Accurate Loop Gain Measurements, Tips & Tricks

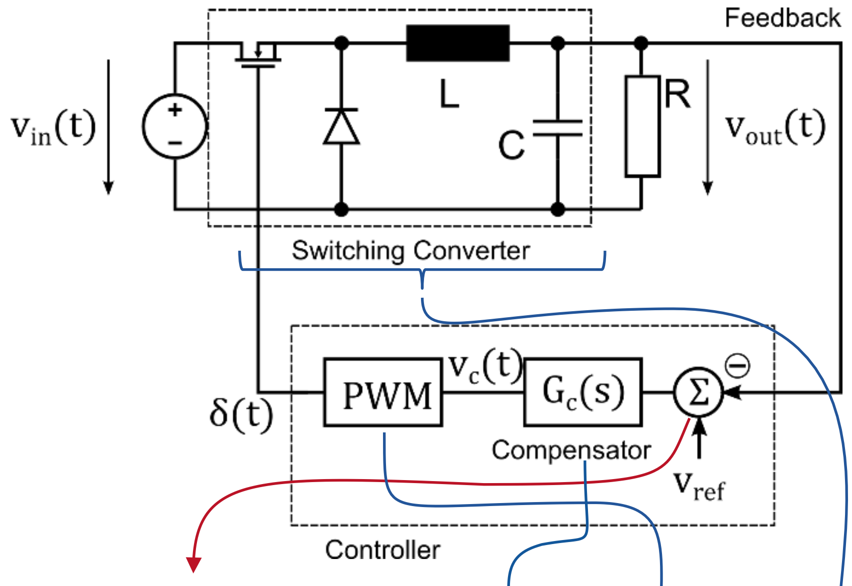
12^{th} Power Analysis & Design Symposium

2023-03-15

Agenda

- Voltage Injection Method
- Stability Margins
- Selecting the Injection Point
- Noise & Injection Level
- Input Filter & Output Filters
- Manipulation with Expression Traces

The Closed-Loop System (Voltage Loop)

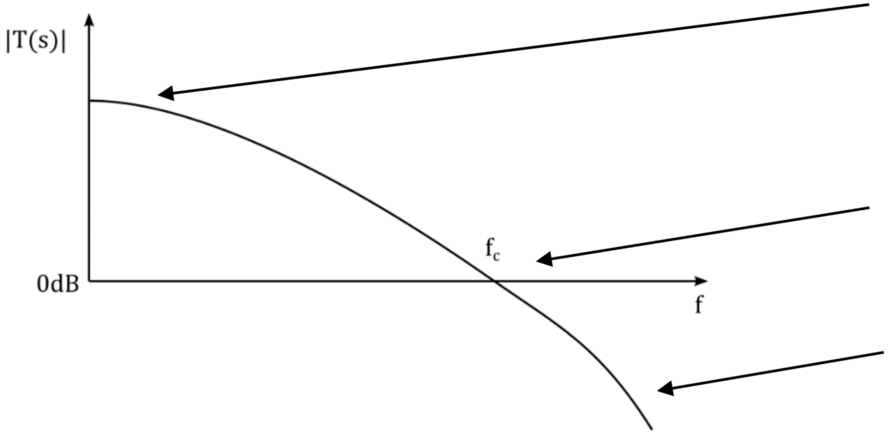


$$\hat{v}_{out}(s) = \left(\hat{v}_{ref}(s) - \hat{v}_{out}(s)\right) \cdot G_c(s) \cdot G_{PWM}(s) \cdot G_{vd}(s)$$

Loop Gain $T(s)$

Loop Gain T(s)

- For good output regulation we need **high loop gain**
- For $T(s) < 1$ the feedback has no 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

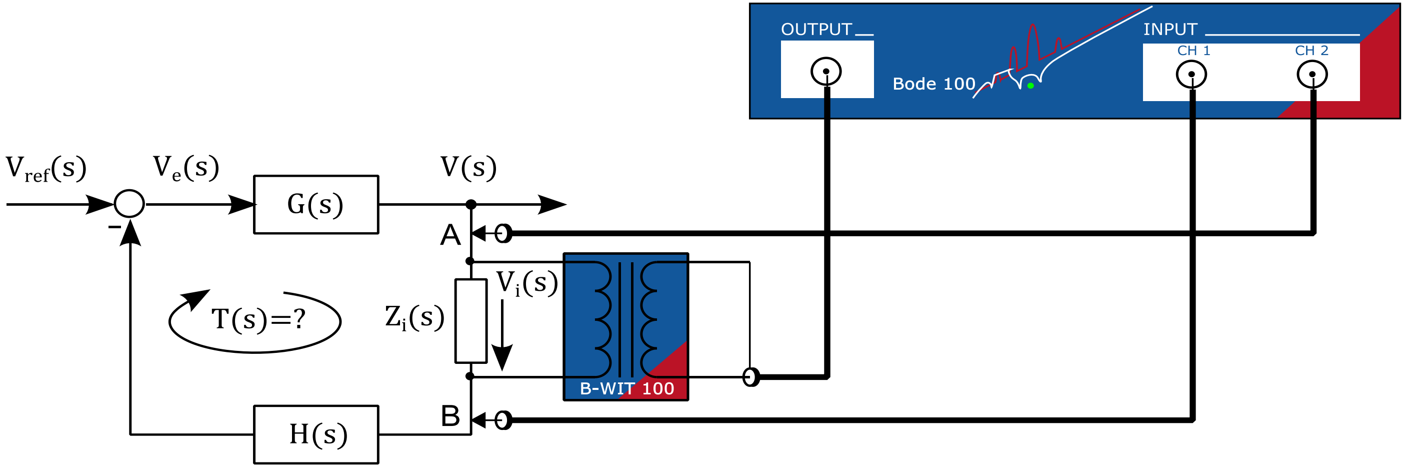
Loop Gain should cross 0dB with slope of -1 (20dB/decade)

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

Measuring Loop Gain (Voltage Injection)

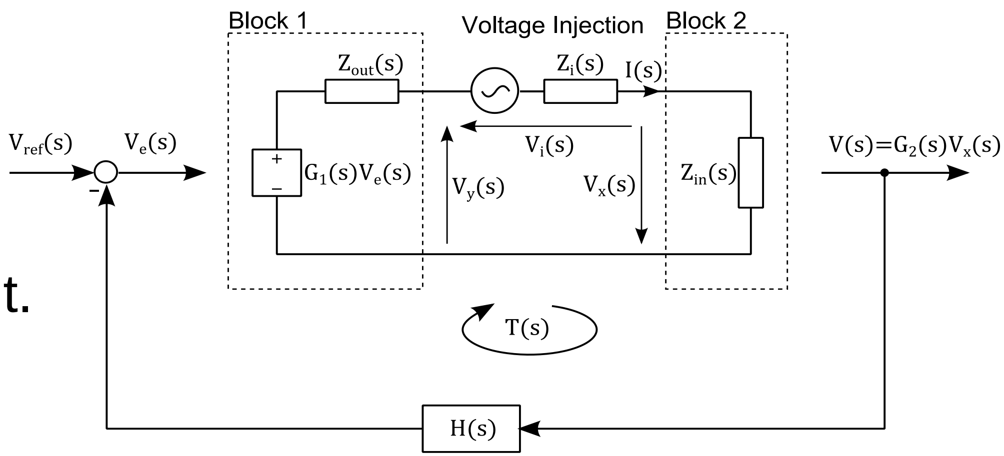
Loop gain is measured by "breaking" the loop at the injection point and inserting a "small" injection resistor (e.g. 10 Ω).

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



The Injection Point (Voltage Injection)

We assumed that signal information flow is unique and only in form of voltages. However, at every connection point there is voltage and current.



Bode 100 measures $T_v(s)$

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

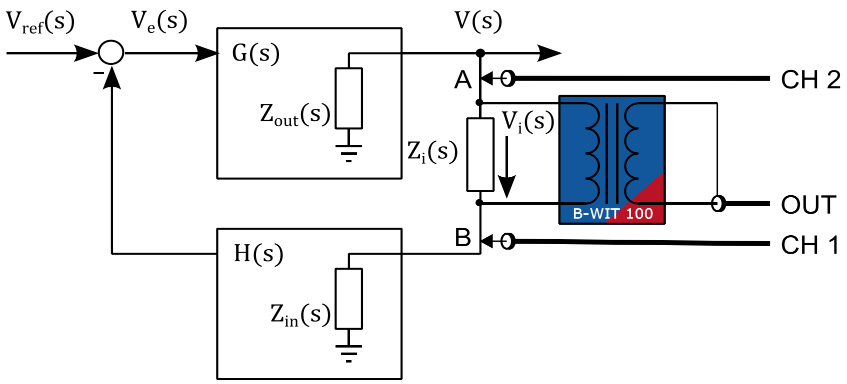
≈ 1 for $|Z_{in}(s)| \gg |Z_{out}(s)|$

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

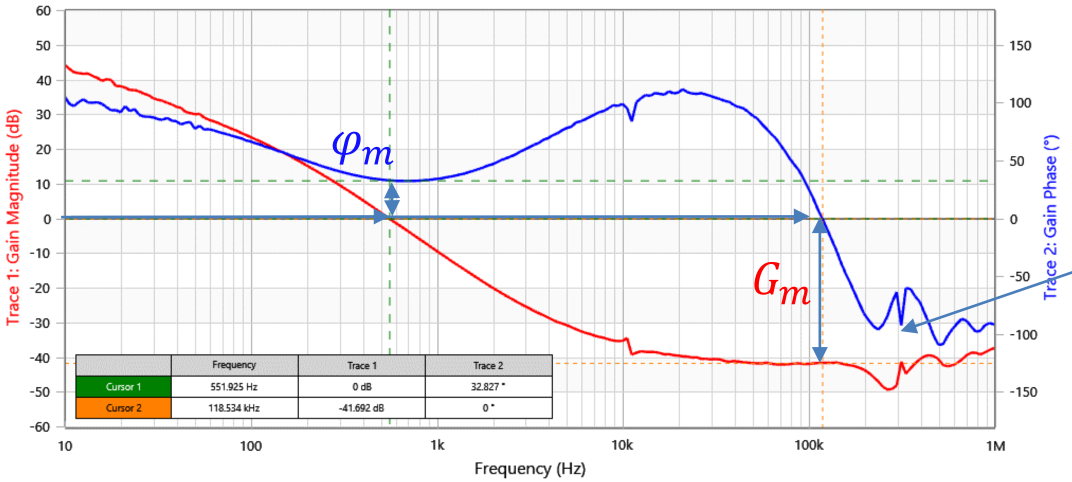
No parallel signal path bypassing the injection resistor!

Measuring Phase Margin and Gain Margin

Note: Only **once** per **switching cycle** a **new duty** cycle value is created.

→ 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



$\varphi_m = 32\,°$

$G_m = 41$ dB

Switching Frequency

$f_s = 315$ kHz

Reading Phase Margin from Measurement

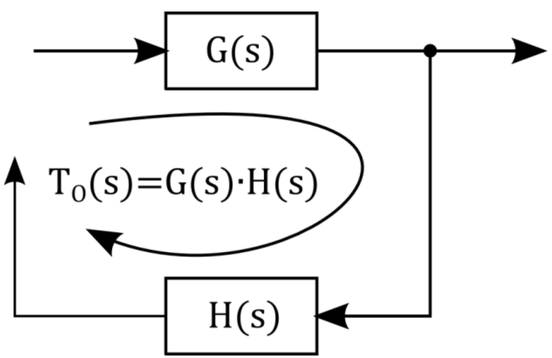
Phase Margin is read directly from the measurement!

