A Generic Test Tool for Power Distribution Networks

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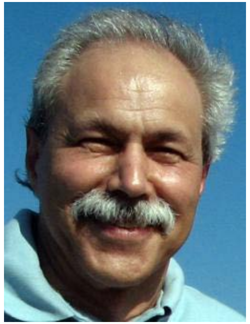
SPEAKERS



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Agenda

- Introduction
- Common PDN Test Tasks
- Universal PDN Test Tool, Concept
- Universal PDN Test Tool, Implementation
- Summary and Conclusions

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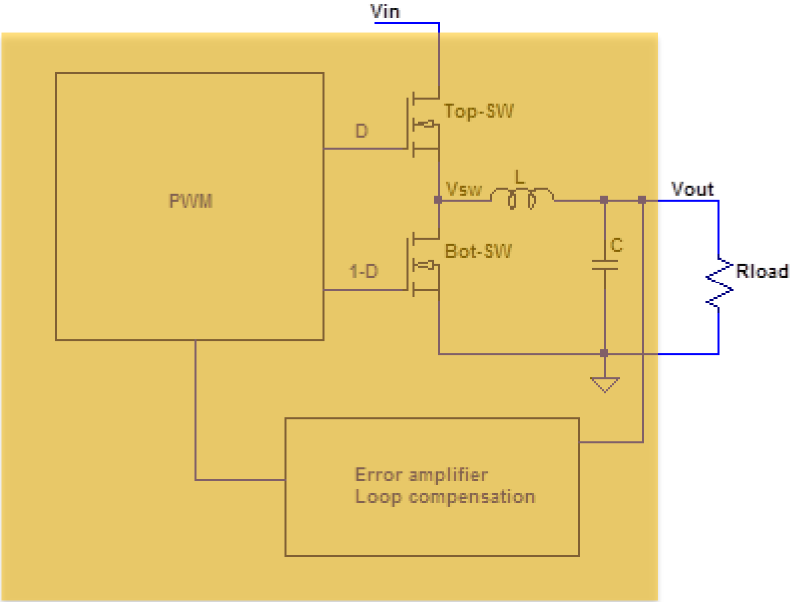
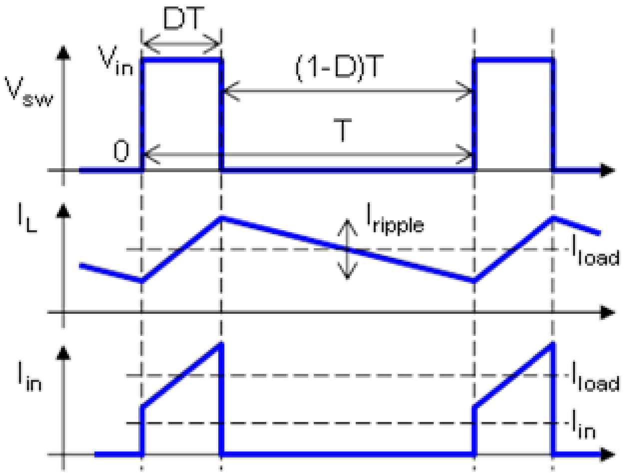
Introduction

Non-isolated single-phase buck converter



Typical waveforms



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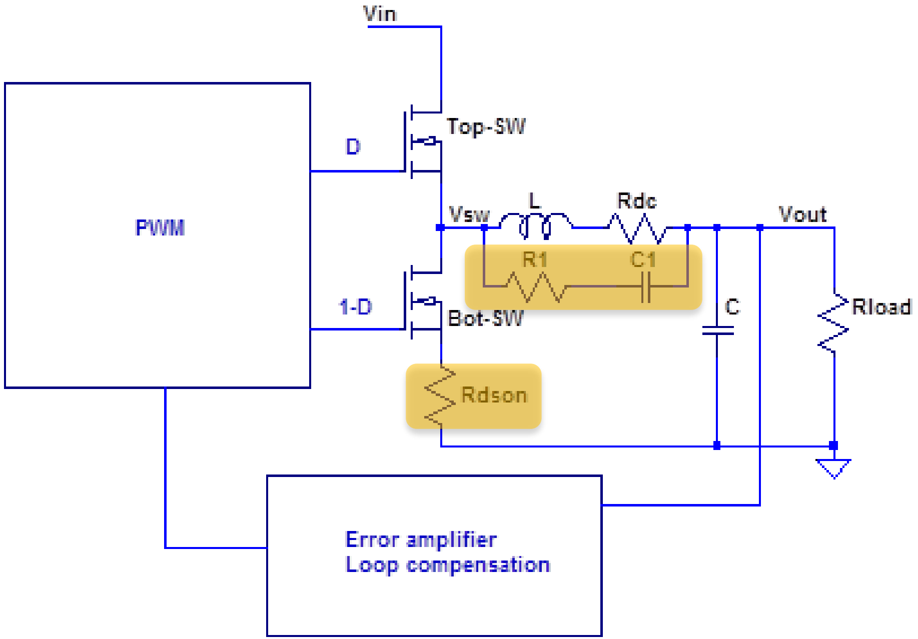
Input and Output Current, Current Sharing

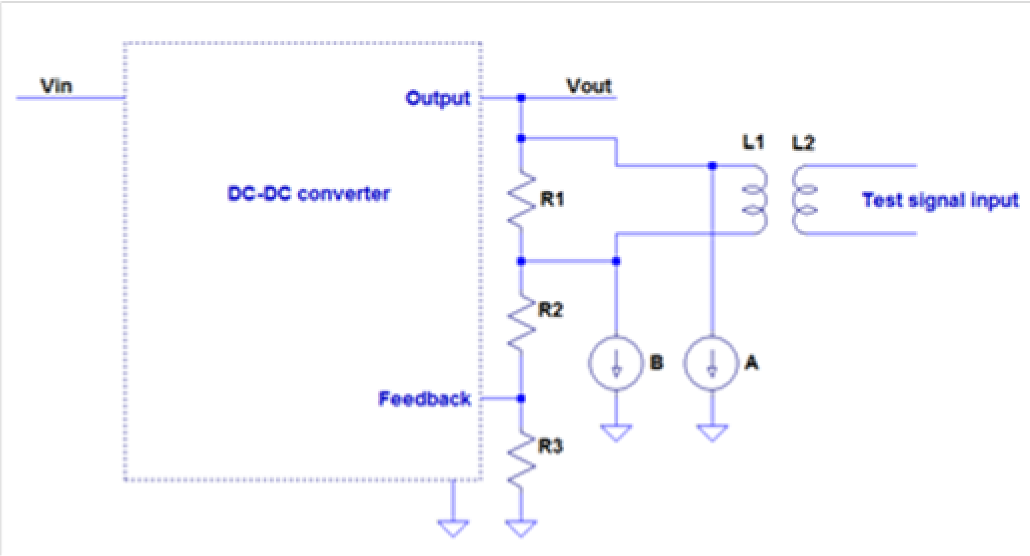
Options:

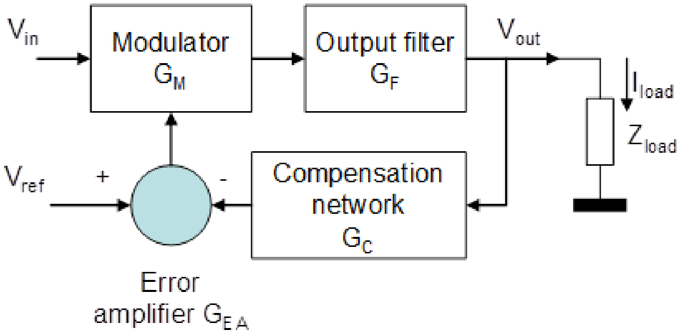
- Inductor current with R-C
- Voltage drop across low-side FET
- Voltage drop across high-side FET
- Voltage drop across shunt element
- Current sensor, shunt



