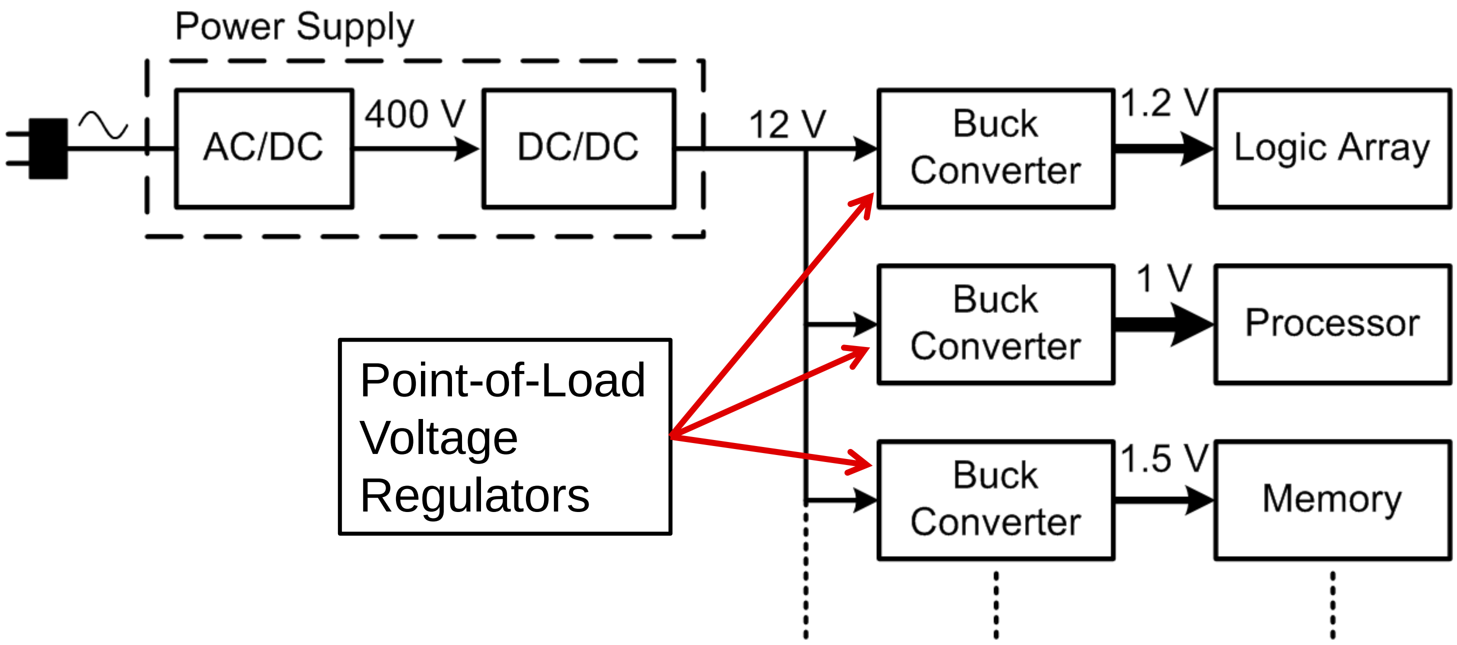
The Technology Behind the World’s Smallest 12V, 10A Voltage Regulator

A low profile voltage regulator achieving high power density and performance using a hybrid dc-dc converter topology

Pradeep Shenoy, Ph.D.

Systems Engineer, DC Solutions

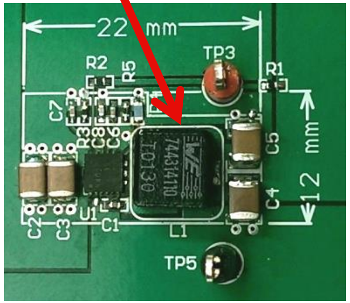
Power Delivery System



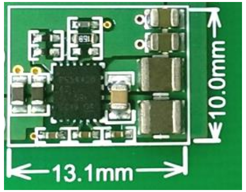
Intermediate Bus Architecture

Why Increase Switching Frequency?

Inductors are usually the largest component.



