Converter Stability in Power Electronics – Introductions into Basic Measurements

2025-05-14 – Graz

OMICRON LAB

About Me

- Working at OMICRON Lab since 2021
  - Hardware Development
  - Rollout of Demoboard
  - Developing Educational Materials

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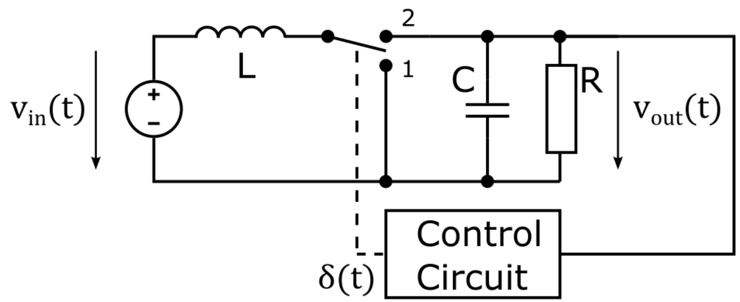
Agenda

- DC/DC Converter Control Loop
- Stability Margins
- Loop Gain Measurement Technique
- Hints for Successful Measurements
- NISM – Non Inversive Stability Measurement
- Live Example

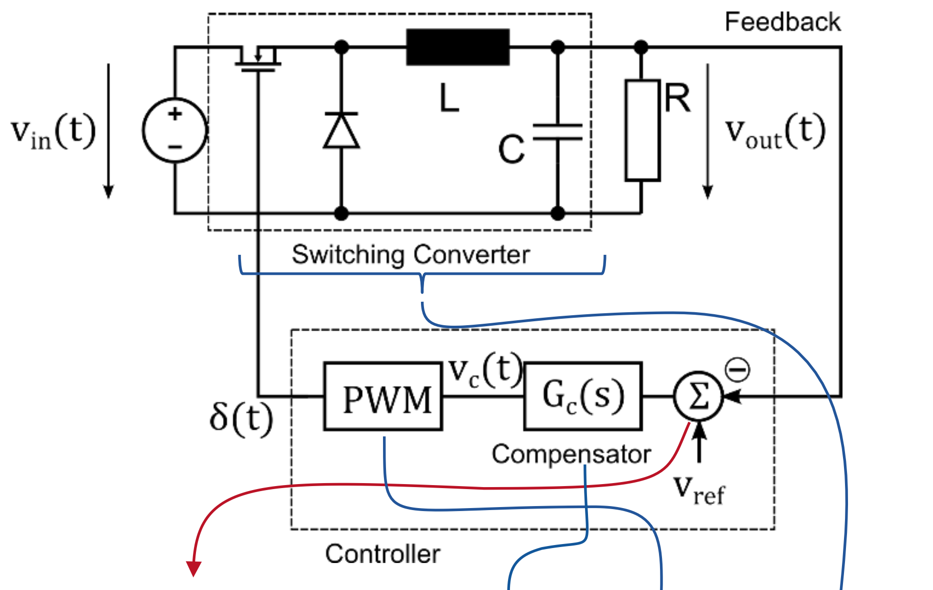
DC/DC Converter – Dynamic System

- How will the system react to:
  - Sudden line-voltage change?
  - A change in the reference voltage or set-point?
- How to optimize a compensator (place the poles and zeros)?
- How to verify control loop stability?



→ Analytical analysis (challenging)
→ Simulation (time domain and frequency domain)
→ Time domain experiments (oscilloscope)
→ Frequency domain experiments (VNA / FRA)

Closed-Loop System (Only Voltage Loop)



$$\hat{v}_{out}(s) = \left(\hat{v}_{ref}(s) - \hat{v}_{out}(s)\right) \cdot \underbrace{G_c(s) \cdot G_{PWM}(s) \cdot G_{vd}(s)}_{\text{Loop Gain } T(s)}$$

Closed Loop Reference to Output

$$G_{ref-out,CL}(s) = \frac{\hat{v}_{ref}(s)}{\hat{v}_{out}(s)} = \frac{G_c(s)G_{PWM}(s)G_{vd}(s)}{1+G_c(s)G_{PWM}(s)G_{vd}(s)}$$

$$G_{ref-out,CL}(s) = \frac{T(s)}{1+T(s)}$$

Loop Gain
$T(s) = G_c(s)G_{PWM}(s)G_{vd}(s)$
(the product of all gains around the loop)

If $T(s) \gg 1$, then $G_{ref-out,CL}(s) \approx 1$.
This means that the output will follow the reference voltage independent of the gains in-between. This effect of the negative feedback is exactly what we want.

Closed Loop Line to Output

Open loop line to output transfer function (power stage)

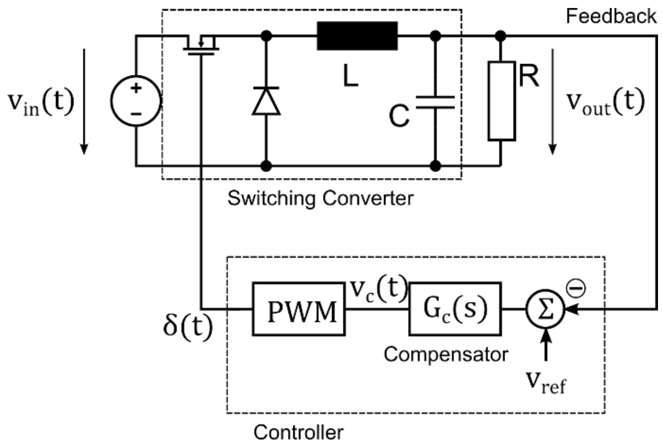
$G_{in-out}(s)$

Negative feedback leads to

$\hat{v}_{out} = \hat{v}_{in} \cdot G_{in-out}(s) - \hat{v}_{out} \cdot T(s)$

therefore

$$G_{in-out,CL}(s) = \frac{G_{in-out}(s)}{1 + T(s)}$$



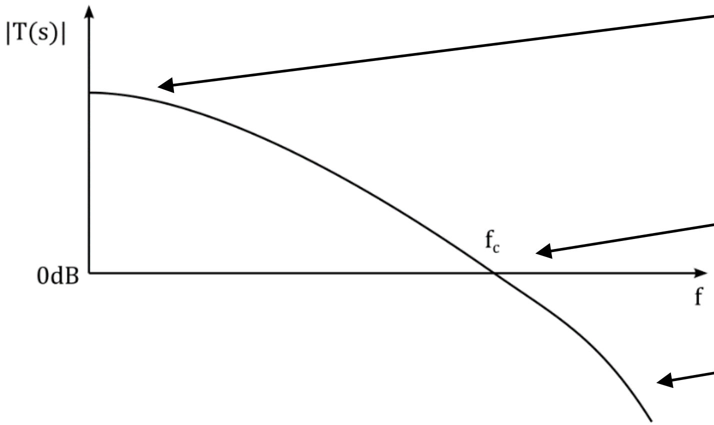
$T(s)$ = large → $G_{in-out,CL}(s)$ = small

→ Good line ripple rejection up to loop bandwidth

→ High PSRR respectively audio susceptibility up to loop bandwidth

Loop Gain T(s) - Open Loop

- For good output regulation we need **high loop gain**
- For $T(s) < 1$ the feedback loses its effect
- High loop gain for all frequencies is not possible and not desired



Low frequency Gain should be relatively high to achieve good regulation. There is always some gain limitation

Loop Gain should cross 0dB with slope of -1 (20dB/decade) → unity gain frequency or crossover frequency

High frequency Gain should be low to damp high frequency noise and increase robustness of system

Stability of the Closed Loop System

Transfer functions of the closed loop:

$$G_{ref-out,CL}(s) = \frac{T(s)}{1+T(s)} \qquad G_{in-out,CL}(s) = \frac{G_{in-out}(s)}{1+T(s)}$$

What happens if $T(s) = -1$?

→ Closed Loop Transfer function will tend to get “infinite”

→ Behavior of the loop is no longer defined (unstable)

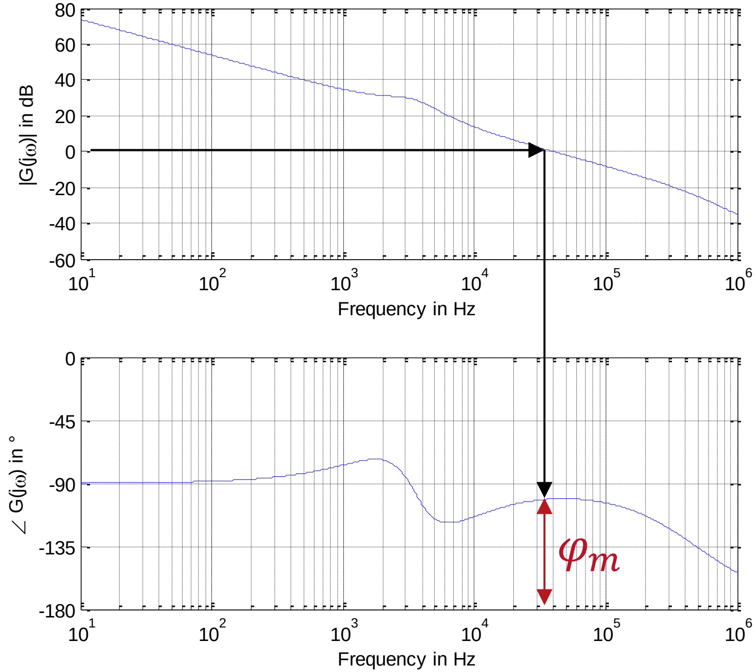
By checking the loop gain $T(s)$ we can check if the closed loop system will be stable or not.

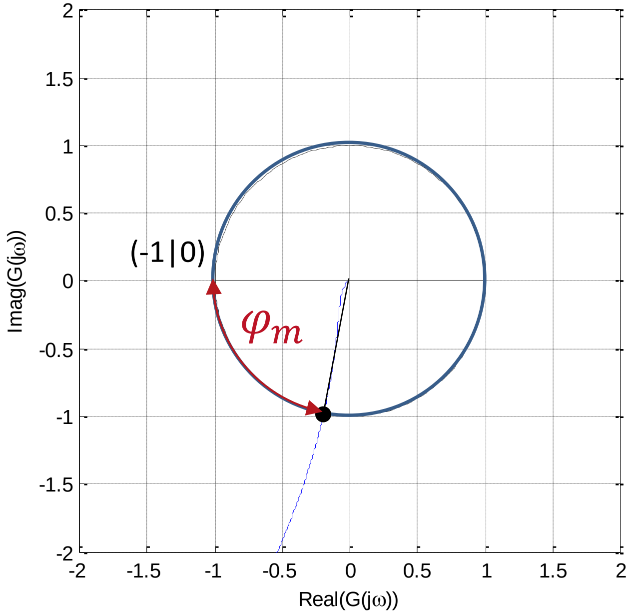
Test: How much distance does $T(s)$ have towards -1

The Phase Margin Test

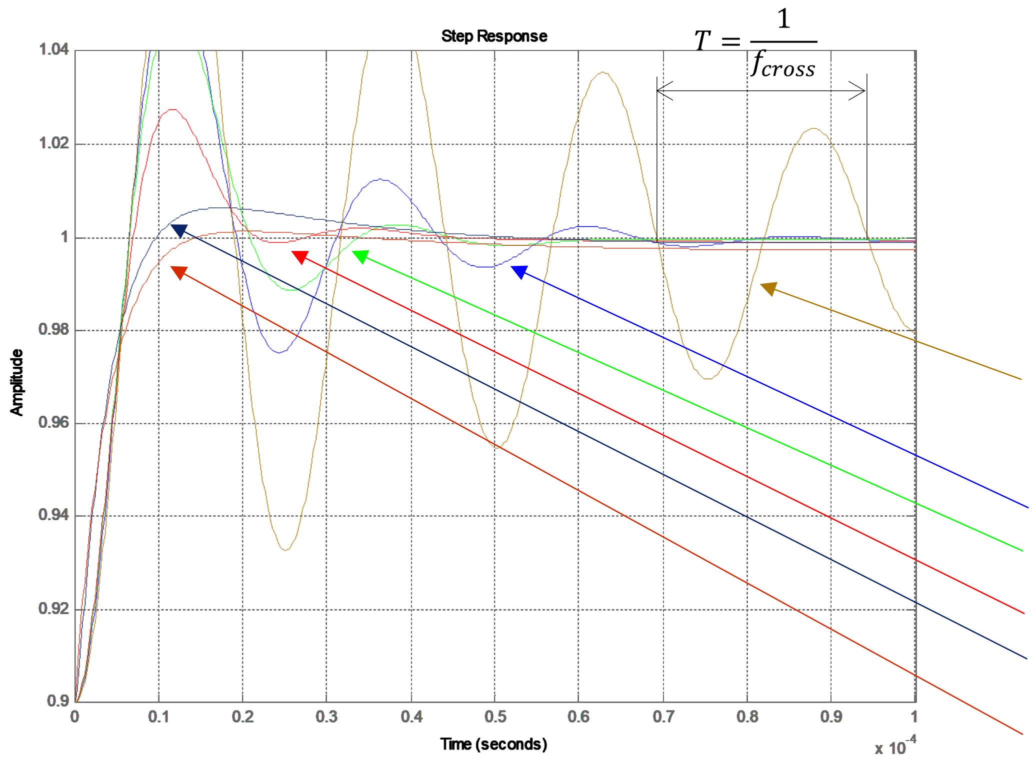
(A special case of the general Nyquist stability criterion)

If phase margin > 0° → the closed loop system is "stable"





How much Phase Margin is desired?



Simulation of synchronous Buck Converter (CCM, small signal)
15 V to 1 V step down
300 kHz switching frequency
≈40 kHz crossover frequency

$\varphi_m = 7.4°$ → High overshoot + ringing
$\varphi_m = 23°$
$\varphi_m = 31°$
$\varphi_m = 45°$
$\varphi_m = 78°$ → Highly damped
$\varphi_m = 87°$

→ **Phase Margin** is a measure of **closed-loop** system **damping at its natural frequency** and a measure of robustness.

