Power Supply Design Seminar

Considerations for Measuring Loop Gain in Power Supplies

Reproduced from
2018Texas Instruments Power Supply Design Seminar SEM2300
TI Literature Number: SLUP387

Power Supplyt Design Seminar resources are available at: **www.ti.com/psds**

Texas Instruments

Considerations for Measuring Loop Gain in Power Supplies

Manjing Xie

Outline

- Introduction – loop gain overview
- Empirical loop gain measurement methods
- Test setup and test examples
  - Frequency analyzer setup
  - Preparing converter for loop gain measurement
  - Connecting equipment to circuit under test
- Summary

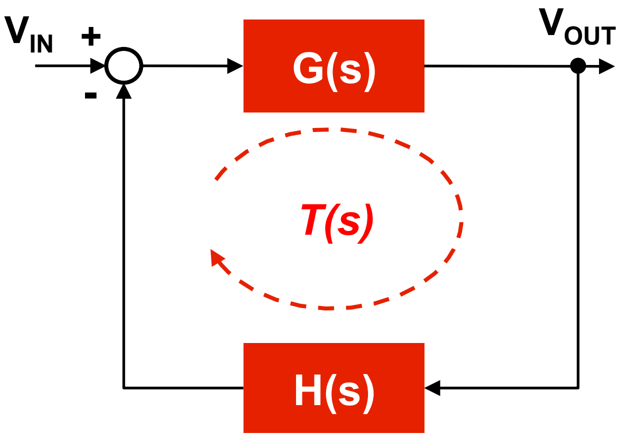
Introduction – Loop Gain Overview

- What is loop gain?
- Why do we measure loop gain?

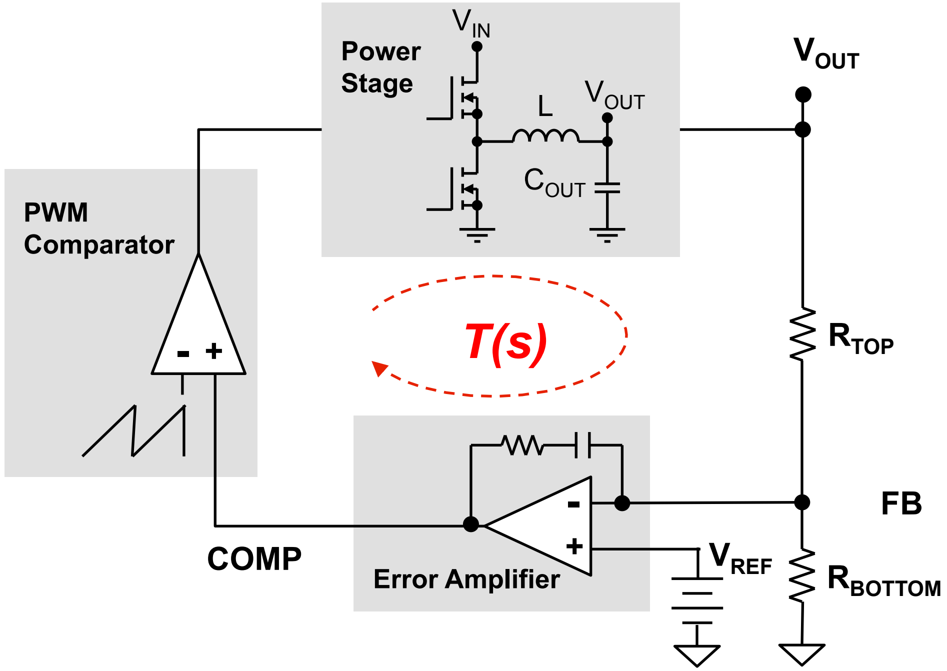
Introduction – What Is Loop Gain?

