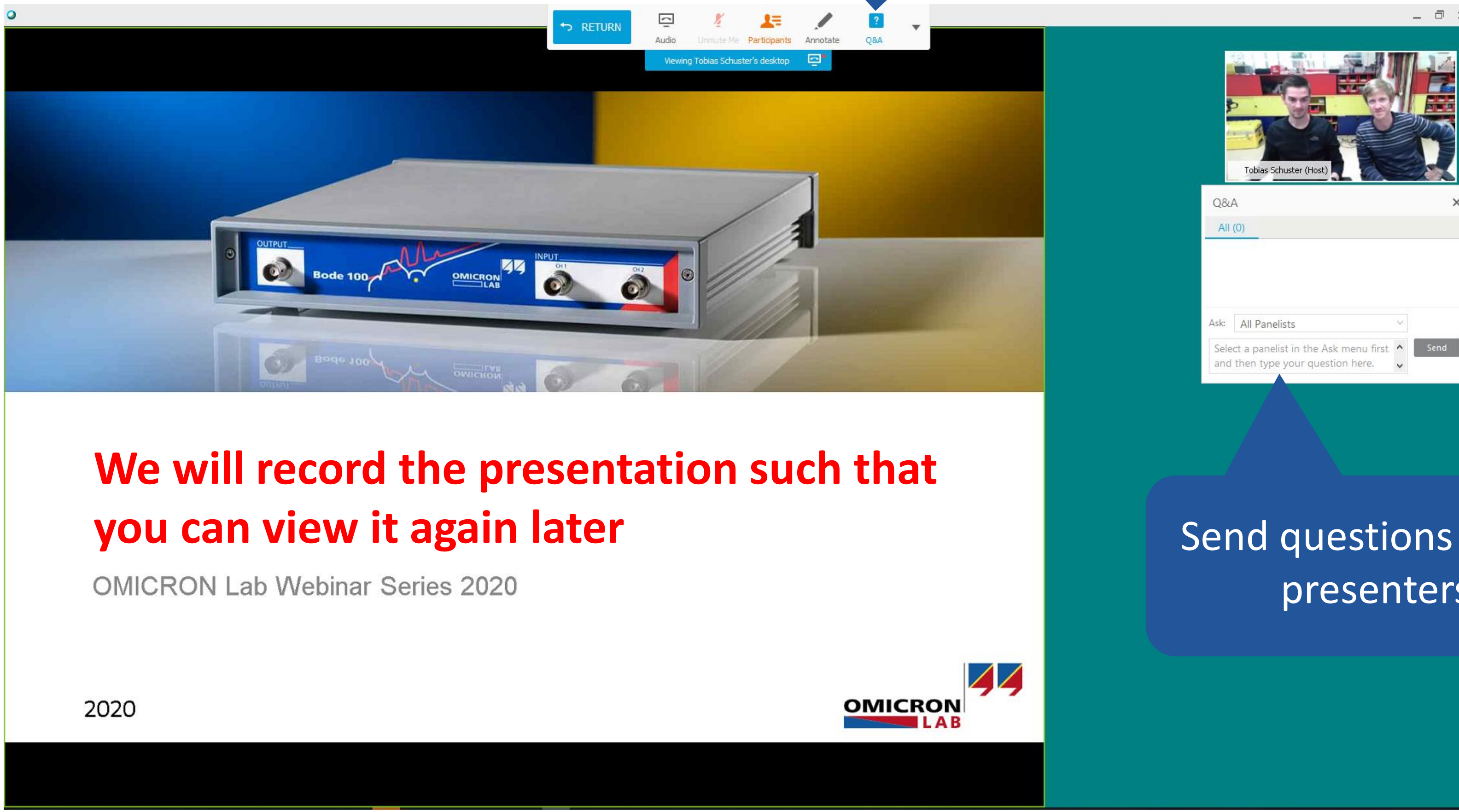
Power Supply Dynamics & Stability

OMICRON Lab Webinar Series 2020

2020-04-28

Webinar Hints

Open the Q&A function



Send questions to the presenters

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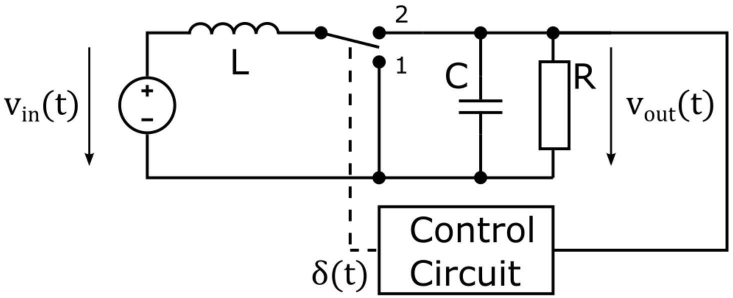
Agenda

- Open-loop transfer functions
- Closed-loop transfer functions & loop gain
- Measuring loop gain
  - Voltage injection method
  - Injection signal level size
  - Choosing the correct injection point
- Measuring plant and compensator
- Hands-On Live-Measurements
  - Measure Loop
  - Measure Plant & Compensator
  - Step-Load Response

DC/DC Converter System

- How will the system react to:
  - Sudden line-voltage change?
  - A change in the reference voltage or set-point?



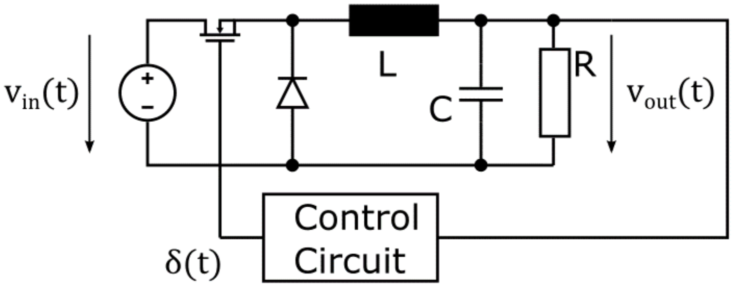
- How to design the compensator (place the poles and zeros)?

→ Dynamic modelling used (can be quite challenging)

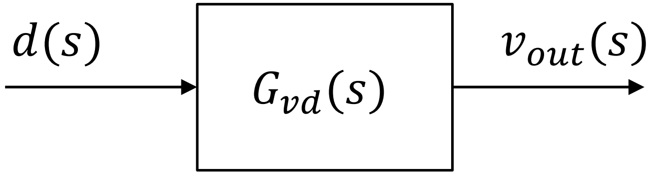
→ It makes sense to verify the design (in time-domain and in frequency domain)

Open Loop Plant Transfer Functions

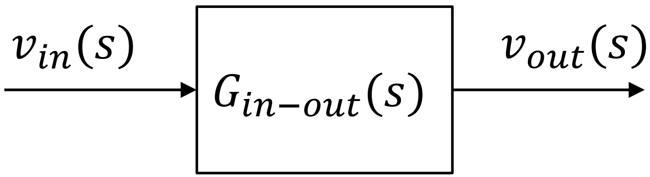
Note: for simplicity lets assume that the transfer function is equal to the frequency response $(s = j\omega)$



- Duty-cycle to output:



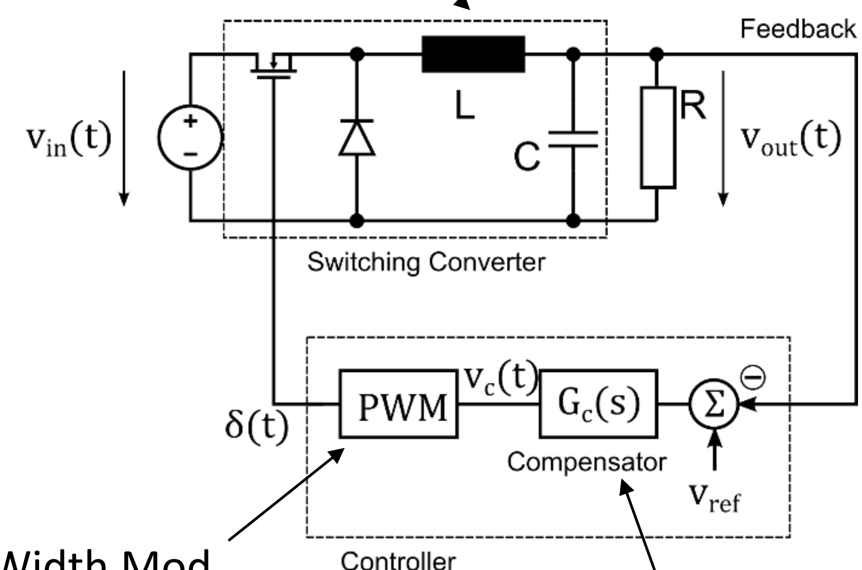
- Line to output:



Closing the Loop

Example: Buck Converter Transfer Functions:

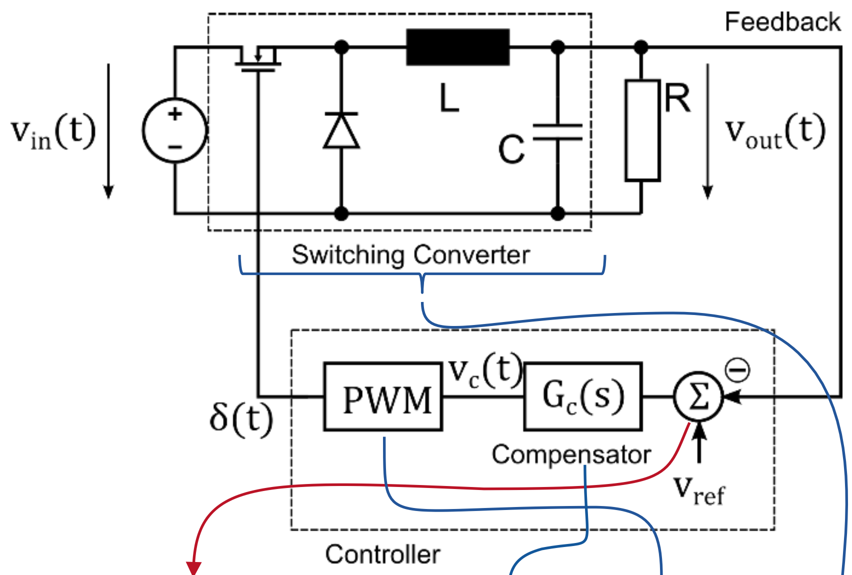
$G_{vd}(s)$ ... Switching Converter Plant



$G_{PWM}(s)$ ... Pulse Width Mod.

