Input Impedance & Input Filter Stability

OMICRON Lab Webinar Series 2020

2020-04-30

Webinar Hints

Open the Q&A function

Send questions to the presenters

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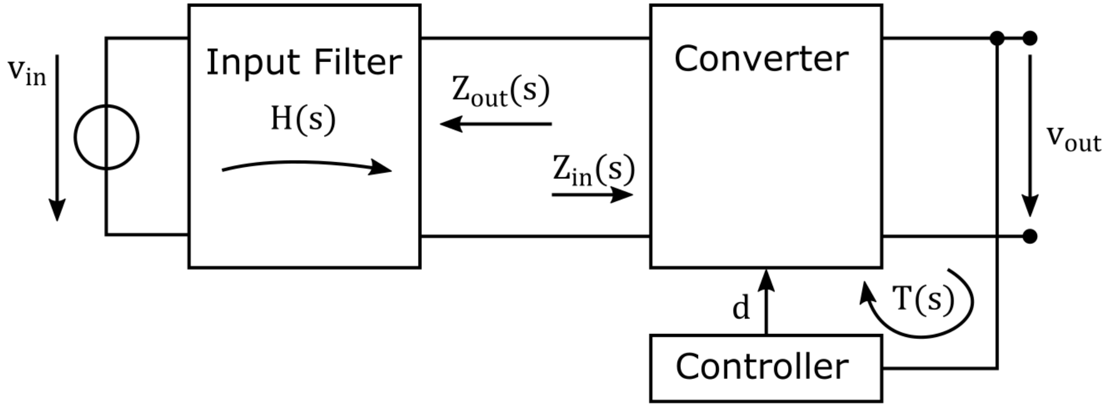
Agenda

- The input filter stability problem
- Experiment: Badly designed input filter
- Damping the input filter
- Input Impedance measurement
  - Modulation
  - Voltage measurement
  - Current measurement
- Hands-On measurements

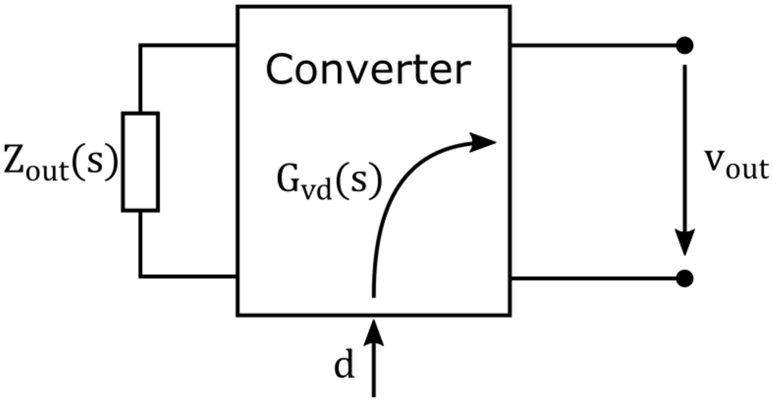
Input Filter Stability Problem



Converter has a **negative input impedance**
(increasing voltage → reduces current → R is negative)
→ negative resistance oscillator is possible

Extra-Element-Theorem (Middlebrook)

Extra element theorem of Middlebrook shows how a transfer function is changed when an additional impedance is added to a linear network



$$G_{vd} = G_{vd}\Big|_{Z_{out}=0} \left(\frac{1 + \frac{Z_{out}}{Z_N}}{1 + \frac{Z_{out}}{Z_D}} \right)$$

$$Z_D = Z_{in}\Big|_{\hat{d}=0}$$

... converter input impedance when no change in duty cycle

$$Z_N = Z_{in}\Big|_{\hat{v}_{out}\to 0}$$

... input impedance with ideal controller (no change in output voltage)

Design Criterion for Stable System

- If $Z_{out} \ll Z_N$ and $Z_{out} \ll Z_D$ then $\frac{1+\frac{Z_{out}}{Z_N}}{1+\frac{Z_{out}}{Z_D}} \approx 1$

  → system performance is not affected by the filter.
  (Z_N and Z_D need to be calculated or simulated)
- If converter is a „black-box“ only the much simpler criterion $Z_{out} \ll Z_{in}$ can be applied on the measured closed loop input impedance Z_{in}

Note: $Z_{out} \ll Z_{in}$ ensures stability but does not guarantee that system performance is unaffected!

Does it happen in reality?

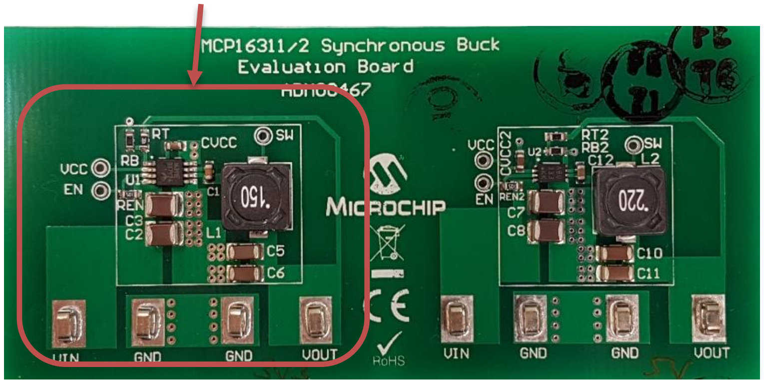
Example:

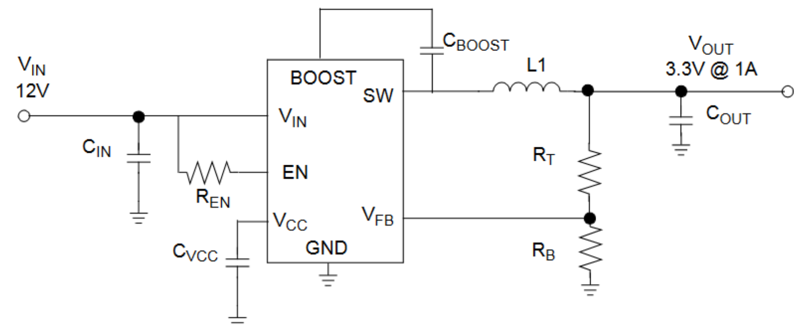
Synchronous Buck converter evaluation board:

$V_{in} \leq 30\ V$

$V_{out} = 3.3\ V$

Component	Value
C_{IN}	2 x 10 µF
C_{OUT}	2 x 10 µF
L1	15 µH
R_T	31.2 kΩ
R_B	10 kΩ
R_{EN}	1 MΩ
C_{VCC}	1 µF
C_{BOOST}	0.1 µF

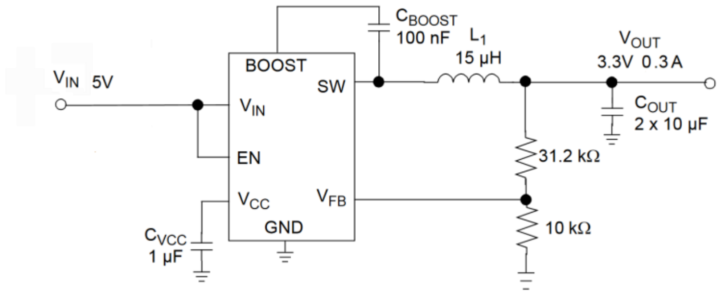


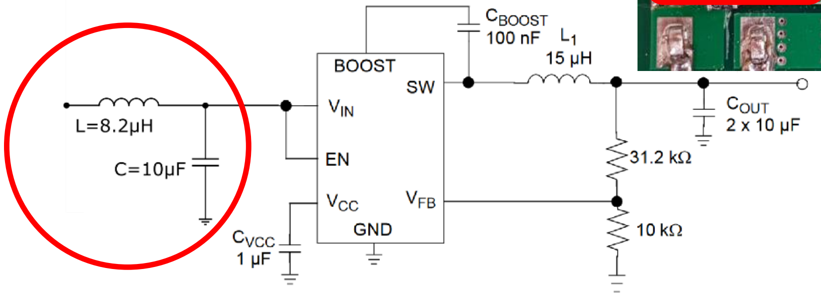


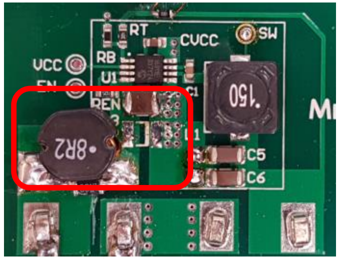
Load:

$I_{out} = 0.3\ A \rightarrow R_L = 11\ \Omega$

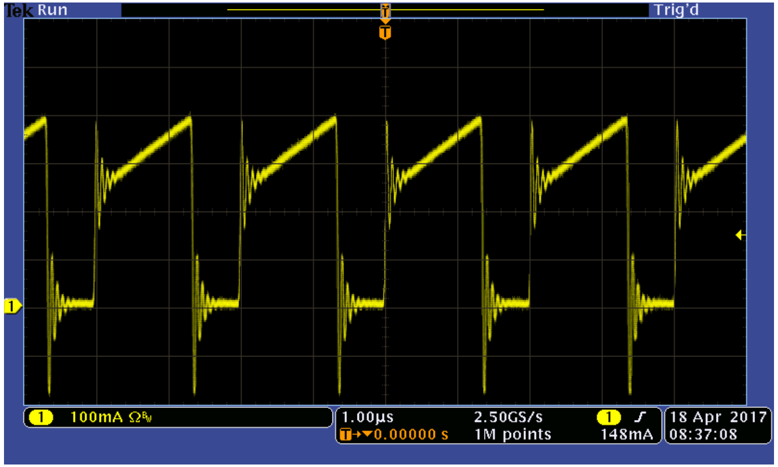
Input Current Ripple



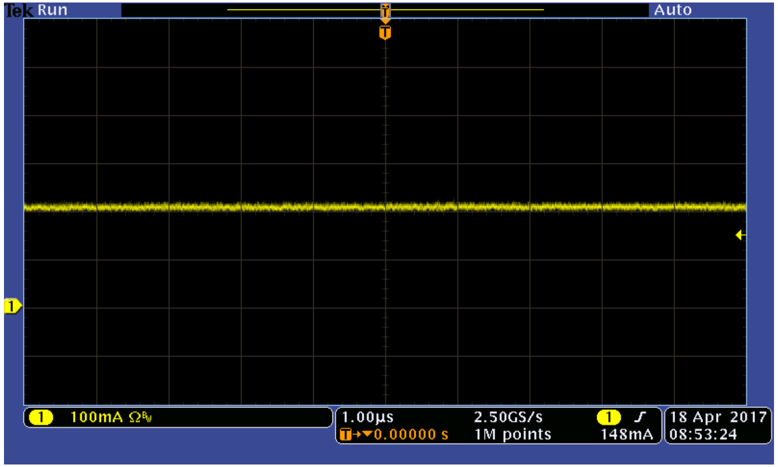




Without input filter



With input filter-beautifully flat...BUT!?



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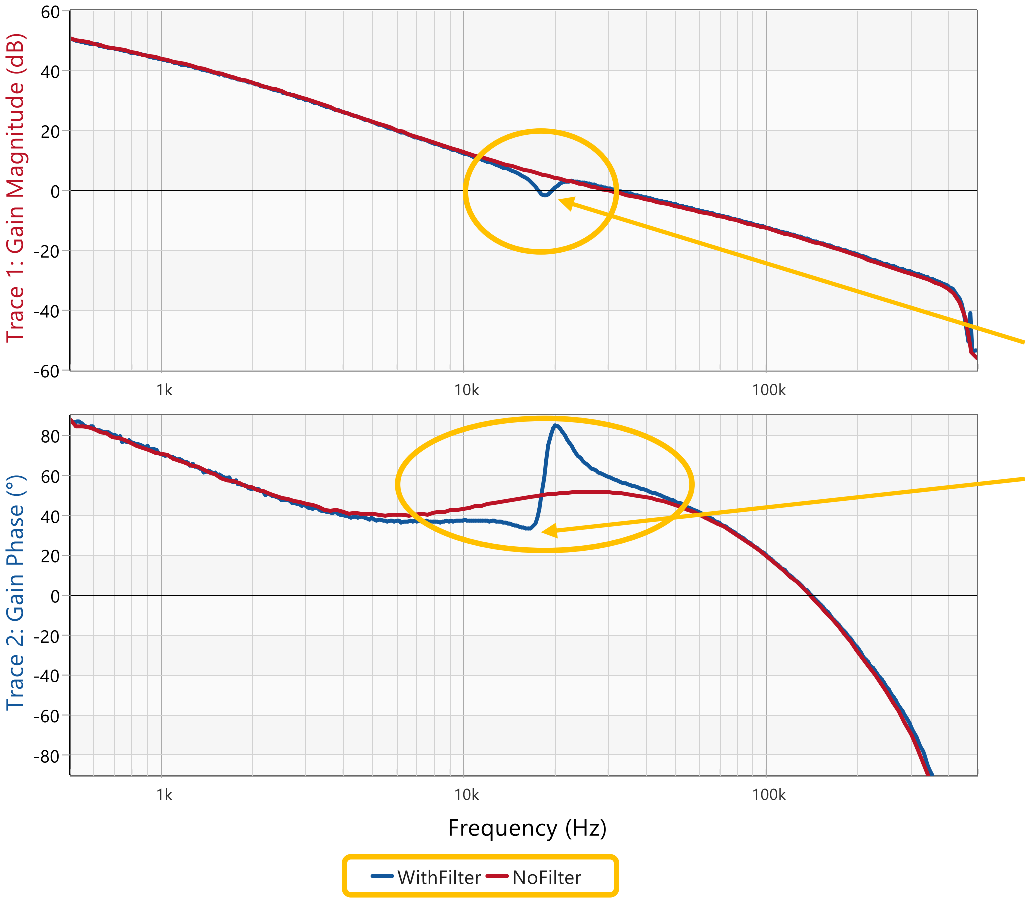
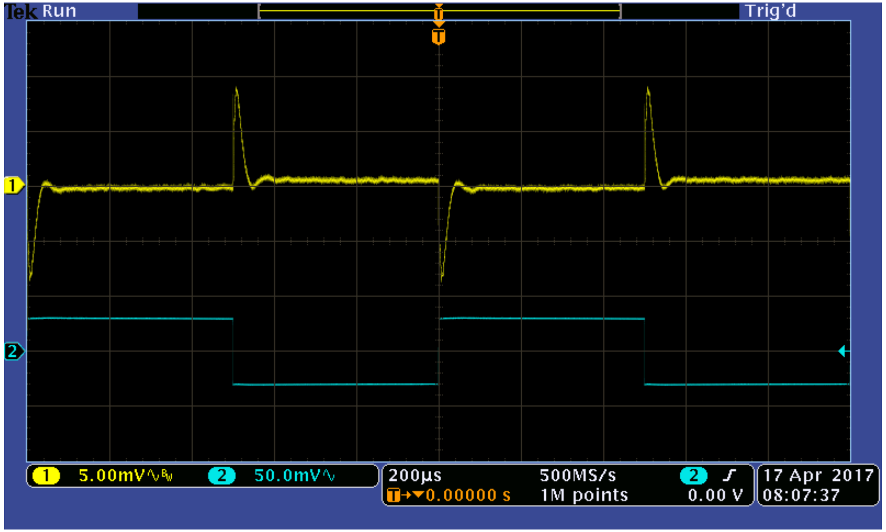
Influence on Loop Gain (Vin = 4V)



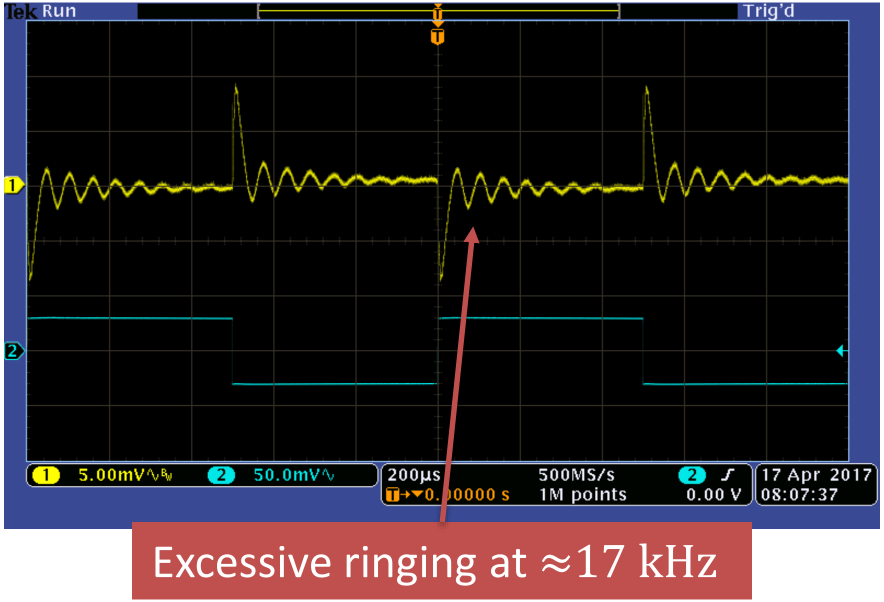
- Note: This is a real measurement result.
- Distortion is not caused by excessive injection level
- Filter adds second crossover frequency
- Reduces phase margin at first crossover
- Will influence the load step response