Loop gain: product of all gains around feedback loop

$$T(s)=G(s)\cdot H(s)$$



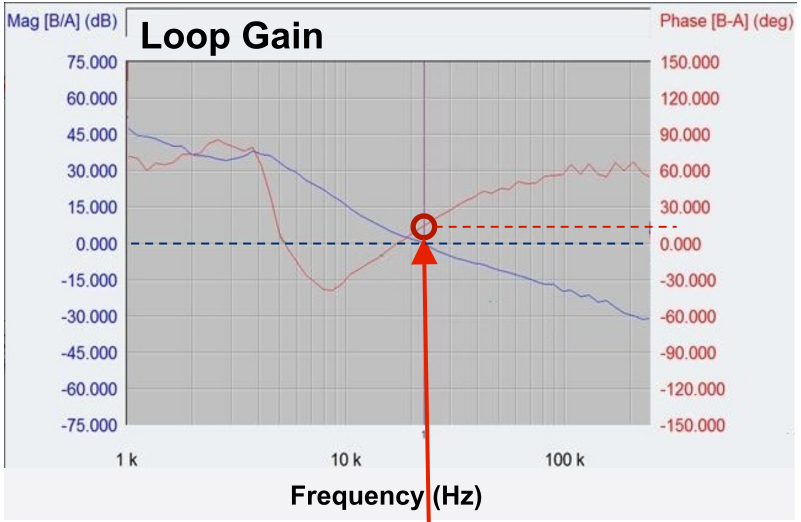
Simple Feedback System

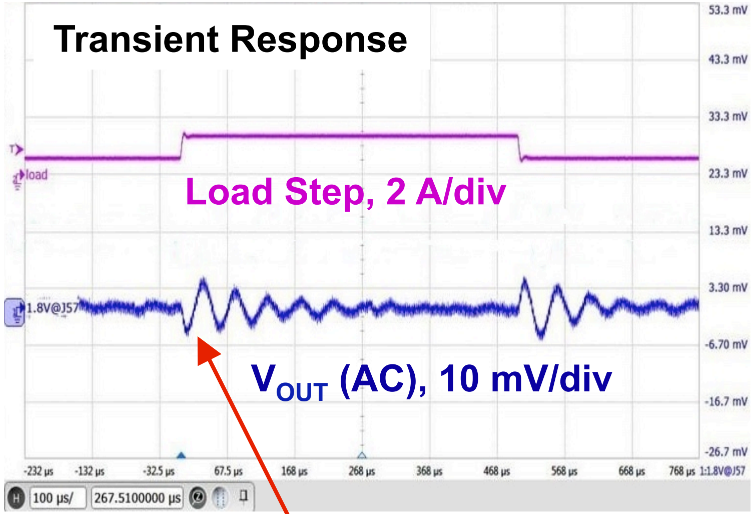


DC/DC Converter Control System

Why Do We Measure Loop Gain?

