Loop Gain Measurements in Power Electronics - from POL to PFC

14th Power Analysis & Design Symposium

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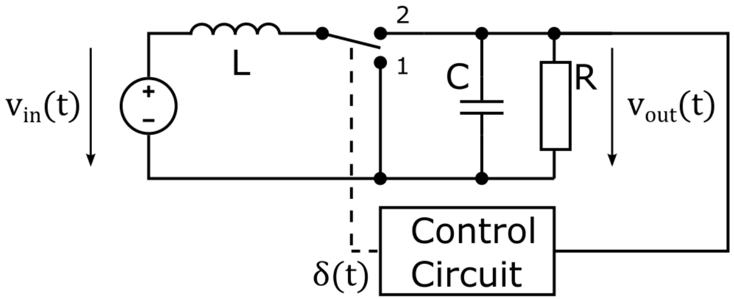
Agenda

- DC/DC Converter Control Loop
- Stability Margins
- Loop Gain Measurement Technique
- Hints for Successful Measurements
- Some Words on Safety
- PFC Example
- Live Example

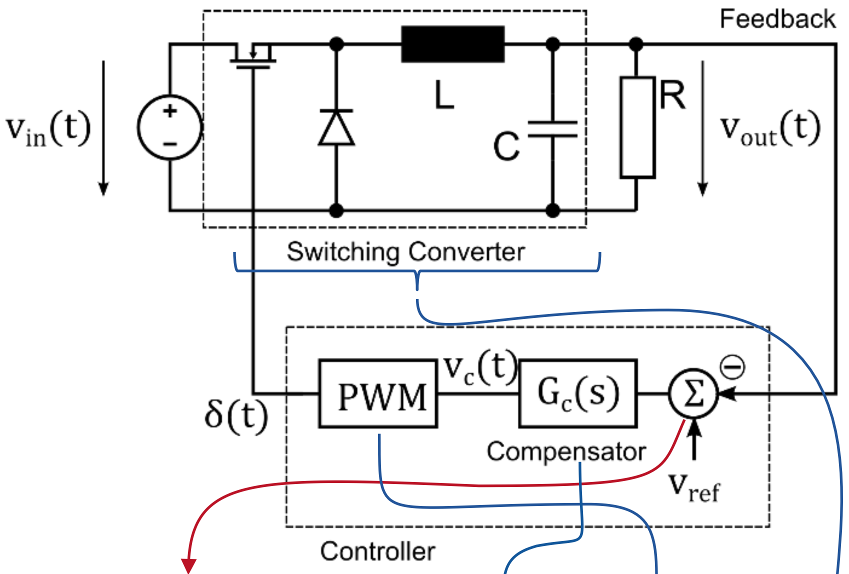
DC/DC Converter – Dynamic System

- 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)



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

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

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

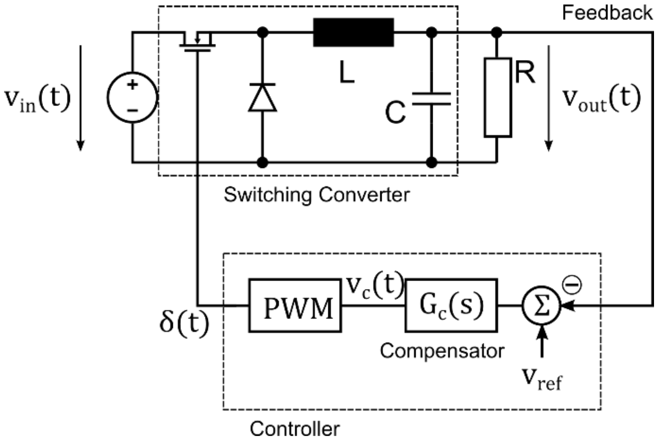
therefore

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

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

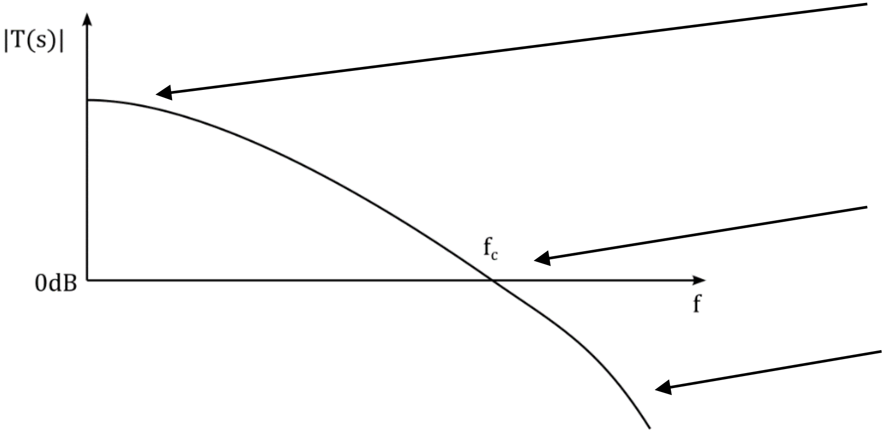
→ Good line ripple rejection up to loop bandwidth

→ 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)

→ Negative feedback will change to positive feedback

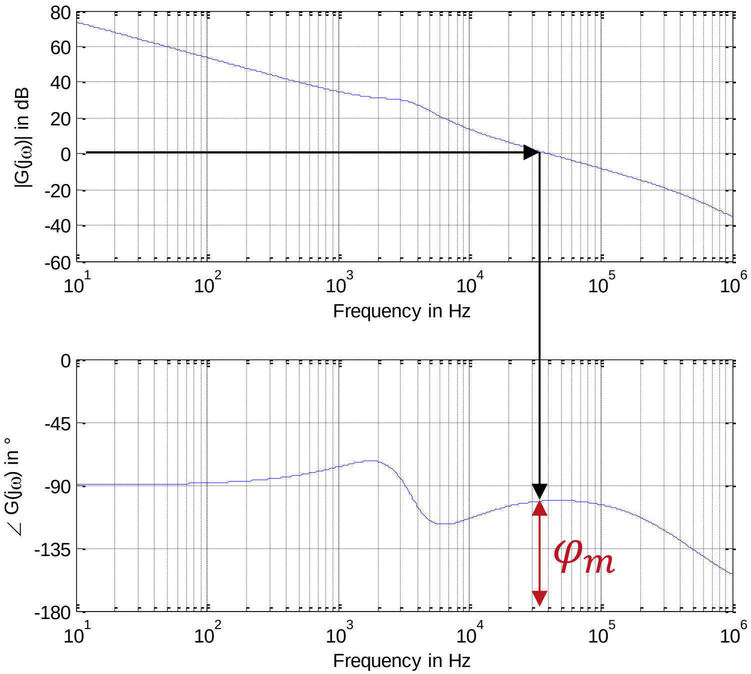
By checking the loop gain $T(s)$ we can check if the closed loop system will be stable or not.

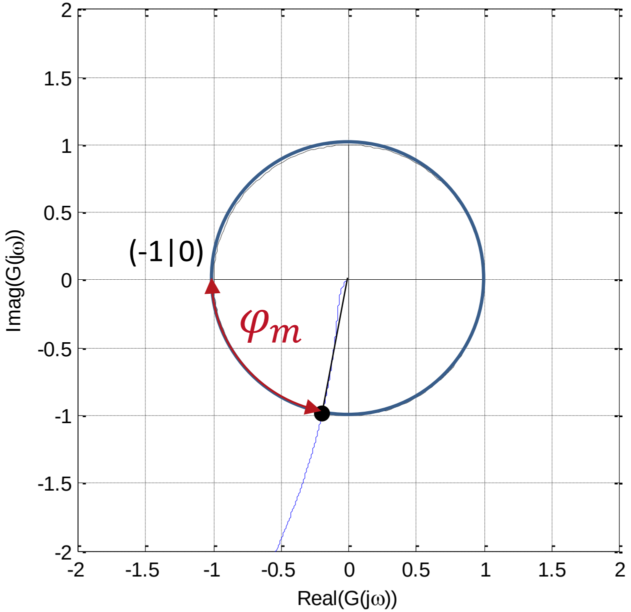
Test: How much distance does $T(s)$ have towards -1

The Phase Margin Test

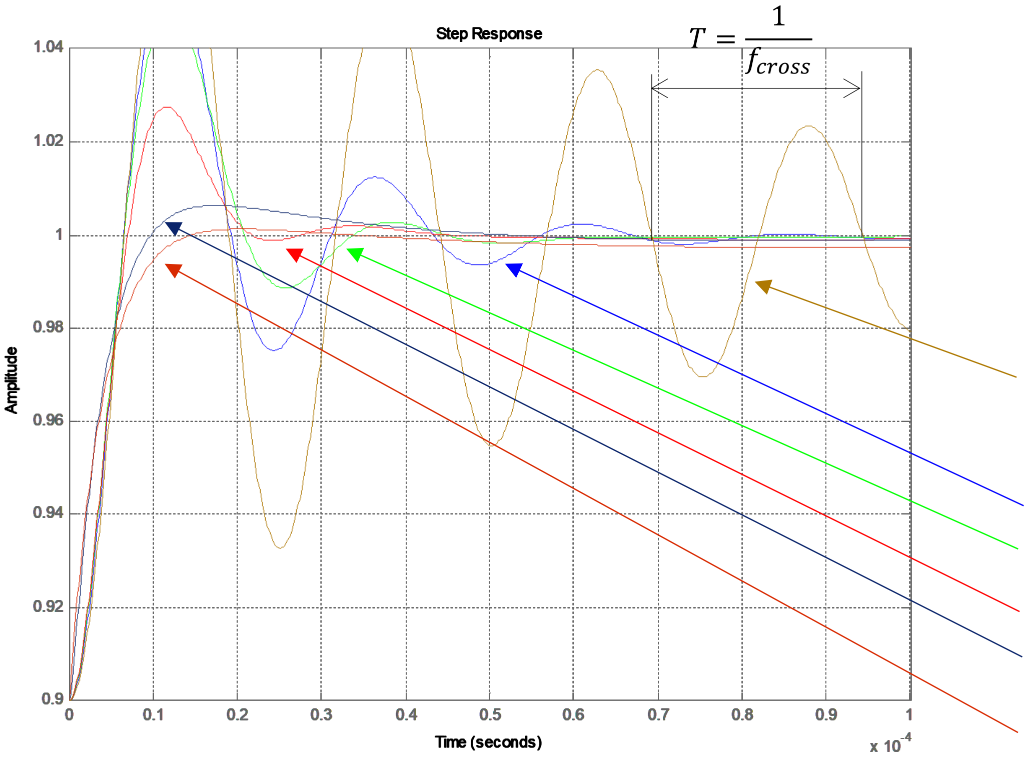
(A special case of the general Nyquist stability criterion)

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

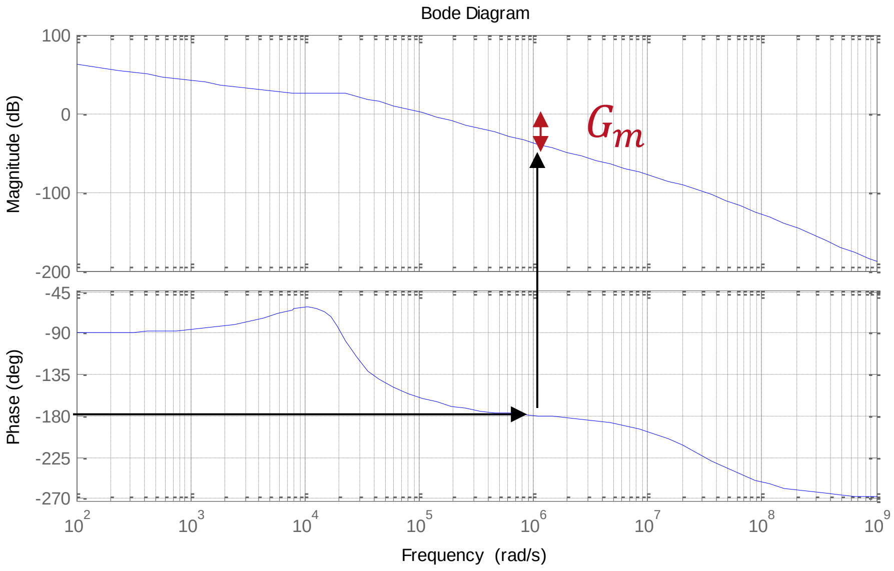
$\varphi_m = 87°$

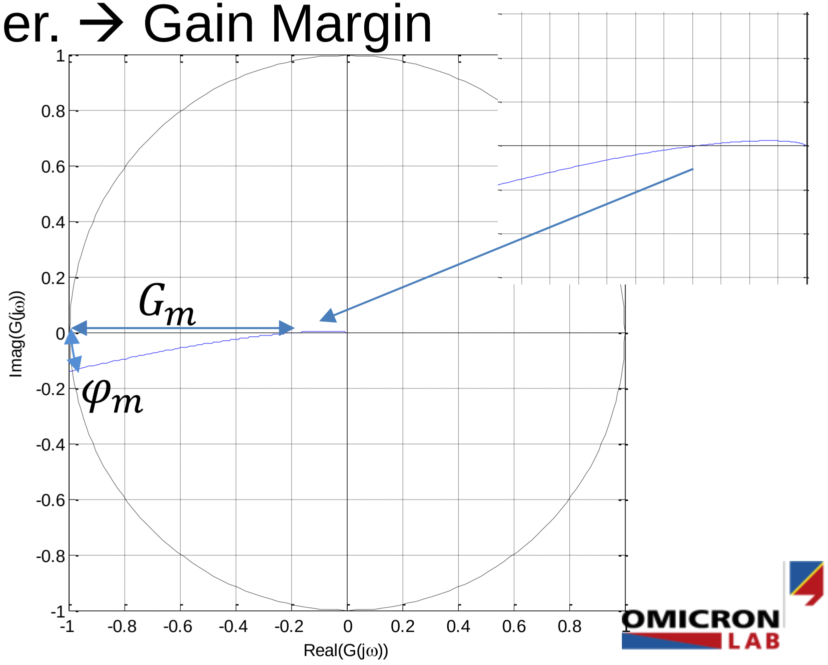
→ **Phase Margin** is a measure of **closed-loop** system **damping at its natural frequency** and a measure of robustness.

