Design of Multi-MHz Series Capacitor Buck Converters Used As Voltage Regulators

Low profile point-of-load dc-dc converter design guidelines

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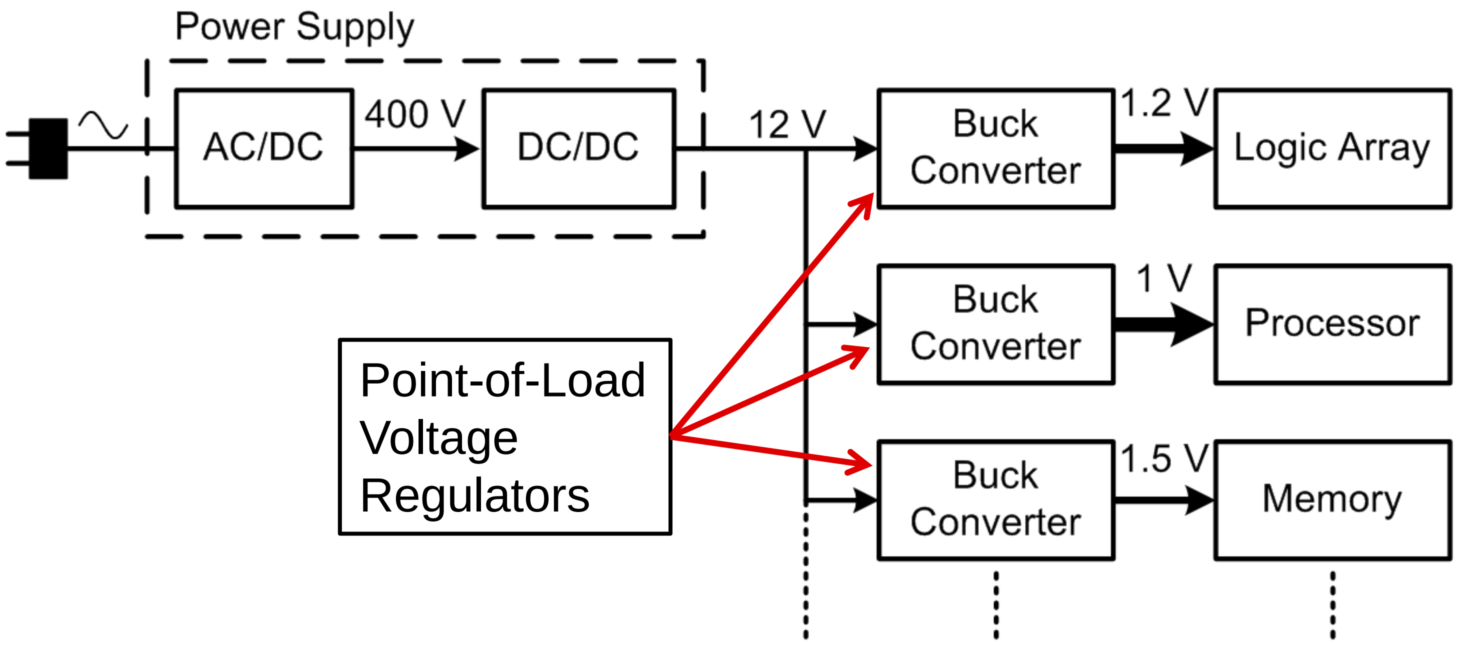
Applied Power Electronics Conference 2017

SLYY129

Power Delivery System

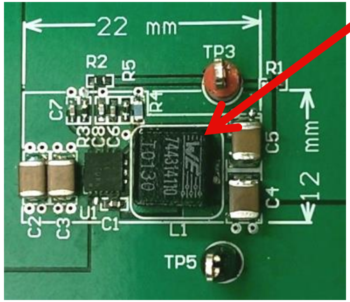


Intermediate Bus Architecture

High Frequency Benefits

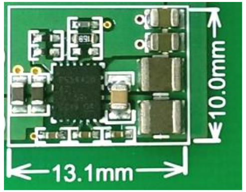
1) Smaller size

Inductors are usually the largest component.