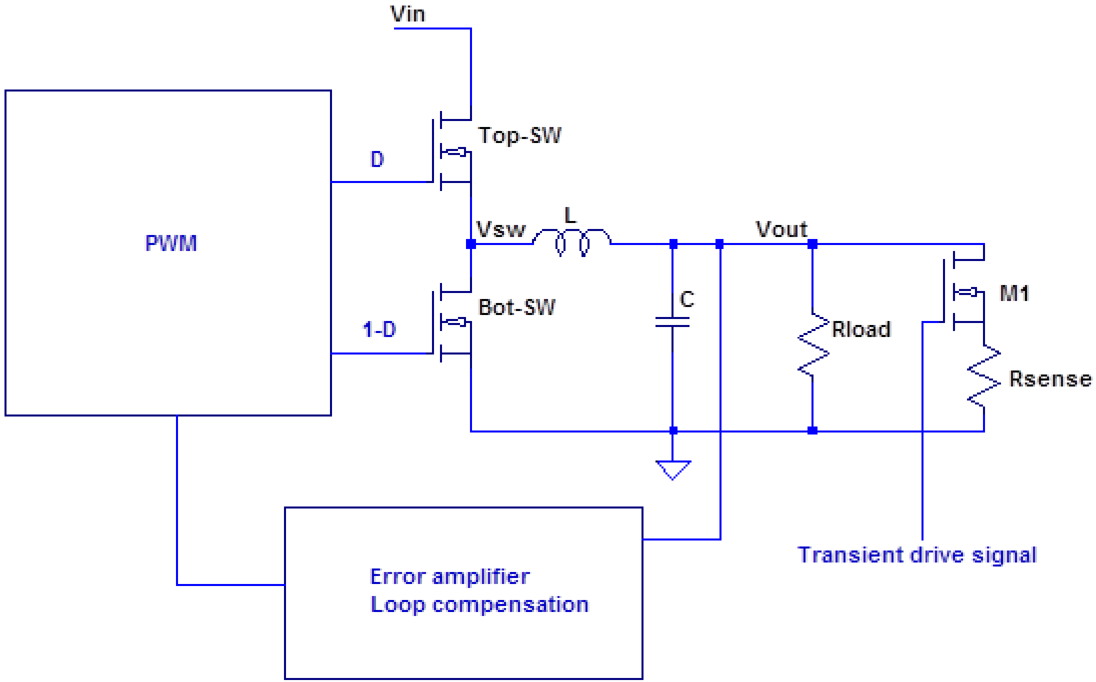
Voltage Loop Gain

$$G_{loop} = G_M \; G_F \; G_C \; G_{EA}$$

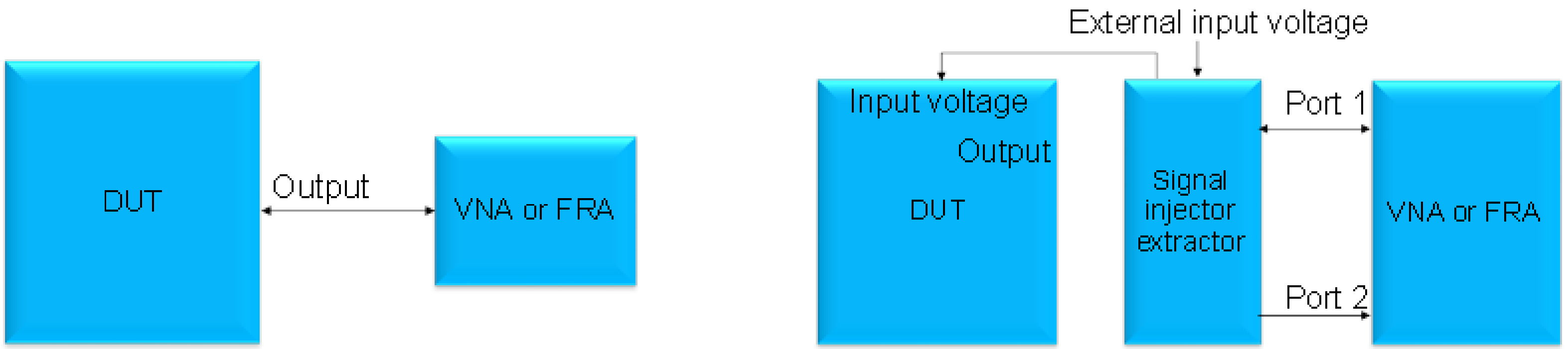




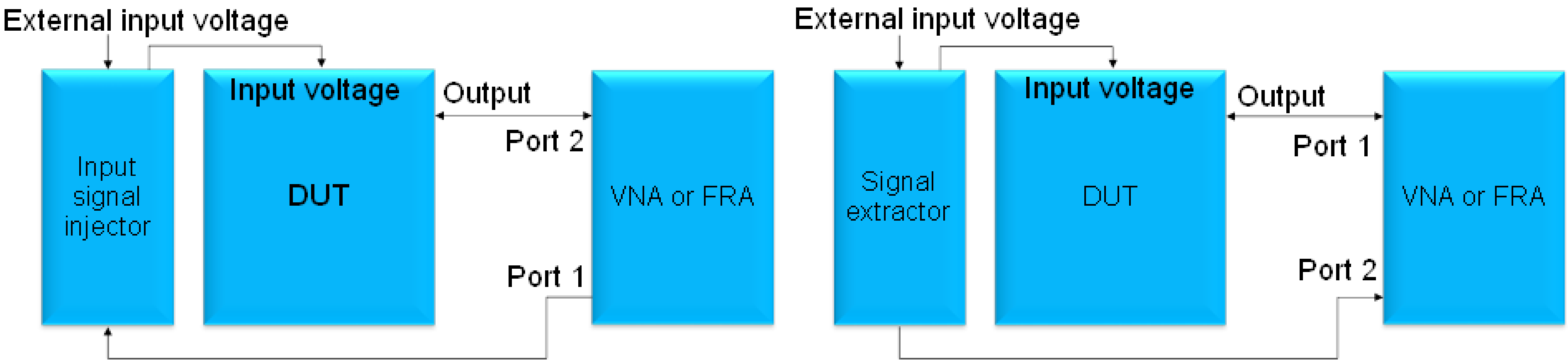
Transient Response to Load Current



Output and Input Impedance



Input-to-Output and Output-to-Input Transfer



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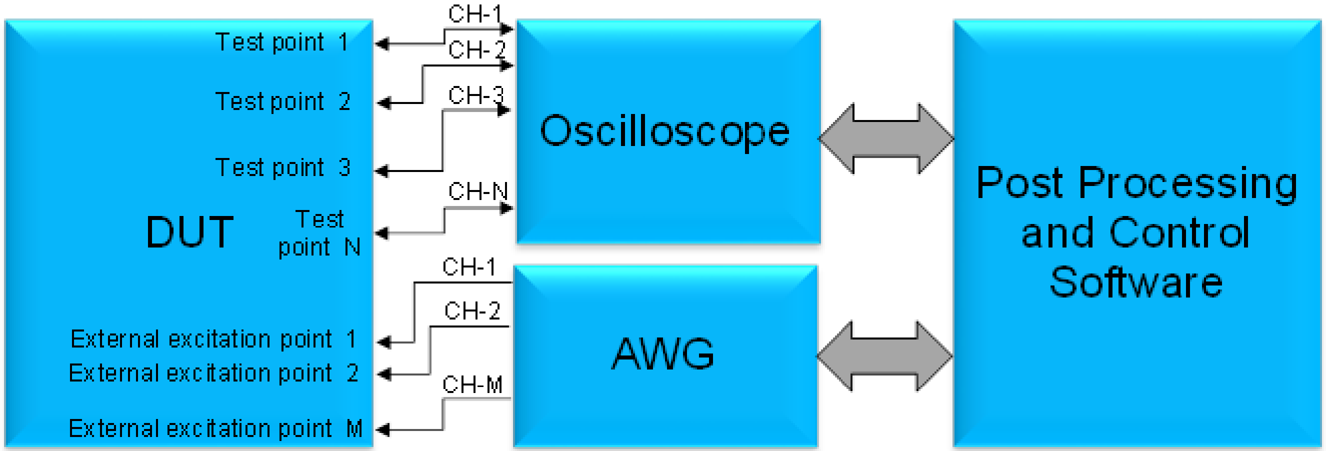
Universal PDN Test Tool, Concept



