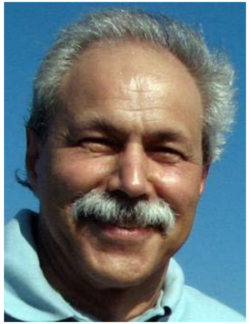
Measuring Current and Current Sharing in Multi-Phase DC-DC Converters

Istvan Novak, (Oracle Corporation)

Peter J. Pupalaikis (Teledyne-LeCroy), Lawrence Jacobs (Teledyne-LeCroy)

SPEAKER



Istvan Novak

Senior Principal Engineer, Oracle Corporation
istvan.novak@oracle.com

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.

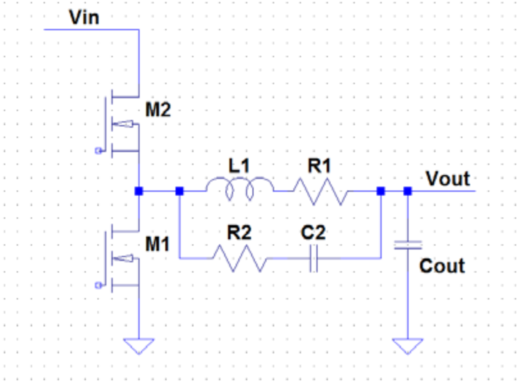
Introduction

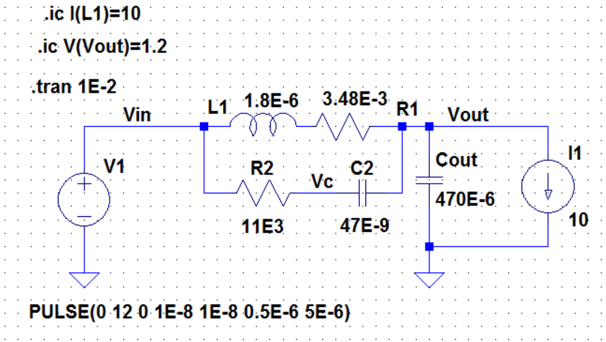
Why measure current:

- Protection
- Overcurrent limit
- Undercurrent limit
- Efficiency and load monitoring

How to measure current:

- Shunt resistor
- Current clamp
- Magnetic sensor
- RC across inductor





RC Across Inductor

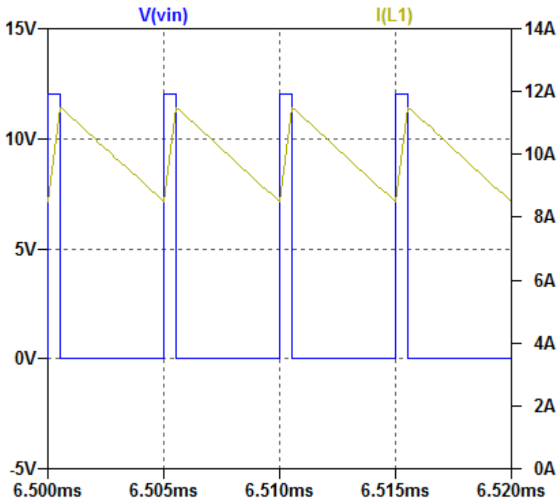
Switch-node voltage and current:

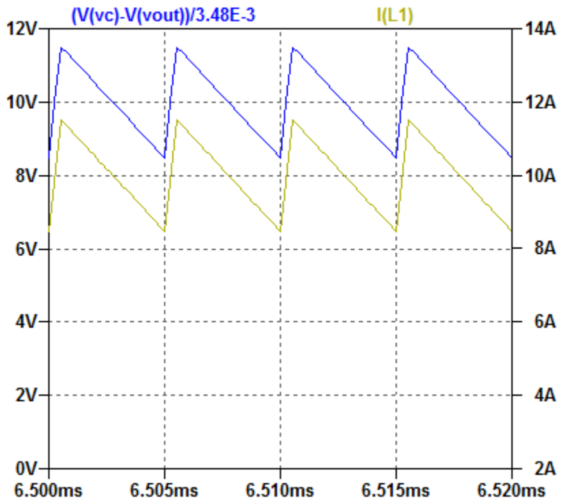
- 12V input, 1.2V output
- Loss-less waveforms

Compare waveforms:

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

τ = 517 us





RC Across Inductor
Time Constant Range

	R2 [Ohm]	C2 [F]	Rs [Ohm]	Approximate.time constant [s]
Probe-tip 1	17.8k	5.6n	10	100u
Probe-tip 2	8.45k	47n	1.18	400u
Probe-tip 3	16k	47n	0	800u
Probe-tip 4	34k	47n	1.18	1600u

High current, low voltage, high loss

Low current, high voltage, low loss

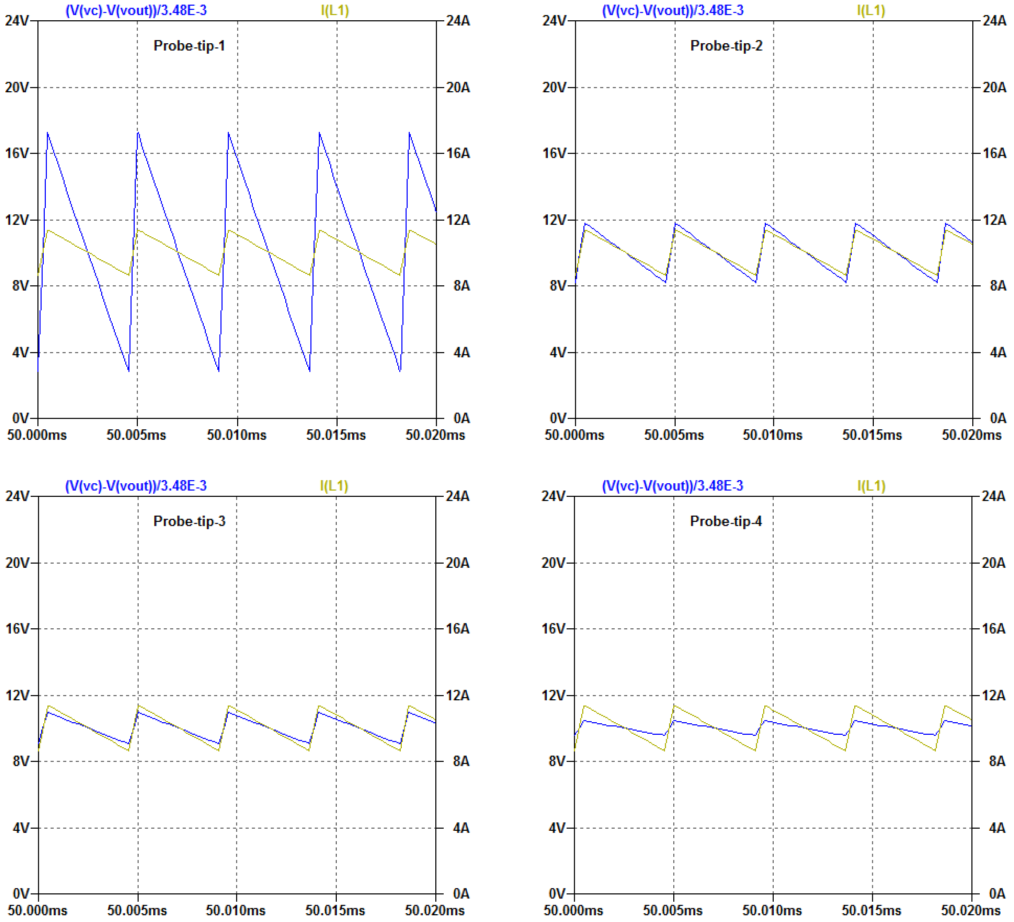
RC Across Inductor Time Constant Mismatch

Same DUT (10A DC)