$G_c(s)$ ... Compensator

The Closed-Loop System



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

Loop Gain $T(s)$

Closed Loop Reference to Output

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

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

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

If $T(s) \gg 1$, then $G_{ref-out,CL}(s) \approx 1$.
This means the output follows the reference
→ Goal of the control loop

Closed Loop Input to Output

Open-loop input to output transfer function

$G_{in-out}(s)$

Closing the feedback loop

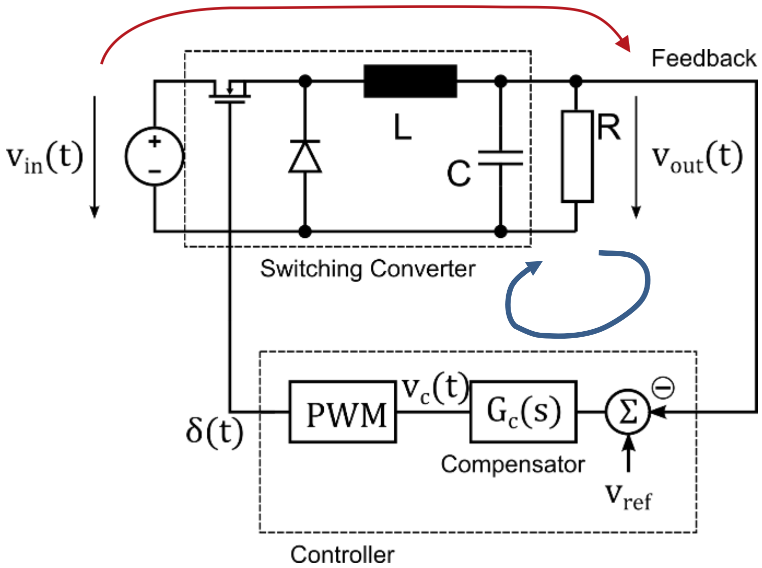
$\hat{v}_{out} = \hat{v}_{in}(s) \cdot G_{in-out}(s) - \hat{v}_{out}(s) \cdot T(s)$

and therefore

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

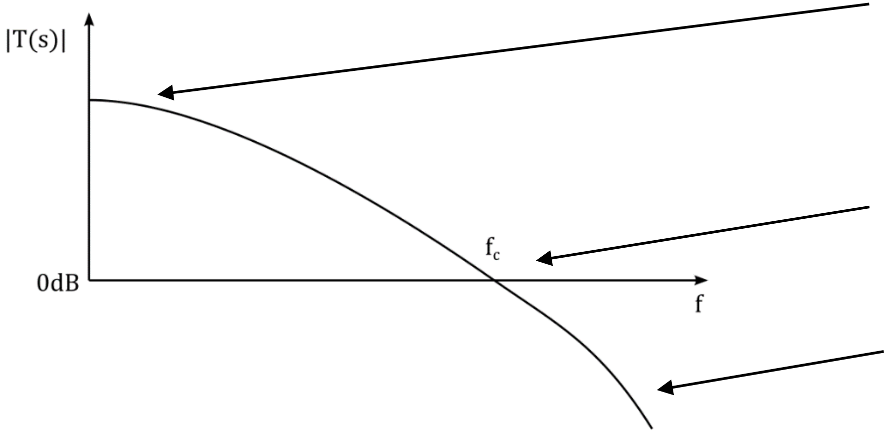
If $T(s) \gg$ then $\mathrm{G}_{\mathrm{in-out,CL}}(s) \ll$

→ This means that line-distortions are rejected (PSRR)



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

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)

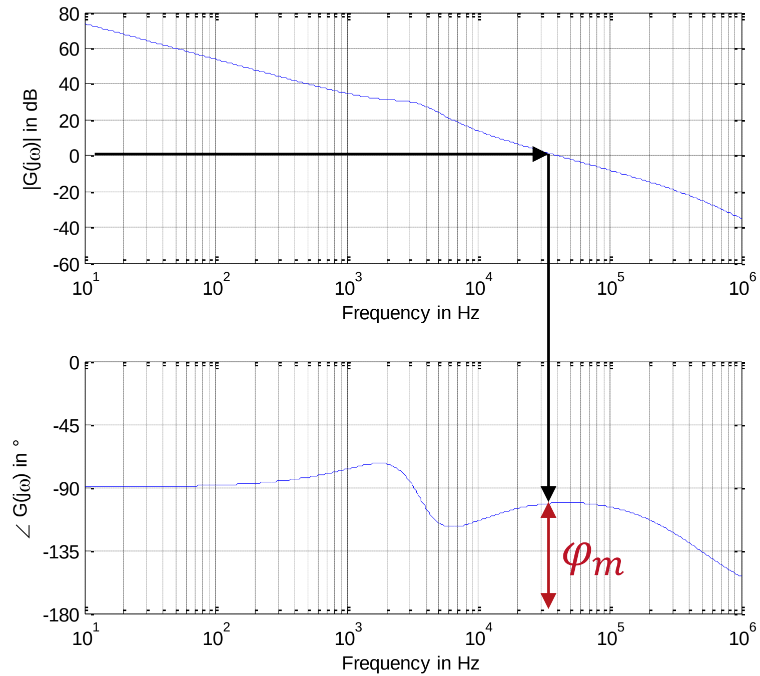
By checking the loop gain $T(s)$ we can check if the closed loop system will be stable or not.

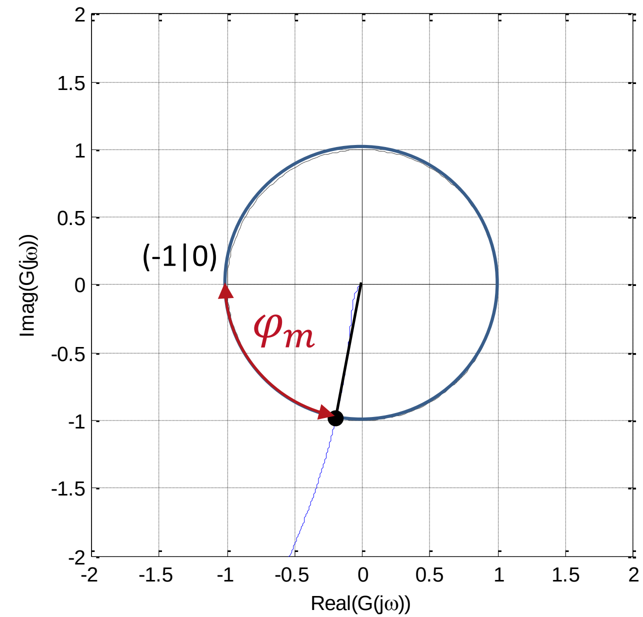
Test: How much distance does $T(s)$ have towards -1

The Phase Margin Test

(A special case of the general Nyquist stability criterion)

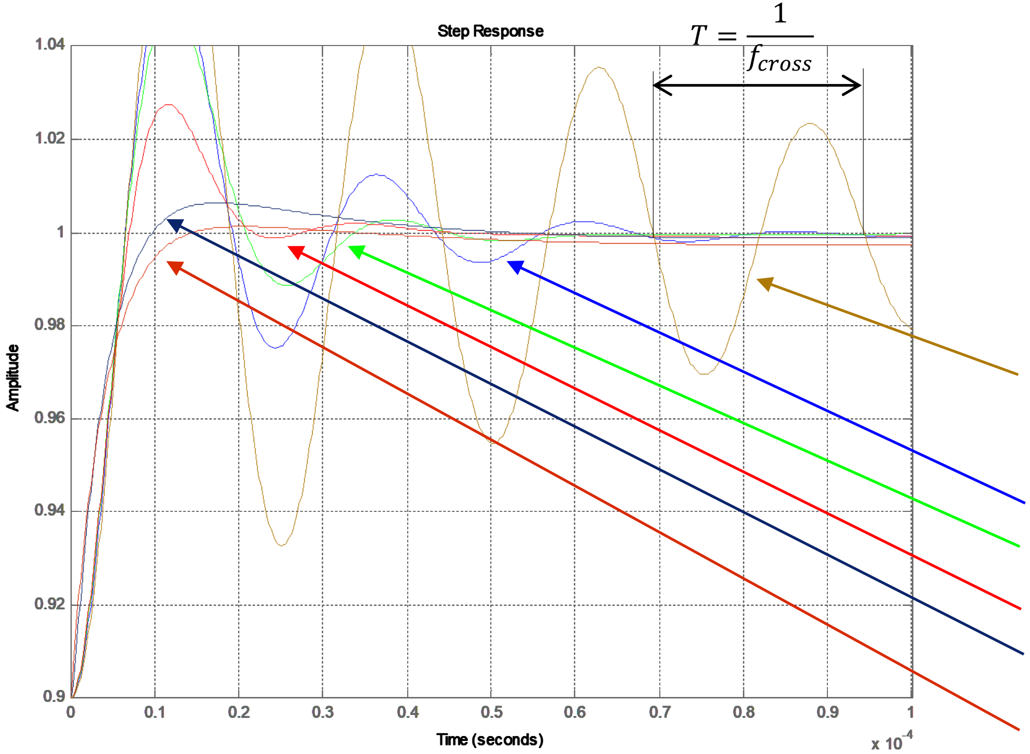
If phase margin >0° → the closed loop system is “stable”





How much Phase Margin is desired?

Example: Voltage-mode Buck Converter Reference to Output Step



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

$\varphi_m = 87°$

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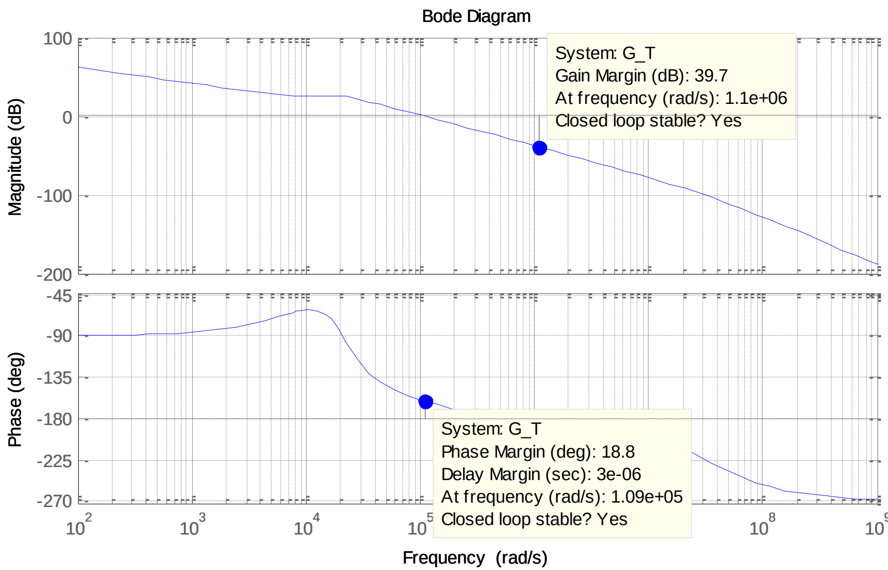
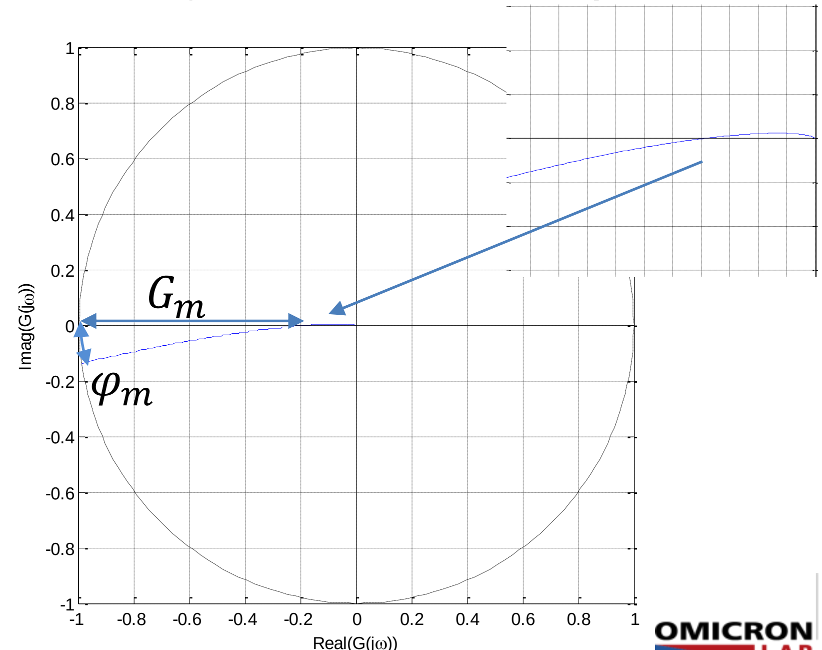
Gain Margin

Second order system → no Gain Margin (phase never reaches -180°). Parasitics the systems → > second order. → Gain Margin

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



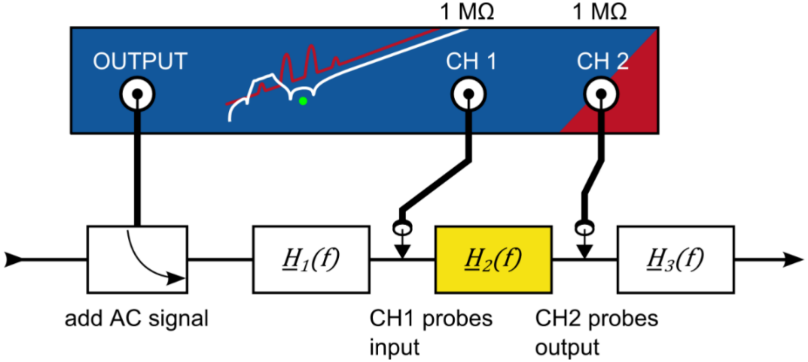


Why Measuring Stability?