1) Smaller size



Converter Volume: 1,270 mm^3

Inductor Volume: 232 mm^3

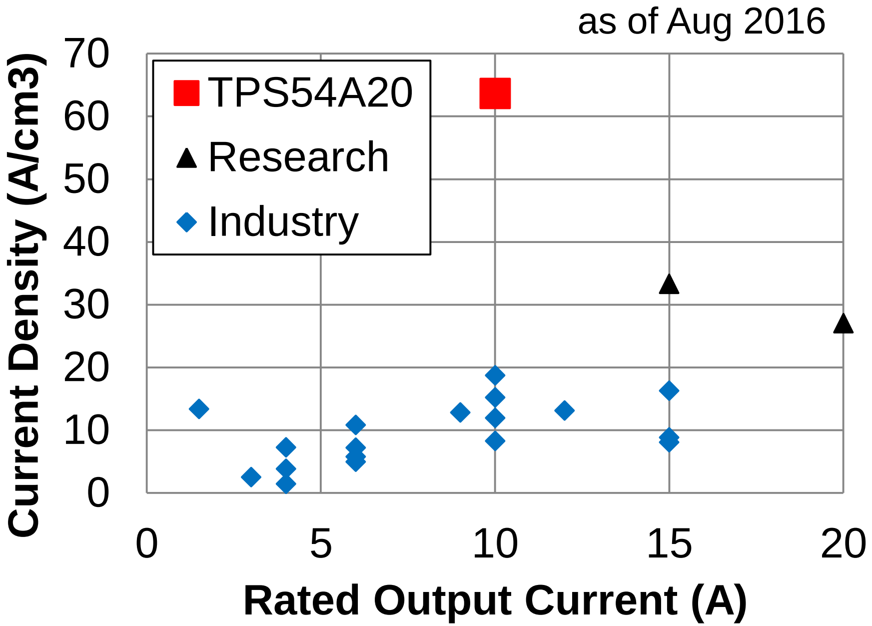
Converter Volume: 157 mm^3

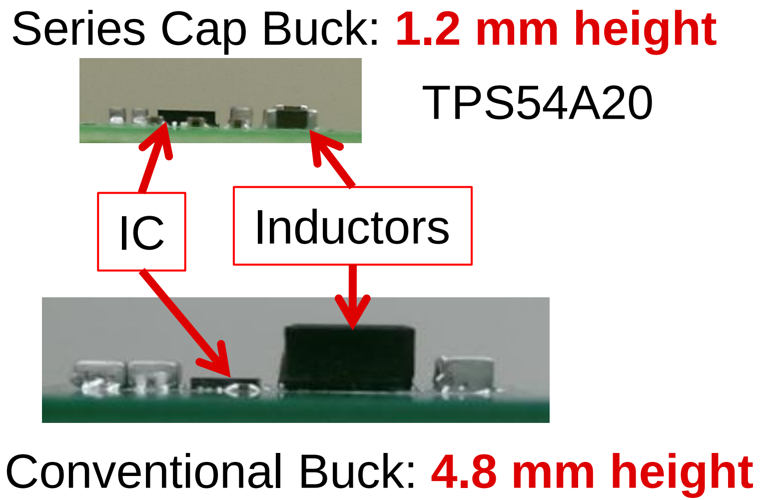
Inductor Volume: 19.2 mm^3

2) Faster Response

3) Lower BOM Cost

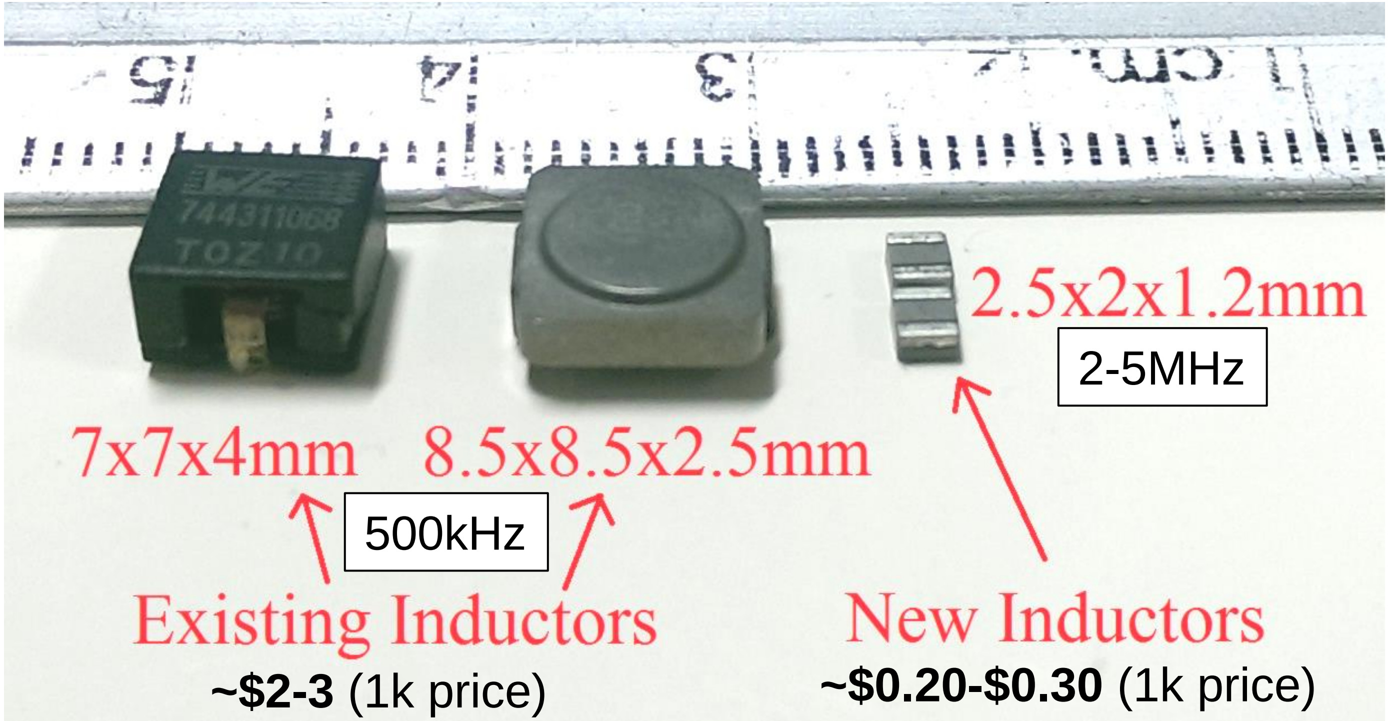
Current Density Comparison





Current density of over 60A/cm³ and power density of 1.25kW/in³

Inductor Size Reduction: 10A Output



High frequency operation → 15 times smaller inductors!

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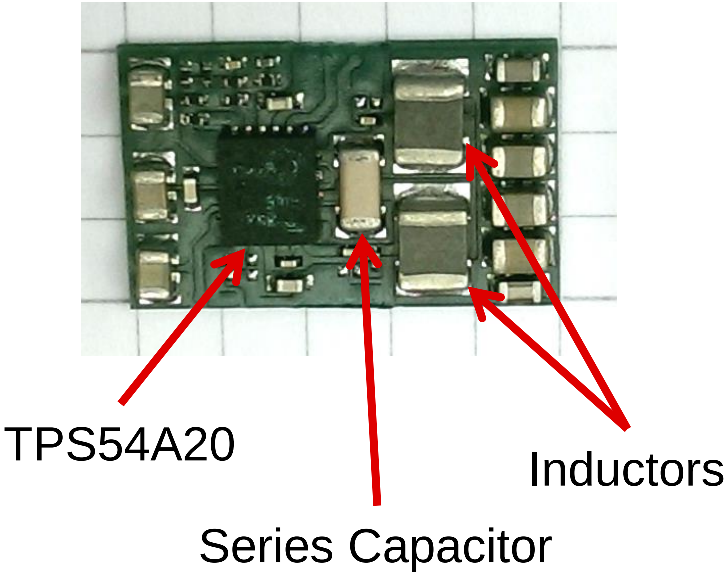
Agenda

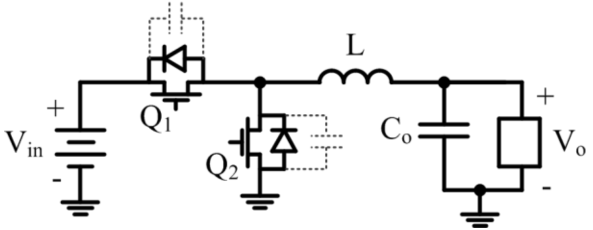
- High Frequency Buck Converter Limitations
- Series Capacitor Buck Converter
- Sample Experimental Results
- Design Considerations for a Series Cap Buck Converter

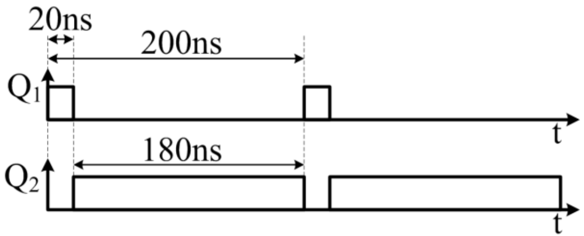
Series cap buck converter prototype



High Freq (HF) Buck Converter Limitations

Buck Converter





Switch Timing Diagram

- High switching loss

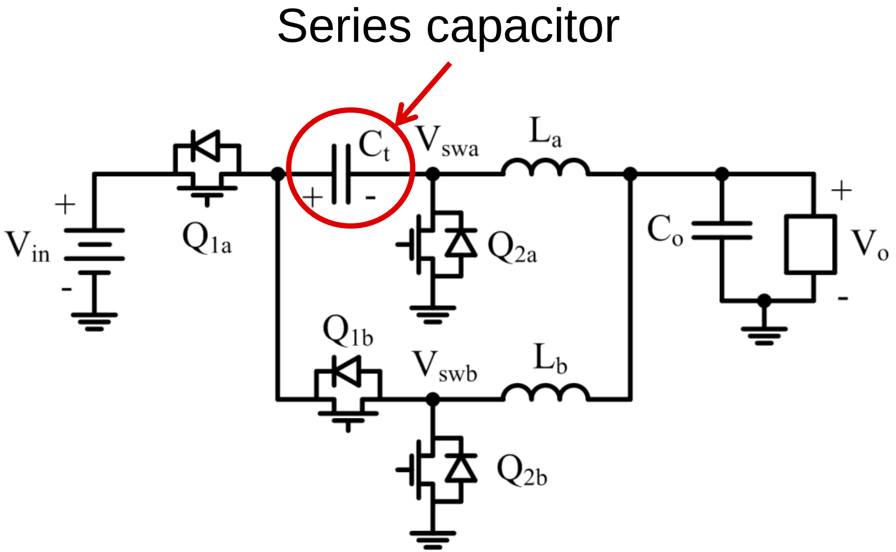
$$P_{loss} \propto f_{sw}$$

- High side switch 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)

TEXAS INSTRUMENTS

Series Capacitor Buck Topology

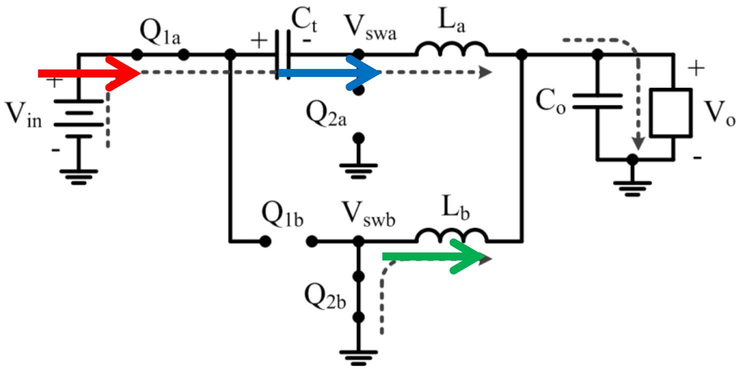


Two-phase, series cap buck converter

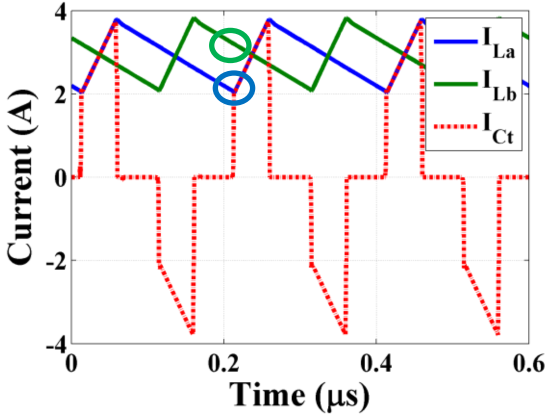
- ✓Benefits
  - ✓Single conversion stage
  - ✓Switching at reduced V_{ds}
  - ✓Series cap soft charge/discharge
  - ✓Automatic current balancing
  - ✓Duty ratio doubled
- Drawback
  - 50% duty cycle limitation
    - Theoretical: $V_{IN,MIN} = 4 \times V_{OUT}$
    - Practical: $V_{IN,MIN} = 5 \times V_{OUT}$

P. S. Shenoy, M. Amaro, J. Morroni and D. Freeman, "Comparison of a Buck Converter and a Series Capacitor Buck Converter for High-Frequency, High-Conversion-Ratio Voltage Regulators," *IEEE Trans. Power Electron.*, vol. 31, no. 10, pp. 7006-7015, Oct. 2016.