500 kHz Buck

Inductor Volume: 232 mm^3



2-5 MHz Series Cap Buck

Converter Volume: 157 mm^3

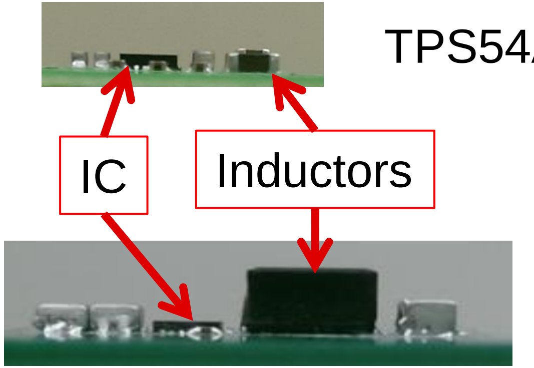
2) Faster Response

3) Lower BOM Cost

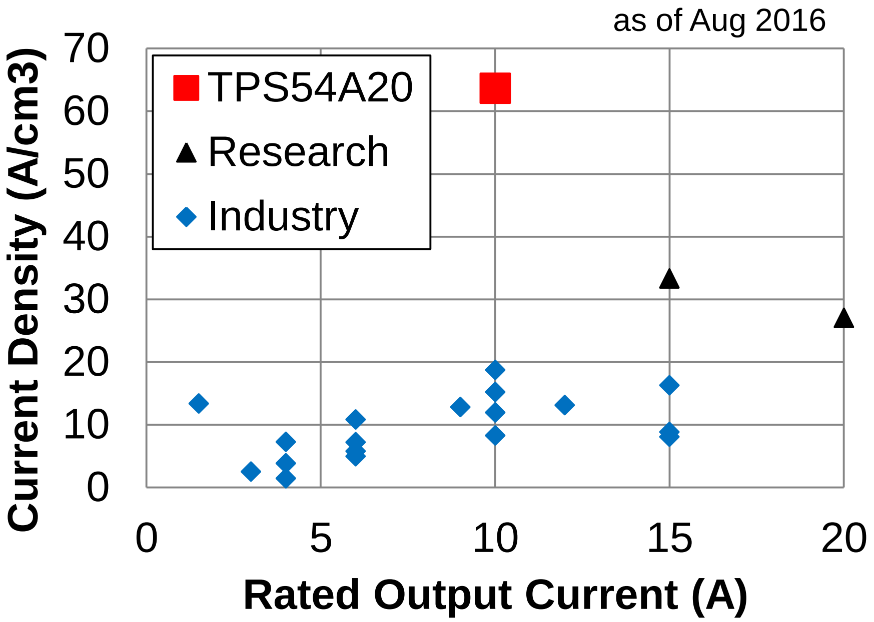
Current Density Comparison

Series Cap Buck: **1.2 mm height**

TPS54A20



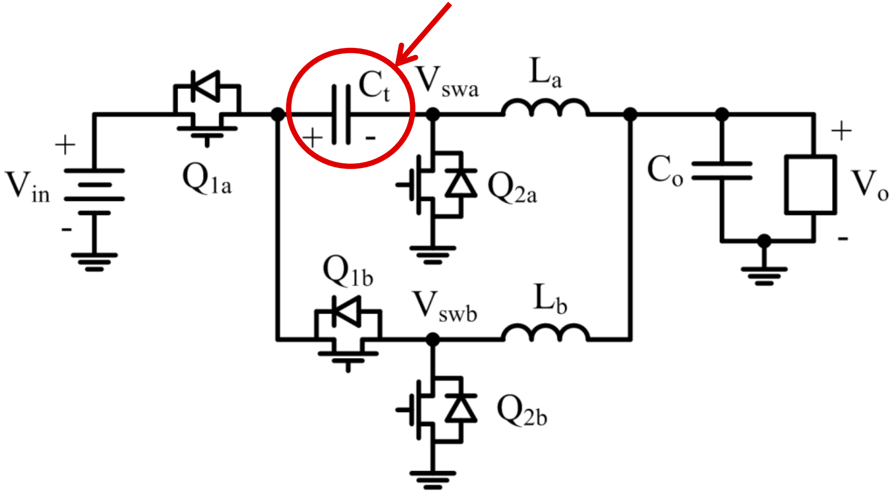
Conventional Buck: **4.8 mm height**



Current density of over 60 A/cm^3 and power density of 1.25 kW/in^3

Series Capacitor Buck Topology

Series capacitor

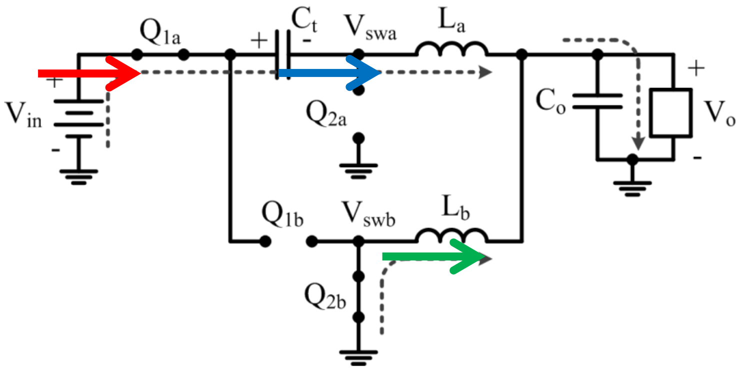


Two-phase, series cap buck converter

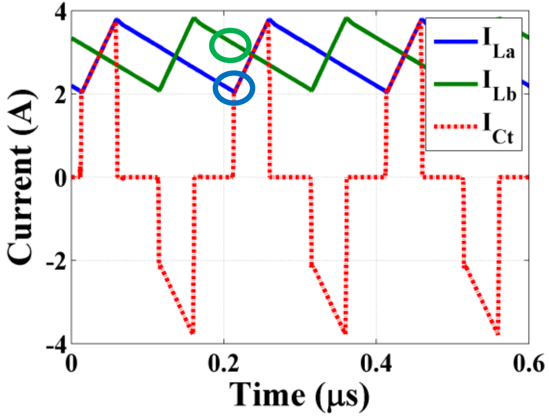
- ✓Benefits
  - ✓**Single** conversion stage
  - ✓Switching at **reduced V_{ds}**
  - ✓Series cap **soft** charge/discharge
  - ✓**Automatic** current balancing
  - ✓Duty ratio **doubled**
- Drawback
  - **50% duty cycle** limitation
    - Theoretical: $V_{IN,MIN} = 4 \times V_{OUT}$
    - Practical: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

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.

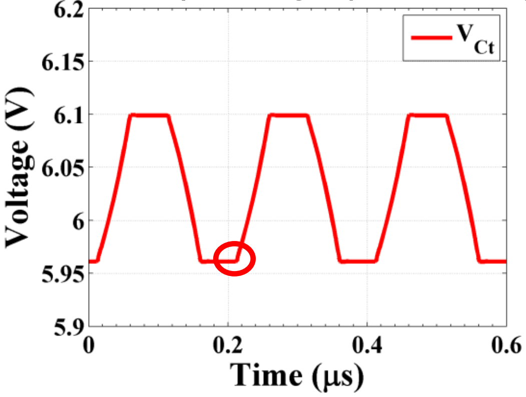
Steady-State Operation: Interval 1



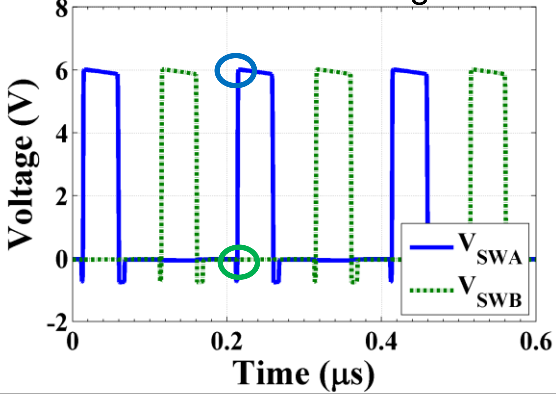
Inductor & series cap currents



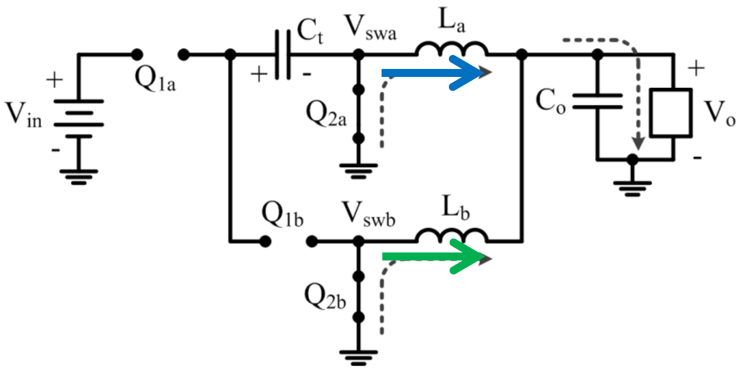
Series cap voltage (differential)