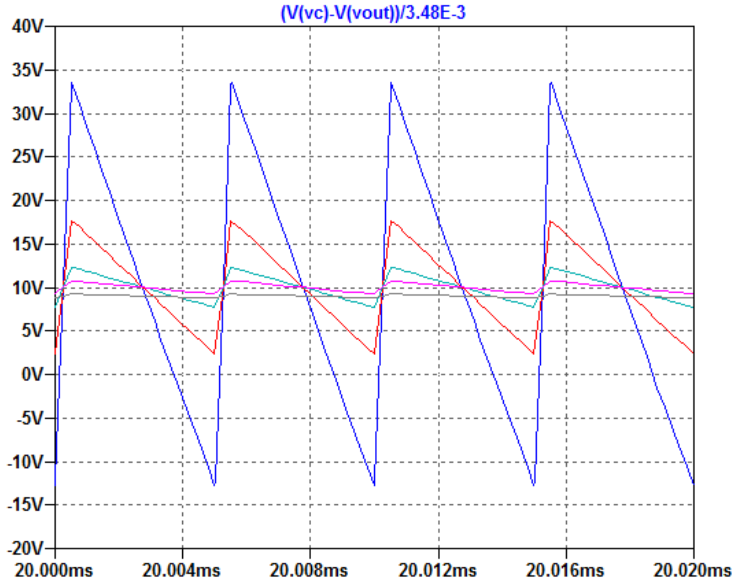
Four different RC networks

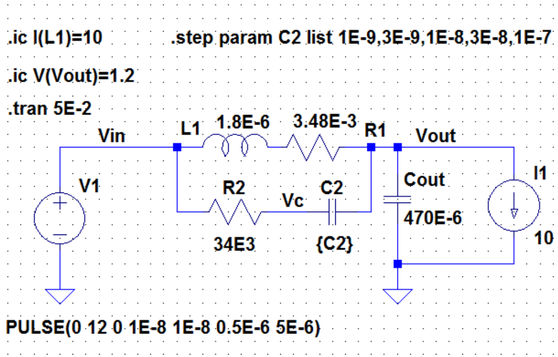
- DC average is the same
- AC swing varies

	R2 [Ohm]	C2 [F]
Probe-tip 1	17.8k	5.6n
Probe-tip 2	8.45k	47n
Probe-tip 3	16k	47n
Probe-tip 4	34k	47n

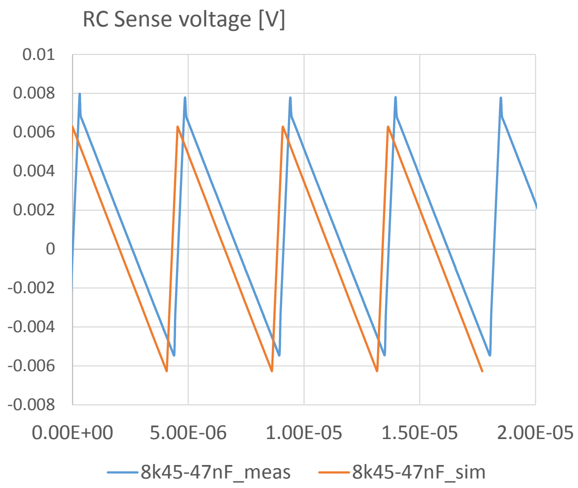


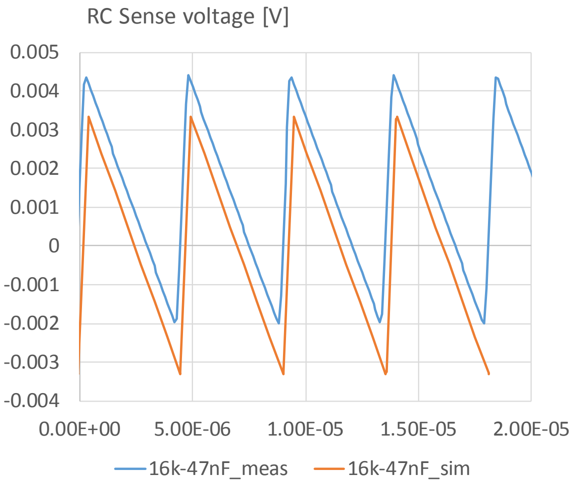
RC Across Inductor: Varying C

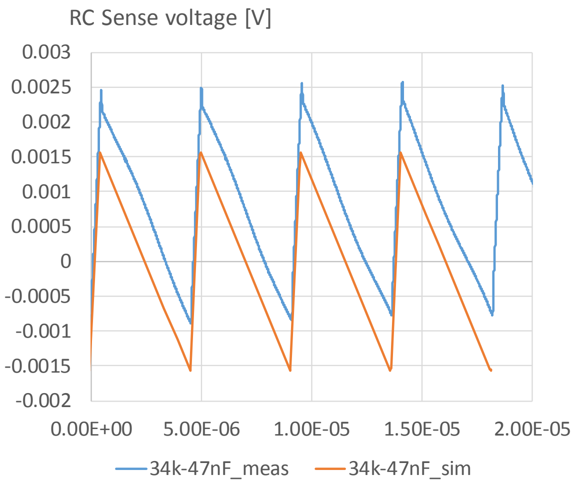




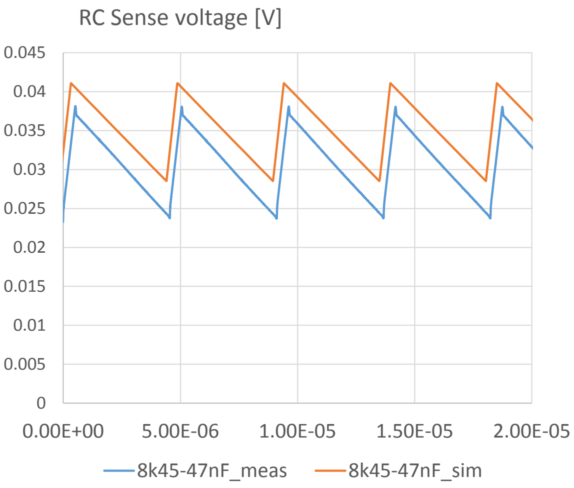
RC Across Inductor
Sense Voltage Correlation, 0A DC Load

