

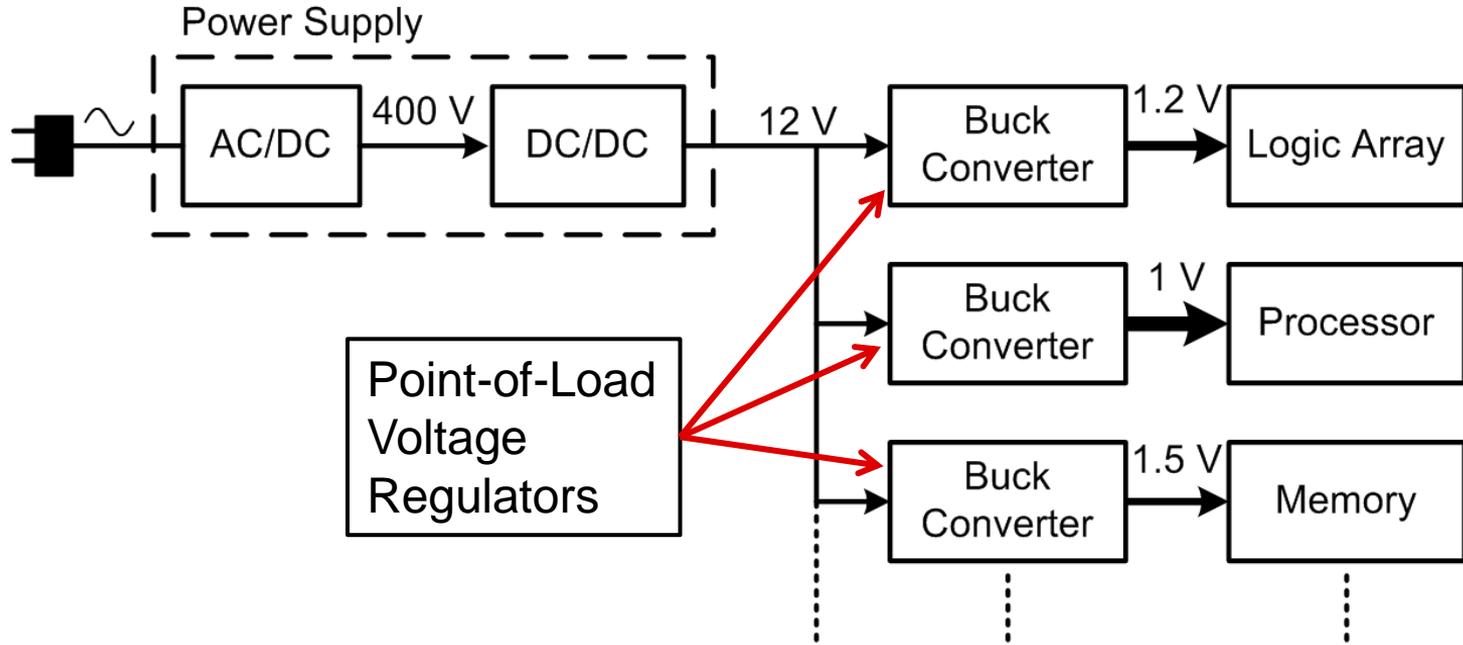
# Design of Multi-MHz Series Capacitor Buck Converters Used As Voltage Regulators

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

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Applied Power Electronics Conference 2017

SLYY129

# Power Delivery System

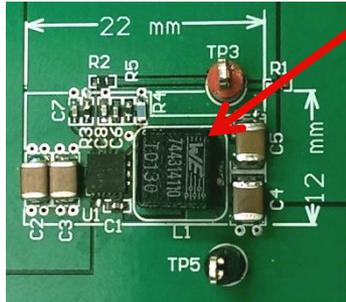


Intermediate Bus Architecture

# High Frequency Benefits

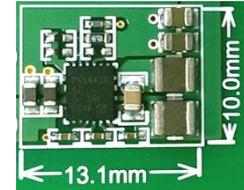
## 1) Smaller size

Inductors are usually the largest component.