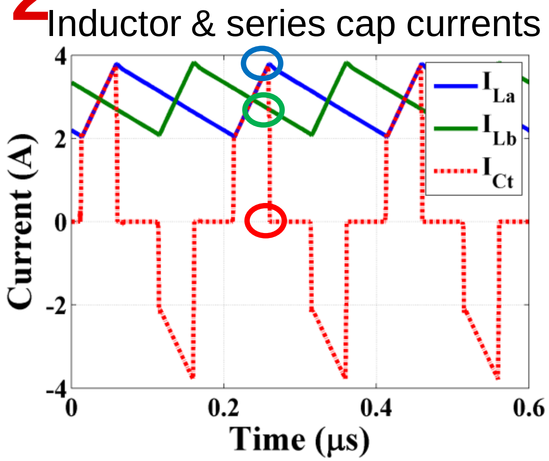


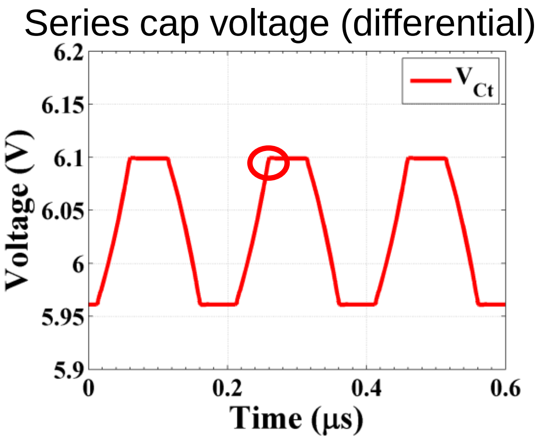
Switch node voltages

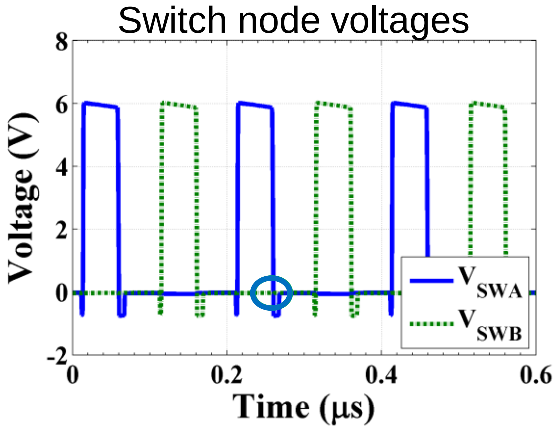


Steady-State Operation: Interval 2

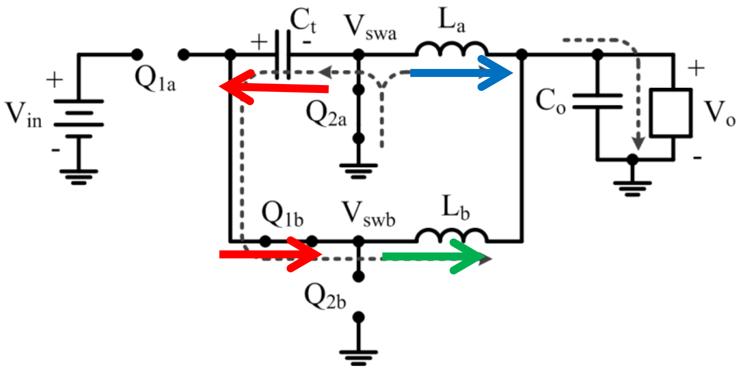




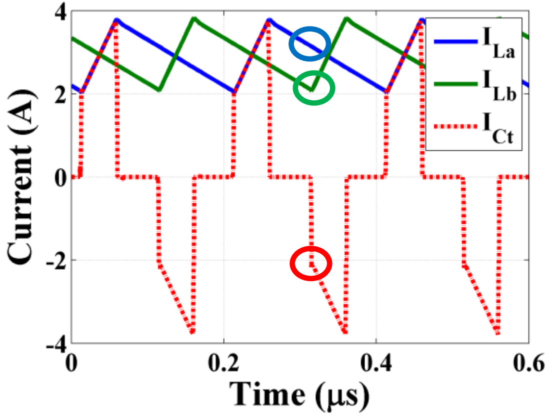




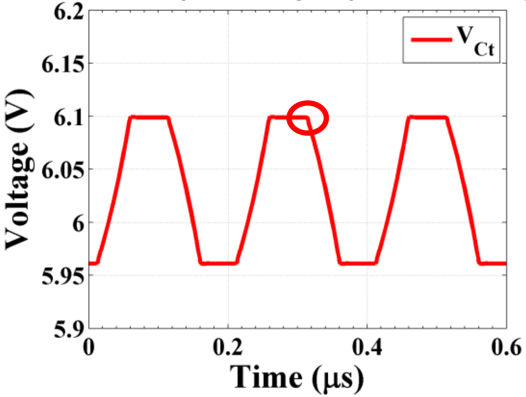
Steady-State Operation: Interval 3



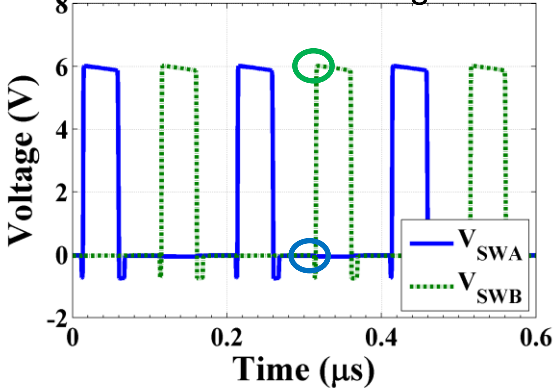
Inductor & series cap currents



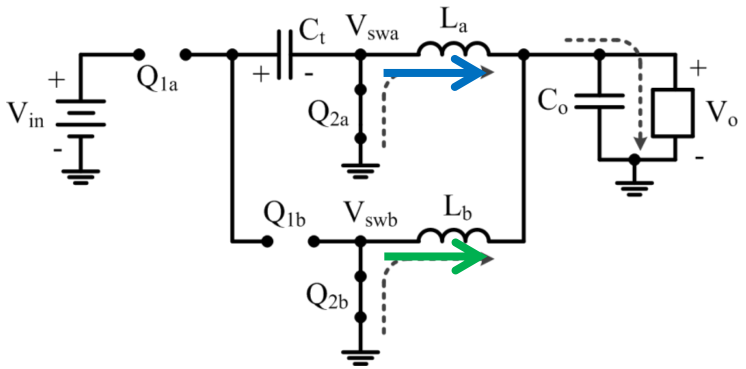
Series cap voltage (differential)



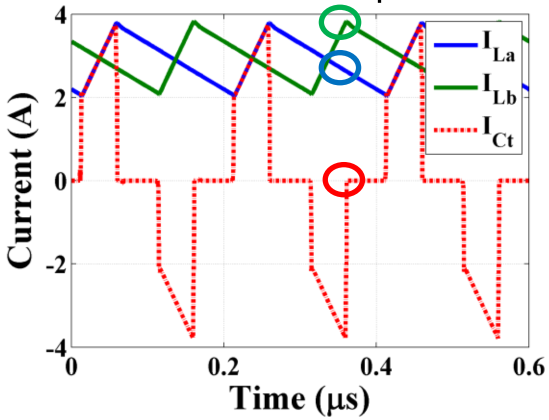
Switch node voltages



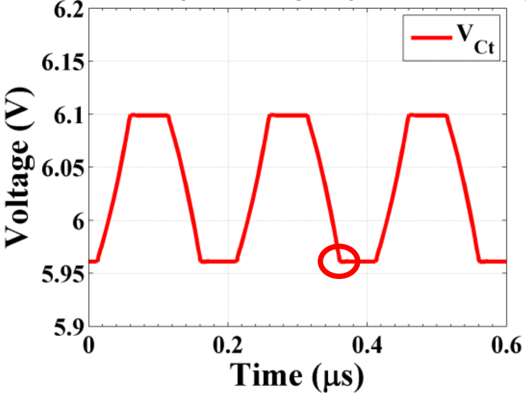
Steady-State Operation: Interval 4



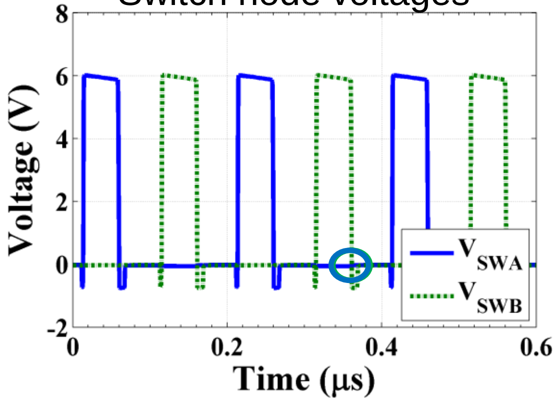
Inductor & series cap currents



Series cap voltage (differential)