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



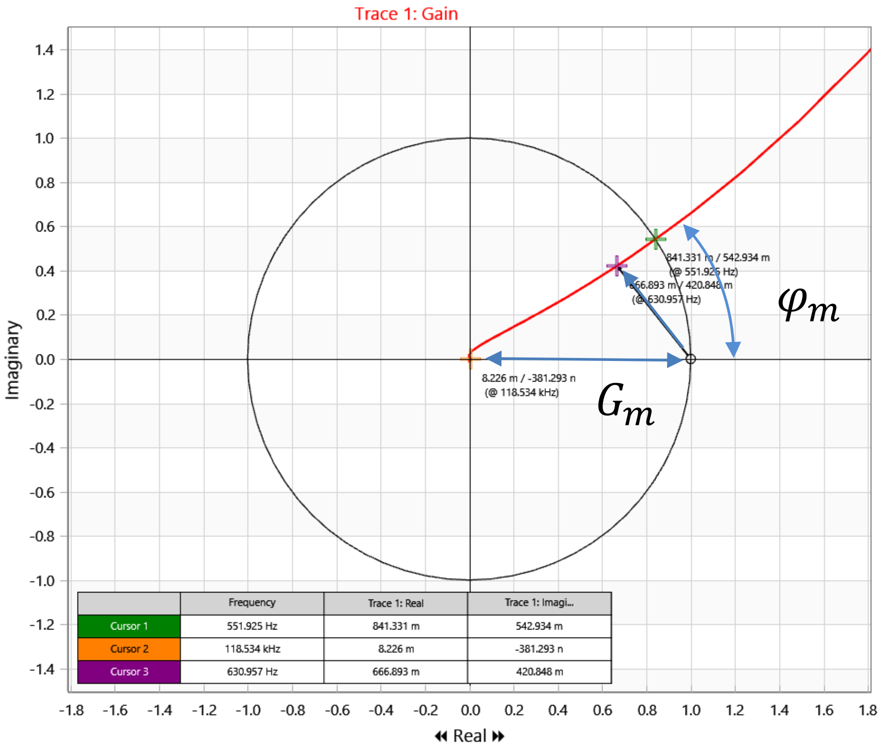


Vector Stability Margin

How copilot imagines an icon for 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

OMICRON LAB

Limits of Loop Gain Measurements

Another great impression from copilot

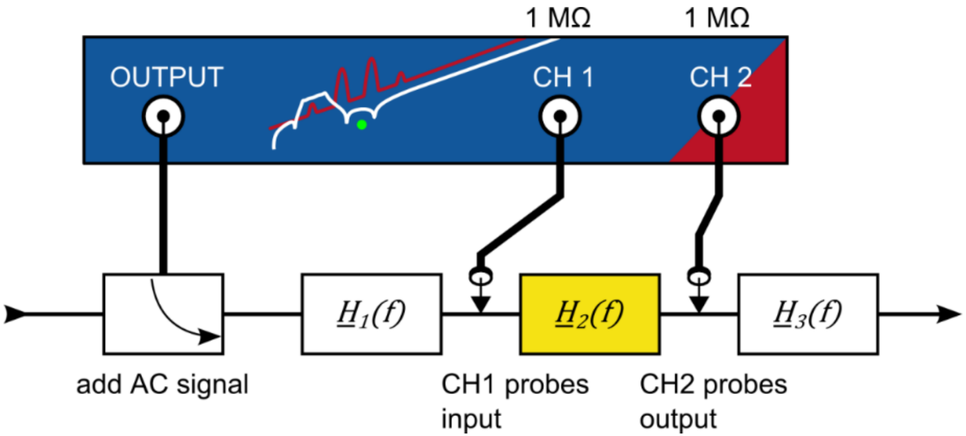
- Not applicable to highly non-linear control like hysteretic control and variations thereof (no compensator) or low-load modes like burst or pulse-skipping.
- Small-signal analysis
  (does not replace large signal transient response).
- Not possible on highly integrated modules (internal feedback).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

→ Think about an output impedance measurement!

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

Measuring Transfer Functions (Gain/Phase)

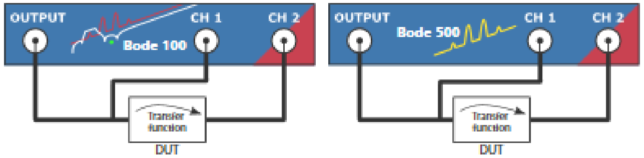
Bode measures the transfer function $\underline{H}_2$(f) from CH1 to CH2



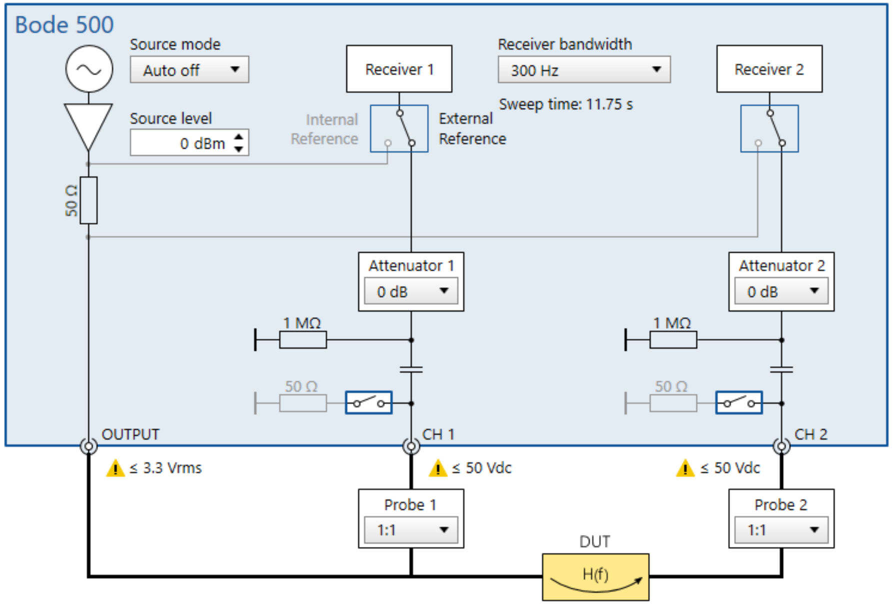
$$\underline{H}_2 = \frac{V_{CH2}(f)}{V_{CH1}(f)}$$

- 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


Bode 500

Source mode: Auto off

Source level: 0 dBm

Receiver bandwidth: 300 Hz

Sweep time: 11.75 s

Attenuator 1: 0 dB

Attenuator 2: 0 dB

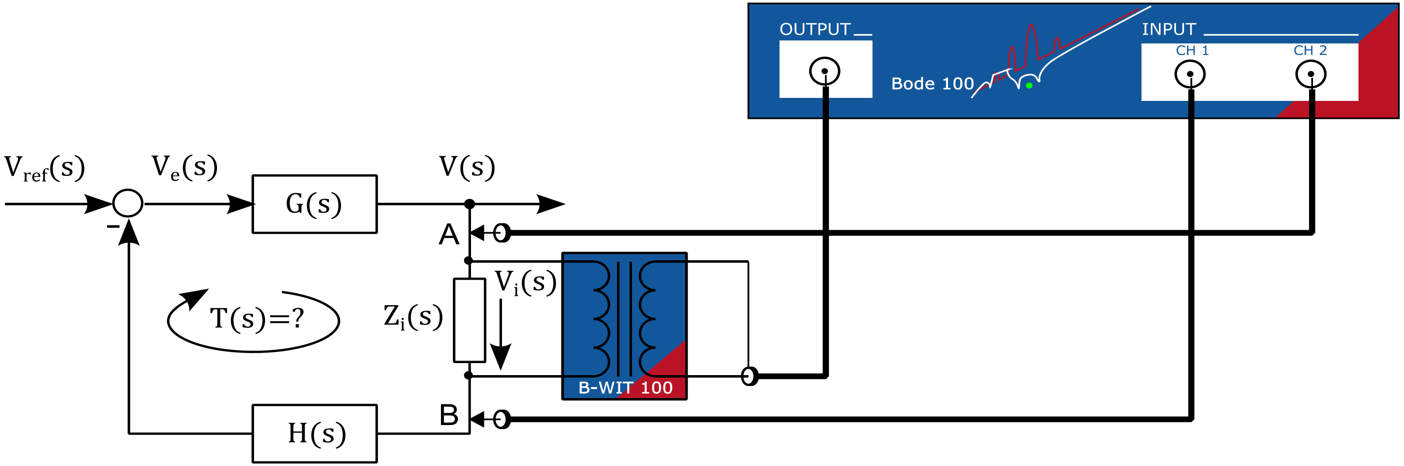
Probe 1: 1:1

Probe 2: 1:1

Measuring Loop Gain (Voltage Injection [2])

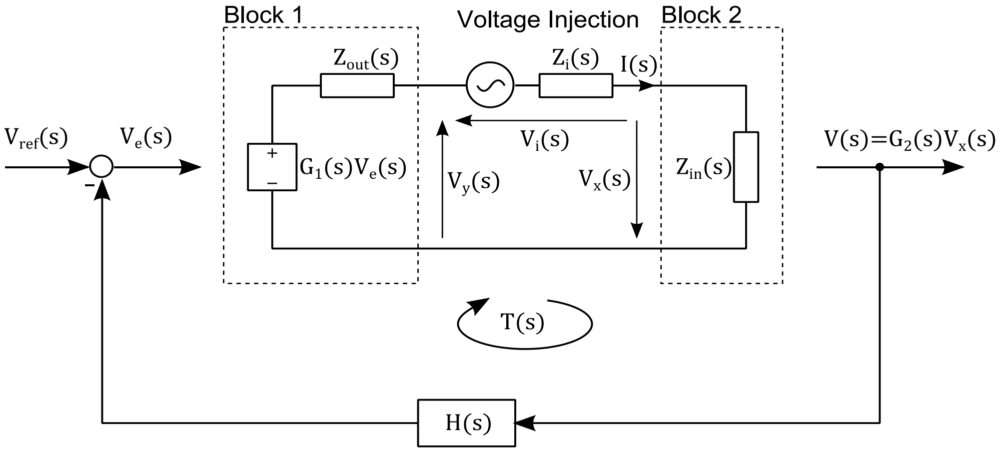
Loop gain is measured by “breaking” the loop at the injection point and inserting a “small” injection resistor (e.g. 10 Ω).