**500 kHz Buck**

Inductor Volume: 232 mm<sup>3</sup>



**2-5 MHz Series Cap Buck**

Converter Volume: 157 mm<sup>3</sup>

## 2) Faster Response

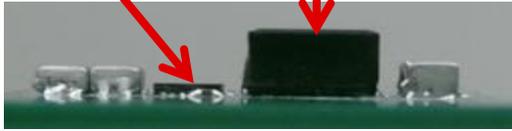
## 3) Lower BOM Cost

# Current Density Comparison

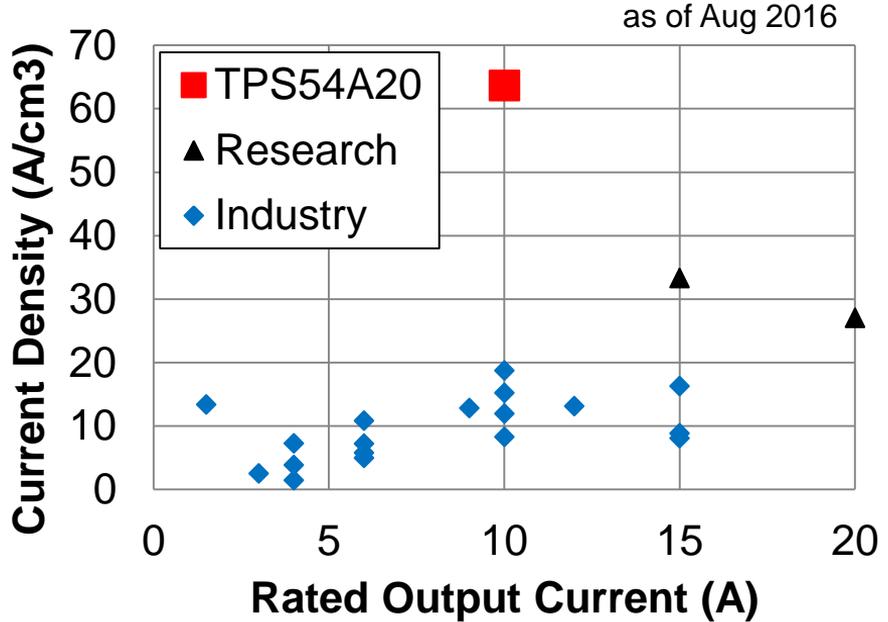
Series Cap Buck: **1.2 mm height**



TPS54A20

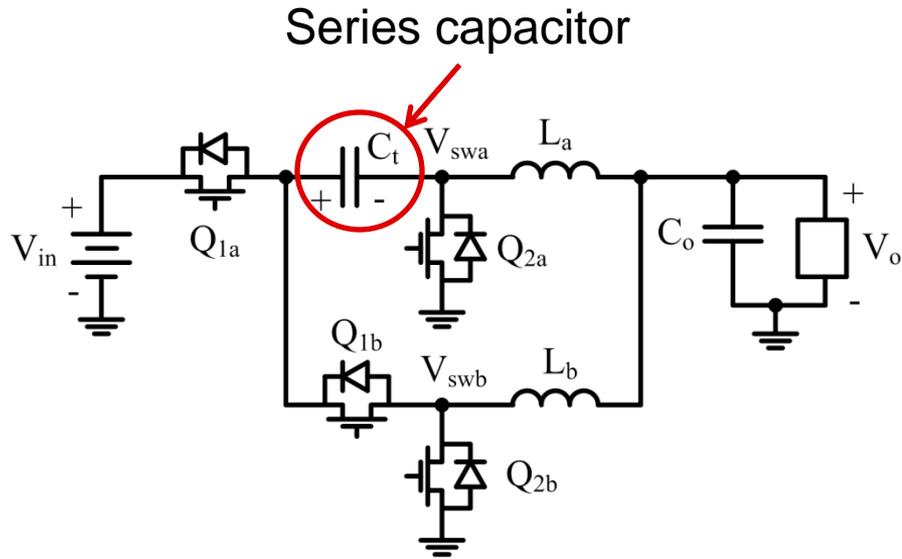


Conventional Buck: **4.8 mm height**



**Current density of over 60 A/cm<sup>3</sup> and power density of 1.25 kW/in<sup>3</sup>**

# Series Capacitor Buck Topology



## ✓ Benefits

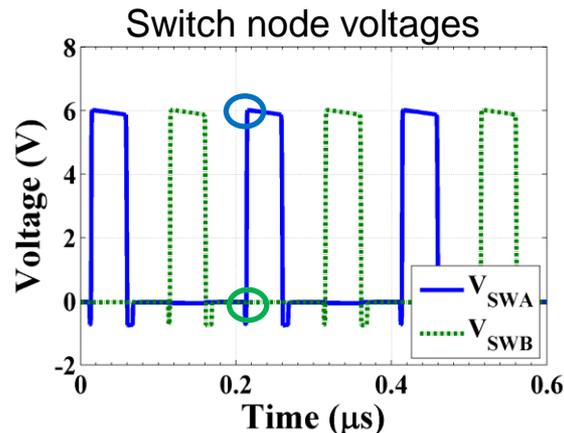
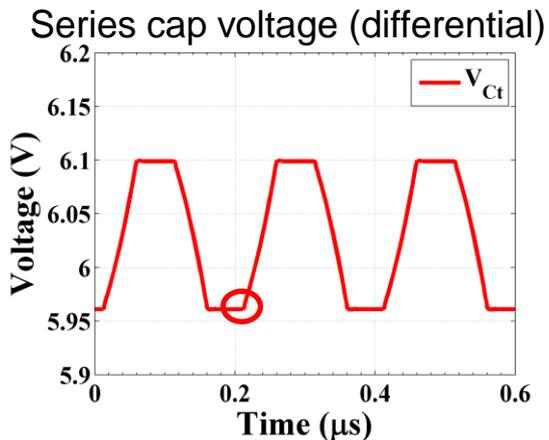
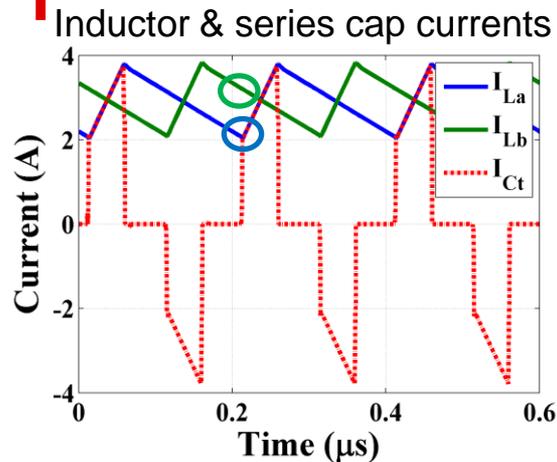
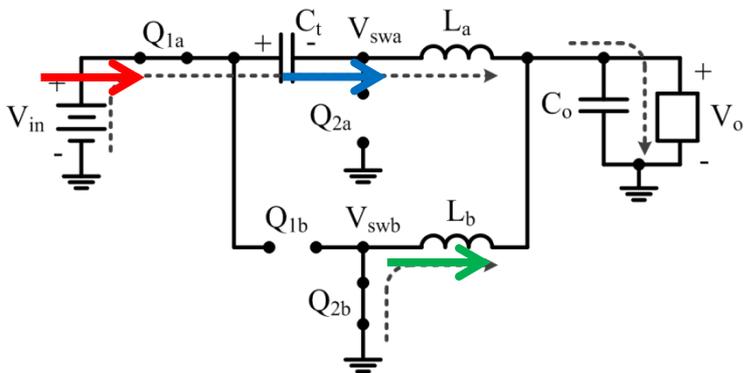
- ✓ **Single** conversion stage
- ✓ Switching at **reduced**  $V_{ds}$
- ✓ Series cap **soft** charge/discharge
- ✓ **Automatic** current balancing
- ✓ Duty ratio **doubled**

## • Drawback

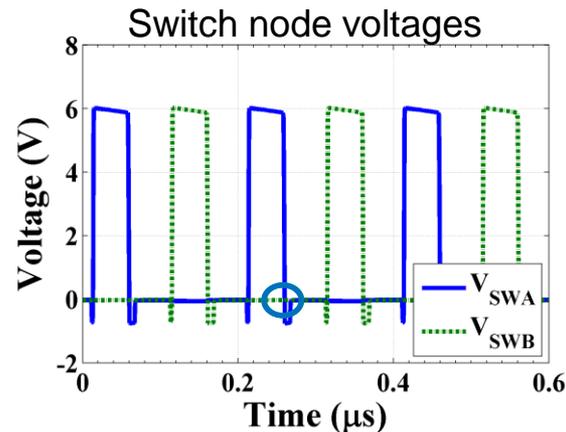
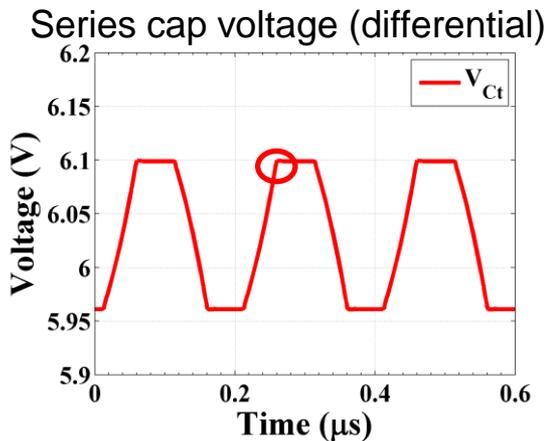
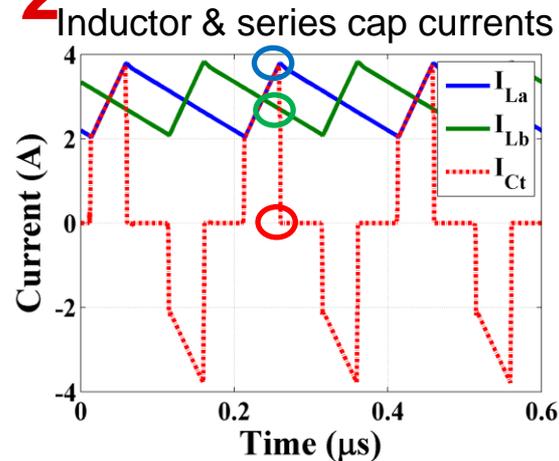
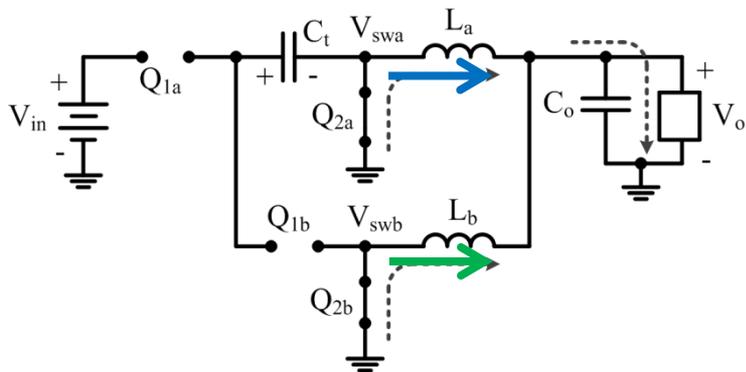
- **50% duty cycle** limitation
  - Theoretical:  $V_{IN,MIN} = 4 \times V_{OUT}$
  - Practical:  $V_{IN,MIN} = 5 \times V_{OUT}$

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.