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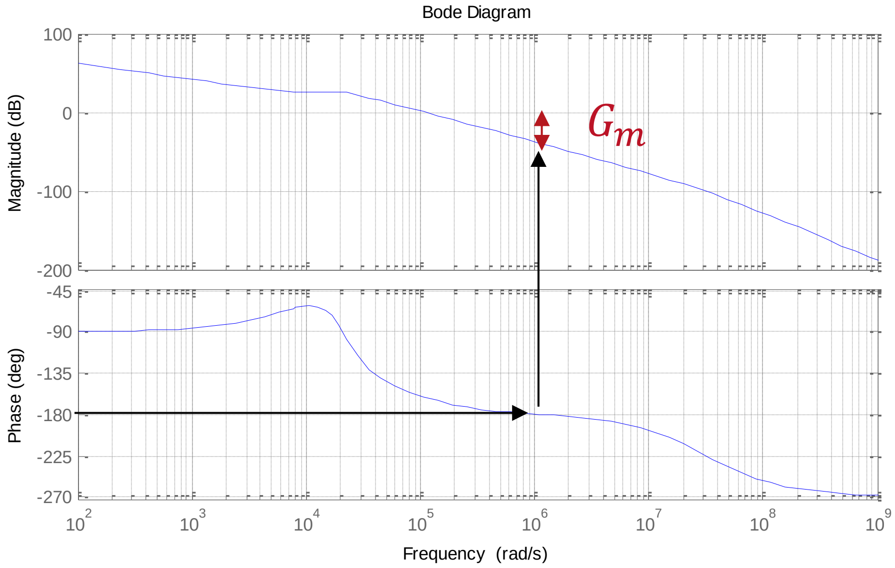
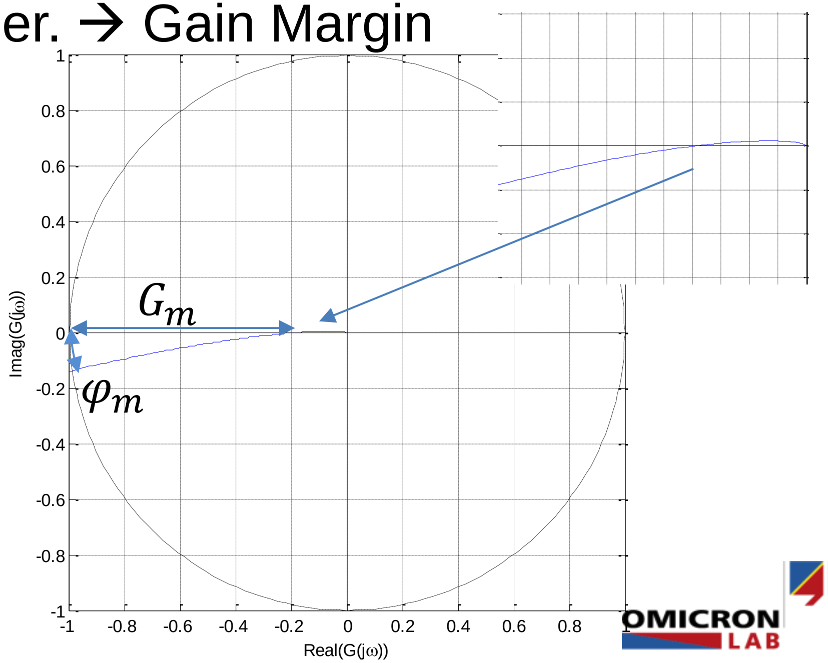
Gain Margin

Gain Margin is the **amount** of **gain** necessary to make the loop hit the instability point. → measure of robustness.

Second order system → no Gain Margin (phase never reaches -180°).

Parasitics the systems → > second order. → Gain Margin

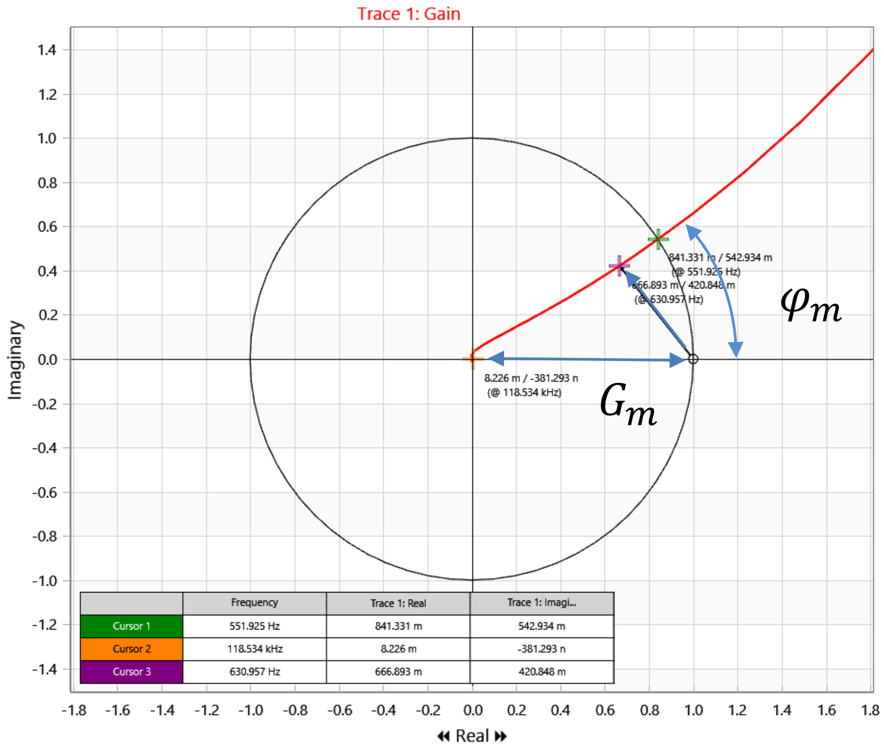




Vector Stability Margin

- Gain Margin and Phase Margin are evaluated separately at two different frequencies.
- Simultaneous change of Gain and Phase could also cause instability.
- Vector Margin is a measure of robustness showing how close the loop gain approaches the critical point.
  - Vector margin > 0.5 represents roughly 30° Phase Margin and 6 dB Gain Margin robustness measure

Nyquist Chart Display



	Frequency	Trace 1: Real	Trace 1: Imagi...
Cursor 1	551.925 Hz	841.331 m	542.934 m
Cursor 2	118.534 kHz	8.226 m	-381.293 n
Cursor 3	630.957 Hz	666.893 m	420.848 m

Note that the **instability point** in measured loop gain is at +1 and not at -1

$\varphi_m = 32\,°$

$G_m = 41\ \text{dB}$

Vector stability margin = 0.537

Why Measuring Stability?

- Low phase margin can add significant ringing and degrade system performance
- Especially linear regulators should have enough phase margin when powering clocks, opamps or ADCs
- Verify system design & simulation to ensure stable operation at all operating points and different environmental conditions

Limits of Loop Gain Measurements

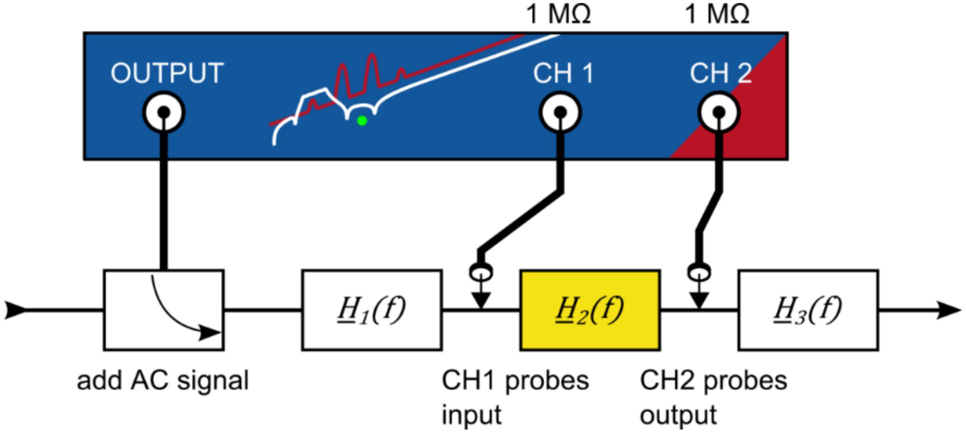
- Not applicable to highly non-linear control like hysteretic control and variations thereof (no compensator) or low-load modes like burst or pulse-skipping.
- Small-signal analysis
(does not replace large signal transient response).
- Not possible on highly integrated modules (internal feedback).

→ Think about an output impedance measurement!

→ Check out: www.picotest.com/measurements/NISM.html

Measuring Transfer Functions (Gain/Phase)

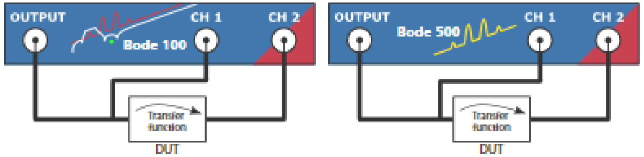
Bode measures the transfer function $\underline{H}_2(f)$ from CH1 to CH2



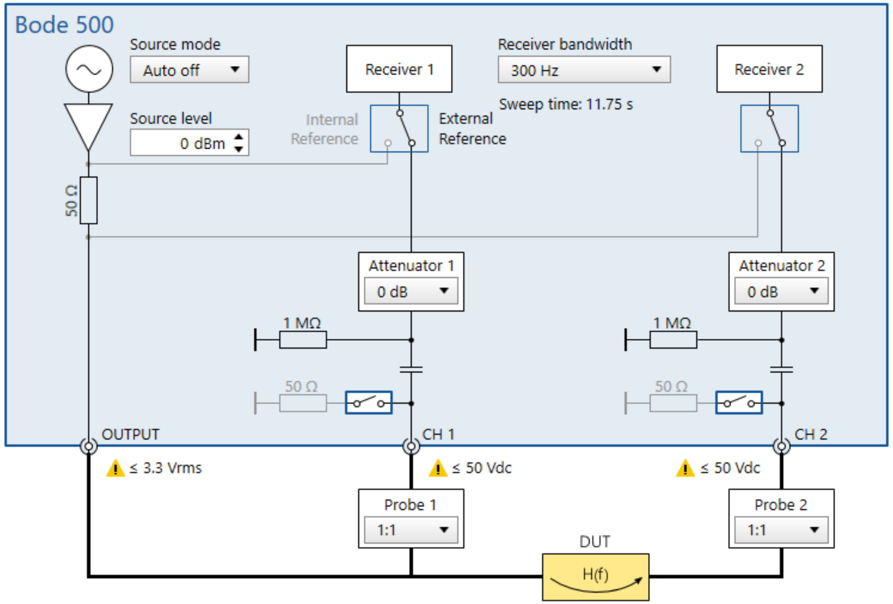
$$\underline{H}_2 = \frac{V_{CH2}(f)}{V_{CH1}(f)}$$

- The signal path between Output to H_2 is not part of the measurement result!
- A transfer function can only be measured / defined for an LTI system or a linearized situation.

Bode Analyzer Suite



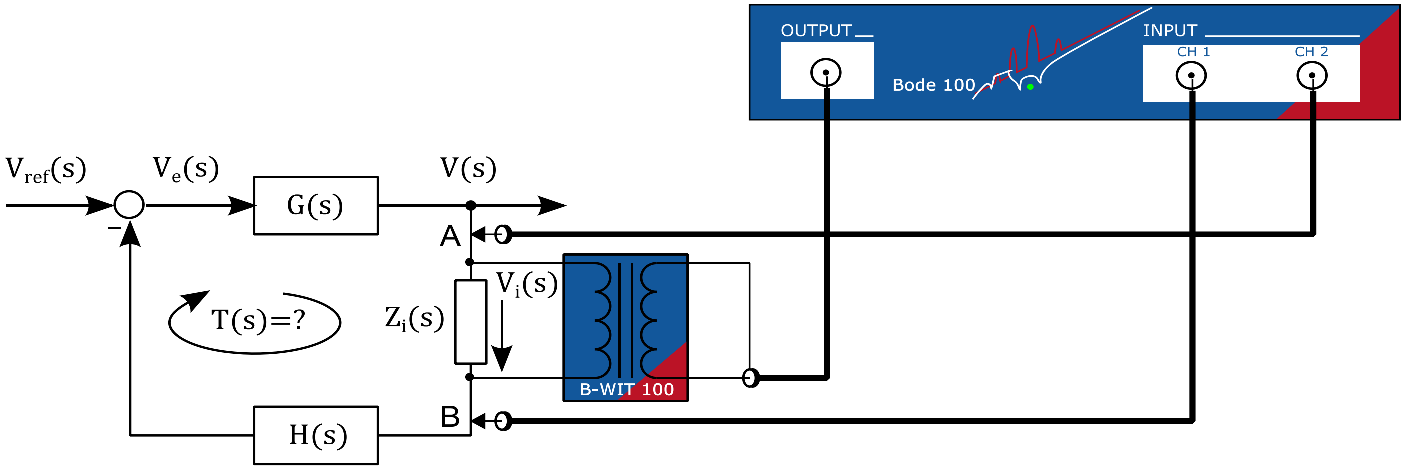
- Use Gain/Phase mode to use Bode as FRA



Measuring Loop Gain (Voltage Injection [2])

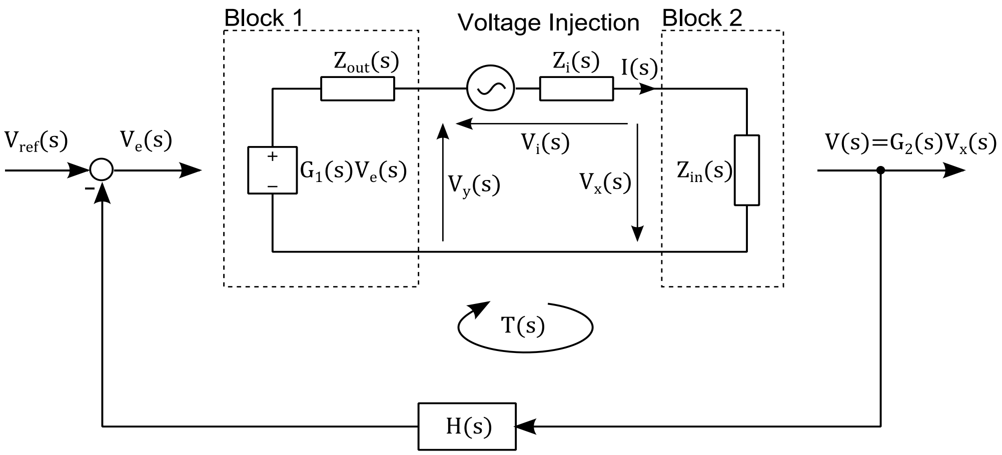
Loop gain is measured by "breaking" the loop at the injection point and inserting a "small" injection resistor (e.g. 10 Ω).