φ_m is the distance to 0° and NOT to -180°

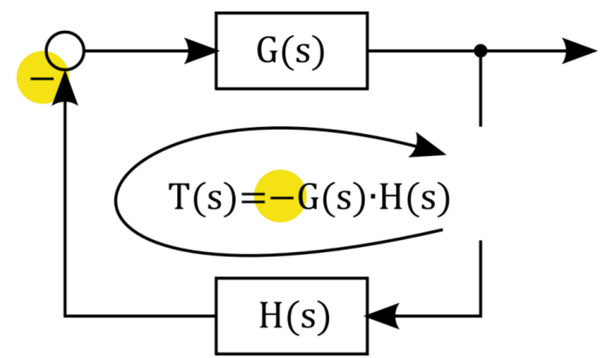
Reason: We measure in the closed loop system → our signal will run through the inverting error amp and get an additional 180° phase shift.

→ The instability point is at +1!

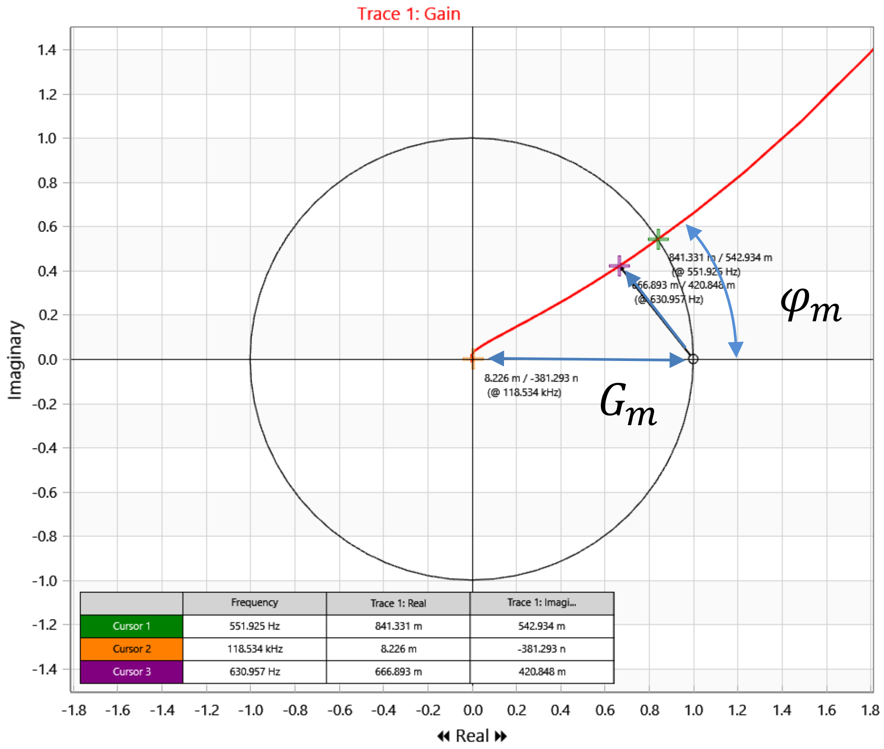
Theoretical open loop gain $T_o(s)$



Measured loop gain $T_v(s)$



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

$\varphi_m = 32\,°$

$G_m = 41\ \mathrm{dB}$

Vector stability margin = 0.537

Selecting the injection point

- Low voltage systems →
  mostly between output voltage and feedback divider
- For high voltage systems this is inconvenient
  - → Higher power - search for injection point in the signal conditioning chain
  - → No signal conditioning – more difficult injection at high voltage
    Injected signal is small compared to dc voltage
    Probes to measure will divide dc and ac
- Very low voltage systems → check remote sensing and sense-ground! Make sure the Bode 100 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.

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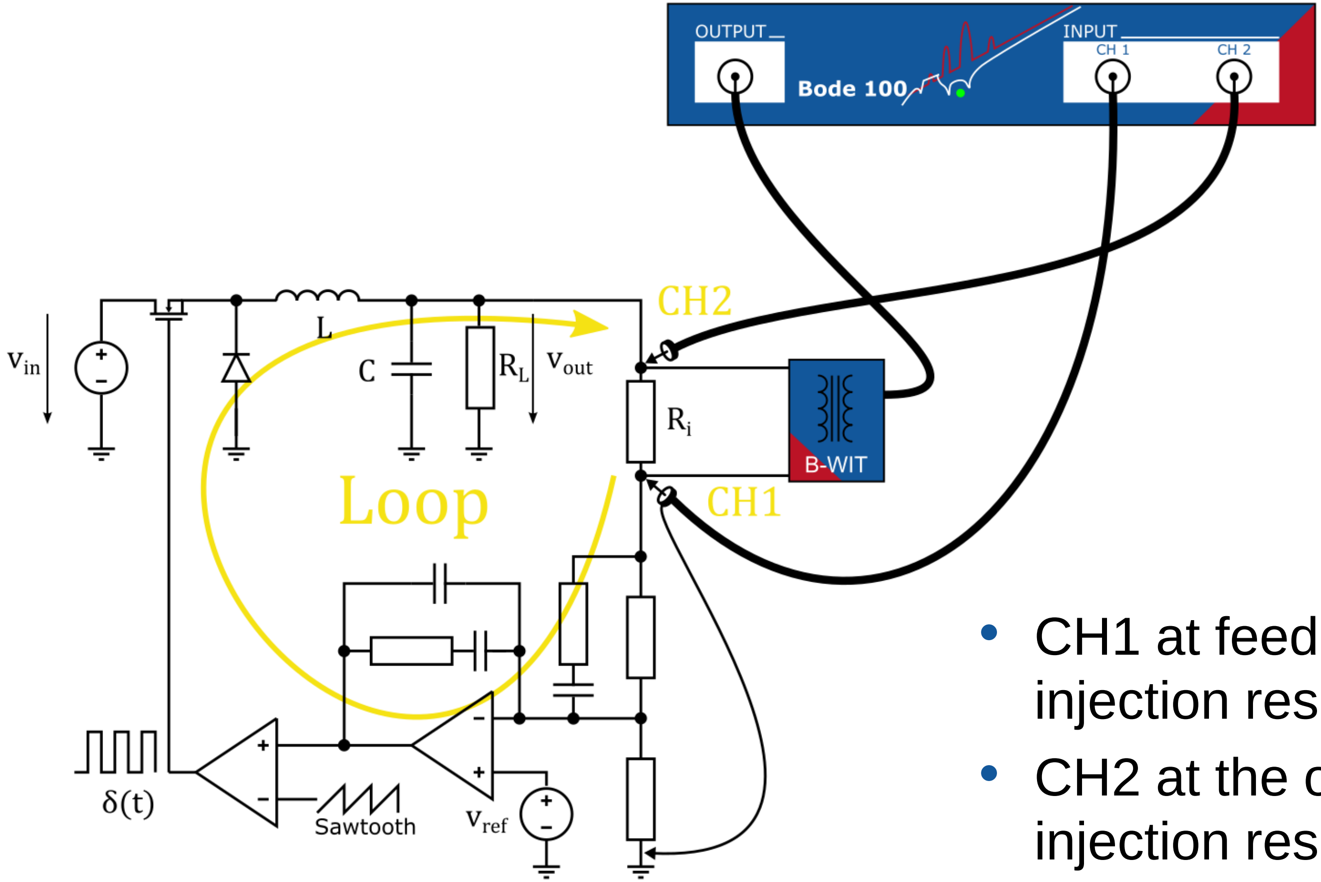
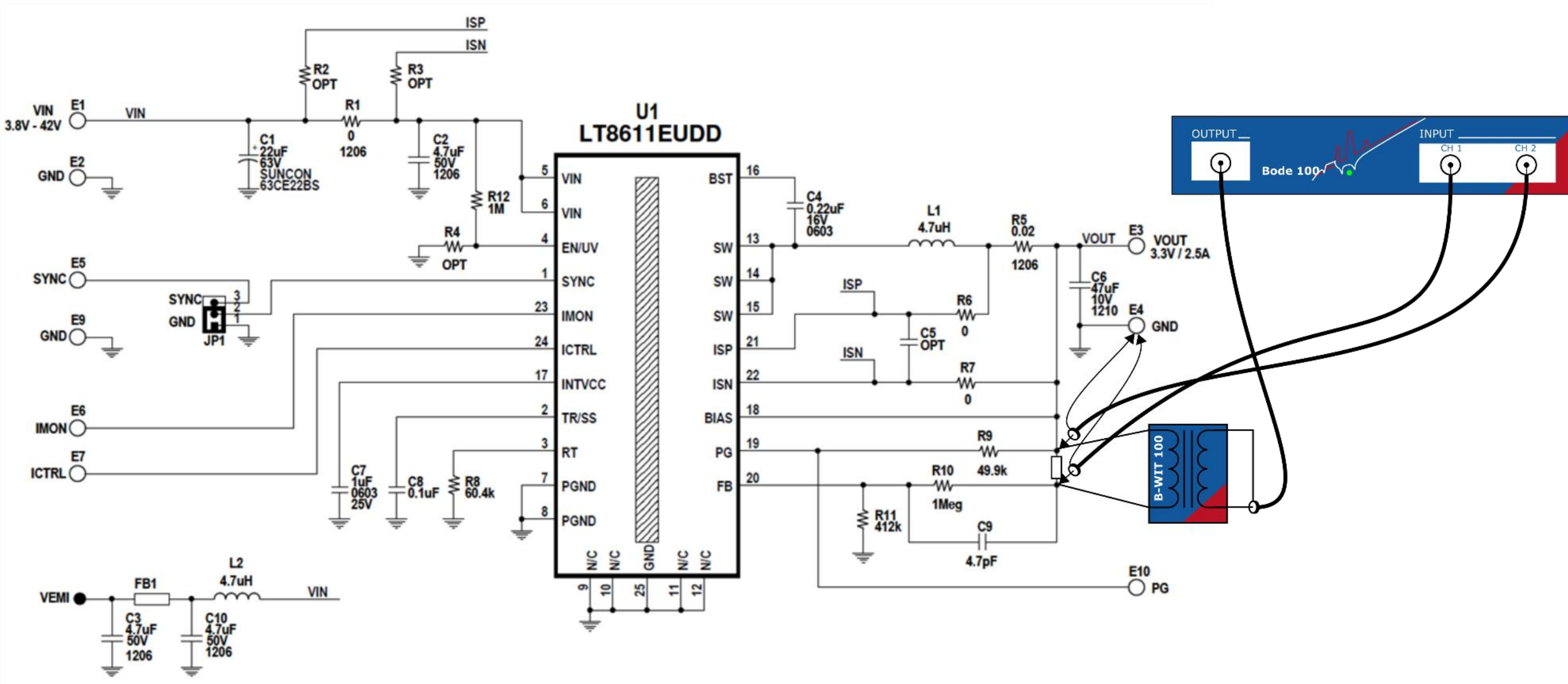
Example: Loop in a Buck



- CH1 at feedback-side of the injection resistor
- CH2 at the output-side of the injection resistor

Example: Buck Demo 1750A



- CH1 at feedback-side of the injection resistor
- CH2 at the output-side of the injection resistor