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 $T_v(s)$

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

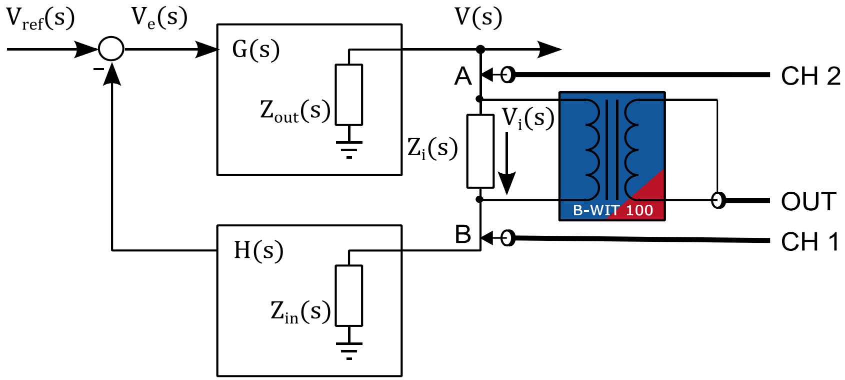
≈1 for $|Z_{in}(s)| \gg |Z_{out}(s)|$

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

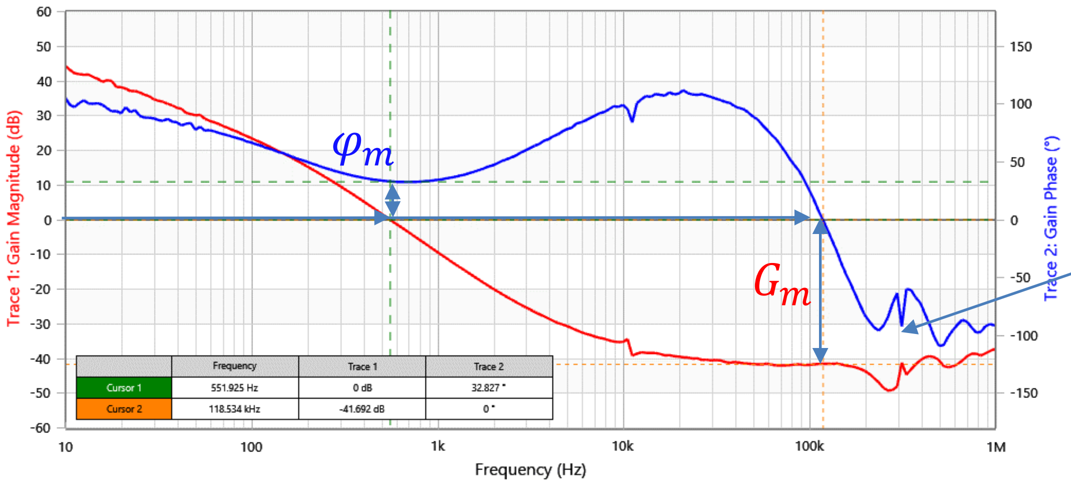
No parallel signal path bypassing the injection resistor!

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**



	Frequency	Trace 1	Trace 2
Cursor 1	551.925 Hz	0 dB	32.827 °
Cursor 2	118.534 kHz	-41.692 dB	0 °

$\varphi_m = 32\ °$

$G_m = 41\ \text{dB}$

Switching Frequency

$f_s = 315\ \text{kHz}$

Reading Phase Margin from Measurement

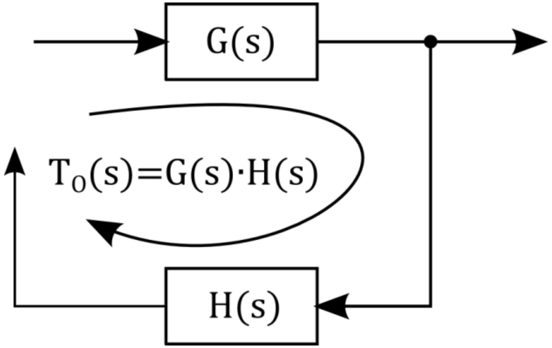
Phase Margin is read directly from the **measurement**!

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

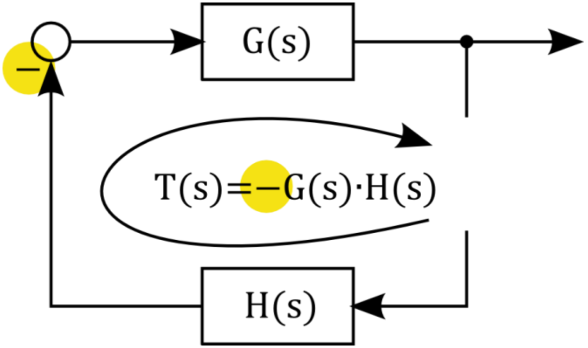
Reason: We measure in the closed loop system → our signal will run through the inverting error amp and get an additional 180° phase shift.

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

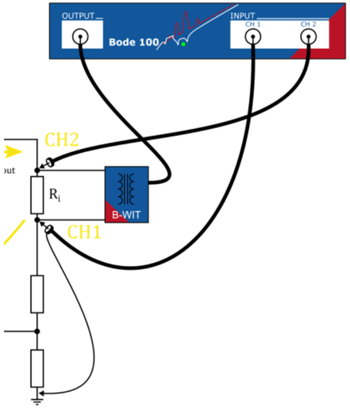
Theoretical open loop gain $T_o(s)$



Measured loop gain $T(s)$

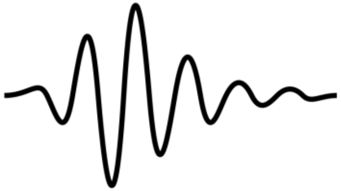


Selecting the injection point



- 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.

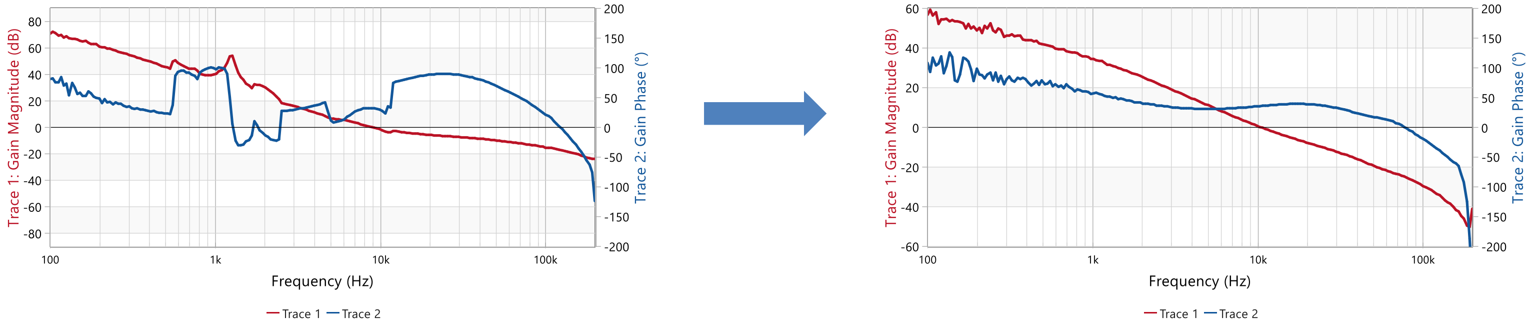
Injection Signal Size



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!

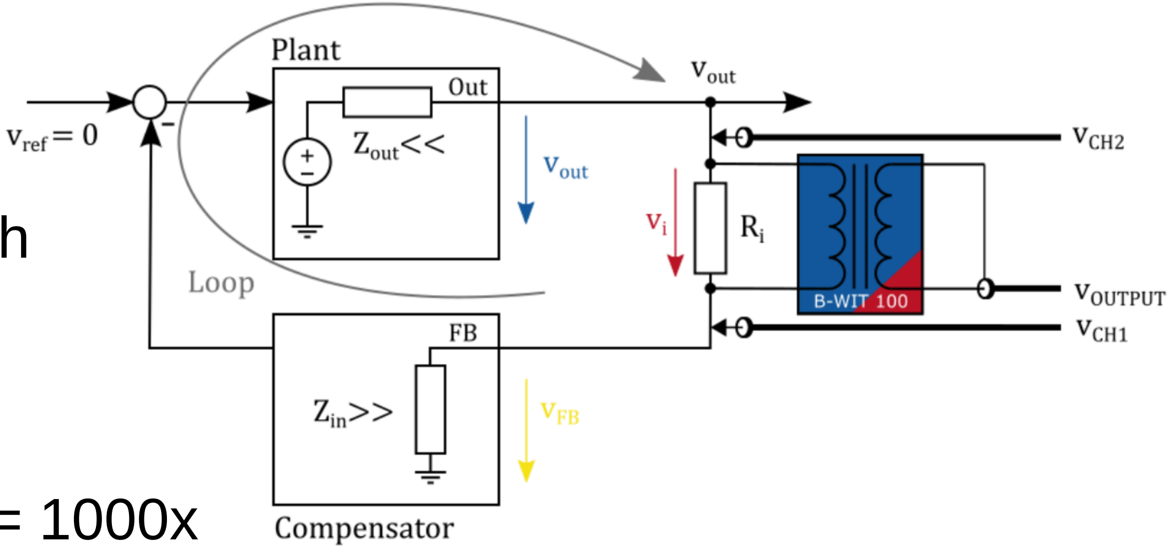
1. Choose an injection signal level and measure
2. Reduce the injection signal by e.g. 10dB

→ 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

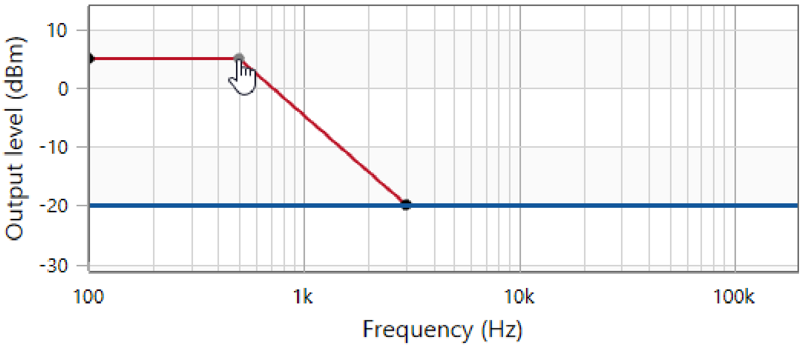
Injection voltage = 30 mV → CH2 needs to measure 30µV

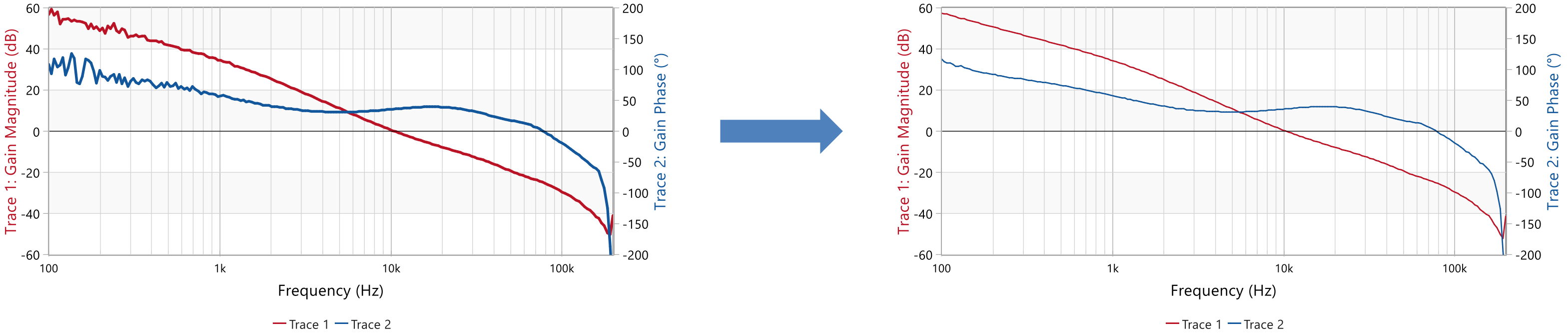
Resolving phase at such high ratio and low signal is tricky.

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

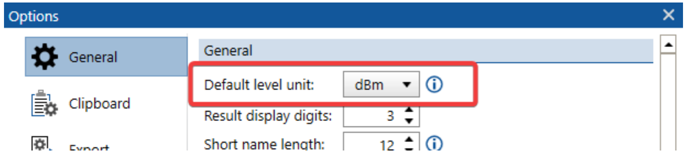
Shaped Level

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





dBm or V ???