The voltage loop gain is measured by $T_v(s) = \dfrac{v_y(s)}{v_x(s)}$



The Injection Point (Voltage Injection [1])

Information flow is not only in form of voltages. At every point there are voltage and current.



Bode 100 measures voltage gain $T_v(s)$

$$T_v(s) = \frac{V_y(s)}{V_x(s)} = T(s)\underbrace{\left(1 + \frac{Z_{out}(s)}{Z_{in}(s)}\right)}_{1^{st}\ term} + \underbrace{\frac{Z_{out}(s)}{Z_{in}(s)}}_{2^{nd}\ term}$$

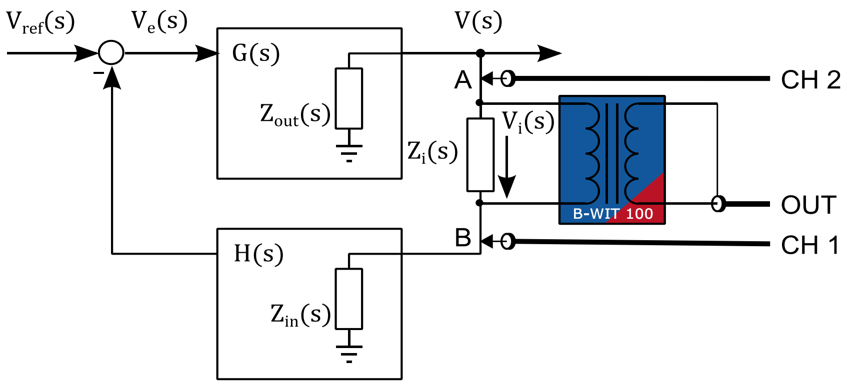
≈1 for $|Z_{in}(s)| \gg |Z_{out}(s)|$

ignore for $|T(s)| \gg \left|\frac{Z_{out}(s)}{Z_{in}(s)}\right|$

Selecting the Voltage Injection Point

To keep the measurement error small, we need to find a suitable injection point fulfilling the condition:

$$|Z_{in}| \gg |Z_{out}|$$



Well suited points:

- Output of a voltage source (top of feedback divider)
- Input of an operational amplifier (Z>>)
- Output of an operational amplifier (Z<<)
- Best between two operational amplifiers

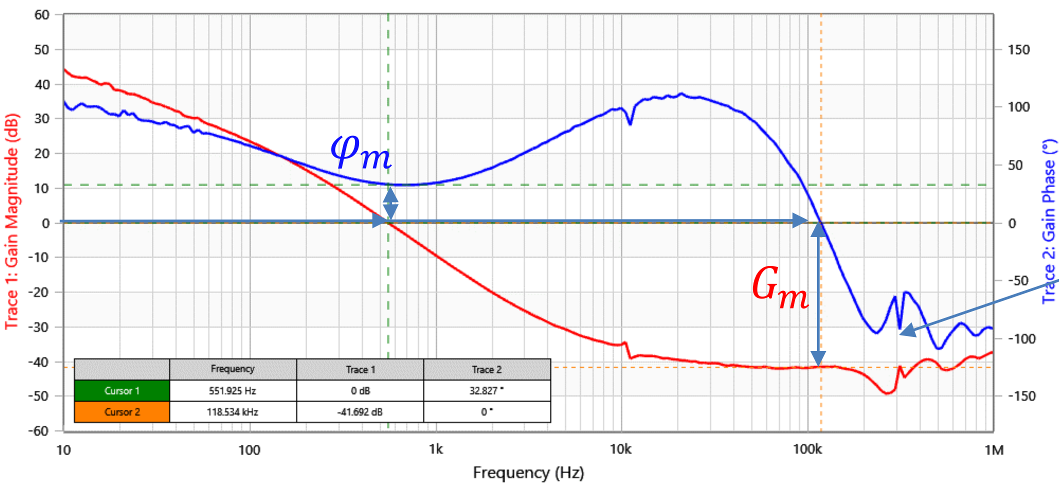
No parallel signal path bypassing the injection resistor!

Nyquist Sampling Theorem

In a typical PWM controlled converter, only **once** per **switching cycle** a **new duty** cycle value is created. → Sampled system.

→ The control loop can only react to frequencies up to $^{f_s}/_2$

→ Loop Gain needs to be measured only to **half the switching frequency**



$\varphi_m = 32\ °$

$G_m = 41\ \text{dB}$

Switching Frequency

$f_s = 315\ \text{kHz}$

Reading Phase Margin from Measurement

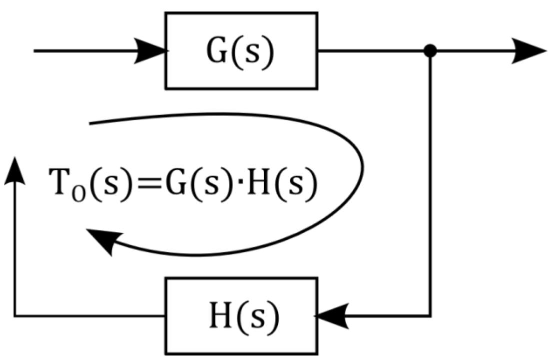
Phase Margin is read directly from the **measurement**!

φ_m as distance to 0° and NOT to -180°

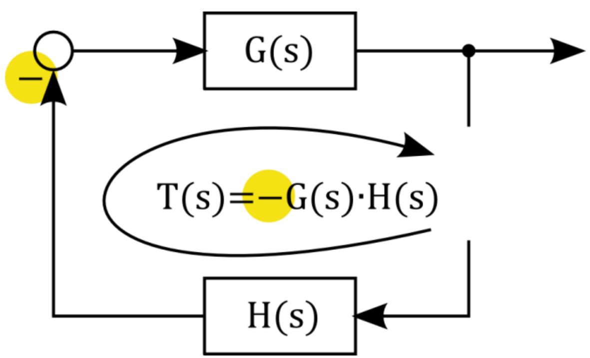
Reason: We measure in the closed loop system → our signal will run through the inverting error amp and get an additional 180° phase shift.

→ The **critical point** for positive feedback is at **+1**!

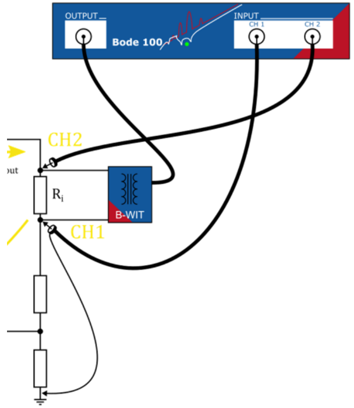
Theoretical open loop gain $T_o(s)$



Measured loop gain $T(s)$



Selecting the injection point



- Low voltage systems
  → Usually between output voltage and feedback divider.
- For high voltage systems
  → No signal conditioning – more difficult injection at high voltage
  Injected AC signal is small compared to large DC voltage
  Probes divide DC and AC lowering signal / noise ratio.

  → Higher power - search for injection point in the signal conditioning chain after output of operational amplifier / buffer amplifier.
- Very low voltage systems → check remote sensing and sense-ground! Make sure the Bode uses the same GND as the controller. Differential probes can avoid grounding issues.
- Digital control? Don't inject directly at ADC pin but in signal conditioning chain or at least before the last filter.

Injection Signal Size

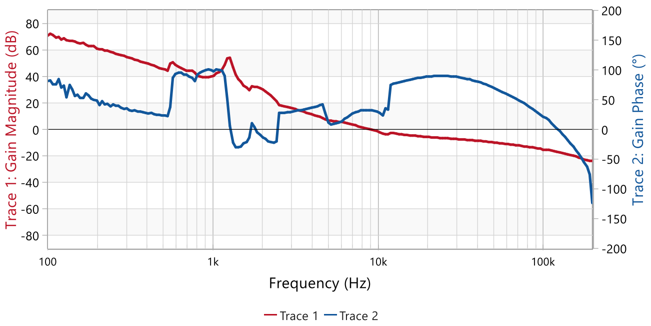
Transfer functions (LTI) are used to design the compensator

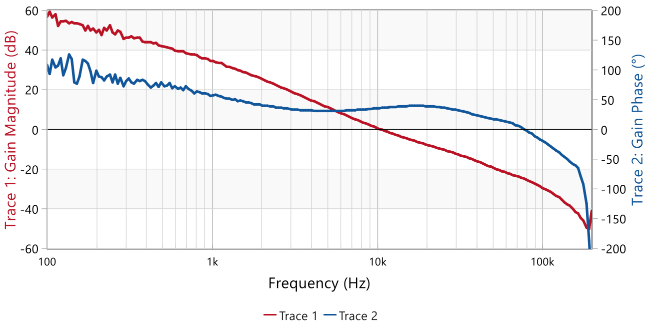
→ Measurement signal should be "small signal" to stay in linear region

→ Measurement **result** must be **independent** of injected **signal** amplitude!

1. Choose an injection signal level and measure
2. Reduce the injection signal by e.g. 10dB

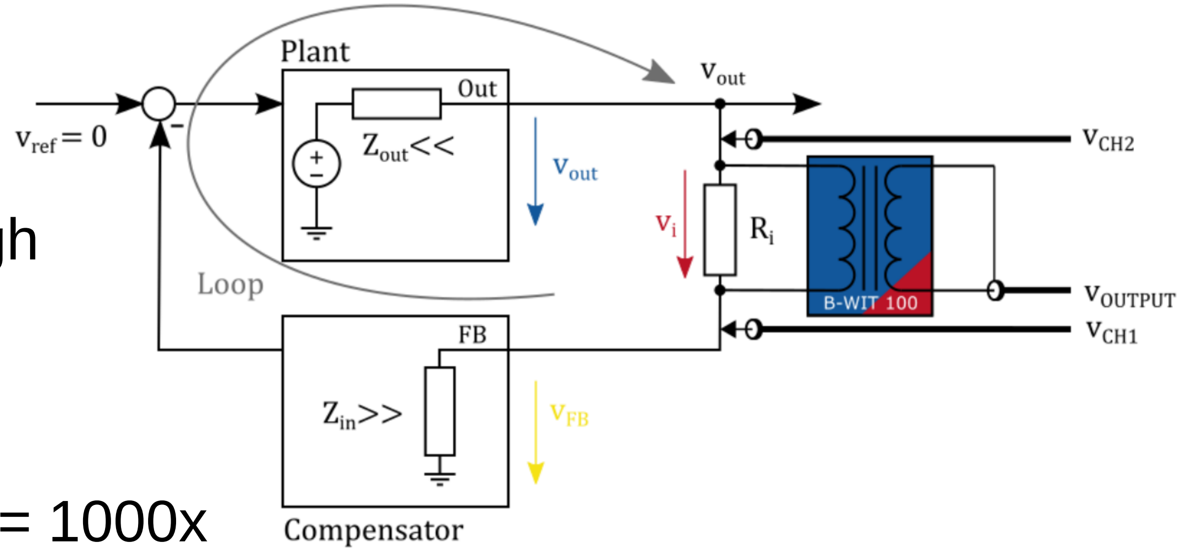
→ If the result changes → do **further reduce** until it stays constant!





Why so much noise at low frequency?

- v_i is "constant"
- $v_i + v_{out} + v_{FB} = 0$
- at low f → gain is high
  → $v_{out} \approx -v_i$
  → $v_{FB} \approx 0$



Example: Gain = 60dB = 1000x

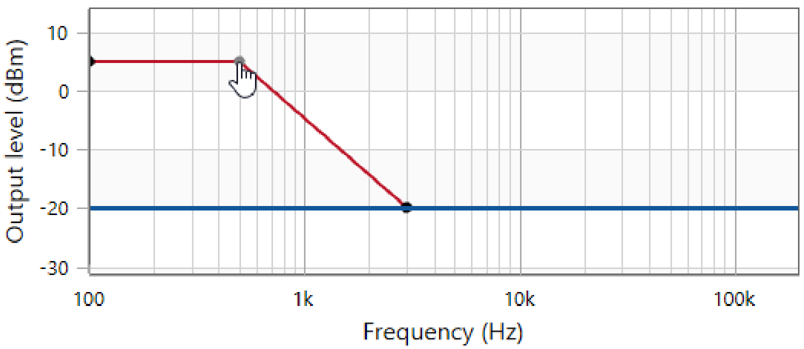
Injection voltage = 30 mV → CH2 needs to measure 30µV

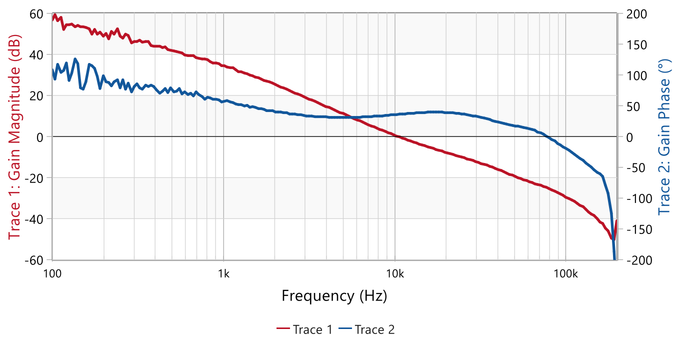
Resolving phase at such high ratio and low signal is tricky.

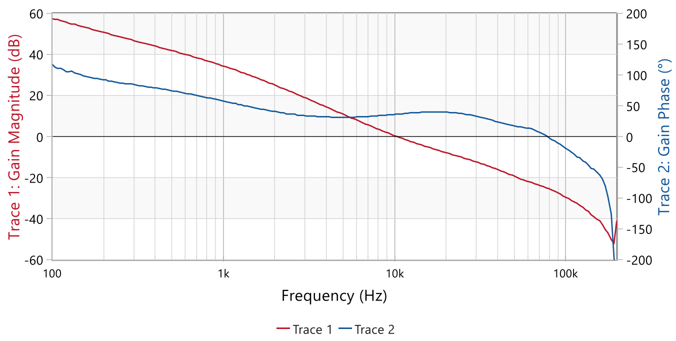
With 300 mV injection → CH2 gets 3 mV which is easier.

Shaped Level

- Correct results and clean curves? → use the "shaped level"!
- Low level at sensitive frequencies and high level where you need more disturbance power.