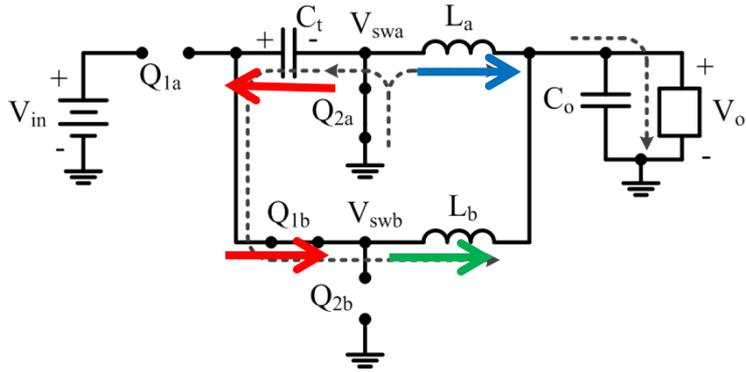
# Steady-State Operation: Interval 1



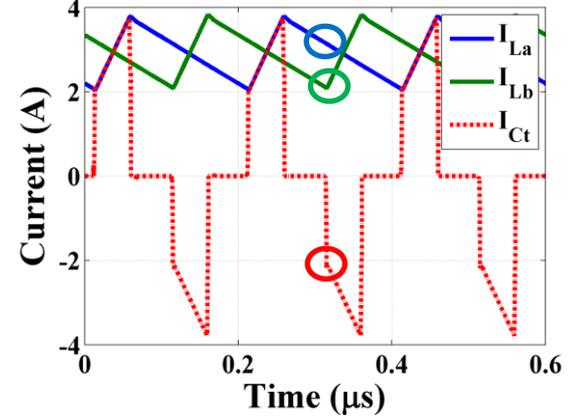
# Steady-State Operation: Interval 2



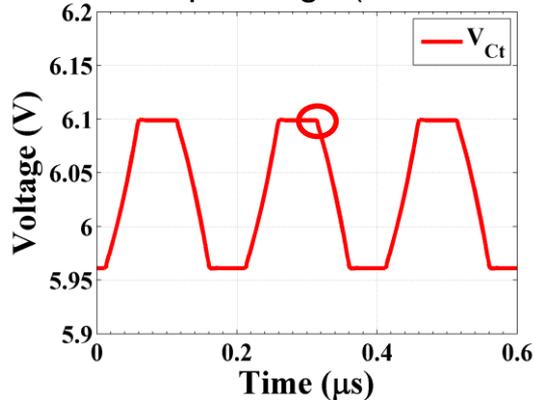
# Steady-State Operation: Interval 3



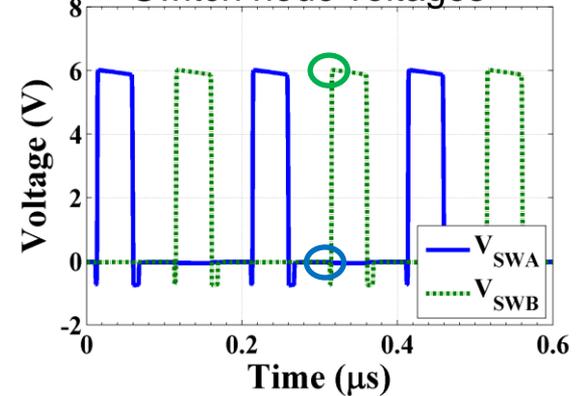
Inductor & series cap currents



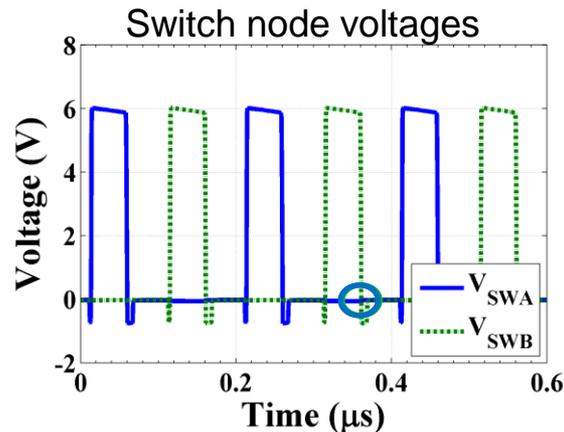
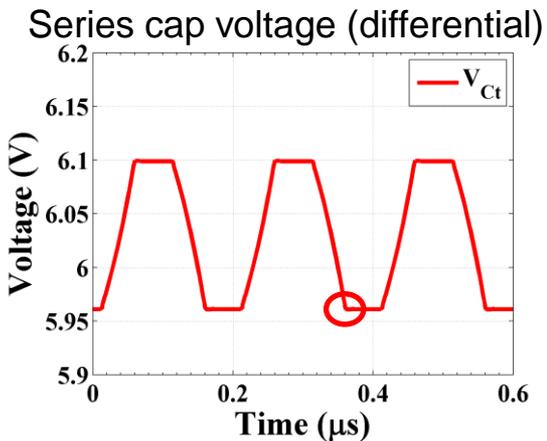
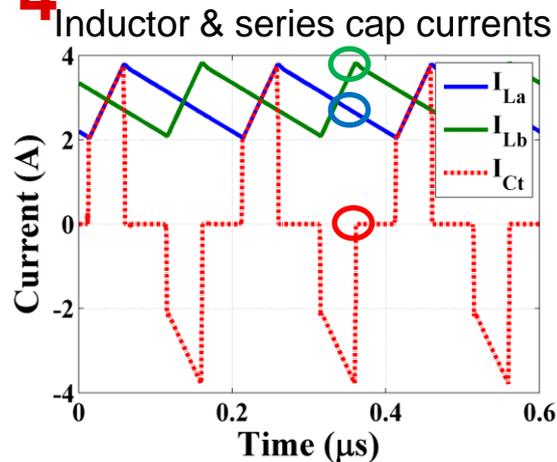
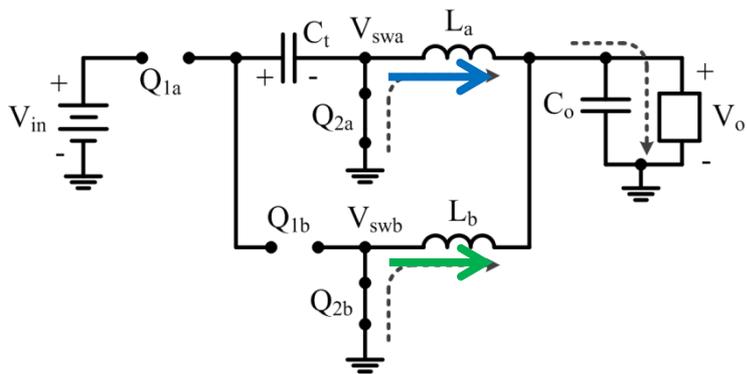
Series cap voltage (differential)



