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

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

Pradeep Shenoy, Ph.D. | Systems Engineer | DC Solutions
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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

**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: $V_{IN,MIN} = 5 \times V_{OUT}$

Steady-State Operation: Interval 1

Series cap voltage (differential)

Inductor & series cap currents

Switch node voltages
Steady-State Operation: Interval 2

- **Series cap voltage (differential)**
  - Voltage (V)
  - Time (μs)

- **Inductor & series cap currents**
  - Current (A)
  - Time (μs)

- **Switch node voltages**
  - Voltage (V)
  - Time (μs)
Steady-State Operation: Interval 3

Series cap voltage (differential)

Inductor & series cap currents

Switch node voltages

8 of 25
Steady-State Operation: Interval 4

Series cap voltage (differential)

Inductor & series cap currents

Switch node voltages
# Example Design Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{OUT}$</td>
<td>Output voltage</td>
<td>±3% of typical</td>
<td>1.164</td>
<td>1.2</td>
<td>1.236</td>
</tr>
<tr>
<td>$I_{OUT}$</td>
<td>Output current</td>
<td></td>
<td>0</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>$V_{IN}$</td>
<td>Input voltage</td>
<td>±10% of typical</td>
<td>10.8</td>
<td>12</td>
<td>13.2</td>
</tr>
<tr>
<td>$\Delta V_{OUT}$</td>
<td>Transient response</td>
<td>5-A load step</td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

12 V\textsubscript{IN}, 1.2 V\textsubscript{O} Efficiency Comparison

![Efficiency vs. Output Current Graph](image)

- 2MHz
- 3.5MHz
- 5MHz
Inductance Impact on Efficiency

• Inductance equation

\[ L = \left( \frac{V_{IN,\text{MAX}} - 2V_O}{K \times I_o/2} \right) \left( \frac{V_O}{V_{IN,\text{MAX}} \times f_{SW}} \right) \]

- K = ΔI_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

[Graph showing efficiency and output current for different inductance values]
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

![Graph showing efficiency vs. output current for different inductor sizes.](chart)
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

![Graph showing efficiency vs output current for different vendors](chart.png)

12 $V_{IN}$, 1.2 $V_O$, 2 MHz/phase

Efficiency (%)

Output Current (A)

- **Vendor A**
- **Vendor B**
- **Vendor C**
- **Vendor D**
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 $V_O$

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

- **Tradeoff**: Startup delay to precharge the series cap
  - 10 mA precharge current into 1 $\mu F$ cap
    - $\rightarrow$ 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

- 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
  \[
  I_{SCAP,RMS} = \sqrt{2 \left( \frac{2V_O}{V_{IN,MIN}} \right) I_{L,RMS}^2} = 3.34$A
  \]
  - 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,
    $V_o = 1.2$ V, $\Delta V_{o,max} = 25$ mV, $V_{IN,min} = 10.8$ V
  \[ C_o \geq \frac{(\Delta I_{o,max})^2 L}{4V_o \Delta V_{o,max}} = 66 \mu F \]

• Load step up:
  \[ C_o \geq \frac{2L(\Delta I_{o,max})^2}{(V_{IN,min} - 4V_o)\Delta V_{o,max}} = 106 \mu F \]

• Select largest value and take variation in to account
Reference Design PMP15008
“Tiny, Low Profile 10 A Point-of-load Voltage Regulator”

Total solution size is 135 mm$^2$ 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

Bode plot taken with 12 V input, 5 A output

Over 50 degrees of phase margin

Over 300 kHz bandwidth
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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