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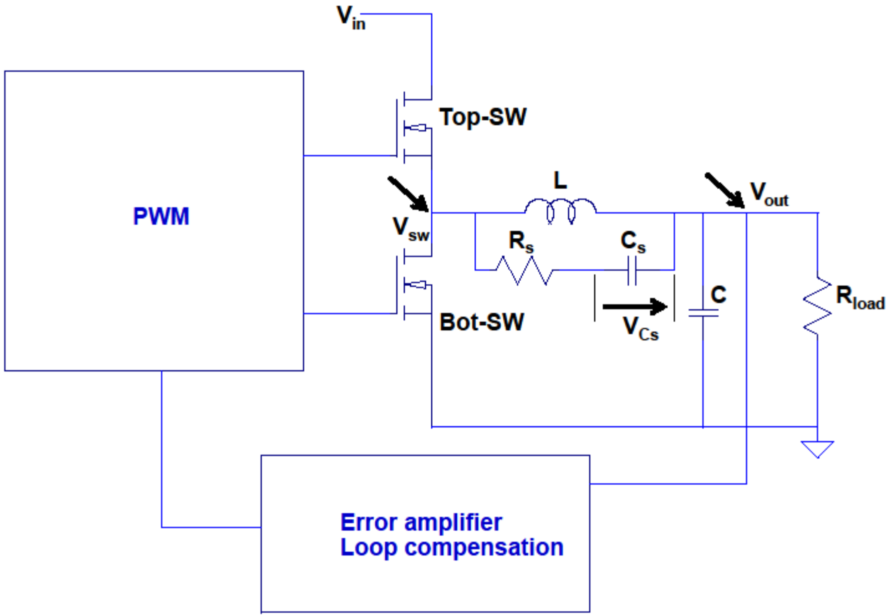
Implementation

- **Voltage Monitoring Points:**
  - Vsw – the switch node voltage
  - Vcs – the differential voltage across Cs
  - Vout – the output voltage
- **Goal:**
  - To correlate the inductor current inferred from VL (Vsw-Vout) and the inductor current inferred from Vcs.



Calculation of IL

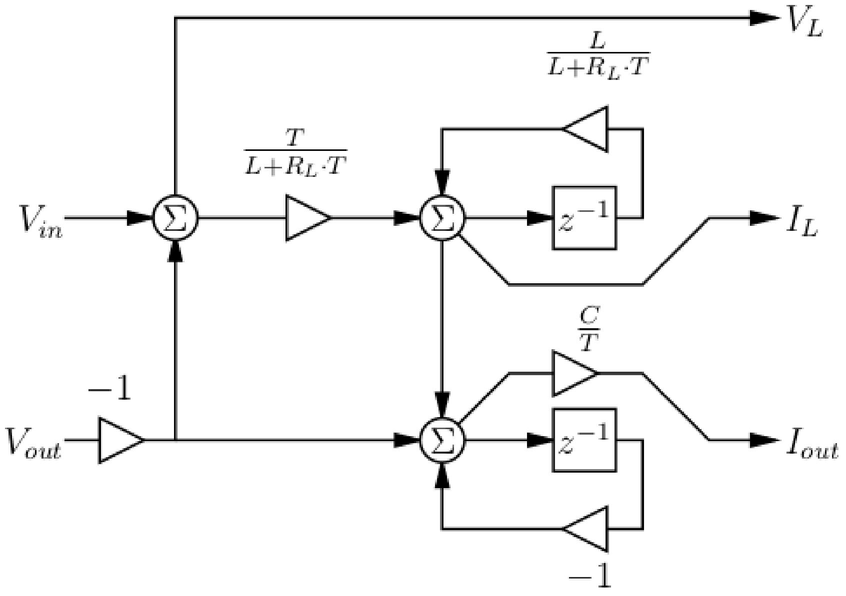
$$I_L(s) = V_L(s) \cdot \frac{\frac{1}{L}}{s + \frac{R_L}{L}} \qquad s \approx \frac{1}{T} \cdot (1 - z^{-1}))$$

$$H_L(z) = \frac{T}{L + R_L \cdot T} \cdot \frac{z}{z - \frac{L}{L + R_L \cdot T}}$$

$$H_L(z) = \frac{L}{L + R_L \cdot T} \approx 1 - 17.6 \cdot 10^{-6}$$
$$= 0.9999824$$

$$\tau = \frac{L}{R_L} = \frac{15\mu}{26.4m} = 568.2\mu s$$

$$5 \cdot \tau = 2.841ms = 284.1kS@100MS/s$$



Noise Considerations

Extreme gain at DC

- $Gain = 20 \cdot \log\left(\frac{1}{R_L}\right)$

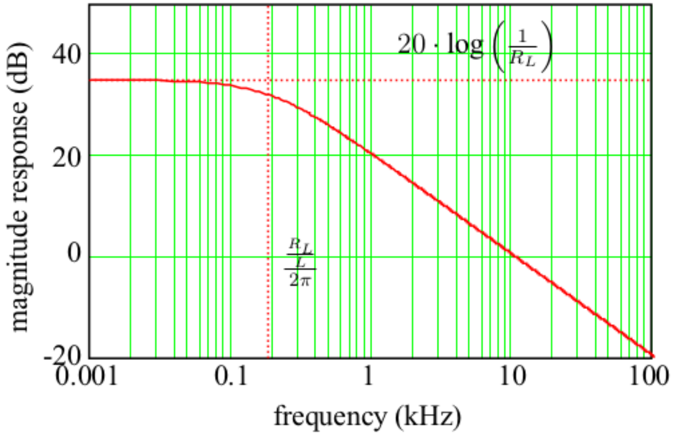
Noise Density depends heavily on VDIV:

- $N_{dBm} = 20 \cdot \log\left(\frac{VDIV \cdot 4}{\sqrt{2}}\right) + 13.010 - SNR - 10 \cdot \log(F)$

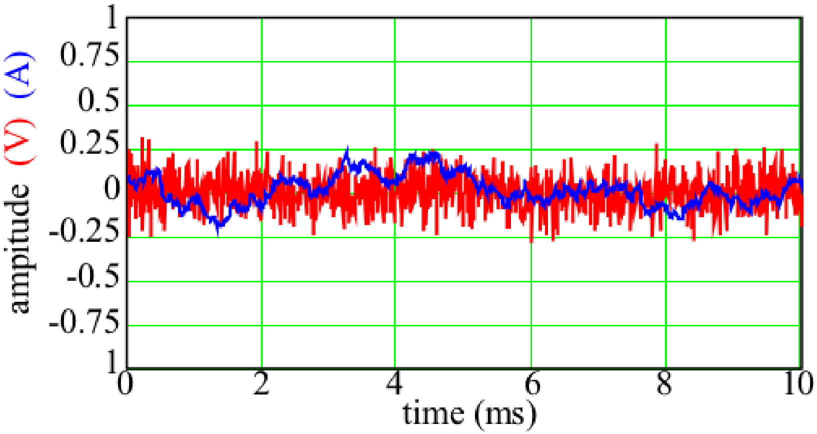
Effect of noise is not necessarily intuitive, but can be simulated.

The expectation for this application is a low frequency wander of +/- 250 mA.

Response of IL Calculation



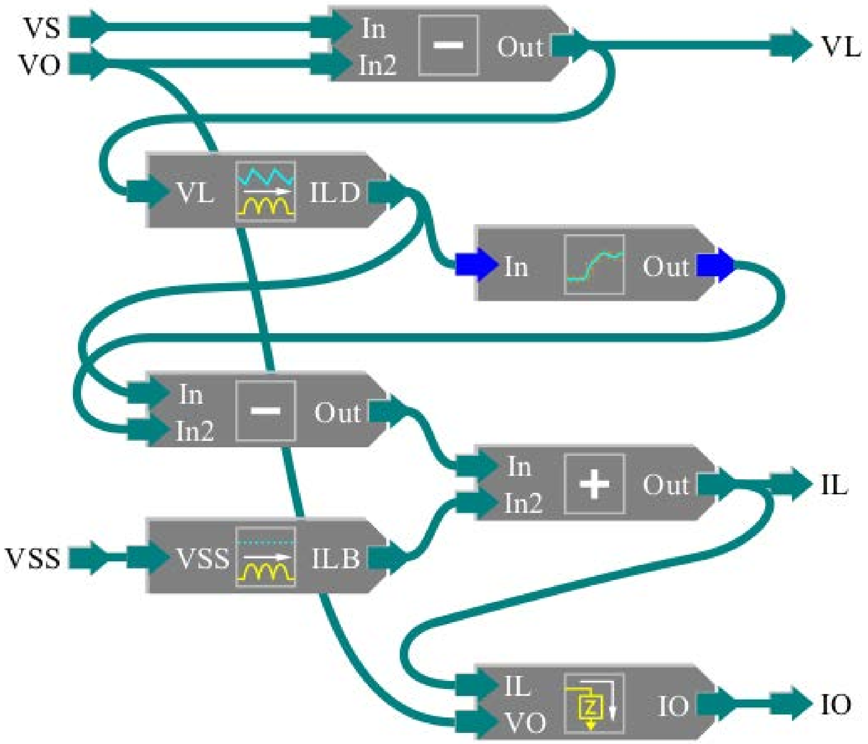
Noise Simulation



Full Inductor Current Processing

- **Makes use of the LeCroy Processing Web**
  - Many special purpose components wired together to produce various output waveforms.
- **Dynamic Current:**
  - Calculated by processing VL (the difference between Vsw and Vout)
  - Filtered to remove low frequency wander (i.e. High pass filter with single pole cutoff around 10 kHz.).
- **Static Current:**
  - Sample switch node waveform at flat spot during off time.

