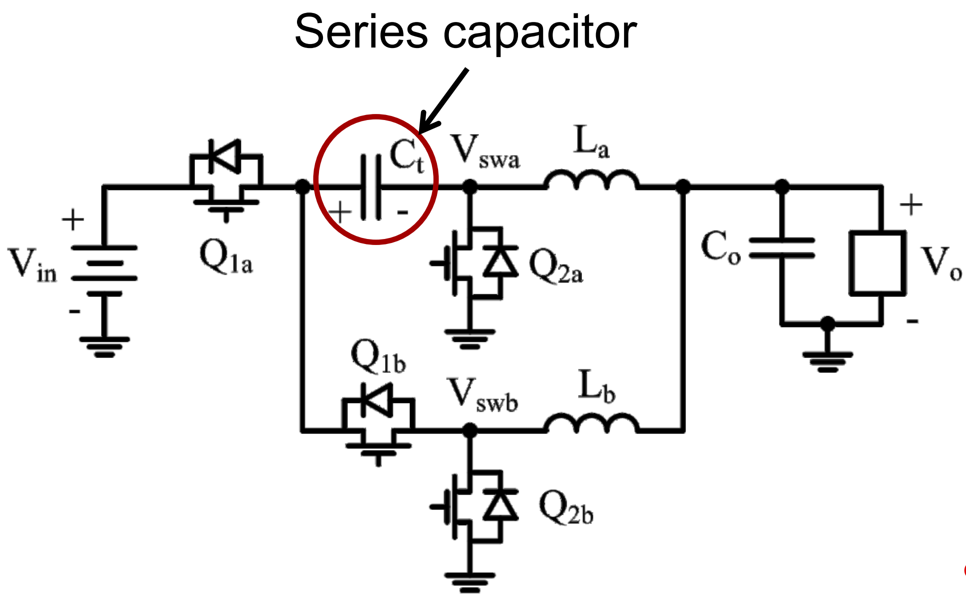
- High switching loss

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

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

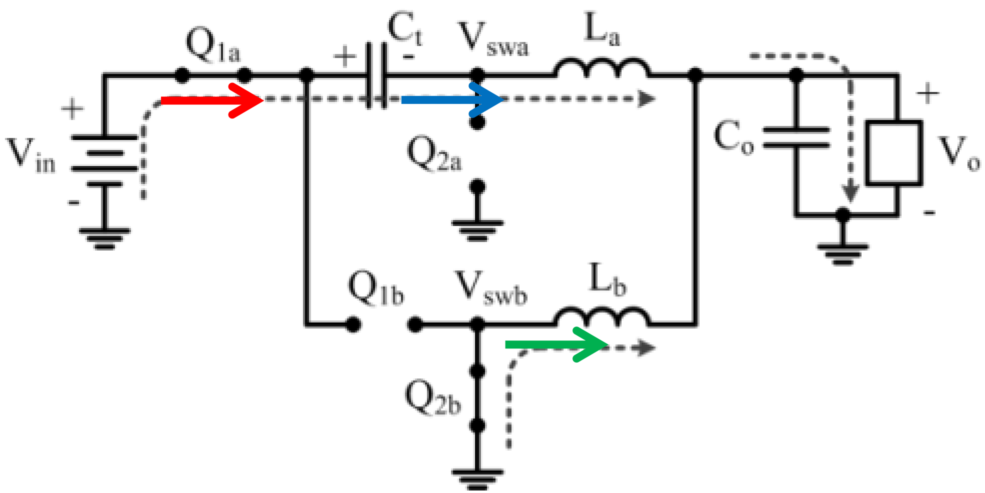
✓Benefits

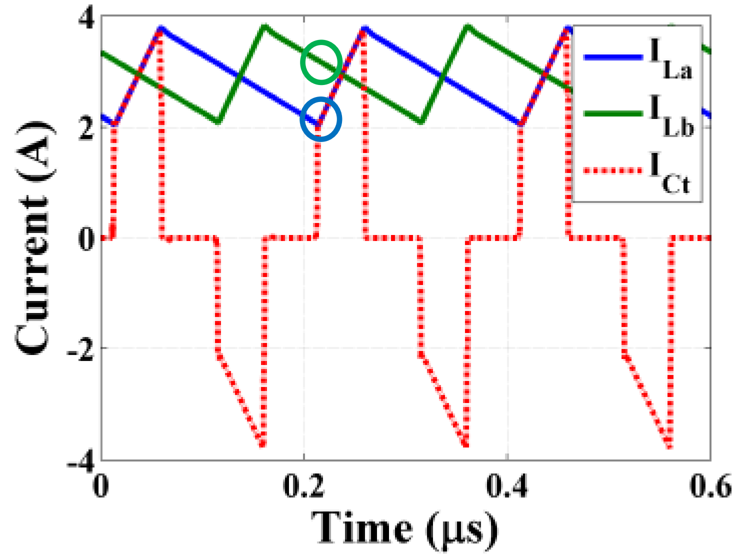
- ✓Single conversion stage
- ✓Lower switching loss
- ✓Cap soft charge/discharge
- ✓Auto current balancing
- ✓On-time doubled

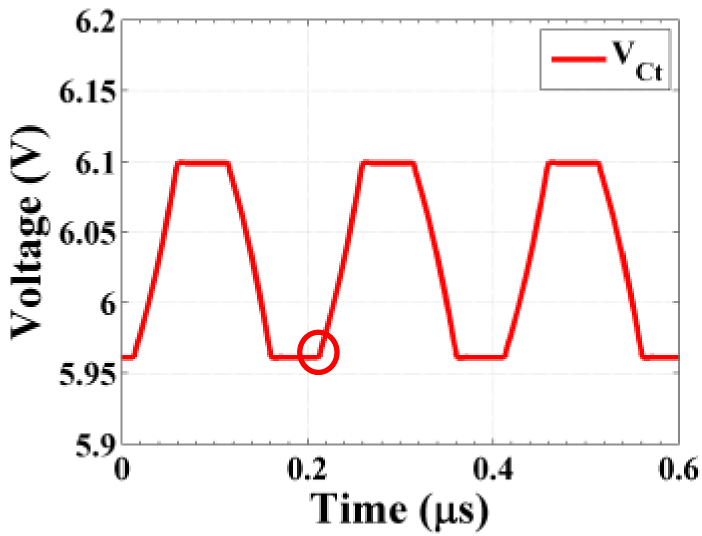
- Drawbacks
  - 50% duty cycle limitation
    - Theoretical: $V_{in,min} = 4 \times V_{out}$
    - Practical: $V_{in,min} = 5 \times V_{out}$