Switch node voltages



# Steady-State Operation: Interval 4



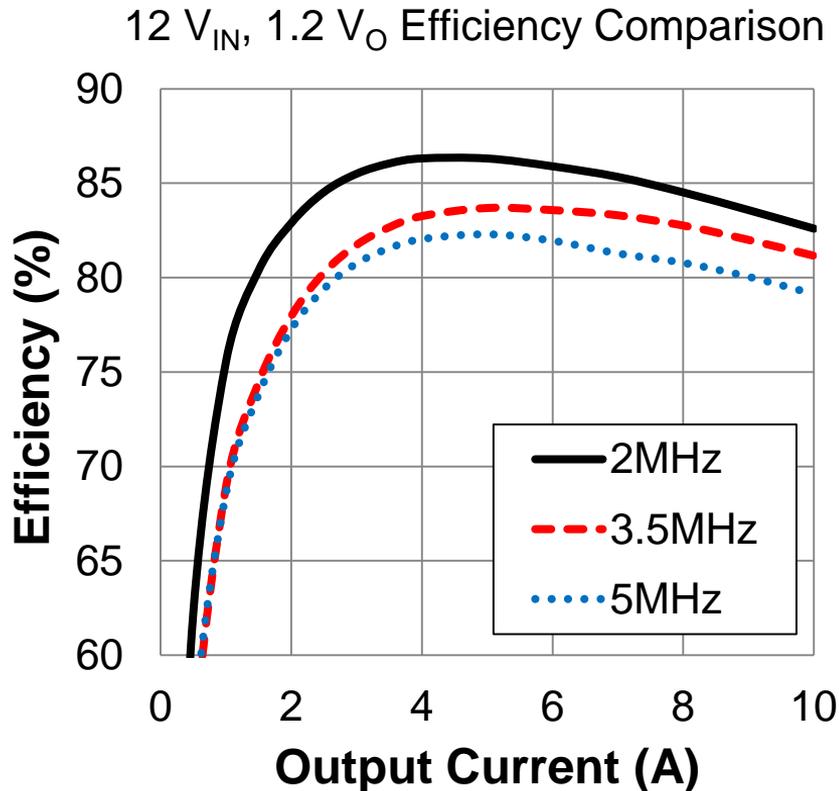
# Example Design Specifications

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

Other aspects to consider:

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

# Choosing the Switching Frequency



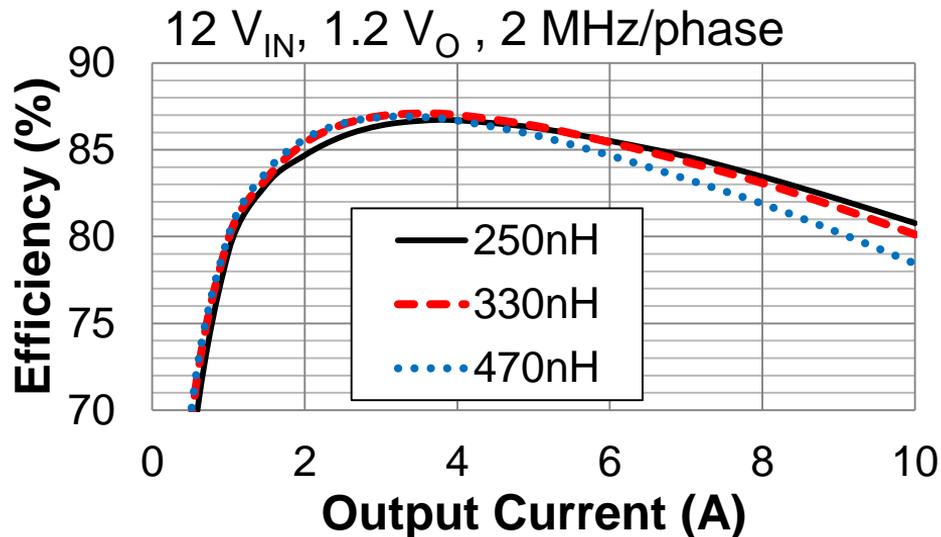
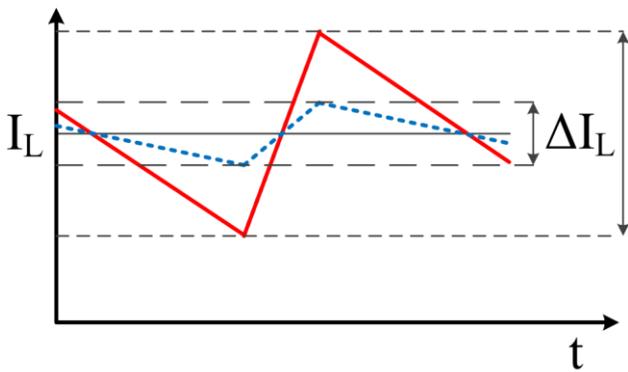
- Higher frequency operation reduces overall **converter size**
  - Lower inductance required
  - Fewer decoupling capacitors
- **Tradeoff**: efficiency decreases with increased switching frequency
- Select 2 MHz per phase for this example

# Inductance Impact on Efficiency

- Inductance equation

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

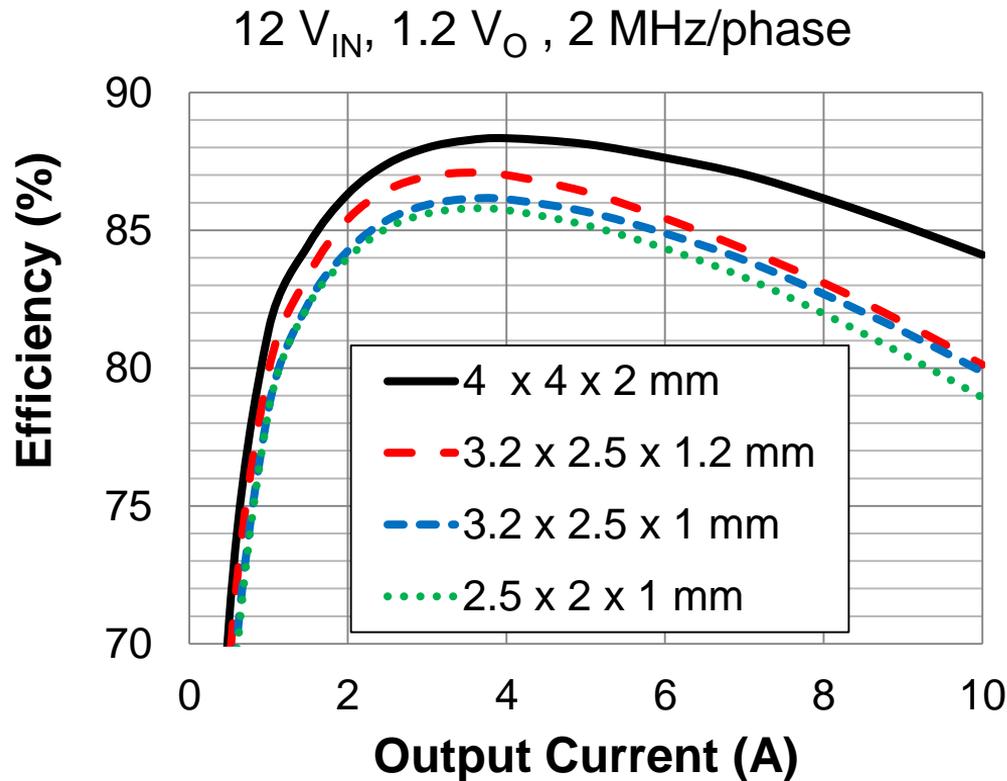
- $K = \Delta I_L / I_L$  where  $I_L$  is current at full load
- $K$  is usually between 0.1 and 0.4