The static and dynamic currents are summed to form IL

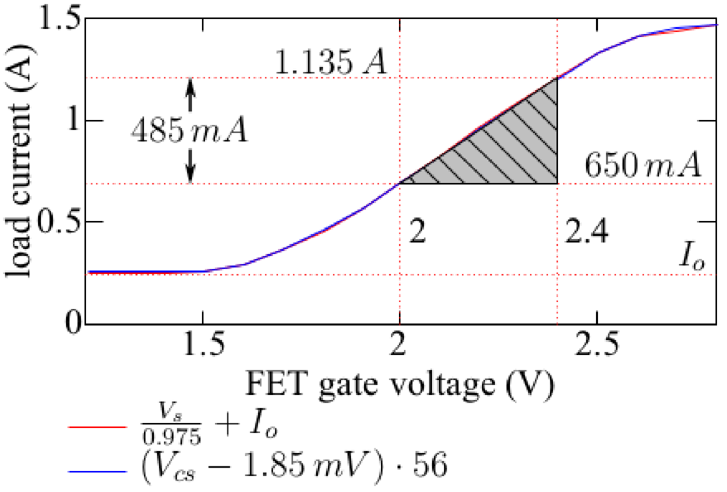


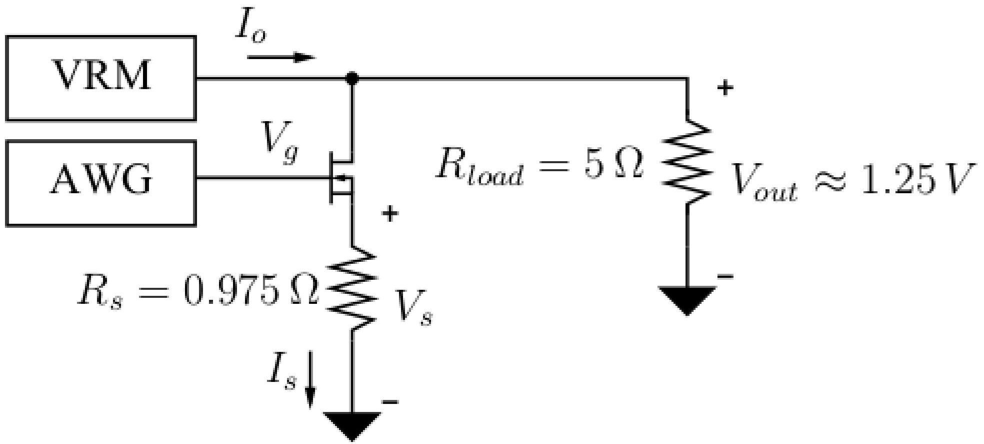
Transient Load Circuitry

Constant static 5 Ohm load. $I_{out} \approx \frac{1.25}{5} = 250mA$

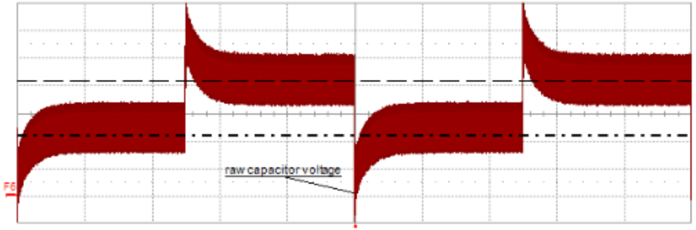
Dynamic Load controlled by FET of up to a parallel 0.975 Ohms.

Vs is monitored with scope



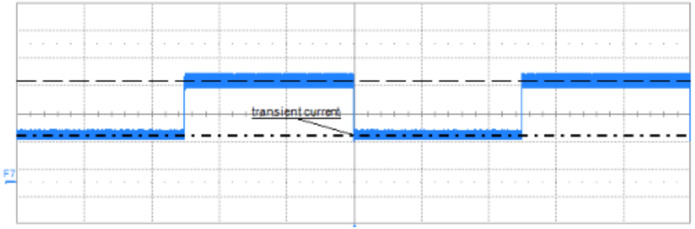


An Unlikely Capacitor Voltage Measurement



(a) raw capacitor voltage V_{cs}

(b) inductor current calculated from V_{cs}

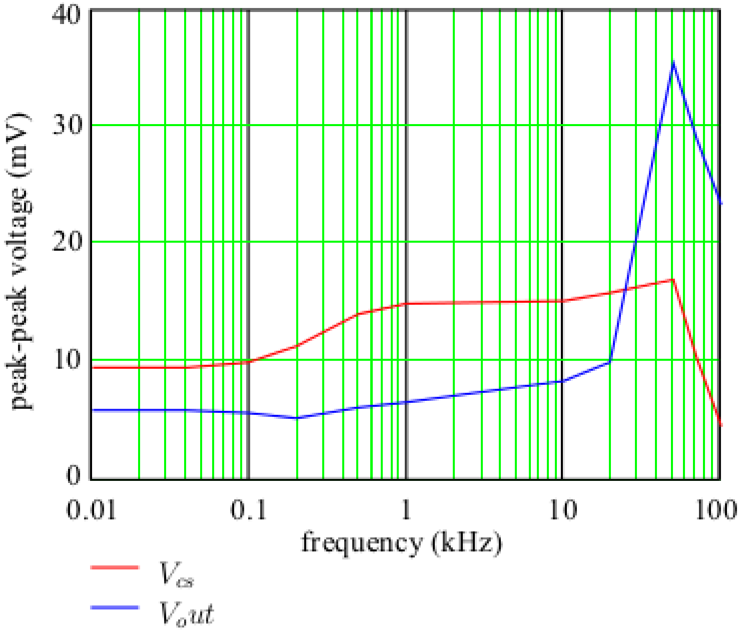


(c) transient current

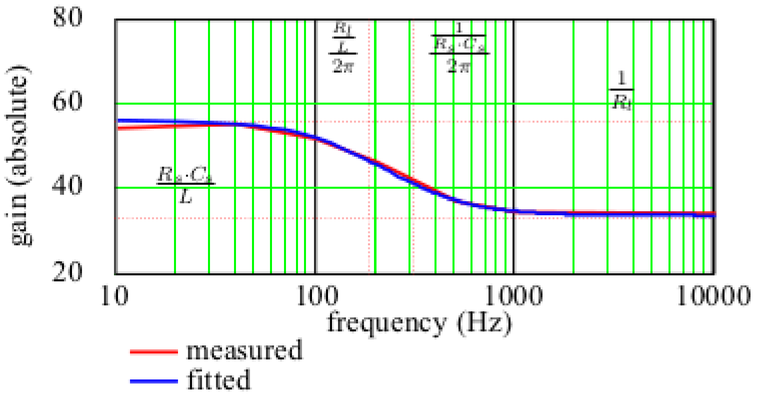
(d) inductor current calculated from V_L

(e) scope settings

AC Calibration of IL



AC Calibration

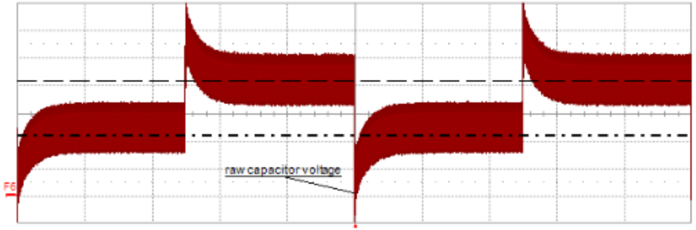


Fitted Results

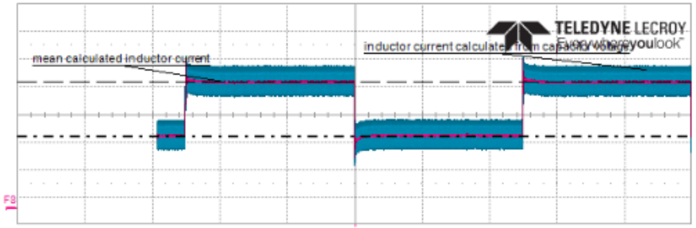
$$H(s) = \frac{s + \frac{1}{R_s \cdot C_s}}{s + \frac{R_L}{L}} \cdot \frac{R_s \cdot C_s}{L}$$