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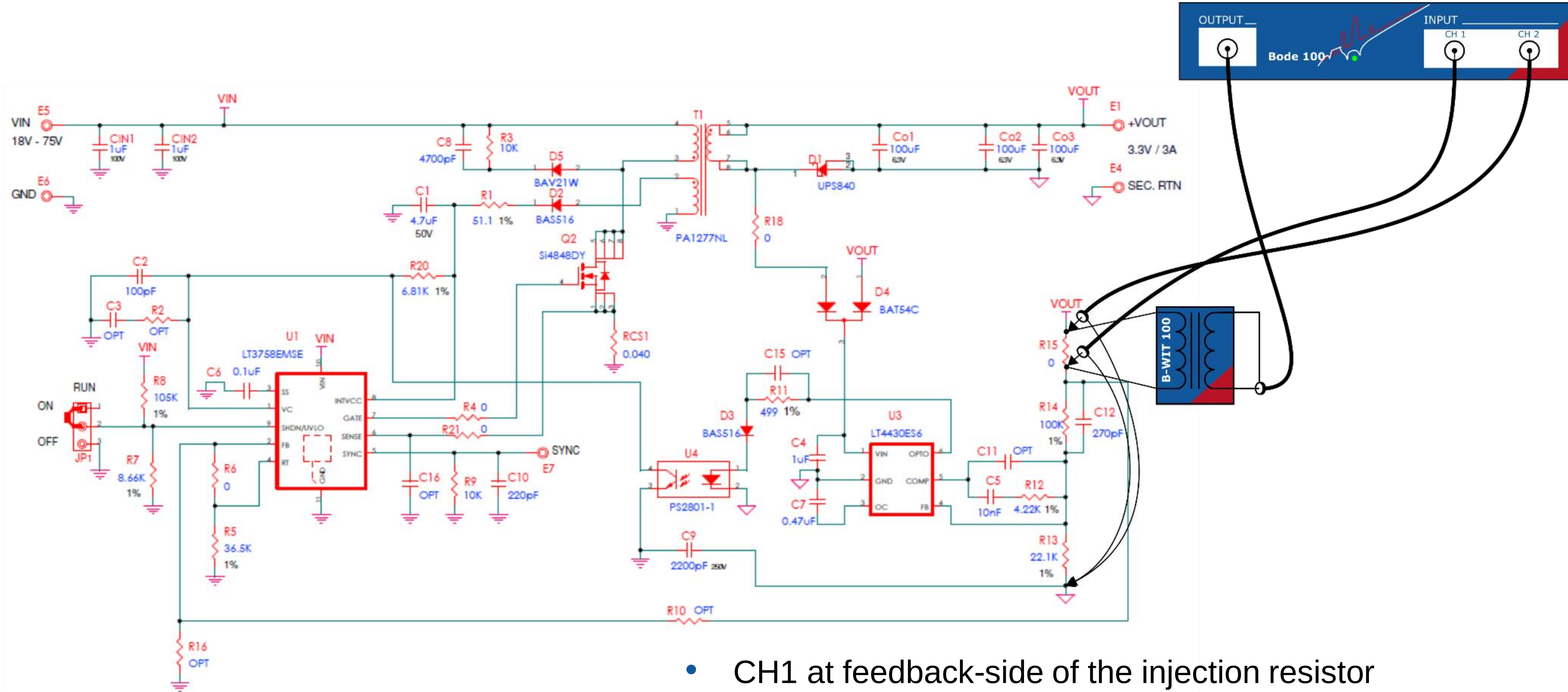
Example: Flyback Demo 1412A



- CH1 at feedback-side of the injection resistor
- CH2 at the output-side of the injection resistor
- Don’t forget about C12!

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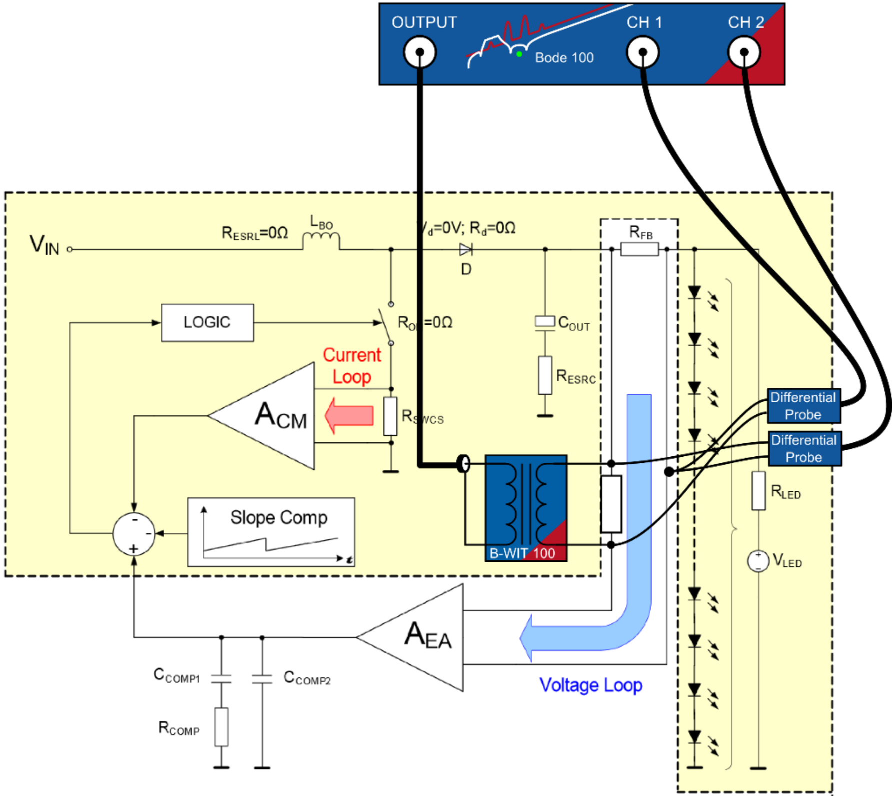
Example: Current Source

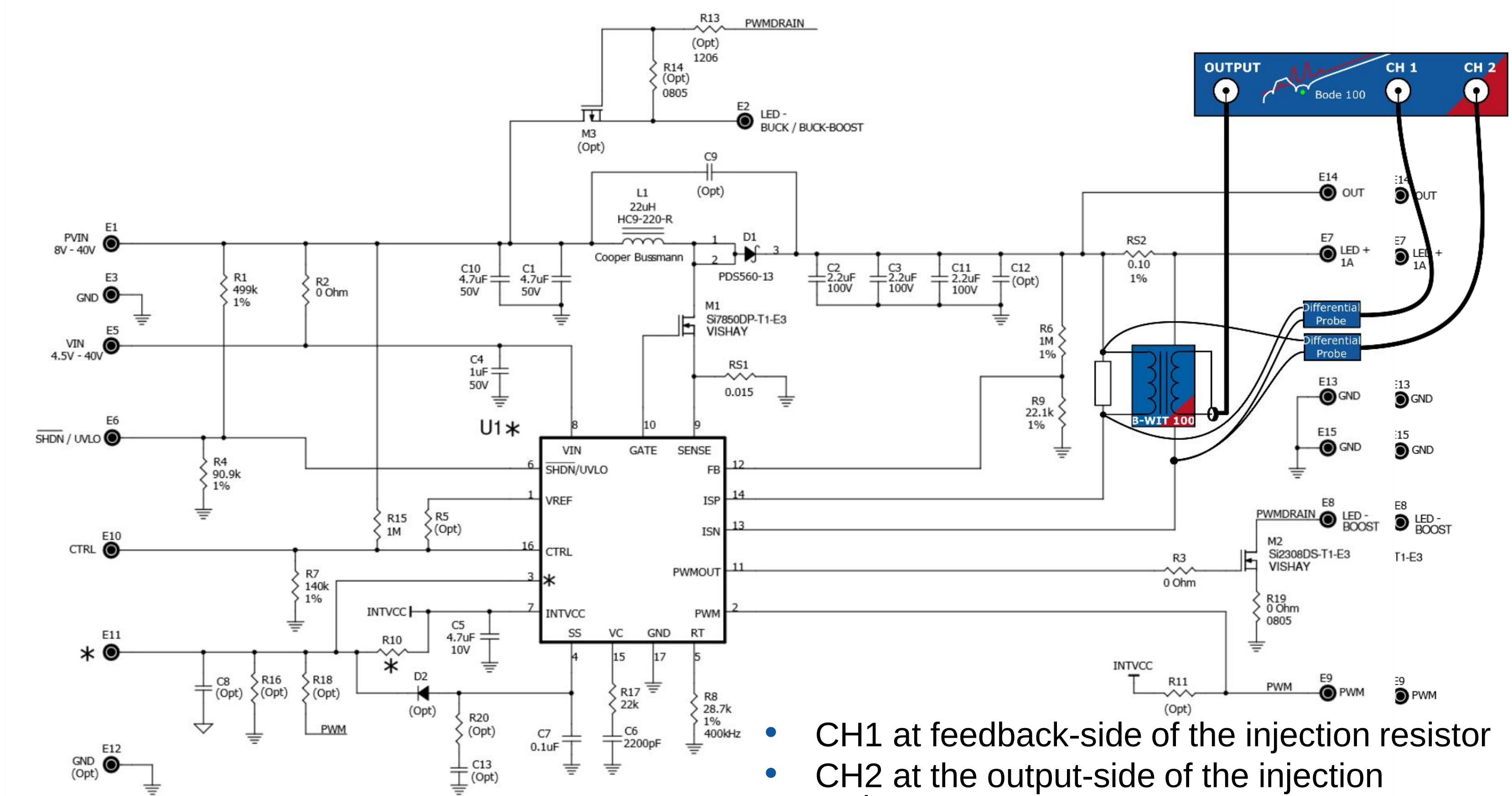
TLD5098 LED Driver board.

Controls the current via measuring voltage at high-side shunt resistor. → Voltage loop.

Injection point satisfying $|Z_{in}(s)| \gg |Z_{out}(s)|$ is given after the current shunt that has low impedance. Impedance towards loop is input of differential amplifier (>>)



Example: LED Driver (Current Source)



- CH1 at feedback-side of the injection resistor
- CH2 at the output-side of the injection resistor
- Probe & controller reference is ISN!