1) Loop gain is good indicator of stability



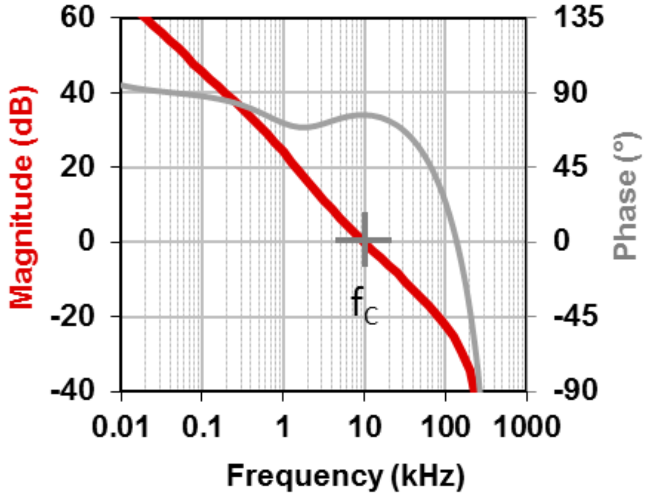


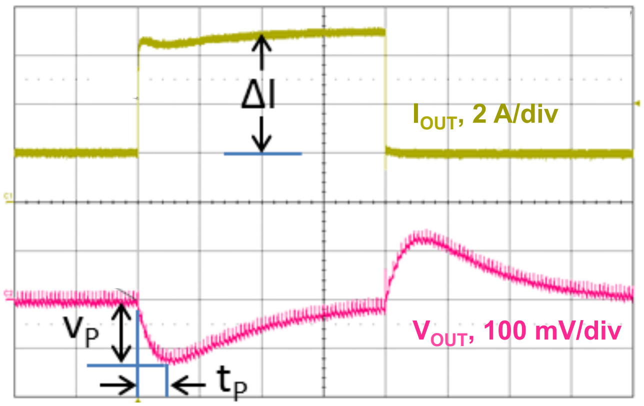
f_C = 22.4 kHz
Phase Margin = 15 º

Output Oscillates at about 20 kHz

Why Do We Measure Loop Gain?

2) Loop gain results guide us to improve load transient response





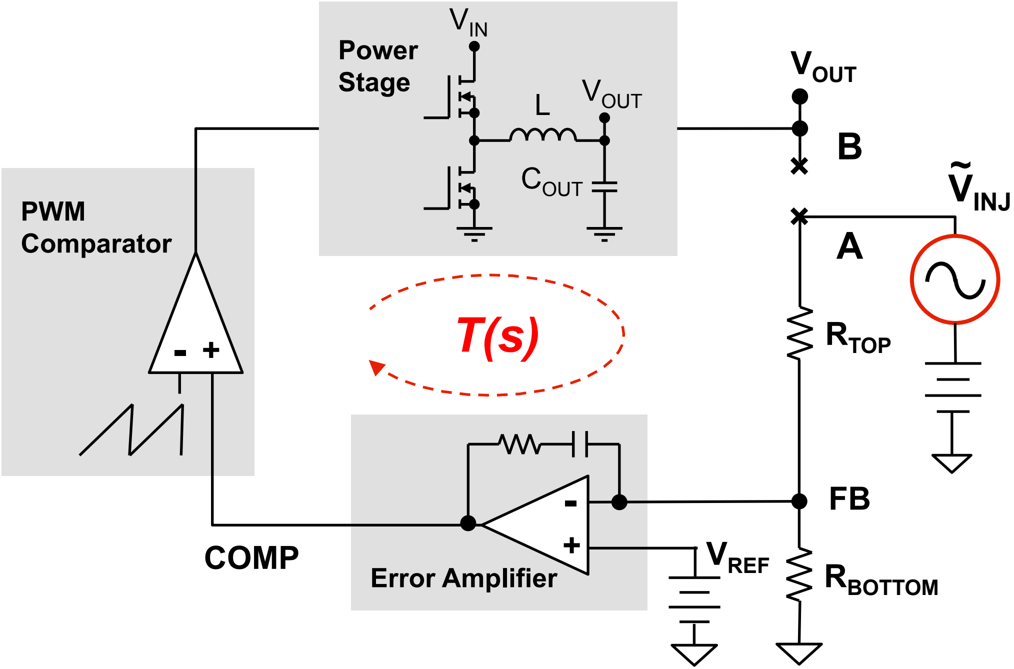
$$t_P = \frac{1}{4 \cdot f_C}$$

$$V_P = \frac{\Delta I}{8 \cdot f_C \cdot C_{OUT}}$$

Given the loop is stable, higher loop bandwidth improves transient response [1]

