Measuring Current and Current Sharing in Multi-Phase DC-DC Converters

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Istvan is a Senior Principle Engineer at Oracle. Besides signal integrity design of high-speed serial and parallel buses, he has been engaged in the design and characterization of power-distribution networks and packages for mid-range servers. He creates simulation models, and develops measurement techniques for power distribution. Istvan has twenty plus years of experience with high-speed digital, RF, and analog circuit and system design. He is a Fellow of IEEE for his contributions to signal-integrity and RF measurement and simulation methodologies and has twenty five patents in the areas of power distribution design and precision measurements.
Introduction

Why measure current:
• Protection
• Overcurrent limit
• Undercurrent limit
• Efficiency and load monitoring

How to measure current:
• Shunt resistor
• Current clamp
• Magnetic sensor
• RC across inductor
Switch-node voltage and current:
- 12V input, 1.2V output
- Loss-less waveforms

Compare waveforms:
- 10A DC load
- 1.8uH 3.48mOhm inductor
- 11kOhm / 47nF RC

$\tau = 517 \text{ us}$
## RC Across Inductor
### Time Constant Range

<table>
<thead>
<tr>
<th></th>
<th>R2 [Ohm]</th>
<th>C2 [F]</th>
<th>Rs [Ohm]</th>
<th>Approximate time constant [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe-tip 1</td>
<td>17.8k</td>
<td>5.6n</td>
<td>10</td>
<td>100u</td>
</tr>
<tr>
<td>Probe-tip 2</td>
<td>8.45k</td>
<td>47n</td>
<td>1.18</td>
<td>400u</td>
</tr>
<tr>
<td>Probe-tip 3</td>
<td>16k</td>
<td>47n</td>
<td>0</td>
<td>800u</td>
</tr>
<tr>
<td>Probe-tip 4</td>
<td>34k</td>
<td>47n</td>
<td>1.18</td>
<td>1600u</td>
</tr>
</tbody>
</table>

High current, low voltage, high loss

Low current, high voltage, low loss
RC Across Inductor
Time Constant Mismatch

Same DUT (10A DC)
Four different RC networks
• DC average is the same
• AC swing varies

<table>
<thead>
<tr>
<th>Probe-tip</th>
<th>R2 [Ohm]</th>
<th>C2 [F]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.8k</td>
<td>5.6n</td>
</tr>
<tr>
<td>2</td>
<td>8.45k</td>
<td>47n</td>
</tr>
<tr>
<td>3</td>
<td>16k</td>
<td>47n</td>
</tr>
<tr>
<td>4</td>
<td>34k</td>
<td>47n</td>
</tr>
</tbody>
</table>
RC Across Inductor: Varying C
RC Across Inductor
Sense Voltage Correlation, 0A DC Load

RC Sense voltage [V]

8k45-47nF_meas  8k45-47nF_sim

16k-47nF_meas   16k-47nF_sim

34k-47nF_meas   34k-47nF_sim

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RC Across Inductor
Sense Voltage Correlation, 10A DC Load
RC Across Inductor
Varying Inductor Loss

Rdc:
- 3 mOhm
- 10 mOhm
- 30 mOhm
- 0.1 ohm
- 0.3 Ohm
- 1 Ohm
RC Across Inductor

Measured Inductor Parameters

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>ESR [Ohm]</th>
<th>ESL [H]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50E-06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.60E-06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.70E-06</td>
<td></td>
<td></td>
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<tr>
<td>1.80E-06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.90E-06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.00E-06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Frequency [Hz]

ESR [Ohm]

ESL [H]
RC Across Inductor Correlation

Same DUT
Two different RC probe tips
• Left plot: 0A DC load
• Right plot: 10A DC load
Note: different scales
**RC Across Inductor: Probe Loading**

Assume symmetric sense amplifier input

Finite differential and common-mode impedance

Source impedances to the two input terminals are different

$R_{cc}$ compensation resistor balances the source impedance

Wrong DC value

Correct DC value
RC Across Inductor: Capacitor Parasitics

1 nH ESL
ESR stepped through:
10 mOhm
100 mOhm
1 Ohm
10 Ohm
RC Across Inductor: Noise Pickup

Current-sense voltage across C2

Noise can be picked up:
- in connecting wires
- in RC probe tip
Ferrite absorbers can reduce noise
Impedance Measurement Noise Floor

\[ B = \frac{\sqrt{2}}{I \cdot \sqrt{M} \cdot \sqrt{K}} \sqrt{\left[ VDIV_V \cdot 10^{\frac{SNR_V}{10}} + \left( \frac{Z}{R_s} \right)^2 \cdot VDIV_I \cdot 10^{\frac{SNR_I}{10}} \right] \cdot (-\ln(1 - F))} \]