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

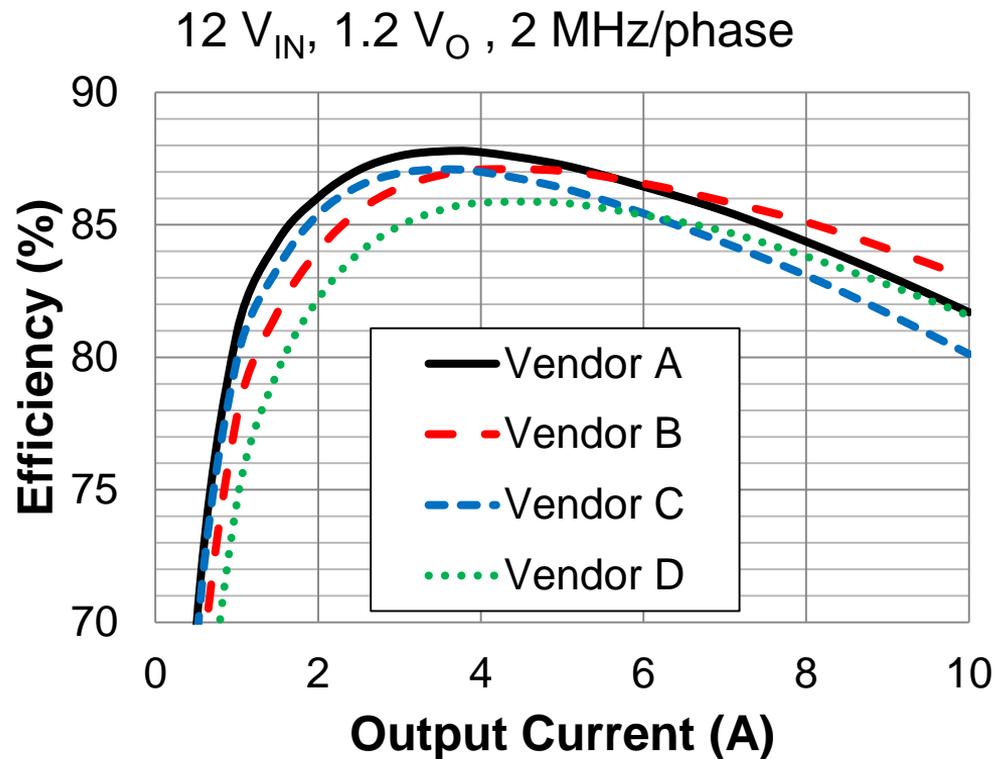
# Inductor Size

- 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**

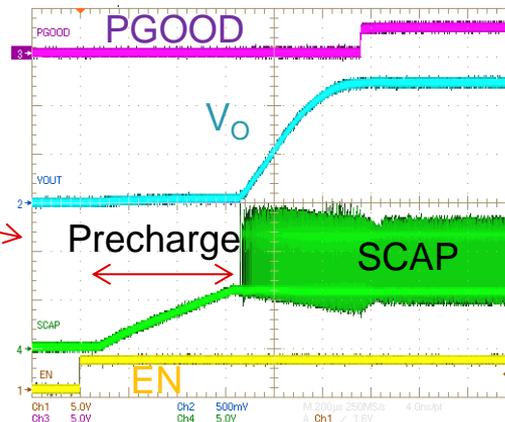
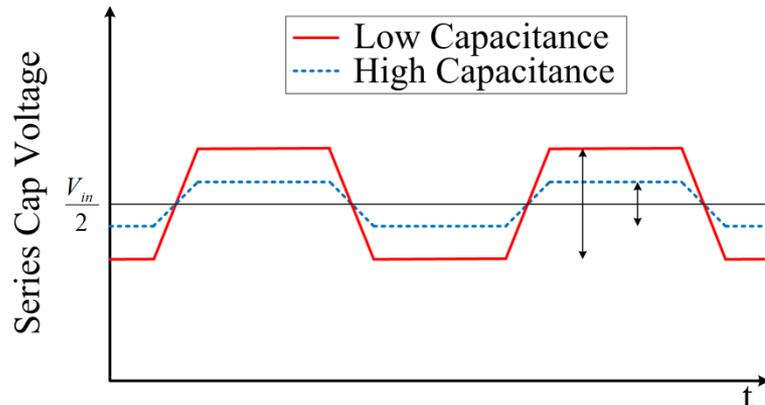


# Series Capacitor Selection

- Select the cap value to keep voltage ripple <8% at **full load, lowest  $V_{IN}$** 
  - Ex: 10 A load, 2 MHz, 10.8 V<sub>IN</sub>, 1.2 V<sub>O</sub>

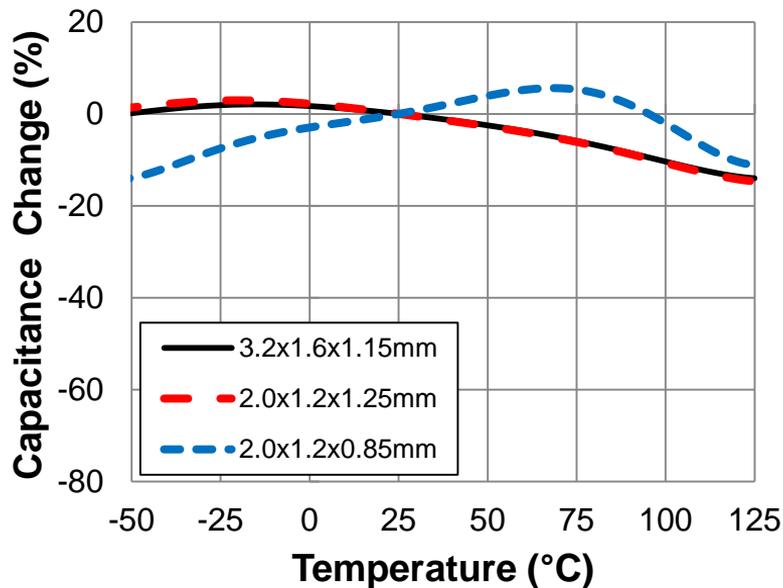
$$C = \frac{DT \left( \frac{i_{out}}{2} \right)}{0.08 \left( \frac{V_{in}}{2} \right)} = \frac{\left( \frac{2 \times 1.2V}{10.8V} \right) \frac{1}{2MHz} \left( \frac{10A}{2} \right)}{0.08 \left( \frac{10.8V}{2} \right)} = 1.29 \mu F$$