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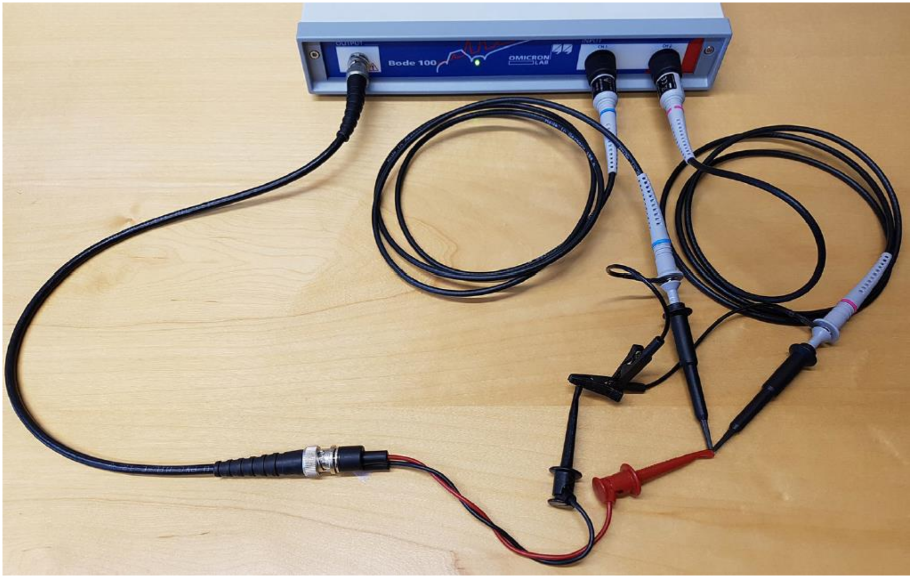
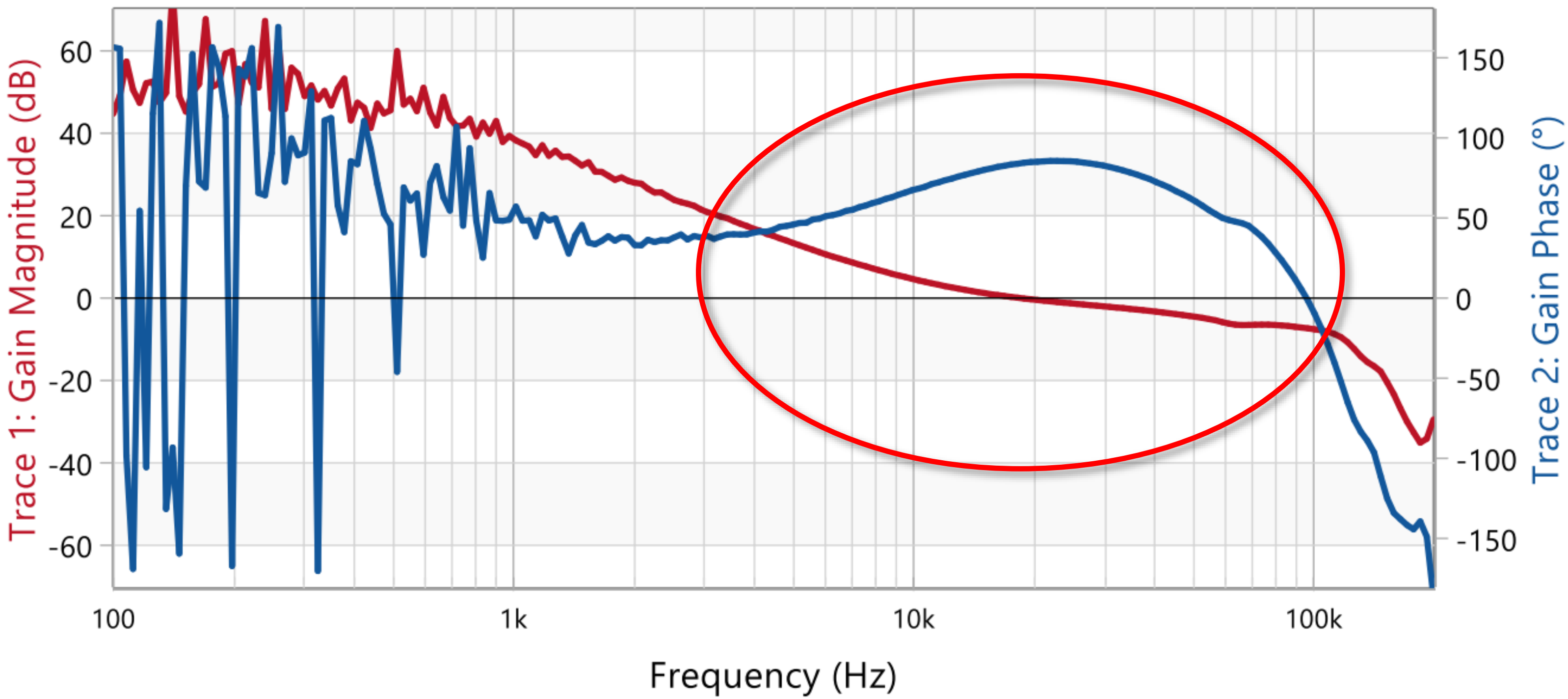
Is Calibration Necessary?

- 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°

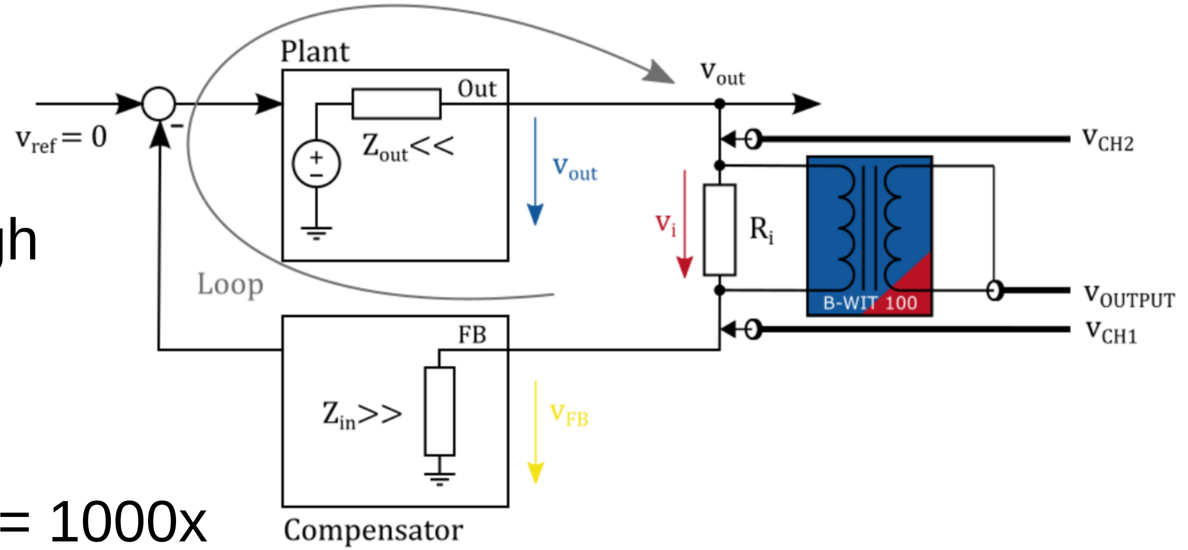
Noise at low frequency...



- Most important region is around the crossover frequency
- Noise at low frequency can be improved

Why so much noise at low frequency?

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



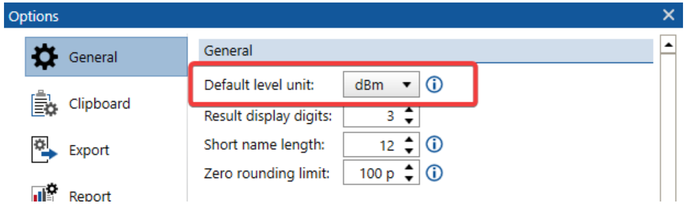
Example: Gain = 60dB = 1000x

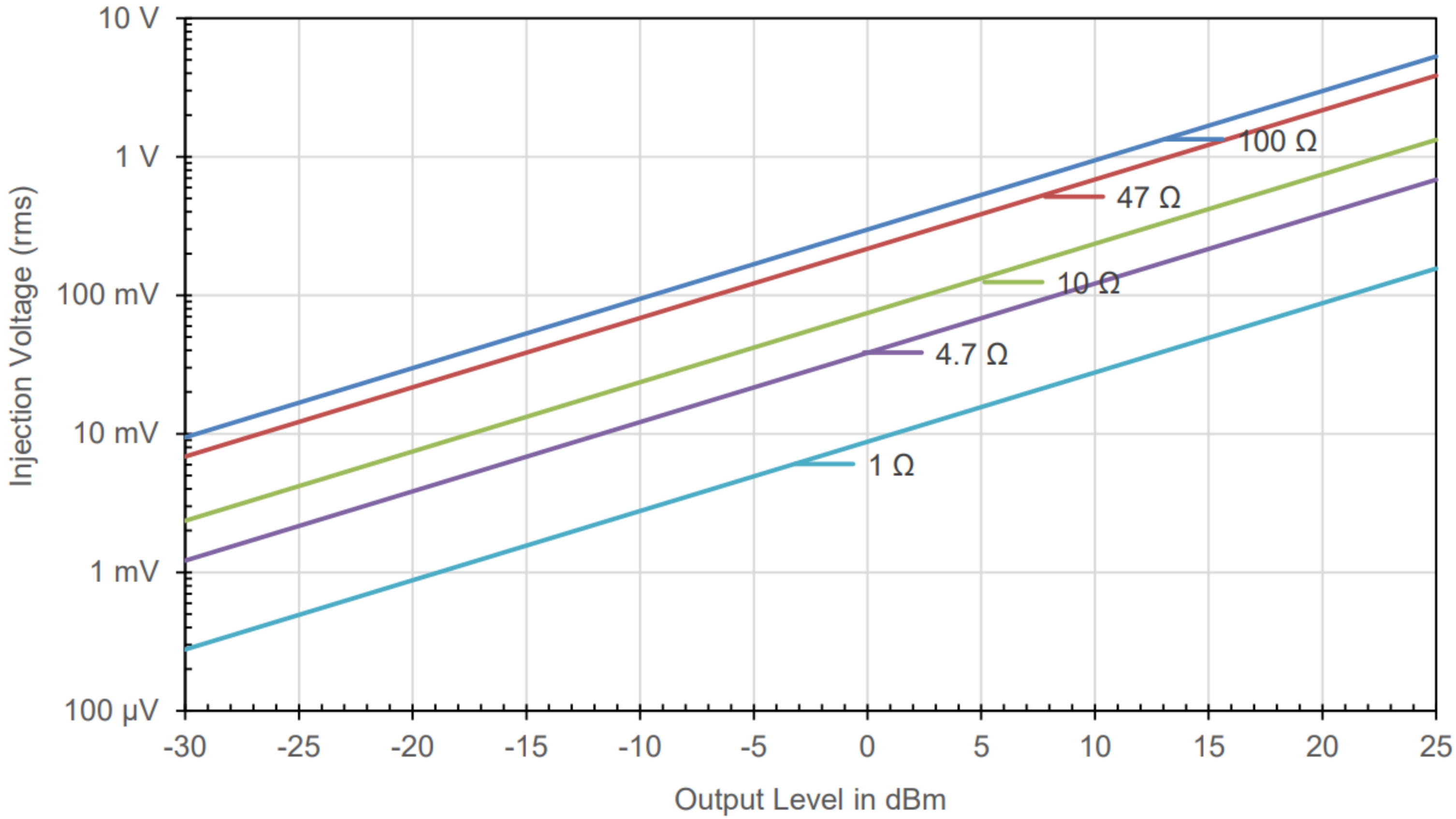
Injection voltage = 30 mV → CH2 needs to measure 30µV

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

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

dBm or V ???