- \( B \) is the bounds on the error, in \( \Omega \) such that for a measured impedance \( \hat{Z} \):
  \[ |\hat{Z} - |Z| \cdot e^{i\theta_2}| < B \]
  with a certainty of \( F/100\% \).
- \( Z \) is the actual impedance being measured
- \( R_s \) is the resistance of the sense resistor used to measure the transient current by inferring the current by a voltage measurement across the resistor.
- \( VDIV_V \) and \( VDIV_I \) are the volt/division settings of the oscilloscope channels measuring the voltage and the voltage across the current sense resistor, respectively.
- \( SNR_V \) and \( SNR_I \) are the normalized signal-to-noise ratios of the oscilloscope channels measuring the voltage and the voltage across the current sense resistor, respectively.
- \( M \) is the number of averaged measurements.
- \( K \) is the number of points in the acquisition
- \( I \) is the amount of transient current injected used to stimulate a voltage transient, and thus an impedance.
Impedance Measurement Noise Floor

Typical Noise Statistics on Impedance Measurements. Voltage Measurement Noise Density at 20mV/div (on the left) and Voltage Measurement Normalized SNR at 20mV/div (on the right).

Zero-impedance noise floor:

$$\lim_{Z \to 0} B = \frac{\sqrt{2} V D I V_V \cdot 10^{-\frac{\text{SNR}_{V_{th}}}{10}} \cdot \sqrt{-\ln(1 - F)}}{I \cdot \sqrt{M} \cdot \sqrt{K}}$$
Impedance Measurement Noise Floor

Typical Noise Statistics on Impedance Measurements. Current Measurement Noise Density at 50mV/div (on the left) and Current Measurement Normalized SNR at 50mV/div (on the right).

Zero-impedance noise floor:

\[
\lim_{Z \to 0} B = \sqrt{2} VDIV^2 \cdot 10^{-\frac{SNR_{V_n}}{10}} \cdot \sqrt{-\ln(1 - F)}
\]
Low-frequency spectral density of output ripple for a three-phase and a six-phase DUT.
Three-Phase DUT: Outline

Top view of a three-phase evaluation board.

- Three independent outputs: combined
- Current-mode control
- 12V input
- 1.2V output
- 3x15A maximum current
- Transient injector at each output
Three-Phase DUT
Small-signal Zout

10 dBm VNA source power
Three connection options

OFF vs. connection
ON vs. connection

TOP-injector vs. DC load
12Vin
7Vin

Bulk capacitors
Transient injector (on the back side)
Three-Phase DUT
Large-signal $Z_{out}$

Output impedance vs. DC load current with 1App test current

Output impedance vs. AC test current with 0A and 20A DC load.
AC pulse current:
- 0.3App
- 1App
- 3App
- 10App
- 30App

AC pulse current: 0.3App, 1App, 3App, 10App, 30App
Three-Phase DUT: Transient Response

- Plot 1: Time [s] vs. Output voltage [V] for different conditions.
- Plot 2: Detailed view of a specific condition.
Three-Phase DUT: Current Sharing

![Graph showing current sharing magnitude across different frequencies.]

- Frequency [Hz]: 10k, 20k, 100k
- Current sharing magnitude: 0.3275 to 0.3400
- Phases: 0, 1, 2
Six-Phase DUT: Outline

- 12V input
- 1.05V output
- Digital control
- 200+A max current
Six-Phase DUT: Output Impedance

Various test conditions:
- Small-signal VNA
- Small-medium-large signal AC
- Small-medium-large signal pulse
Six-Phase DUT
Current Sharing, Frequency Domain

**Current Sharing Magnitude**

- **Frequency [Hz]**
  - Range: $10^2$ to $10^5$

**Current Sharing Phase**

- **Phase:**
  - Phase 0
  - Phase 1
  - Phase 2
  - Phase 3
  - Phase 4
  - Phase 5

- **Phase [degrees]**
  - Range: $-100$ to $20$

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Six-Phase DUT: Current Sharing, Time Domain
Production Board: Current Sharing

- Controlled system activity
- Six-phase converter
- Monitoring mode
Conclusions

• Time constant mismatch of RC sense circuit can be compensated for in DSP engine
• Few steps of fixed RC time constants cover full practical range
• Finite probe input impedance requires balancing of source impedance
• Resistor in series to RC capacitor can help suppress high-frequency noise
• Small-signal, large-signal, frequency domain and time-domain results agree within the bounds of linearity as long as connections are the same
• Monitoring mode can test current sharing vs. frequency of live DUTs
Thank you!

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QUESTIONS?