Switch node voltages



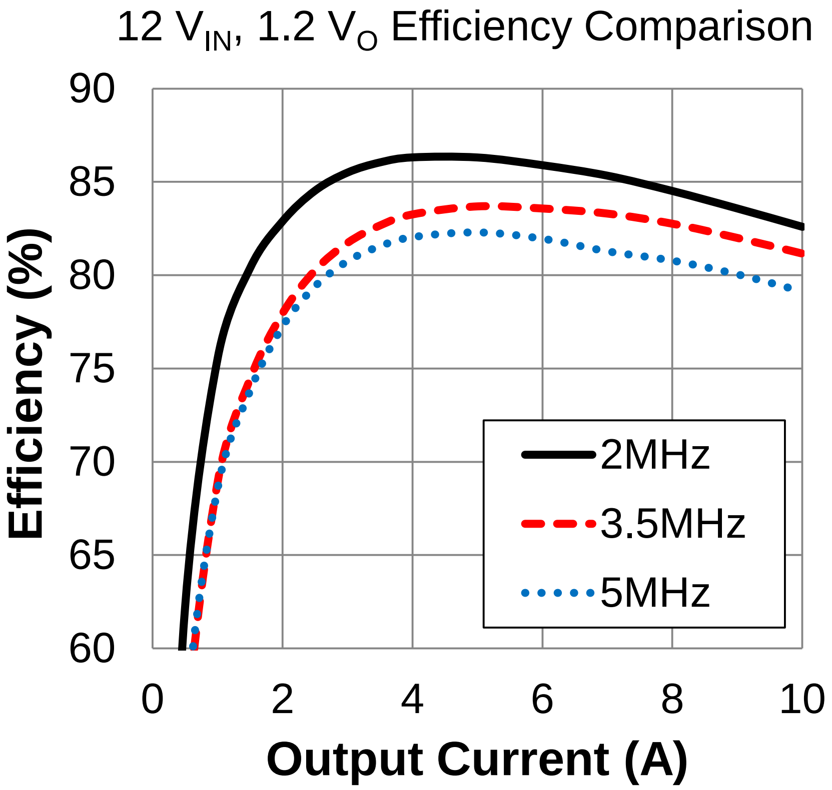
Example Design Specifications

Parameter		Conditions	Min	Typ	Max	Unit
V_{OUT}	Output voltage	±3% of typical	1.164	1.2	1.236	V
I_{OUT}	Output current		0	8	10	A
V_{IN}	Input voltage	±10% of typical	10.8	12	13.2	V
ΔV_{OUT}	Transient response	5-A load step		25		mV

Other aspects to consider:

- Overall converter size
- Power (heat) dissipation
- Solution cost

Choosing the Switching Frequency



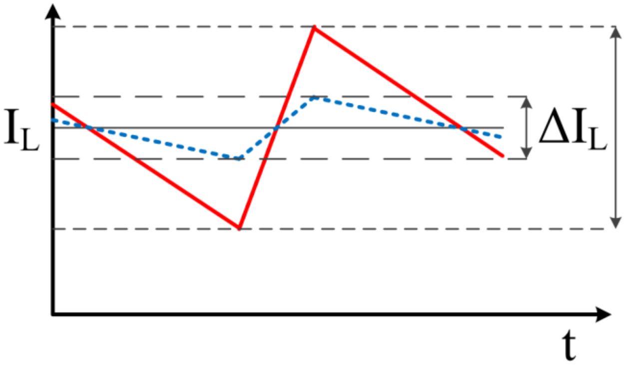
- Higher frequency operation reduces overall **converter size**
  - Lower inductance required
  - Fewer decoupling capacitors
- **Tradeoff**: efficiency decreases with increased switching frequency
- Select 2 MHz per phase for this example

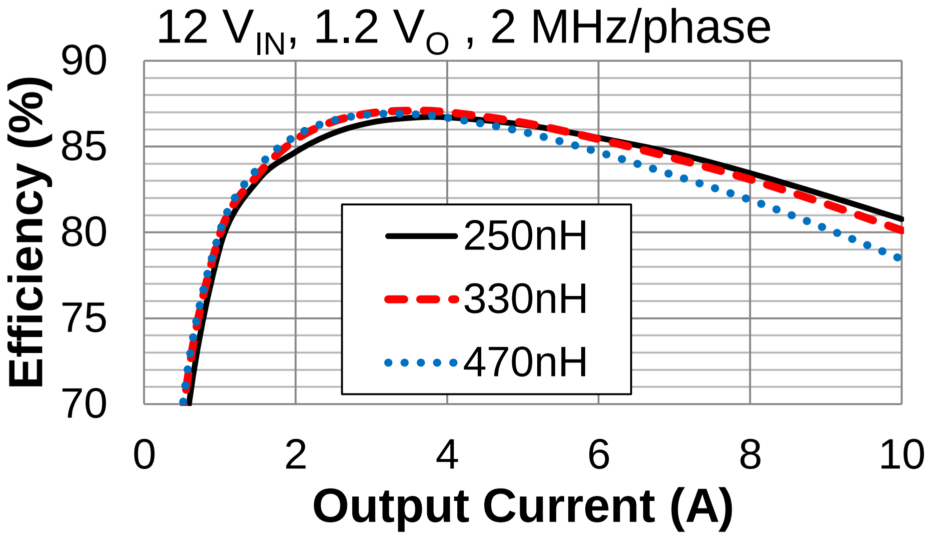
Inductance Impact on Efficiency

- 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

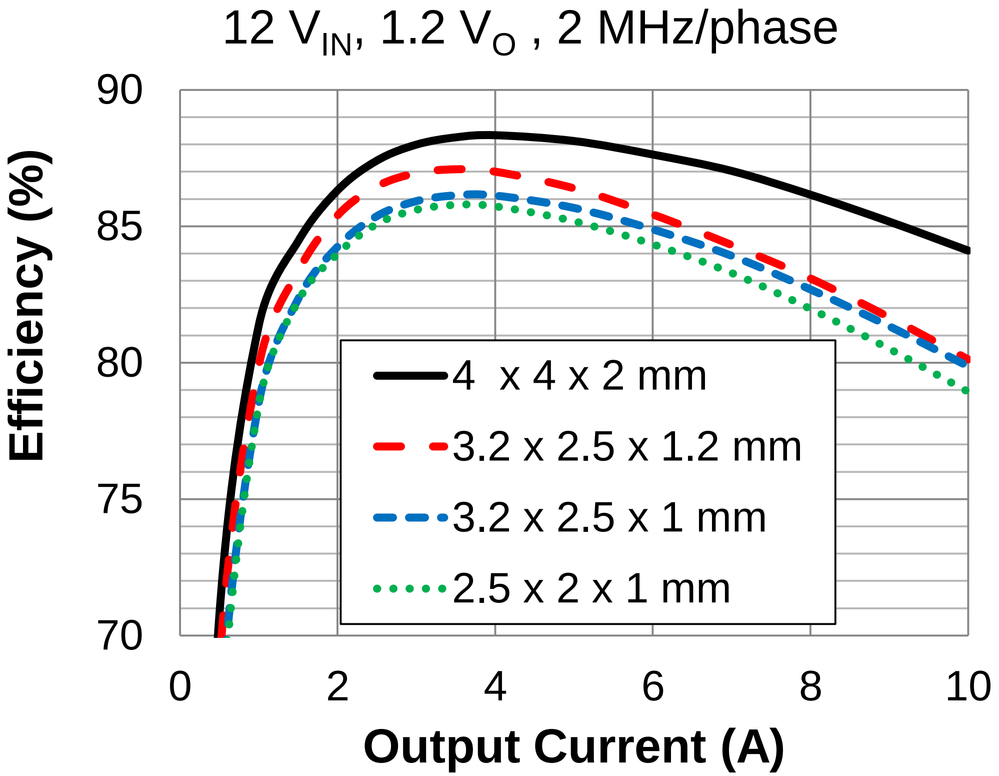




- Higher inductance tends to increase **peak efficiency**
- Lower inductance has higher **full load efficiency**