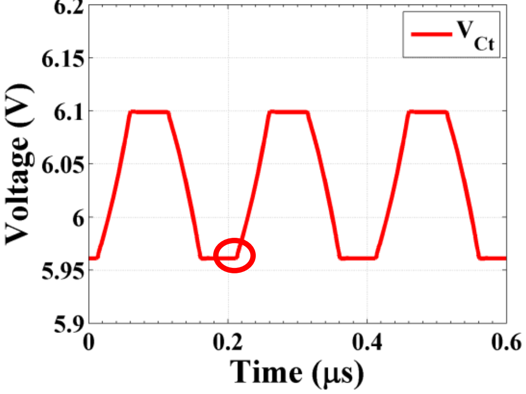
Steady-State Operation: Interval 1



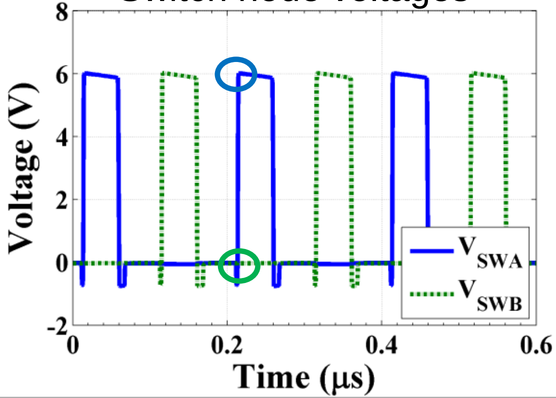
Inductor & series cap currents



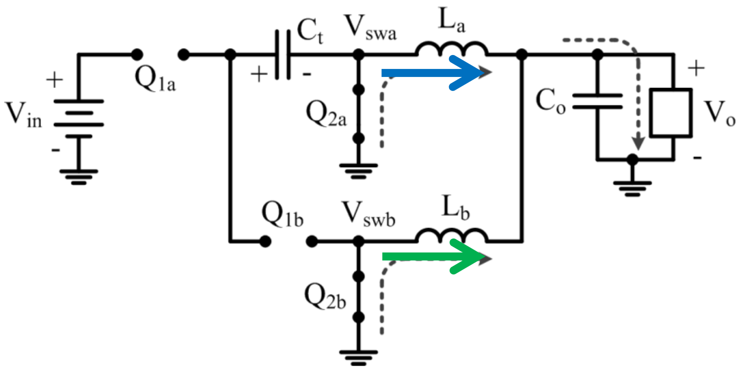
Series cap voltage (differential)



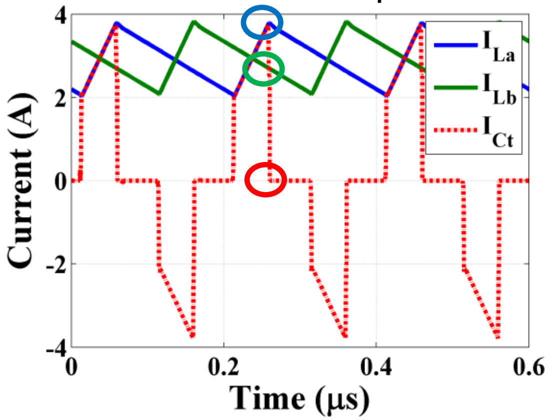
Switch node voltages



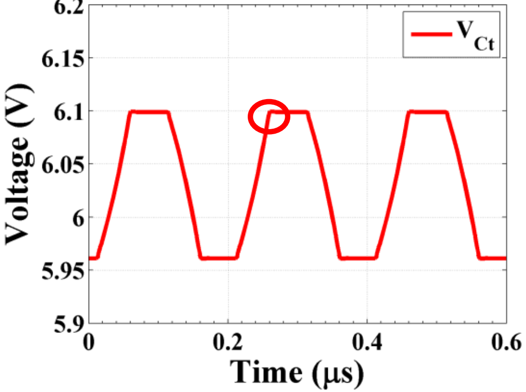
Steady-State Operation: Interval 2



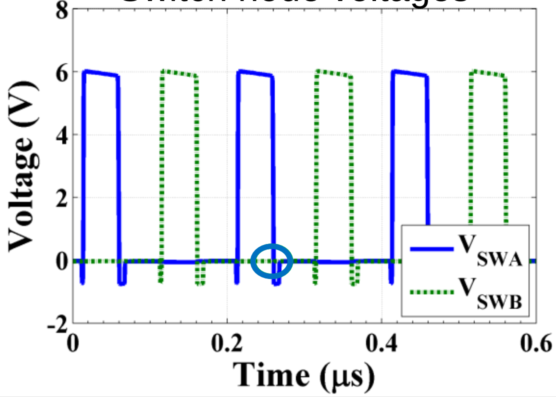
Inductor & series cap currents



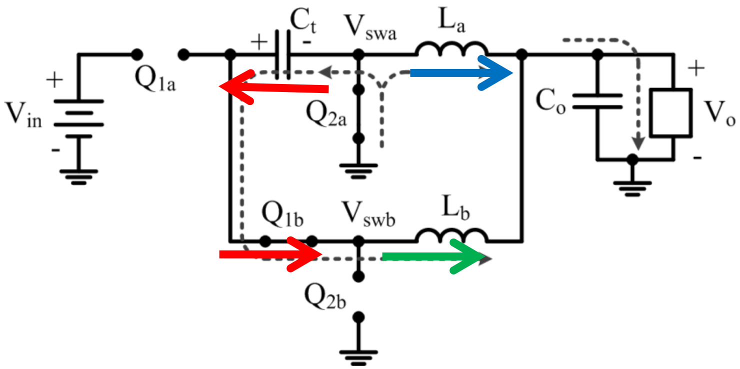
Series cap voltage (differential)



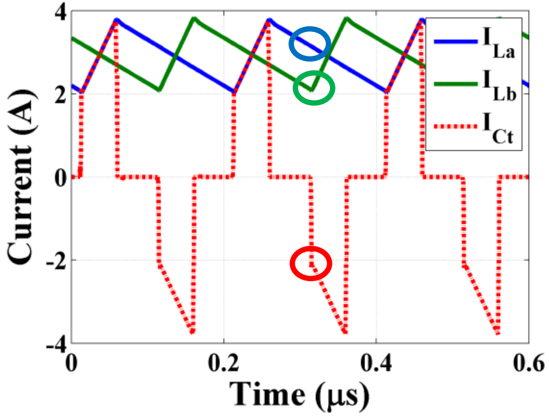
Switch node voltages



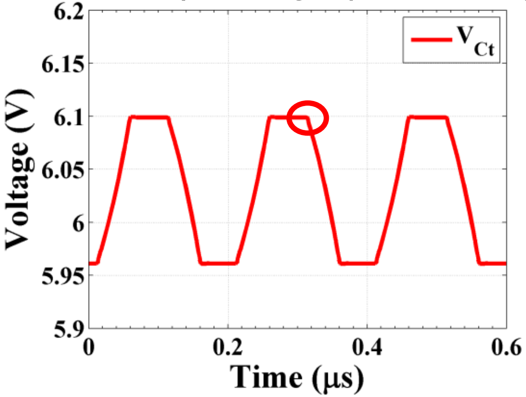
Steady-State Operation: Interval 3



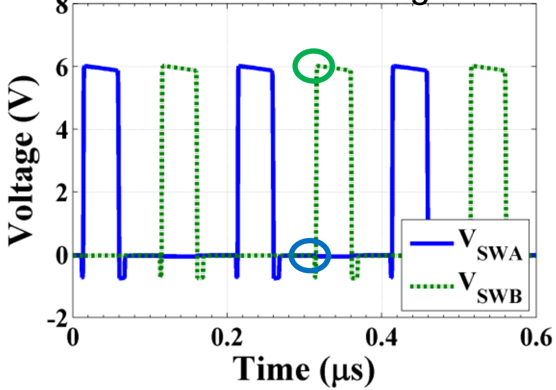
Inductor & series cap currents



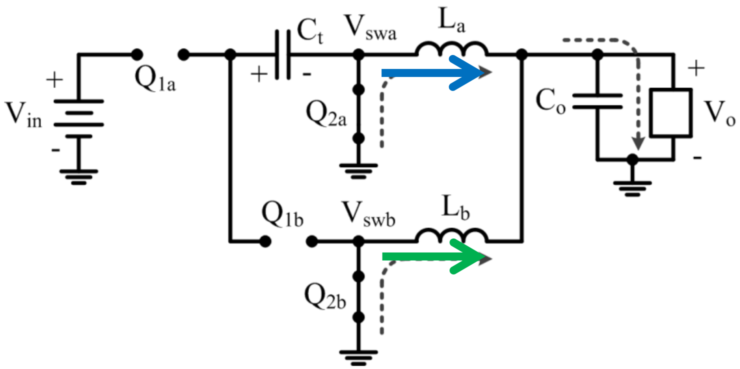
Series cap voltage (differential)