Loop Gain Measurement Method

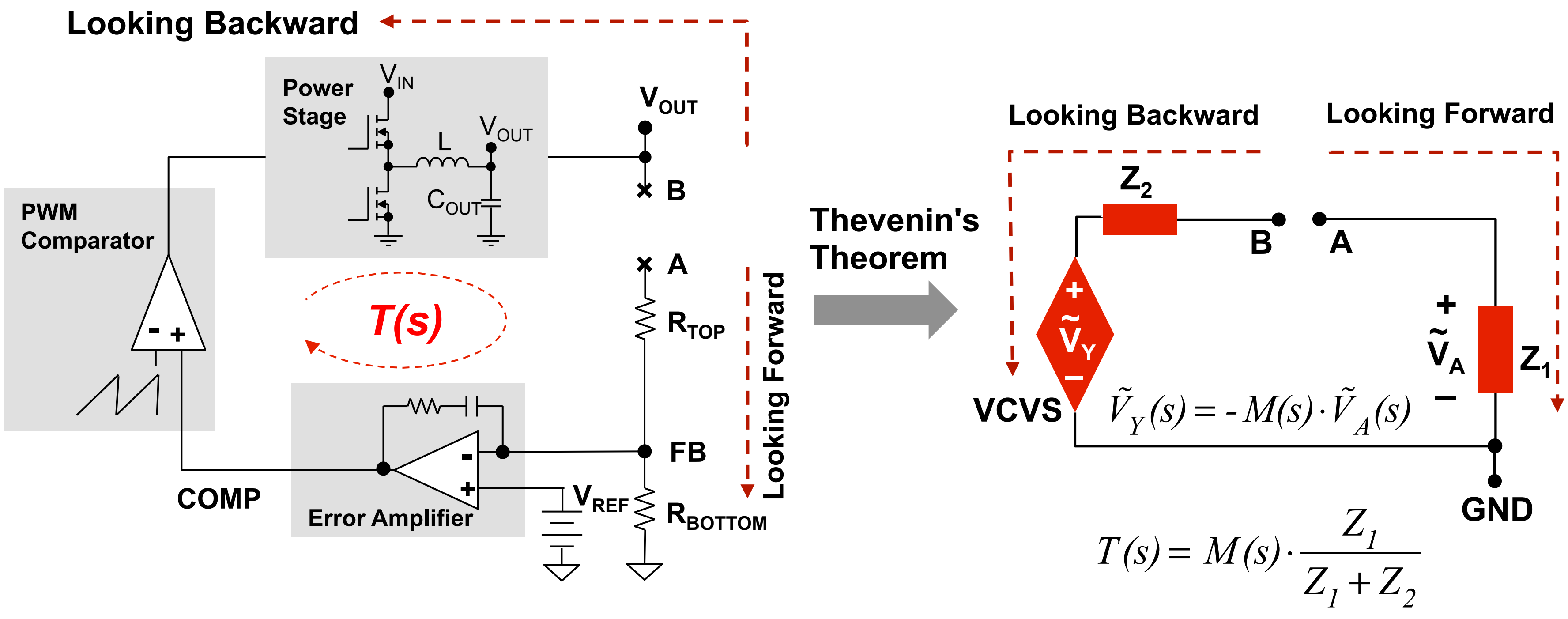
Loop Gain Measured in Open-Loop Setup



- Difficult to maintain correct DC operating point due to high DC gain
- Easy to saturate circuits by injecting too much AC disturbance