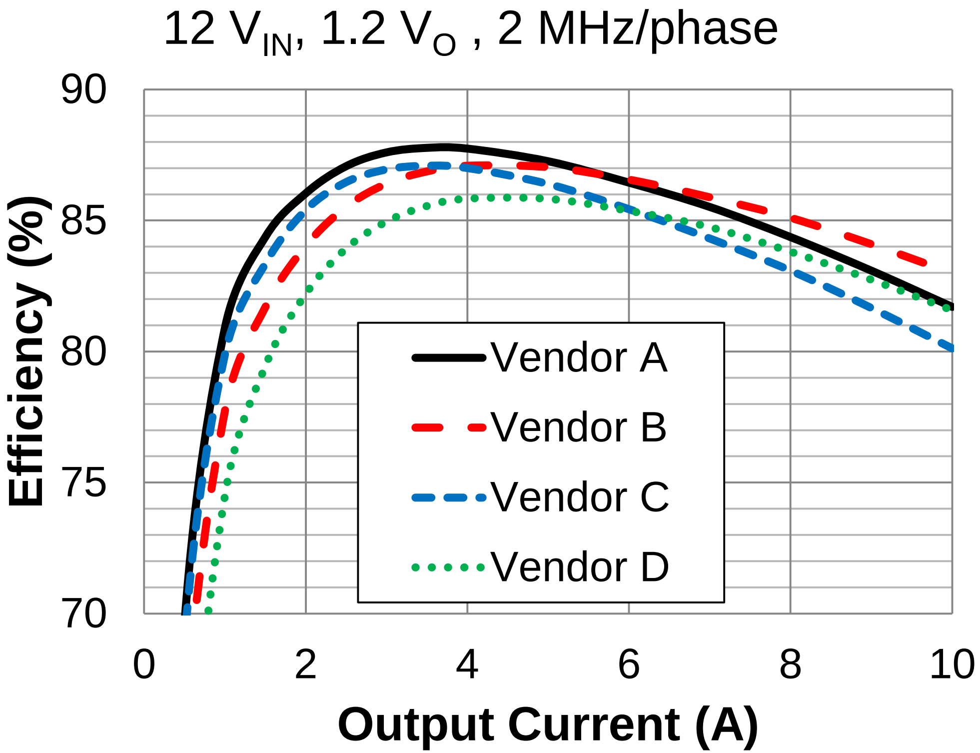
Inductor Size

- 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

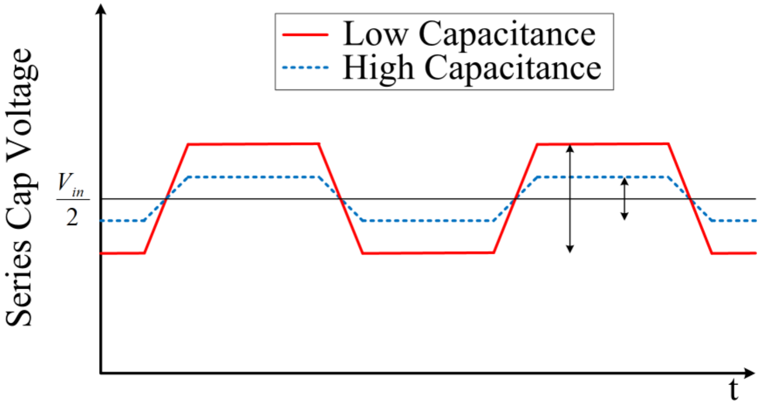
- Finding the right inductor **vendor matters**
  - Various core material, construction, etc.
  - Should not judge an inductor by DC resistance alone
- Measured results for
  - **Same** inductance
  - **Same** size
- If possible, experimentally **test inductors**



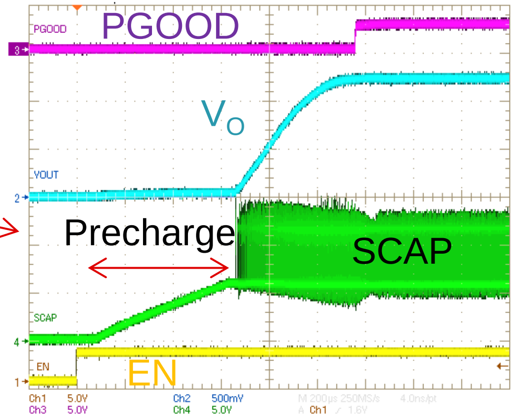
Series Capacitor Selection

- 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

$$C = \frac{DT\left(i_{out}/2\right)}{0.08\left(V_{in}/2\right)} = \frac{\left(\frac{2\times 1.2V}{10.8V}\right)\frac{1}{2MHz}\left(10A/2\right)}{0.08\left(10.8V/2\right)} = 1.29\mu F$$



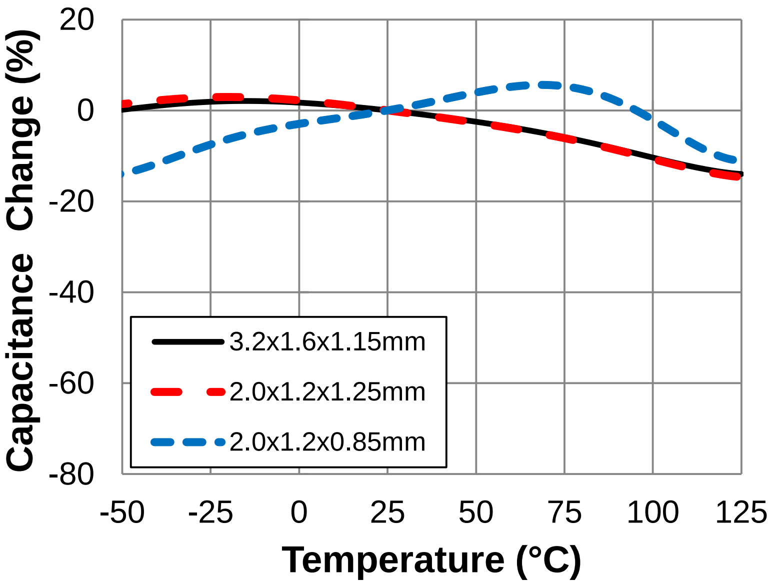
- **Tradeoff**: Startup delay to precharge the series cap
  - 10 mA precharge current into 1 µF cap → 625 µs to precharge to 6 V ($V_{IN,typ}$/2)