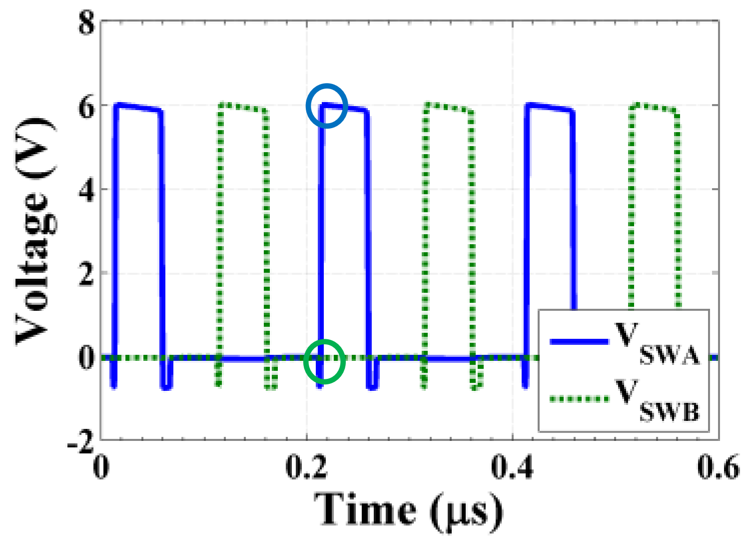
P.S. Shenoy, M. Amaro, D. Freeman, and J. Morroni, “Comparison of a 12V, 10A, 3MHz buck converter and a series capacitor buck converter,” in *Proc. IEEE Applied Power Electron. Conf.*, pp. 461-468, Mar. 2015.