Small-Signal Load Step Response

No or damped input filter

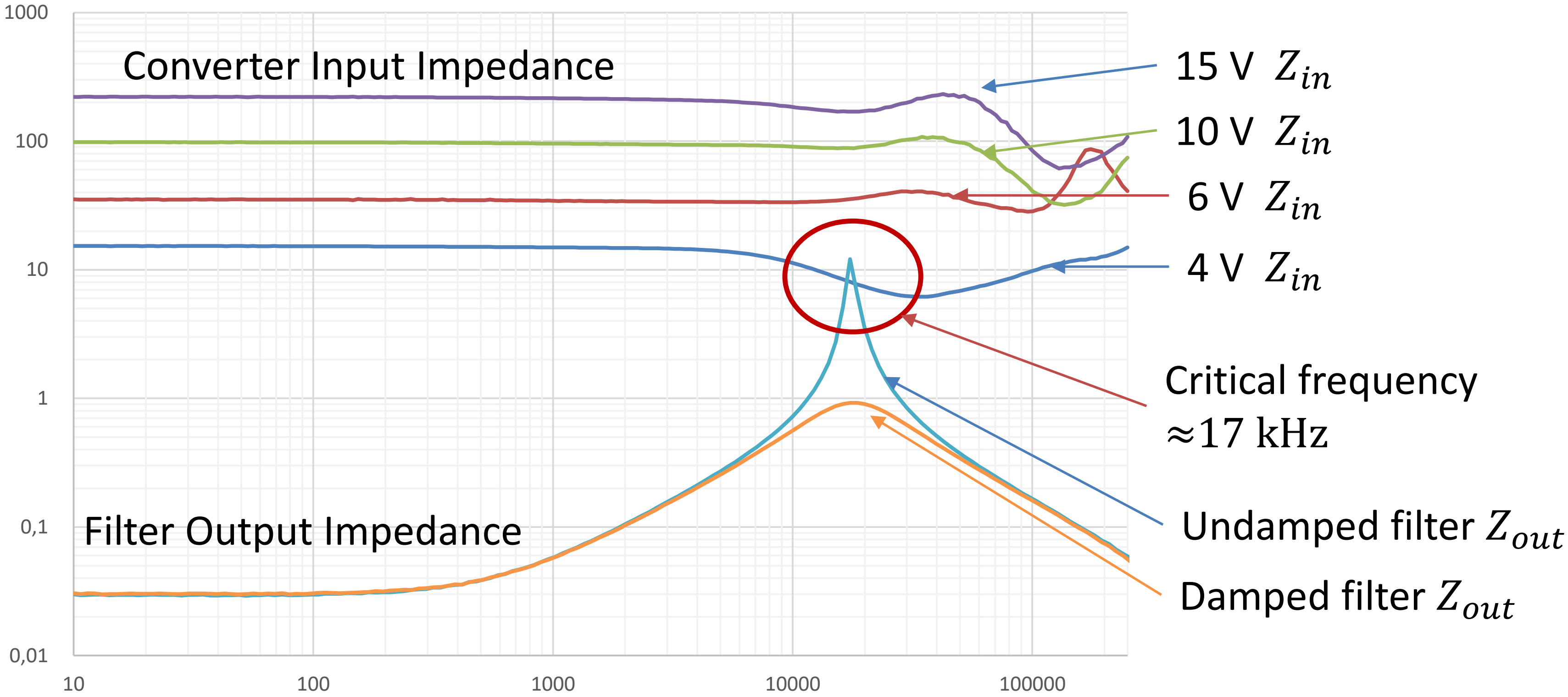


Un-Damped input filter

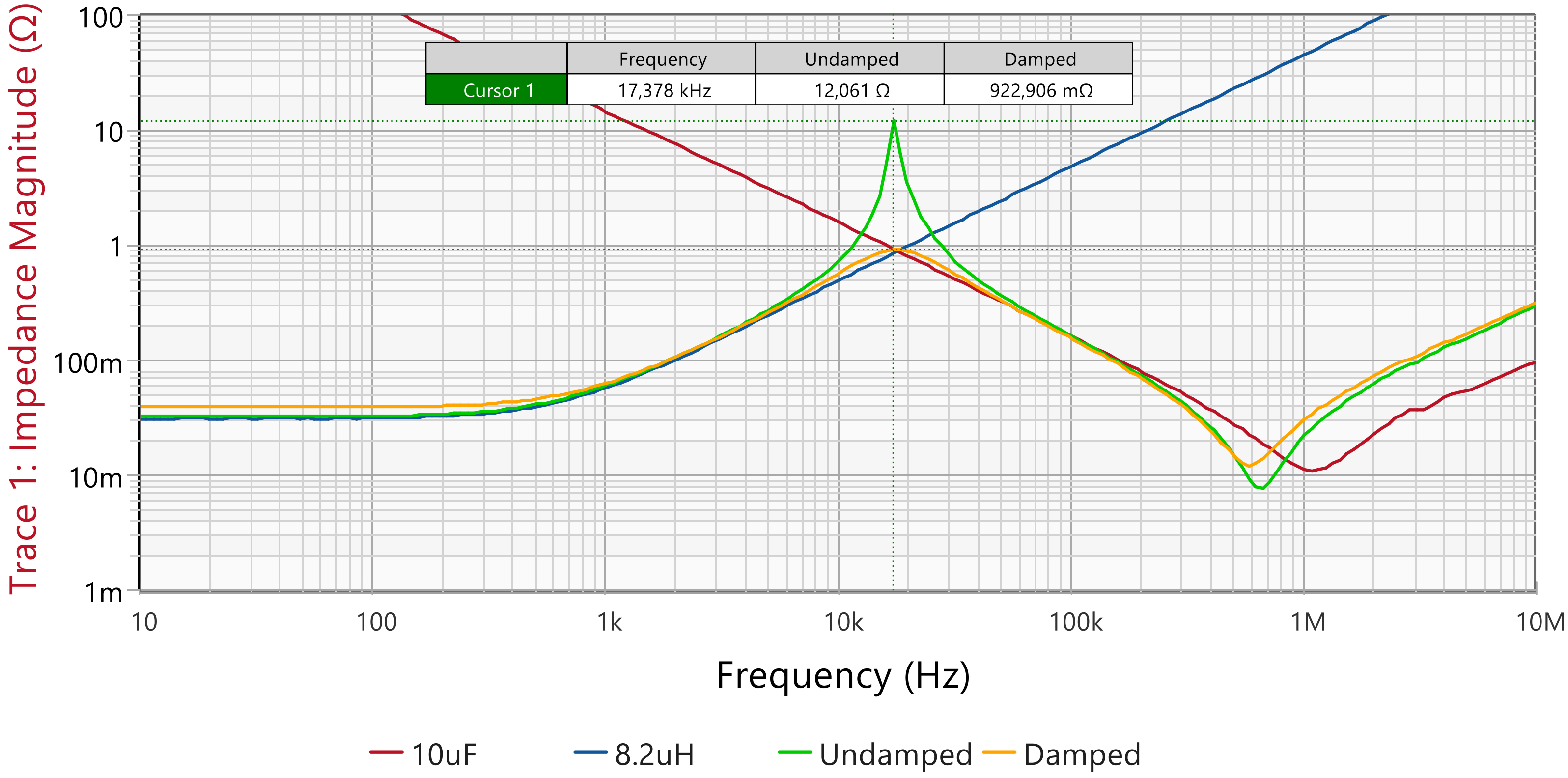


50 mA load steps created with Picotest J2111A current injector and G5100A AWG.
Scope: 1:1 probe and averaging on to remove switching ripple.