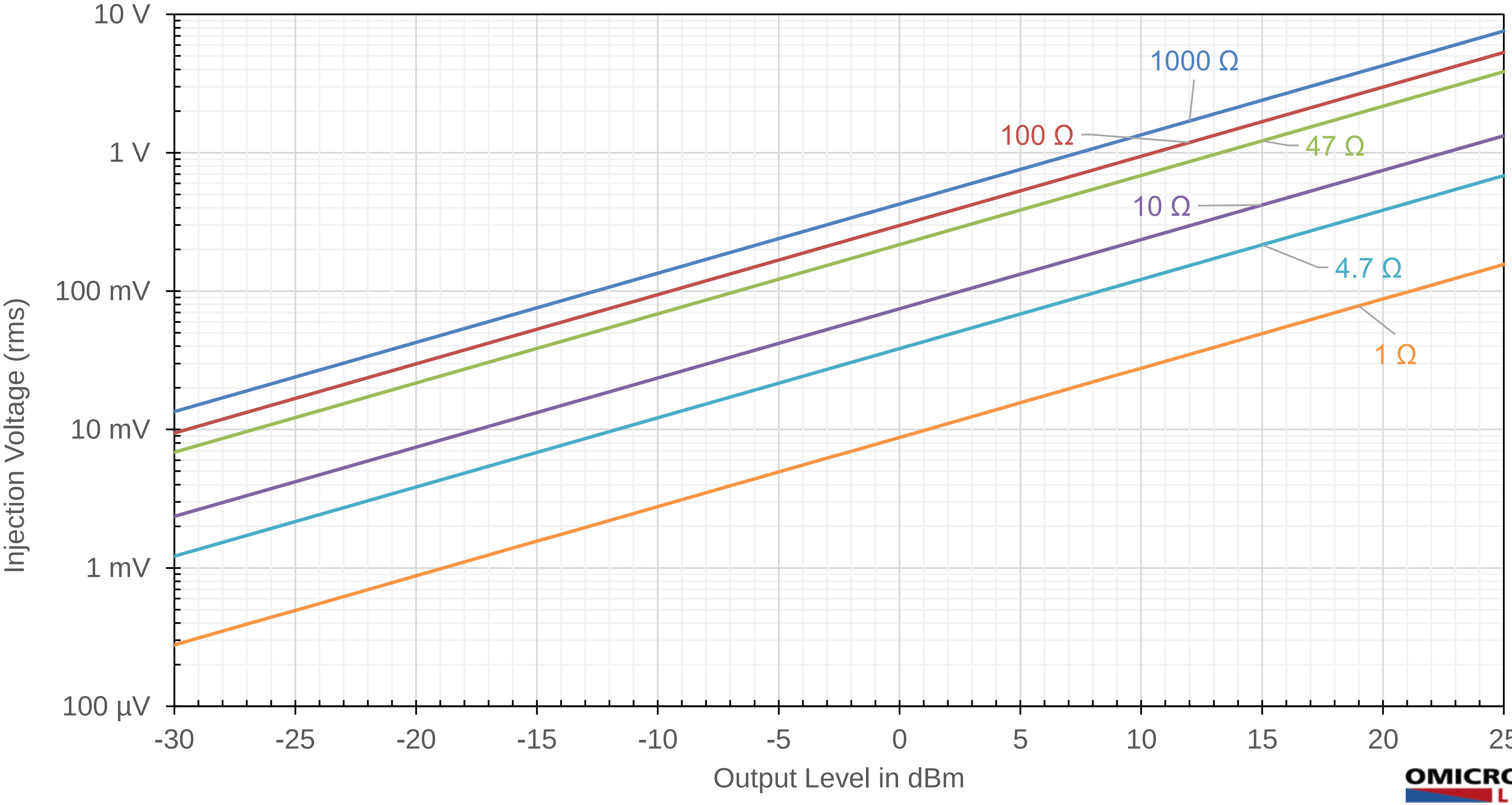


General

Default level unit: dBm

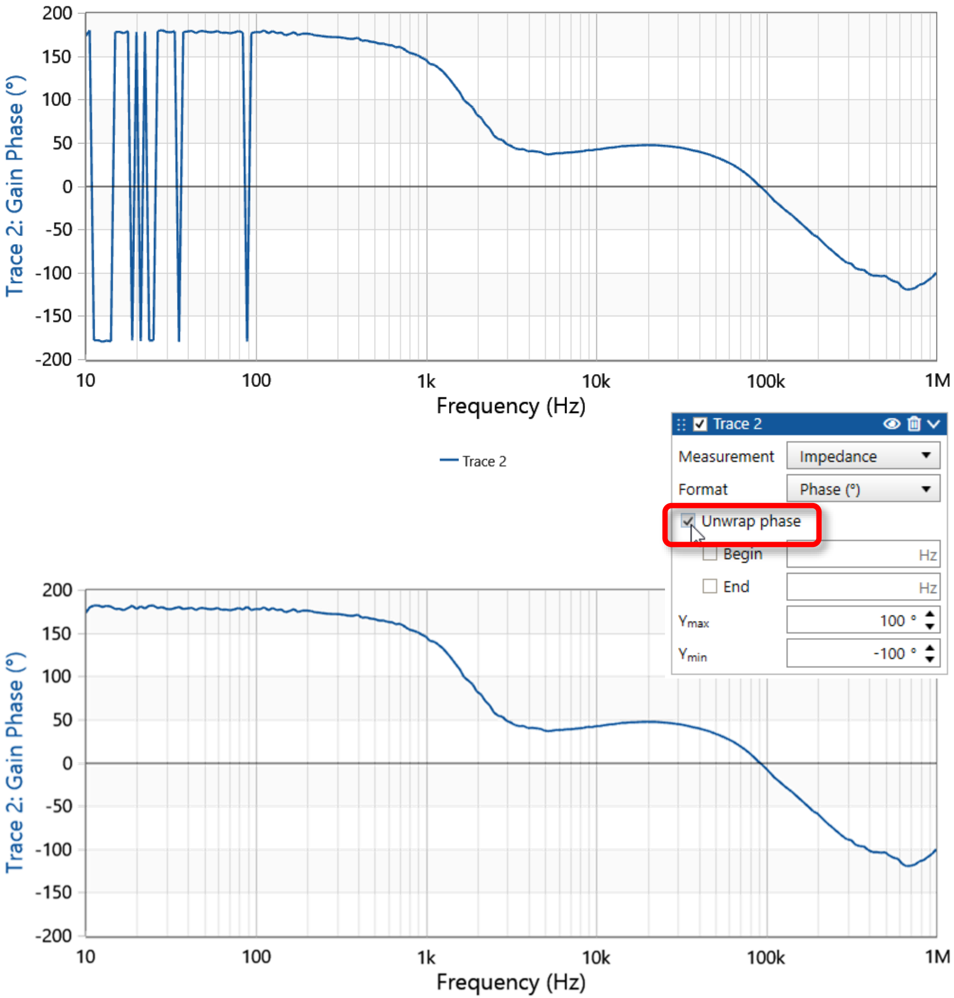
Result display digits: 3

Short name length: 12



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...



☑ Trace 2

Measurement: Impedance

Format: Phase (°)

☑ Unwrap phase

☐ Begin Hz

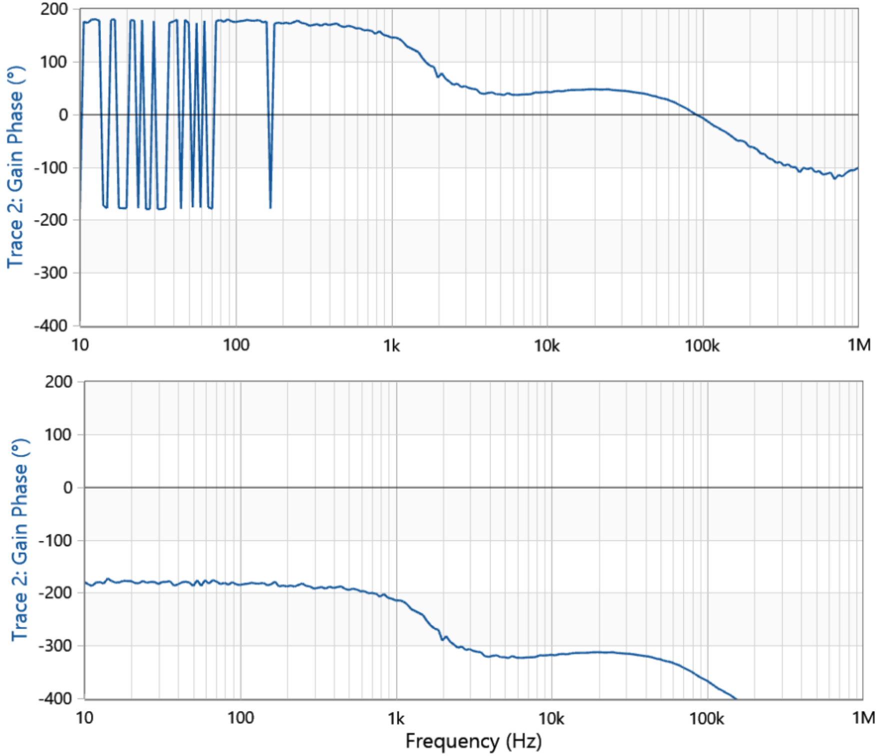
☐ End Hz

Y_{max} 100 °

Y_{min} -100 °

Phase Wrapping Continued

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



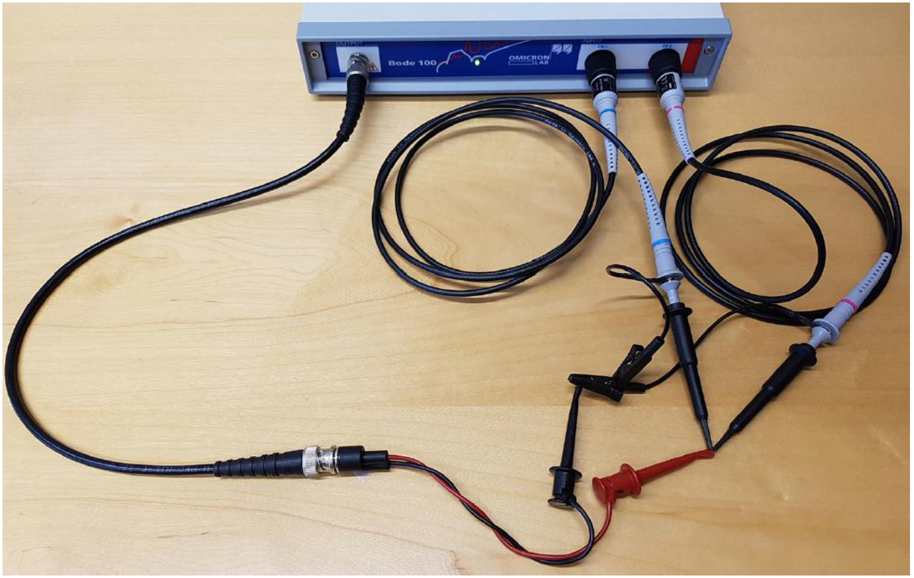
Solutions:

- Ignore phase wrapping
- Reduce phase noise
- Sweep backwards

Is Calibration Necessary?

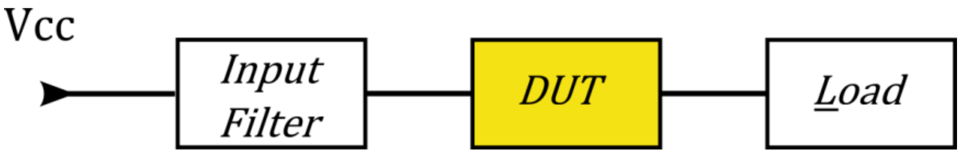
Normally not. Basic accuracy of the setup should be sufficient if probes are compensated correctly!

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

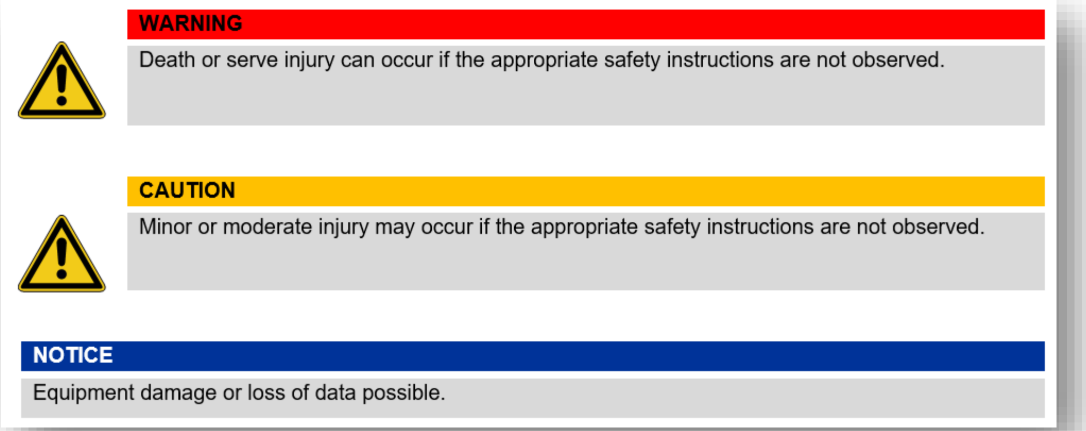
→ Always measure loop gain under **all expected load conditions** and with the **input filter** connected

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.