Steady-state operation: Step 1

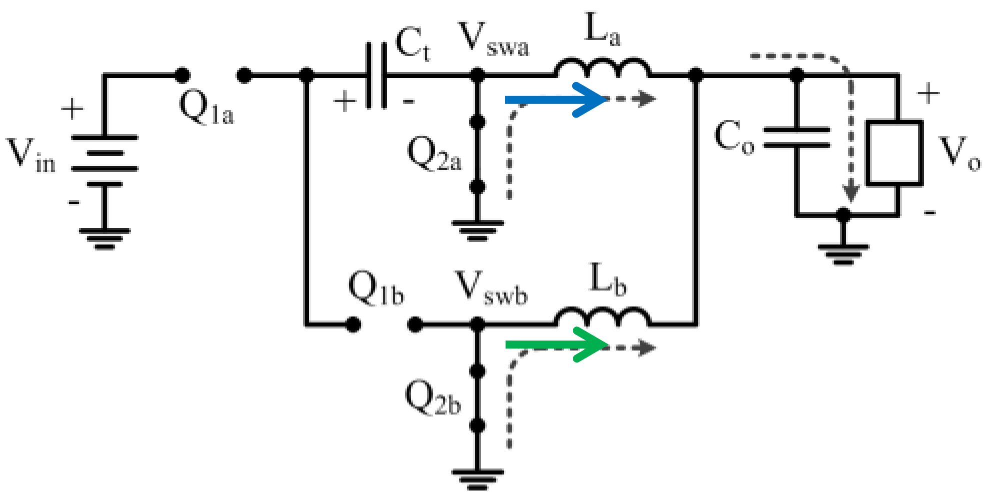


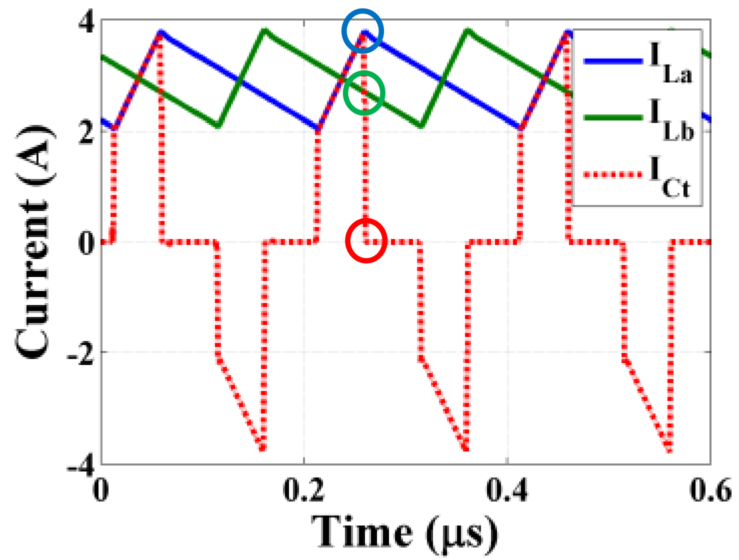


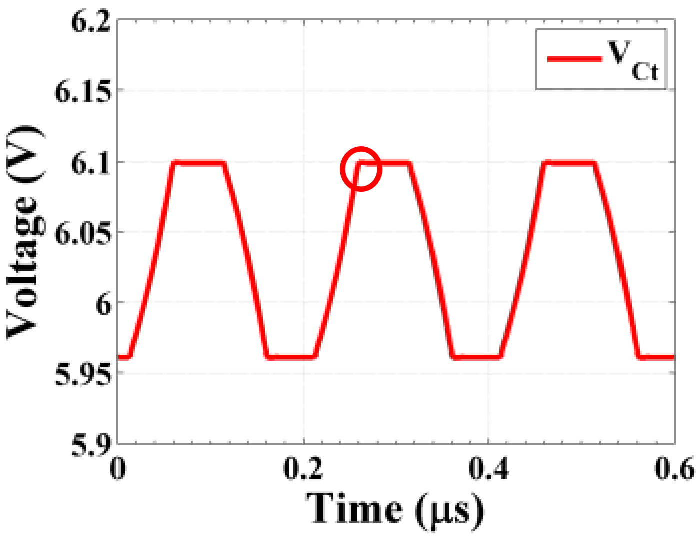


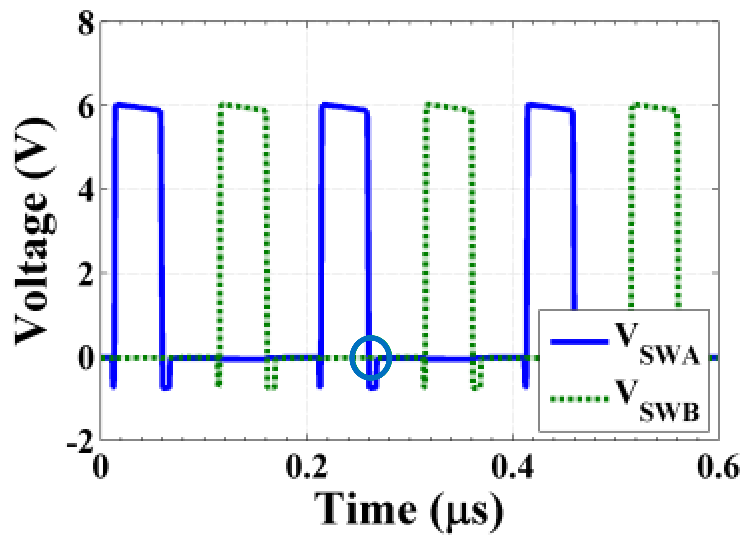


Steady-state operation: Step 2

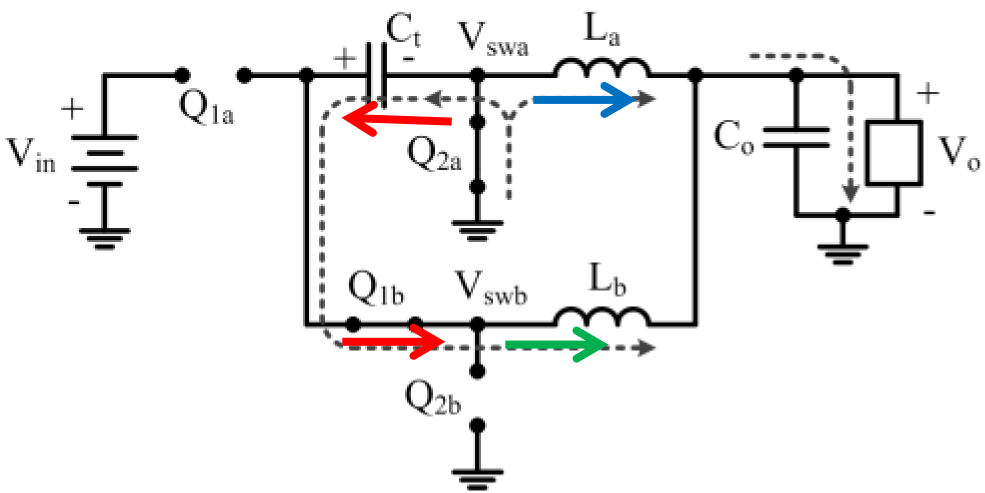


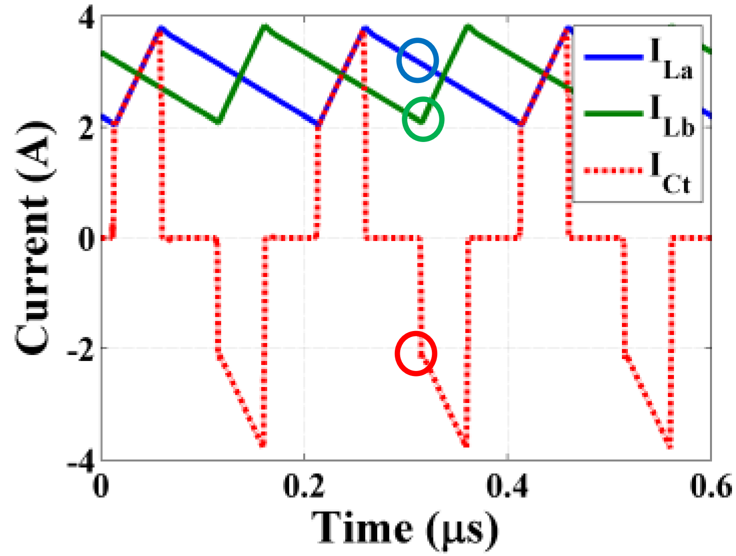


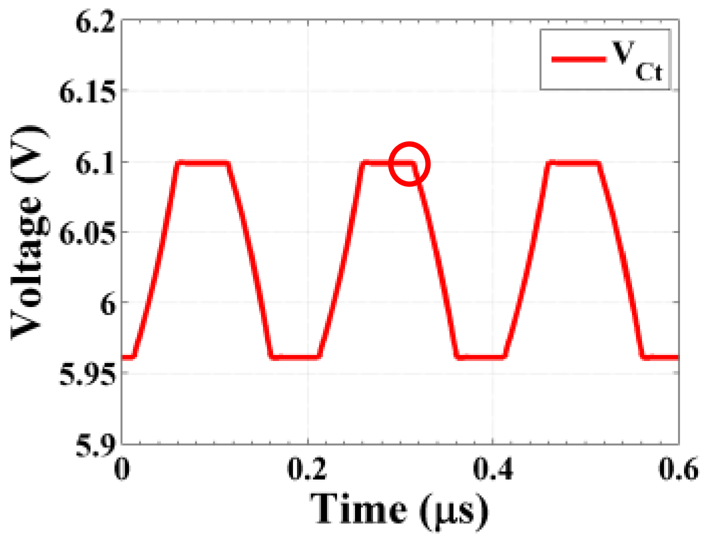