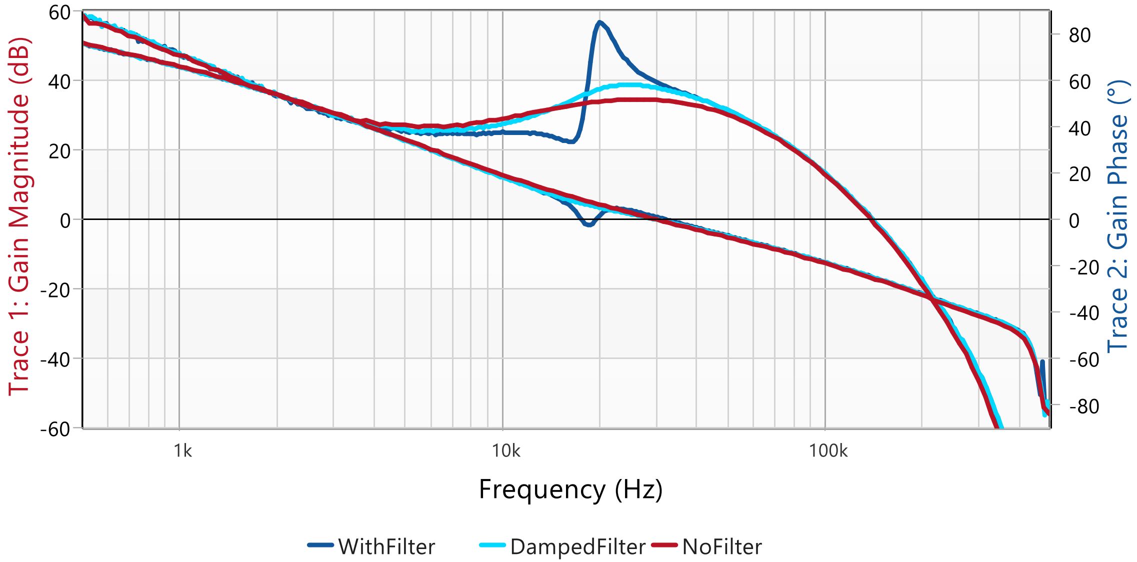
Checking the Impedance Condition

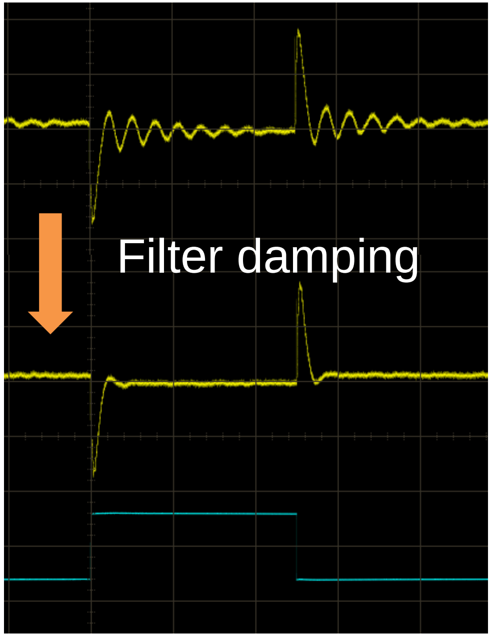


LC Input-Filter Output Impedance



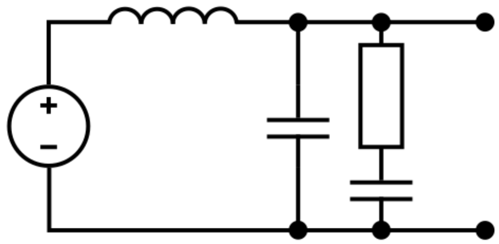
Damping the Input Filter

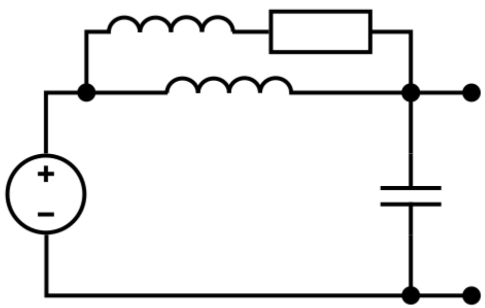




- After damping the influence on loop gain is small
- Stability and performance are not affected anymore

Practical Input Filter Damping



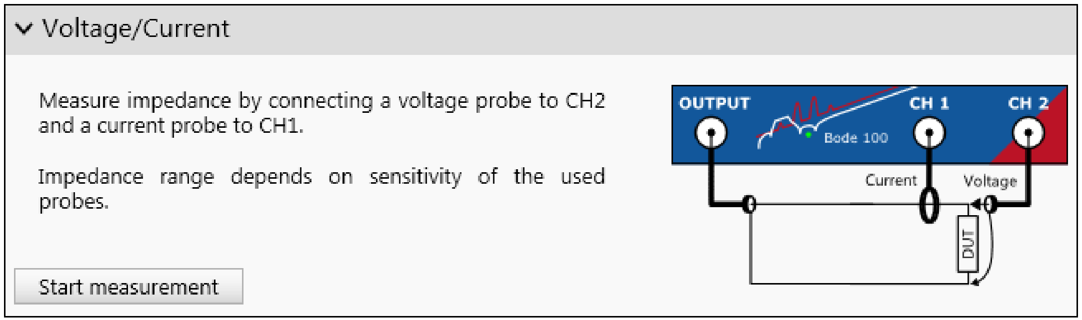


- R-C Parallel Damping
  - additional DC blocking capacitor
  - ESR of blocking capacitor might be sufficient
- R-L Parallel Damping
  - Damping inductor << filter inductor since DC resistance is higher
  - ESR of inductor might be sufficient

See literature [1], [2], [3] etc. for optimal damping (minimize component size).

Measuring Input Impedance

Use Voltage/Current measurement mode of BAS



Advantage of Voltage/Current mode in BAS 3.X:

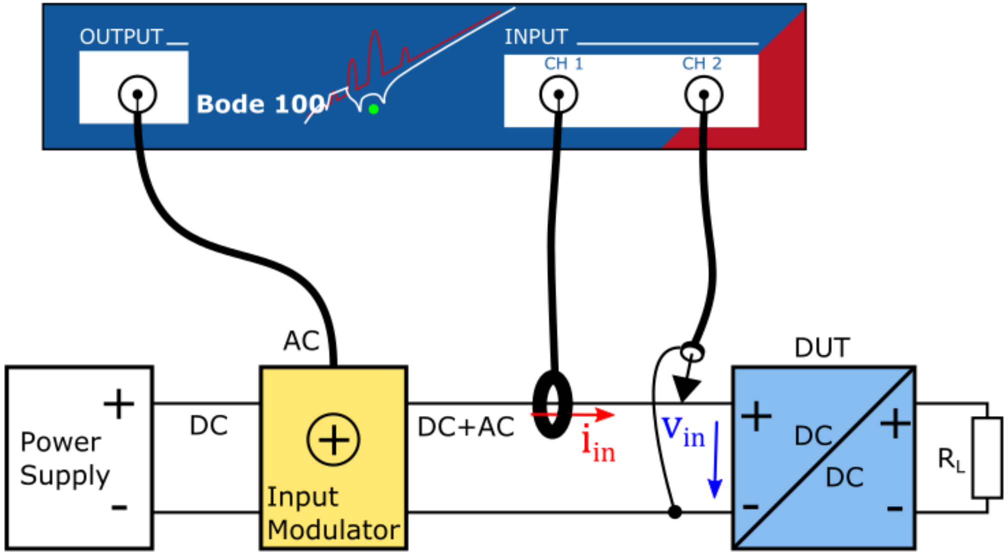
- Impedance result formats (Ls, Cs etc...)
- Thru or Open/Short/Load calibration can be applied
- Arbitrary probe factor can be set in hardware setup

Input Impedance Measurement

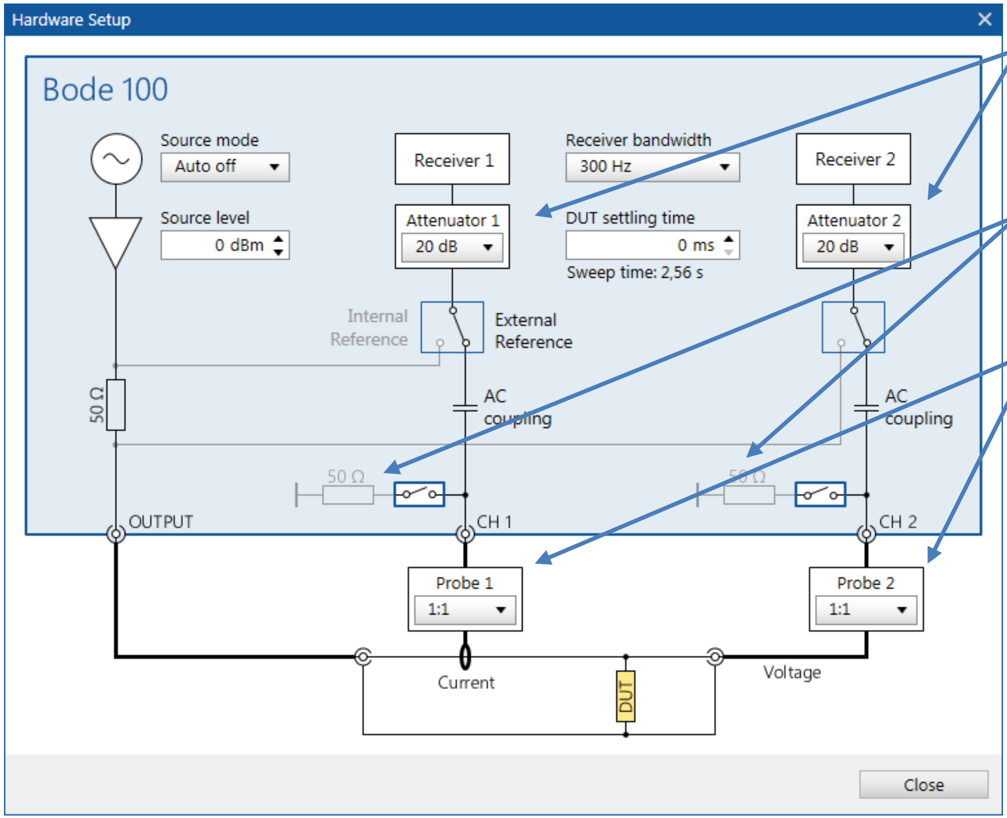
Voltage/Current mode calculates: $Z = Gain = \frac{V_{CH2}}{V_{CH1}} = \frac{v_{in}}{i_{in}}$

Requirements:

- AC modulation of input
- Input current measurement
- Input voltage measurement



Bode 100 Hardware Setup



- Attenuators to improve signal / noise
- Channel termination 1 MΩ or 50 Ω
- Arbitrary probe factor (use negative value to invert channel)

Hint: The Bode 100 hardware is configured at the time when a measurement or calibration is started!