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

Measuring Transfer Functions (Gain/Phase)

Bode 100 measures the transfer function $\underline{H}_2$ from CH1 to CH2



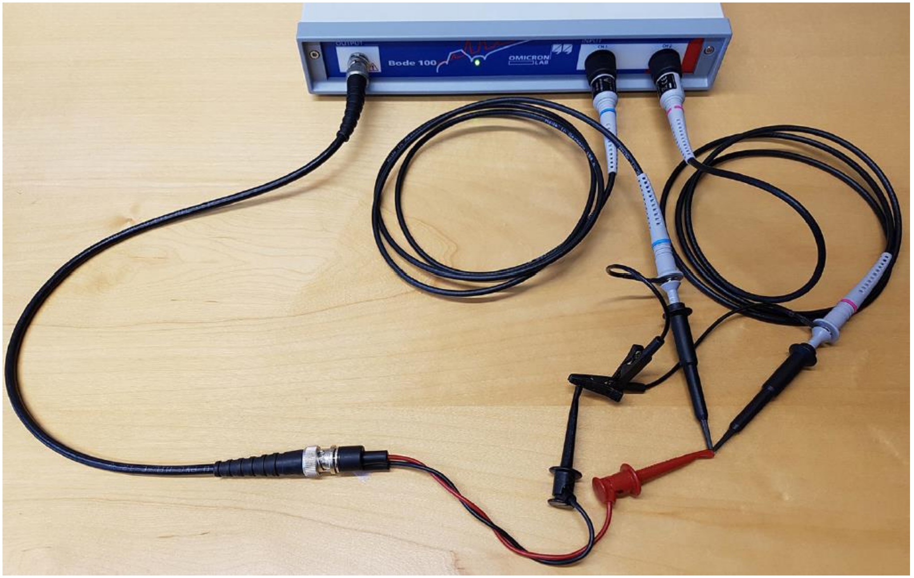
$$Gain = \frac{V_{CH2}}{V_{CH1}}$$

- The signal path from Output to H_2 is not part of the measurement result!
- A transfer function can only be measured / defined for an LTI system
- In case of a switching converter only **once** per **switching cycle** a **new duty** cycle value is created. Therefore the control loop can only react to frequencies up to ${}^{f_s}/_{2}$.

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

Is Calibration Necessary?

- Normally not. Basic accuracy of the setup should be sufficient.
- Not sure? → Check it out!

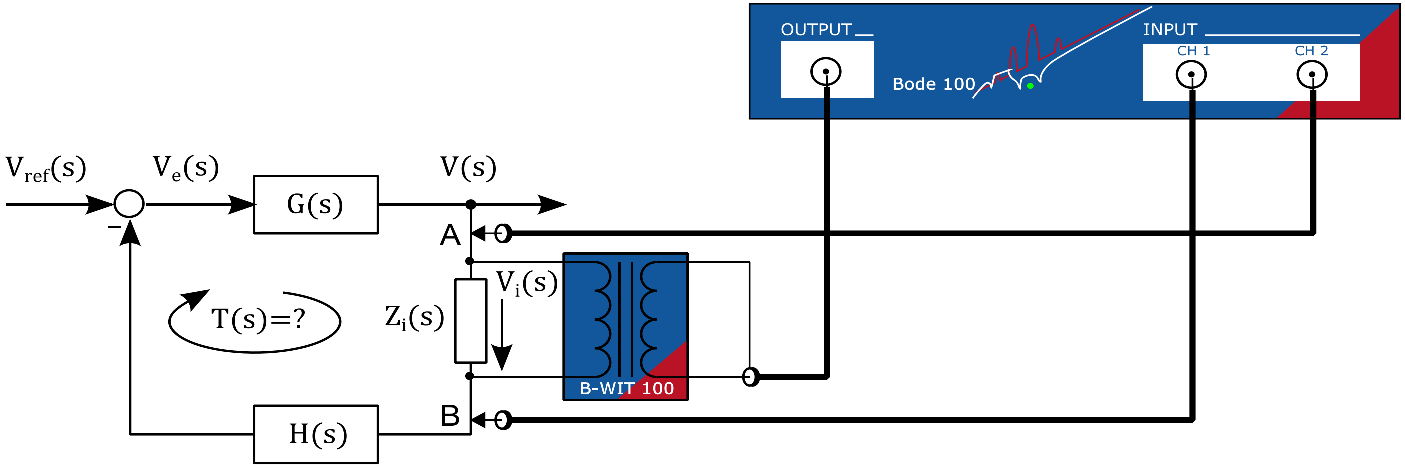


Should result in a flat line at 0 dB and 0°

Measuring Loop Gain (Voltage Injection)

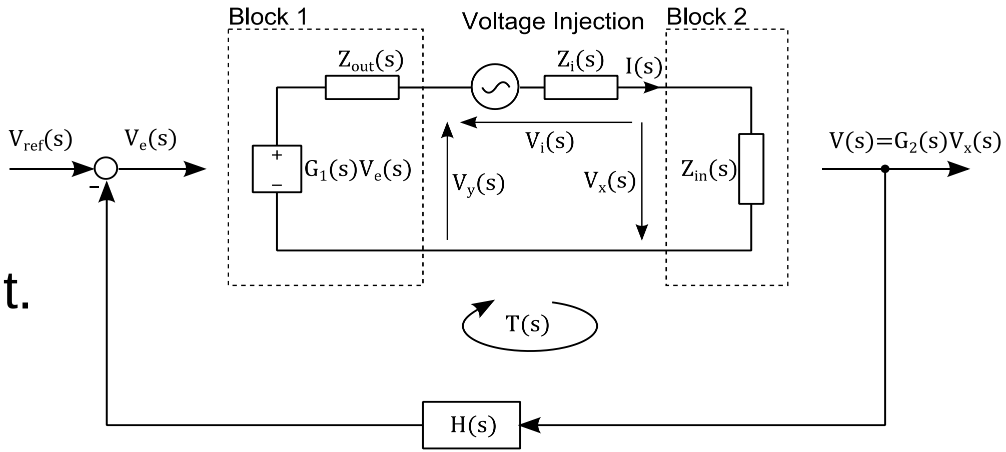
Loop gain is measured by "breaking" the loop at the injection point and inserting a "small" injection resistor (e.g. 10 Ω).

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



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 $T_v(s)$

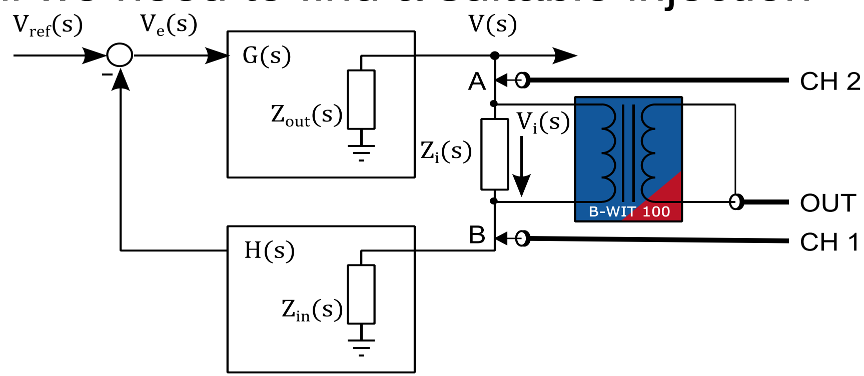
$$T_v(s) = \frac{V_y(s)}{V_x(s)} = T(s)\underbrace{\left(1 + \frac{Z_{out}(s)}{Z_{in}(s)}\right)}_{1^{st}\ term} + \underbrace{\frac{Z_{out}(s)}{Z_{in}(s)}}_{2^{nd}\ term}$$

≈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 that fulfills the two conditions:

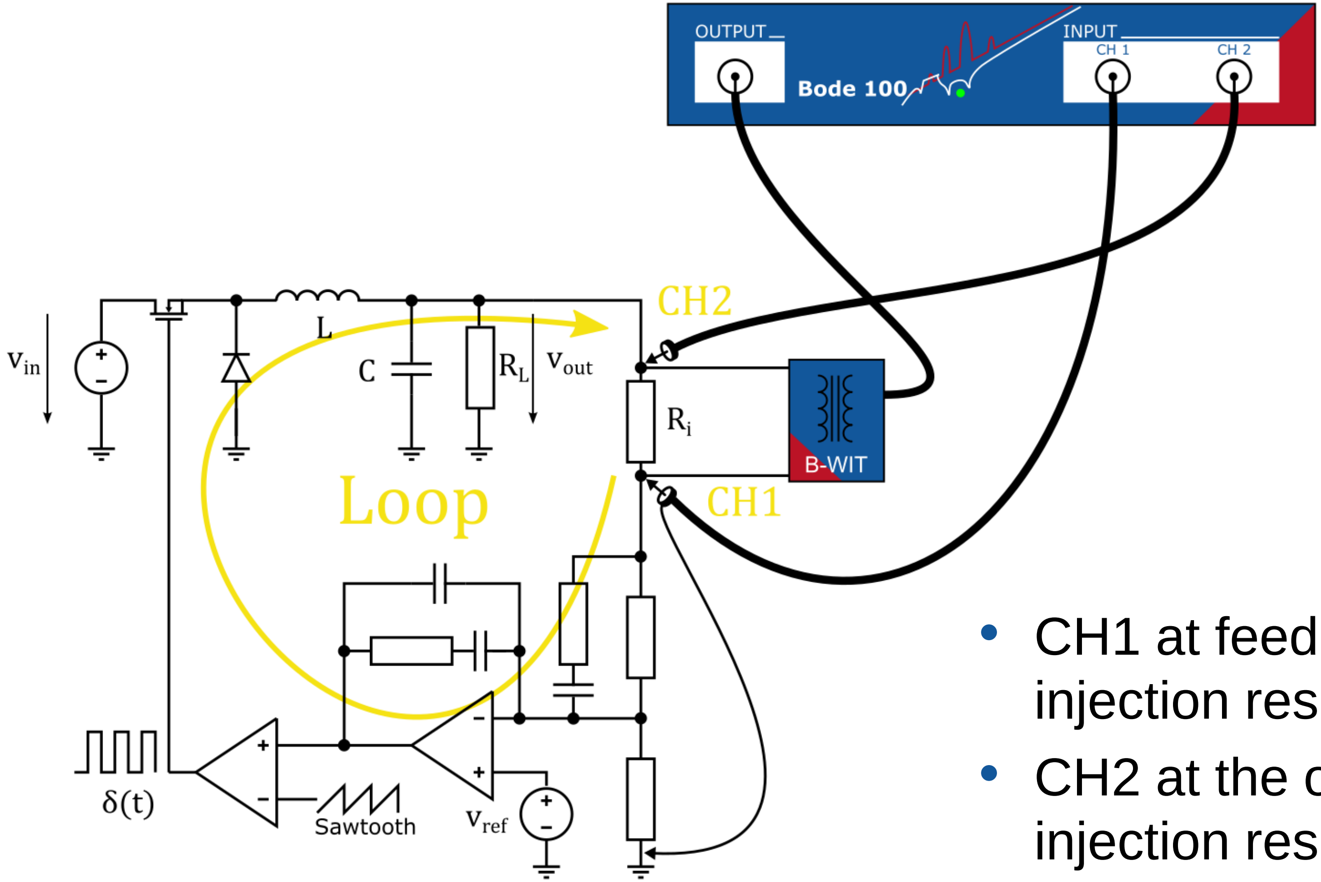


1. $|Z_{in}| \gg |Z_{out}|$
2. $|T| \gg \left|\frac{Z_{out}}{Z_{in}}\right|$
3. Ensure that **no parallel** signal **path bypassing** the injection point!

Generally well suited points:

- Output of a voltage source
- Input of an operational amplifier
- Output of an operational amplifier
- Best between two op-amps

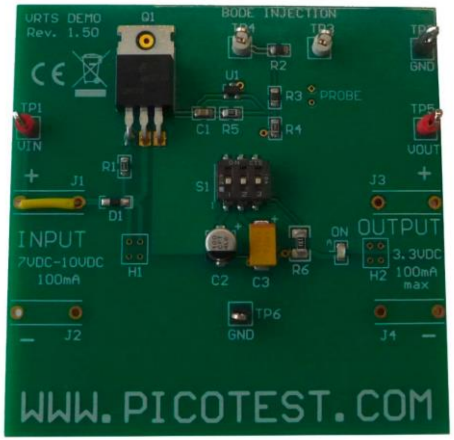
Measure the Loop in a Buck

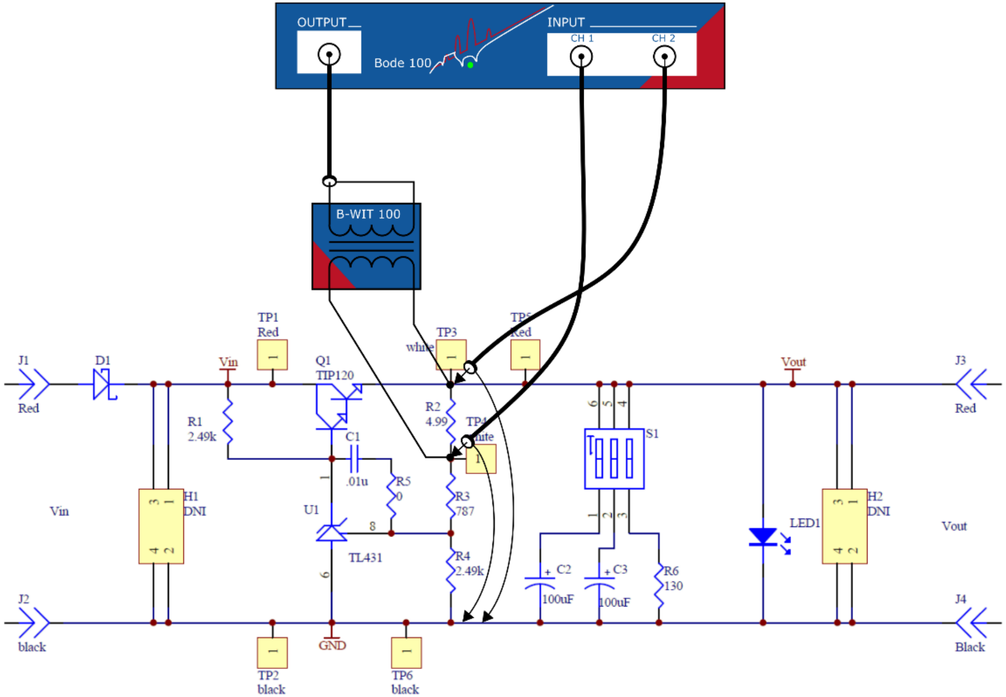


- CH1 at feedback-side of the injection resistor
- CH2 at the output-side of the injection resistor

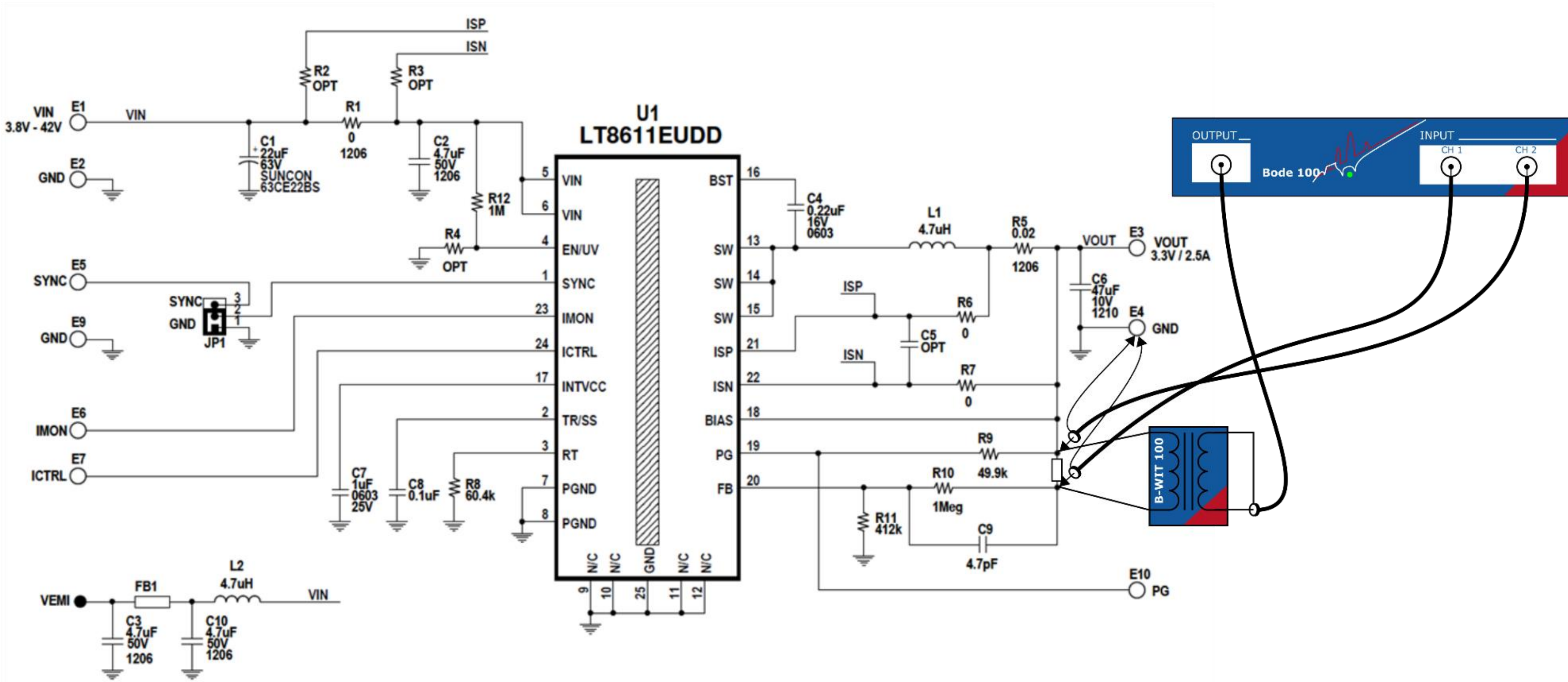
Some Injection Point Examples

VRTS 1.5 Linear regulator with 3.3V output voltage.





Step Down Converter: Demo 1750A



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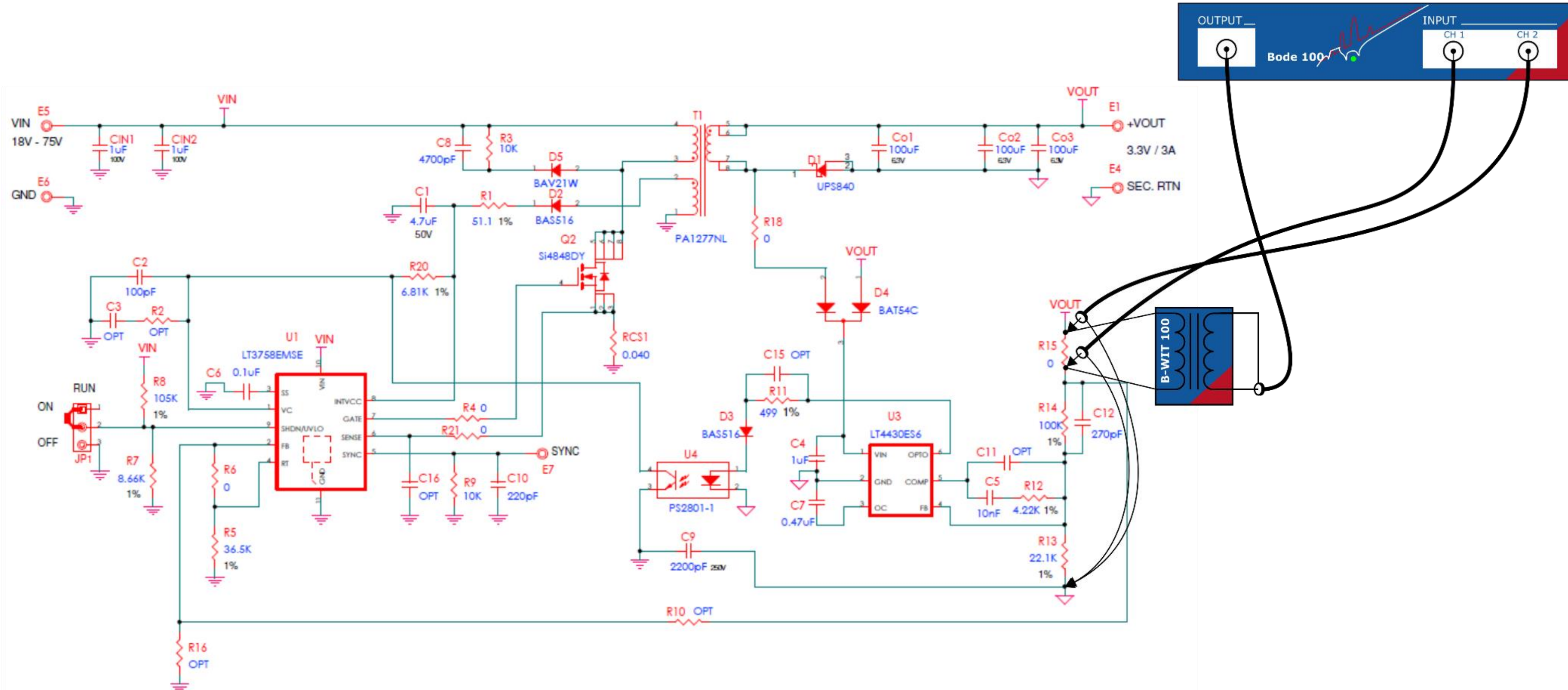
Flyback Converter: Demo 1412A