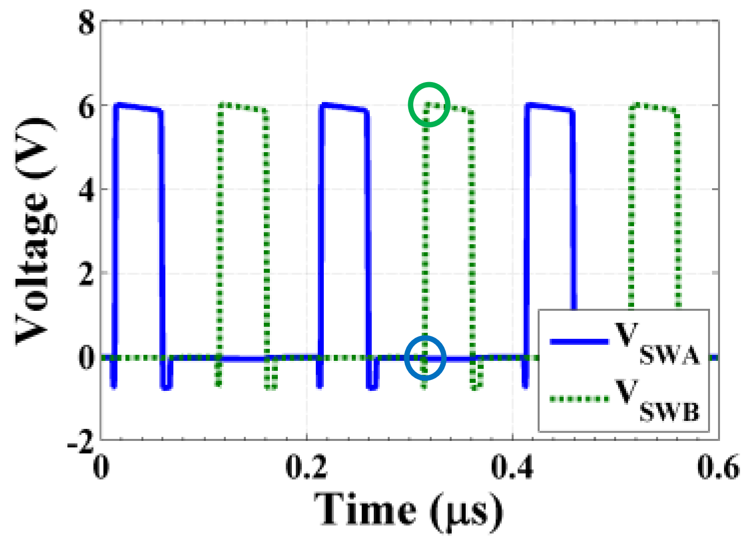


Steady-state operation: Step 3

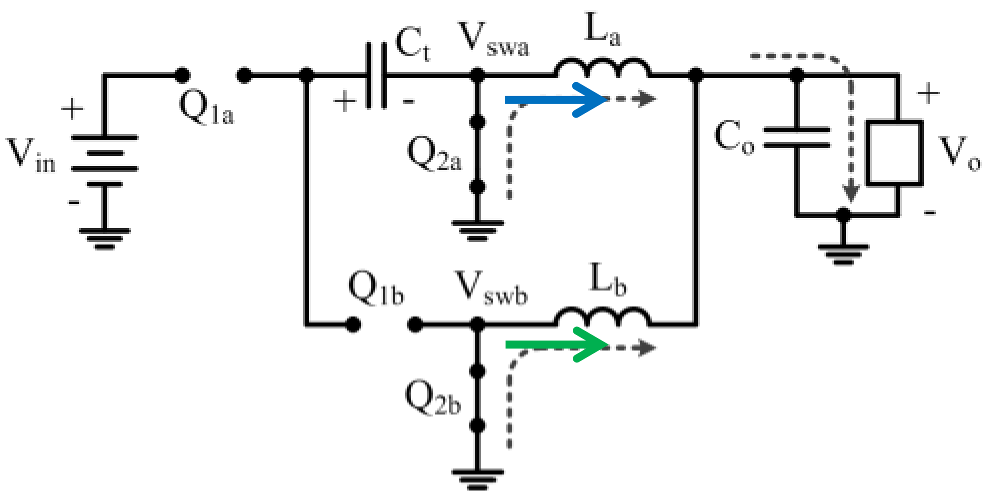


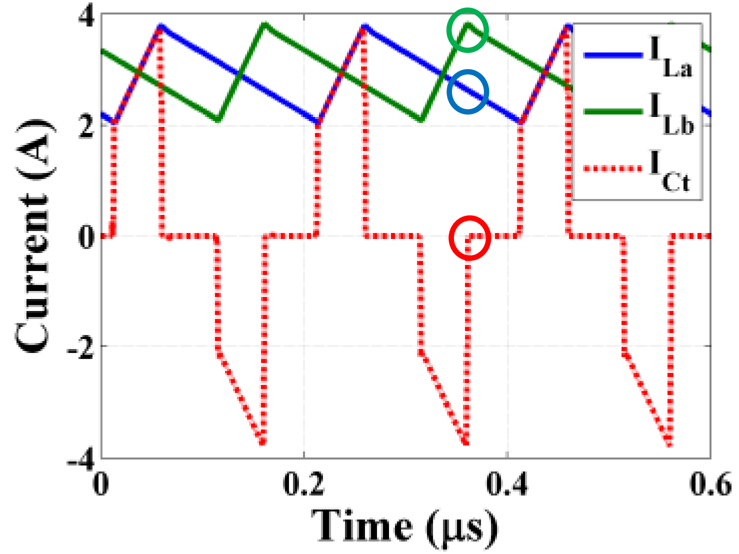


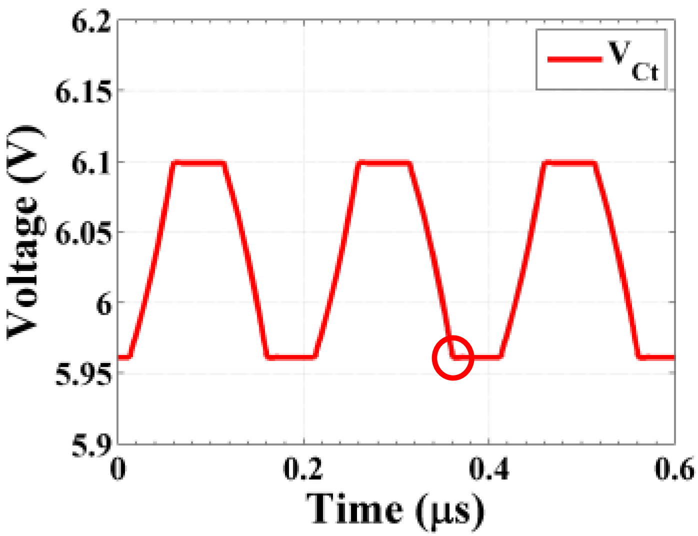


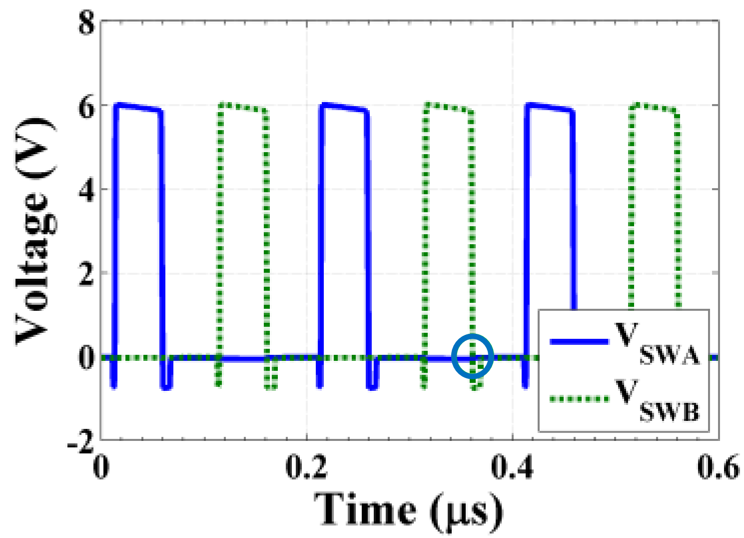


Steady-state operation: Step 4





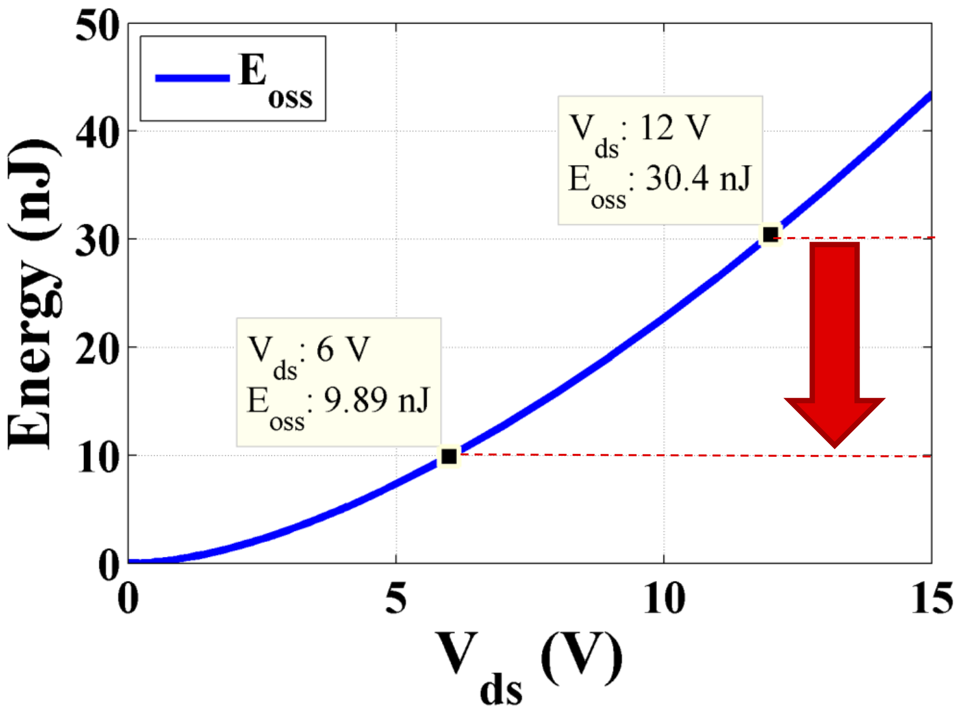




Reduced switching loss