Modulating the DUT Input

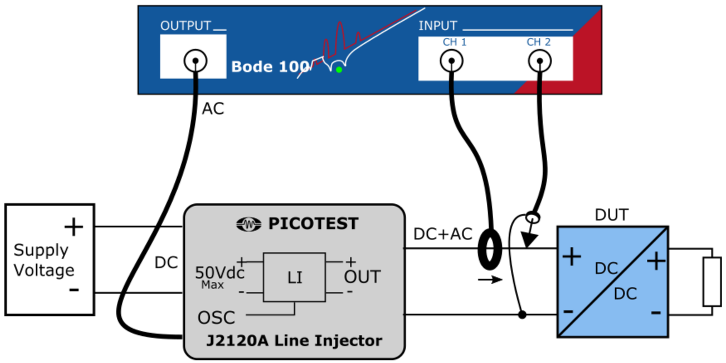
Input voltage must be modulated proportionally to Bode 100 output signal (challenging depending on voltage level and power level).

- Use specific devices
  - Picotest J2120A Line Injector (50 V / 5 A)
  - Picotest J2121A Line Injector (400 V / 20 A)
- Inductive coupling / signal injection
- Capacitive coupling / signal injection

An external power amplifier might be needed for modulation if the 13 dBm (20 mW @ 50 Ω) are not sufficient.

Modulating the DUT Input (2)

Picotest J2120A/J2121A



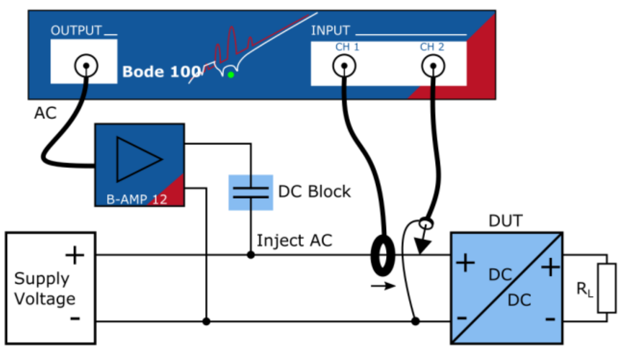
Advantage:

- Easy to use

Disadvantages:

- Maximum ratings fixed
- Introduces DC voltage loss

Signal injection (capacitive coupling)



Advantage:

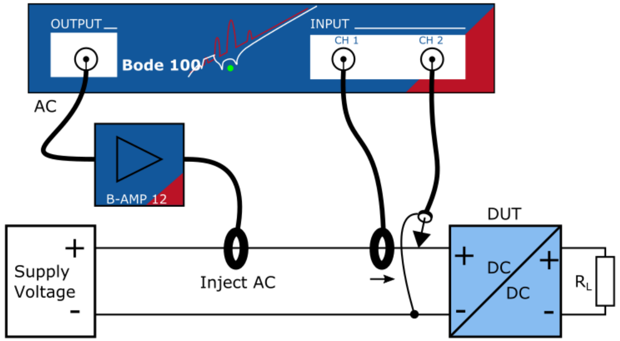
- Scaleable

Disadvantage:

- Maybe an amplifier needed
- DC block limits lower frequency

Modulating the DUT Input (3)

Signal Injection (inductive coupling)



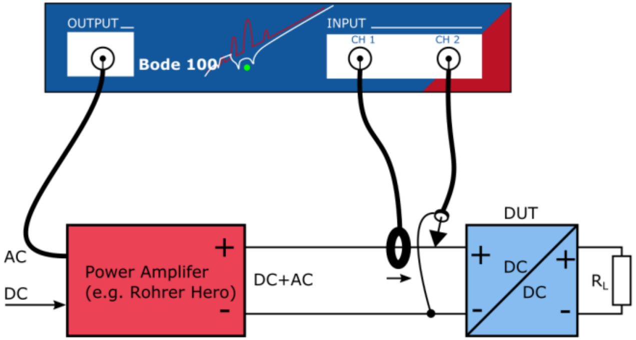
Advantage:

- Scaleable

Disadvantages:

- Maybe an amplifier needed
- Hard to get right injection probe

Configurable power amplifier



Advantages:

- Powerful
- Fully configurable

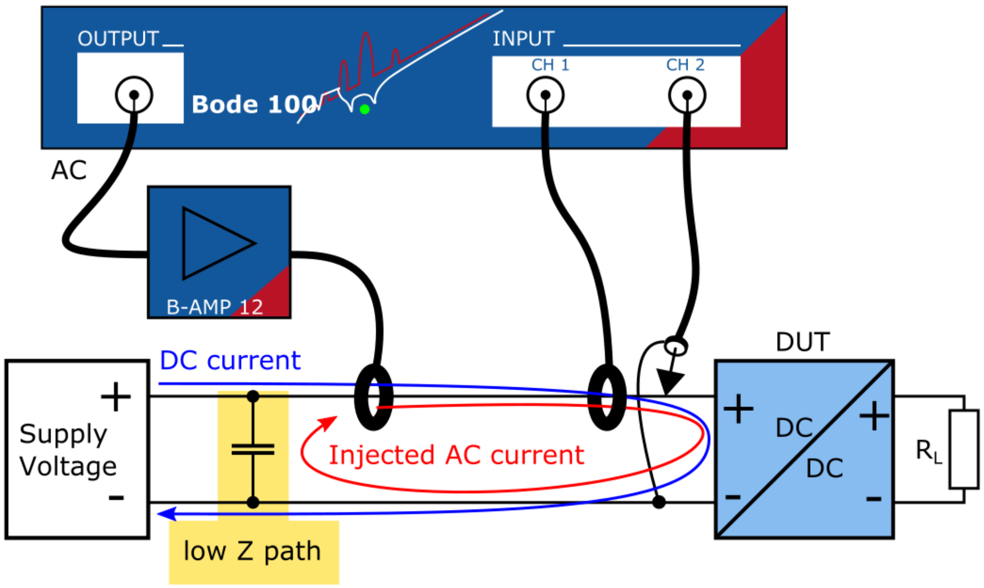
Disadvantage:

- Price

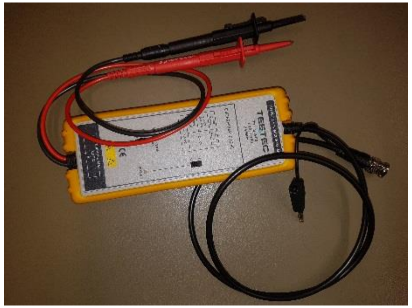
Injection Method Hint

Provide a low-impedance current path for the injected AC measurement signal

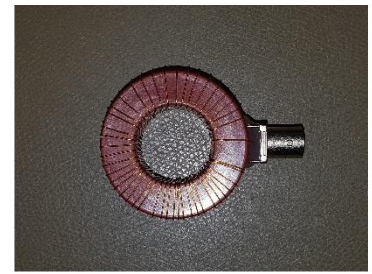
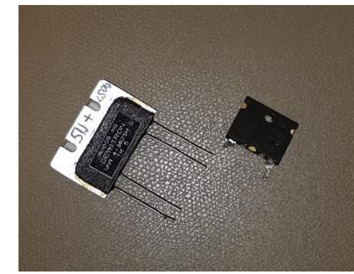
- Increases injected signal size
- Improves measurement results
- Enables calibration (Open, Short, Load) without DC power applied



Measuring the Input Voltage

	1:1 Connection (BNC cable)	10:1 Passive Probe	Active Differential Probe (safety isolation probe)
			
Price	low	medium	high
Isolation	no	no	yes
Noise	low	medium	high

Measuring the Input Current

	Hall-Effect Probe (BNC connector)	Active Rogowsky Current Probe	Current Transformer (Current Monitor)	Shunt Resistor
				
Price	high	medium	medium	low
Isolation	yes	yes	yes	no
LF Limit	DC	Hz...kHz	Hz...kHz	DC
HF limit	20 - 50 MHz	20 - 30 MHz	MHz	MHz
DC sensitive	compensated	no	yes	power limit