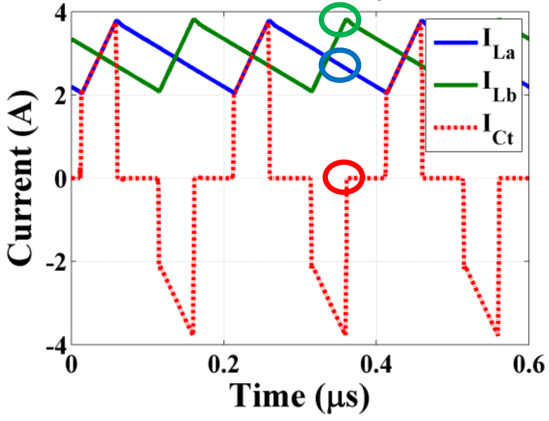
Switch node voltages



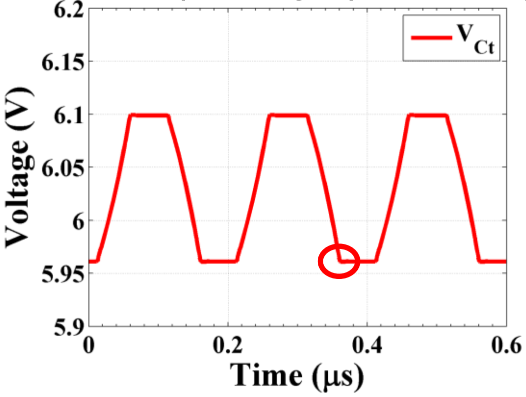
Steady-State Operation: Interval 4



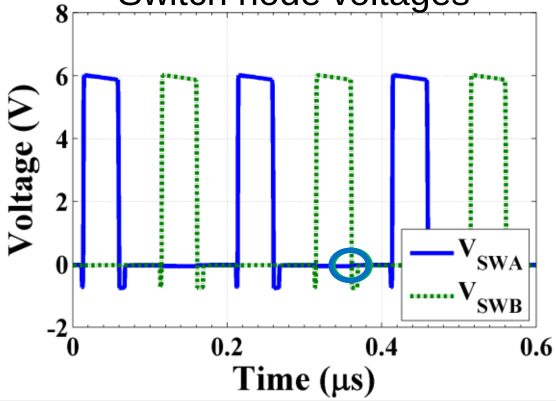
Inductor & series cap currents



Series cap voltage (differential)



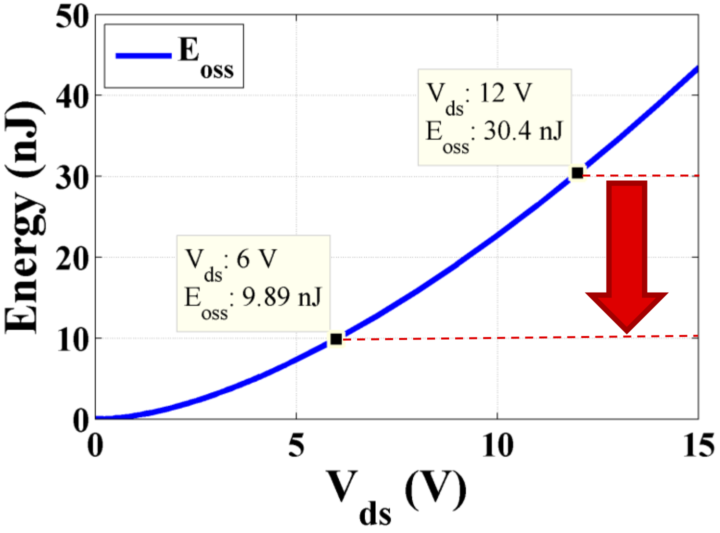
Switch node voltages



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



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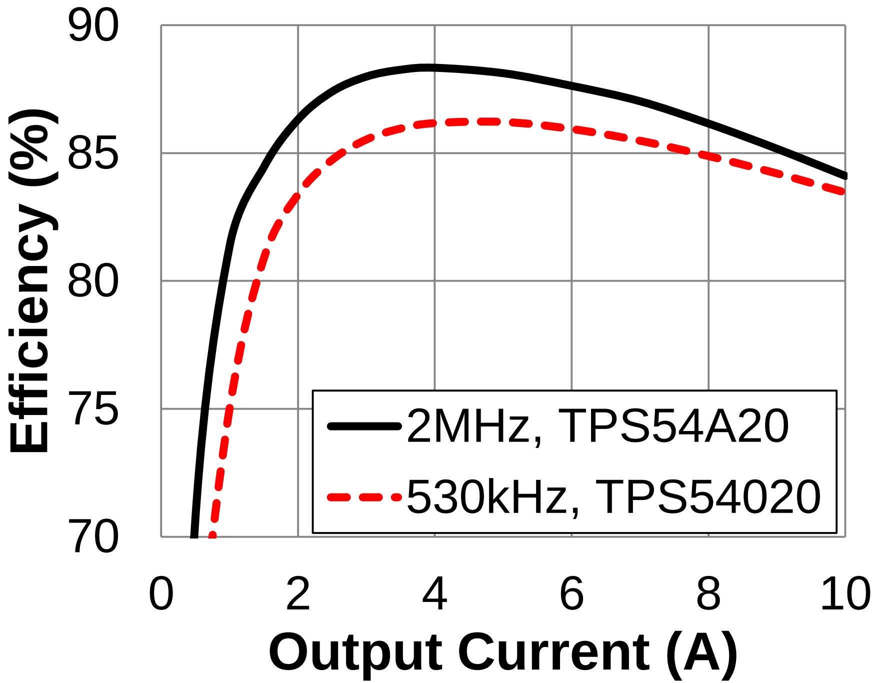
Measured Efficiency Comparison



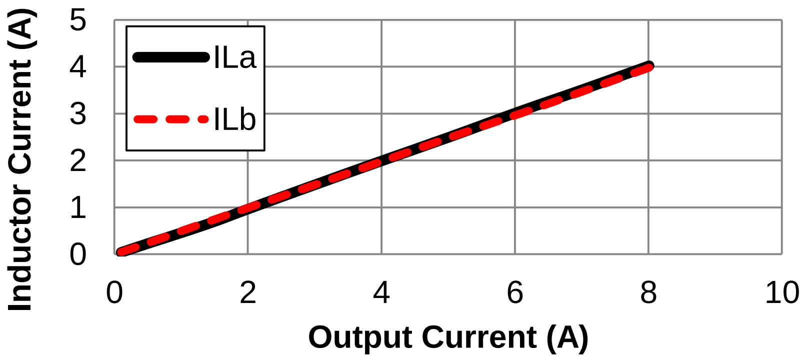
- Conditions:
  - 12V in, 1.2V out
  - Room temp, no air flow
- Higher efficiency over the load range
- Inductors selected for equivalent DCR

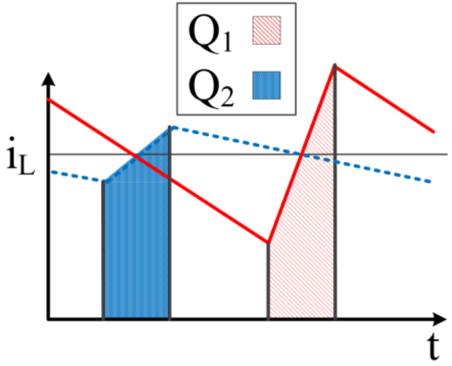
Higher peak efficiency at ~4 times the switching frequency

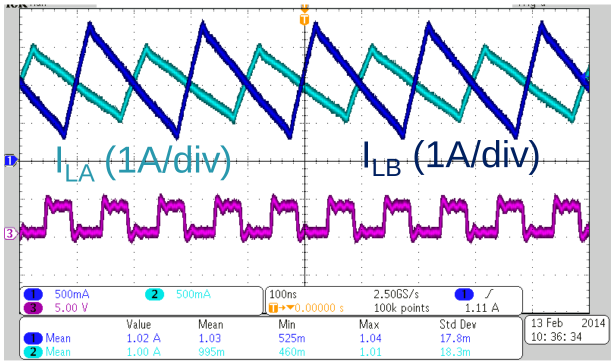
Auto Current Sharing

- Series cap forms average current feedback mechanism
  - Inductors charge/discharge cap
  - Charge balance maintained
- Robust to variations in L, DCR

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

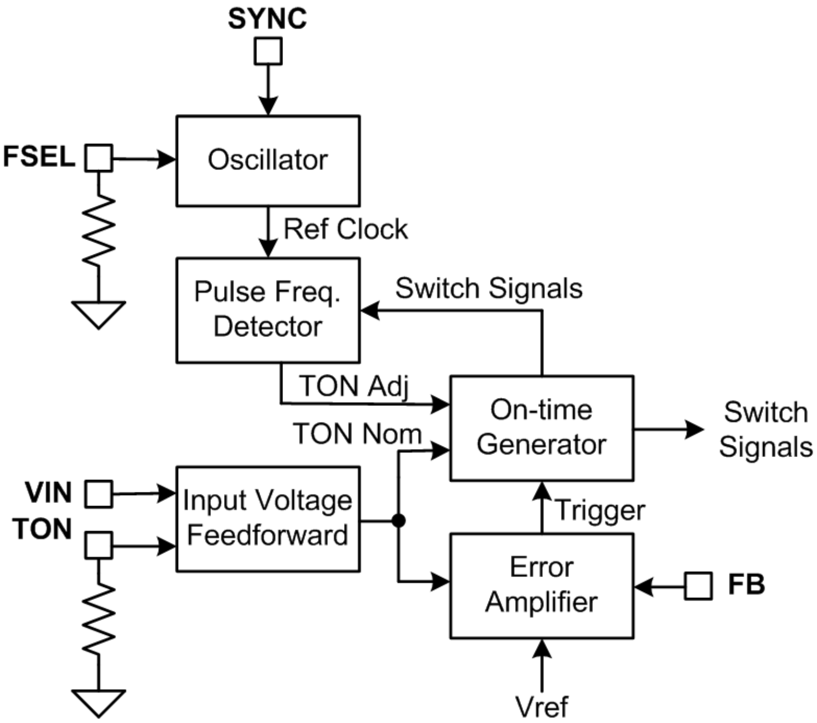






P.S. Shenoy, et al., “Automatic current sharing mechanism in the series capacitor buck converter,” in *Proc. IEEE Energy Conversion Conf. Expo.*, Sept. 2015.