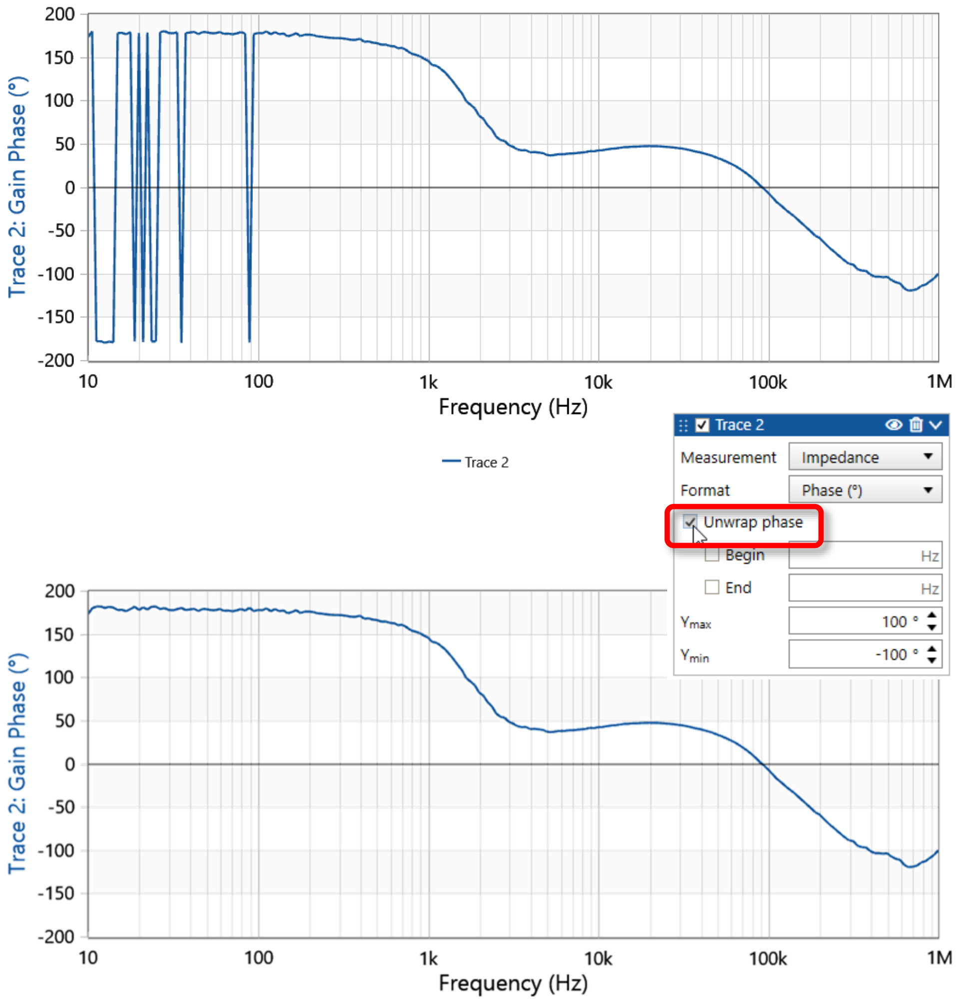






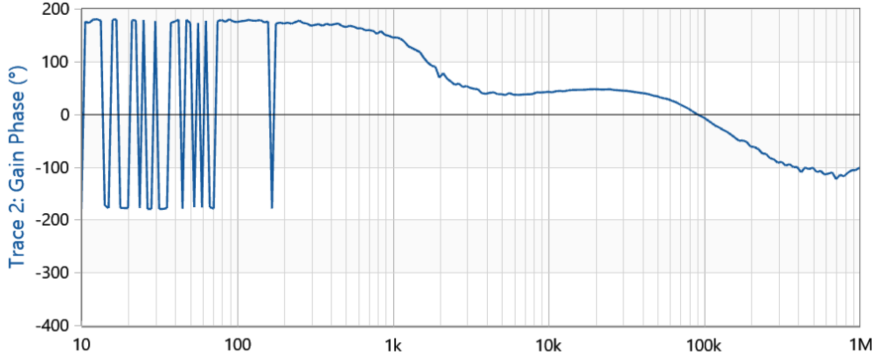
Phase-Wrapping

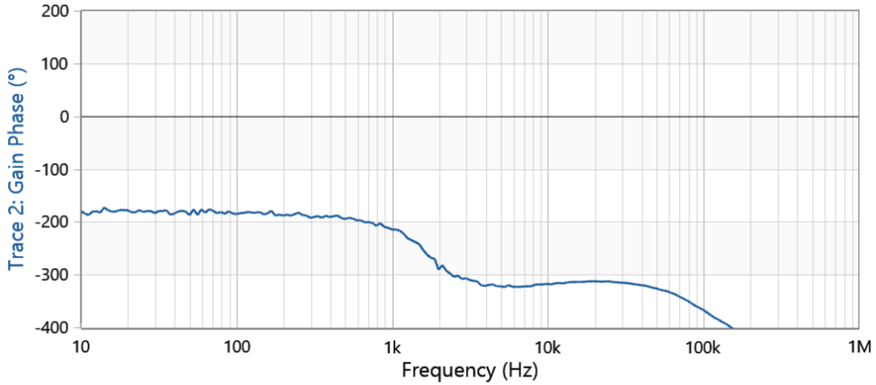
- -180° and +180° phase shift looks the same
- If phase is close to 180° a little noise can cause a large visual effect
- Unwrapping can display continuous phase but...



Phase Wrapping Continued

- What if the first value is at -180° and not at +180°?





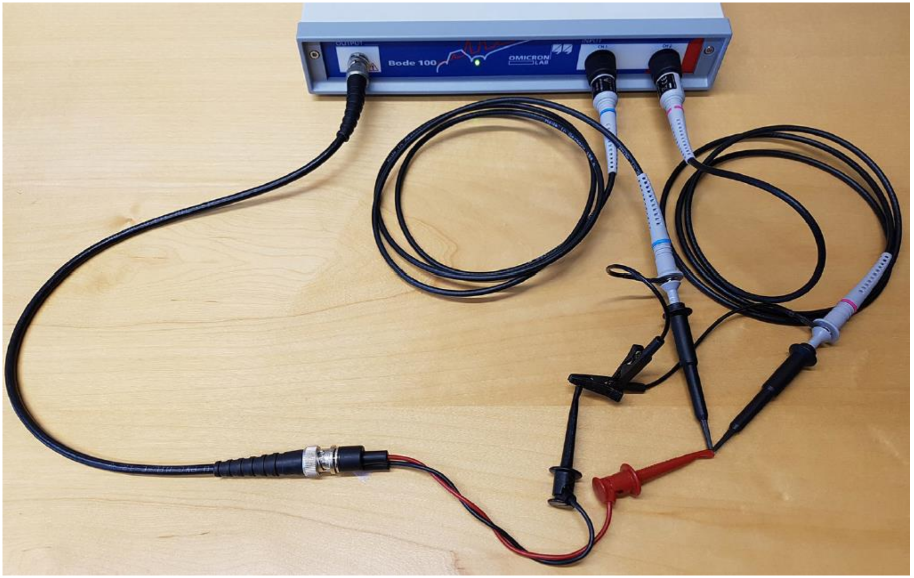
Solutions:

- Ignore phase wrapping
- Reduce phase noise
- Sweep backwards

Is Calibration Necessary?

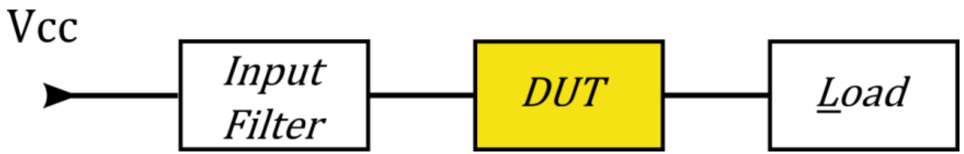
Normally not. Basic accuracy of the setup should be sufficient if probes are compensated correctly!

Not sure? → Check it out!



- Should result in a flat line at 0 dB and 0°
- Use with and without B-WIT 100 to check if probes and B-WIT 100 are functional

Please consider

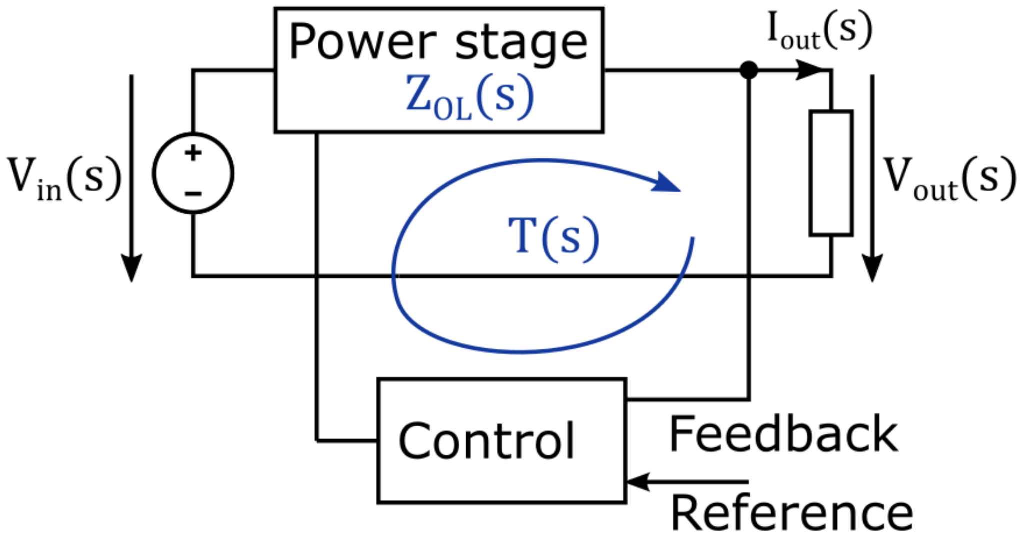


- The input filter can influence the stability (Middlebrook)
- The load can influence the measurement or plant transfer function
- The operating point can influence the plant transfer function

→ Always measure loop gain under **all expected load conditions** and with the **input filter** connected

Note: Electronic loads can cause strange effects if their control loop interacts with the system and power supplies can impact the loop if their stability is low.

Output Impedance



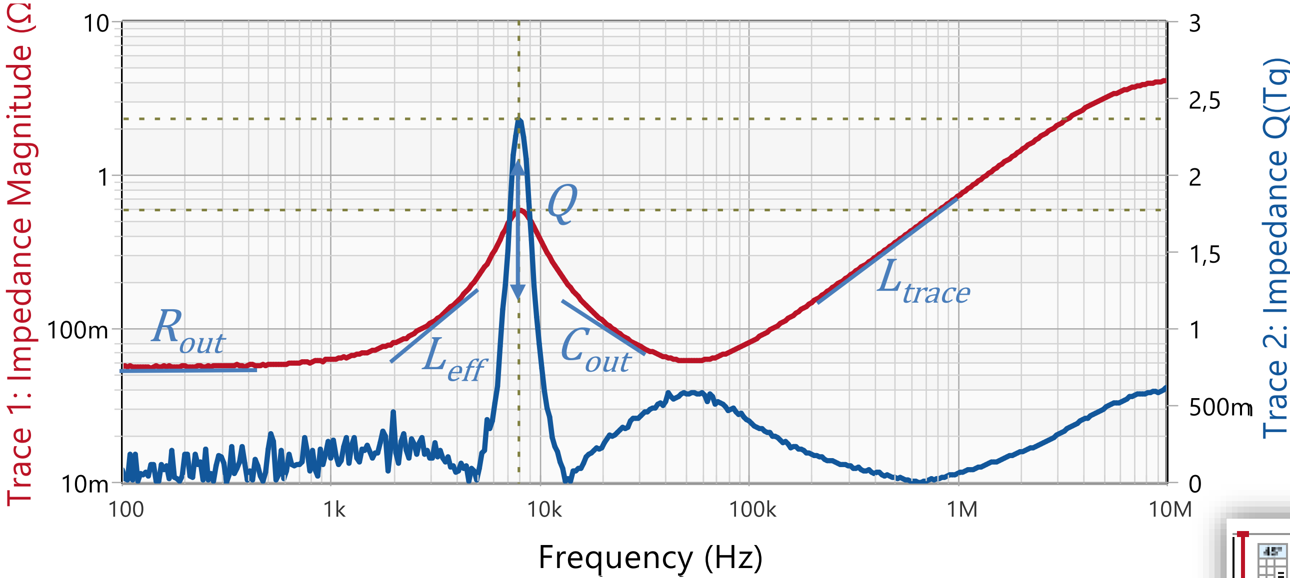
- Closing the loop changes the output impedance to:

$$Z_{out}(s) = \frac{Z_{OL}(s)}{1 + T(s)}$$

T(s)...Loop Gain
$Z_{OL}(s)$...Open-Loop Output Impedance
$Z_{out}(s)$...Closed-Loop Output Impedance

NISM (Non-Invasive Stability Measurement)

- Q correlates to Phase Margin φ_m
- Peak in Z_{out} correlates to the Q of the closed loop system