Some Words on Safety

Follow all rules and laws applicable to your workplace!

...RTFM (Read The ... **Manual**!)



WARNING

Death or serve injury can occur if the appropriate safety instructions are not observed.

CAUTION

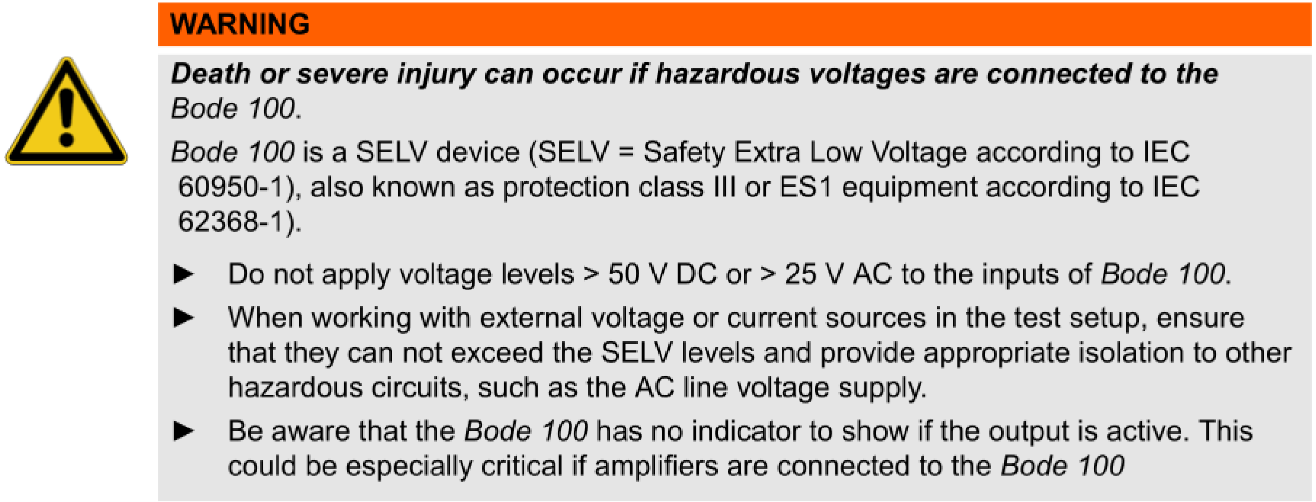
Minor or moderate injury may occur if the appropriate safety instructions are not observed.

NOTICE

Equipment damage or loss of data possible.

Some More Words on Safety

Bode 100 and Bode 500 are SELV devices (Safety Extra Low Voltage).



WARNING

Death or severe injury can occur if hazardous voltages are connected to the *Bode 100.*

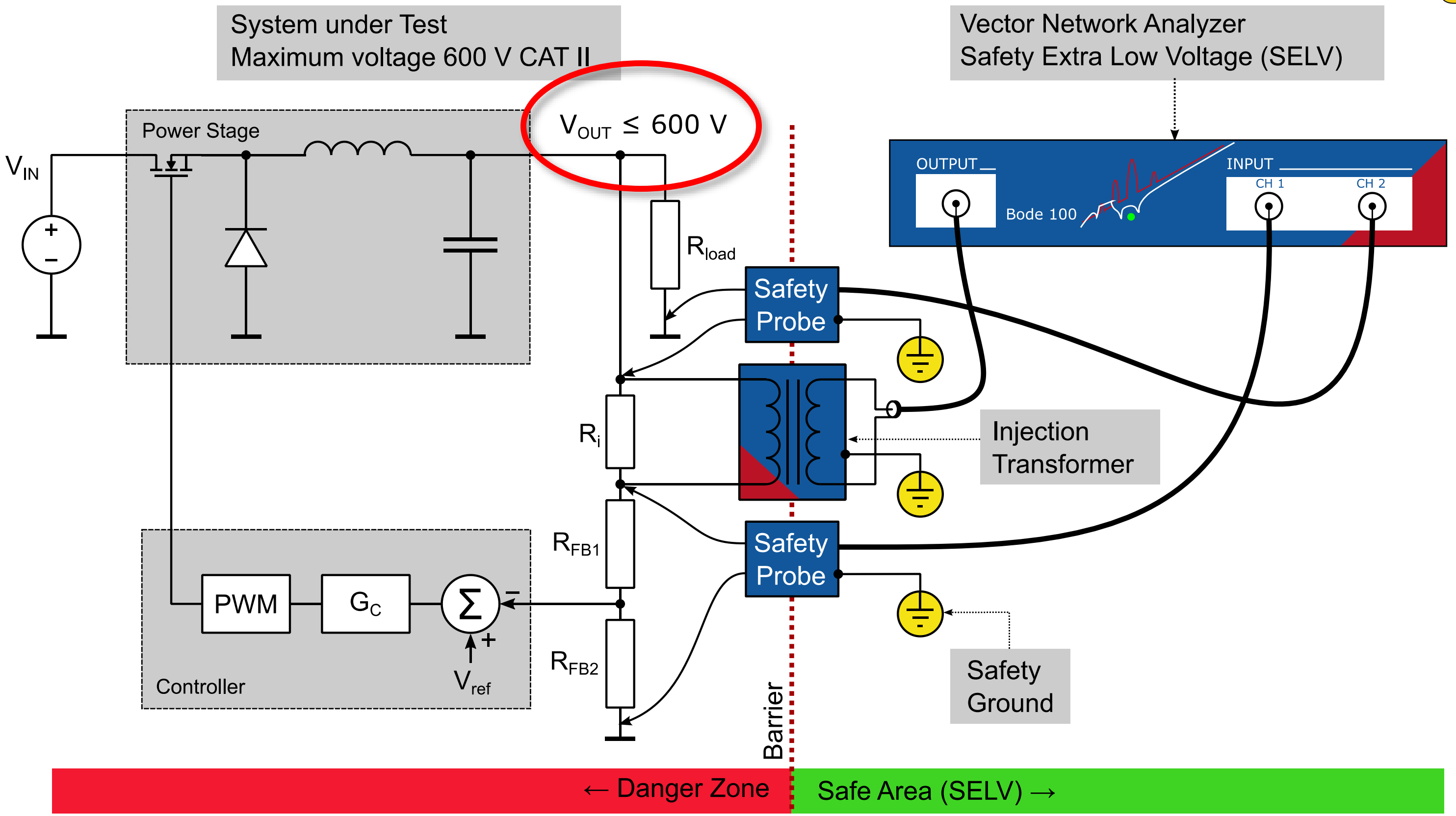
Bode 100 is a SELV device (SELV = Safety Extra Low Voltage according to IEC 60950-1), also known as protection class III or ES1 equipment according to IEC 62368-1).

- ▶ Do not apply voltage levels > 50 V DC or > 25 V AC to the inputs of *Bode 100.*
- ▶ When working with external voltage or current sources in the test setup, ensure that they can not exceed the SELV levels and provide appropriate isolation to other hazardous circuits, such as the AC line voltage supply.
- ▶ Be aware that the *Bode 100* has no indicator to show if the output is active. This could be especially critical if amplifiers are connected to the *Bode 100*

If your DUT is above SELV?

1. Identify all safety relevant rules applicable
2. Take appropriate measures such as
   - Physical barrier (separate danger zone and safe area)
   - **Connect ground terminal of Bode to laboratory ground** using a solid connection of 3.6mm² no longer than 10m
   - Don’t forget: USB of Bode is connected to the housing / shield
3. Use appropriate isolation **between DUT and Bode**
   - B-WIT 100 and B-LFT provide safe isolation up to 600 V CATII
   - Active high-voltage differential probes

An Isolated Measurement Setup



Using Galvanically Isolated Sources

- Laboratory power supplies are typically galvanically isolated from mains.
- Isolation transformers or variable transformers can also provide galvanic isolation from mains.

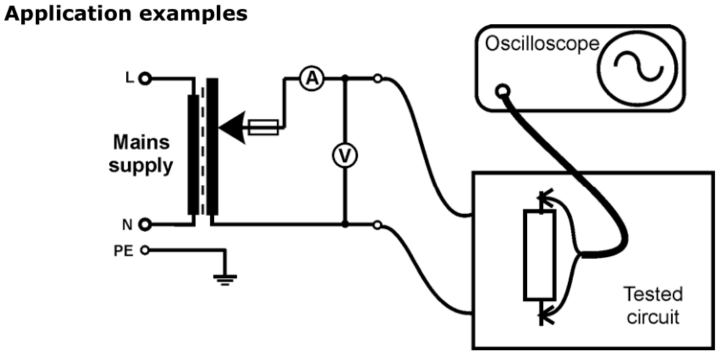
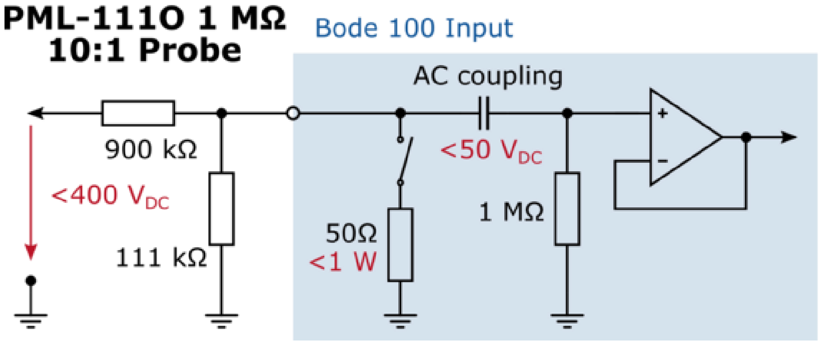


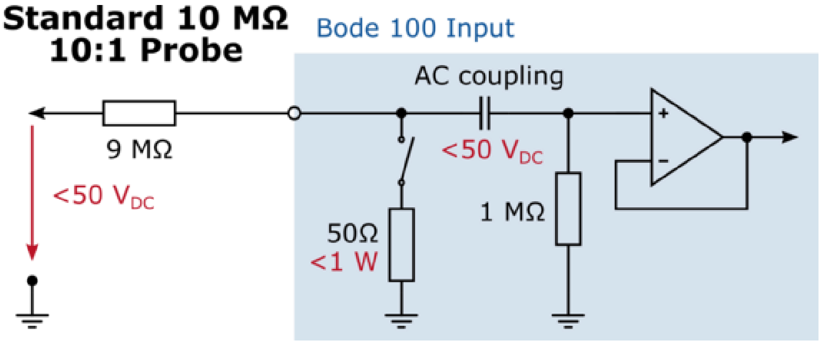
Figure 4.1: Observing in circuit

Source: www.metrel.si

Probes...

Don’t use 10:1 scope probes with Bode 100 or Bode 500!
A standard 10 MΩ 10:1 scope-probe will not divide the dc-signal when used with Bode 100 or Bode 500!