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

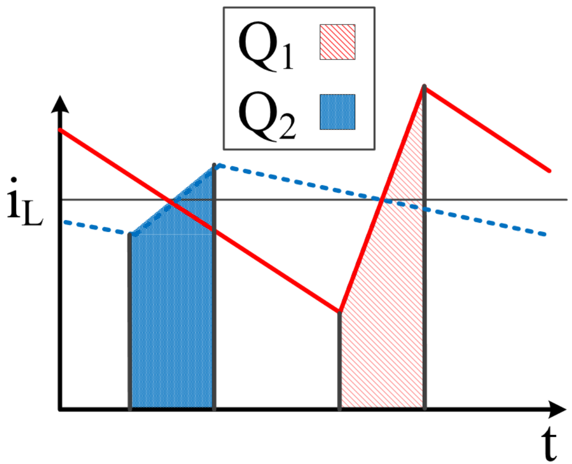
Energy loss per switching cycle



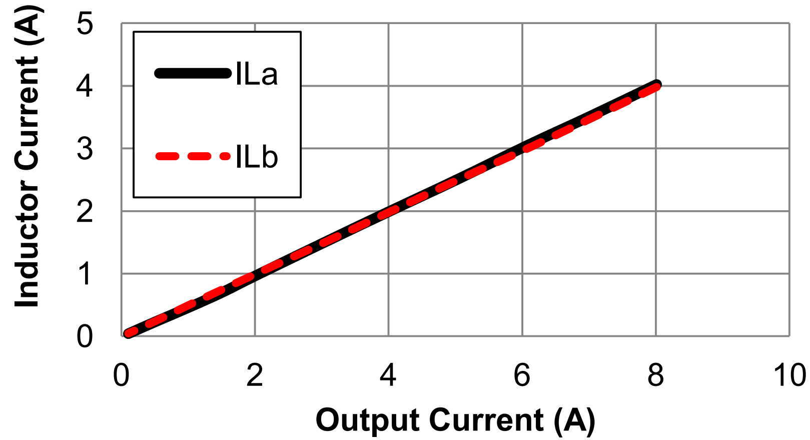
P.S. Shenoy, M. Amaro, D. Freeman, and J. Morroni, "Comparison of a Buck Converter and a Series Capacitor Buck Converter for High Frequency, High Conversion Ratio Voltage Regulators," *IEEE Trans. Power Electron.*, 2016.