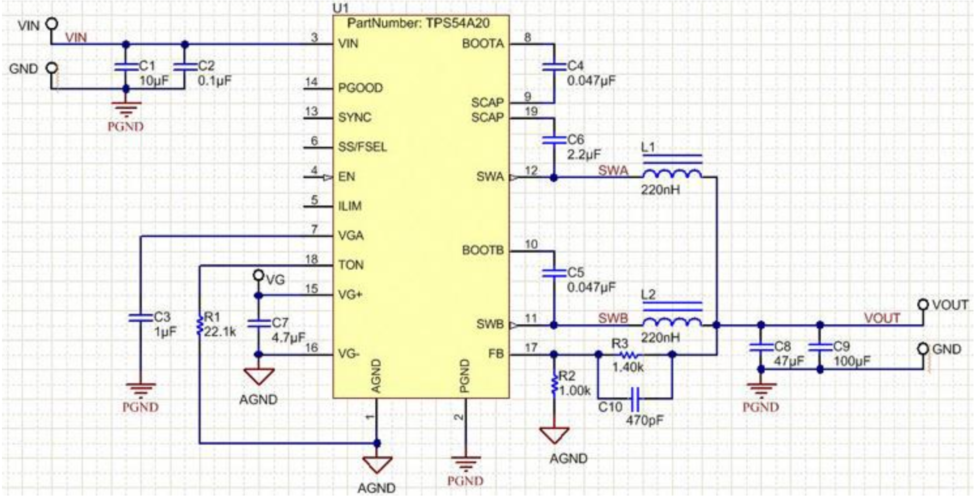
High Frequency Controller



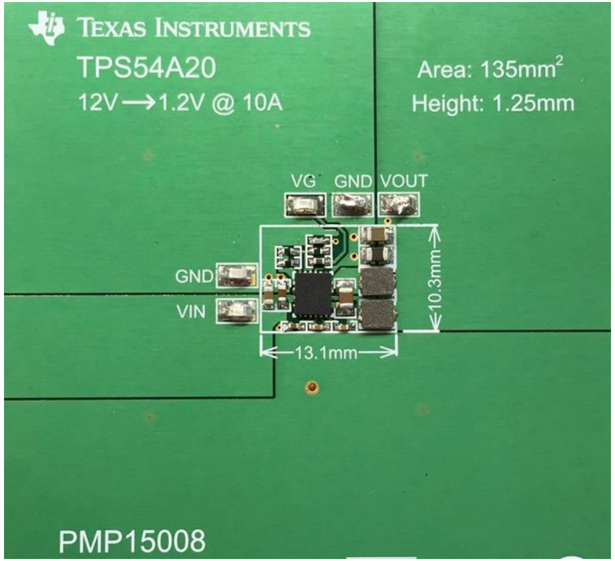
- Adaptive constant on-time control
  - Fast transient response
  - Internal compensation
- Frequency synchronization by adapting on-time
  - Fixed frequency in steady state
  - Can use external clock or internal oscillator

Reference Design PMP15008

"Tiny, Low Profile 10 A Point-of-load Voltage Regulator"



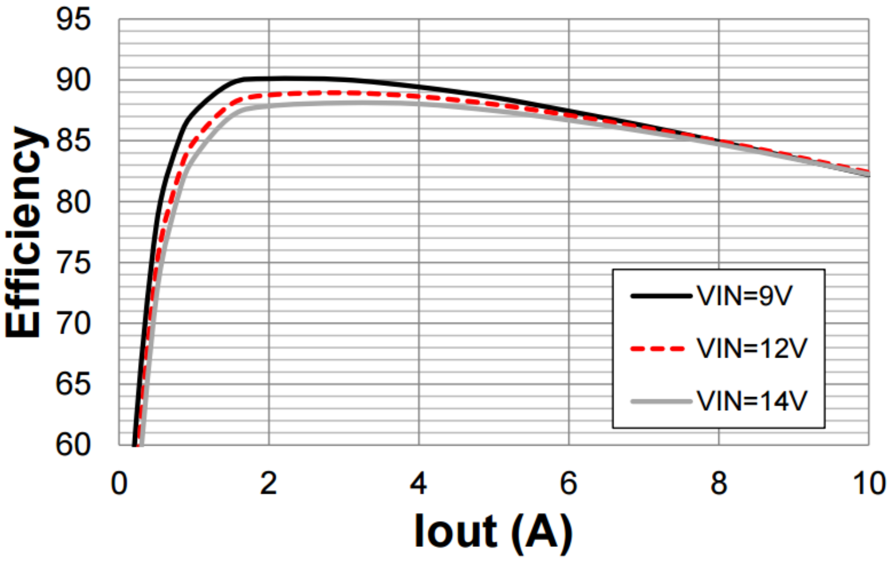
Board Image

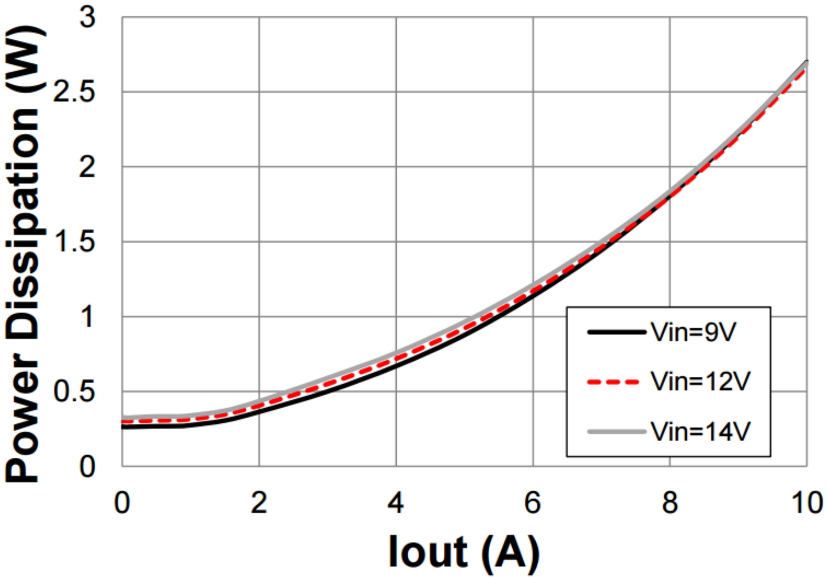


Total solution size is 135mm² and 1.25mm tall

Efficiency and Power Loss

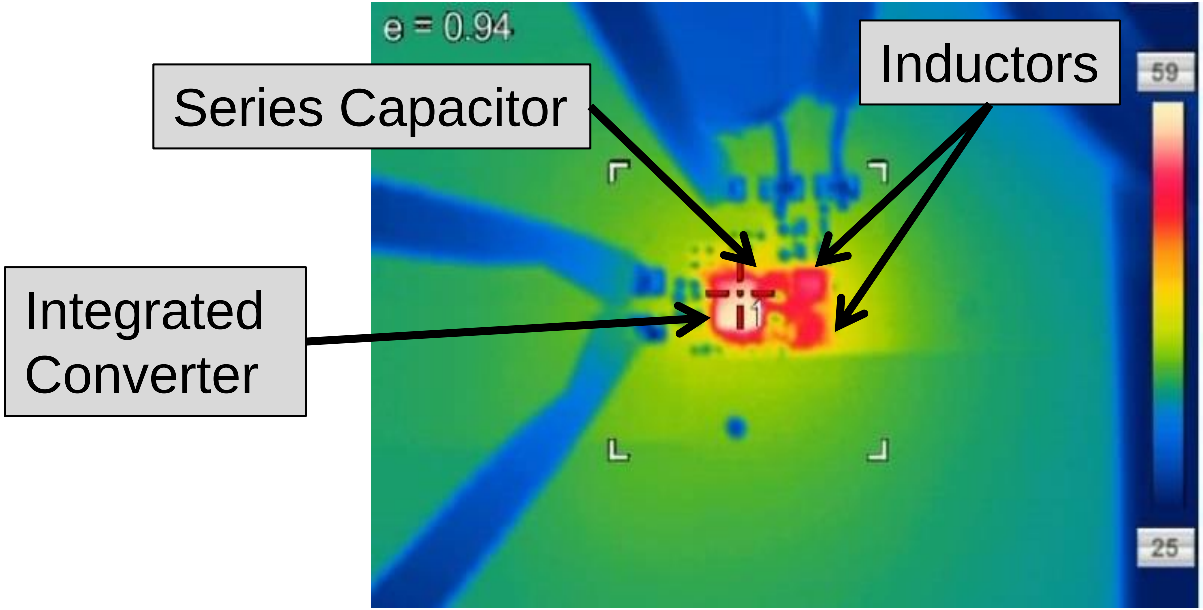
2 MHz per phase, 1.2V_{OUT}, room temperature, no air flow, two layer board