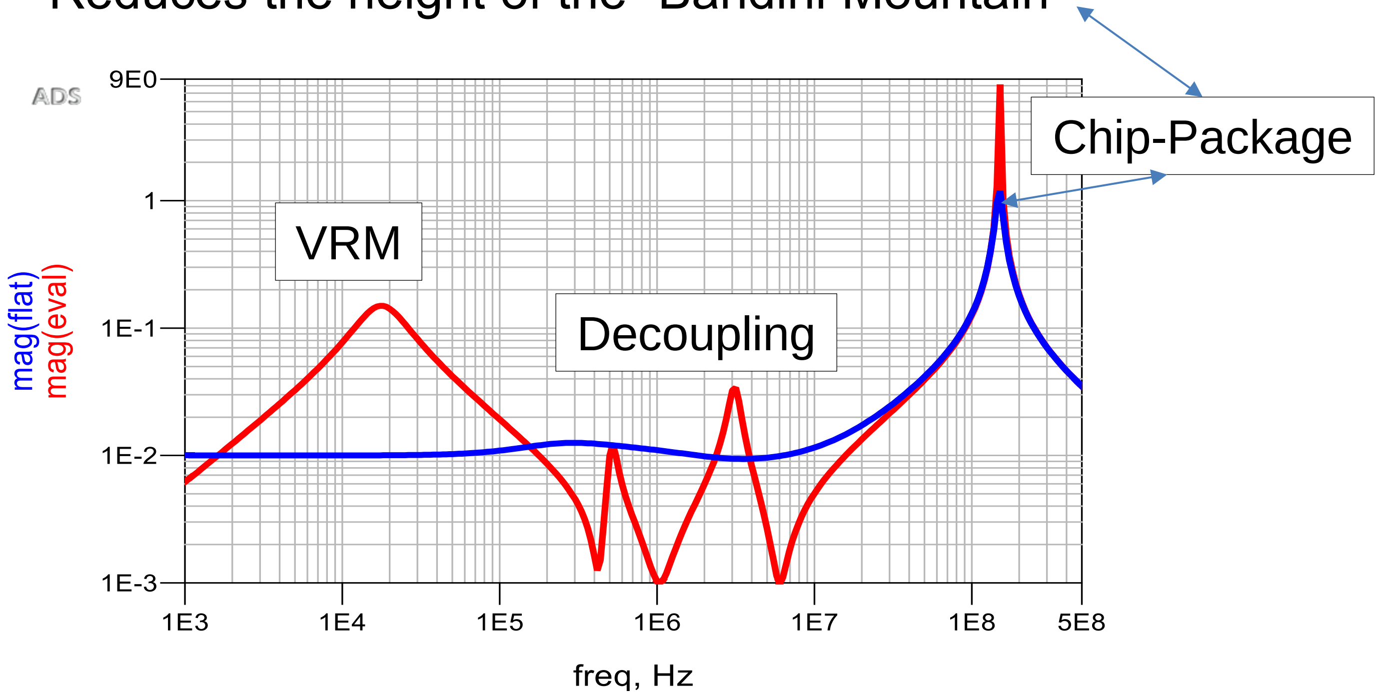


$$Q = \frac{\sqrt{\cos(\varphi_m)}}{\sin(\varphi_m)}$$

The Flat-Impedance Approach

PICOTEST

- The only reliable way to avoid resonances
- Represents a constant source "resistance" to the load
- Reduces the height of the "Bandini Mountain"



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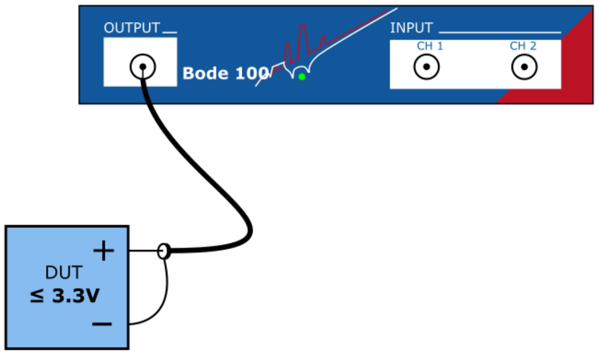
The PDN Impedance Plot

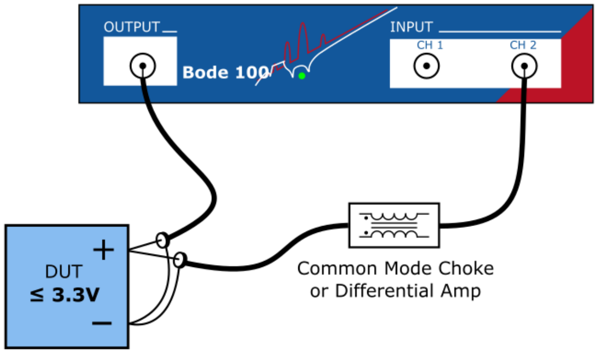
1. Contains information about the stability (oscillation tendency) of the voltage regulator
2. Reveals resonance frequencies of the decoupling network
3. The resonance peaks can cause performance degradation of the supplied load

➢ Let's measure it!

(it sounds more difficult than it is)

Measuring PDN Impedance ≤ 3.3 Vdc





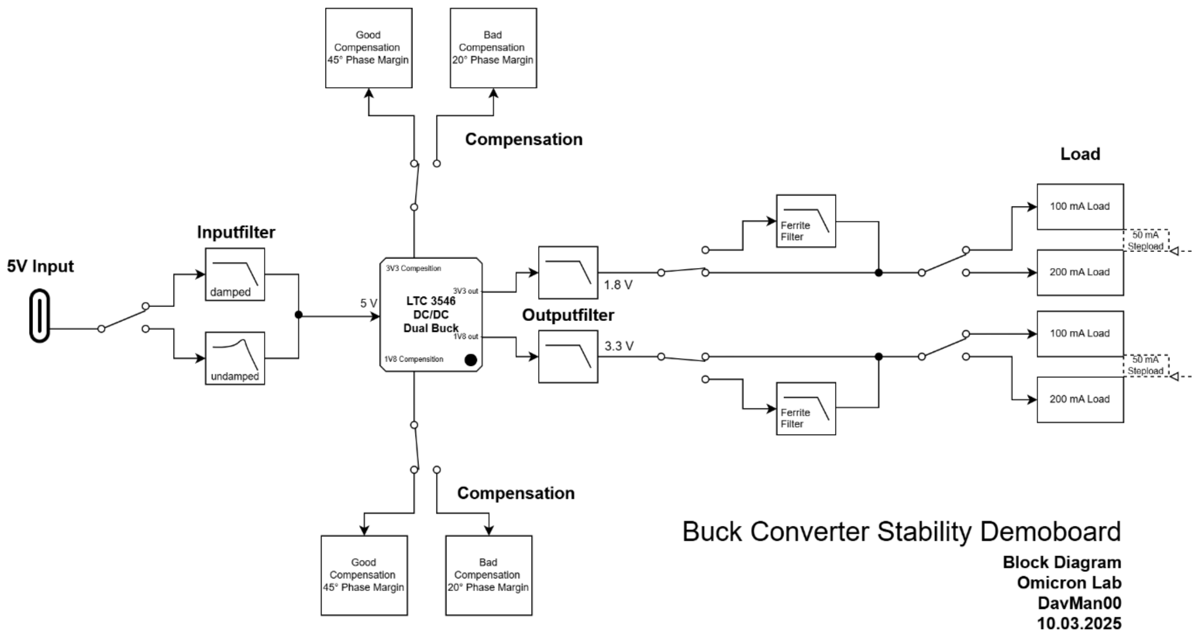
One-Port Method:
- Simplest setup providing quick results
- Not really suitable for mΩ measurements

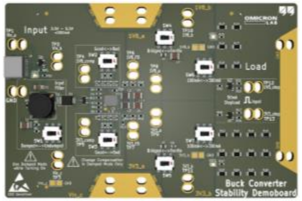
2-Port Shunt-Thru:
- Best suitable for mΩ measurements
- Take care of the GND-loop!
- Use amplifier to get more signal

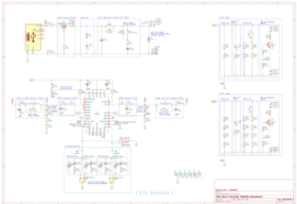
➢ Both methods can also measure OFF-State impedance

Let's try it in real life!