✗ It is not practical to measure loop gain in open-loop setup

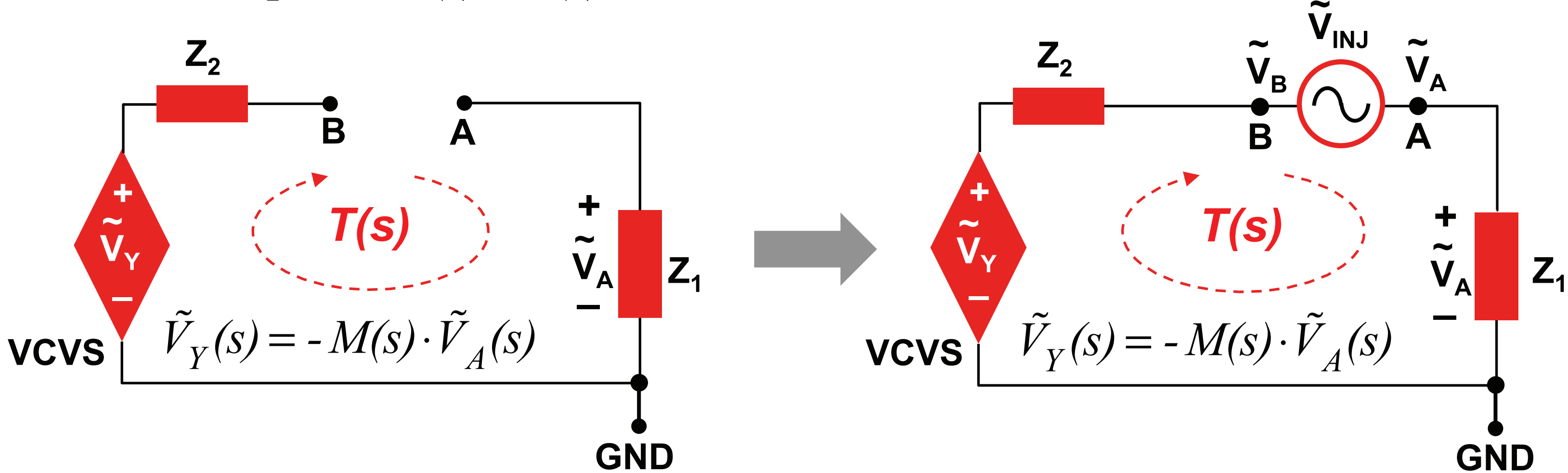
Equivalent Circuit of Feedback System



Loop Gain Measurement – Voltage Injection Method

When Z_2 = 0 Ω, $T(s)=M(s)$

Measure open loop gain with feedback loop closed



System closed-loop response: $\tilde{V}_B(s) = \dfrac{T(s)}{1+T(s)}\tilde{V}_{INJ}(s), \quad \tilde{V}_A(s) = \dfrac{-1}{1+T(s)}\tilde{V}_{INJ}(s)$ **when z_2 = 0 Ω**

System open-loop gain: $T(s) = -\dfrac{\tilde{V}_B(s)}{\tilde{V}_A(s)}$ **when Z_2 = 0 Ω**

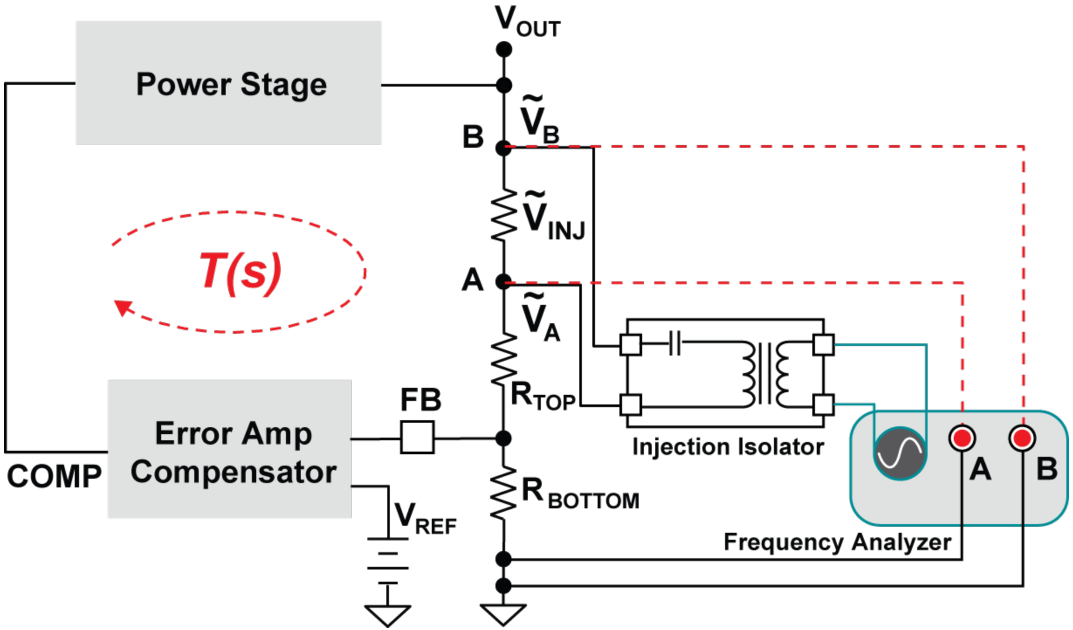
Derivation

Test Setup

- Frequency analyzer setup
- Selecting the correct injection isolator
- Preparing converter for loop gain measurement
- Minimizing error