Options
General
Clipboard
Export
Report
General
Default level unit:
dBm
Result display digits:
3
Short name length:
12
Zero rounding limit:
100 p

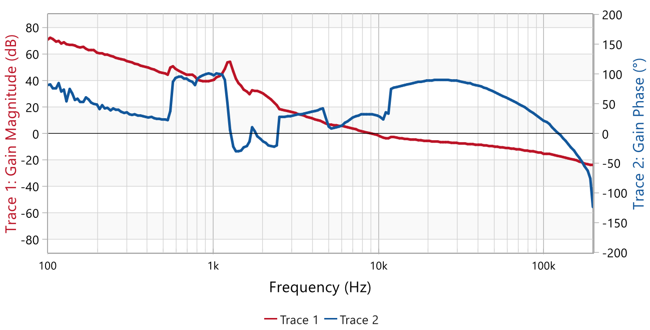

10 V
1 V
100 mV
10 mV
1 mV
100 µV
Injection Voltage (rms)
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
Output Level in dBm
100 Ω
47 Ω
10 Ω
4.7 Ω
1 Ω

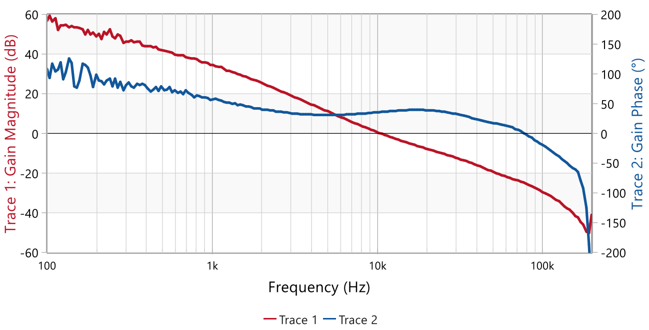
Injection Signal Size

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 signal size!

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!





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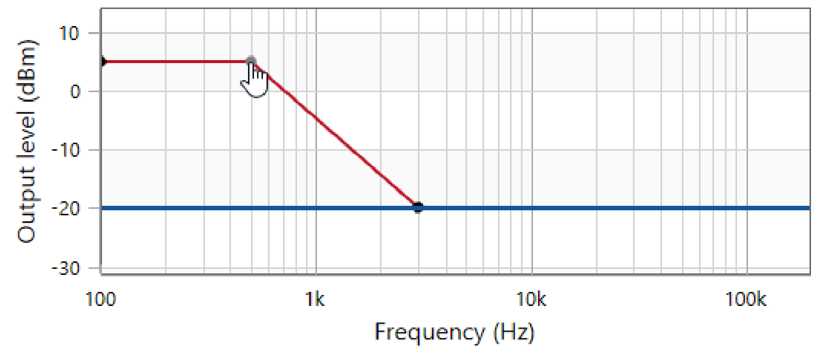
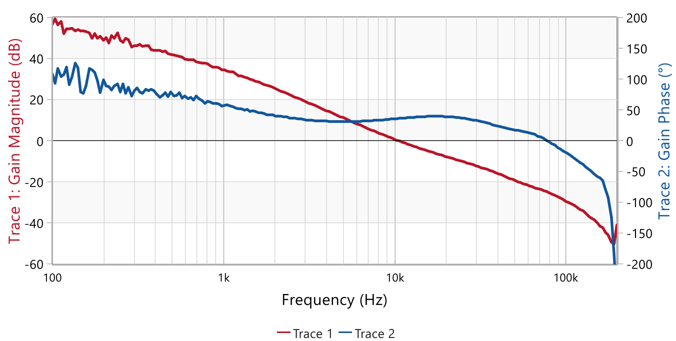
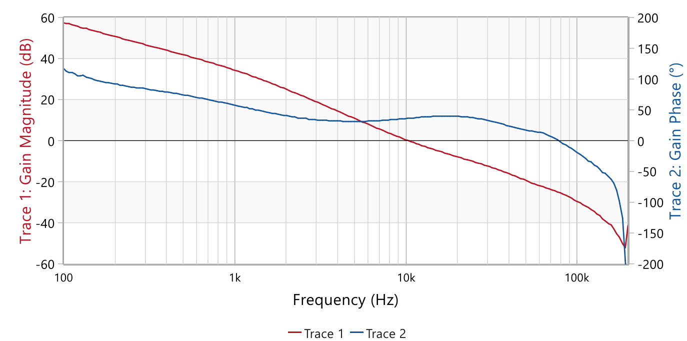
Shaped Level

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

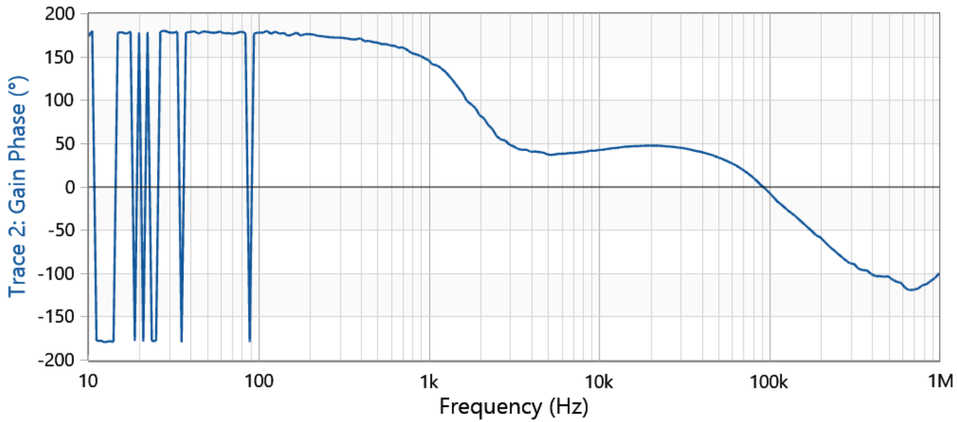


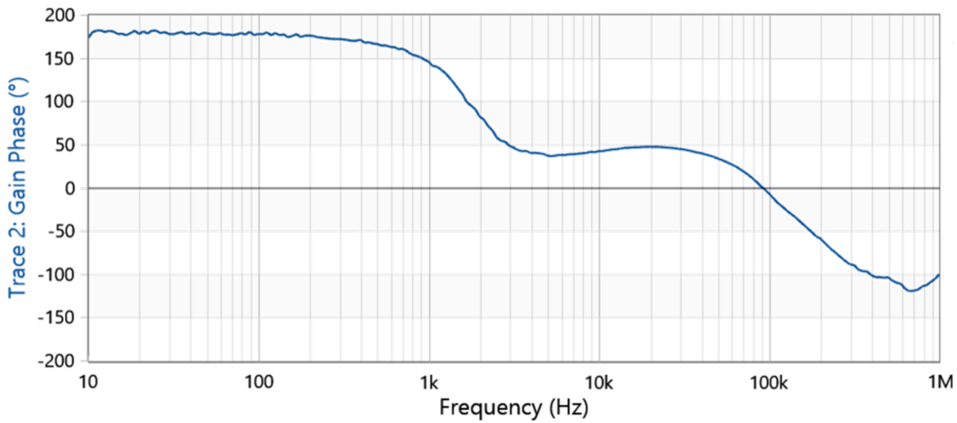




Phase-Wrapping

- -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...





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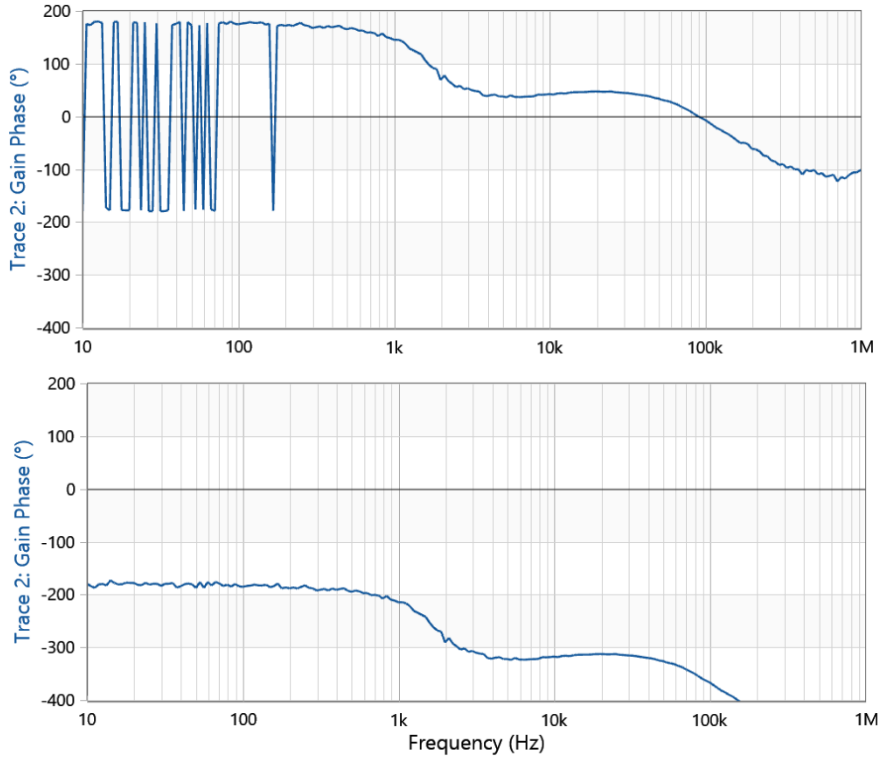
Phase Wrapping Continued

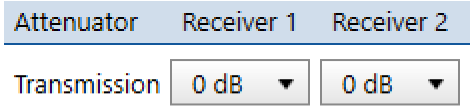
- What if the first value is at -180° and not at +180°?



Solutions:

- Ignore phase wrapping
- Reduce phase noise
- Sweep backwards

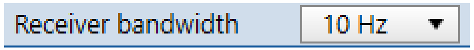
Input Attenuators



- With external 10:1 probes, 0 dB setting is often usable.
- If a Receiver Overload occurs even if it shouldn't arise based on the injected signal size → Check the voltages using a scope! Maybe a lot of switching noise is present.

Attenuator Setting	Full-Scale Voltage
0 dB	100 mVrms
10 dB	320 mVrms
20 dB	1 Vrms
30 dB	3.2 Vrms
40 dB	10 Vrms

Receiver Bandwidth (RBW)



- Lower RBW → Better noise rejection & sensitivity
- Higher RBW → Faster measurement
- Typical starting value for loop measurements on switchers: 10 – 300 Hz

RBW Setting	Typical 201-points sweep time*
10 Hz	55 s
30 Hz	18 s
100 Hz	6 s
300 Hz	3 s

*100 Hz – 1 MHz log sweep
More than 201 points are normally not necessary to resolve a bode-diagram

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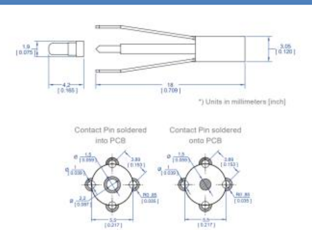
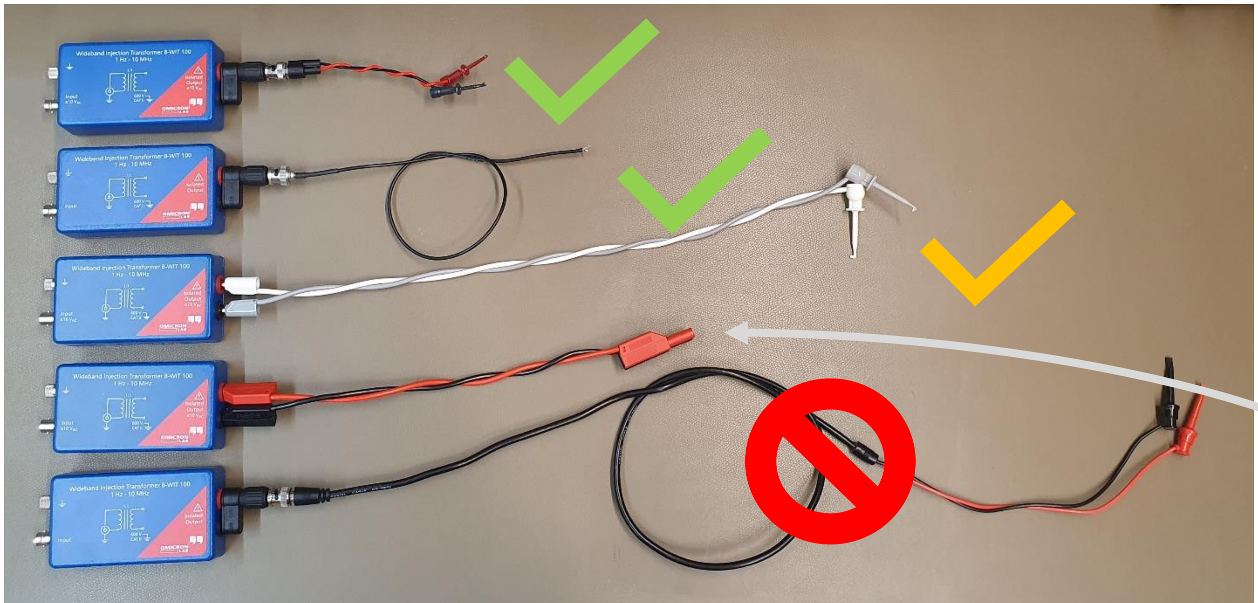
Measuring the Voltage