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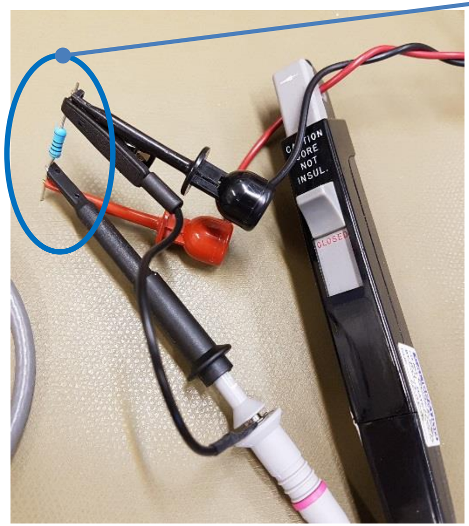
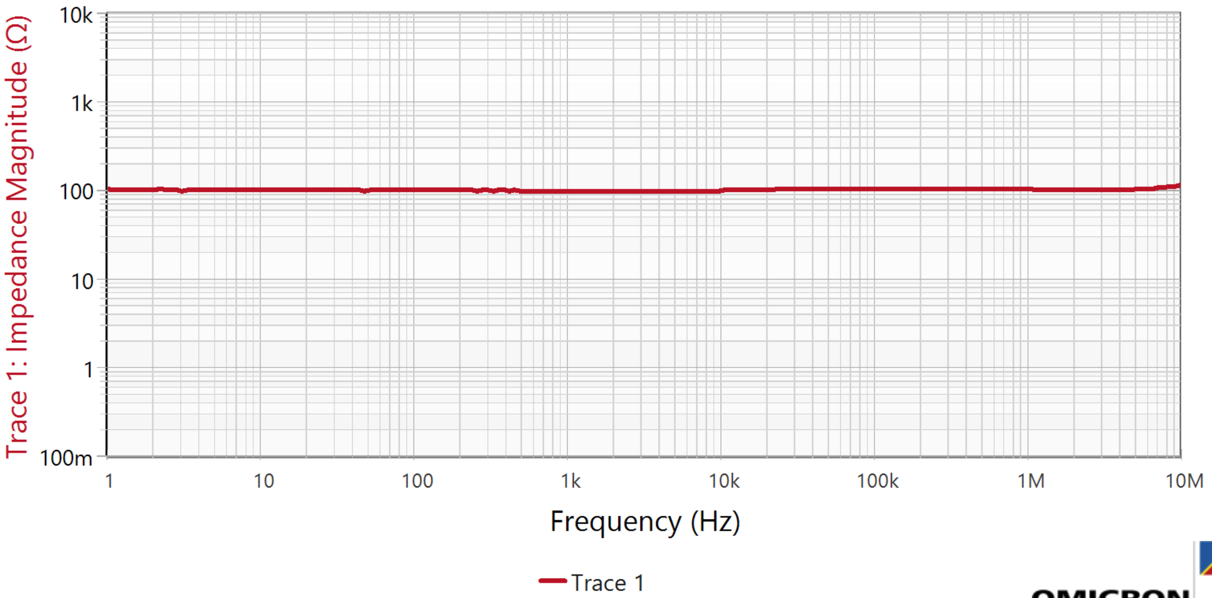
Measurement Setup Verification

Use a known impedance (e.g. a 100 Ω resistor) as DUT

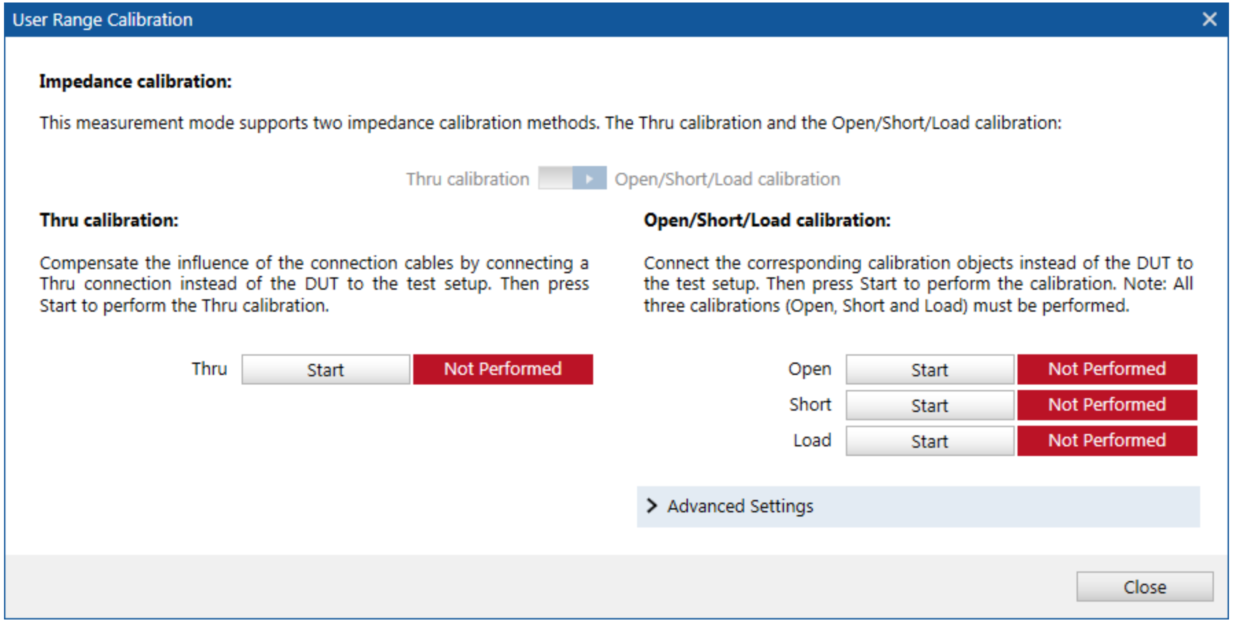


Uncalibrated measurement result:



Calibration

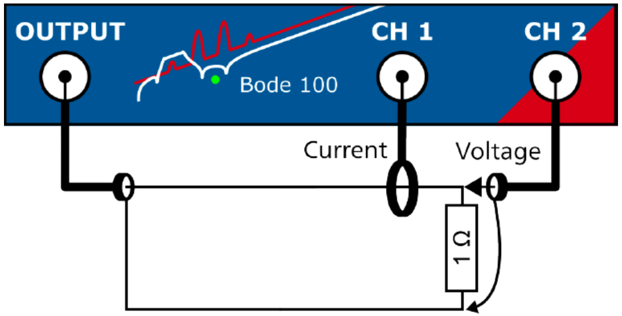
BAS 3.X supports either Thru calibration **or** Open/Short/Load calibration in Voltage/Current mode



Thru Calibration

Calibrates the underlying Gain measurement ($Z = Gain$)

Use a 1 Ω resistor instead of DUT to perform Thru calibration
(1 Ω ≙ Gain of 1)



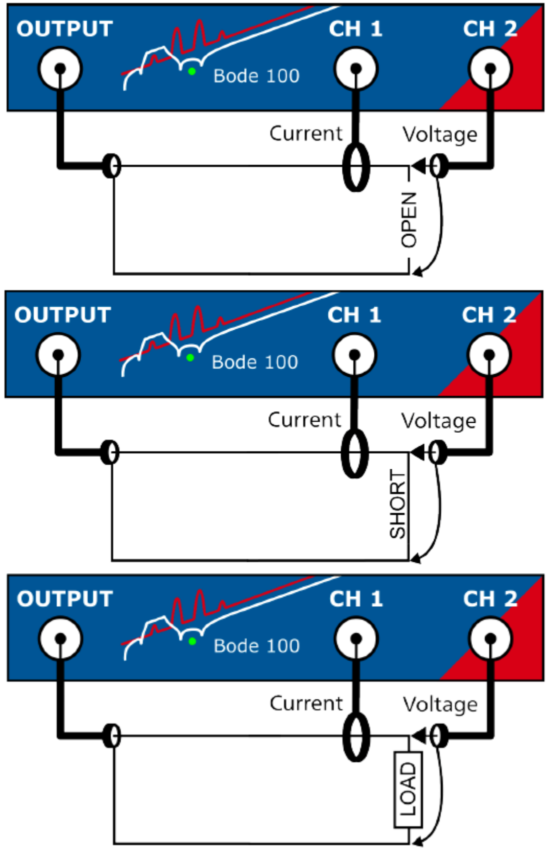
Advantages:

- Simple
- Only one measurement (calibration) needed

Disadvantage:

- Resistor is never ideal
  (1 Ω resistor shows significant reactance at high frequency)
  Example: 10nH @ 1 MHz
  → 63 mΩ ... 6% error

Open/Short/Load Calibration



Full impedance calibration

Advantages:

- Highest accuracy and widest frequency range
- Compensates more effects than Thru