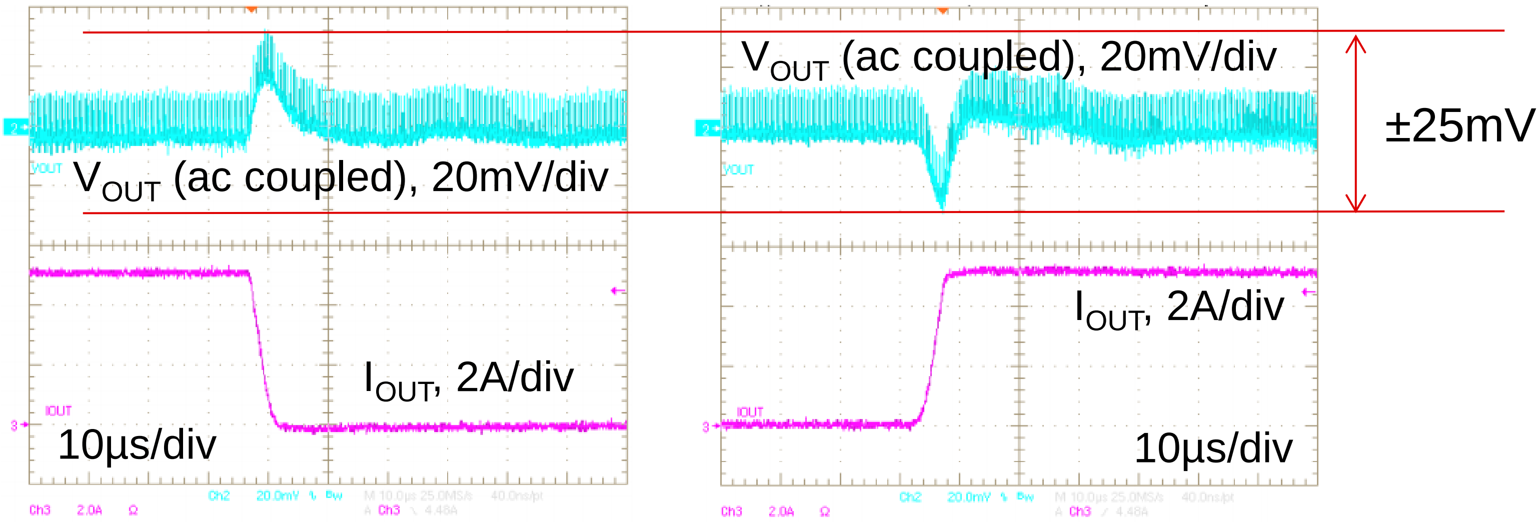
Over 90% efficiency at 9V input, less than 3W loss at full load

Thermal Image



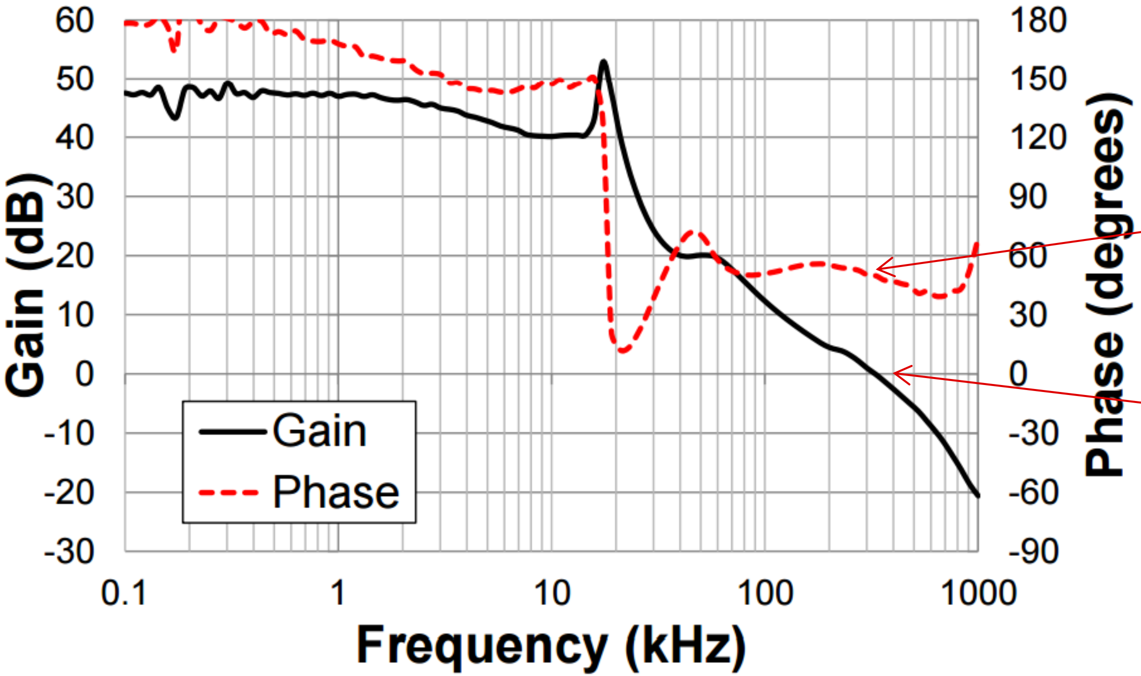
Less than 35 deg. C temp rise at 12V input, 8A output

Load Transient Response



2% variation in V_{OUT} during 5A load change

High Bandwidth and Ample Phase Margin



Over **50 degrees** of phase margin

Over **300kHz** bandwidth

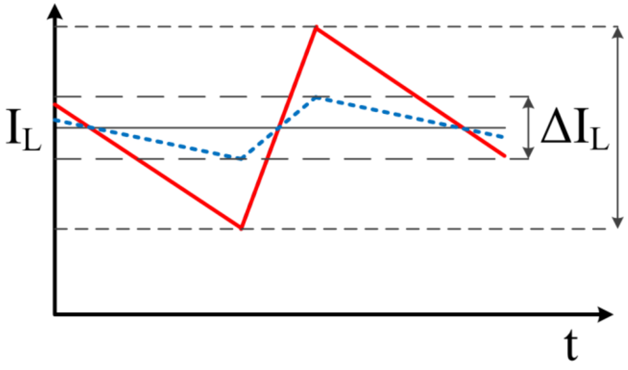
Bode plot taken with 12V input, 5A output

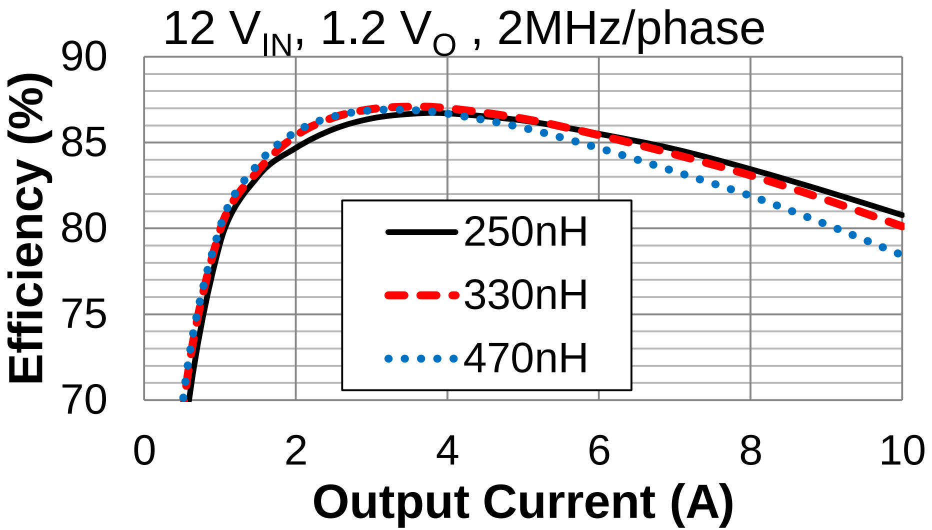
Inductance Impact on Efficiency

- Inductance equation

$$L = \left(\frac{V_{IN,MAX} - 2V_O}{K \times {I_O}/{2}}\right)\left(\frac{V_O}{V_{IN,MAX} \times f_{SW}}\right)$$