	Coaxial test connectors or pigtail solder	1:1 Connection BNC cable or probe	10:1 Passive Probe PML 111O	Active Differential Probe (high voltage probe)
				
Price	depends	low	medium	higher
Isolation	no	no	no	yes
Noise	lowest	low	medium	high
Voltage	≤ 50 Vdc	≤ 50 Vdc	≤ 400 Vdc	depends

Don't use 10:1 scope probes with Bode 100!
A standard 10 MΩ 10:1 scope-probe will not divide the dc-signal when used with Bode 100!

Injection Transformer Connection

- Capacitance to GND will increase with longer cables

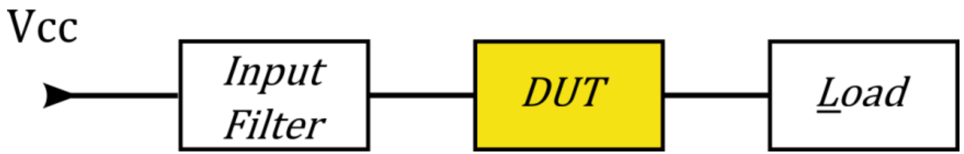


Use appropriate cables, connections and probes when working on hazardous voltages!

Operating Conditions & Stability

- If measurements are still noisy, maybe there is some disturbance on the system
  - Check output voltage and input voltage with an oscilloscope!
    If there are oscillations, excessive ripple or other unexpected disturbances, this can impact the measurement
- Multi-mode systems can have multiple loops. Example are chargers with constant current and constant voltage modes.
  - Measure the loops separately
  - Ensure stable operating condition of the system during the measurement avoiding control mode transitions

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.

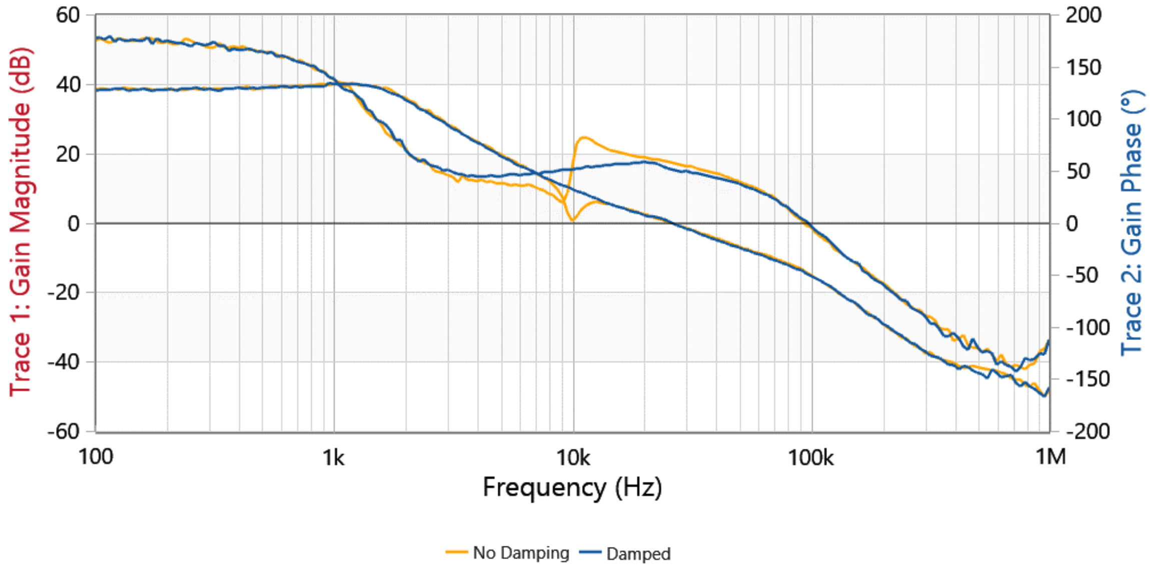
Non-linear Control & Other Stuff

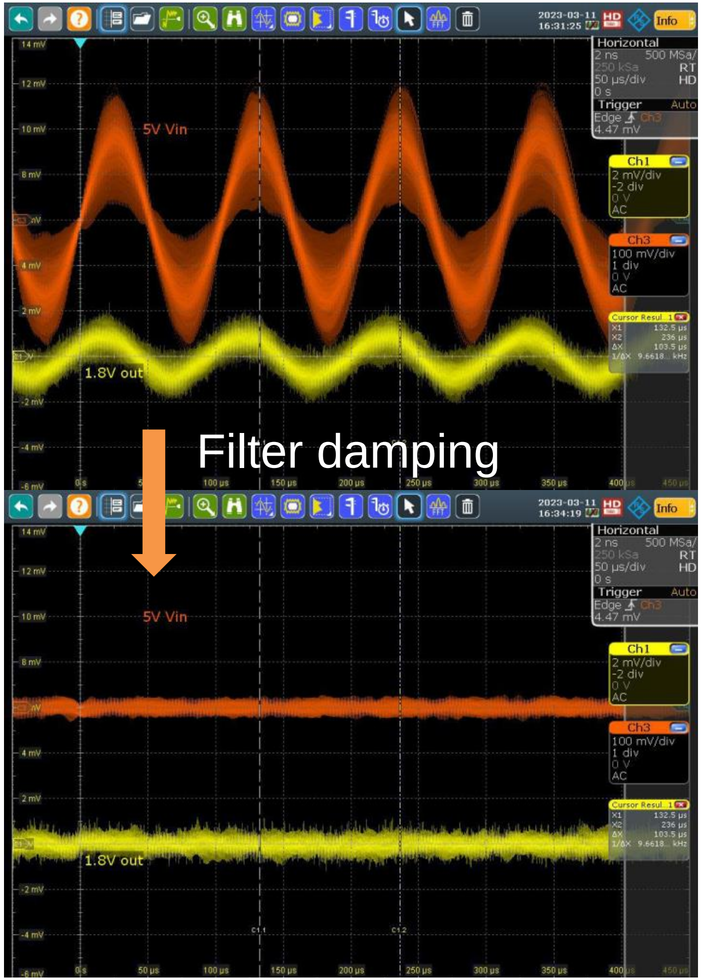
- Are you sure your system is linearly controlled?
- Maybe some pulse-skipping or burst mode is active?
- Hysteretic control is not linear!
- Primary-side regulation?
- Internal compensation and internal feedback?

→ Think about an output impedance measurement!

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

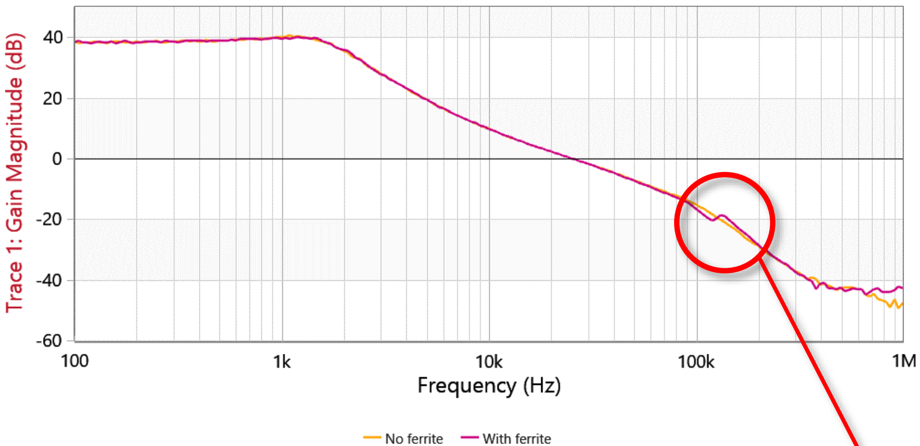
Input Filter Impact on Loop

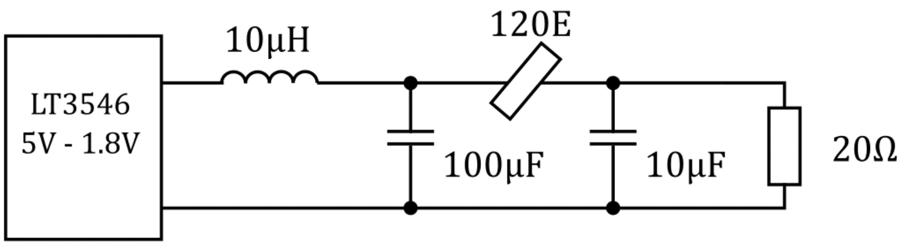




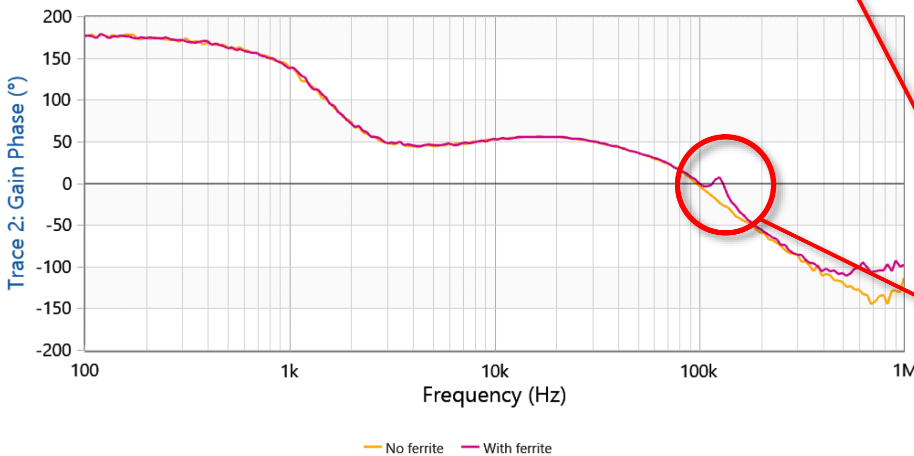
- If input filter is insufficiently damped it can impact the loop
- With proper damping impact on loop is low

Ferrite Bead in the Output (53° PM)