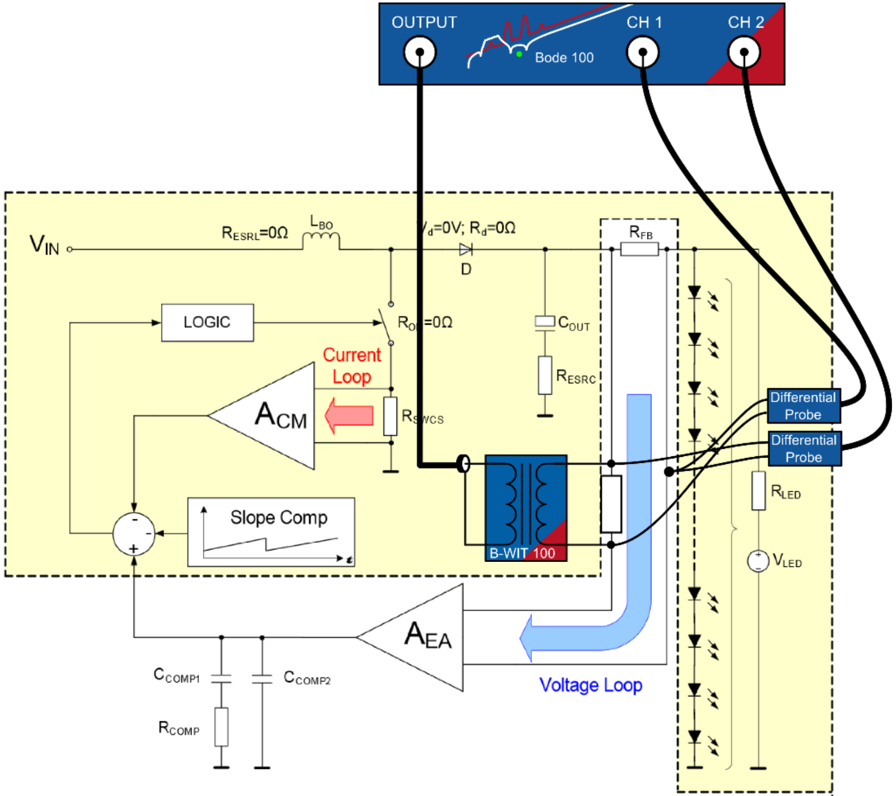


Voltage Loop Gain Example

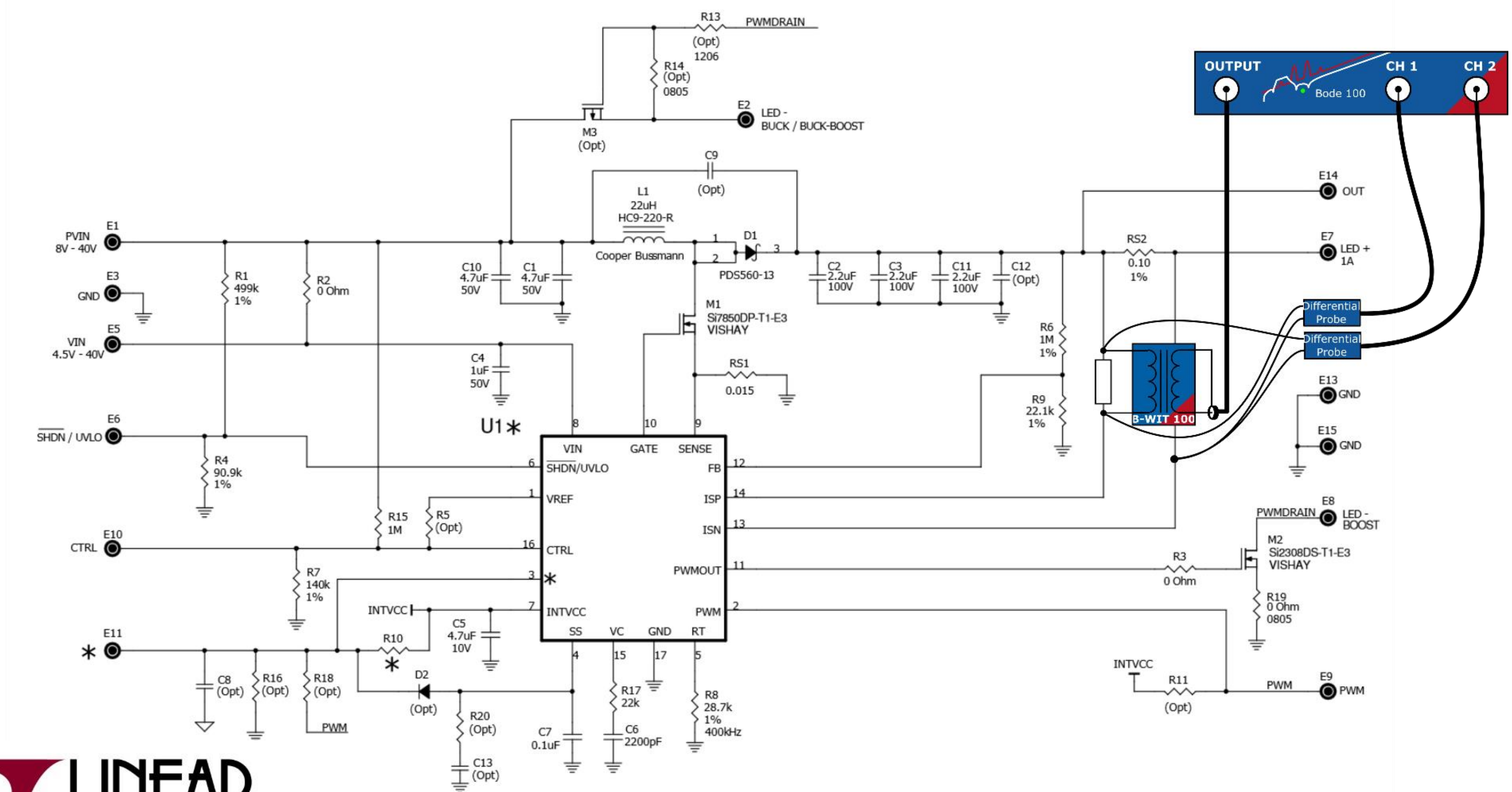
TLD5098 LED Driver board.

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 (>>)



High Voltage LED Driver: Demo 1268b-A



Reading Phase Margin from Measurement

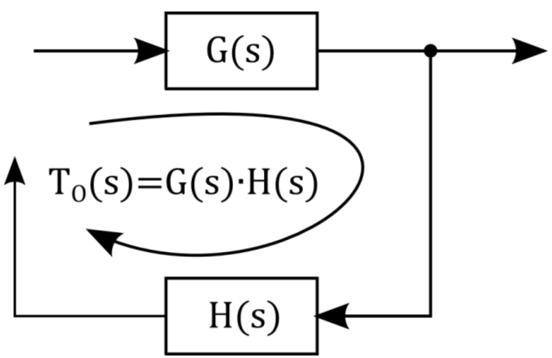
Phase Margin is read directly from the measurement!

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

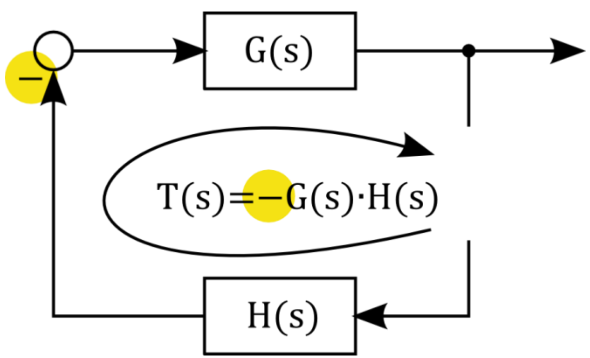
Reason: We measure in the closed loop system → our signal will run through the inverting error amp and get an additional 180° phase shift.

→ The instability point is at +1!

Theoretical open loop gain $T_o(s)$



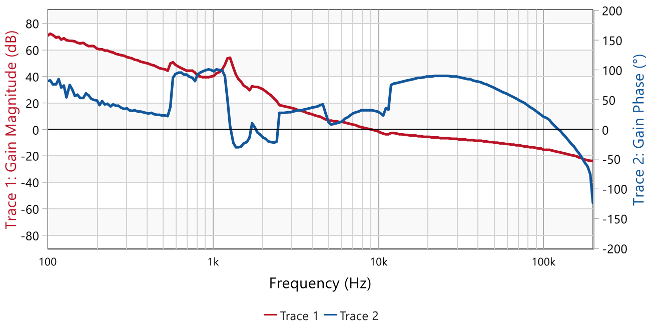
Measured loop gain $T_v(s)$

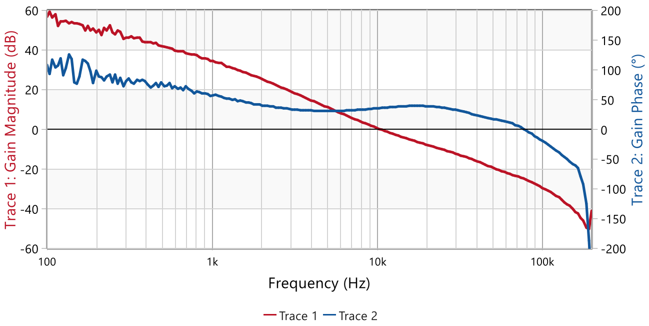


Injection Signal Size

Small signal models (linear) are used to design the compensator
→ Measurement signal should be "small signal"
→ Measurement result must be independent of signal size!

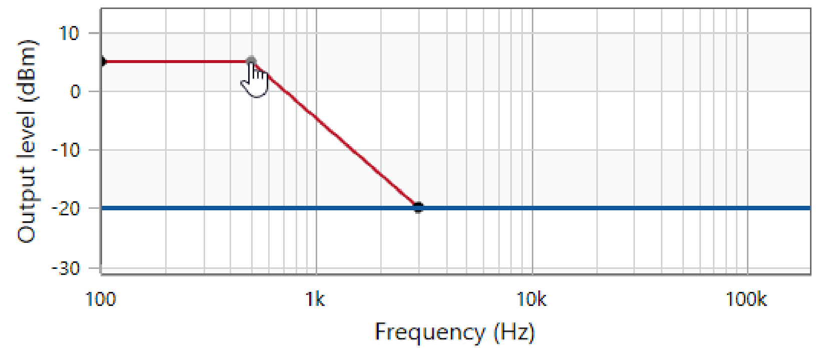
1. Choose an injection signal level and measure
2. Reduce the injection signal by e.g. 10dB
→ If the result changes → do **further reduce** until it stays constant!