Results fitted to: $H(s)^{-1}$

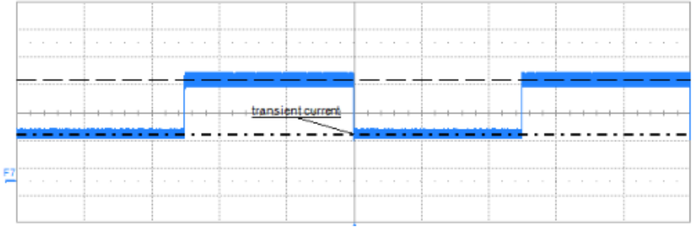
Correct Calculation of IL



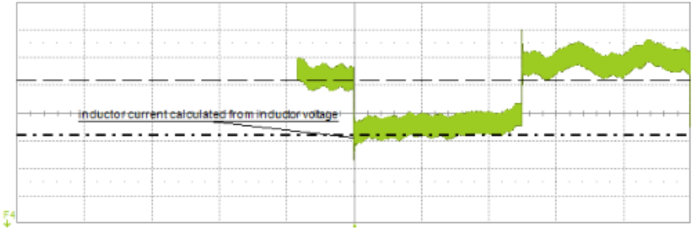
(a) raw capacitor voltage V_{cs}



(b) inductor current calculated from V_{cs}



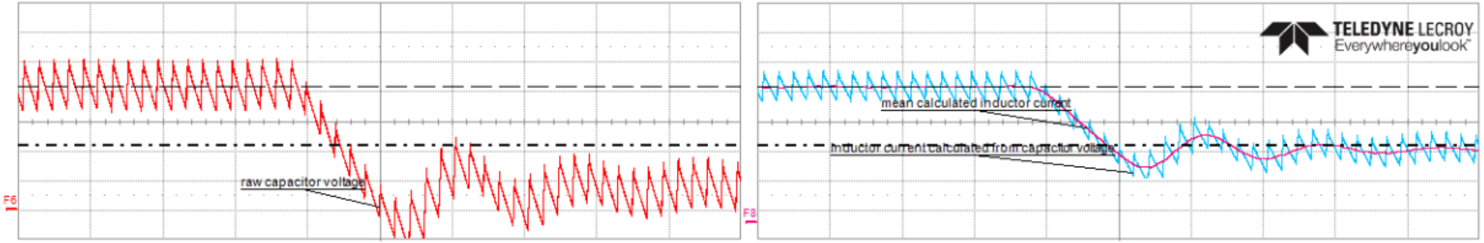
(c) transient current



(d) inductor current calculated from V_L

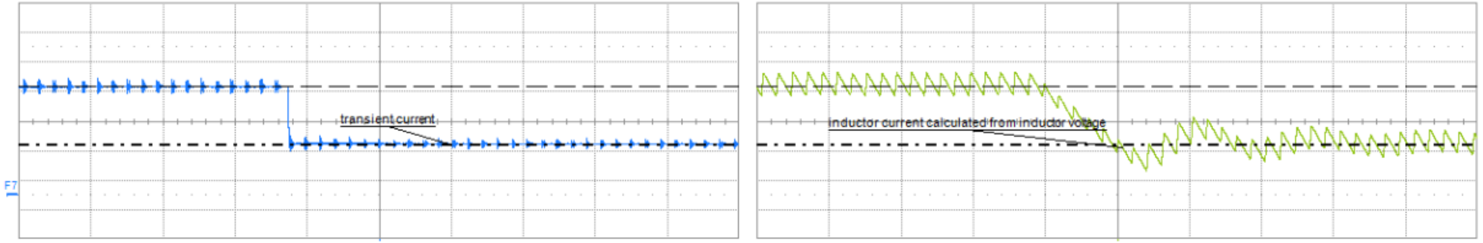
(e) scope settings

Correct Calculation of IL



(a) raw capacitor voltage V_{cs}

(b) inductor current calculated from V_{cs}



(c) transient current

(d) inductor current calculated from V_L

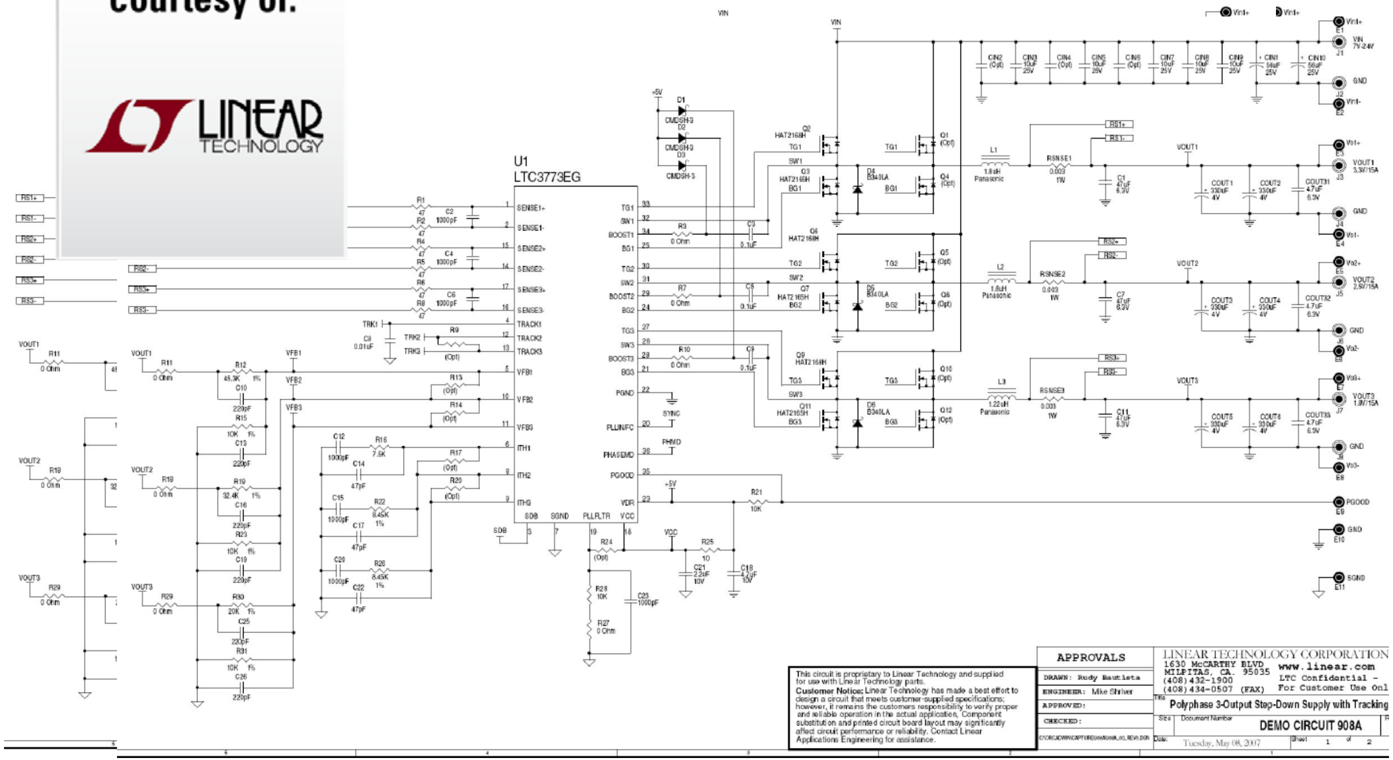
	F3 web edit	F4 web edit	F6 web edit	F7 web edit	F8 web edit
	250 mA/div	250 mA/div	5.00 mV	250 mA/div	250 mA/div
	10.0 µs/div	10.0 µs/div	10.0 µs/div	10.0 µs/div	10.0 µs/div
-·-·-	650 mA	1.923 A	10.79 mV	420 mA	650 mA
······	1.135 A	2.408 A	20.50 mV	905 mA	1.135 A
Δ	485 mA	485 mA	9.70 mV	485 mA	485 mA