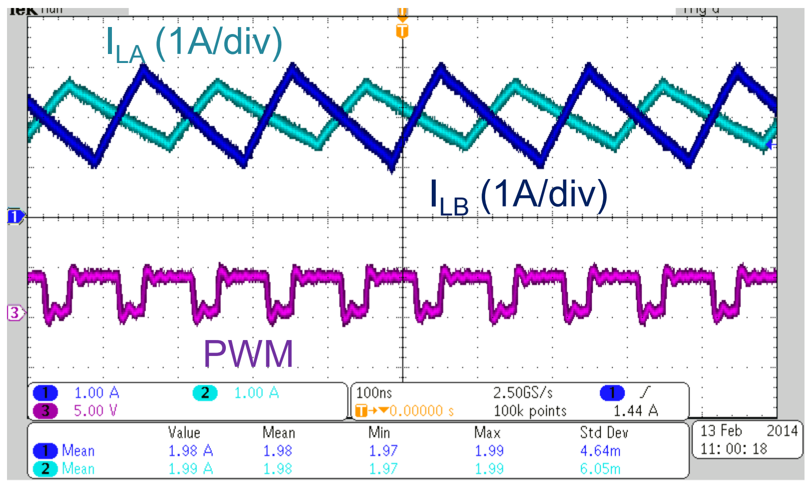
Auto current sharing

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



Current sharing: La ≈ 100nH, Lb ≈ 200nH

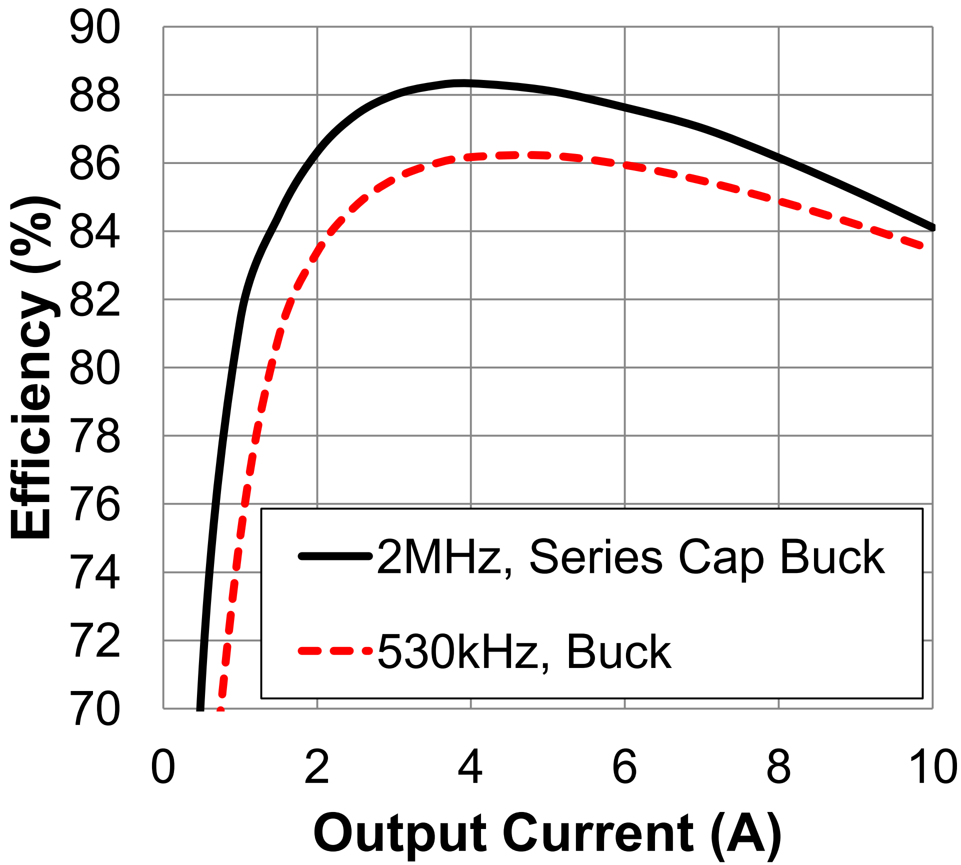




1) ILB, 2)ILA, 3) PWM, Vo=1.8V,Io=4.0A

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

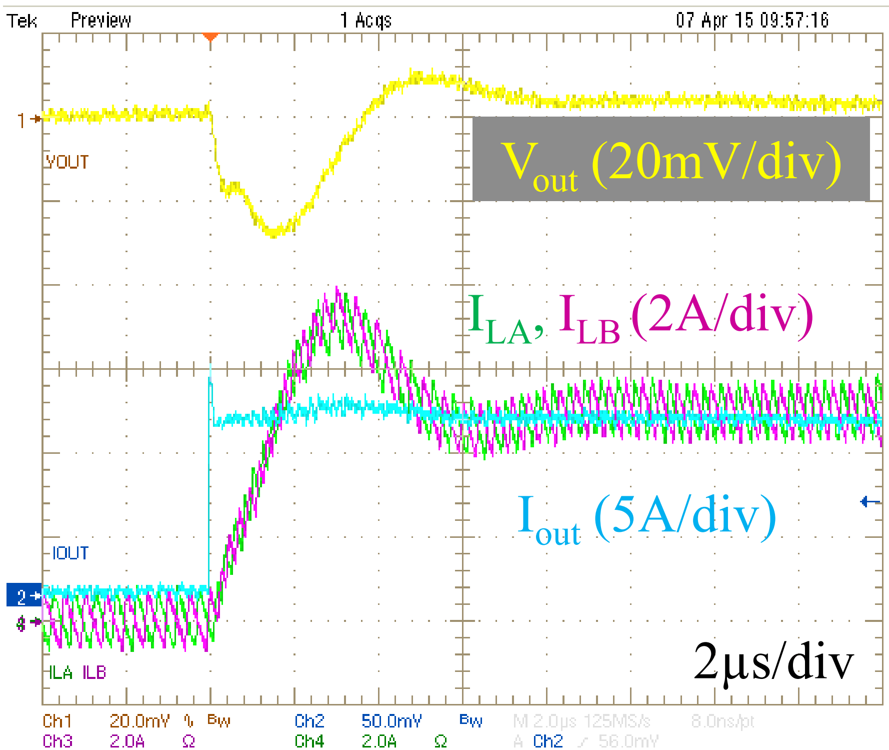


- Conditions:
  - 12V in, 1.2V out
  - Room temperature, no air flow
- Higher efficiency over the load range
- Inductors selected for equivalent DCR

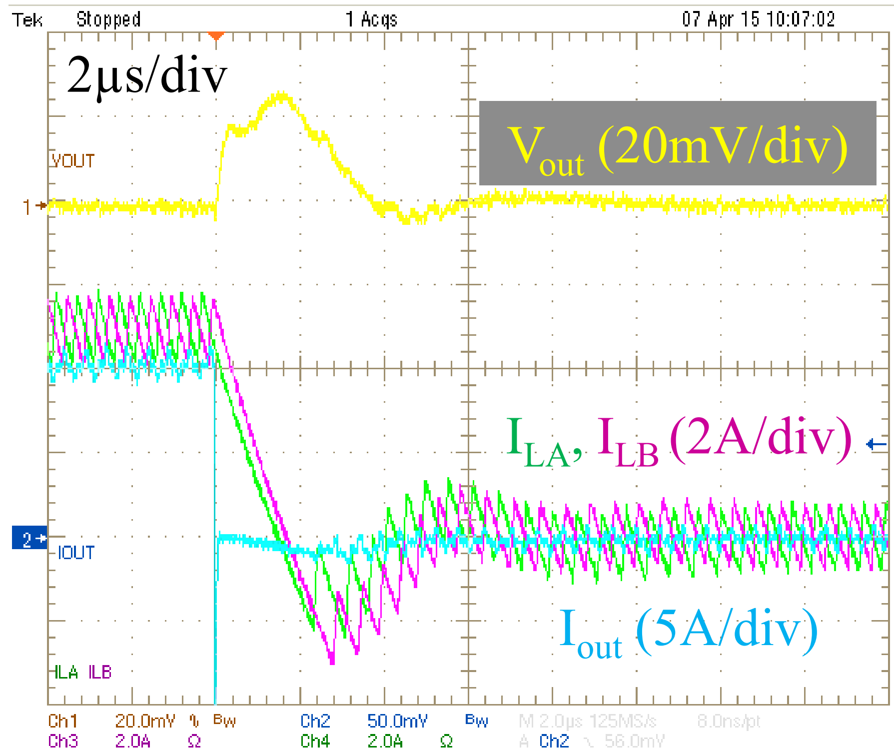
Higher efficiency at ~4 times the switching frequency