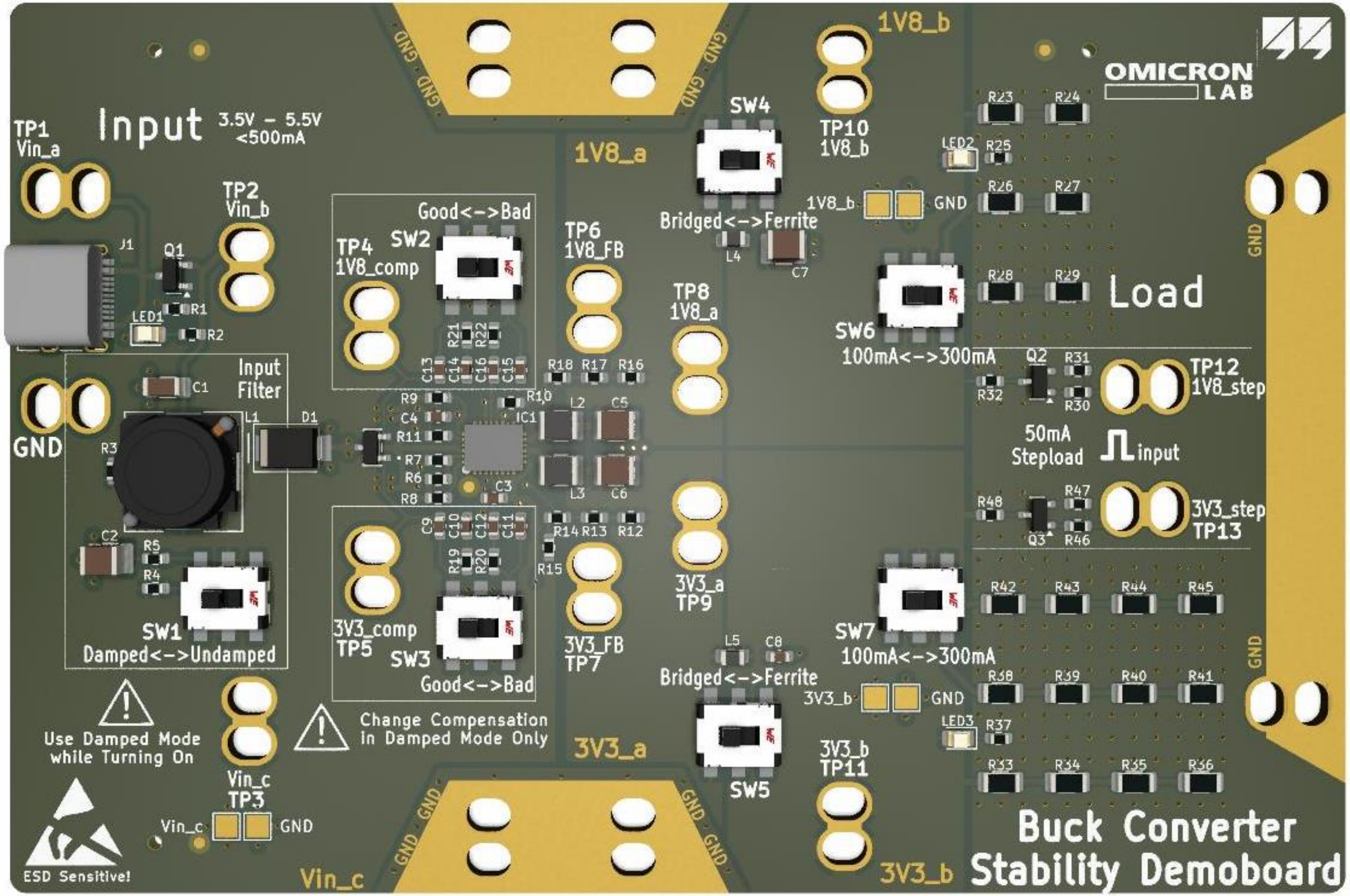
Buck Converter Stability Demoboard

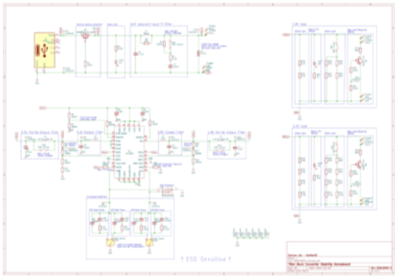


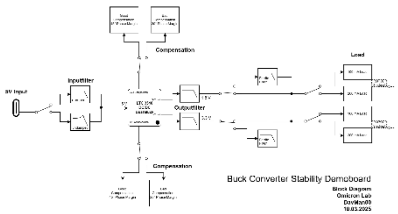


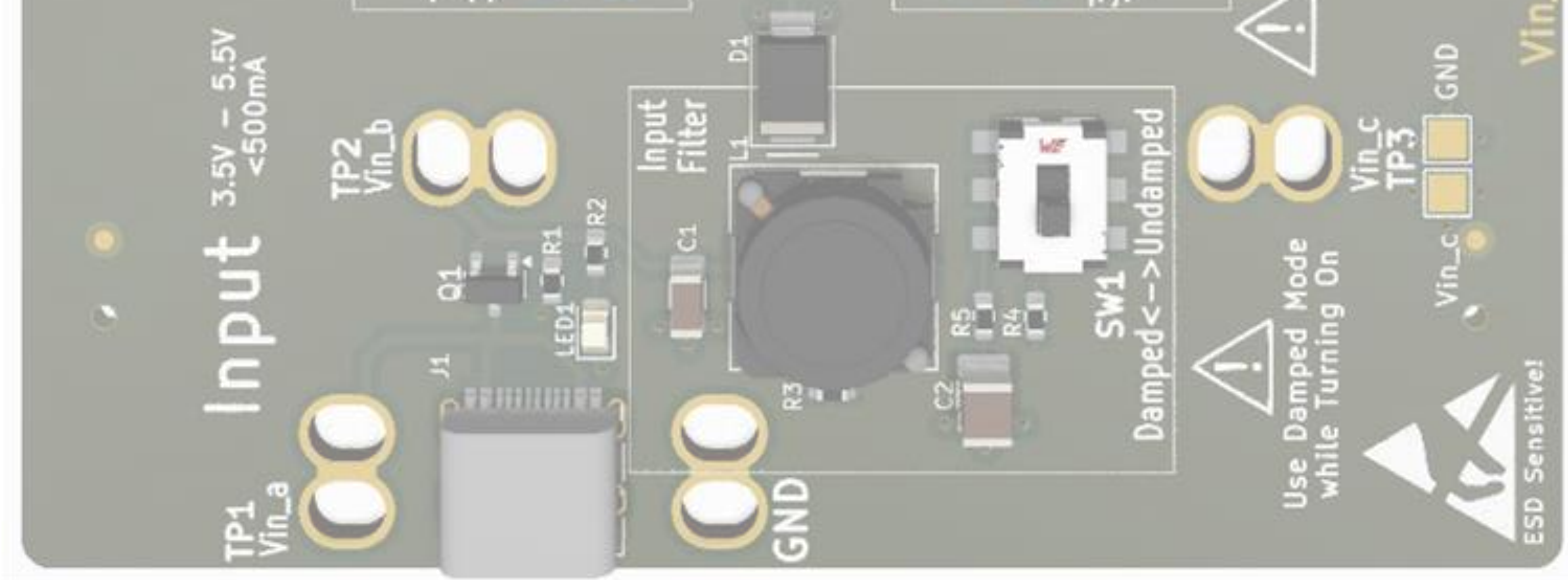


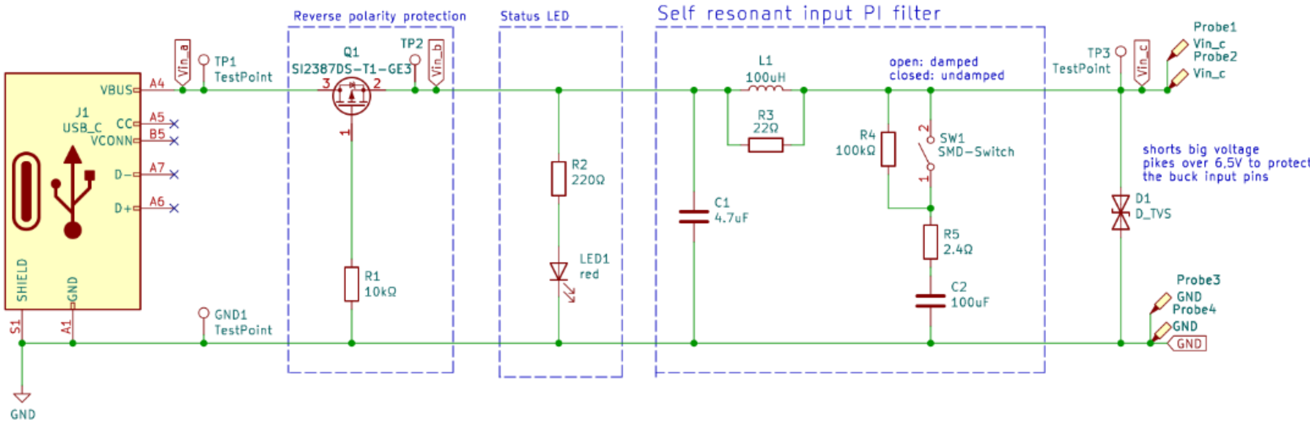
Buck Converter Stability Demoboard

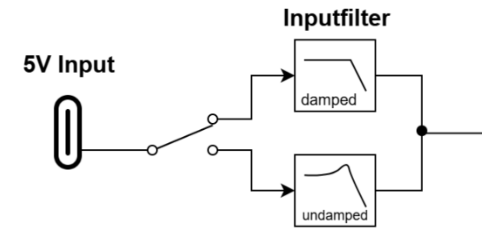




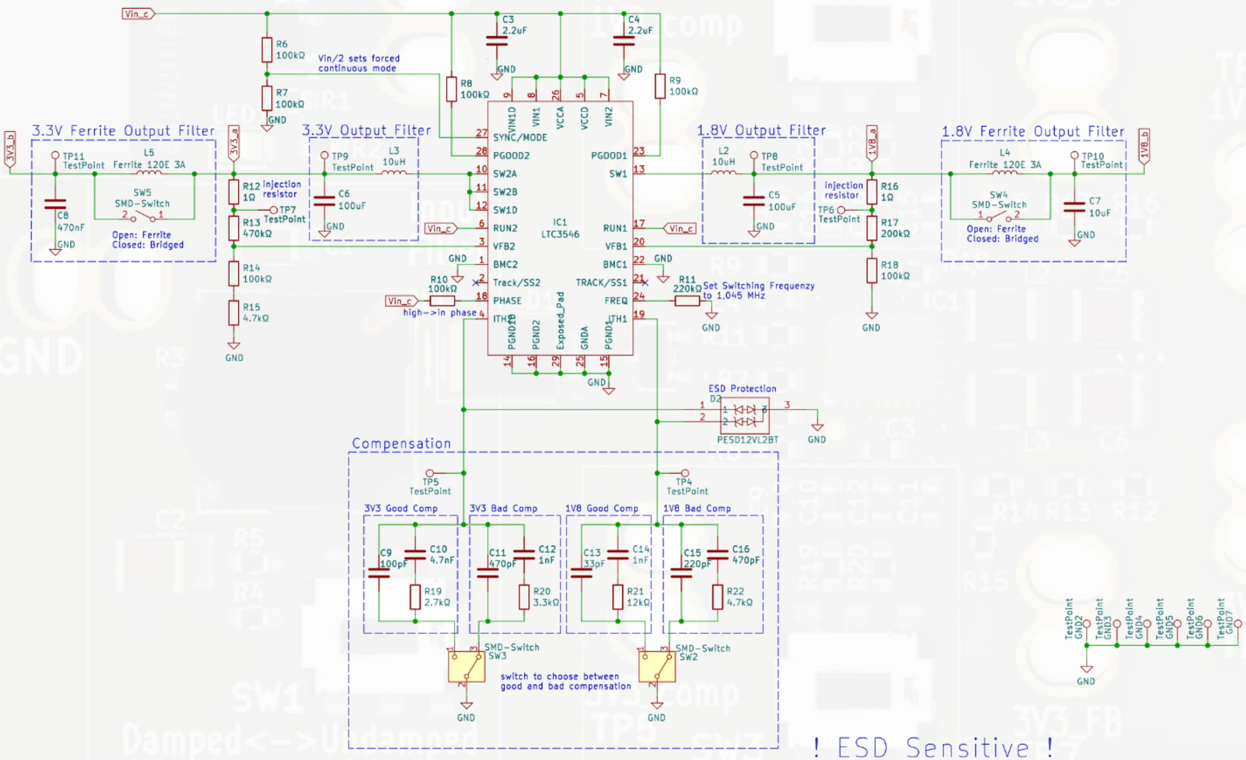


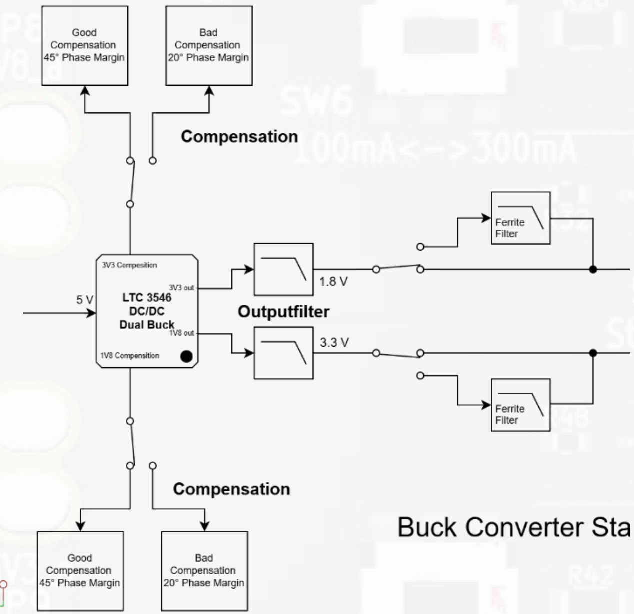

Input 3.5V – 5.5V
<500mA
TP1
Vin_a
TP2
Vin_b
Q1
R1
R2
LED1
J1
GND
D1
L1
Input Filter
C1
C2
R3
R4
R5
SW1
Damped<–>Undamped
Use Damped Mode while Turning On
Vin_c
TP3
GND
ESD Sensitive!

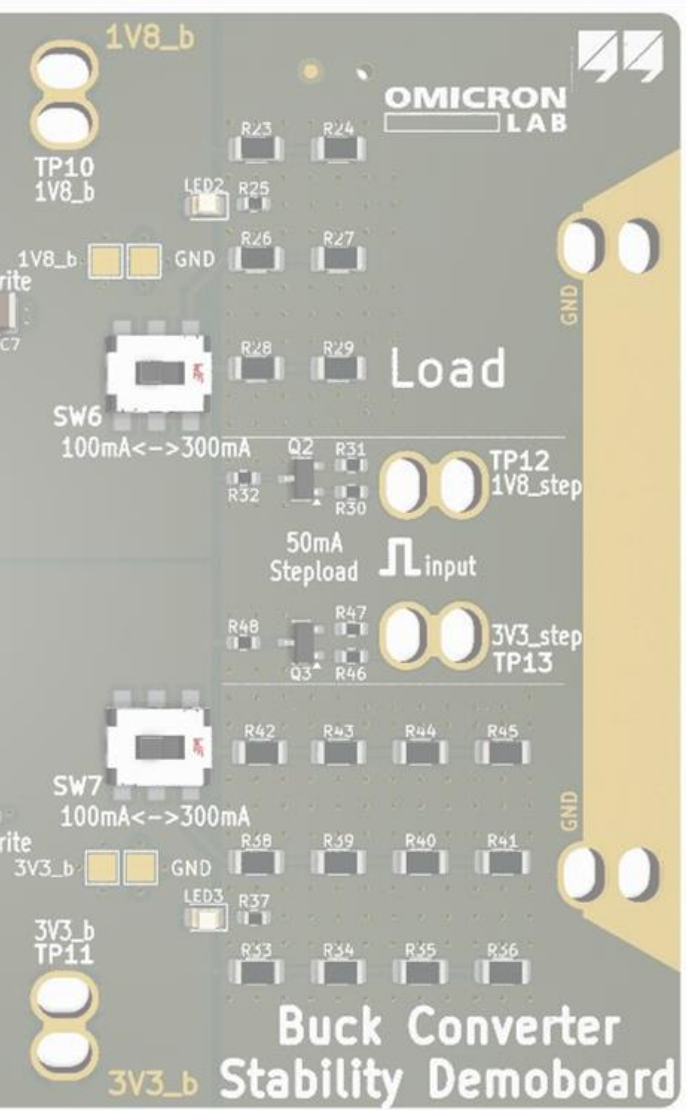

Reverse polarity protection
Status LED
Self resonant input PI filter
J1
USB_C
VBUS
CC
VCONN
D-
D+
SHIELD
GND
TP1
TestPoint
GND1
TestPoint
Q1
SI2387DS-T1-GE3
TP2
R1
10kΩ
R2
220Ω
LED1
red
L1
100uH
R3
22Ω
C1
4.7uF
open: damped
closed: undamped
R4
100kΩ
SW1
SMD-Switch
R5
2.4Ω
C2
100uF
TP3
TestPoint
Probe1
Vin_c
Probe2
Vin_c
shorts big voltage
pikes over 6,5V to protect
the buck input pins
D1
D_TVS
Probe3
GND
Probe4
GND
GND


5V Input
Inputfilter
damped
undamped

Buck Converter Sta







1V8_b
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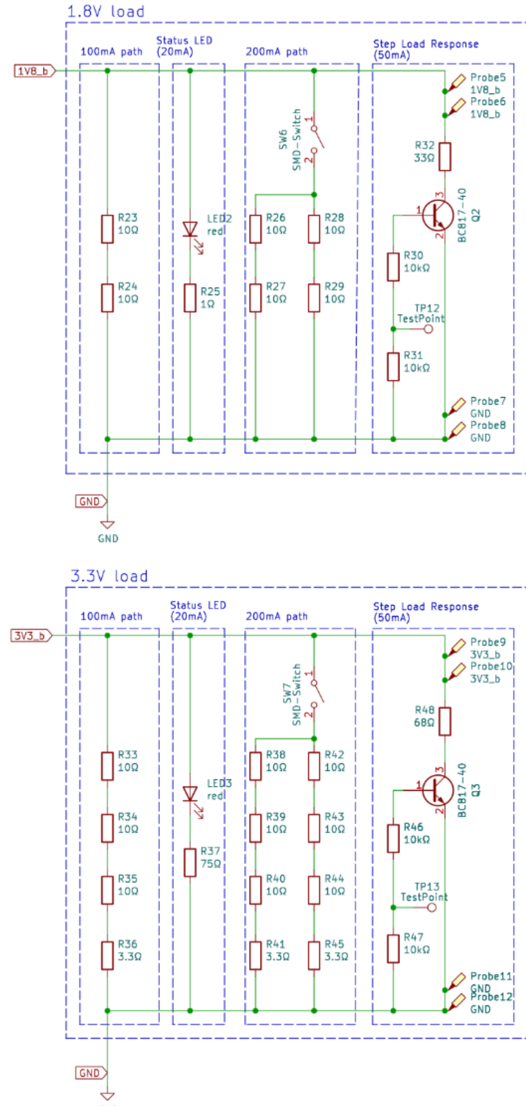
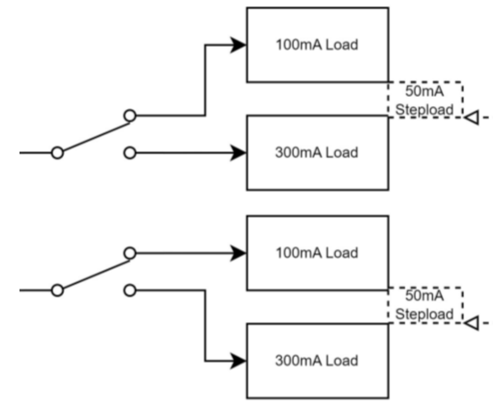
R23
R24
TP10
1V8_b
LED2
R25
R26
R27
1V8_b
GND
R28
R29
Load
SW6
100mA<->300mA
Q2
R31
R32
R30
TP12
1V8_step
50mA
Stepload
input
R48
R47
3V3_step
TP13
Q3
R46
R42
R43
R44
R45
SW7
100mA<->300mA
R38
R39
R40
R41
3V3_b
GND
LED3
R37
3V3_b
TP11
R33
R34
R35
R36
3V3_b
Buck Converter
Stability Demoboard
GND



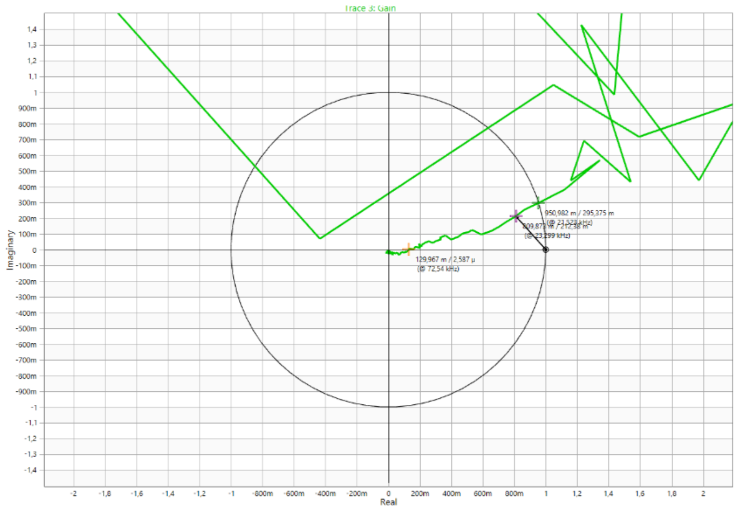
1.8V load
100mA path
Status LED (20mA)
200mA path
Step Load Response (50mA)
1V8_b
GND
3.3V load
3V3_b