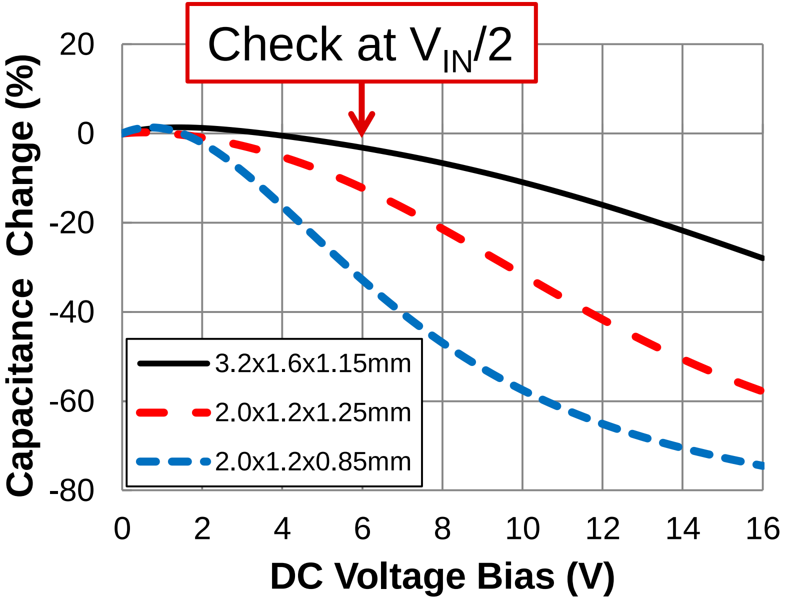
TEXAS INSTRUMENTS

DC Voltage and Temp Impact on Ceramic Caps

Capacitance **varies** with temperature



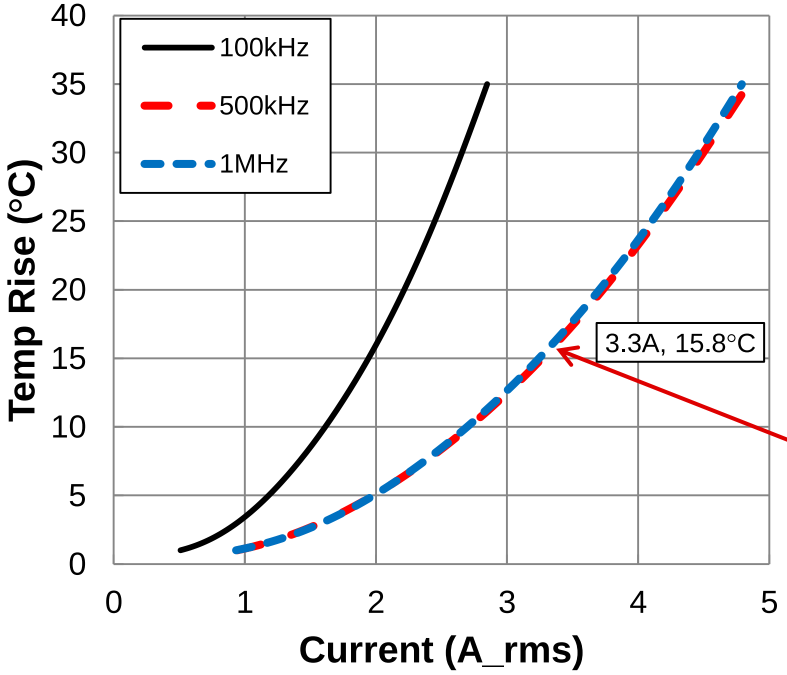
Capacitance **decreases** with DC voltage



Select a capacitor taking capacitance **variation** into account

Series Capacitor Self Heating

Capacitor temp **rises** with current



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

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

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

Output Capacitor Selection

- Load step down:
  - Ex: $\Delta I_{o,max}$ = 5 A, L = 330 nH, Vo = 1.2 V, $\Delta V_{o,max}$ = 25 mV, $V_{IN,min}$ = 10.8 V

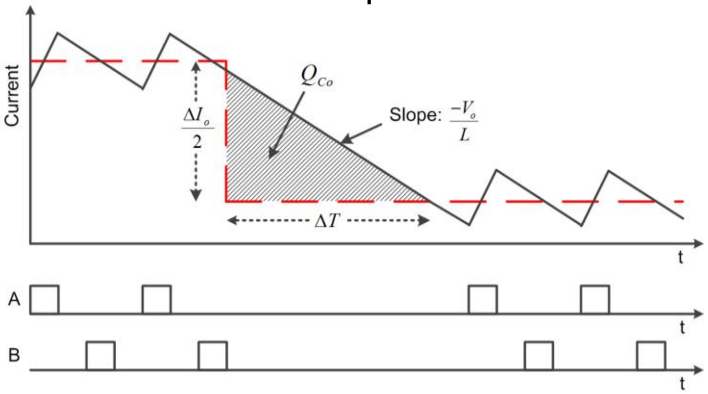
$$C_o \geq \frac{(\Delta I_{o,\max})^2 L}{4V_o \Delta V_{o,\max}} = 66\mu\text{F}$$

- Load step up:

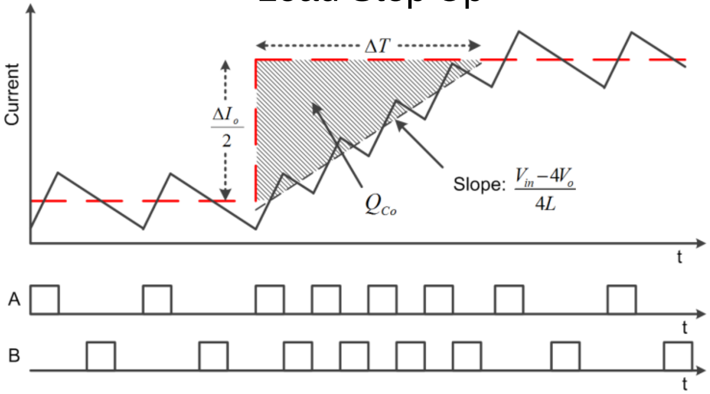
$$C_o \geq \frac{2L(\Delta I_{o,\max})^2}{(V_{IN,\min} - 4V_o)\Delta V_{o,\max}} = 106\mu\text{F}$$