Fast load transient response

Load step up



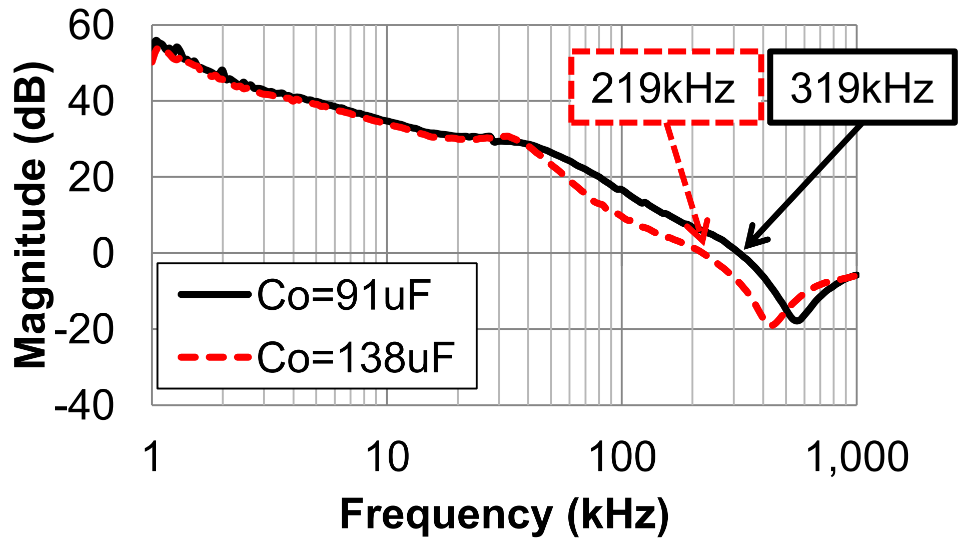
Load step down

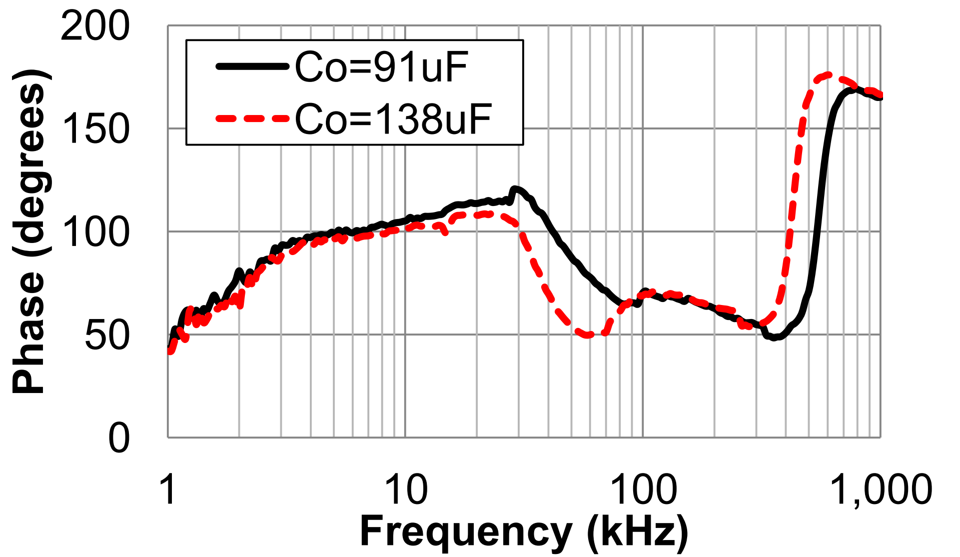


- 12V in, 1.0V out; 500A/μs full load steps; 2MHz per phase
- Deviation in V_{out} <25mV; Settling time <4μs
- Excellent dynamic current sharing

Closed loop performance

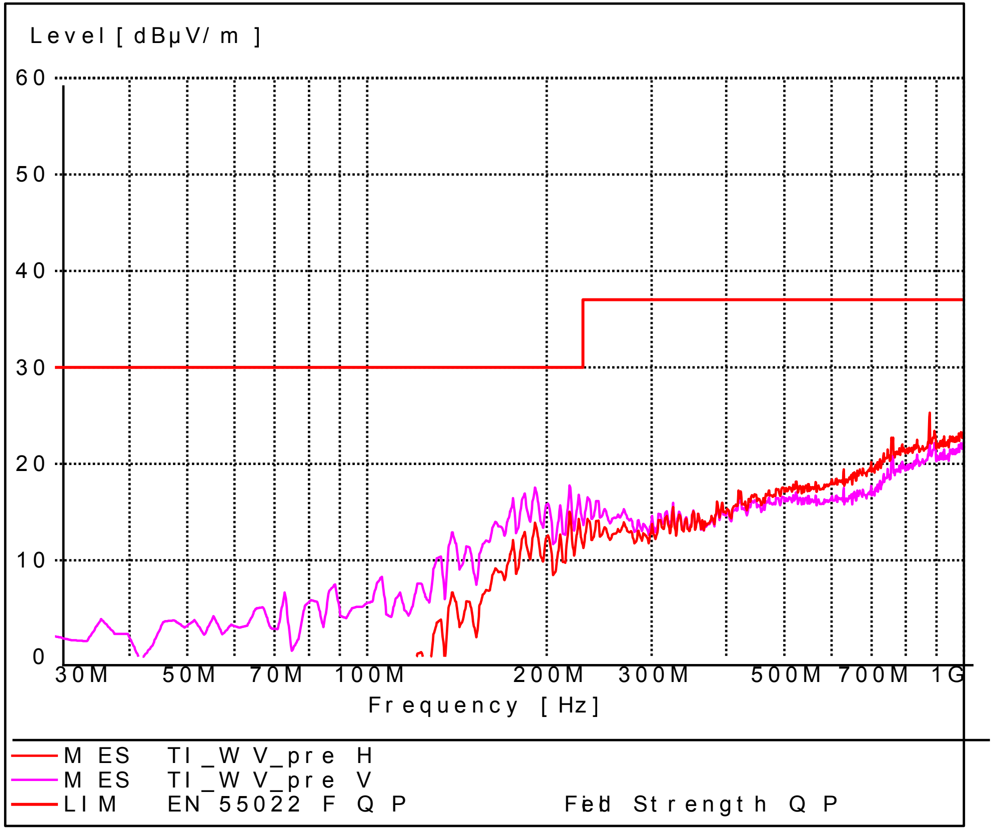
- Conditions:
  - 12V in, 1.2V out
  - 2.5A load
  - Room temperature
- High bandwidth
  - Over 200kHz crossover frequency
- Stable
  - Over 45 degrees phase margin





Electromagnetic Interference (EMI)