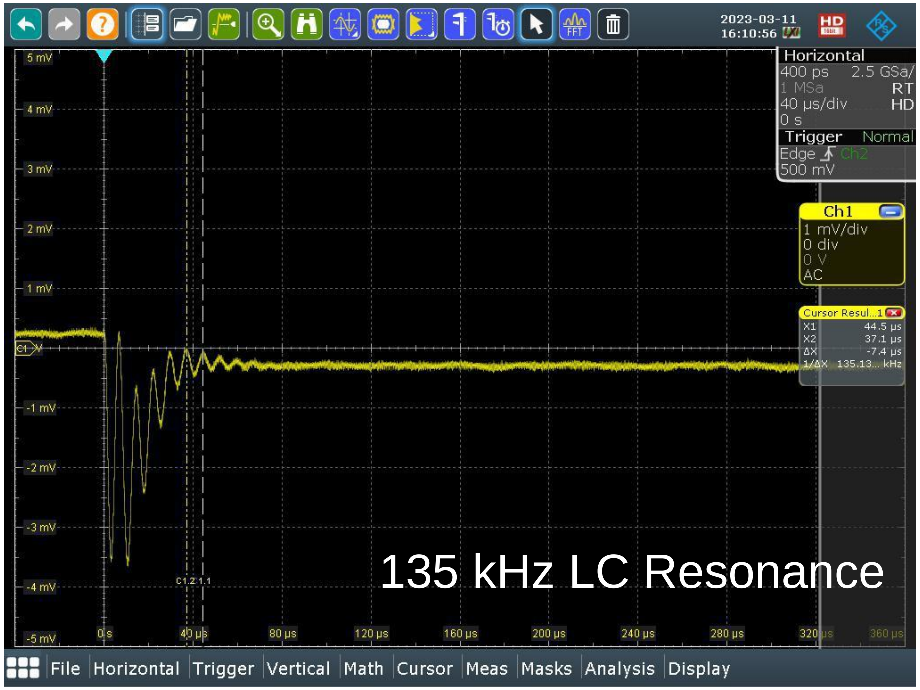


- Ferrite has 120 Ω at 100 MHz
- But 3 Ω XL at 1 MHz ~0.45 µH with
- Only 30mΩ ESR
- $f_r = \frac{1}{2\pi\sqrt{LC}}$

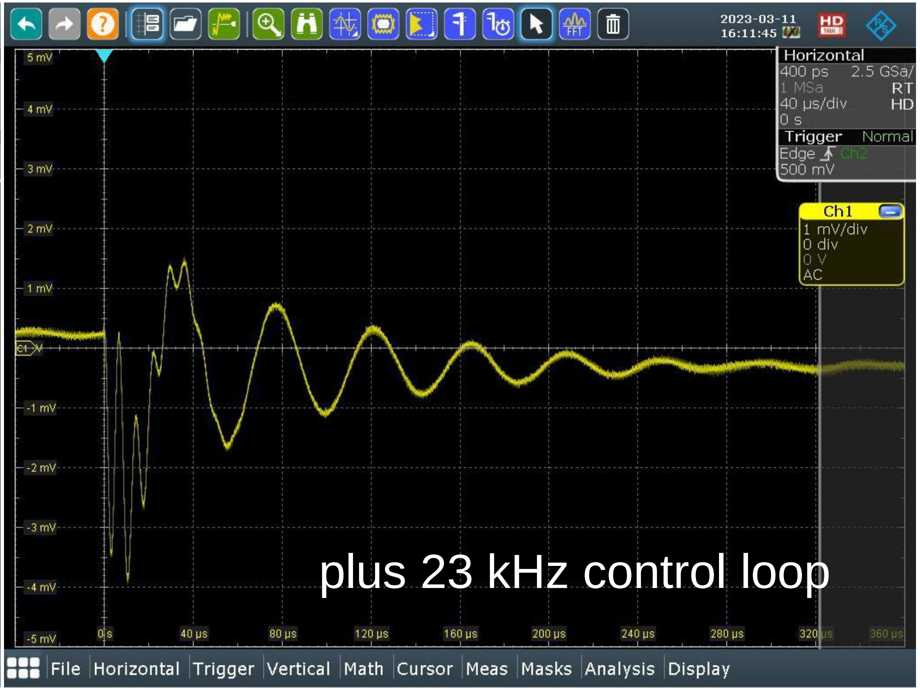


Step Load with Ferrite Bead

53° Phase Margin



11° Phase Margin



50mA load step to the 100mA base load

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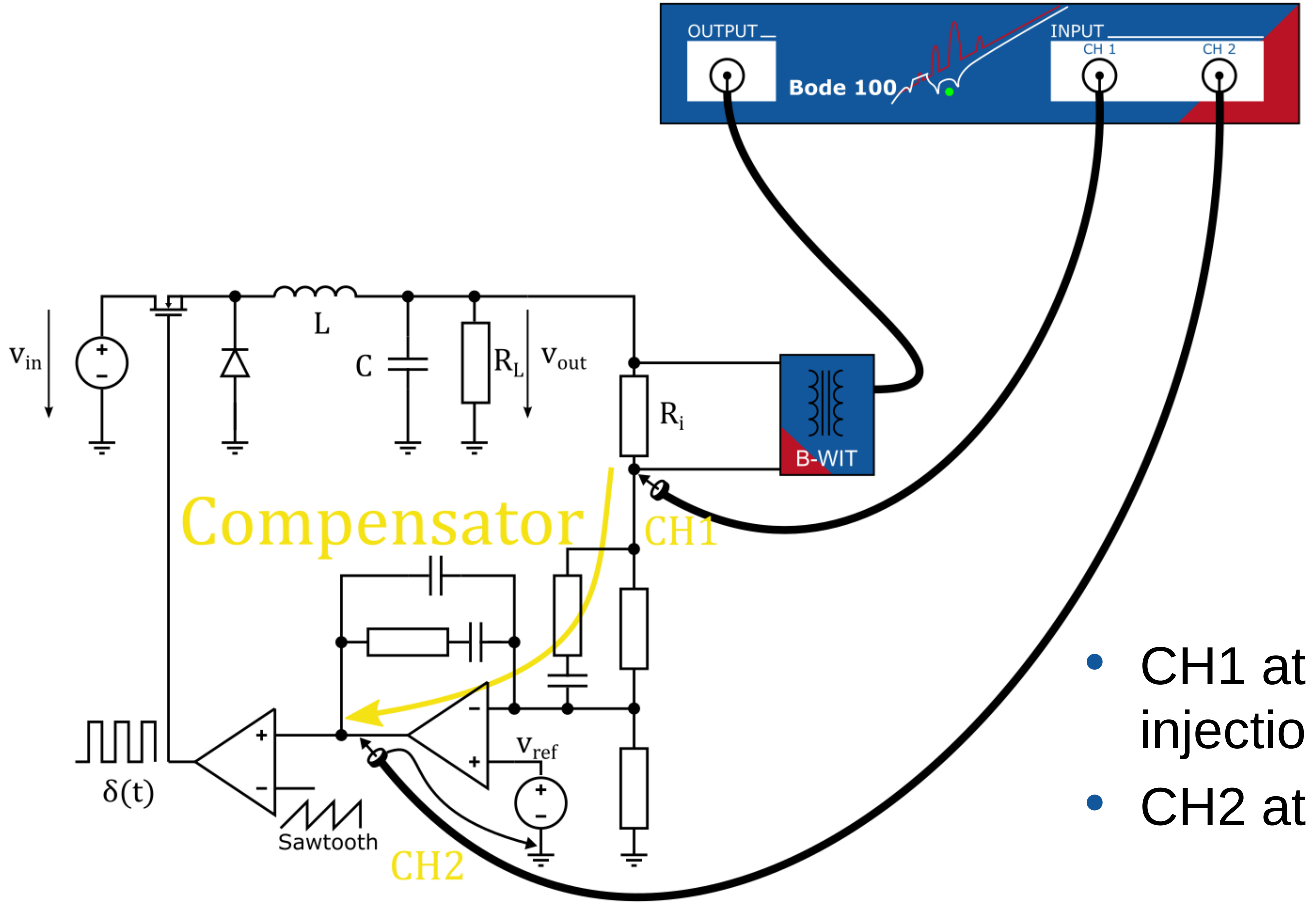
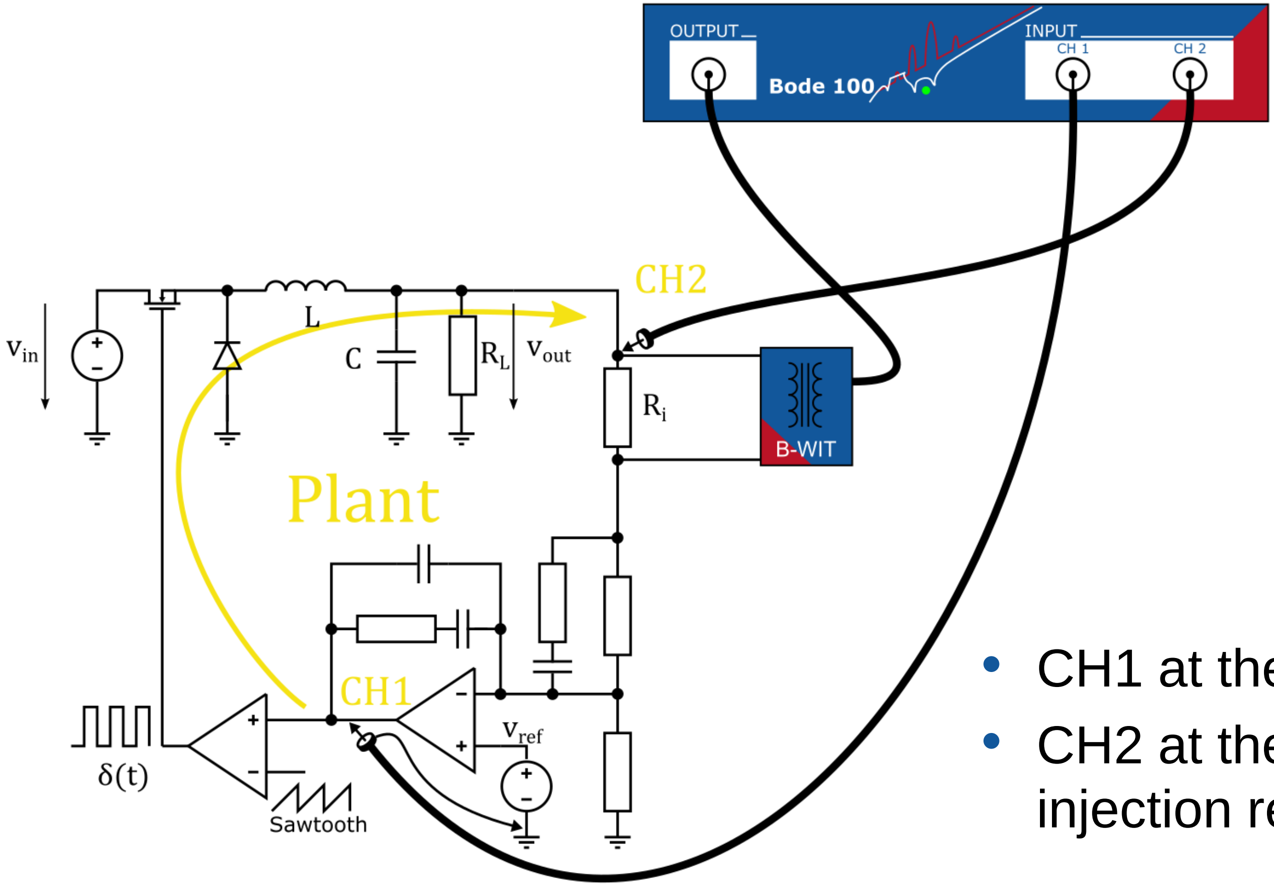
Measure the Compensator in Analog Control