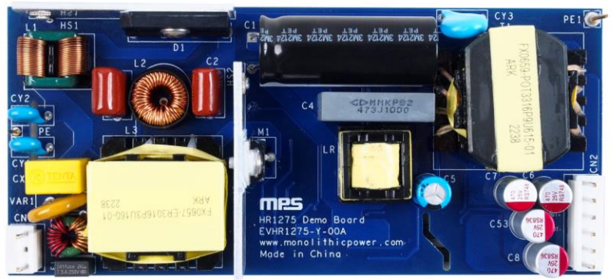




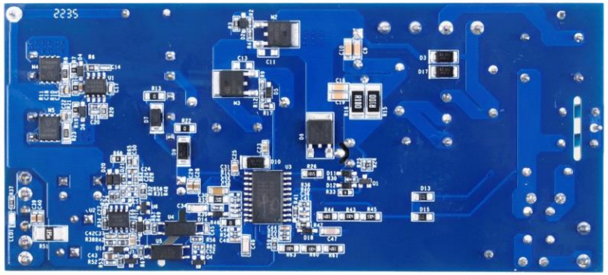
- PMK PML-111O 10:1 probe up to 400 V DC
- PMK PHV 1000-O 100:1 probe up to 2000 V DC

Challenging Example: PFC VBUS-Loop

- DUT EVHR1275-Y-00A (Digital controller evaluation board with universal input and 19.5 V / 9.23 A output)



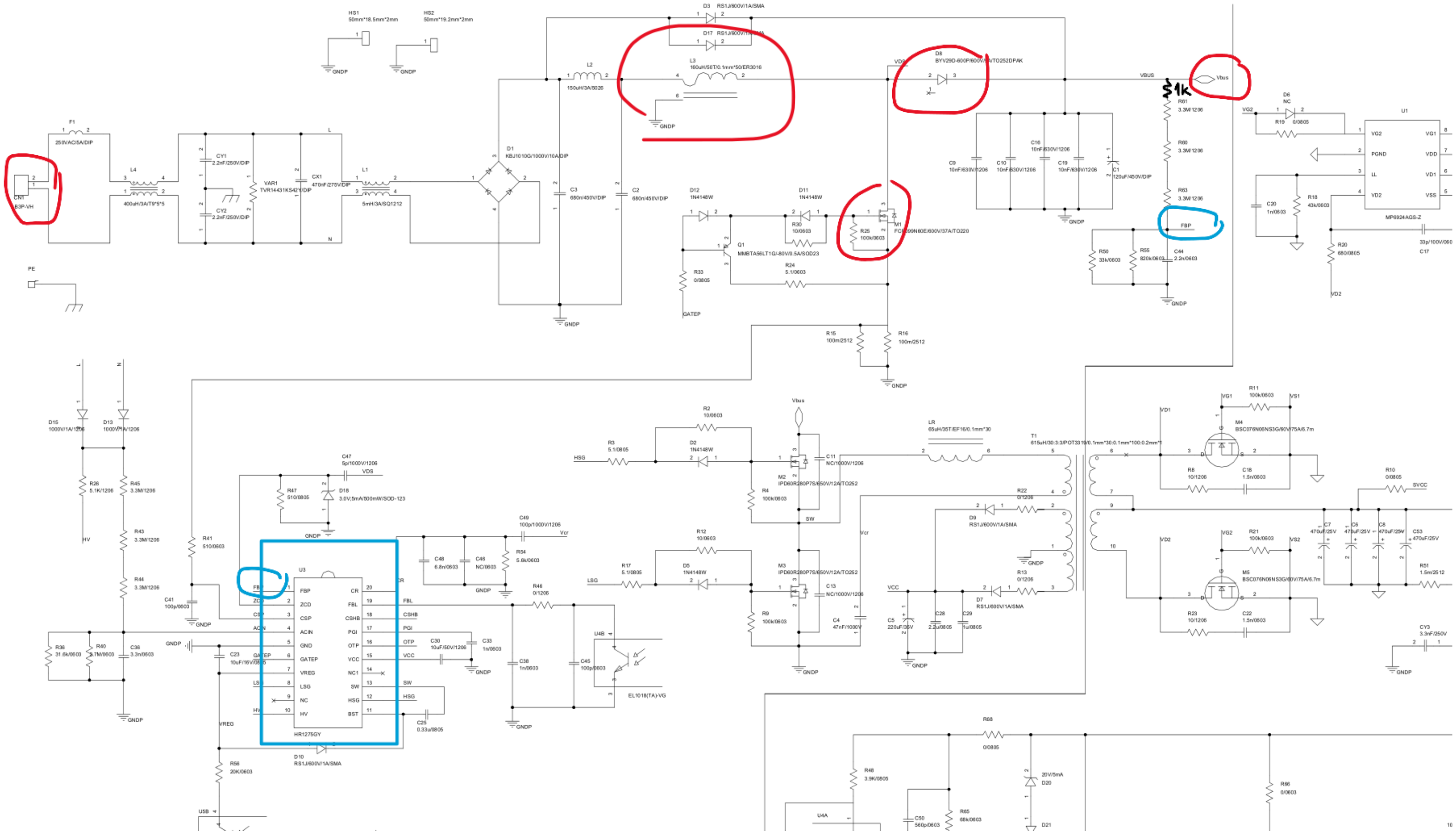
Top View



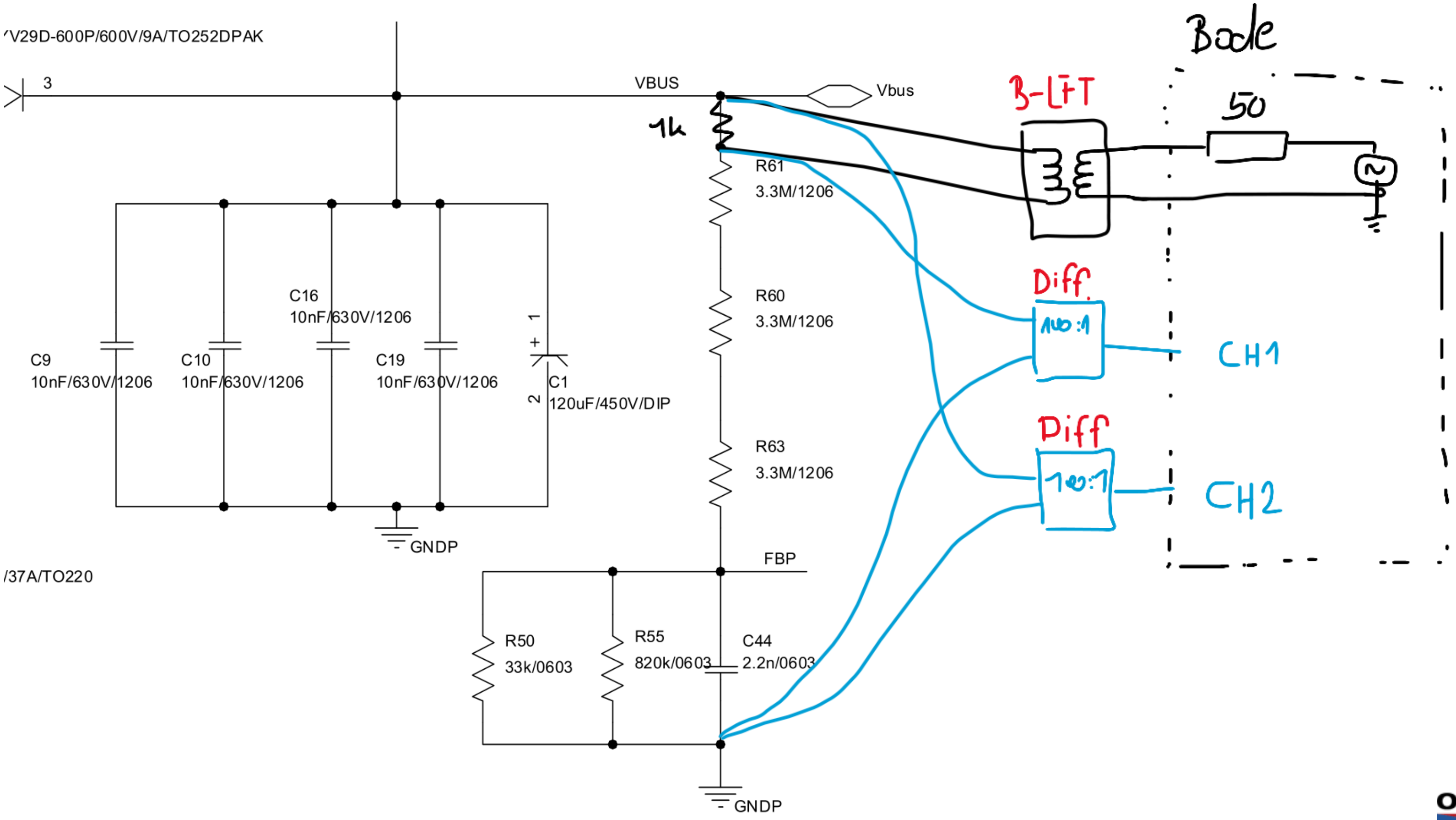
Bottom View

- VBUS is 400 V DC
- VBUS ripple of 100 Hz
- Voltage loop is slow (~15 Hz)
- Measurement starts at 1 Hz
- No signal conditioning circuit → injection point not beneficial

Search for Injection Point

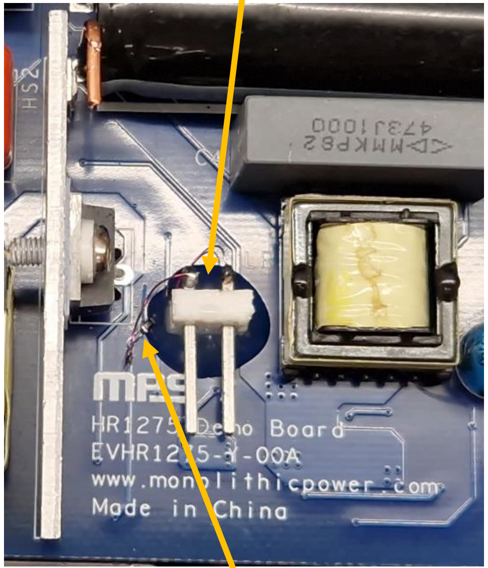


Voltage Injection Continued...