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

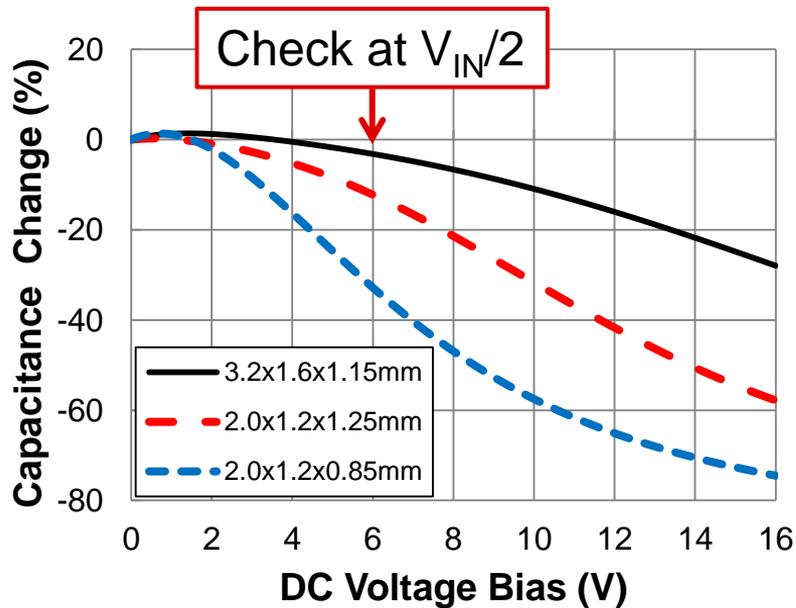


# DC Voltage and Temp Impact on Ceramic Caps

Capacitance **varies** with temperature



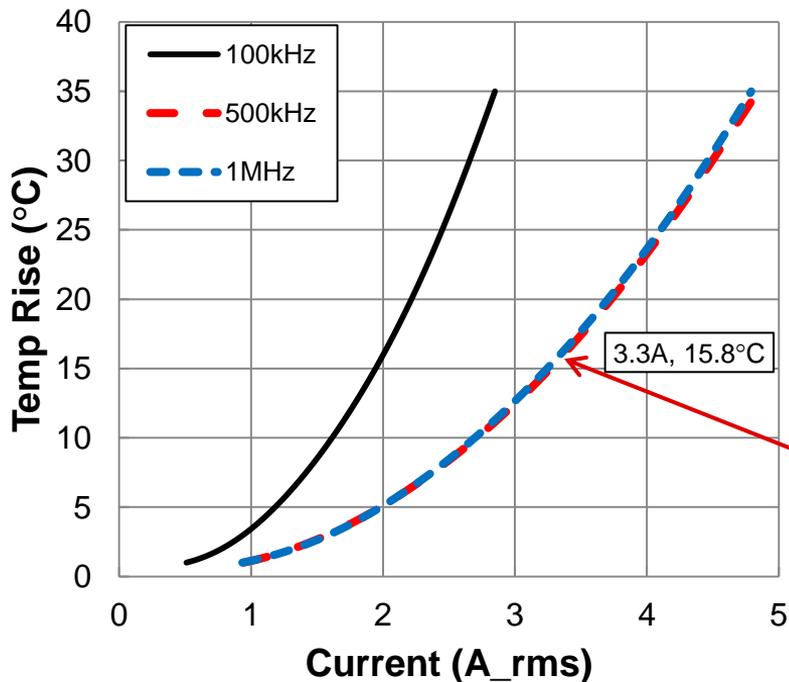
Capacitance **decreases** with DC voltage



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<sub>IN,MIN</sub>, 1.2 V<sub>O</sub>, I<sub>L,RMS</sub> = 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:

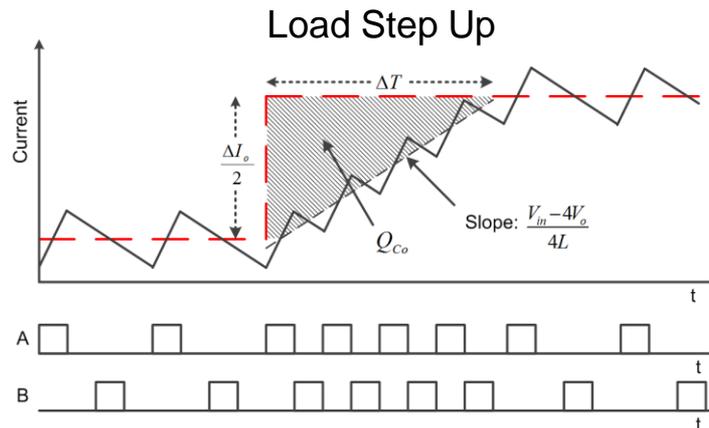
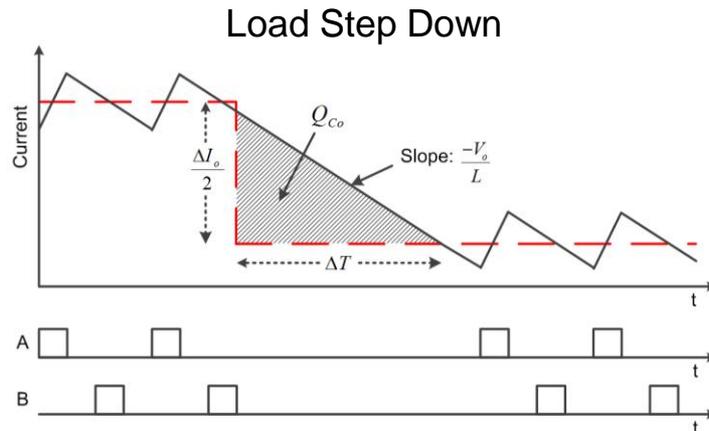
- Ex:  $\Delta I_{o,max} = 5 \text{ A}$ ,  $L = 330 \text{ nH}$ ,  
 $V_o = 1.2 \text{ V}$ ,  $\Delta V_{o,max} = 25 \text{ mV}$ ,  $V_{IN,min} = 10.8 \text{ V}$

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

- Load step up:

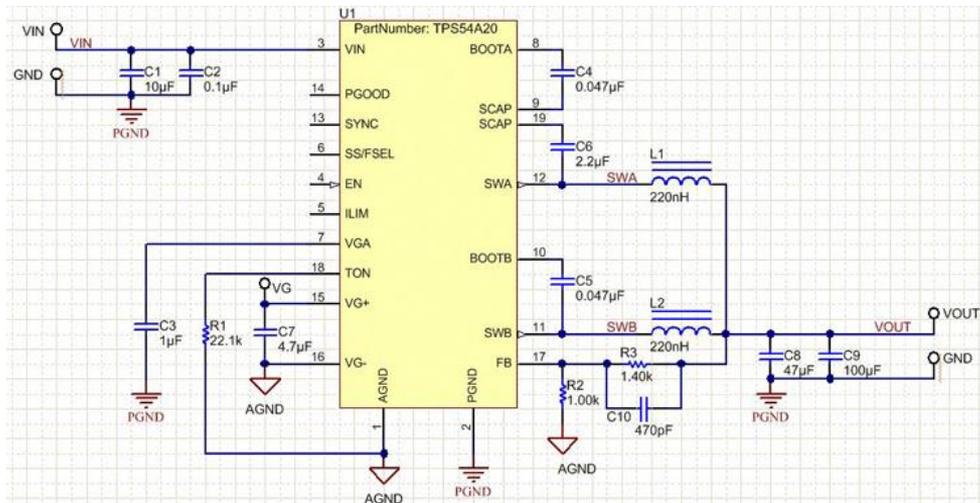
$$C_o \geq \frac{2L(\Delta I_{o,max})^2}{(V_{IN,min} - 4V_o)\Delta V_{o,max}} = 106\mu\text{F}$$