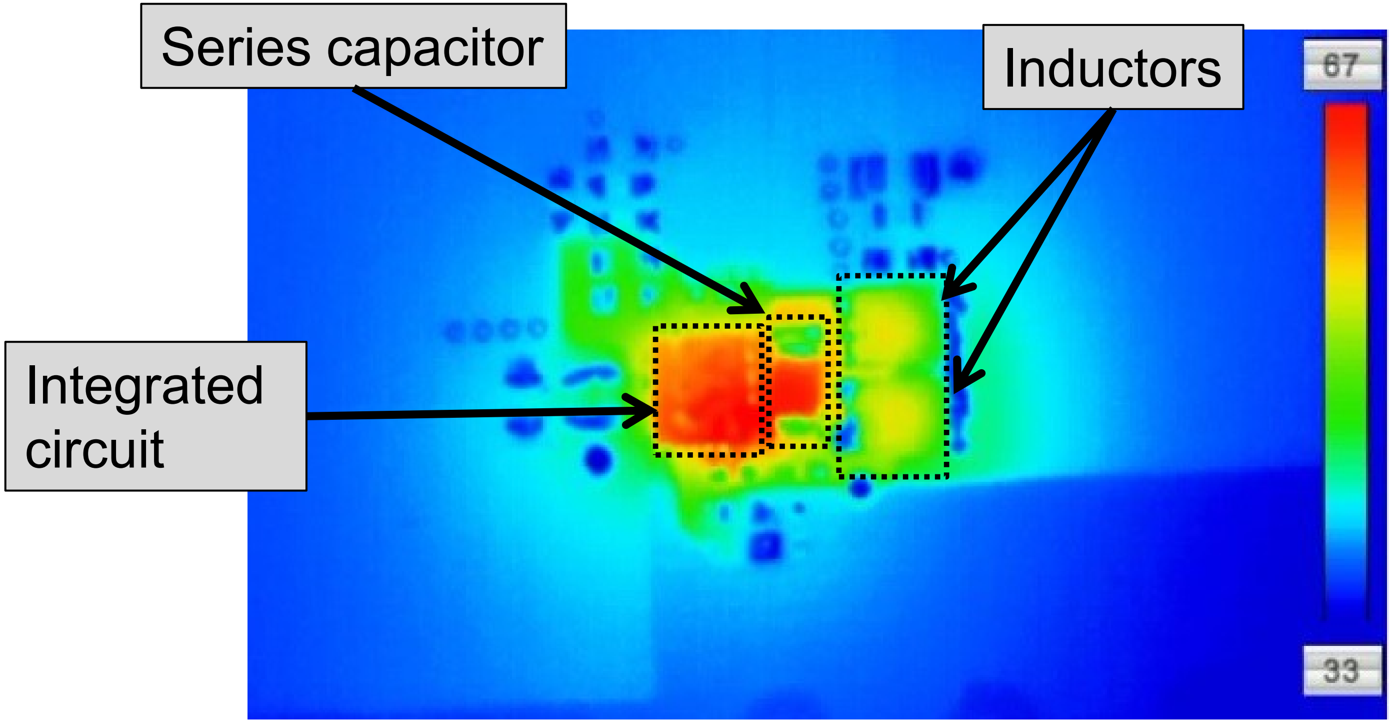
12V in, 1.2V out, 10A load, no snubber



Passes CISPR Class B Standard

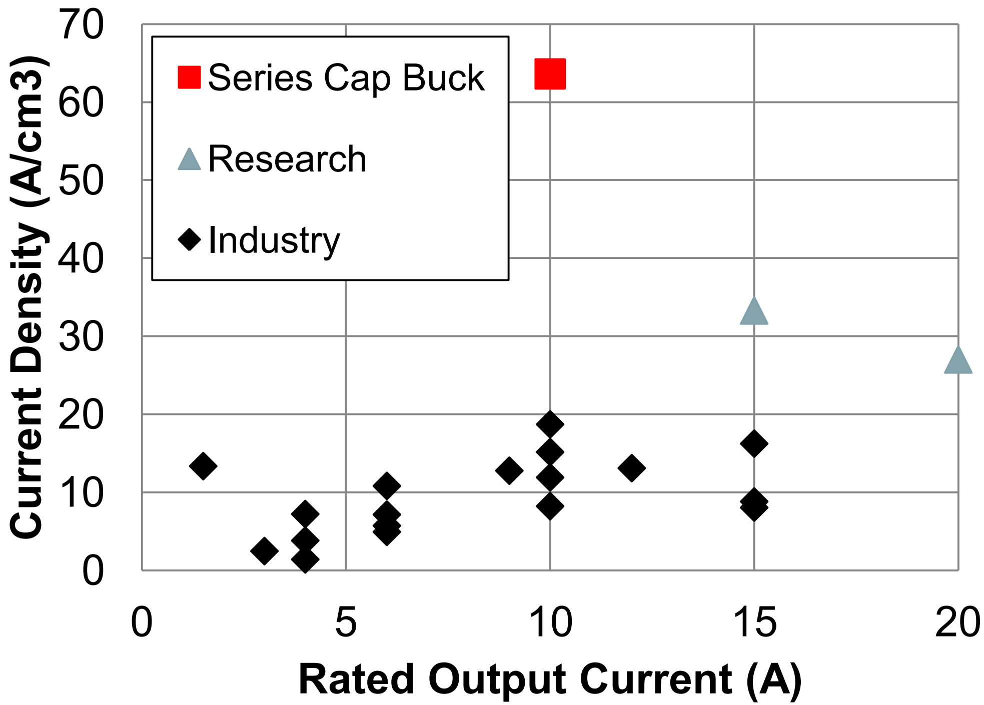
Where's the heat?

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

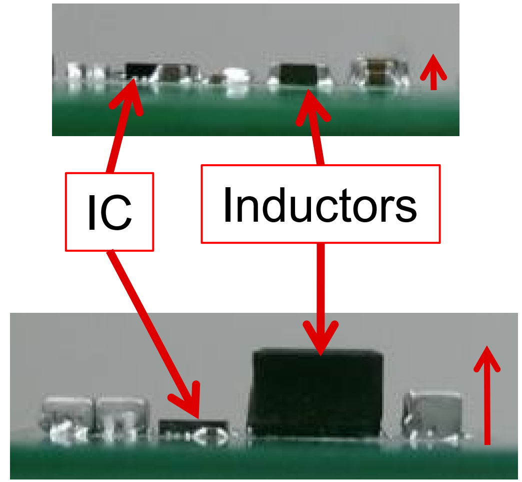


The inductors are (still) not the thermal bottleneck

Current density comparison



Series cap buck: 1.2mm height



Buck: 4.8mm height

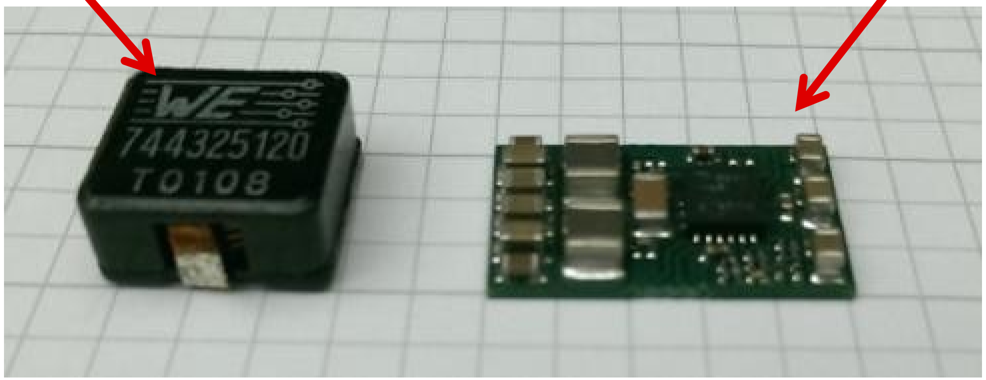
A 3x to 7x improvement in total solution current density

P.S. Shenoy, et al., "A 5 MHz, 12 V, 10 A, Monolithically Integrated Two-Phase Series Capacitor Buck Converter," in *Proc. IEEE Applied Power Electron. Conf.*, Mar. 2016.

Series capacitor buck total solution size

10A inductor for a regular buck
10.2x10.2x4.7mm = 489mm^3

10A series cap buck prototype
16x10x1.85mm* = 296mm^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/cm^3**
  - Power density at 1.2V out is **1.25kW/in^3**
- No compound semiconductors (GaN, GaAs, etc.) or special magnetics are needed!