  - K = $\Delta I_L / I_L$ where I_L is current at full load
  - K is usually between 0.1 and 0.4





- Higher inductance tends to increase peak efficiency
- Lower inductance has higher full load efficiency

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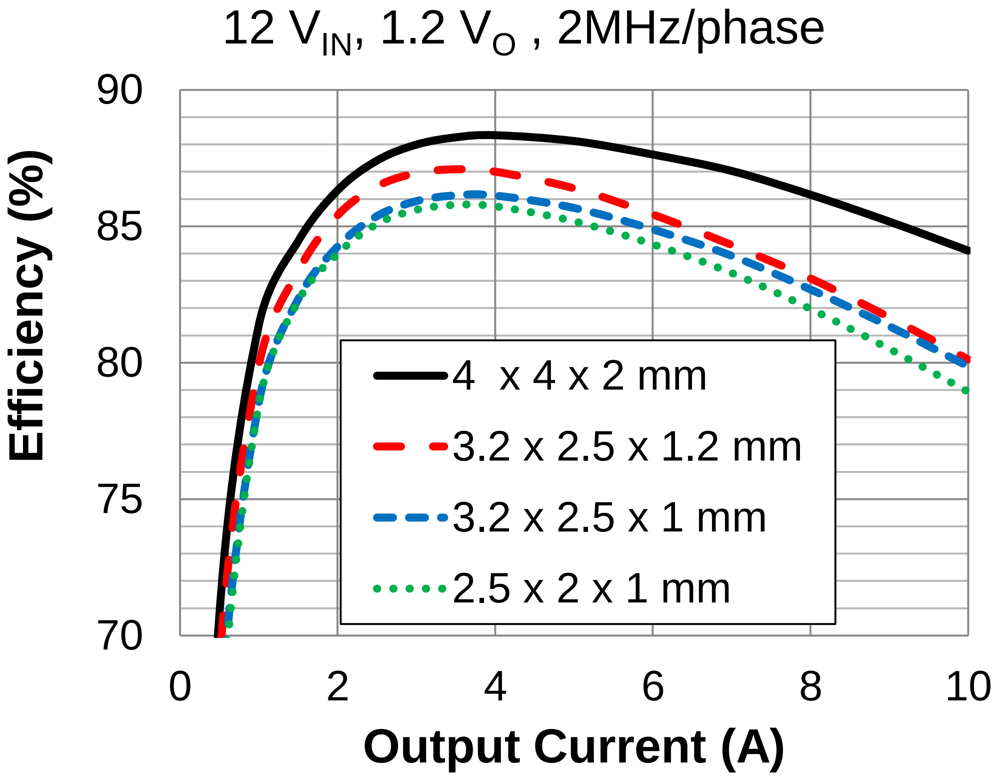
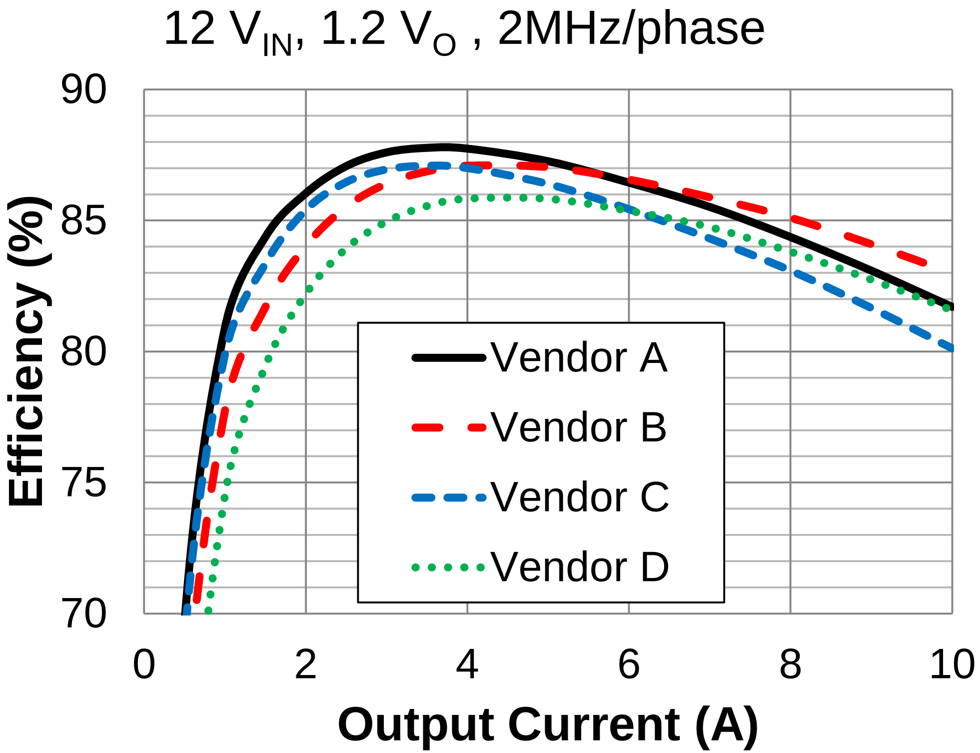
Inductor Size

- Larger inductors tend to result in higher efficiency
  - Thicker wire
  - Lower winding resistance
  - Benefit seen in mid to high load current range
- Measured results for
  - Same inductance
  - Same vendor
  - Same core material



Inductor Vendor

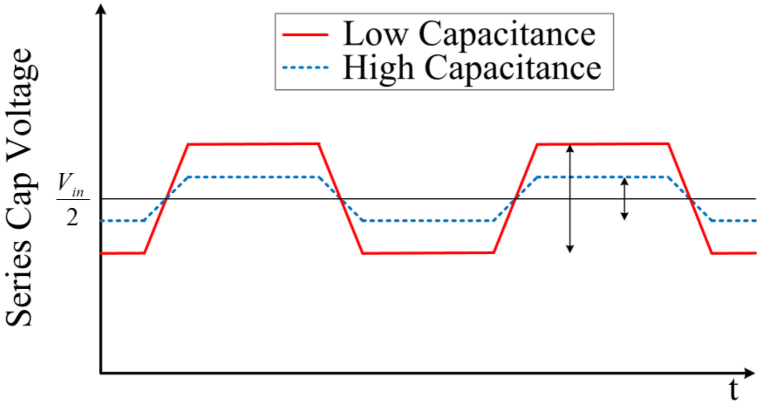
- Finding the right inductor vendor matters
  - Various core material, construction, etc.
  - Should not judge an inductor by DC resistance alone
- Measured results for
  - Same inductance
  - Same size
- If possible, experimentally test inductors



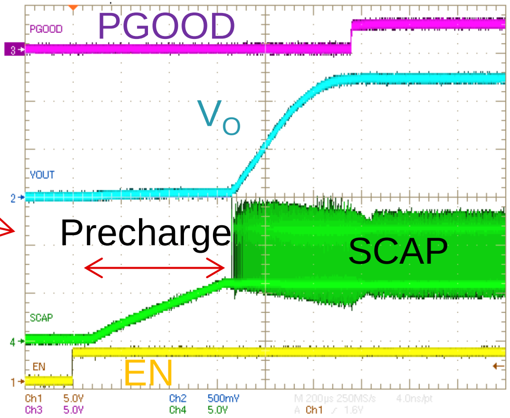
Series Capacitor Selection

- Select the cap value to keep voltage ripple <8% at full load, lowest V_{IN}
  - Ex: 10 A load, 2 MHz, 10.8 V_{IN}, 1.2 V_O

$$C=\frac{DT\left(\frac{i_{out}}{2}\right)}{0.08\left(\frac{V_{in}}{2}\right)}=\frac{\left(\frac{2\times1.2\text{V}}{10.8\text{V}}\right)\frac{1}{2\text{MHz}}\left(\frac{10\text{A}}{2}\right)}{0.08\left(\frac{10.8\text{V}}{2}\right)}=1.29\mu\text{F}$$