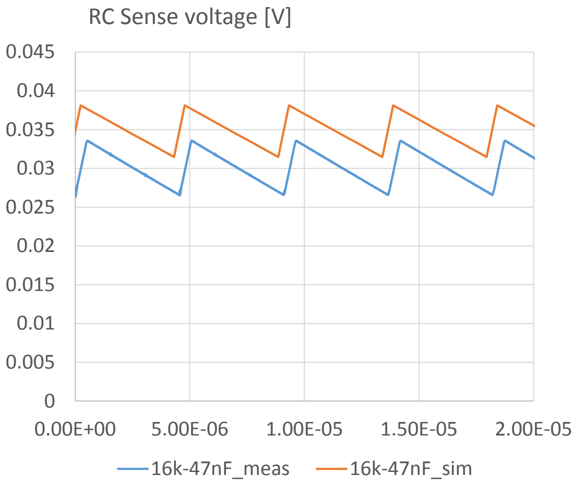


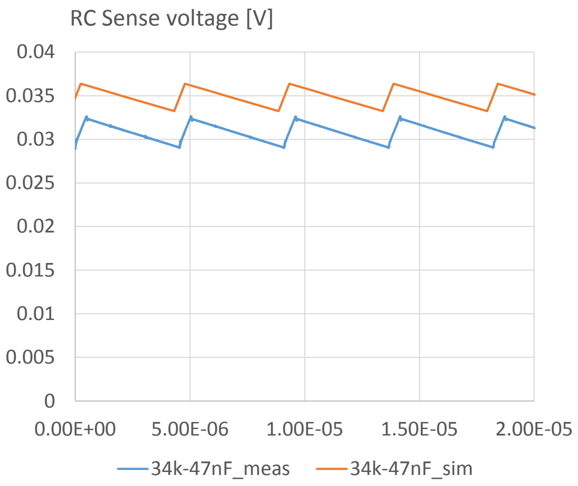




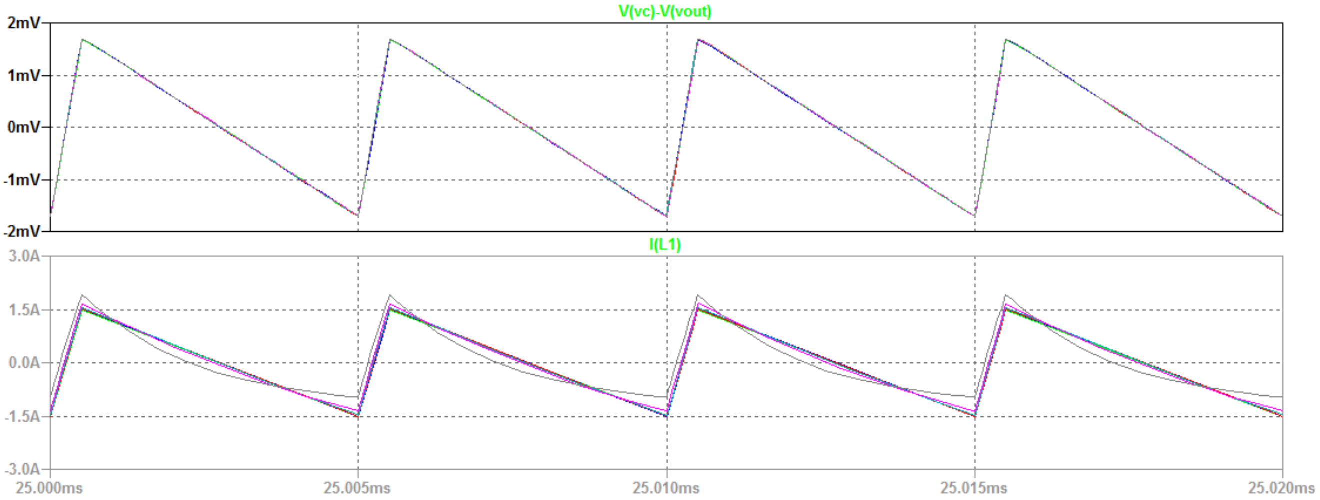
RC Across Inductor
Sense Voltage Correlation, 10A DC Load





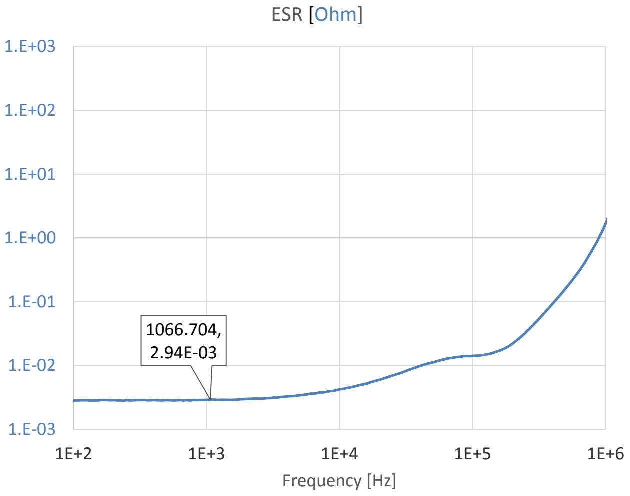


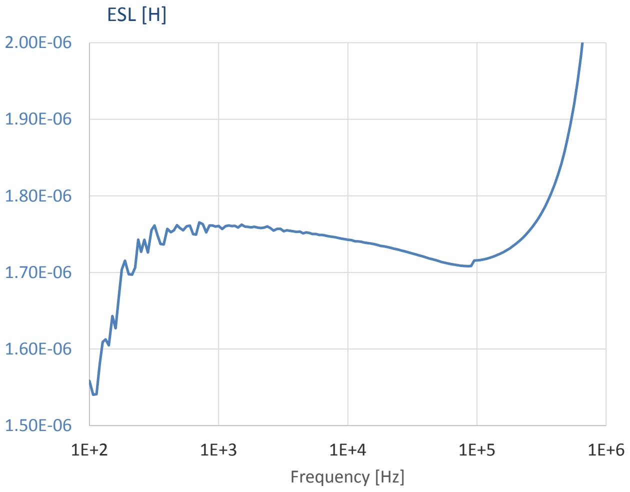
RC Across Inductor
Varying Inductor Loss



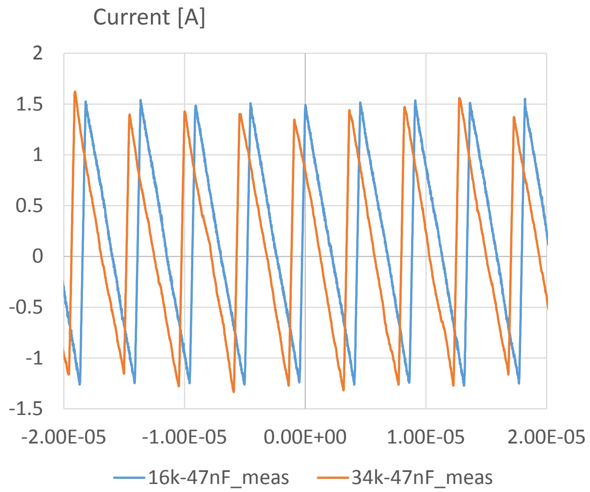
Rdc:
3 mOhm
10 mOhm
30 mOhm
0.1 ohm
0.3 Ohm
1 Ohm

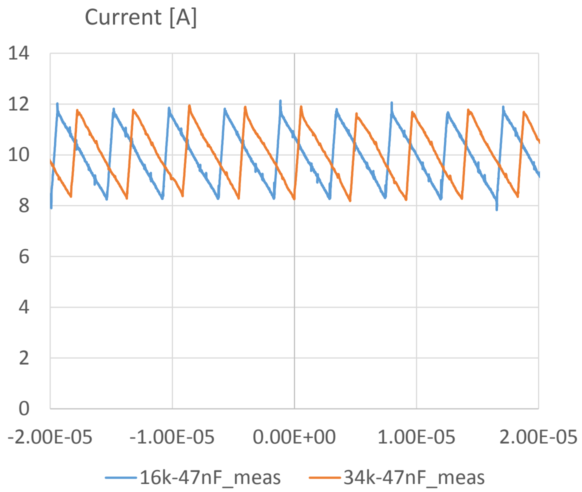
RC Across Inductor
Measured Inductor Parameters