- Select **largest value** and take variation in to account

Load Step Down

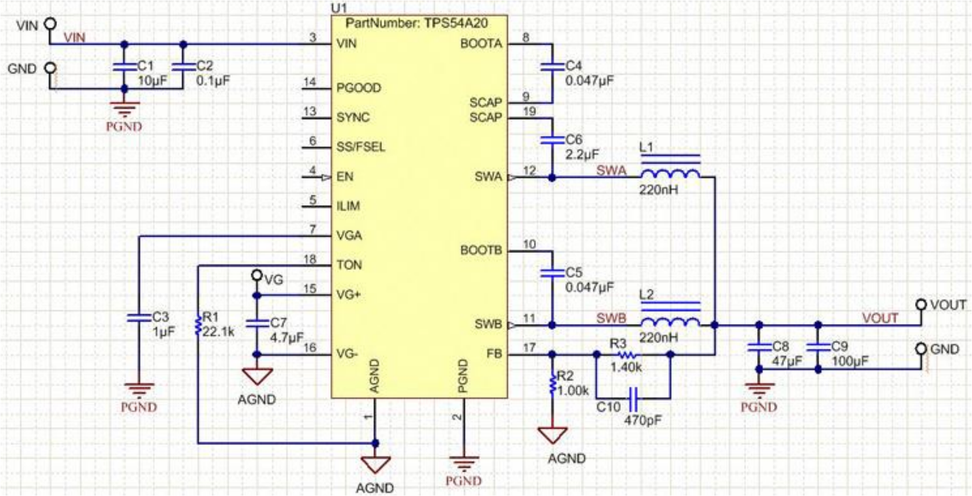


Load Step Up



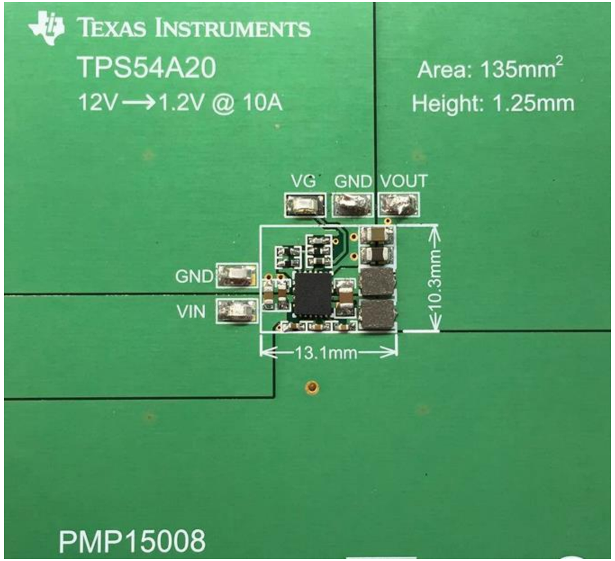
Reference Design PMP15008

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



Schematic

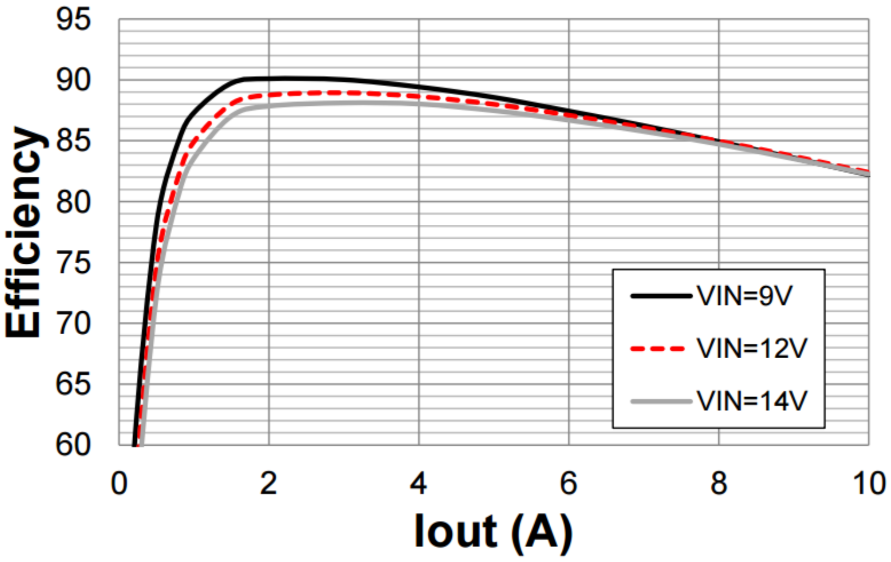
Board Image

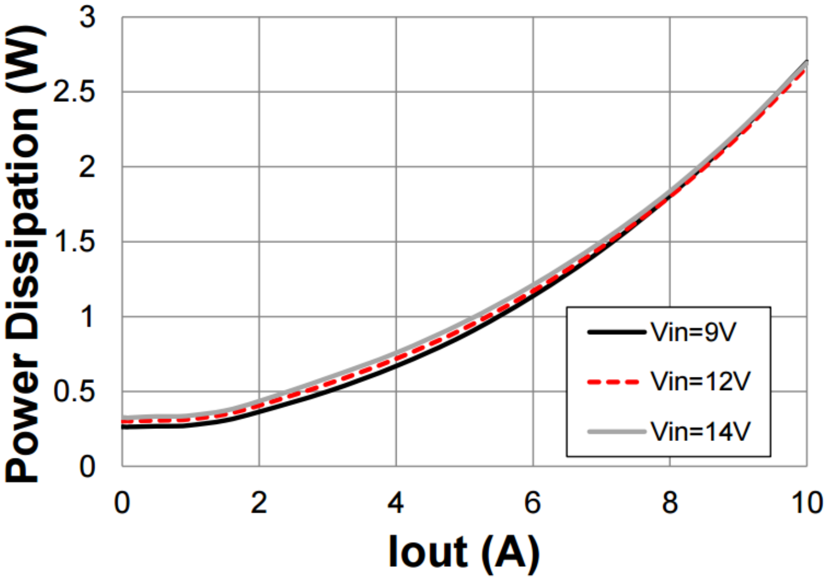


Total solution size is 135 mm² and 1.25 mm tall

Efficiency and Power Loss

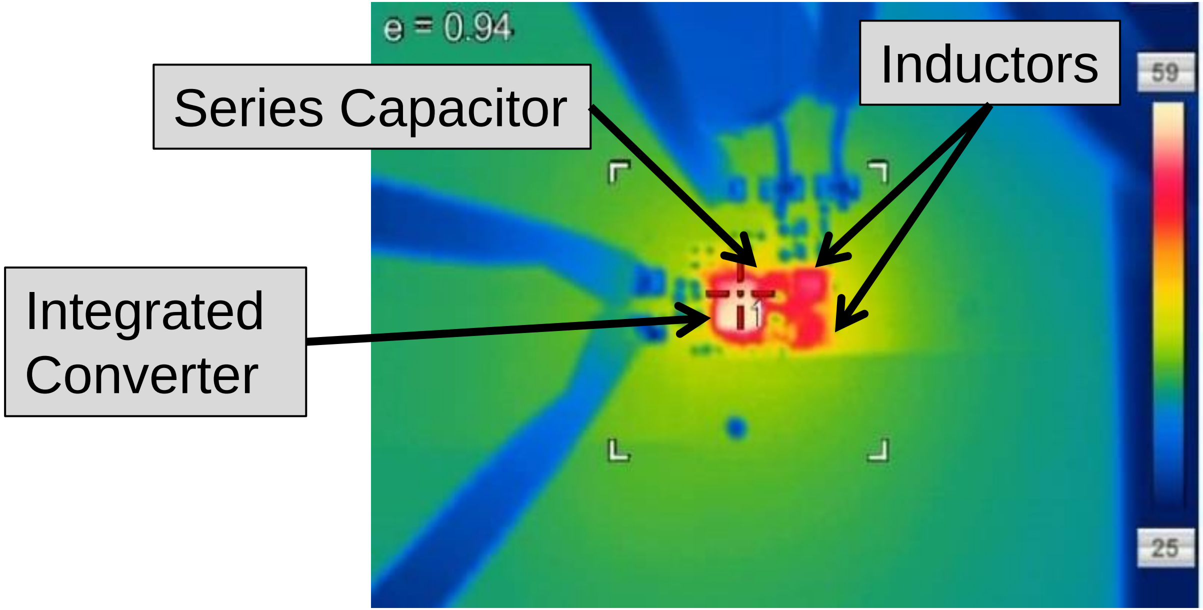
2 MHz per phase, 1.2 V_{OUT}, room temperature, no air flow, two layer board