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



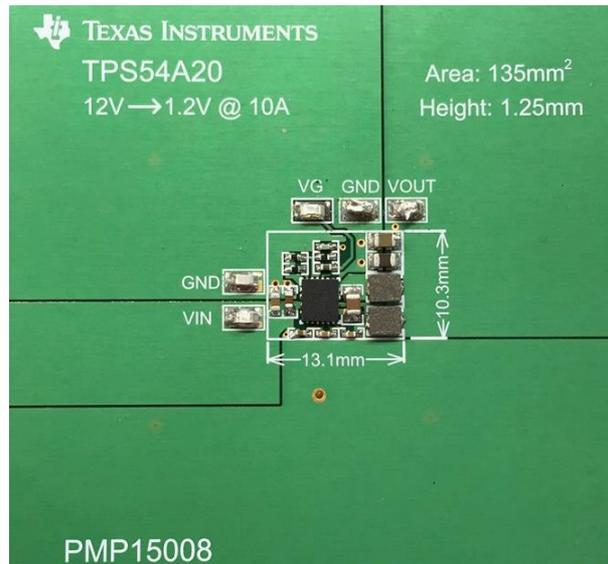
# Reference Design PMP15008

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



Schematic

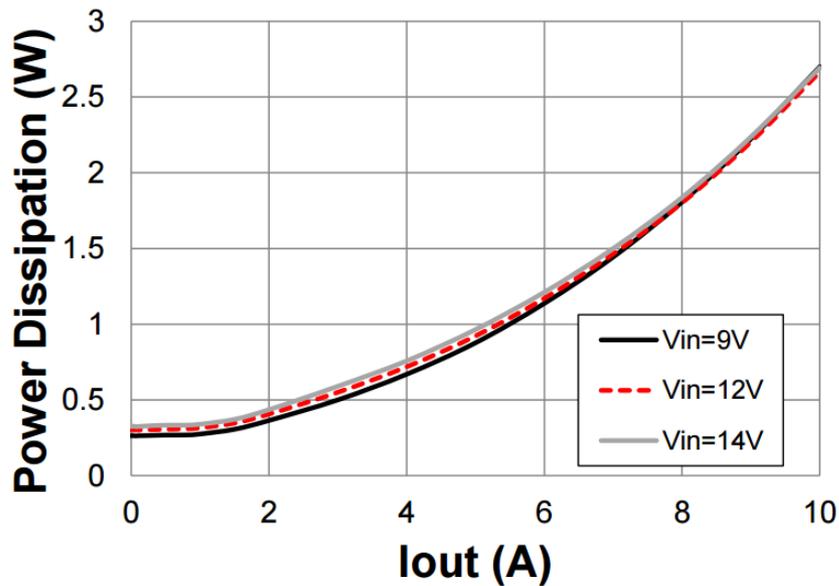
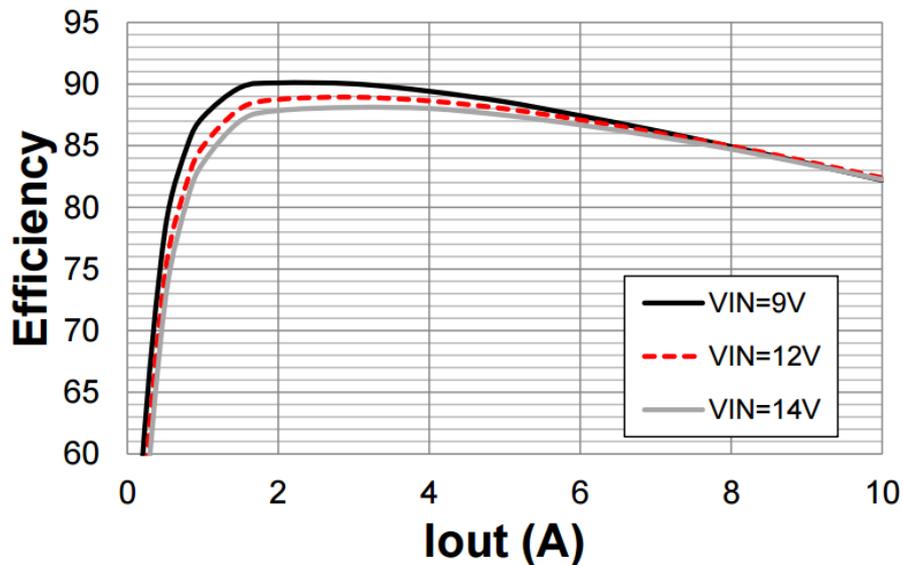
Board Image