RC Across Inductor Correlation





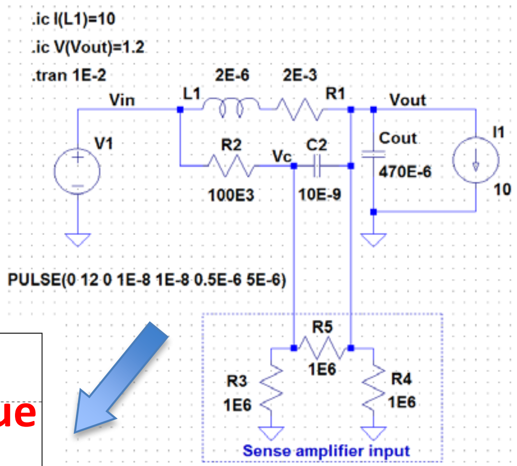
Same DUT

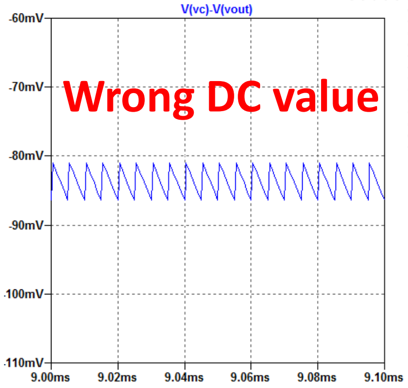
Two different RC probe tips

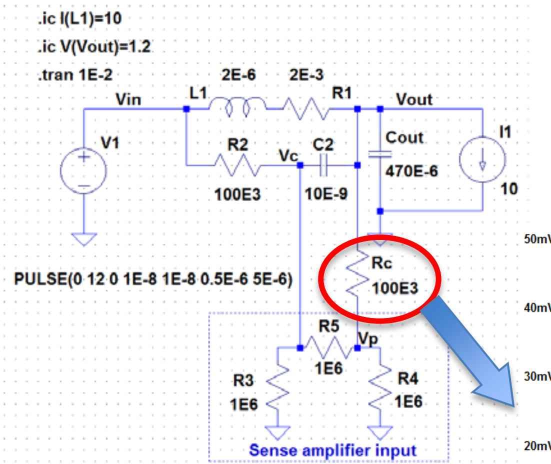
- Left plot: 0A DC load
- Right plot: 10A DC load

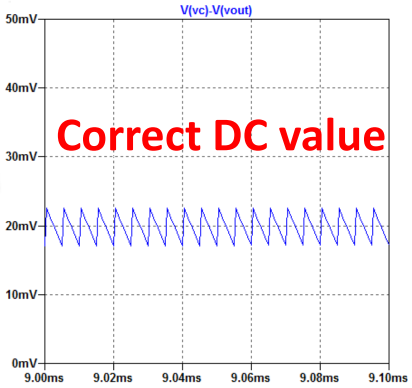
Note: different scales

RC Across Inductor: Probe Loading









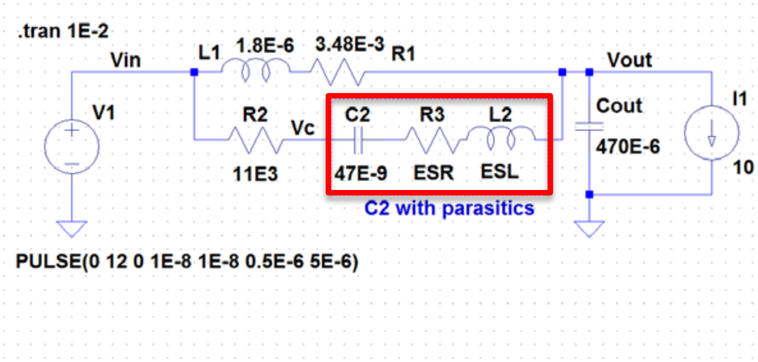
Assume symmetric sense amplifier input

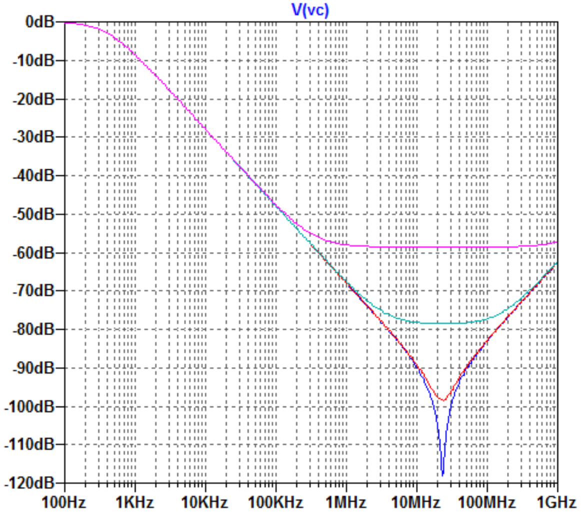
Finite differential and common-mode impedance

Source impedances to the two input terminals are different

Rc compensation resistor balances the source impedance

RC Across Inductor: Capacitor Parasitics





1 nH ESL

ESR stepped through:

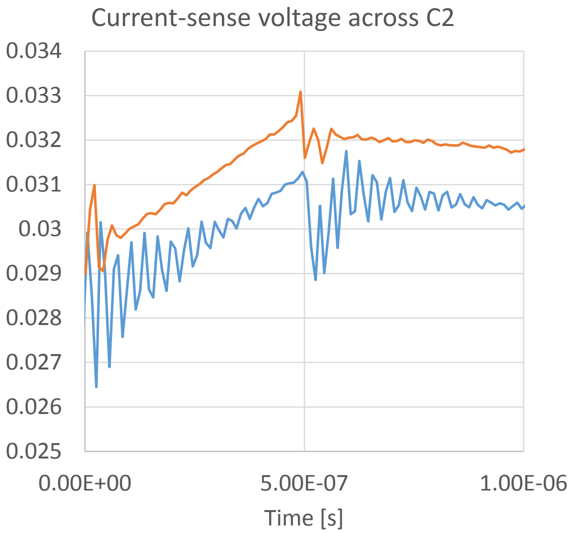
10 mOhm

100 mOhm

1 Ohm

10 Ohm

RC Across Inductor: Noise Pickup



Noise can be picked up:

- in connecting wires
- in RC probe tip

Ferrite absorbers can reduce noise

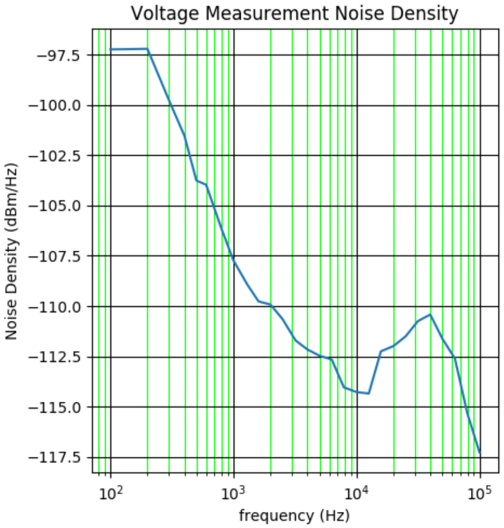
Impedance Measurement Noise Floor

$$B = \frac{\sqrt{2}}{I \cdot \sqrt{M} \cdot \sqrt{K}} \sqrt{\left[VDIV_V \cdot 10^{-\frac{SNR_{V_n}}{10}} + \left(\frac{Z}{R_S}\right)^2 \cdot VDIV_I \cdot 10^{-\frac{SNR_{I_n}}{10}} \right] \cdot (-\ln(1-F))}$$

- B is the bounds on the error, in Ω such that for a measured impedance $\hat{Z}$:
  $\left|\hat{Z} - |Z| \cdot e^{j \cdot \Theta_Z}\right| < B$
  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).

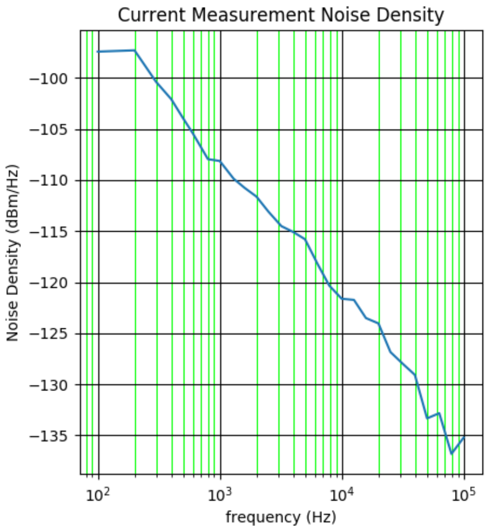


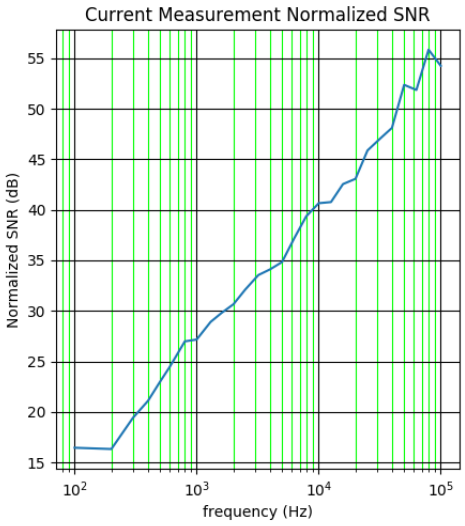
Zero-impedance noise floor:

$$\lim_{Z\to 0} B = \frac{\sqrt{2}\cdot VDIV_V \cdot 10^{-\frac{SNR_{V_n}}{10}}}{I\cdot\sqrt{M}\cdot\sqrt{K}} \cdot \sqrt{-\ln(1-F)}$$

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).