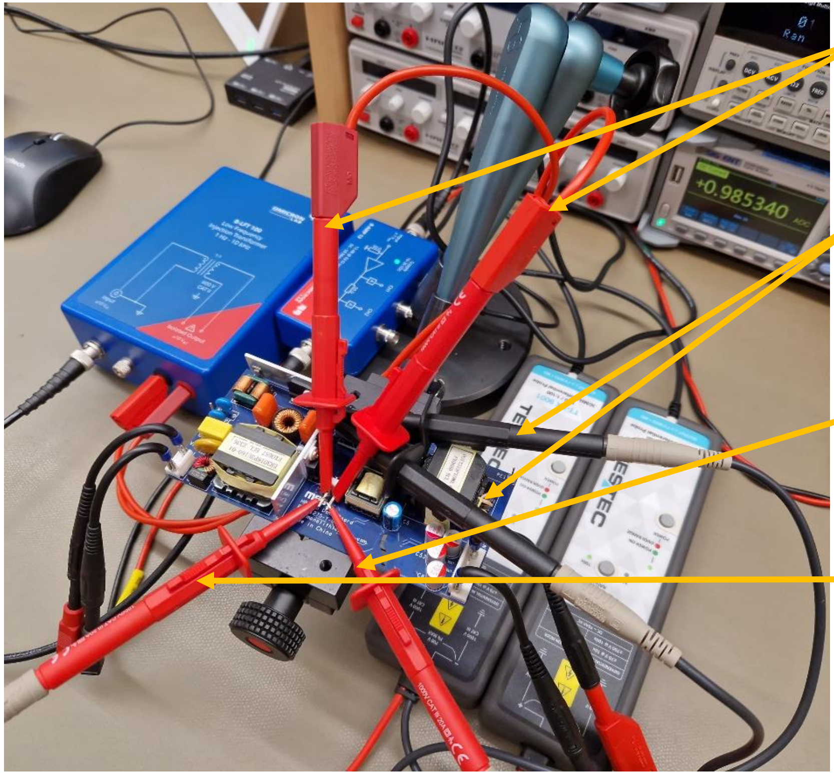


Example Setup

Test Pins



1 kΩ Injection Resistor



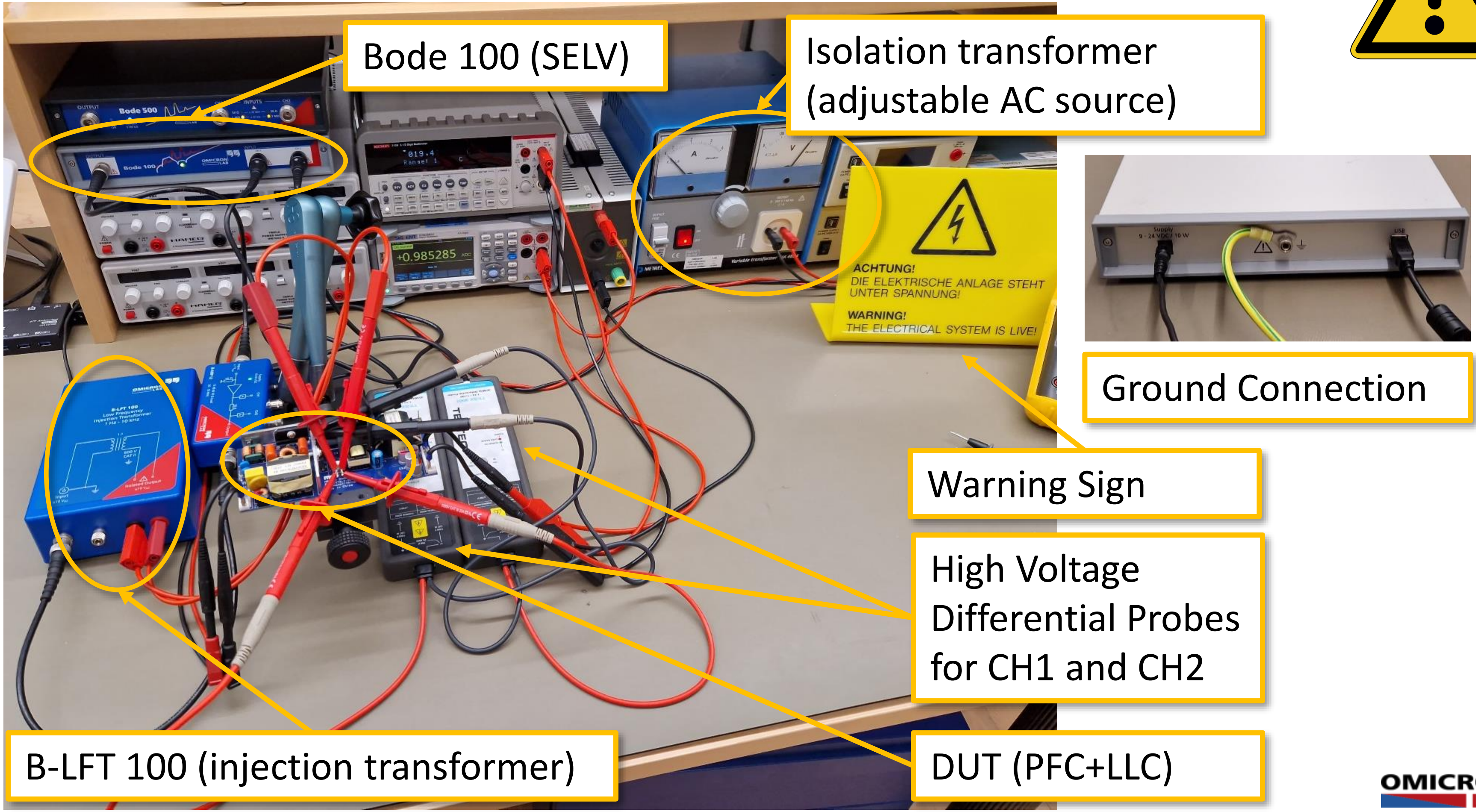
Injection

VBUS
negative
NOT GND!

VBUS (400 V)
to CH2

VFB (400 V)
to CH1

Example Setup



Bode 100 (SELV)

Isolation transformer (adjustable AC source)

Ground Connection

Warning Sign

High Voltage Differential Probes for CH1 and CH2

B-LFT 100 (injection transformer)

DUT (PFC+LLC)

Bode 100 Configuration

- Use Gain/Phase measurement mode
- Start frequency: 1 Hz
- Stop frequency: 1 kHz or less
- Number of points: 201 or less
- Receiver attenuators: Max. sensitivity at 0 dB (active differential probes are set to 100:1)
- Receiver bandwidth: 1 Hz for max. filtering
- Signal level depends on application

Source Config.

- Example with B-LFT 100 plus B-AMP 12

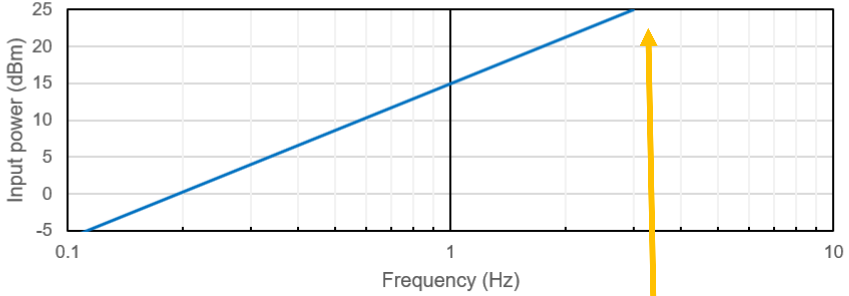
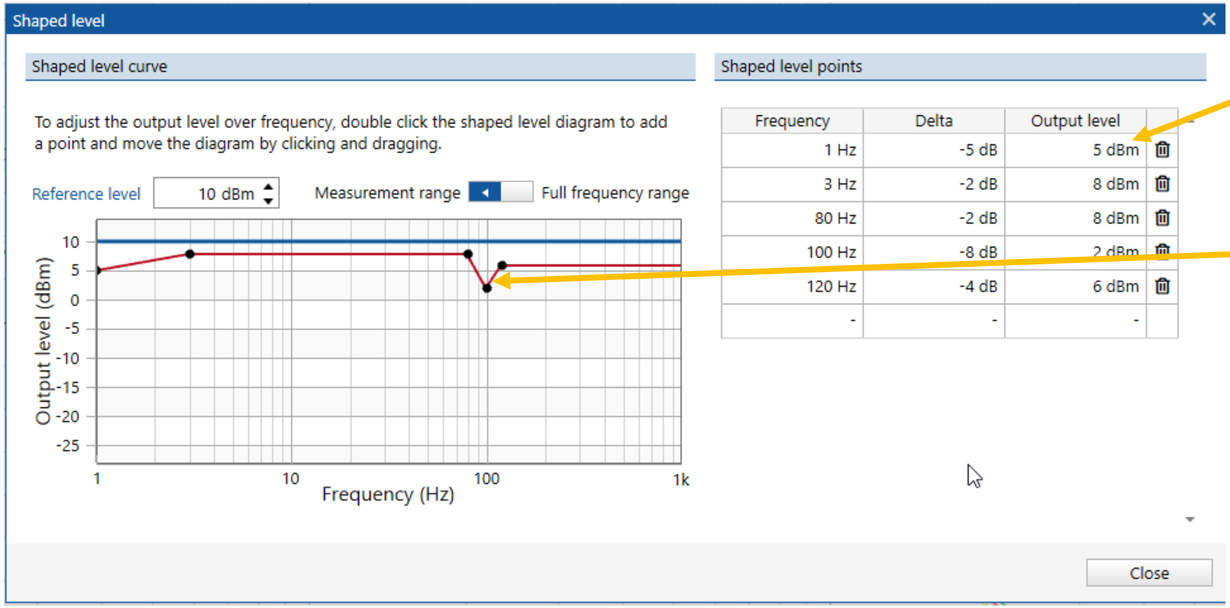


Figure 5-4: Typical *B-LFT 100* no-saturation[9] power level



Shaped level curve

To adjust the output level over frequency, double click the shaped level diagram to add a point and move the diagram by clicking and dragging.

Reference level: 10 dBm

Measurement range: Full frequency range

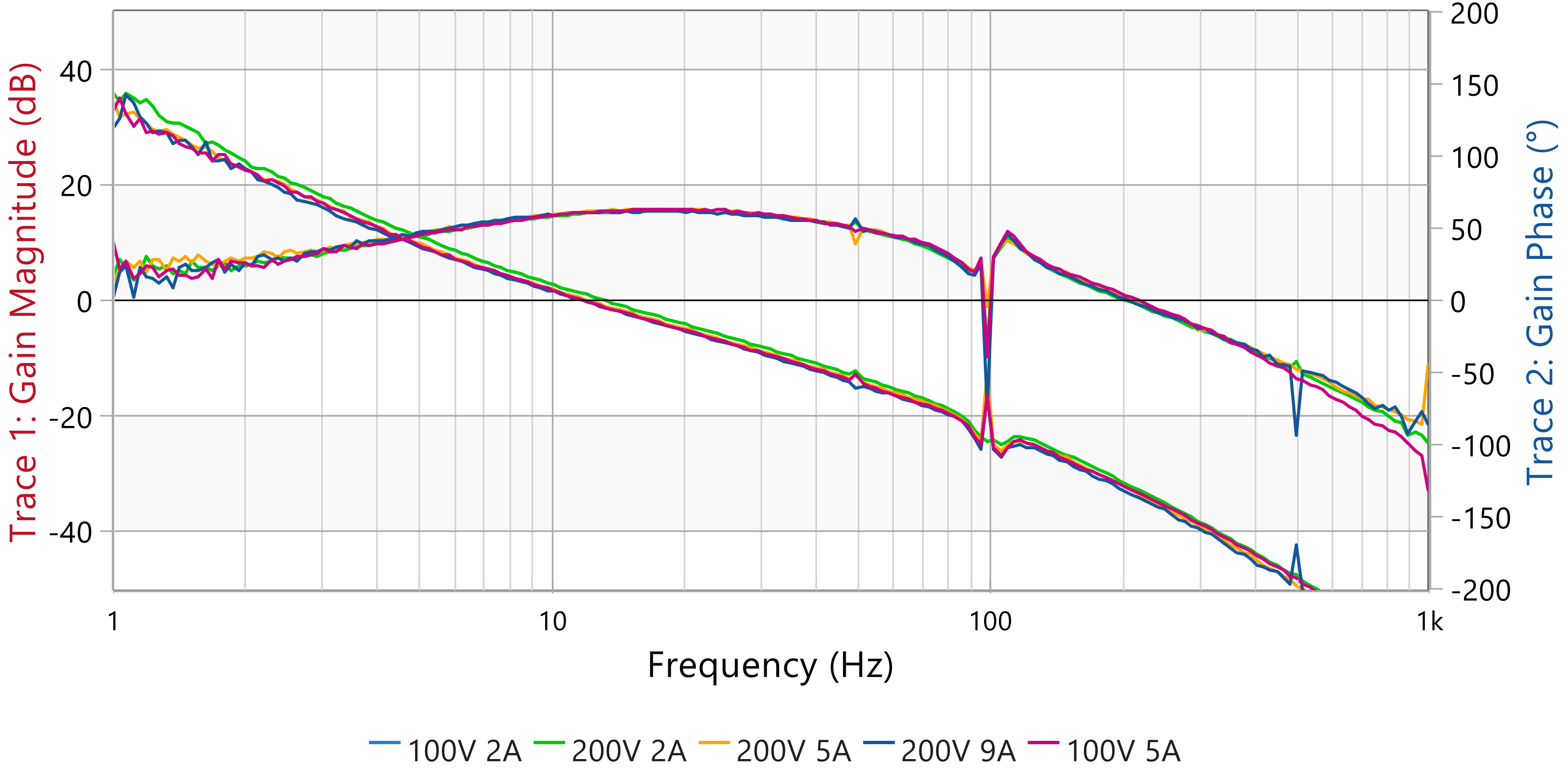
Shaped level points

Frequency	Delta	Output level
1 Hz	-5 dB	5 dBm
3 Hz	-2 dB	8 dBm
80 Hz	-2 dB	8 dBm
100 Hz	-8 dB	2 dBm
120 Hz	-4 dB	6 dBm
-	-	-