Tbase	0.00 ms	Trigger	C4 DC
	2.00 ms/div	Stop	250 µV
2 MS	100 MS/s	Edge	Positive

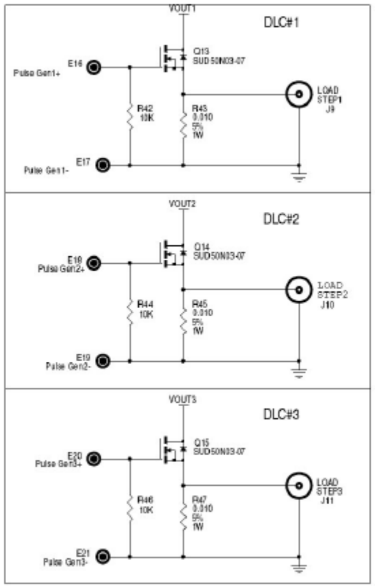
DUT and the Transient Generator

Board courtesy of:

LINEAR TECHNOLOGY



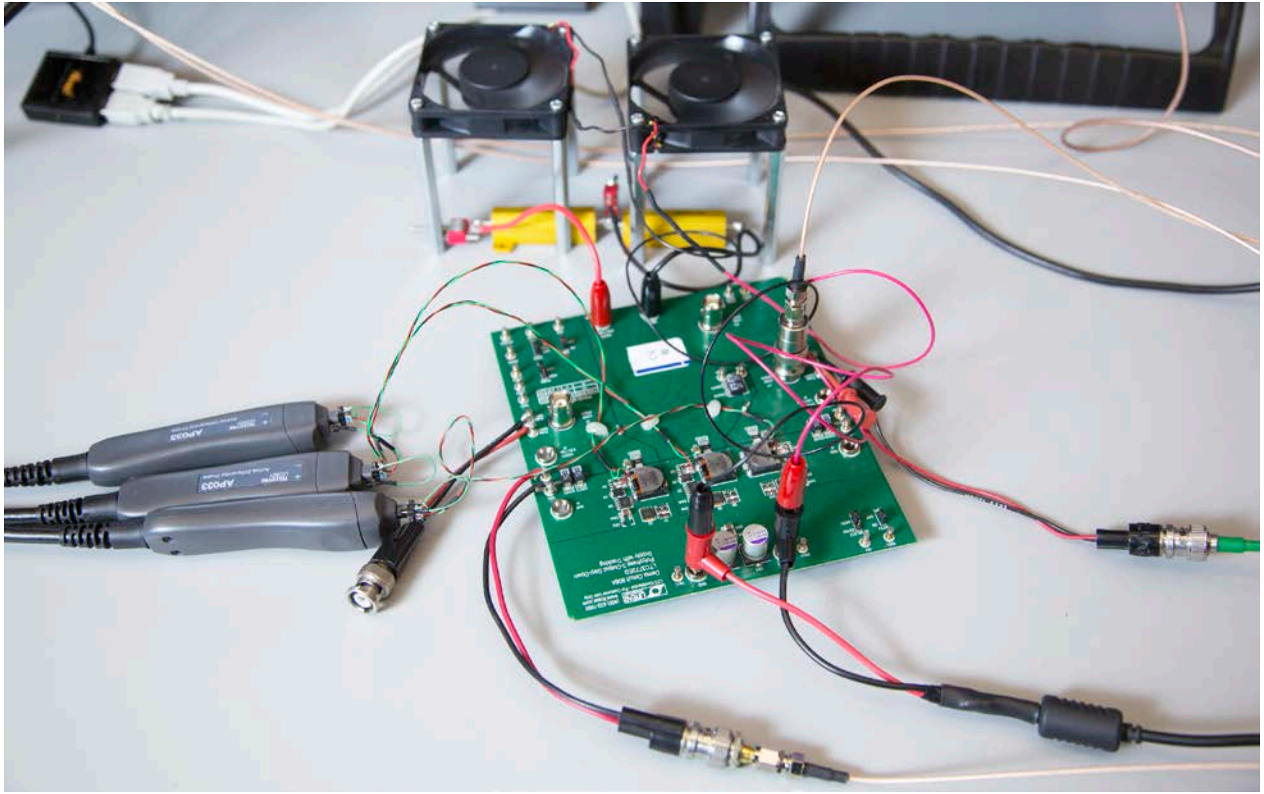
Dynamic Load Circuits



Disclaimer

- In the development of this paper we worked rapidly in a manner to explore various measurement possibilities and sometimes handled metrology and full measurement accuracy somewhat loosely.
- This most certainly results in measurement inaccuracies that will be addressed in the future and should not reflect badly on the DUT.
- The results shown are our best efforts at reasonable calibration but are mostly indicative of potential instrument capabilities that can be provided in the future.

Device Under Test Setup

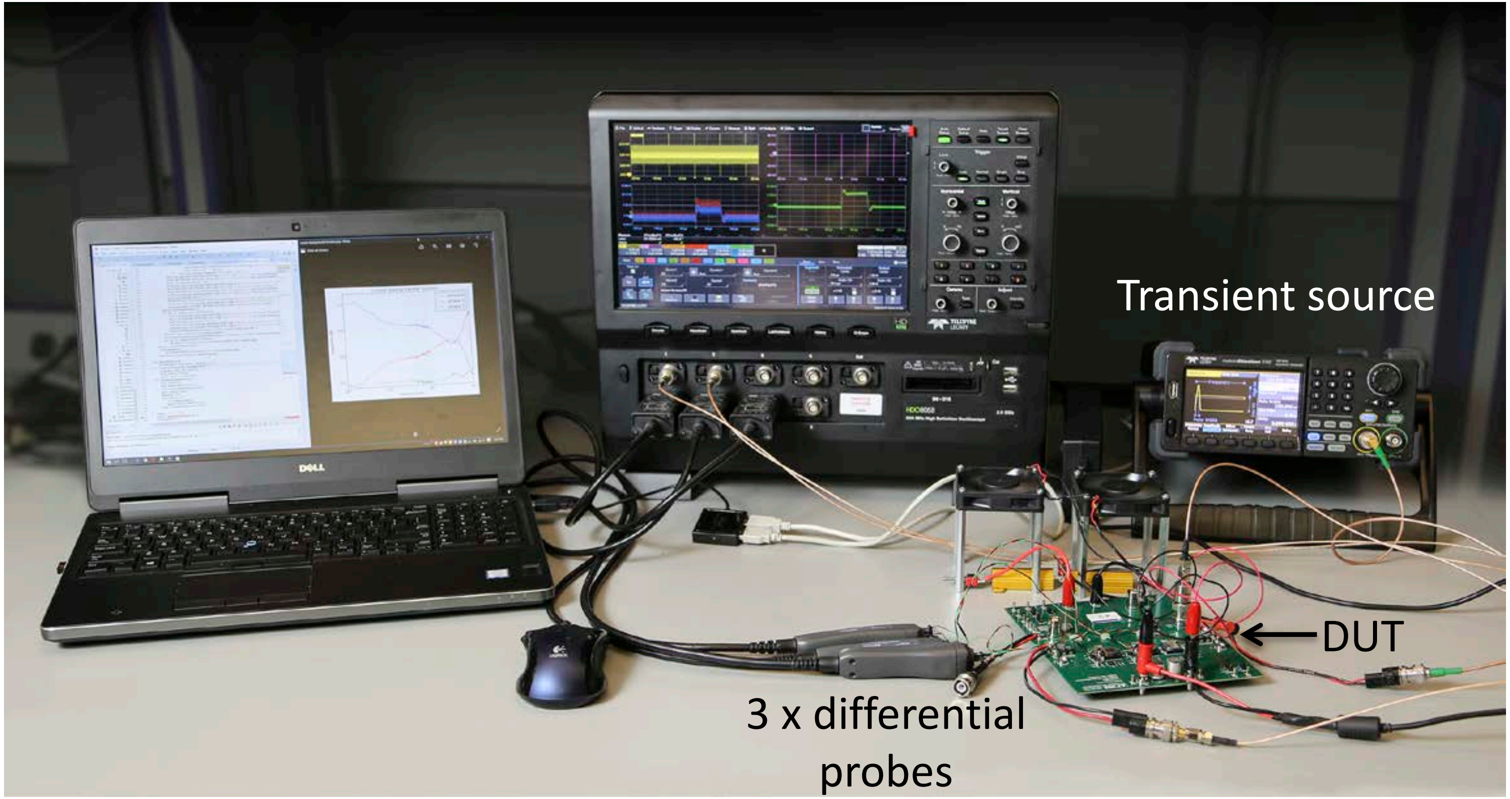


DUT: 3-phase non-isolated buck converter

Board courtesy of:

LINEAR TECHNOLOGY

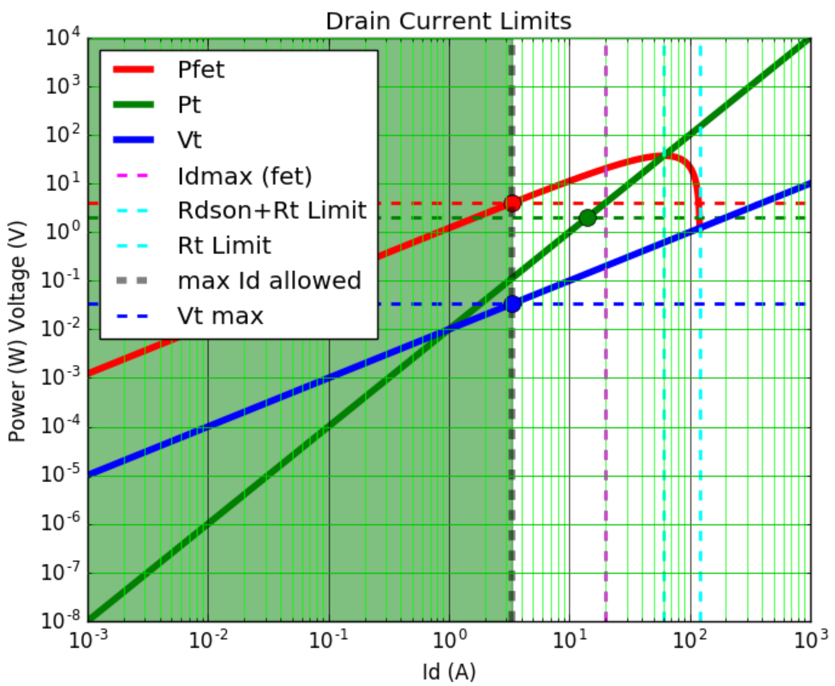
Lab Setup



Transient Generator Limits

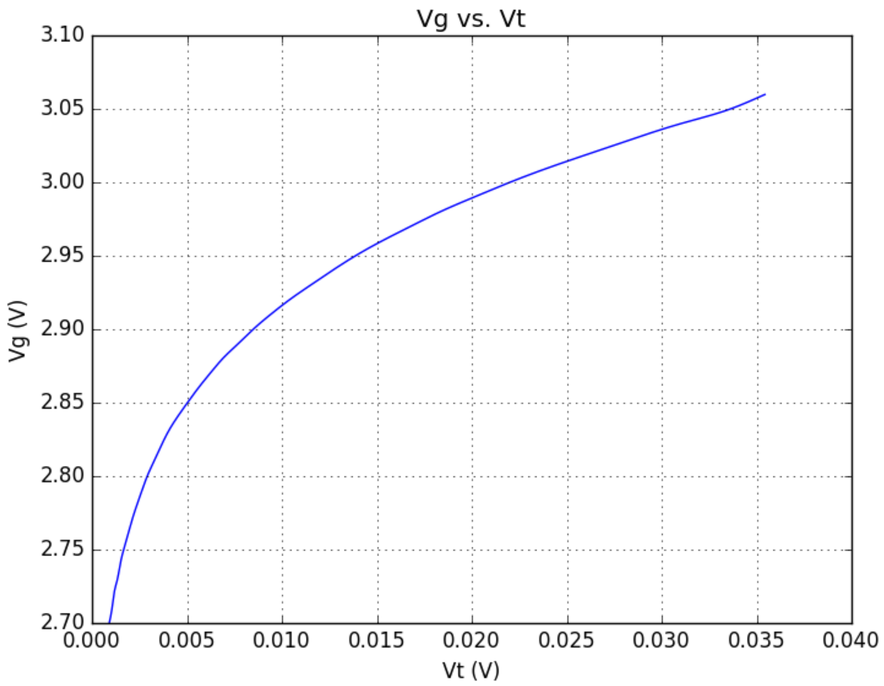
- FET max power dissipation: 4 W
- Maximum drain current: 20 A
- Max Vout: 1.22 V
- Source resistor: 10 mOhms, 2W max
- Rdson 10 mOhms

Drain current must be restricted to 3.372 A due to FET power dissipation specification.
At this current, the maximum source resistor voltage (Vt) measured will be 33.72 mV.
Complete list of remaining drain current limitations:
14.14 A allowed due to source resistor power rating.
20.0 A allowed due to fet max drain current specification.
61.0 A possible due to Rdson and source resistor values.
anything below this line is not possible based on the values provided.
122.0 A possible due to source resistor value.



Transient Generator Calibration

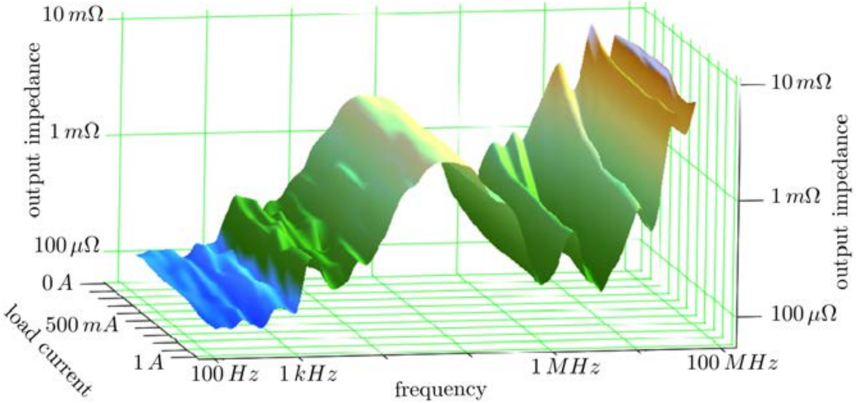
- The FET gate voltage is slowly raised, while measuring the voltage across the source resistor.
- We stop when the voltage across the source resistor reaches the max voltage of 33.72 mV
- A spline is fit to the data so that we can interpolate values of gate voltage needed to generate desired drain currents.
- Idea is to operate in a linear region with given signal swing – bias for class A operation is subtracted from DC load current supplied by electronic load.

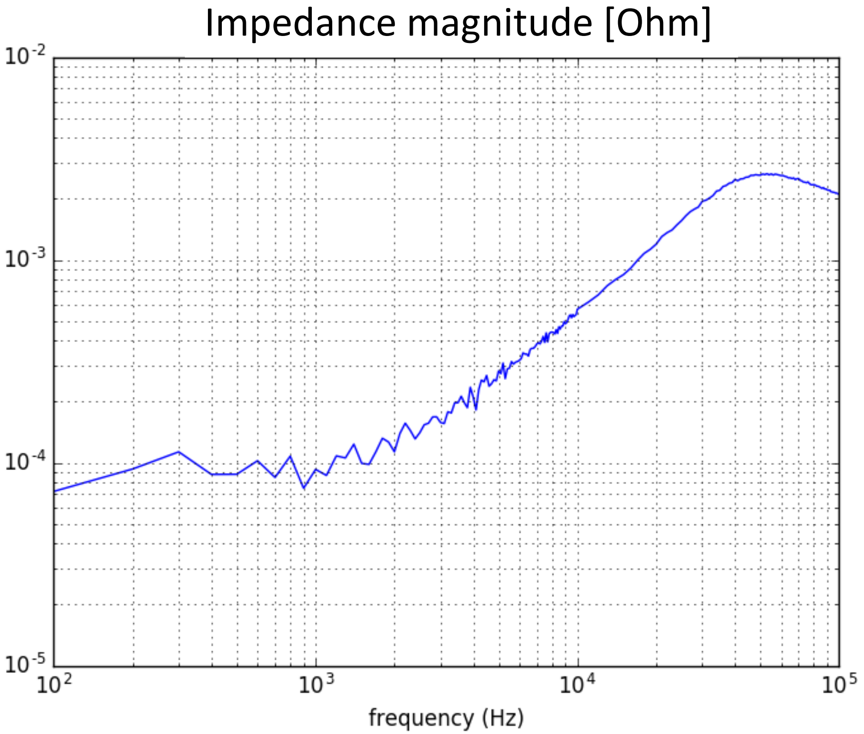


Output Impedance vs. DC Load Current (Light Load)

Potential variables:

- DC load current
- DC input voltage
- DC output voltage
- Temperature
- AC excitation current