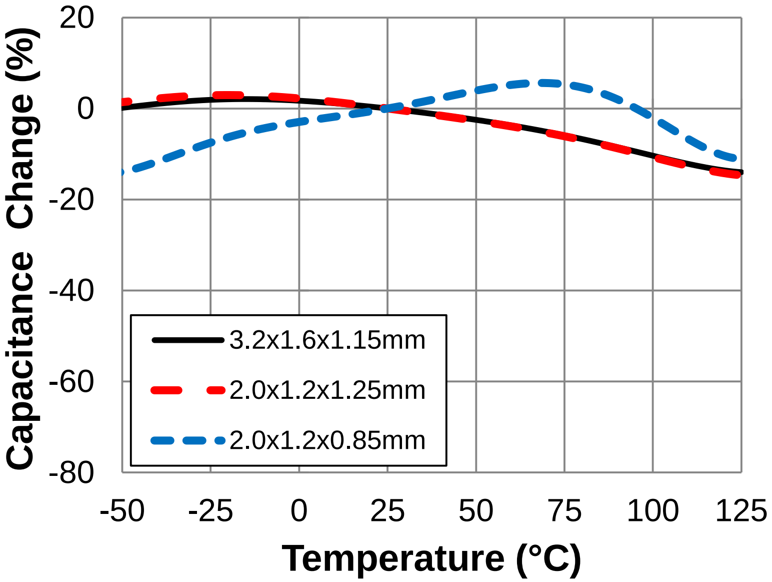


- **Tradeoff**: Startup delay to precharge the series cap
  - 10 mA precharge current into 1 µF cap → 625 µs to precharge to 6 V ($V_{IN,typ}$/2)

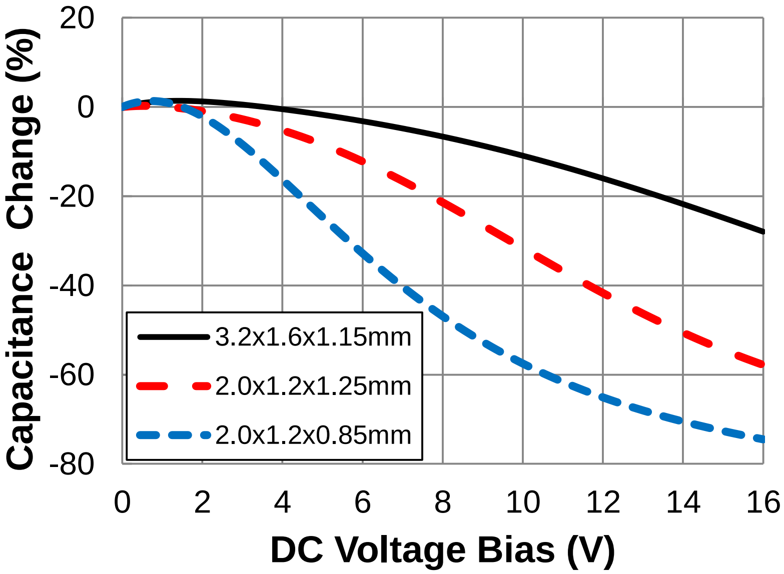


DC Voltage and Temp Impact on Capacitance

- Capacitance varies with temperature



- Capacitance decreases with DC voltage
- Examine capacitance at $V_{IN}/2$



Select a capacitor taking capacitance variation into account

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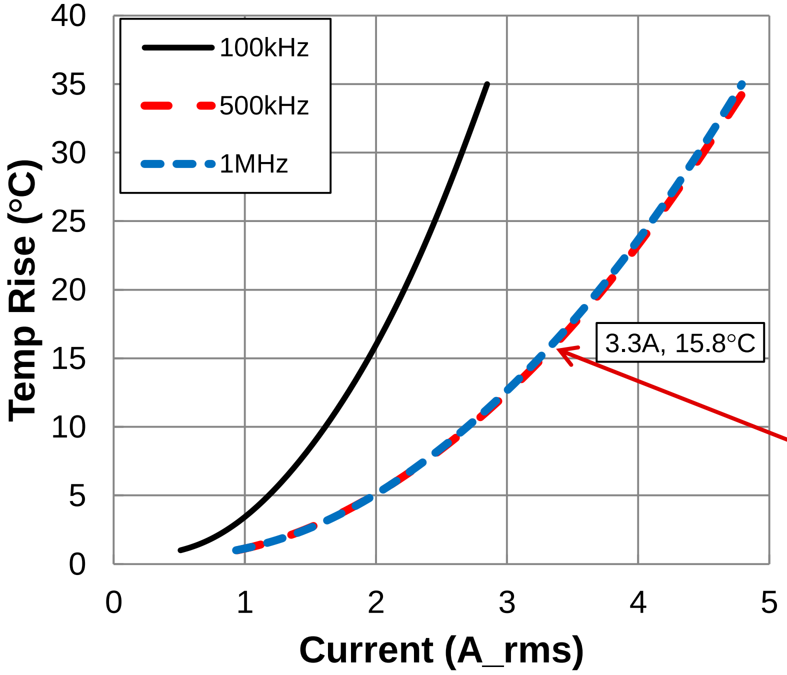
Series Capacitor Self Heating

Capacitor temp rises with current



- Ensure series cap temperature stays within limits
  - Calculate RMS current
  - Check datasheet/online tools
- Ex: $10.8V_{IN,MIN}$, $1.2V_O$, $I_{L,RMS} = 5.02A$

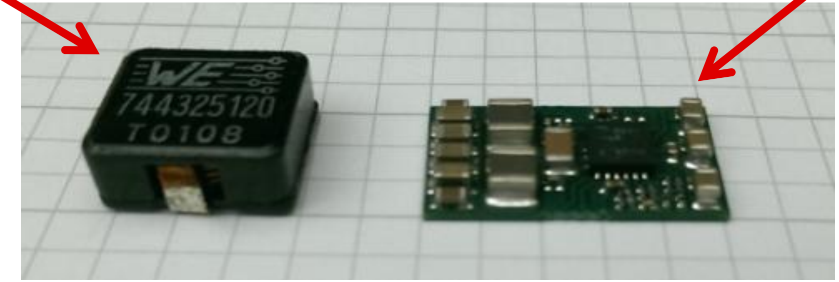
$$\boxed{I_{SCAP,RMS} = \sqrt{2\left(\frac{2V_O}{V_{IN,MIN}}\right)I_{L,RMS}^2} = 3.34A}$$

  - 2.2µF cap, 1206 (3.2 x 1.6 x 1.15mm)
  - Result: **15.8°C temp rise**
- X7R capacitors with 125°C operating temperature rating recommended

Total Solution Size

Inductor on 10A buck EVM
10.2x10.2x4.7mm = 489mm^3

10A series cap buck prototype
16x10x1.85mm = 296mm^3

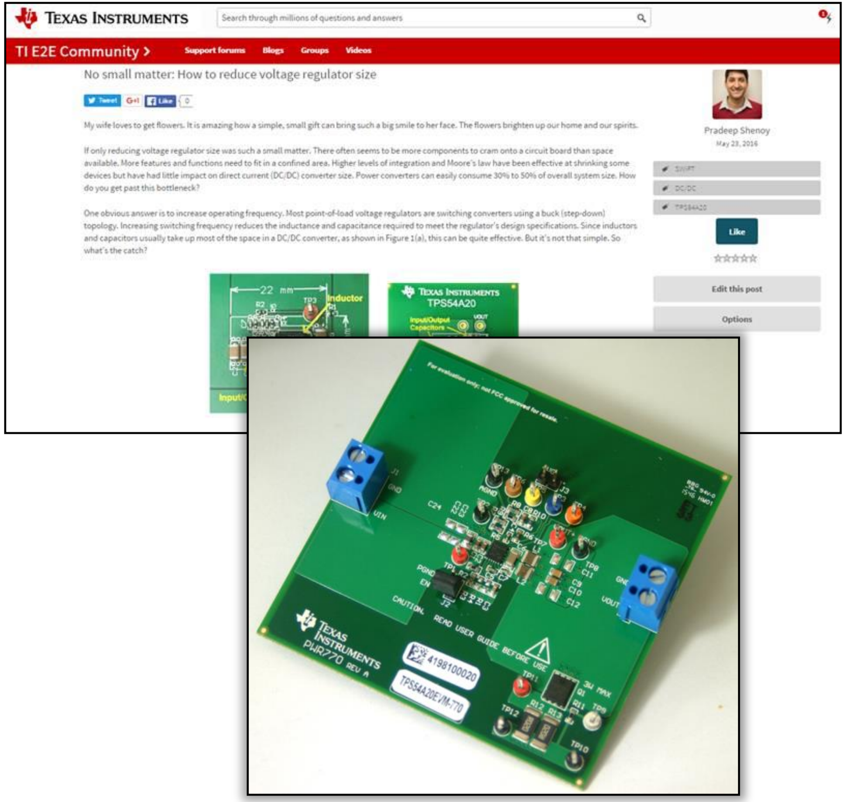


The total solution size is 65% smaller in volume than just the inductor on a competitor's 10A evaluation module!

SUMMARY

- High frequency (HF) operation of switching converters enables size reduction and performance improvements
- Buck converters have fundamental limitations that limit HF operation
- The series capacitor buck converter has unique properties that support HF operation
- Design recommendations for an HF series cap buck converter demonstrate the ease of implementation

Additional Resources



- View the [TPS54A20 product page.]
- View the reference design “Tiny, Low Profile 10A Point-of-load Voltage Regulator.”
- Download the application note “Introduction to the Series Capacitor Buck Converter.”
- Watch the video training series “Designing with TI’s Series Capacitor Buck Converter.”

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