Avoid saturation below 3 Hz

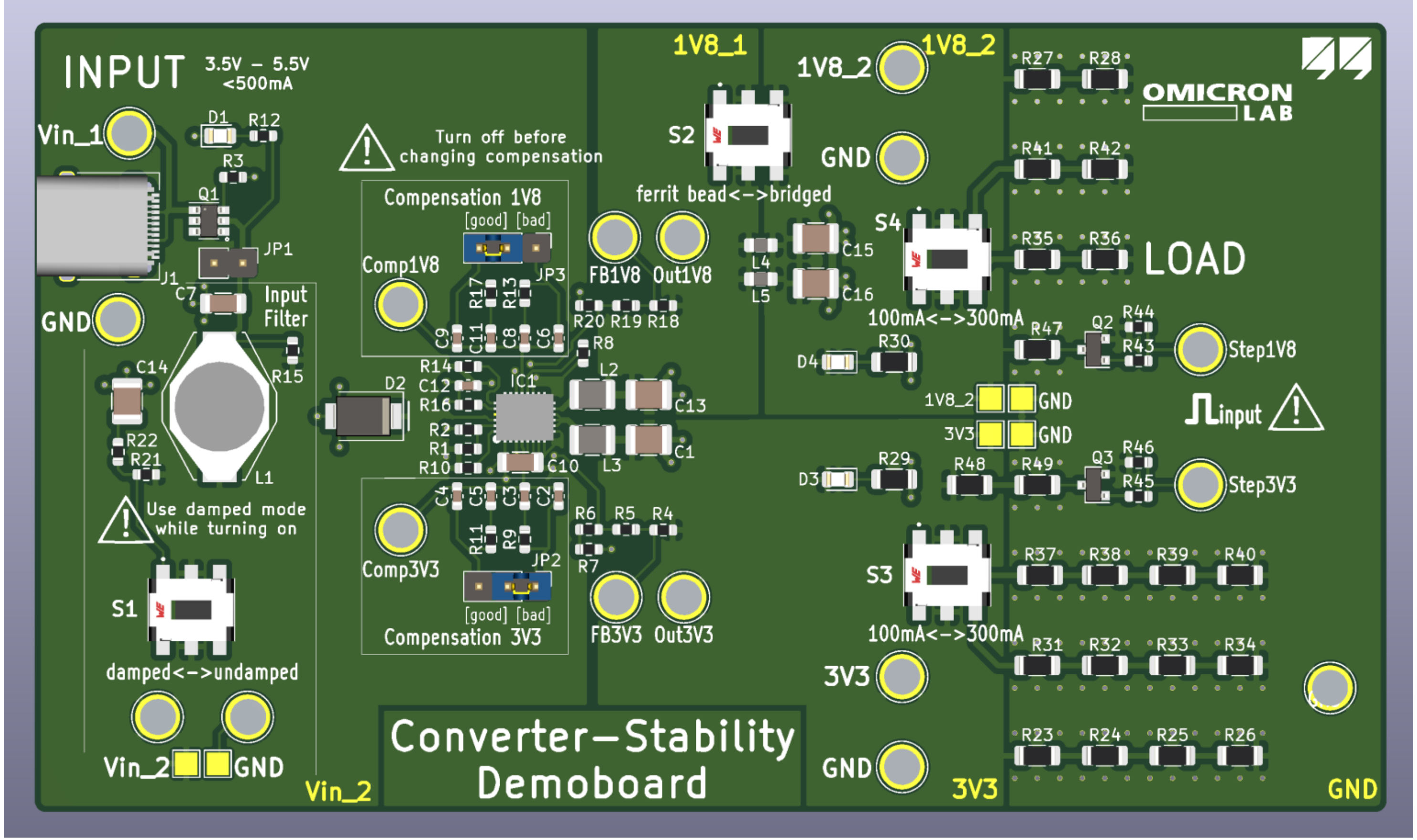
Avoid Overload at 100 Hz

Measurement Result

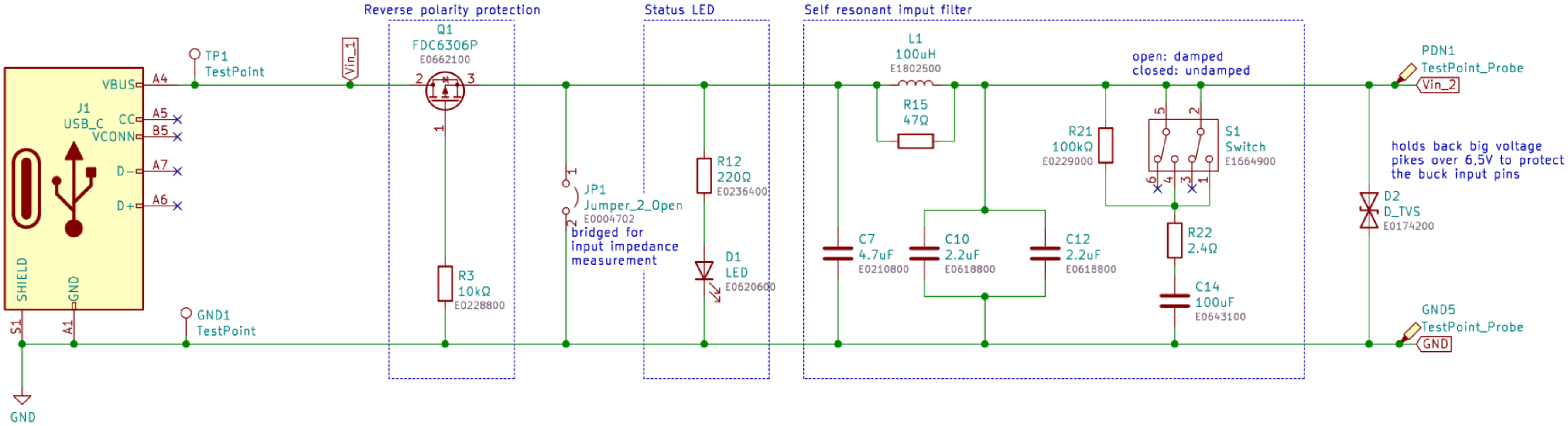


Let’s try it in real life!

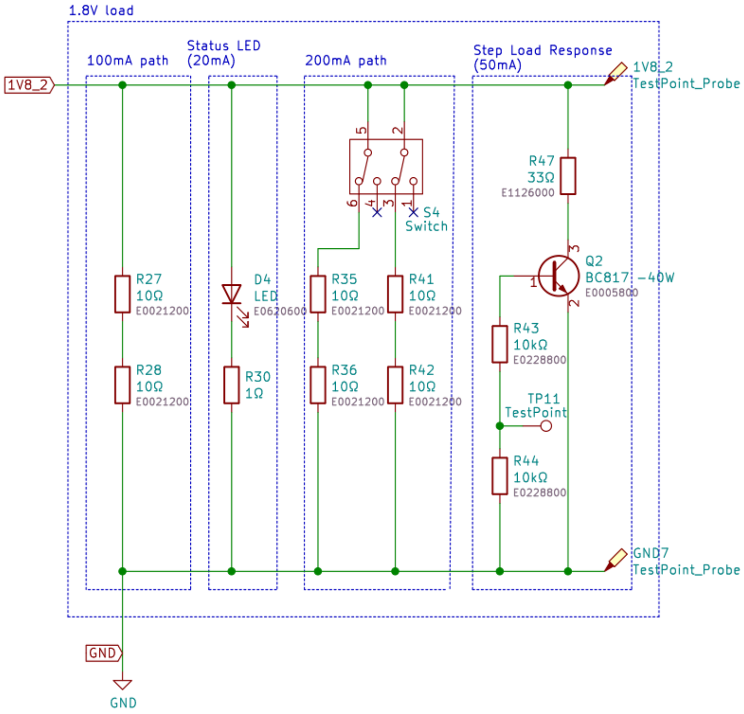
Hands-On (Converter Stability Demoboard)

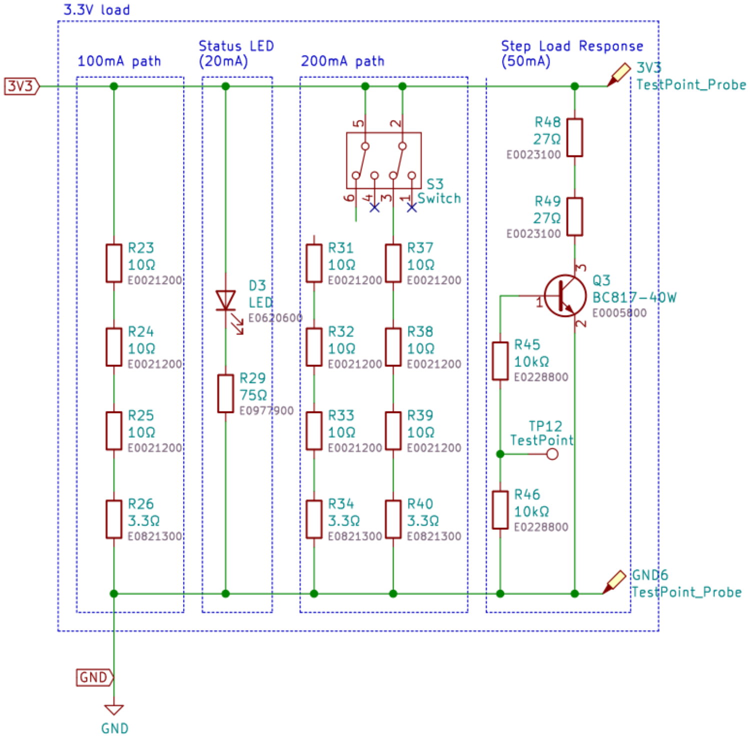


Input Filter Section

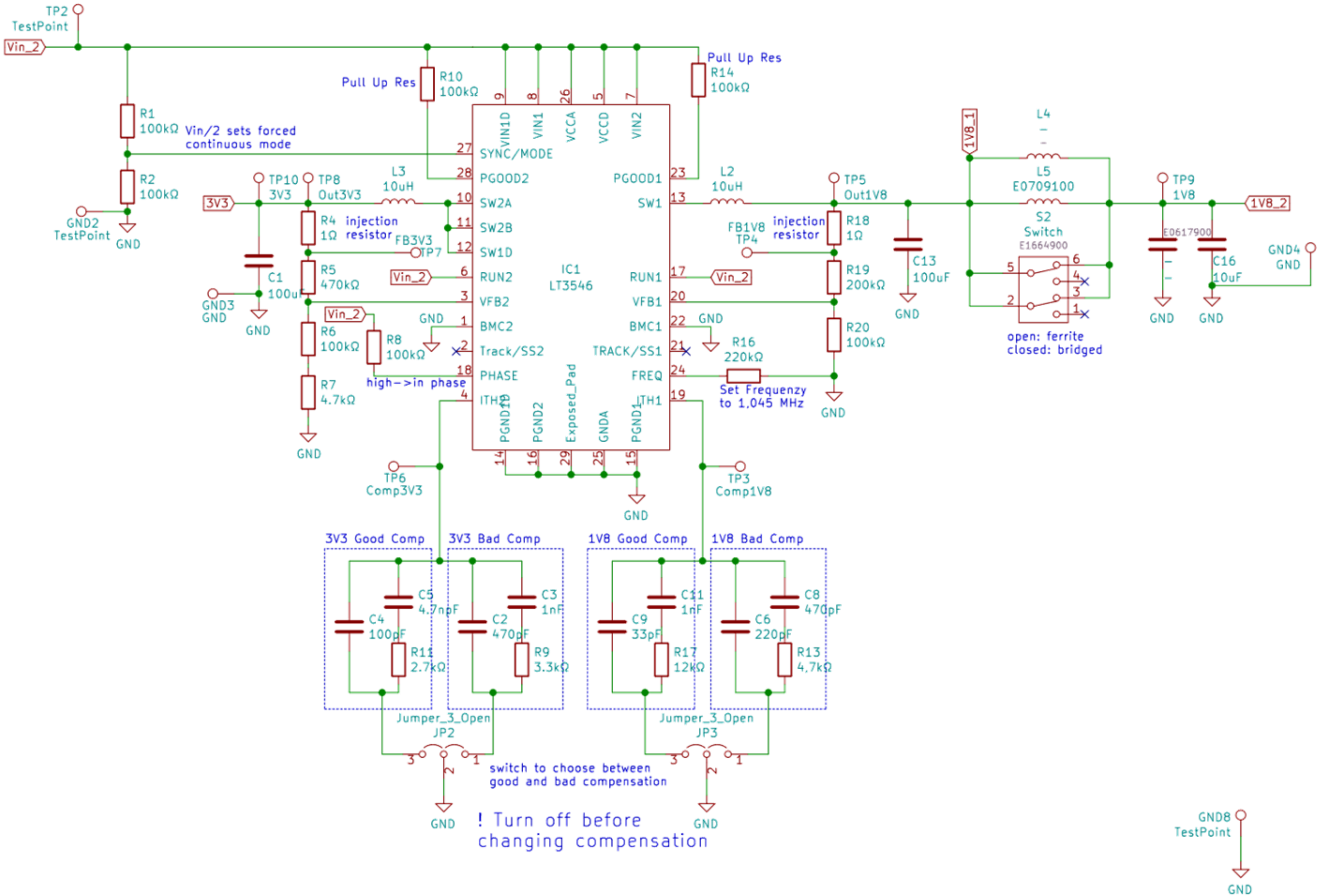


Load Section





Dual DC/DC Section



Vin/2 sets forced continuous mode

injection resistor

high->in phase

injection resistor

Set Frequenzy to 1,045 MHz

open: ferrite
closed: bridged

switch to choose between good and bad compensation

! Turn off before changing compensation

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.

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