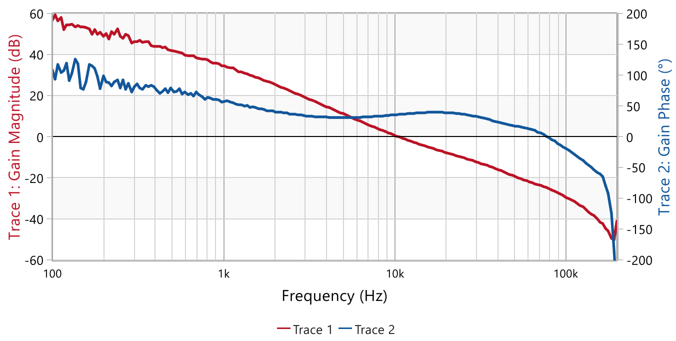


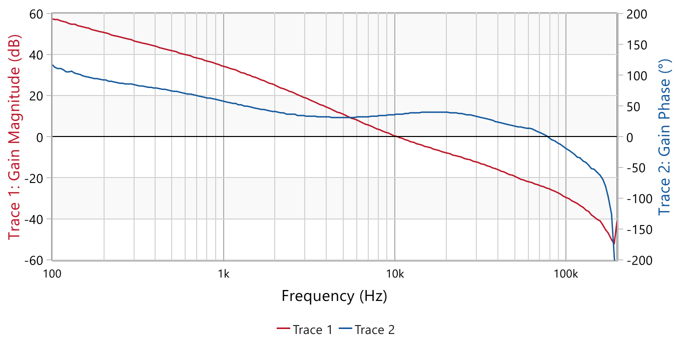


Shaped Level

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







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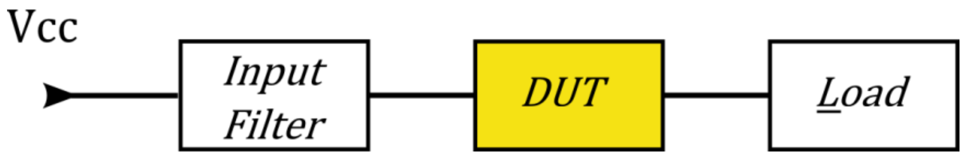
Please consider

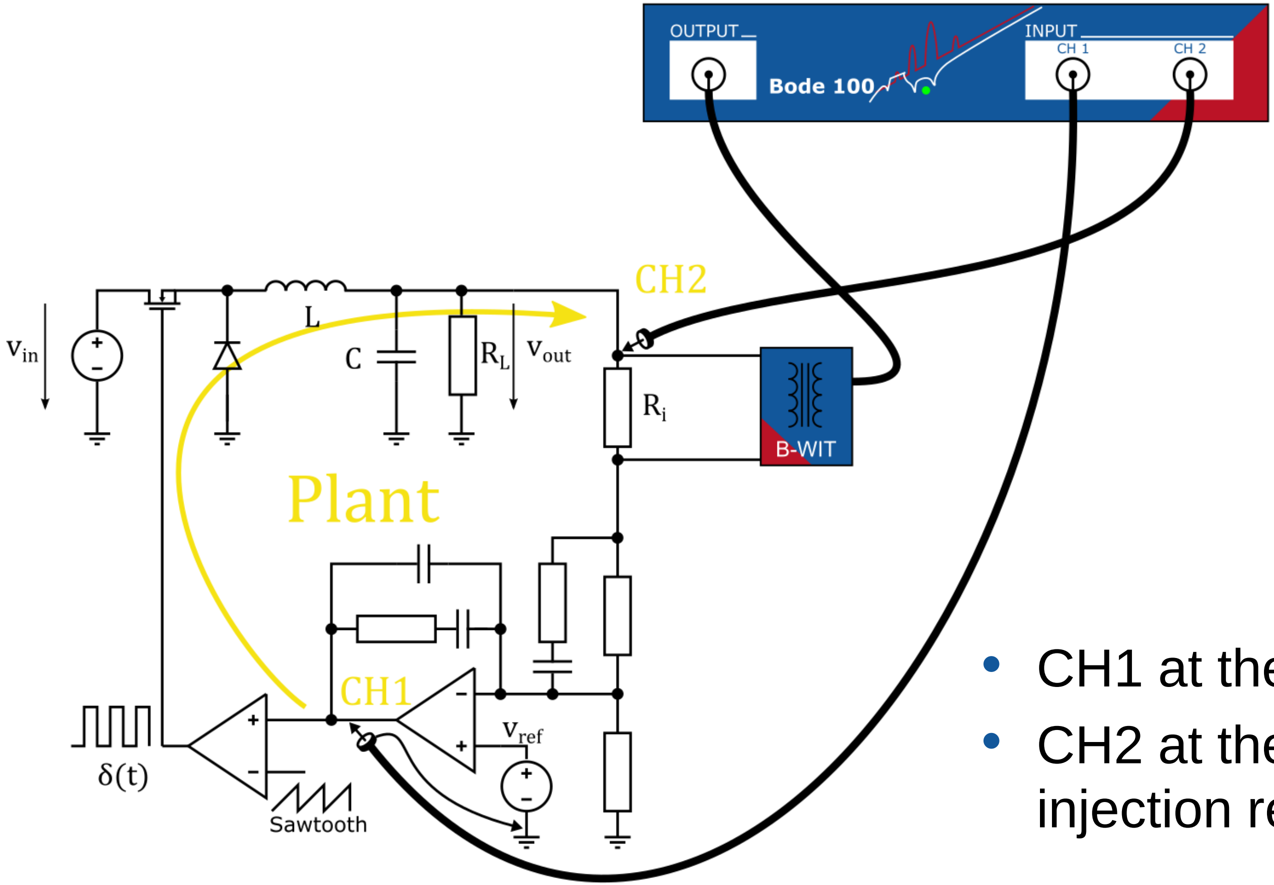


- The input filter can influence the stability (Middlebrook)
- The load can influence the measurement or plant transfer function
- The operating point can influence the plant transfer function

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

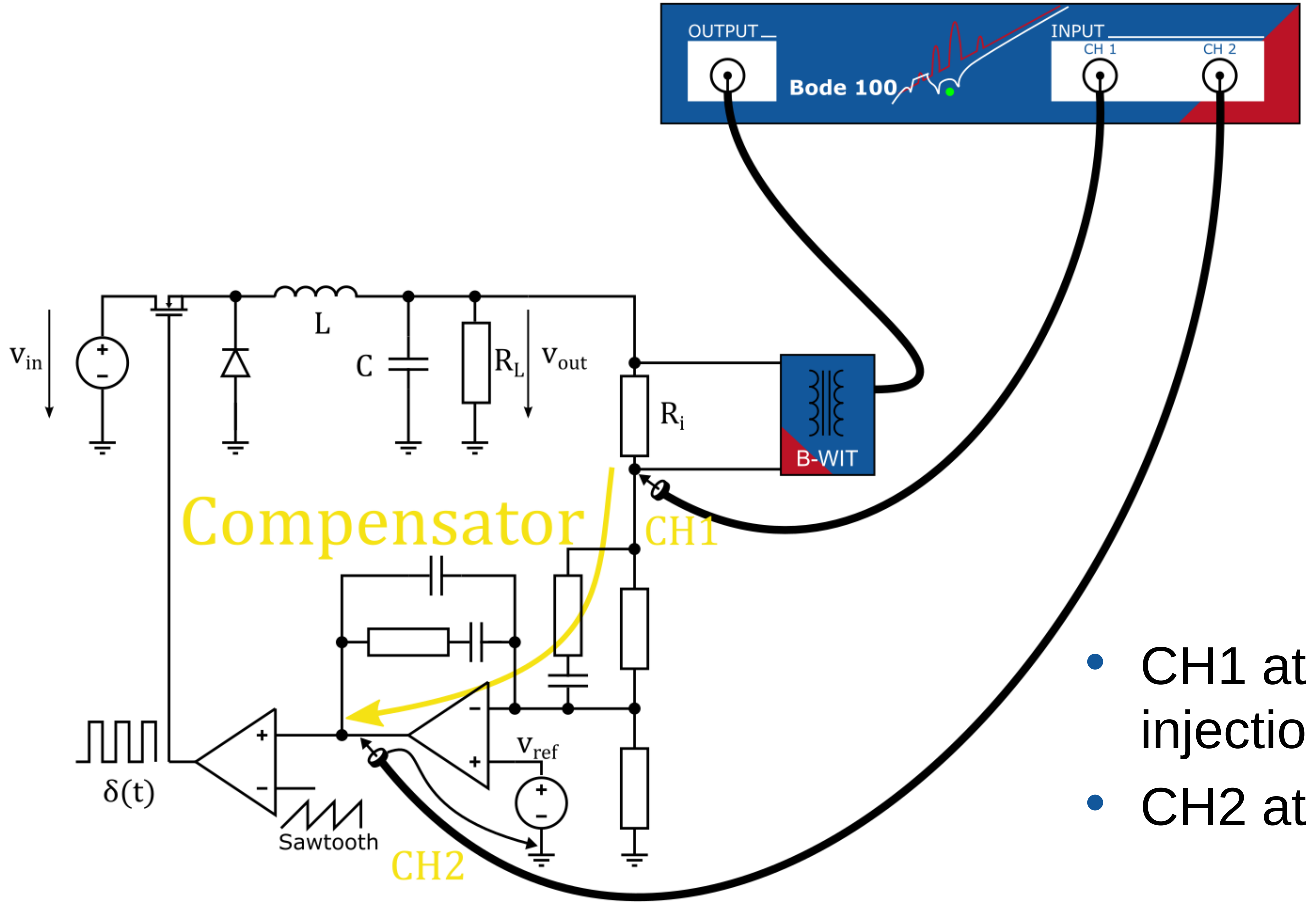
Note: Electronic loads can cause strange effects if their control loop interacts with the system.

Measure the Plant in Analog Control



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

Measure the Compensator in Analog Control



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

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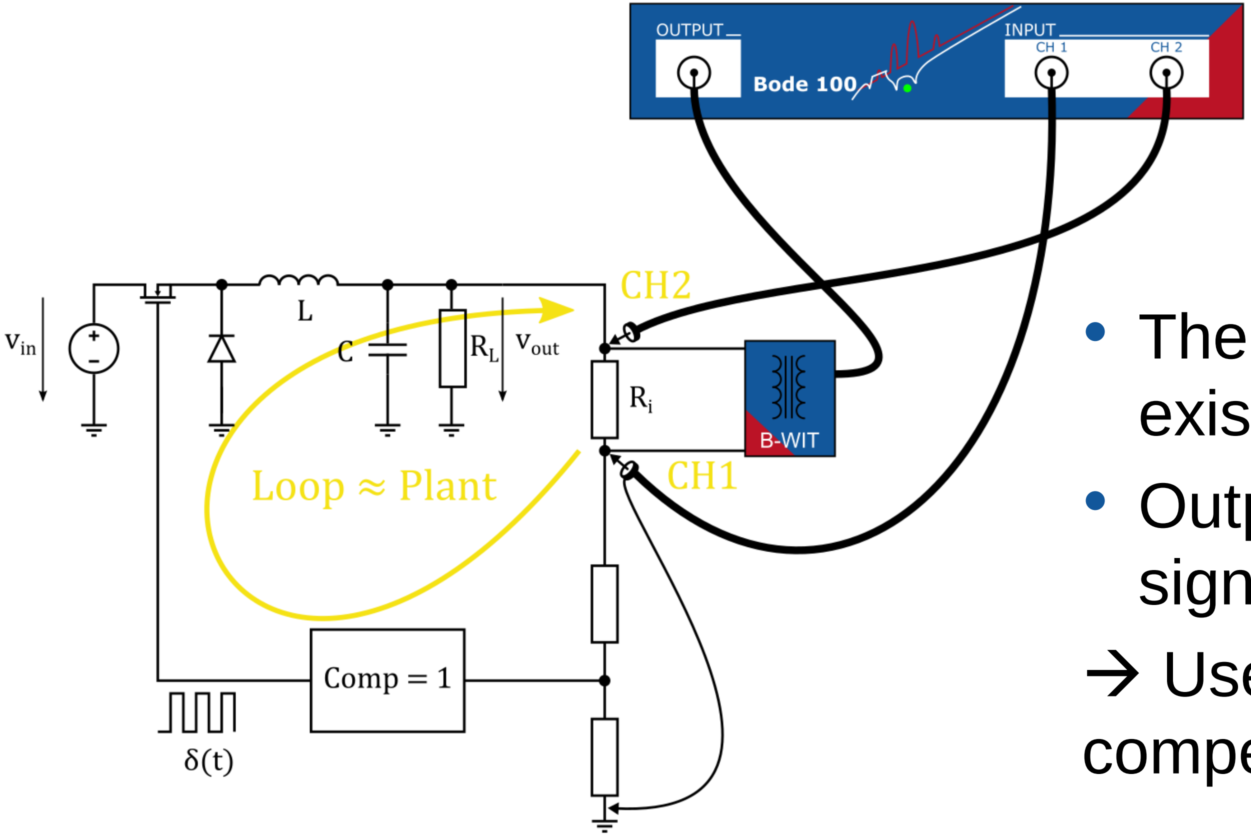
Measure the Plant in Digital System