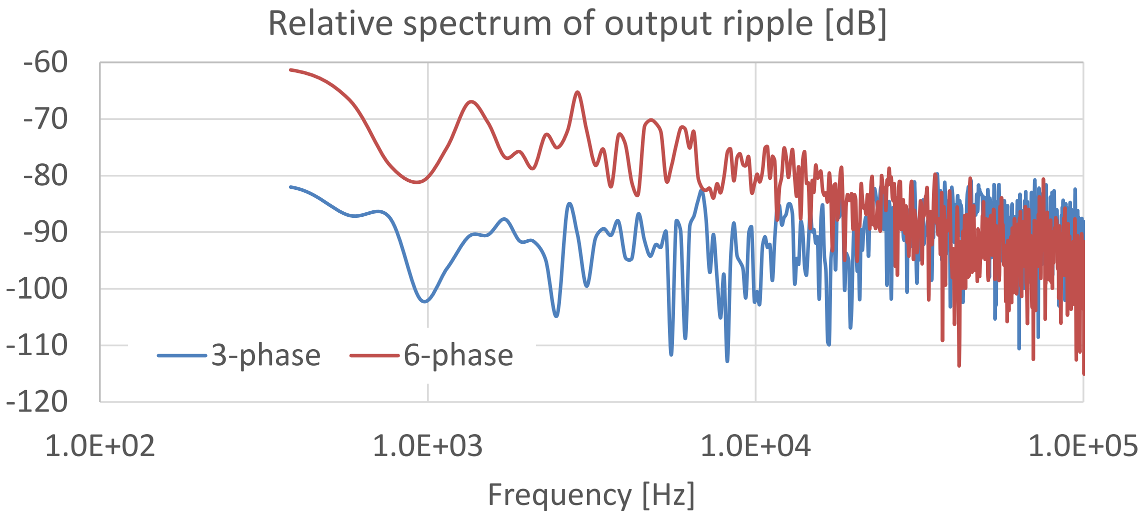




Zero-impedance noise floor:

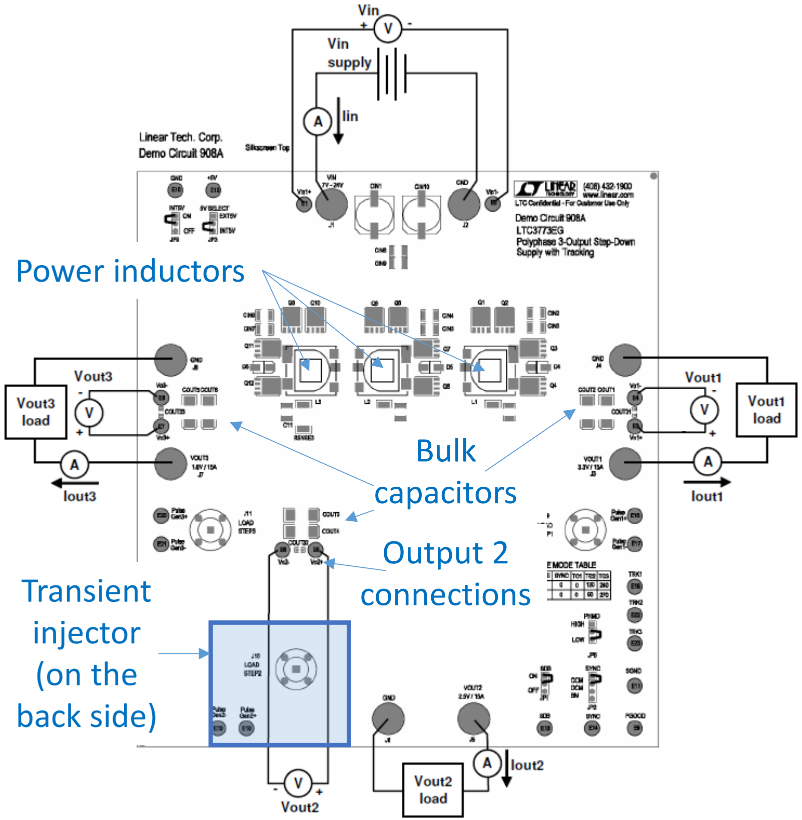
$$\lim_{Z \to 0} B = \frac{\sqrt{2} \cdot VDIV_V^2 \cdot 10^{-\frac{SNR_{V_n}}{10}}}{I \cdot \sqrt{M} \cdot \sqrt{K}} \cdot \sqrt{-\ln(1 - F)}$$

Low-Frequency DUT Noise



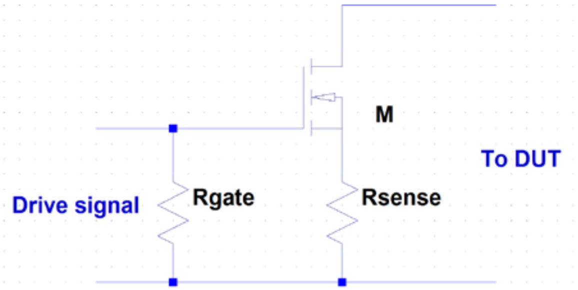
Low-frequency spectral density of output ripple for a three-phase and a six-phase DUT.

Three-Phase DUT: Outline



Top view of a three-phase evaluation board.

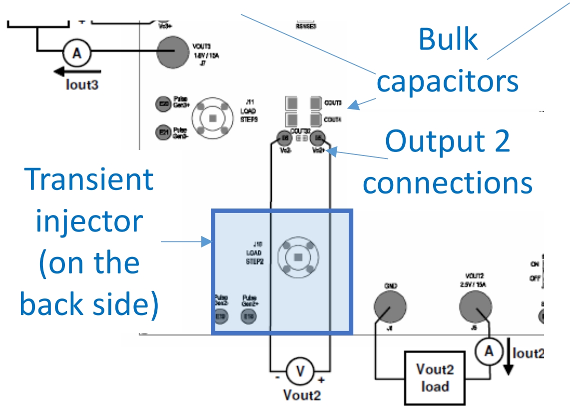
- Three independent outputs: combined
- Current-mode control
- 12V input
- 1.2V output
- 3x15A maximum current
- Transient injector at each output