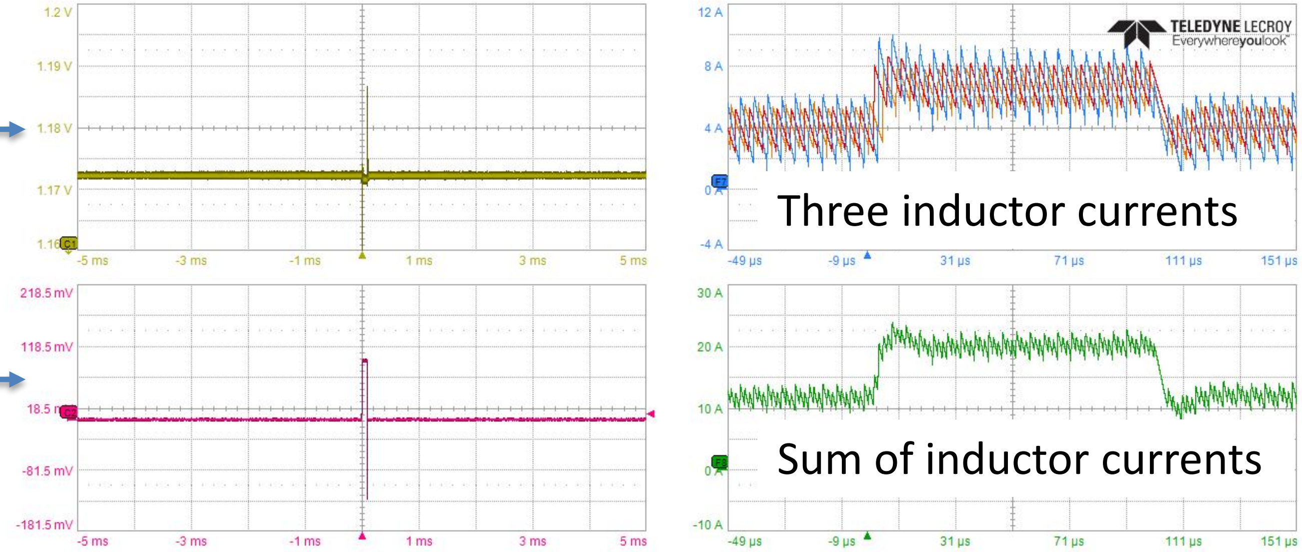




Transient Current Step

Output voltage transient

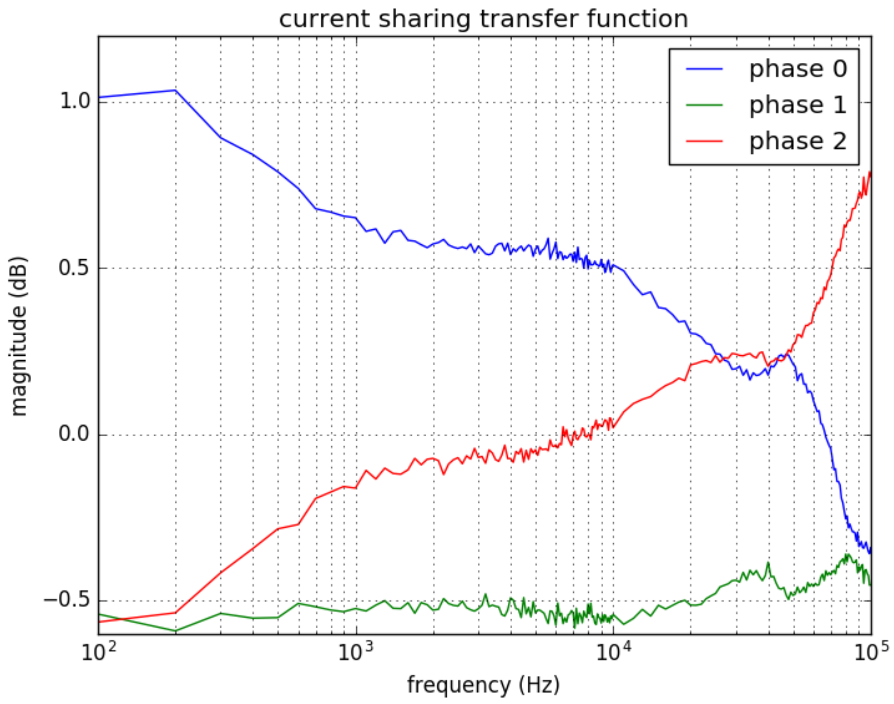
Current-sense voltage

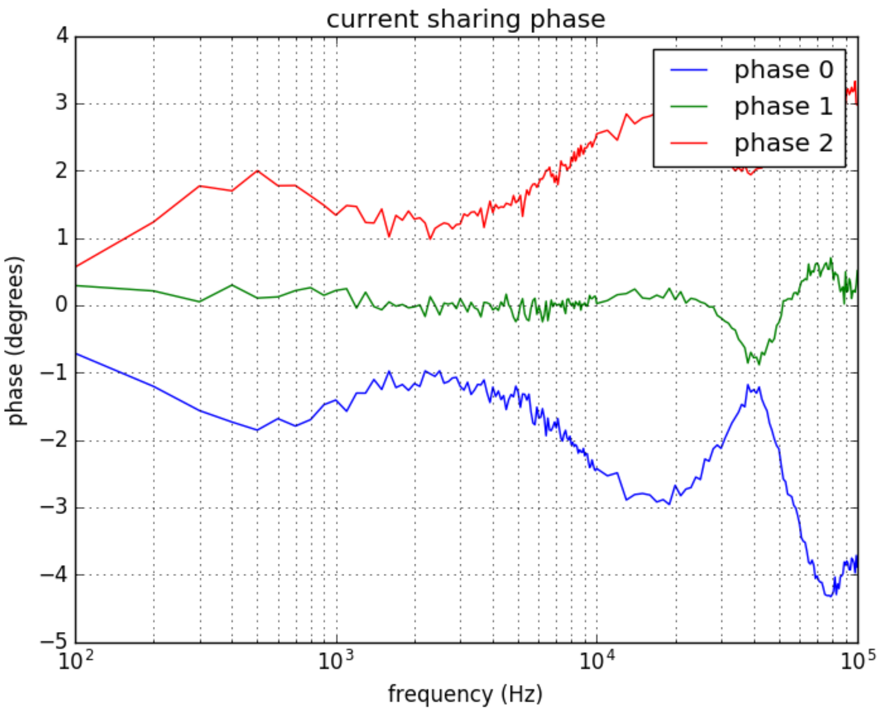


StdVer	P1:pkpk(F7)	P2:ampl(F7)	P3:max(F7)	P4:min(F7)	P5:sdev(F7)	P6:mean(F7)	P7:base(F7)	P8:top(F7)	P9:- - -	P10:- - -	P11:- - -	P12:- - -
value	8.99155 A	8.99147 A	10.00326 A	1.01179 A	1.996851 A	6.882286 A	1.01179 A	10.00326 A				
mean	9.6482 A	9.6482 A	9.9259 A	277.7 mA	2.02196 A	5.7901 A	277.7 mA	9.9259 A				
min	8.62923 A	8.62918 A	9.53236 A	-546.62 mA	1.965231 A	5.247878 A	-546.62 mA	9.53236 A				
max	10.40299 A	10.40290 A	10.31239 A	1.18111 A	2.066058 A	6.953764 A	1.18111 A	10.31239 A				
sdev	433.1 mA	433.1 mA	151.2 mA	430.1 mA	25.71 mA	688.0 mA	430.1 mA	151.2 mA				
num	200	200	200	200	200	200	200	200				
status	✓	⎍	✓	✓	✓	✓	⎍	⎍				

C1 A B D50	C2 BwL DC50	F5 InductorD...	F6 InductorD...	F7 InductorD...	F8 ((F5+F6)+...	Tbase 0.00 ms	Trigger C2 DC
5.00 mV	50.0 mV	2.00 A/div	2.00 A/div	2.00 A/div	5.00 A/div	1.00 ms/div	Norm. 10.5 mV
-1.18000 V	-18.50 mV	20.0 µs/div	20.0 µs/div	20.0 µs/div	20.0 µs/div	1 MS 100 MS/s	Edge Positive
200 #							

Current Sharing vs. Frequency





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Summary

- Various PDN measurement tasks today are covered with different instruments and connections
- A universal PDN test tool is proposed, which produces multiple metrics with the same instruments and minimum number of connections
- Inductor current measurements are possible using Vcs and VL
  - *Although VL measurement may need low frequency correction*
- Next Steps are to use sampled switch node voltage to restore low frequency accuracy
- Extensive calibration is required for any measurement because of large component variability (especially estimation of RL).
- The same instrumentation can be used for time-domain and frequency-domain tests
- Post-processing of inductor currents of multi-phase converters provides current-sharing transfer function

Thank you!

QUESTIONS?