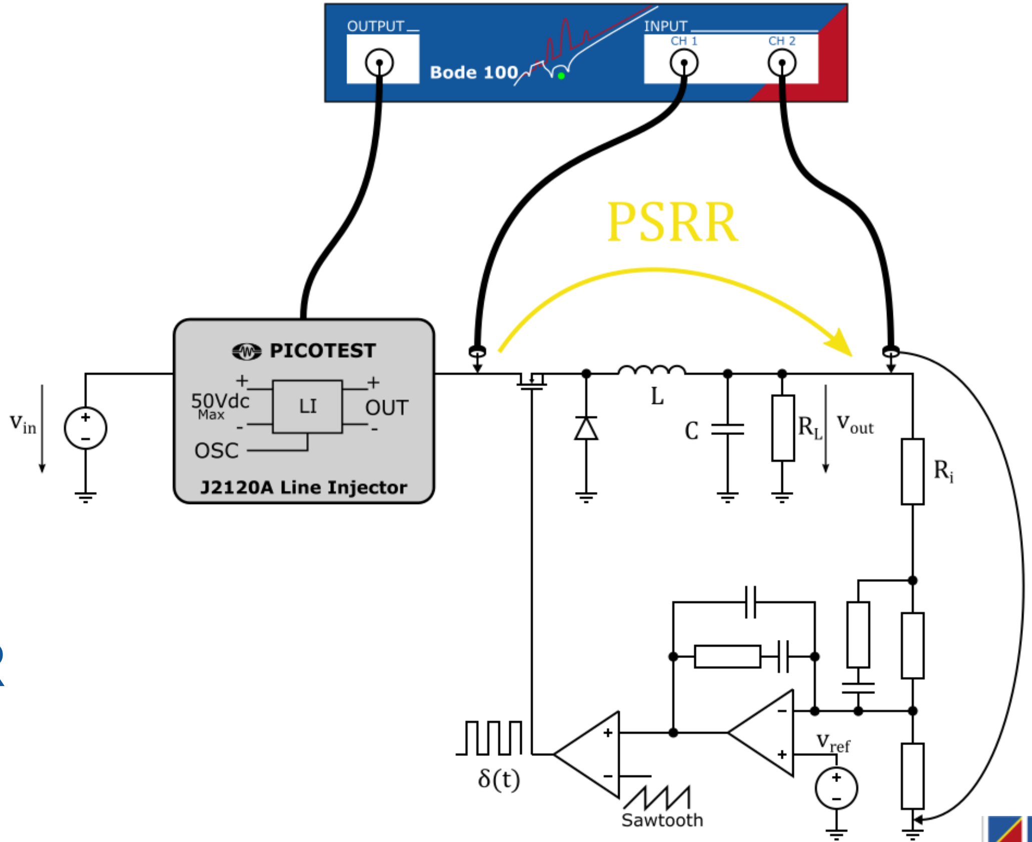
- The COMP-pin is not existing (in Processor)
- Output is duty-cycle signal

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

Measuring Line-Output (PSRR)

- Modulate the line using e.g. a Picotest injector
  - J2120A (5A 40V)
  - J2121A (20A 400V)
- Connect CH1 to input
- Connect CH2 to output

→ Result: line-to-output transfer function or PSRR

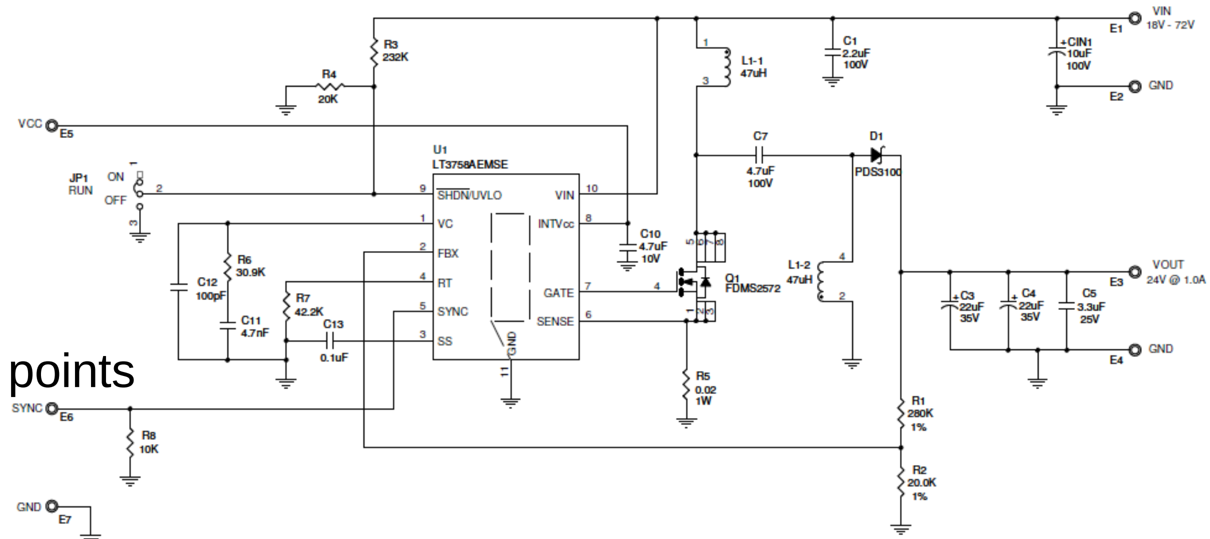


Hands-On a SEPIC!

Linear (Analog) Demo Circuit 1342B

- Input: 18 V – 72 V, Output: 24V, 1A
- Switching frequency 300 kHz

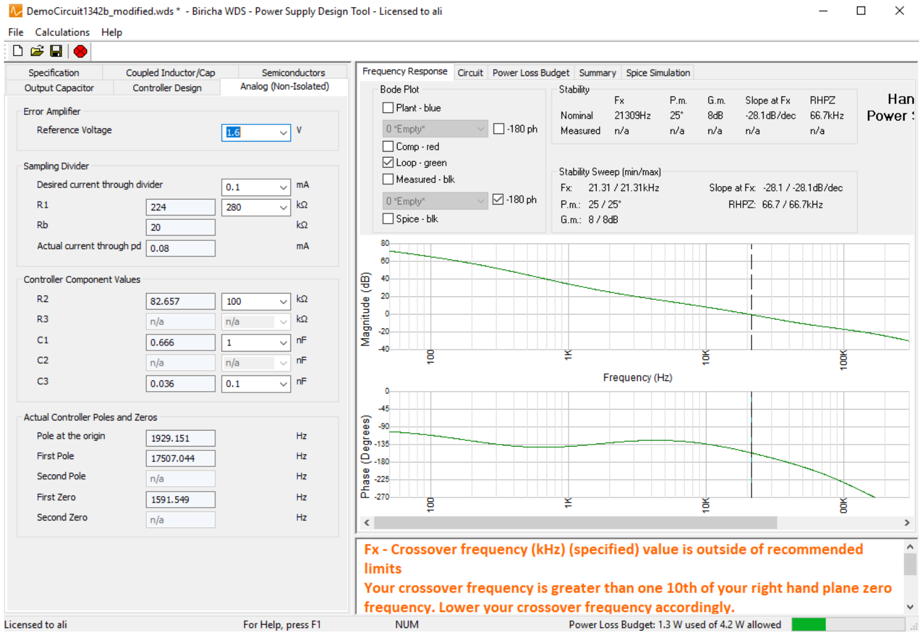
- Stability information
  - Crossover frequency ≈ 8 kHz
  - Phase Margin > 65° in all operating points
  - → Very stable control loop design
  - → Too boring - let's modify the control loop



Making Things “*more Interesting*”

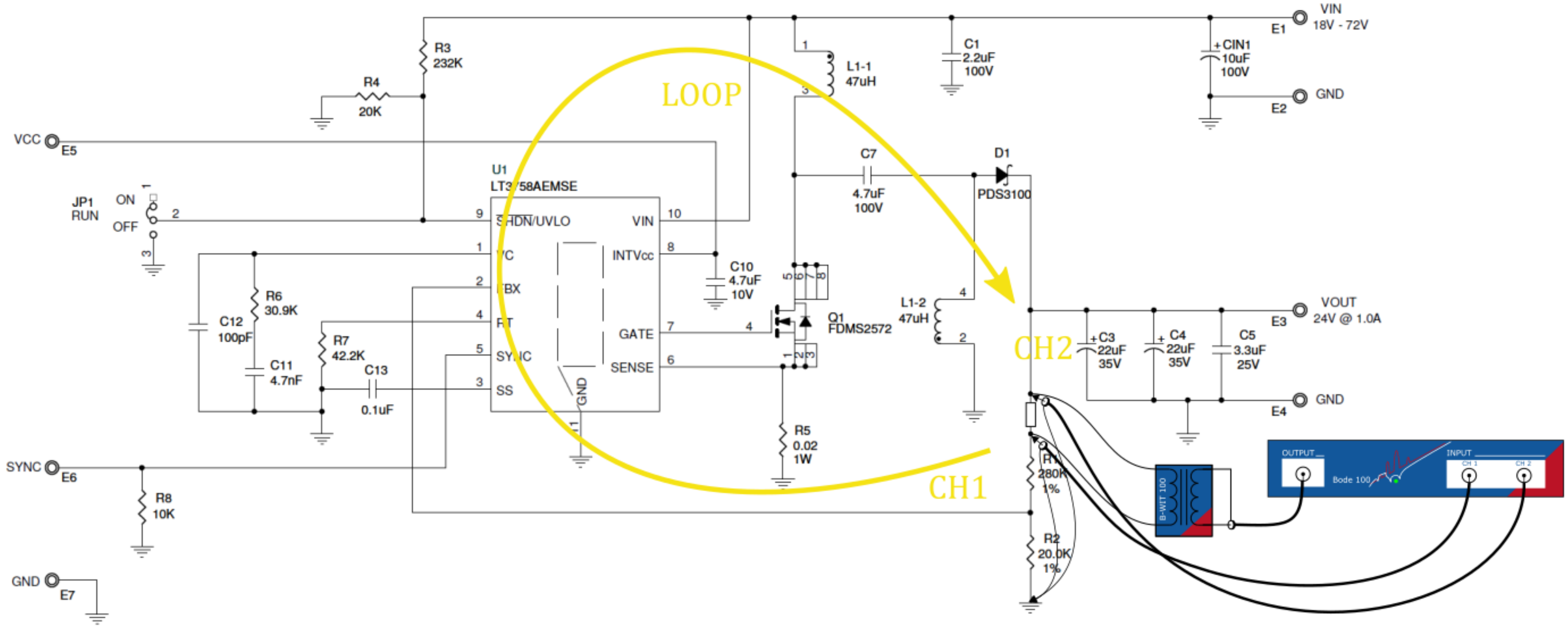
1. Simulate circuit in Biricha WDS
2. Verify simulation with Bode 100
3. Modify Type II Transconductance compensator for less phase margin
4. Solder new component values on the board