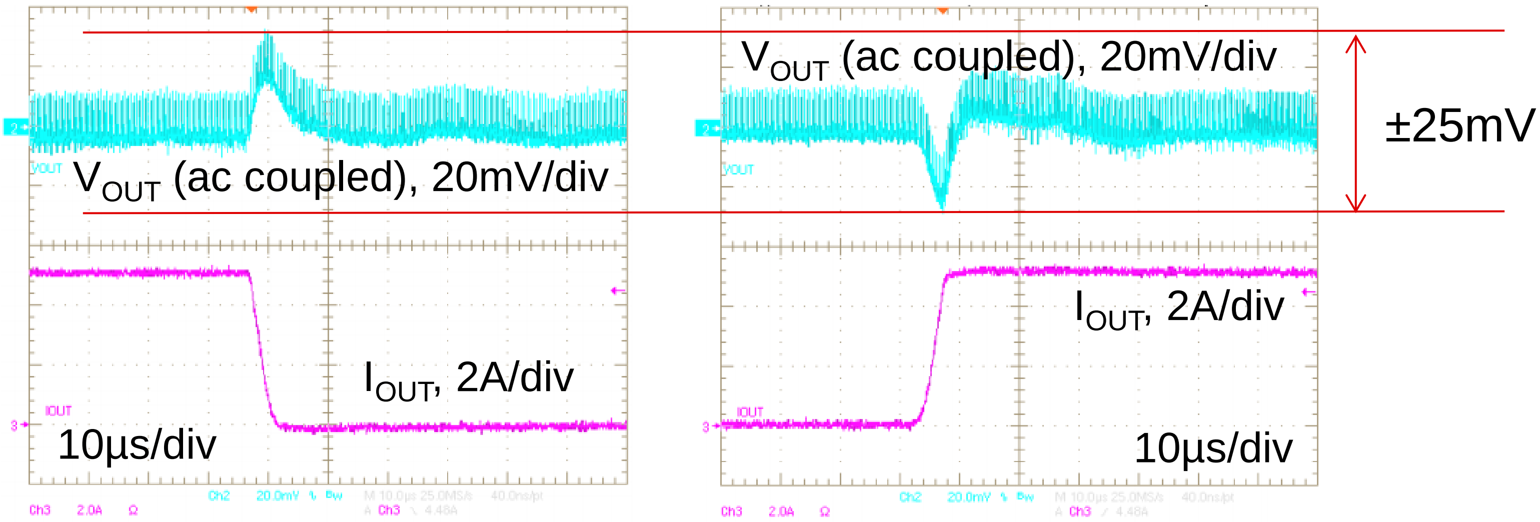
Over 90% efficiency at 9 V input, less than 3 W loss at full load

Thermal Image



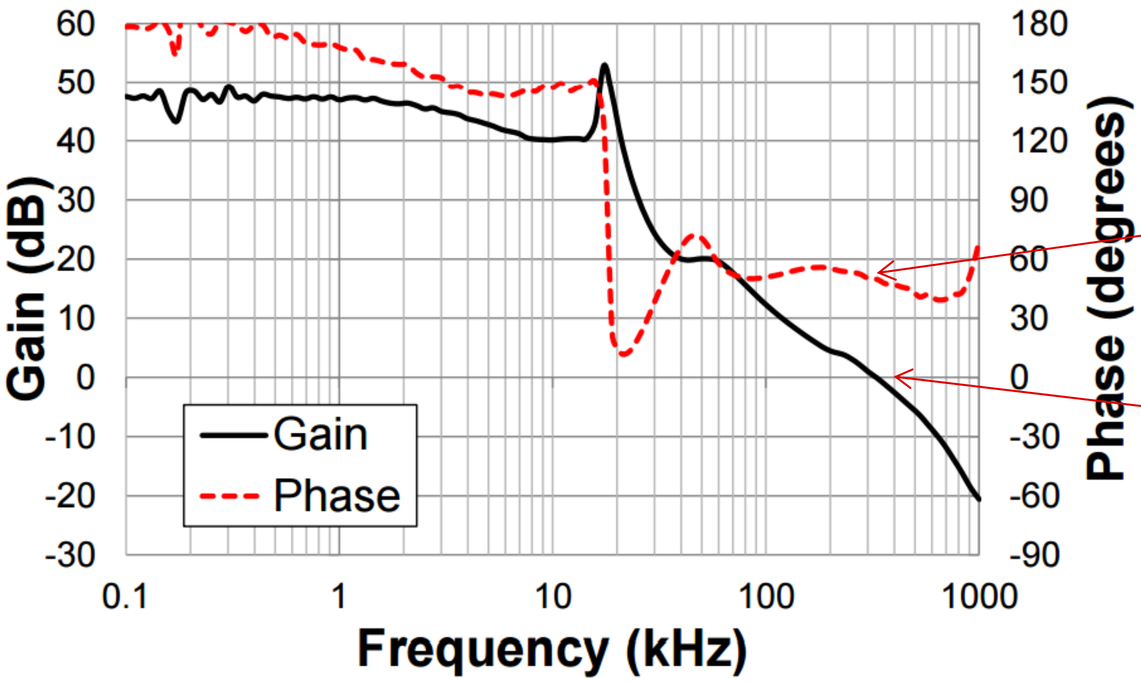
Less than 35°C temp rise at 12 V input, 8 A output

Load Transient Response



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

High Bandwidth and Ample Phase Margin

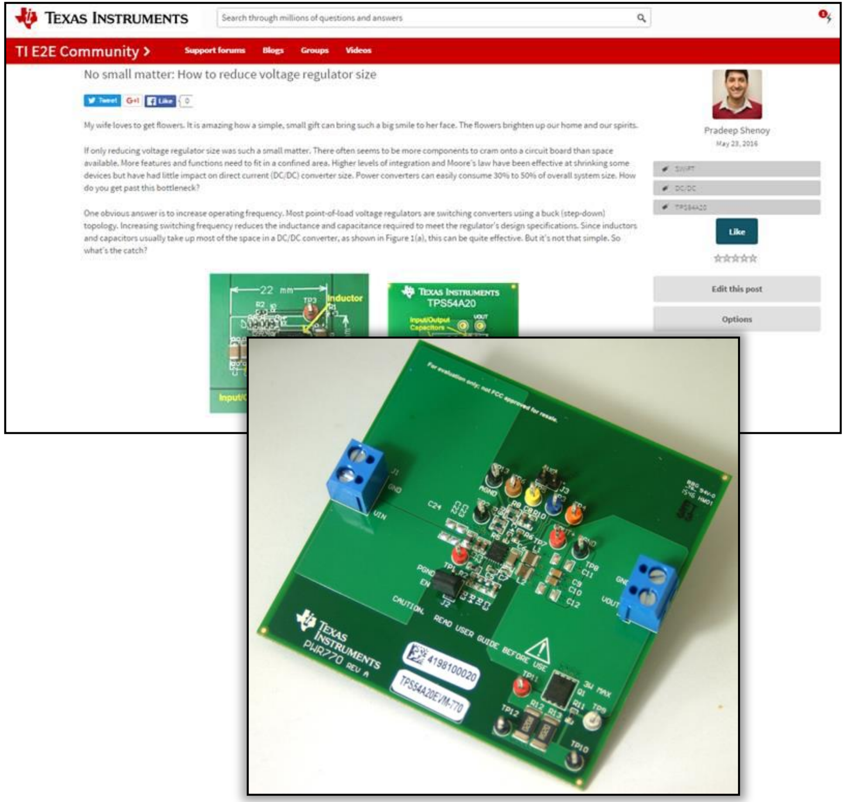


Over **50 degrees** of phase margin

Over **300 kHz** bandwidth

Bode plot taken with 12 V input, 5 A output

Additional Resources



- 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."

SUMMARY

- High frequency operation of switching converters supports **size reduction** and **performance improvements**
- The series capacitor buck converter has unique properties that facilitate **efficient** high frequency operation
- **Design recommendations** for a multi-MHz series cap buck converter enable easy implementation
- **Experimental results** demonstrate the stable, fast, efficient capabilities of an example voltage regulator

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