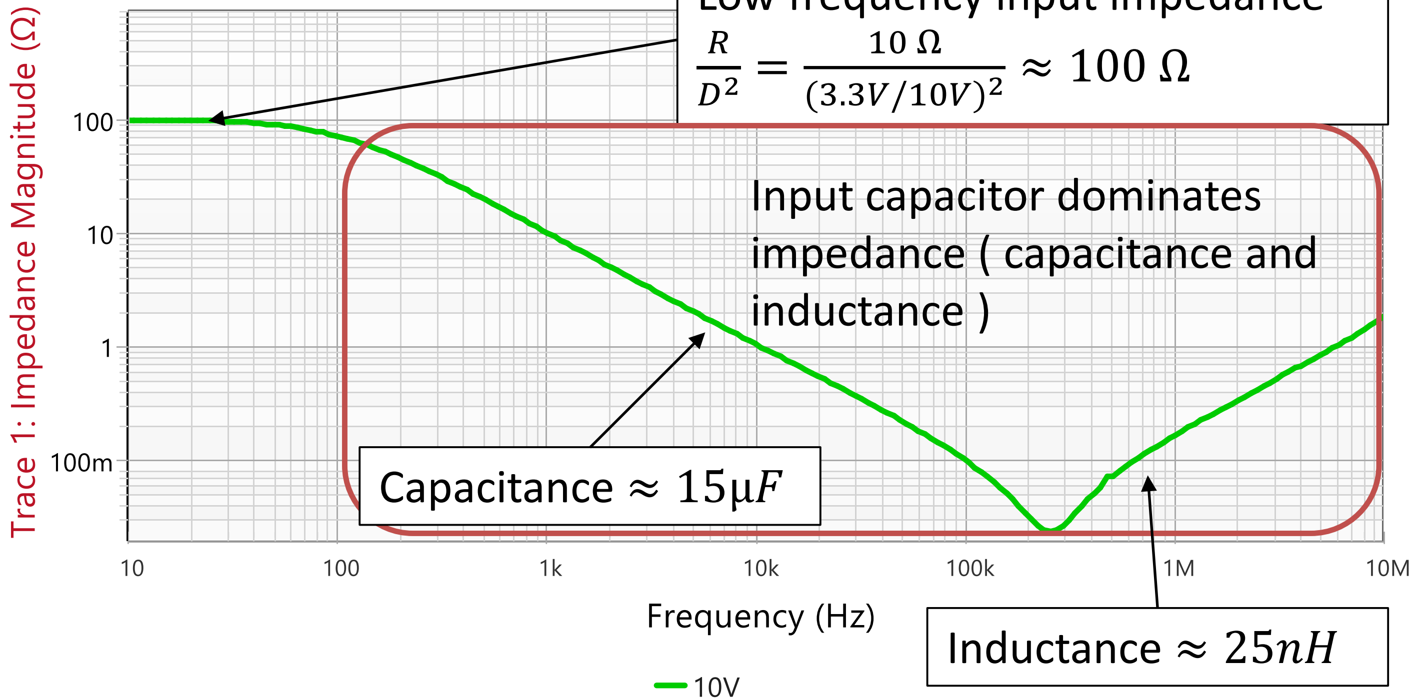
Disadvantage

- Not every test-setup is suitable for Short and Open **(especially when DC cannot be removed!)**
- 3 calibration measurements needed

Measure Input Impedance (with Input C)

Low frequency input impedance

$$\frac{R}{D^2} = \frac{10\ \Omega}{(3.3V/10V)^2} \approx 100\ \Omega$$



Component	Value
C_{IN}	2 x 10 µF
C_{OUT}	2 x 10 µF
L1	15 µH
R_T	31.2 kΩ
R_B	10 kΩ
R_{EN}	1 MΩ
C_{VCC}	1 µF
C_{BOOST}	0.1 µF

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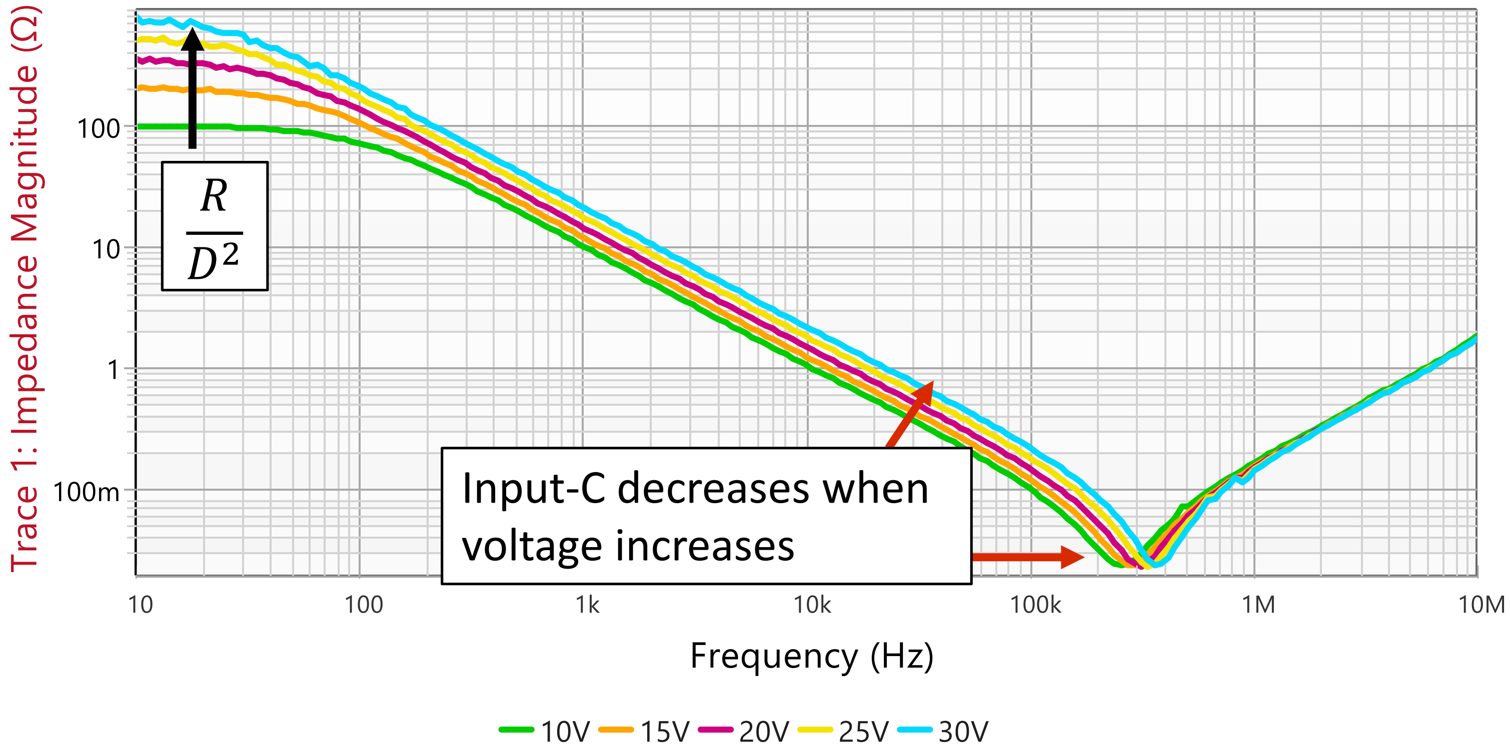
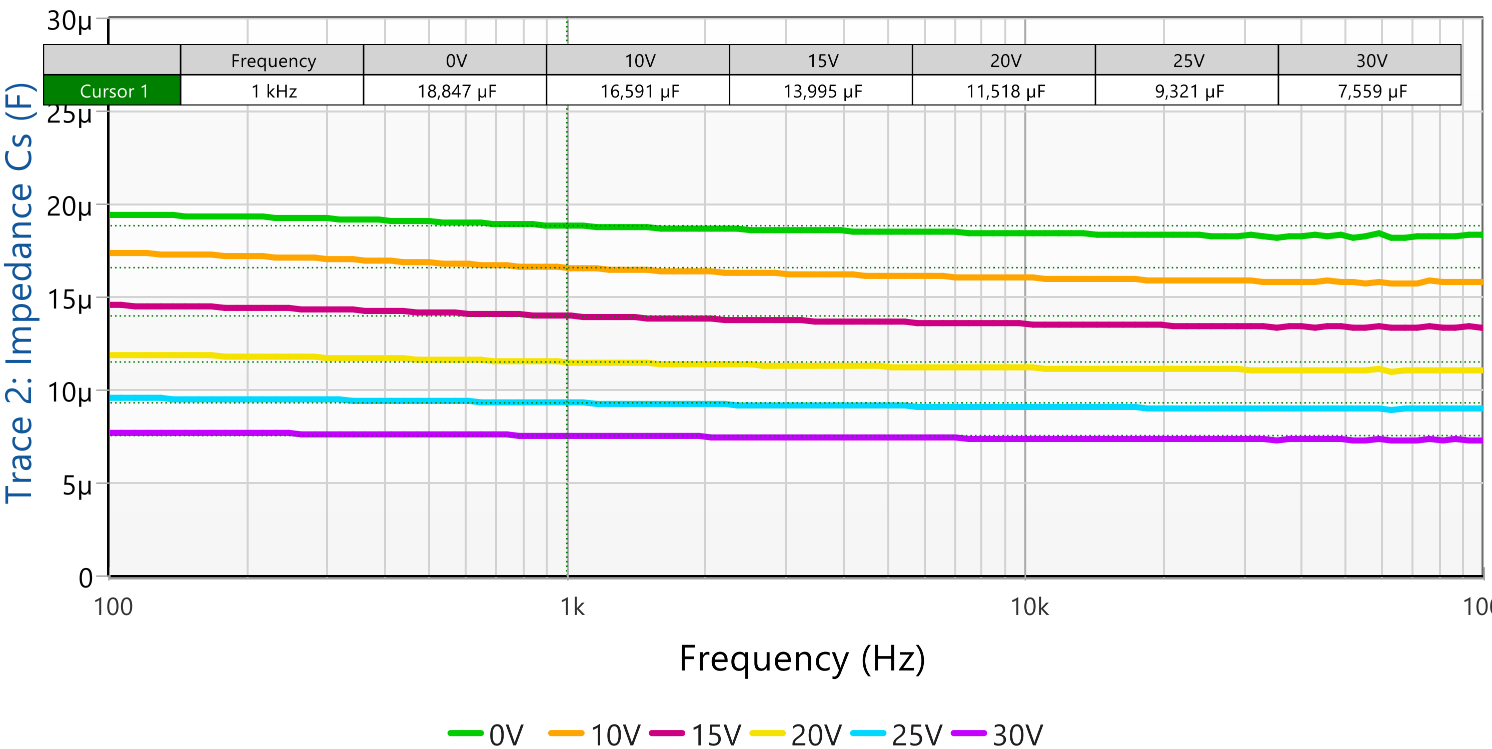
Input Impedance depends on Input Voltage