	Original	Modified
R6	30.6 kΩ	100 kΩ
C11	4.7 nF	1 nF
C12	100 pF	100 pF

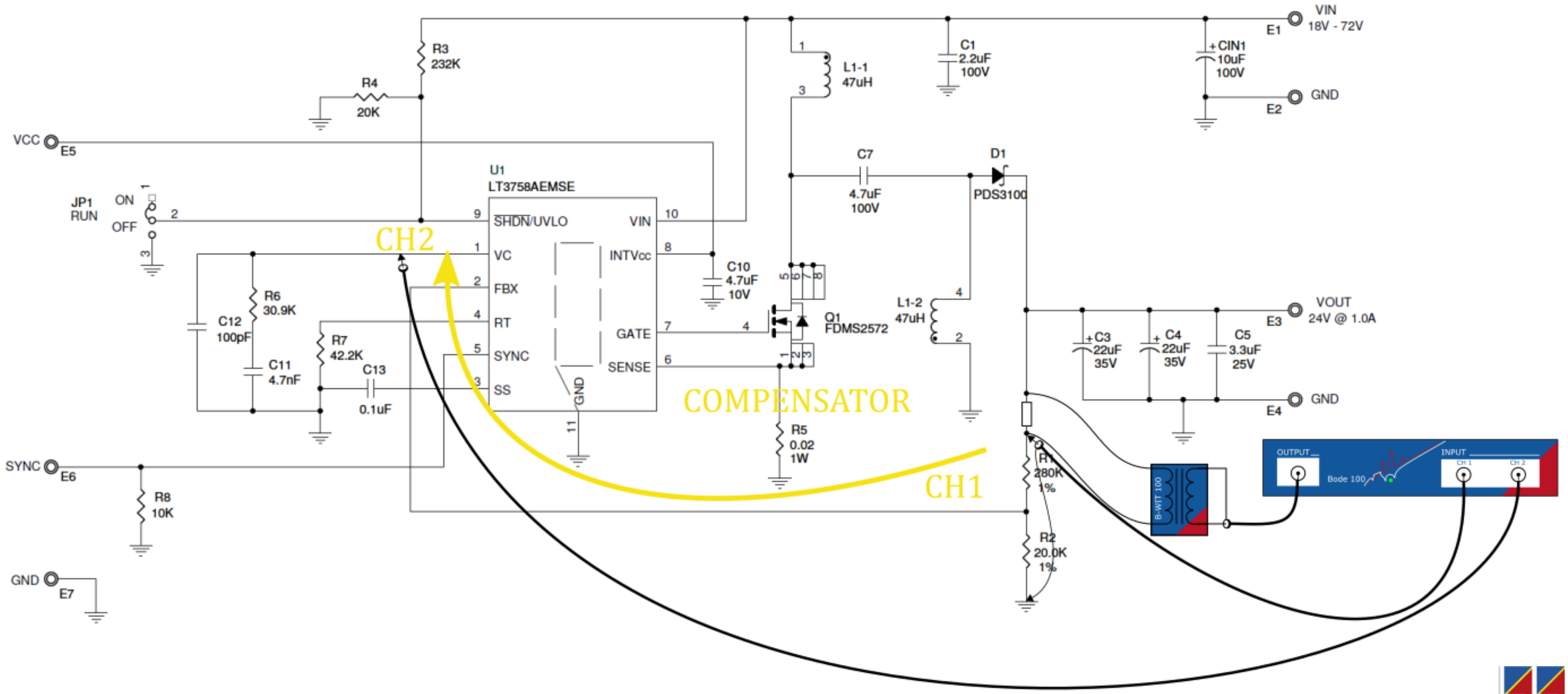


Biricha WDS Design Software
(www.biricha.com)

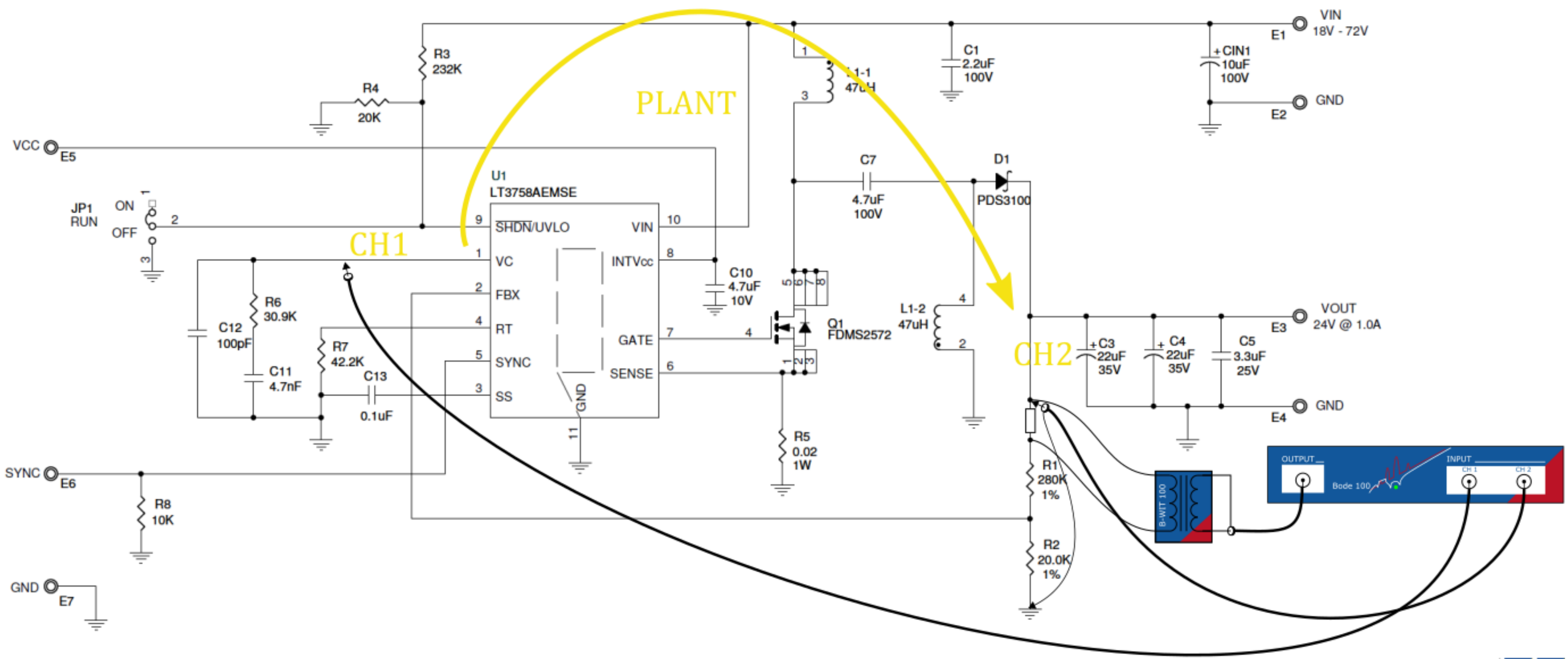
Measuring the Loop of the 1342B



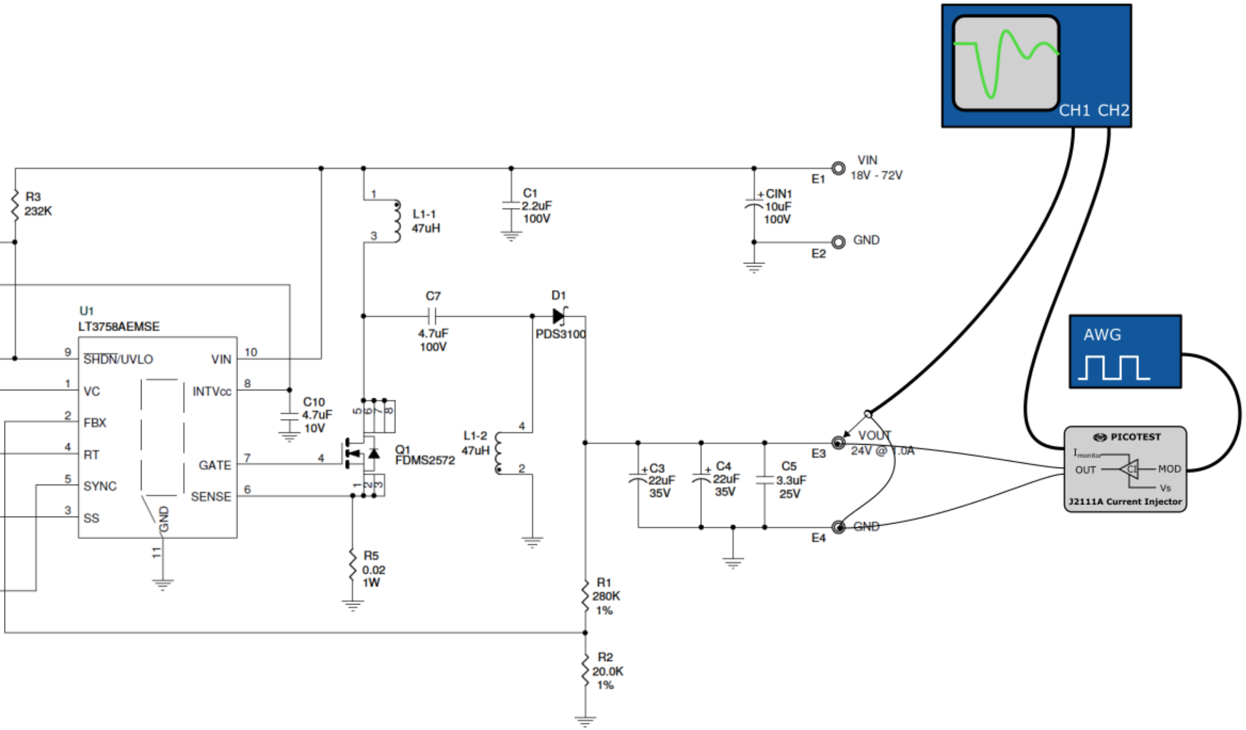
Measure the Compensator



Measure the Plant of the 1342B



Small-Signal Step-Load Response



- Trigger to repetitive load steps
- Use averaging to remove switching ripple and noise
- → Small signal stability in time-domain

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/

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!

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