**Total solution size is 135 mm<sup>2</sup> and 1.25 mm tall**

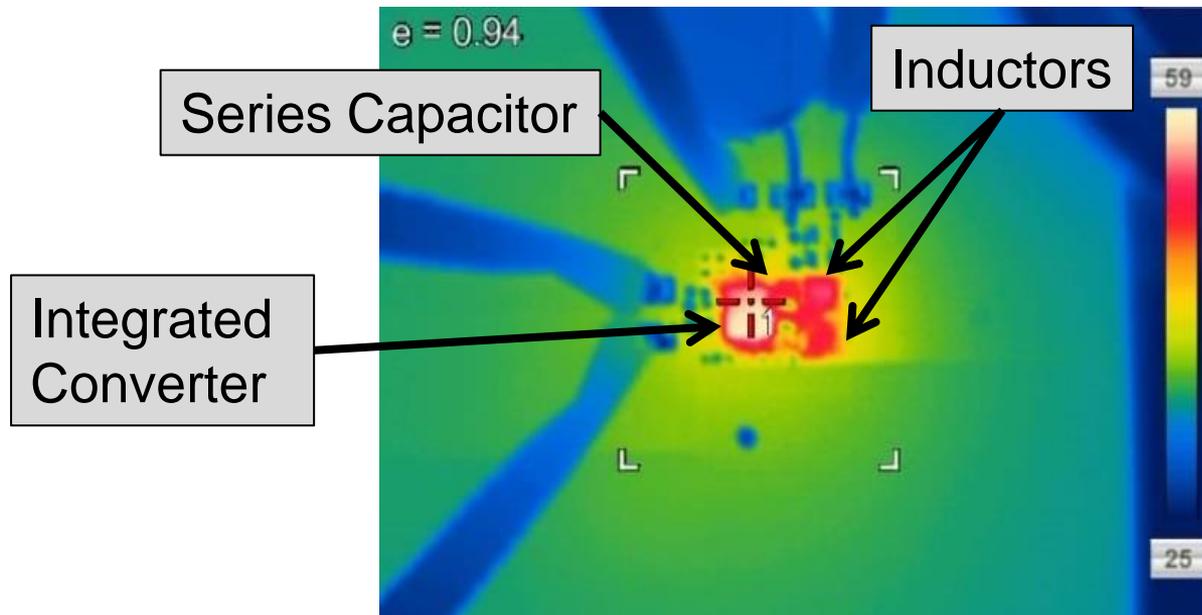
# Efficiency and Power Loss

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



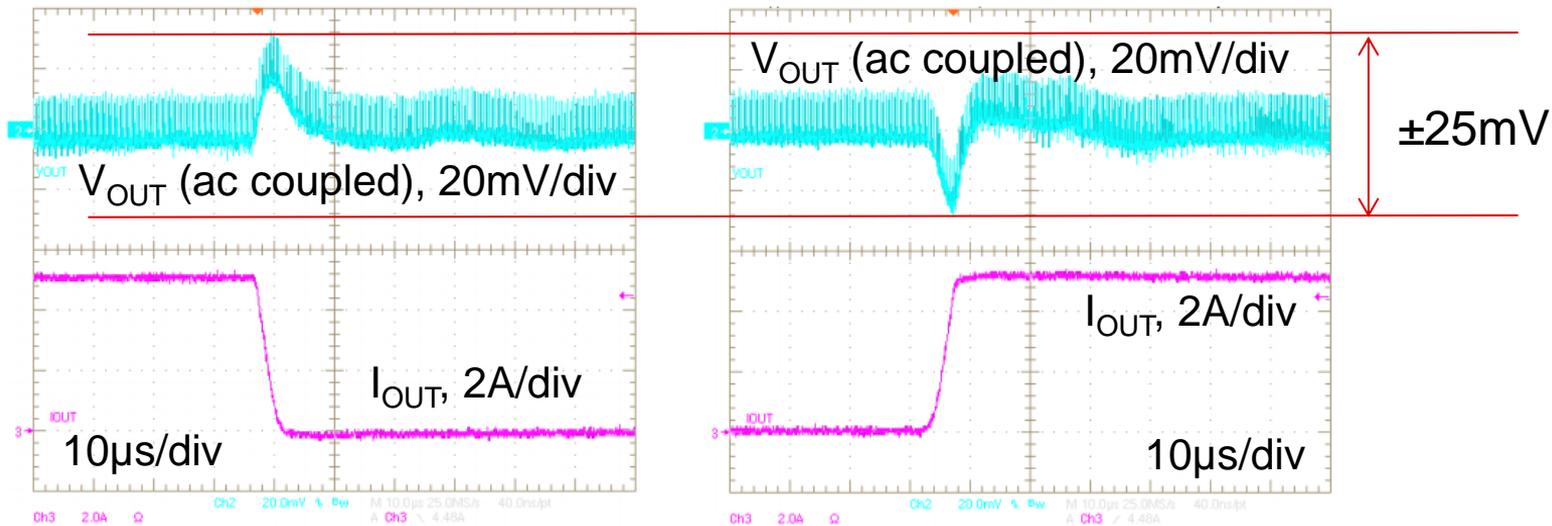
**Over 90% efficiency at 9 V input, less than 3 W loss at full load**

# Thermal Image



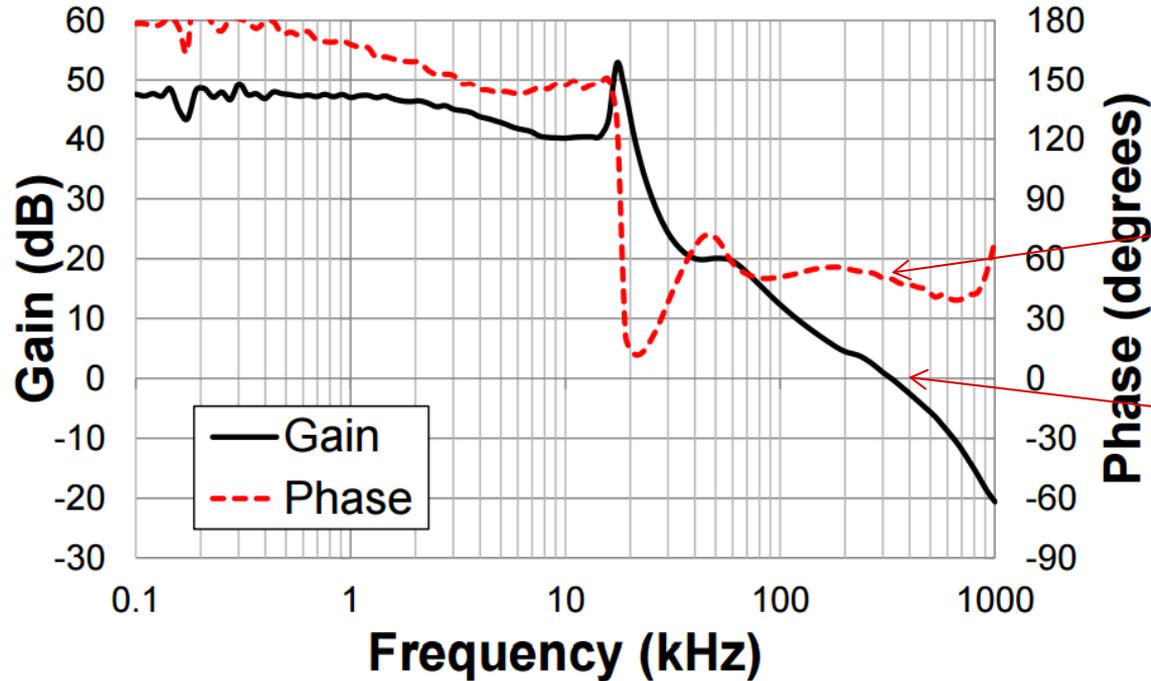
**Less than 35°C temp rise at 12 V input, 8 A output**

# Load Transient Response



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

# High Bandwidth and Ample Phase Margin

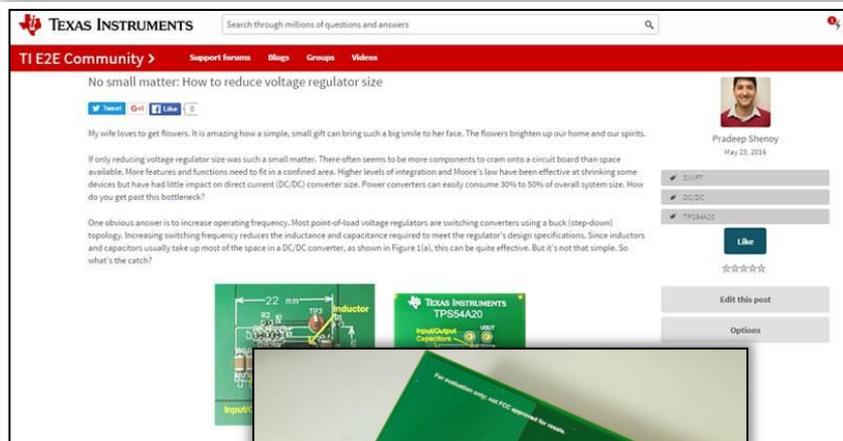


Over **50 degrees**  
of phase margin

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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