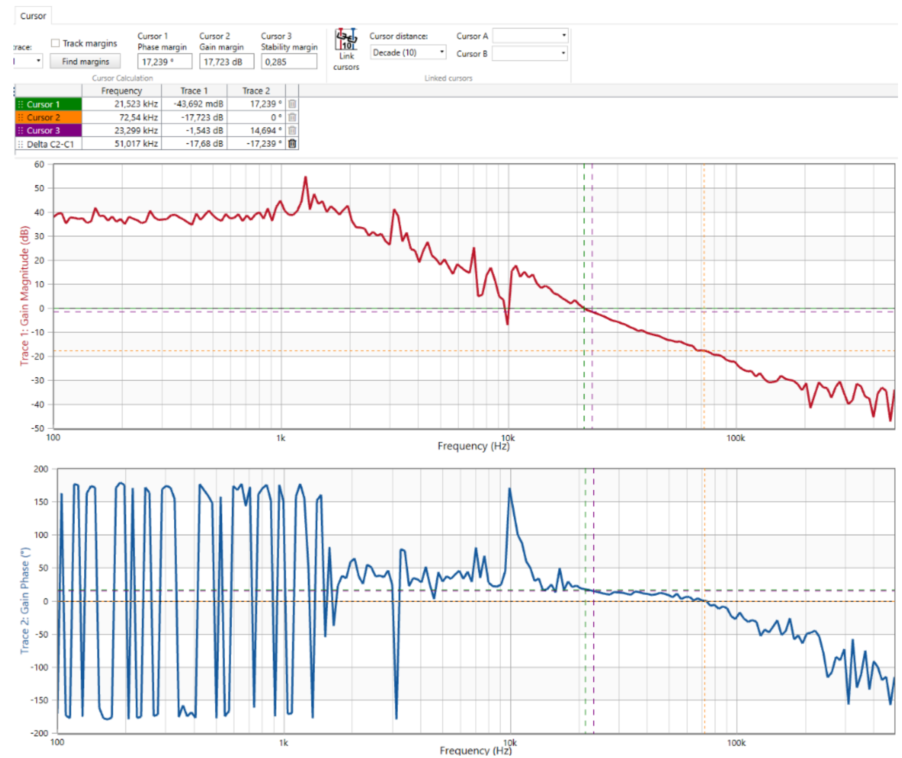
Load



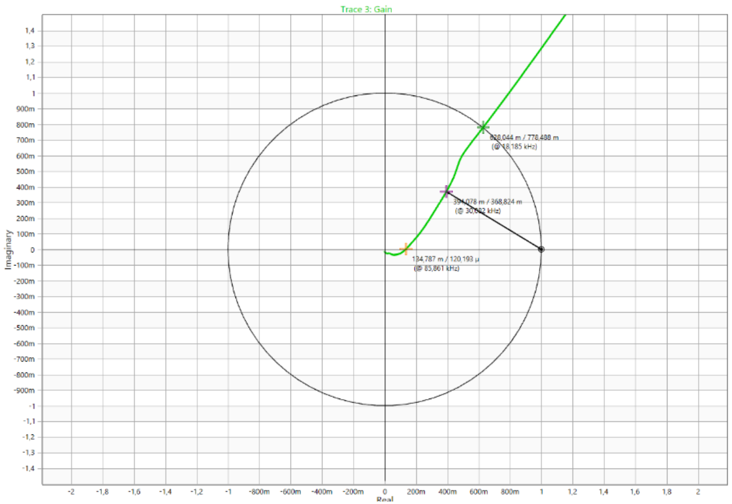
100mA Load
50mA Stepload
300mA Load
100mA Load
50mA Stepload
300mA Load