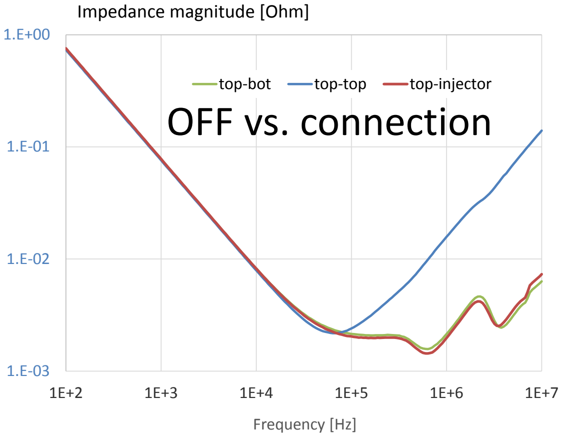


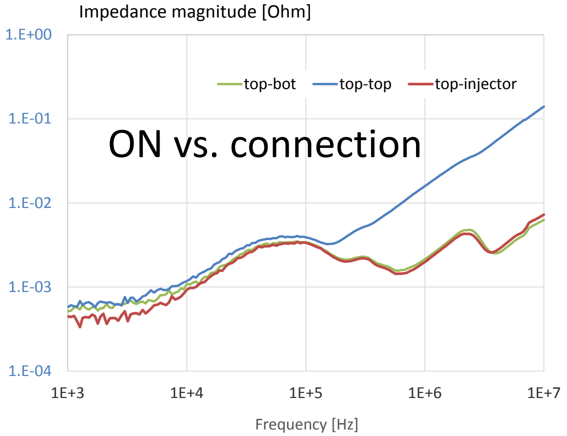
Three-Phase DUT

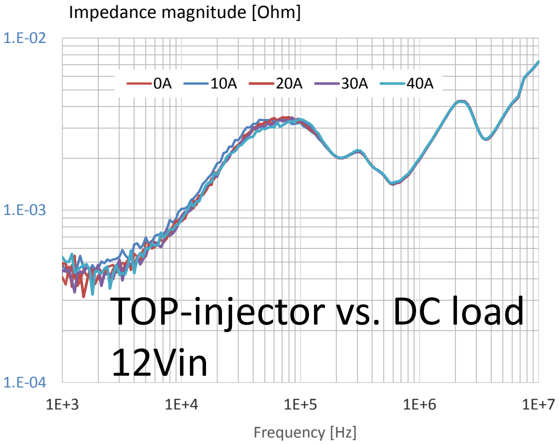
Small-signal Zout

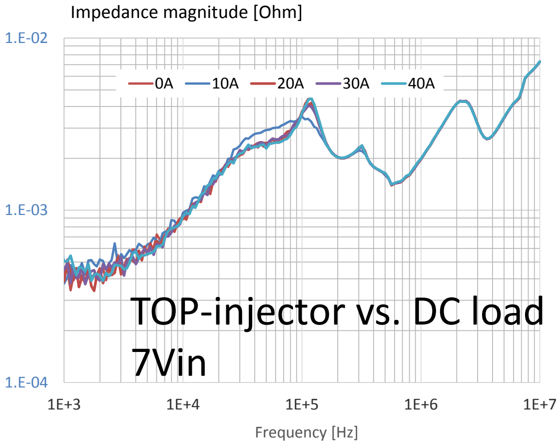
10 dBm VNA source power
Three connection options





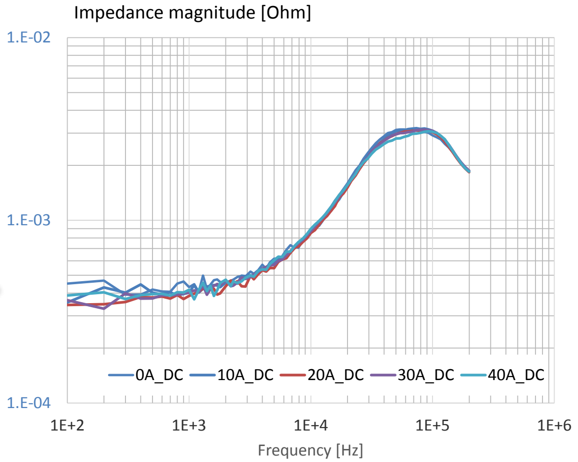






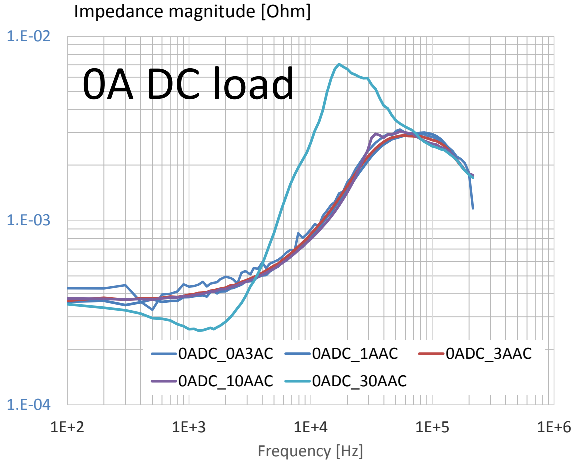
Three-Phase DUT
Large-signal Zout

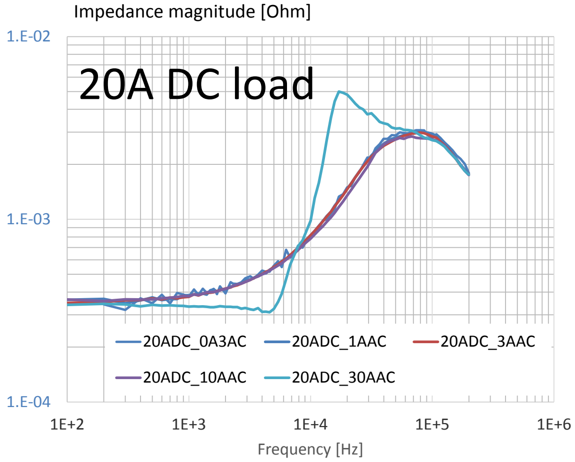
Output impedance vs. DC load current with 1App test current



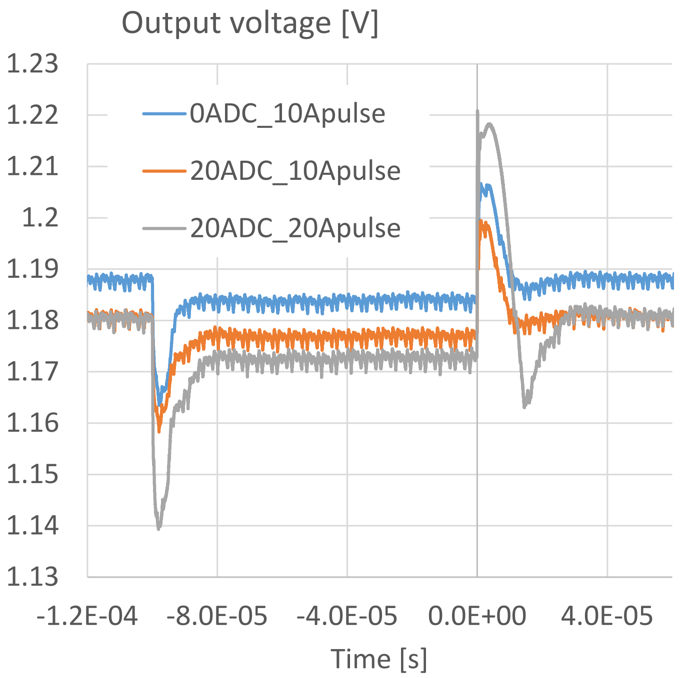
Output impedance vs. AC test current with 0A and 20A DC load. AC pulse current:

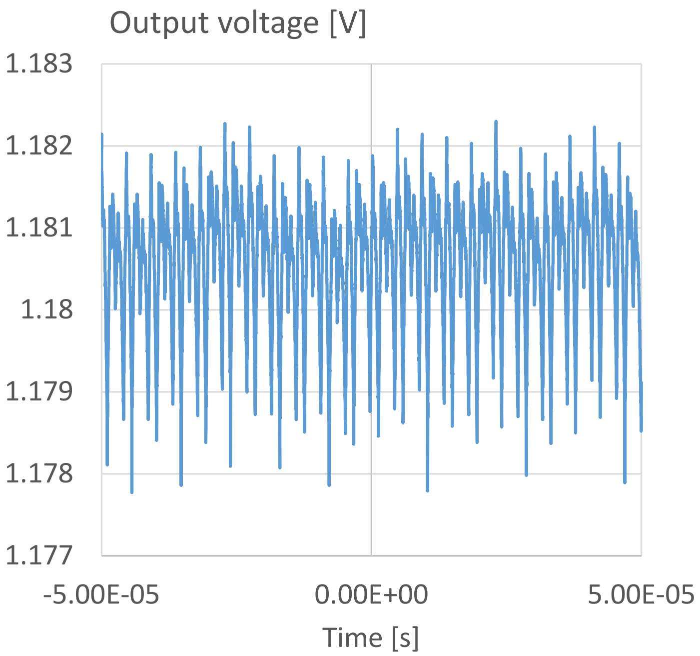
0.3App
1App
3App
10App
30App



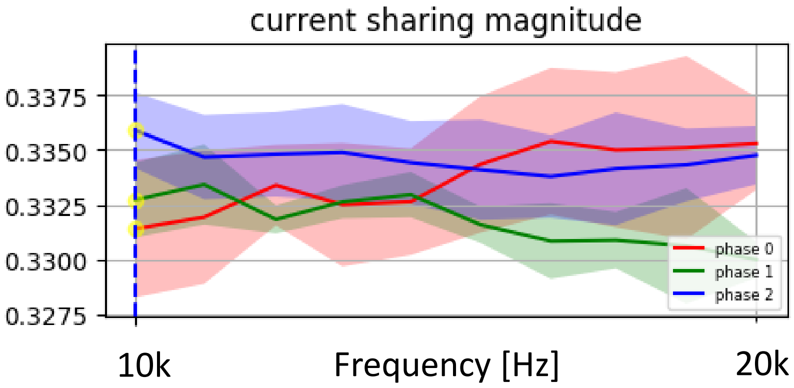


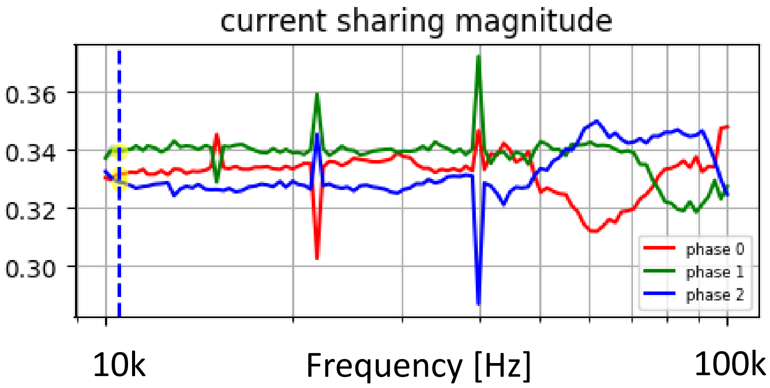
Three-Phase DUT: Transient Response



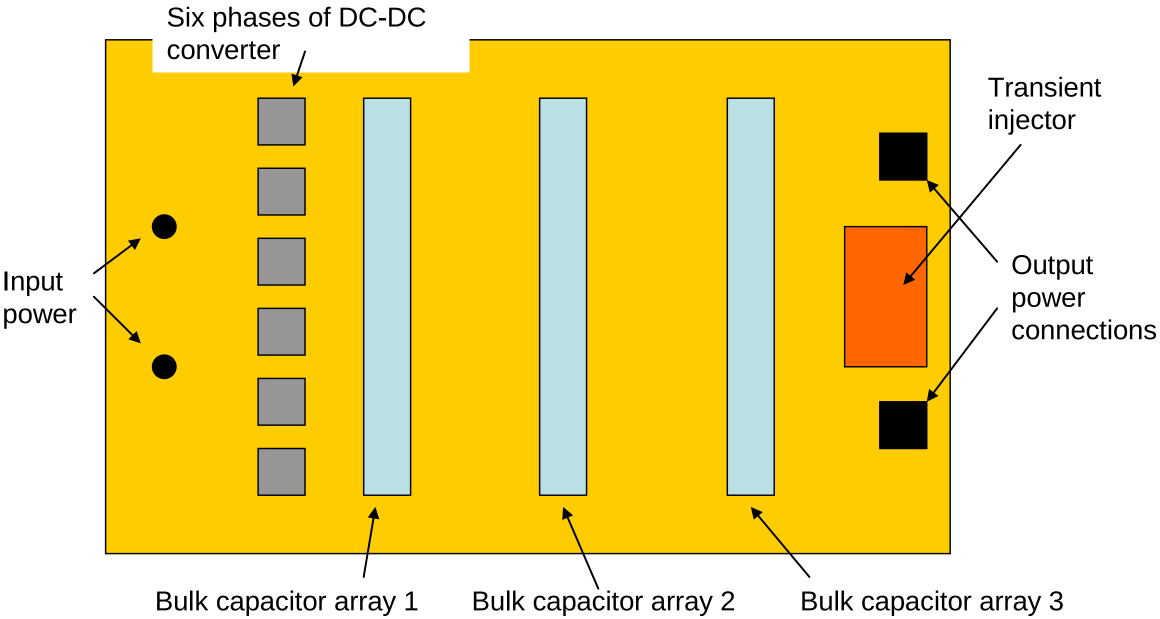


Three-Phase DUT: Current Sharing



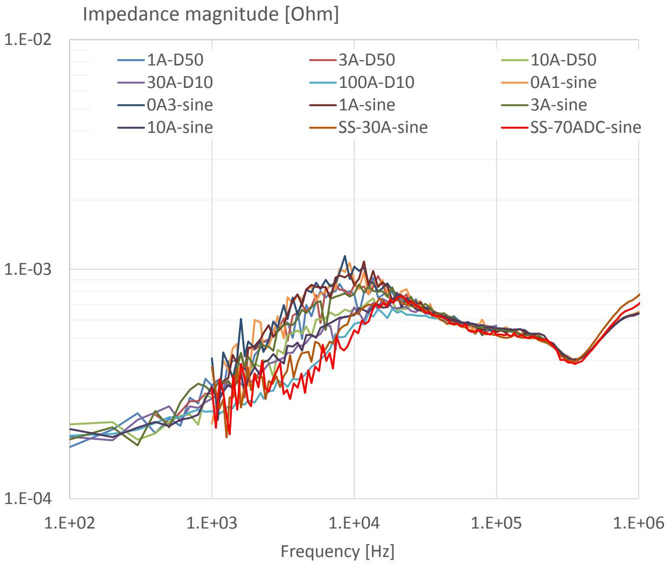


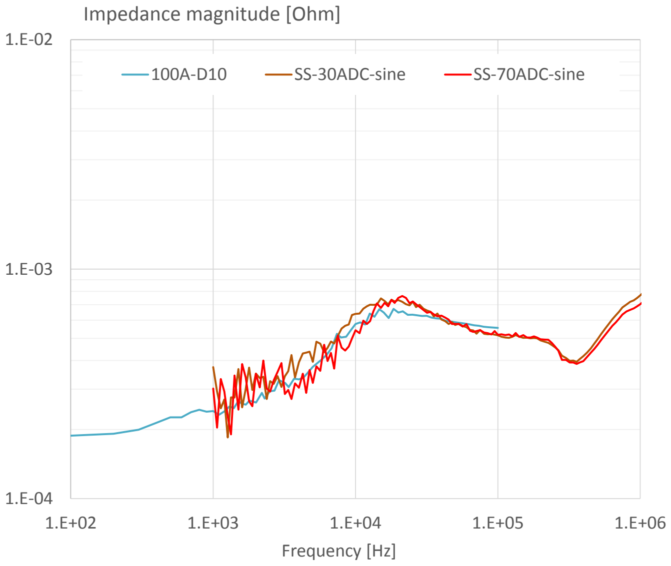
Six-Phase DUT: Outline



- 12V input
- 1.05V output
- Digital control
- 200+A max current

Six-Phase DUT: Output Impedance

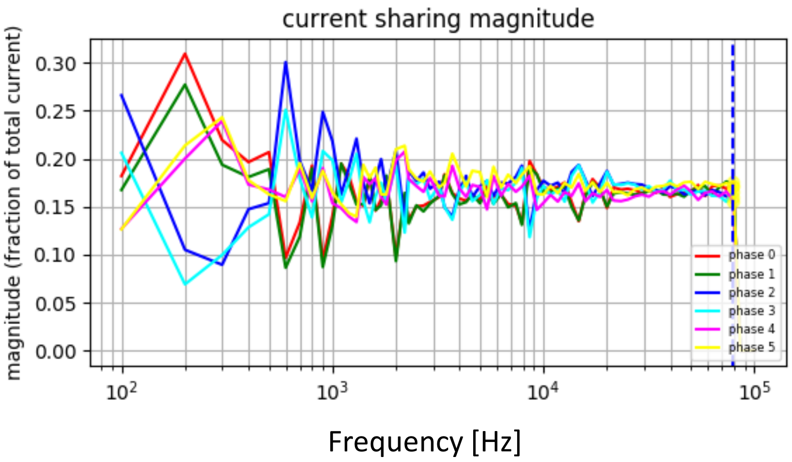


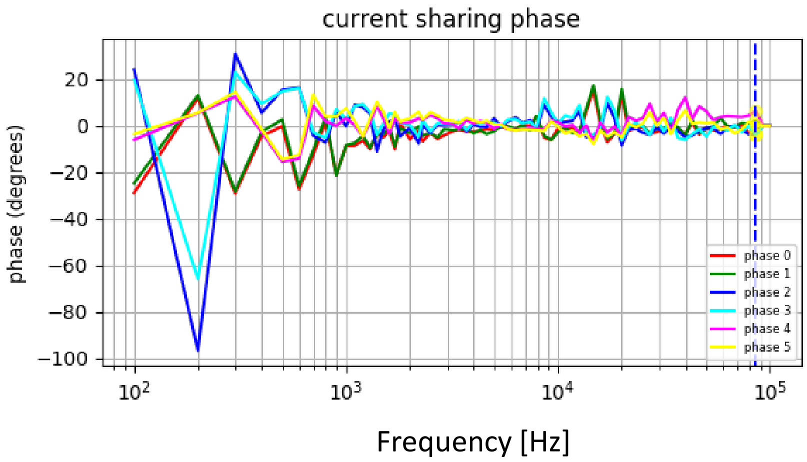