Input capacitor DC voltage sensitivity

Two parallel $10\mu F$ ceramic caps:



	Frequency	0V	10V	15V	20V	25V	30V
Cursor 1	1 kHz	18,847 µF	16,591 µF	13,995 µF	11,518 µF	9,321 µF	7,559 µF

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Input capacitor DC voltage sensitivity

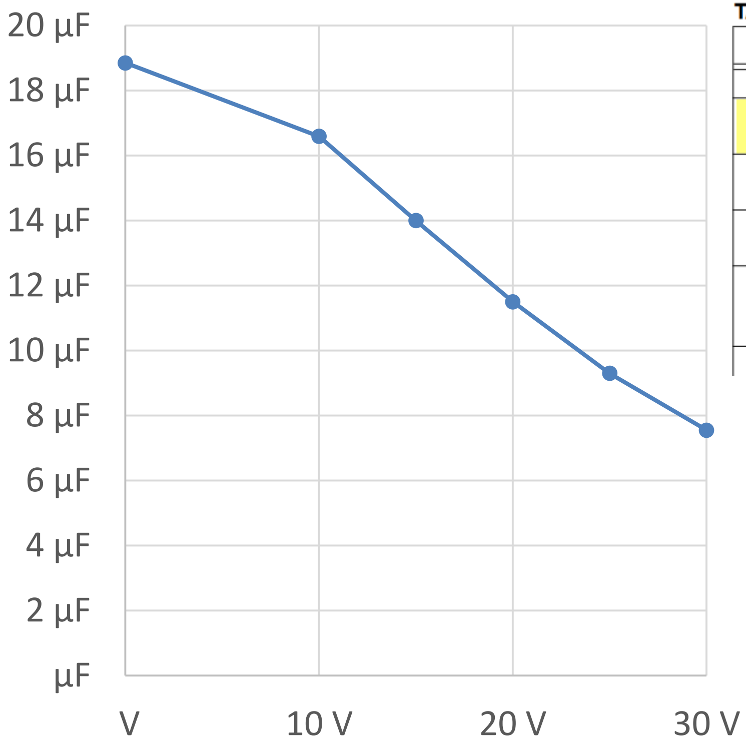

TABLE B-1: BILL OF MATERIALS (BOM)

Qty	Reference	Description	Manufacturer	Part Number
2	C1, C12	CAP CER 0.1 µF 50V X7R 10% 0603	TDK Corporation	C1608X7R1H104K
4	C2, C3, C7, C8	CAP CER 10 µF 50V X7S 1210	TDK Corporation	C3225X7S1H106M
4	C5, C6, C10, C11	CAPACITOR, 1206, X7R, 16V, 10 µF	TDK Corporation	C3216X7R1C106K
2	CVCC, CVCC2	CAP CER 1 µF 16V 10% X7R 0603	TDK Corporation	C1608X7R1C105K
8	J1, J2, J3, J4, J5, J6, J7, J8	PC TEST POINT TIN SMD	Harwin Plc.	S1751-46R
1	L1	CHOKE, SMD, 15 µH	Wurth Group	7447779115

Most ceramic capacitors are highly sensitive to DC voltage!

At 30V this 10µF cap has <4µF

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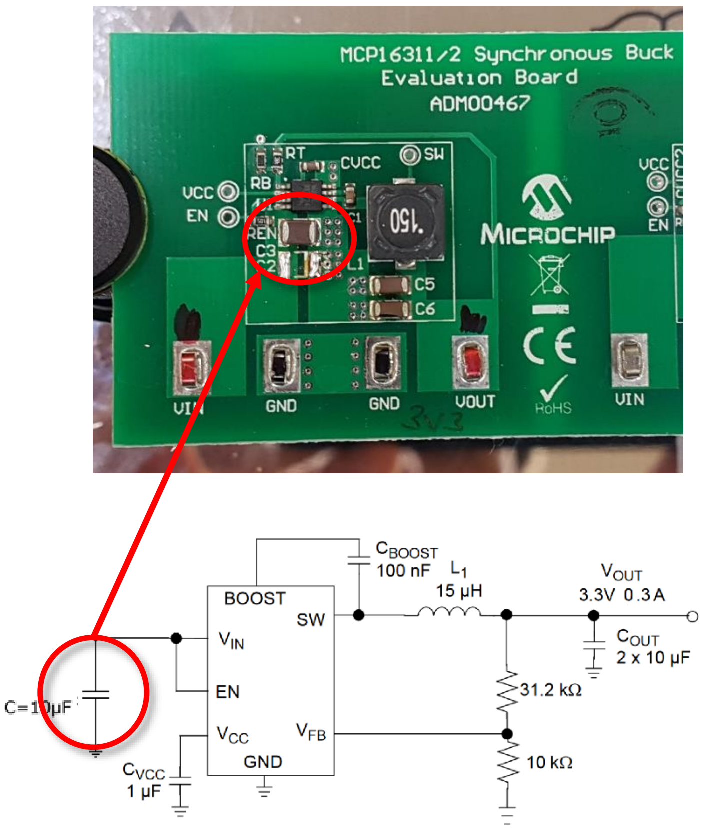
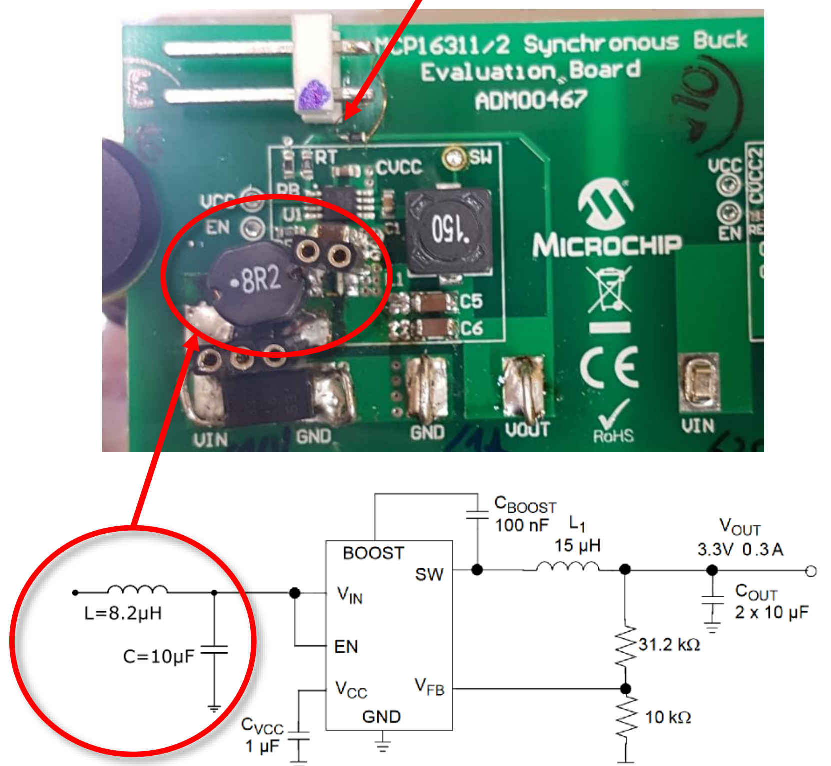
Hands-On Measurement DUT

Injection Point





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Hands-On Measurements

1. Input Impedance Measurement (No Filter)
2. Filter Impedance Measurement
3. Measure System Dynamics without Filter
   - Loop Gain Measurement
   - Transient Response
4. Add Input Filter
   - Impact on Loop Gain
   - Impact on Transient Response
5. Damping the Input Filter

References and Further Reading

[1] R. W. Erickson and D. Maksimovic, *Fundamentals of Power Electronics*, 2nd ed. 2001. Norwell, Mass: Springer, 2001.

[2] R. D. Middlebrook, Input filter considerations in design and application of switching regulators, IEEE Industry Applications Society Annual Meeting, October 1976, pp. 91-107

[3] Dean Venable, “Source-Load Interactions in Multi-Unit Power Systems”, Venable Technical Paper #12

[4] Yuri Panov and Milan Jovanovic, Practical Issues of Input/Output Impedance Measurements in Switching Power Supplies and Application of Measured Data to Stability Analysis, Delta Power Electronics Laboratory

[5] OMICRON Lab, Input Impedance & Filter Stability, https://www.omicron-lab.com/applications/detail/news/input-impedance-filter-stability/

Feel free to ask questions via the Q&A function...

If time runs out, please send us an e-mail and we will follow up.

You can contact us at: info@omicron-lab.com

Thank you for your attention!