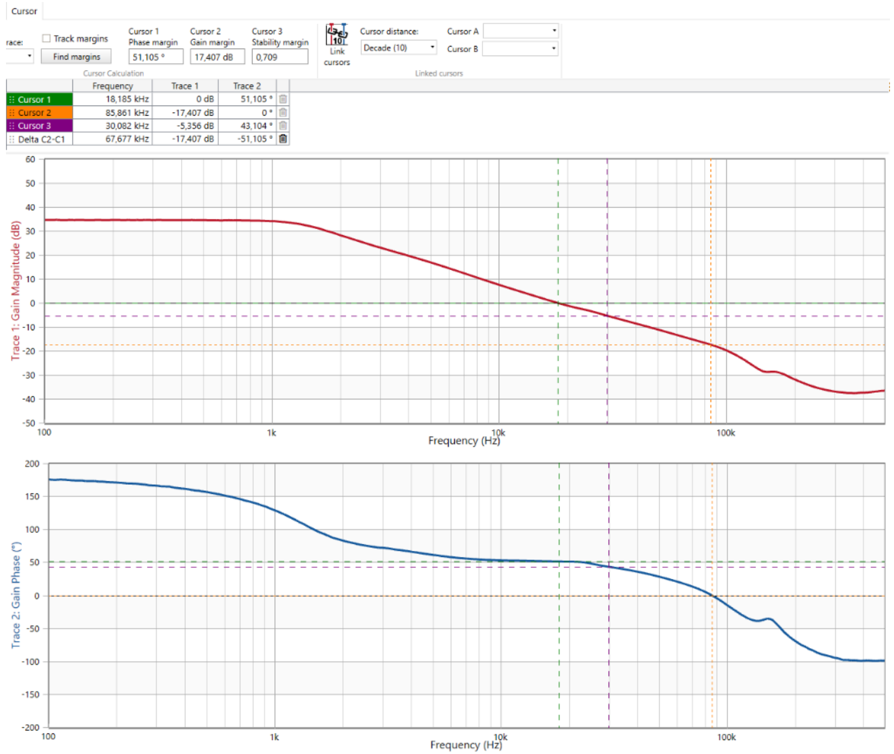
Open Loop Gain – Worst Case



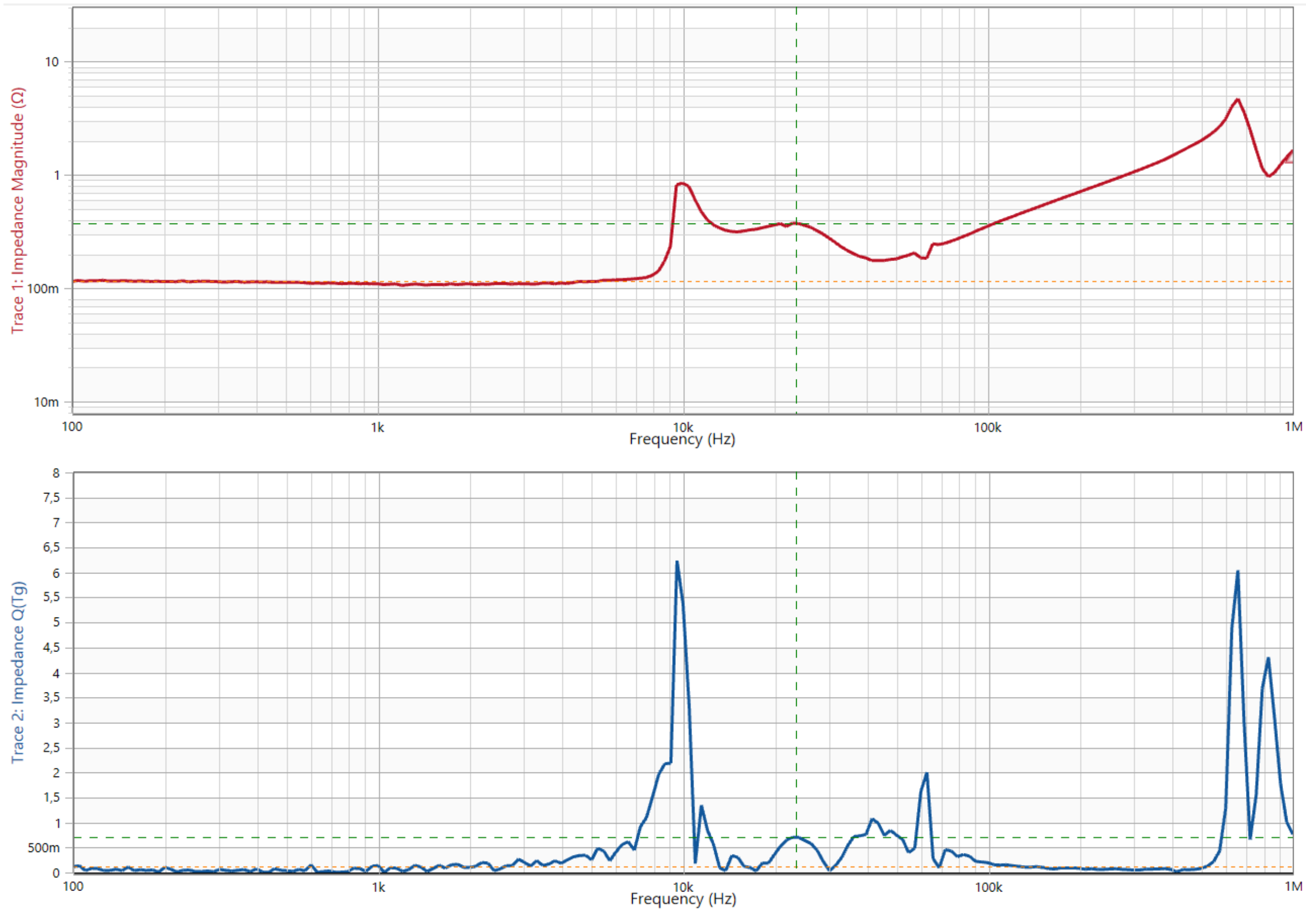


Open Loop Gain – Goal

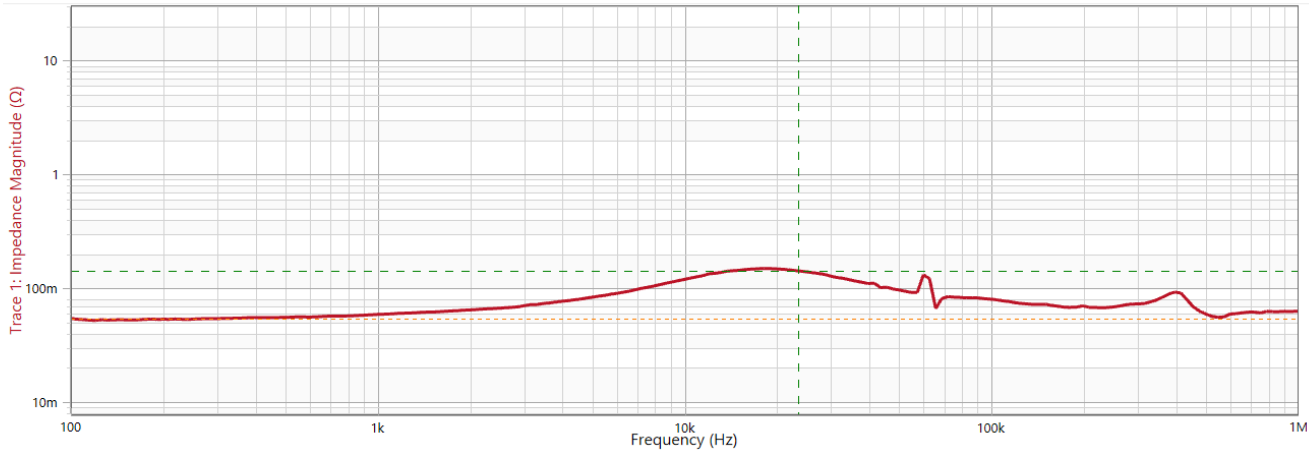


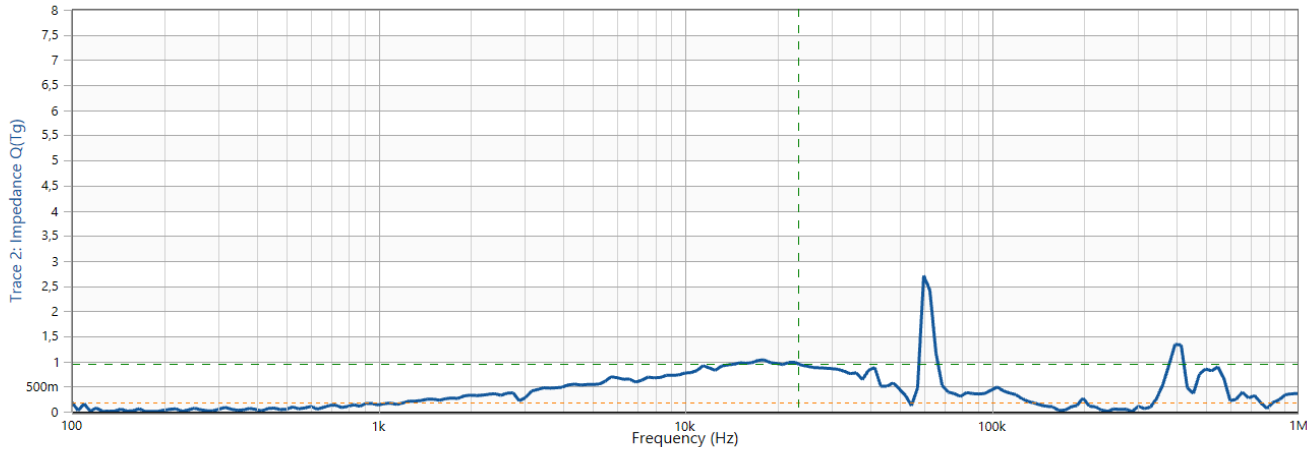


Output Impedance – Worst Case

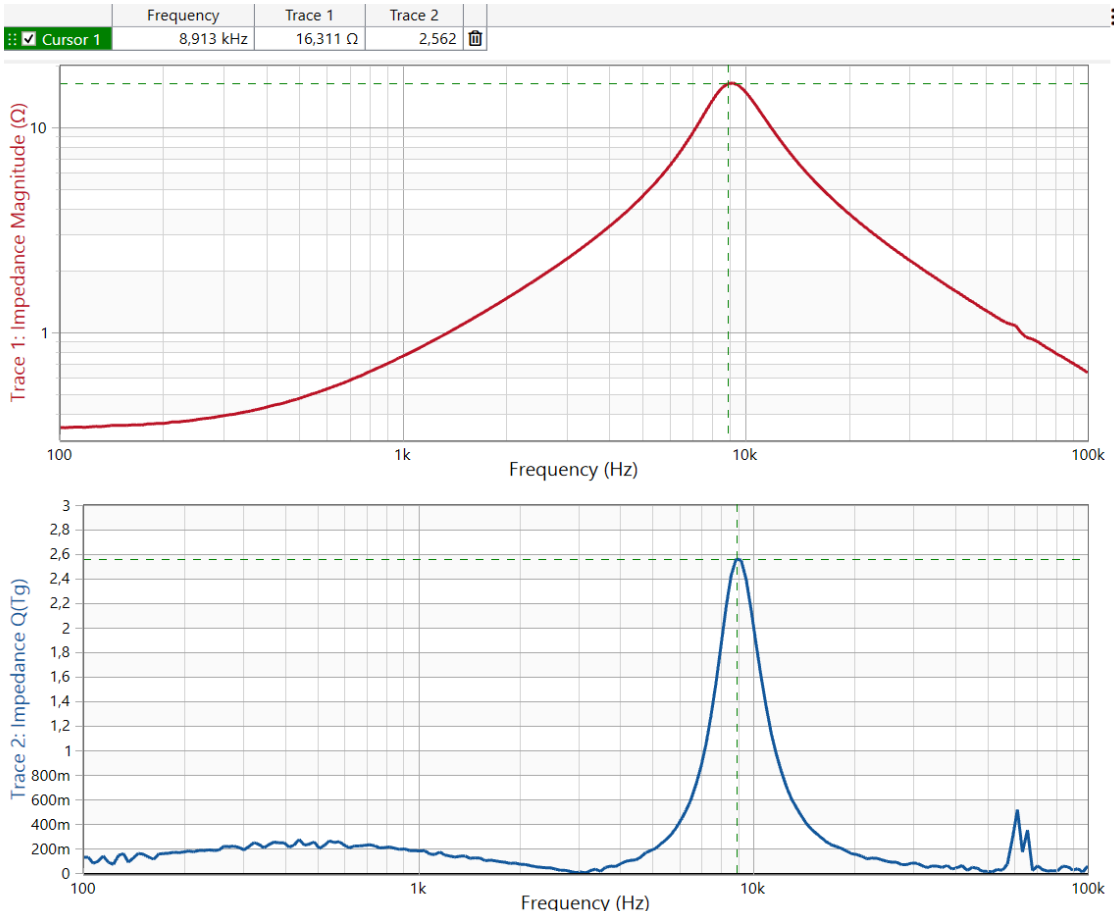


Output Impedance – Goal

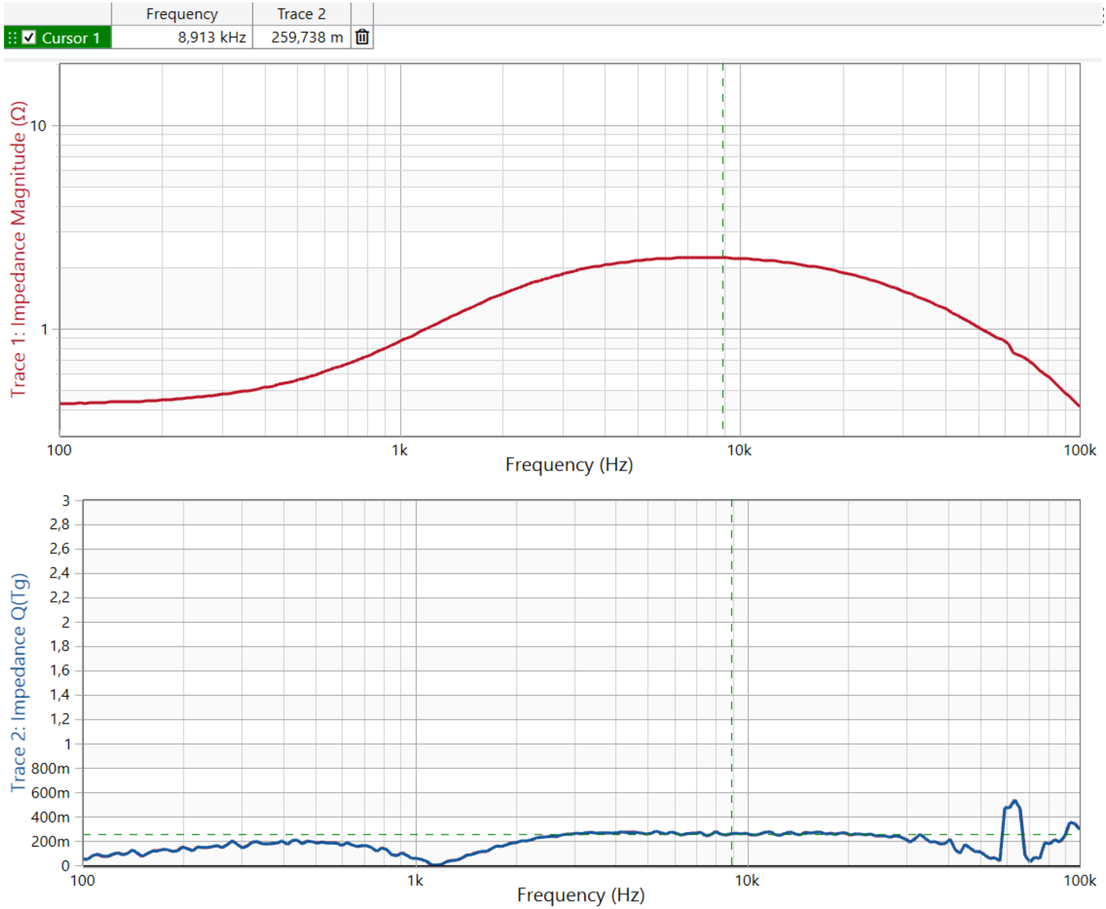




Input Filter Output Impedance – Worst Case



Input Filter Output Impedance – Goal



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, “Measurement of loop gain in feedback systems,” *International Journal of Electronics*, vol. 38, no. 4, pp. 485–512, Apr. 1975.

[3] Dean Venable, “Practical Testing Techniques For Modern Control Loops”, Venable Technical Paper #16

[4] OMICRON Lab, DC/DC Converter Stability Measurement, https://www.omicron-lab.com/applications/detail/news/dcdc-converter-stability-measurement/

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

Thank you for your attention!

If you have questions or proposals to the OMICRON Lab team, please contact us via info@omicron-lab.com.

My personal e-mail: david.mantler@omicron-lab.com

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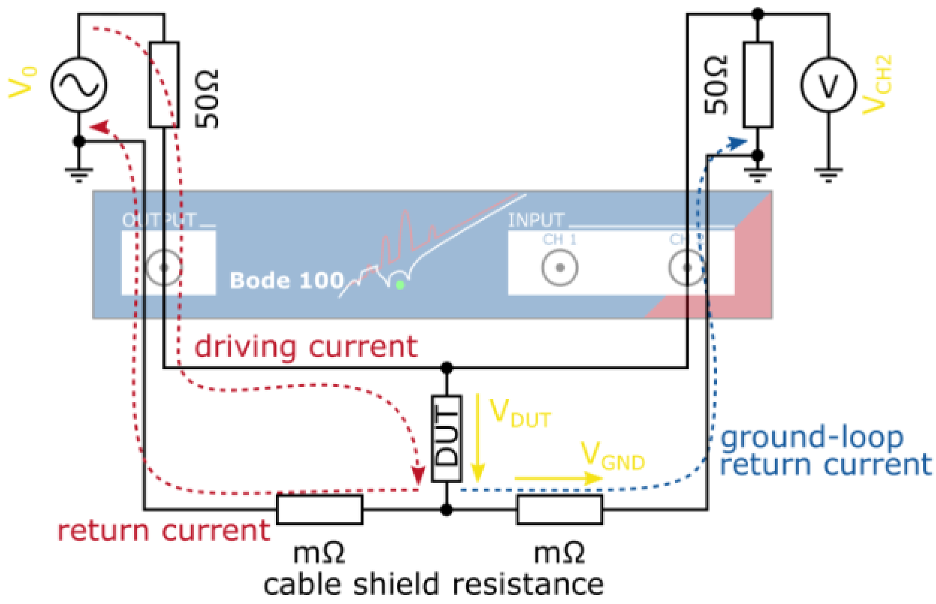
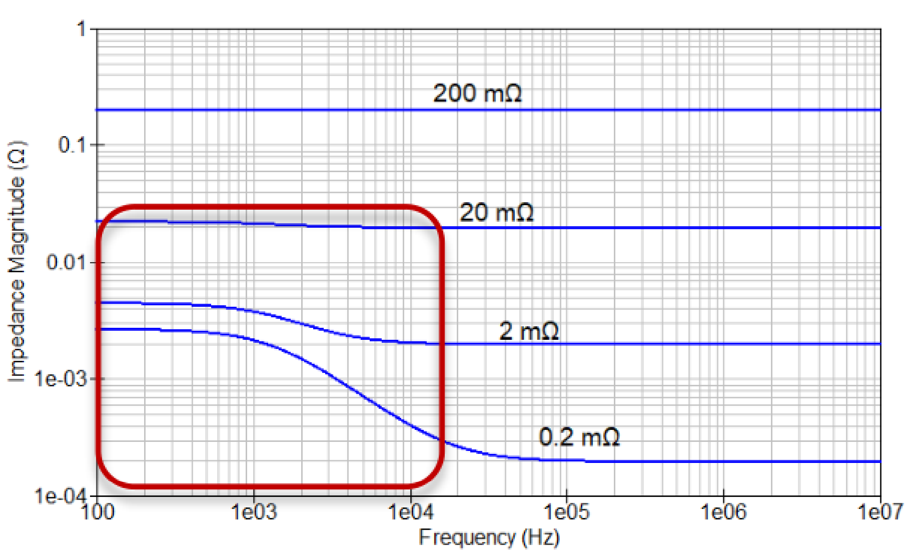
Appendix

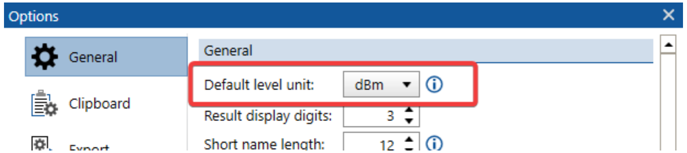
Ground Loop Error

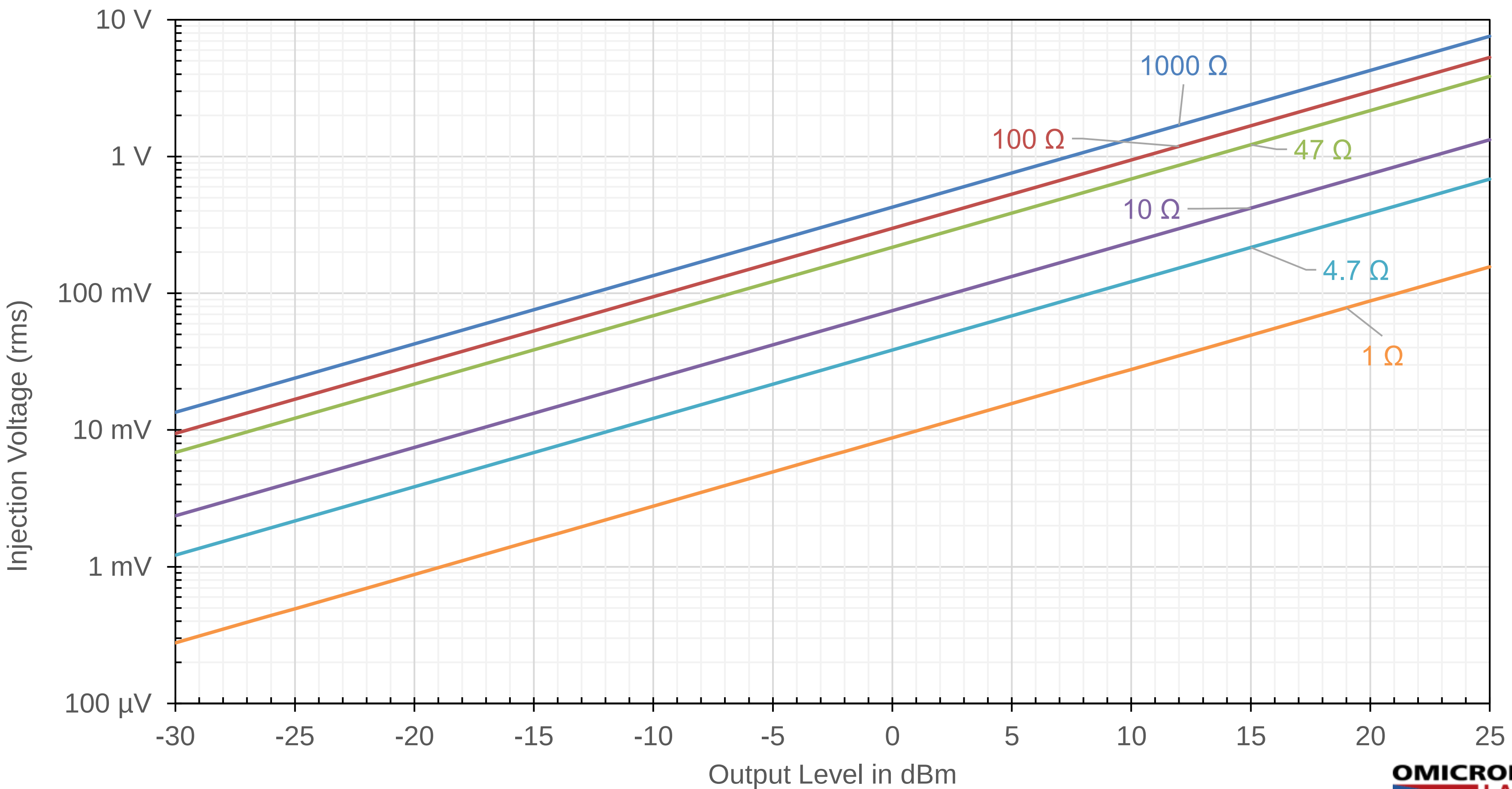
- Current flows over cable shield and instrument ground
- Causes error at low frequency and low Z





dBm or V ???





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