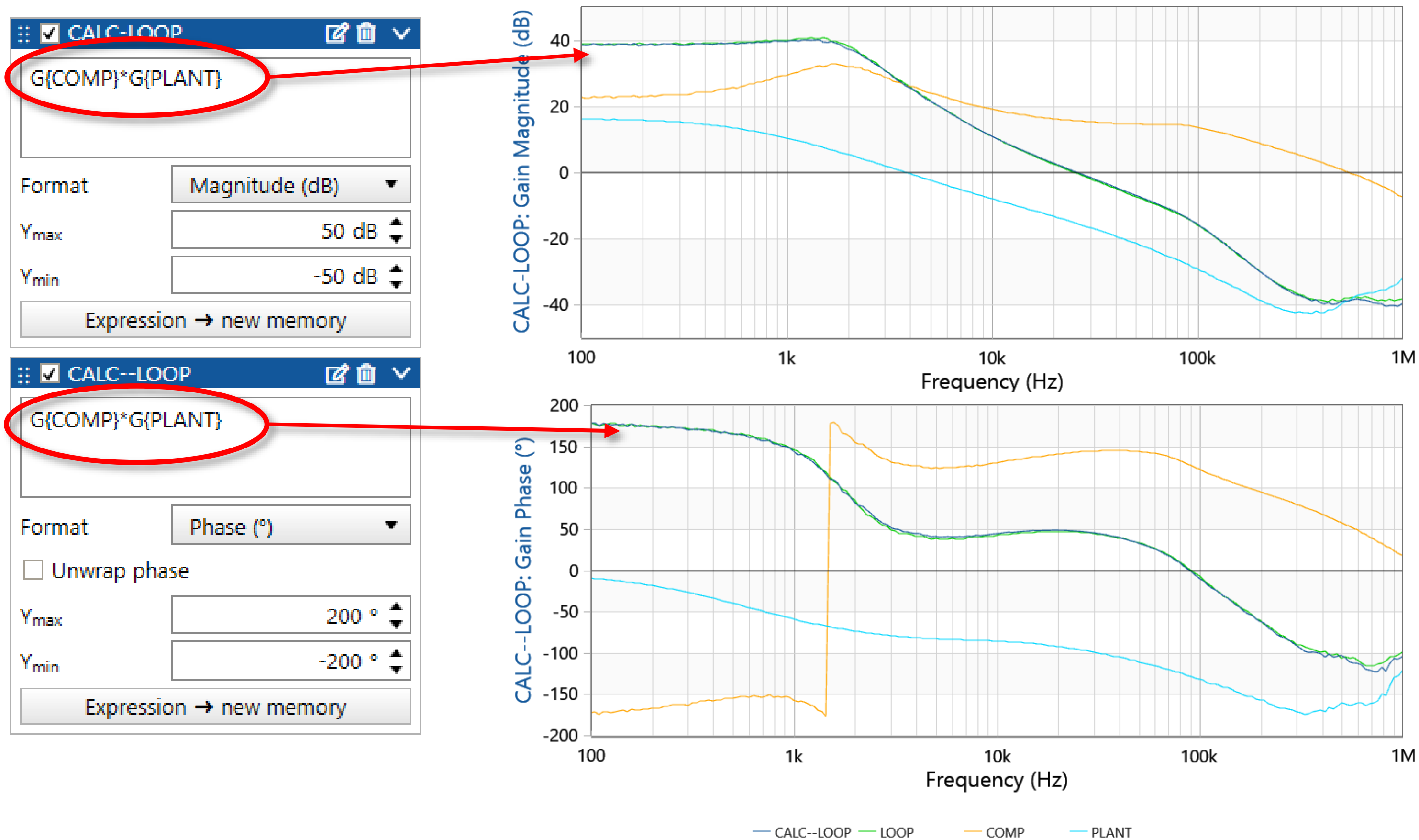
- CH1 at feedback-side of the injection resistor
- CH2 at the COMP-pin

Measure the Plant in Analog Control



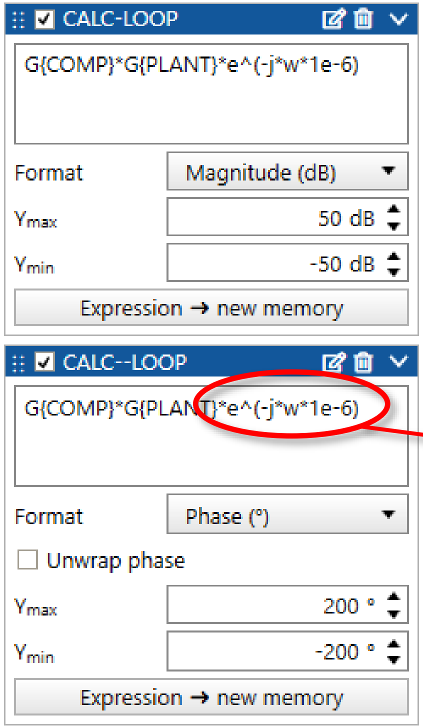
- CH1 at the COMP-pin
- CH2 at the output-side of the injection resistor

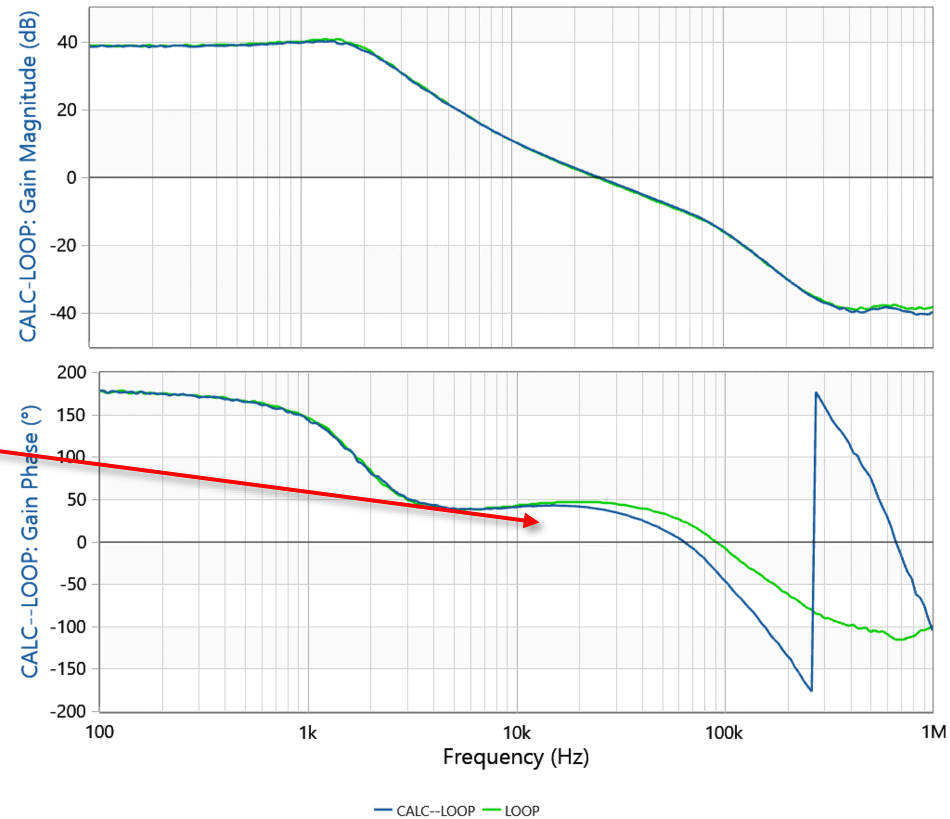
Expression Editor



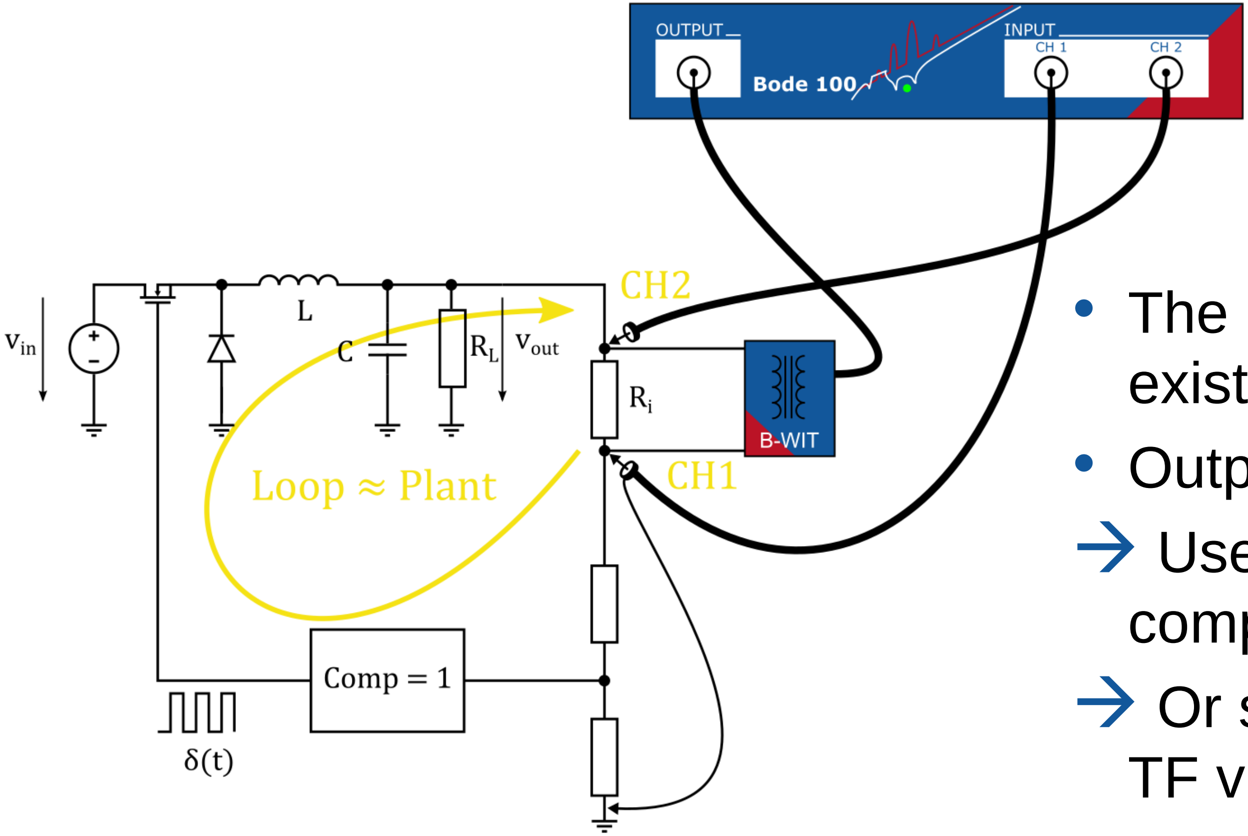
Expression Editor

- Add a 1µs time delay (e.g. digital control) to estimate phase loss:





Measure Plant in Digitally Controlled System



- The COMP-pin is not existing (in Processor)
- Output is duty-cycle signal

→ Use loop-setup and set compensator to Gain = 1

→ Or subtract compensator TF via math

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: florian.haemmerle@omicron-lab.com

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