Various test conditions:

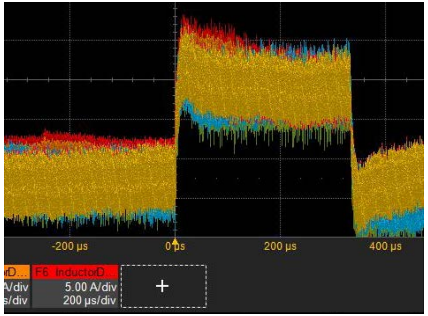
- Small-signal VNA
- Small-medium-large signal AC
- Small-medium-large signal pulse

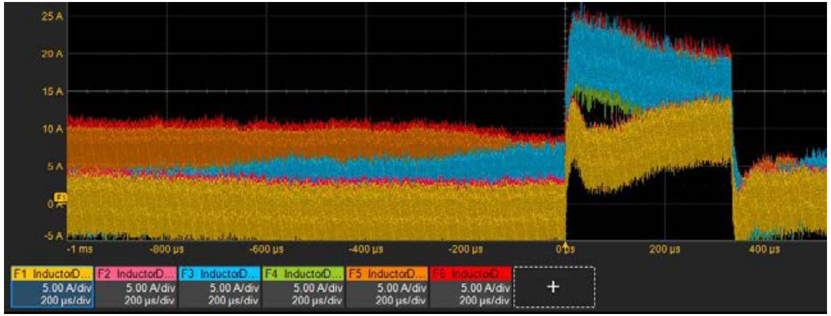
Six-Phase DUT
Current Sharing, Frequency Domain

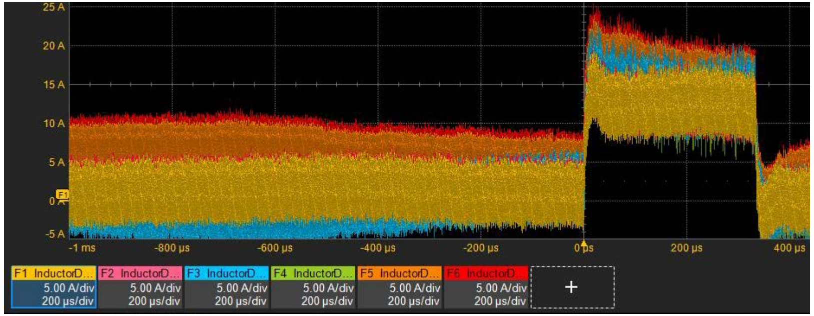


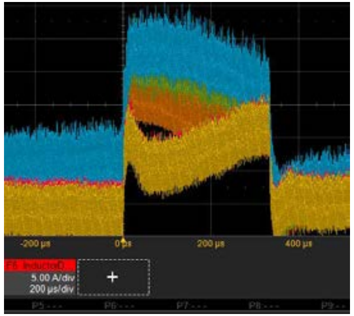


Six-Phase DUT: Current Sharing, Time Domain

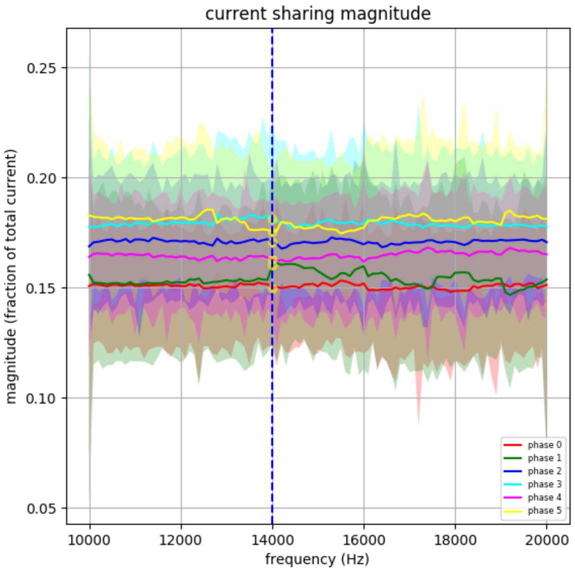


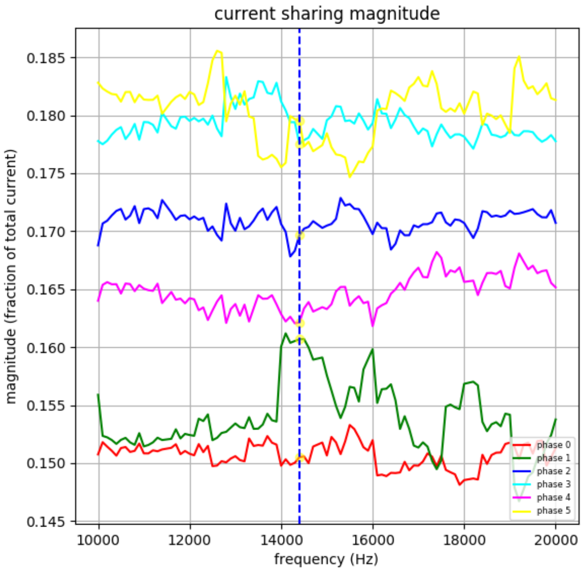






Production Board: Current Sharing





- 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!

QUESTIONS?