Typical Loop Gain Measurement Setup

- **Setting up equipment**
  - Frequency analyzer
  - Source injection isolator
- **Setting up power supply**
  - Identify voltage injection point
  - Connect equipment to circuit



Frequency Analyzer's Functions

- Provides AC voltage source: $\tilde{V}_{SRC}$
- Measures response: $\tilde{V}_A$ *and* $\tilde{V}_B$
- Calculates loop gain: $T(s) = -\dfrac{\tilde{V}_B}{\tilde{V}_A}$

Receiver A

Receiver B

Voltage Source

R_{OUT} = 50 Ω

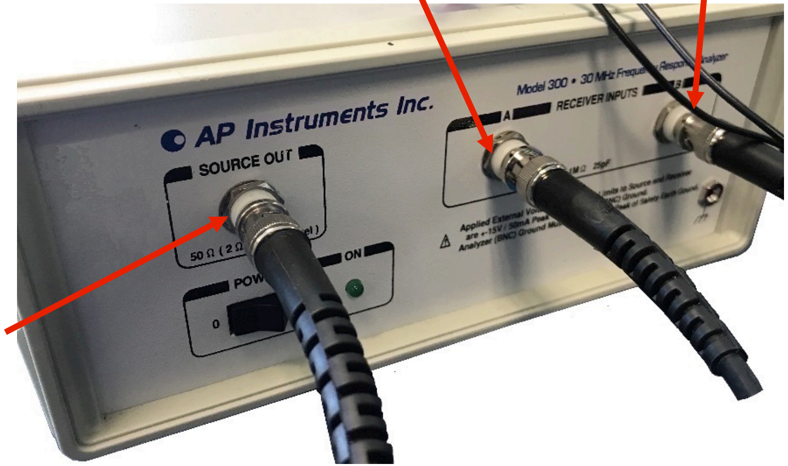
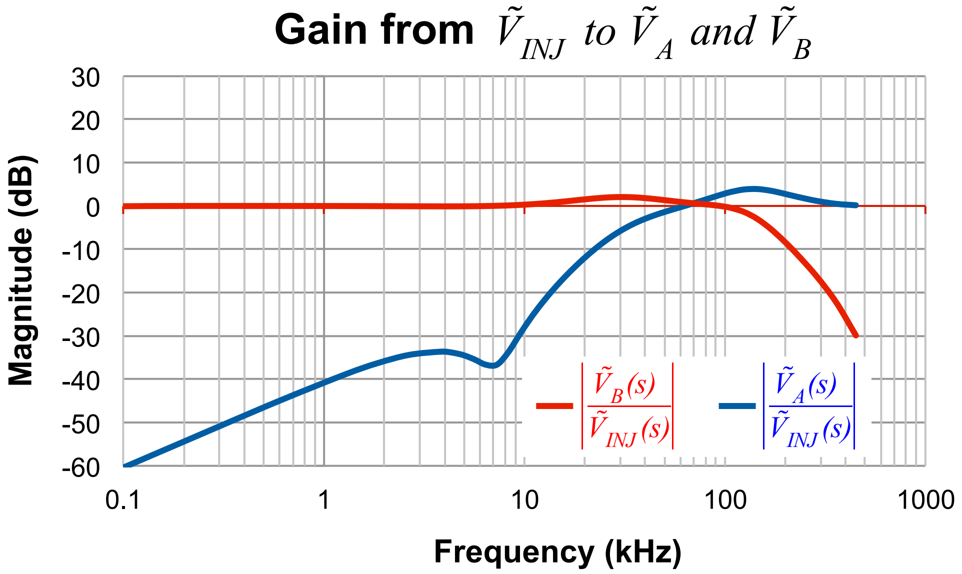


Image reproduced with permission from AP Instruments, Inc.

Injecting Sufficient AC Voltage

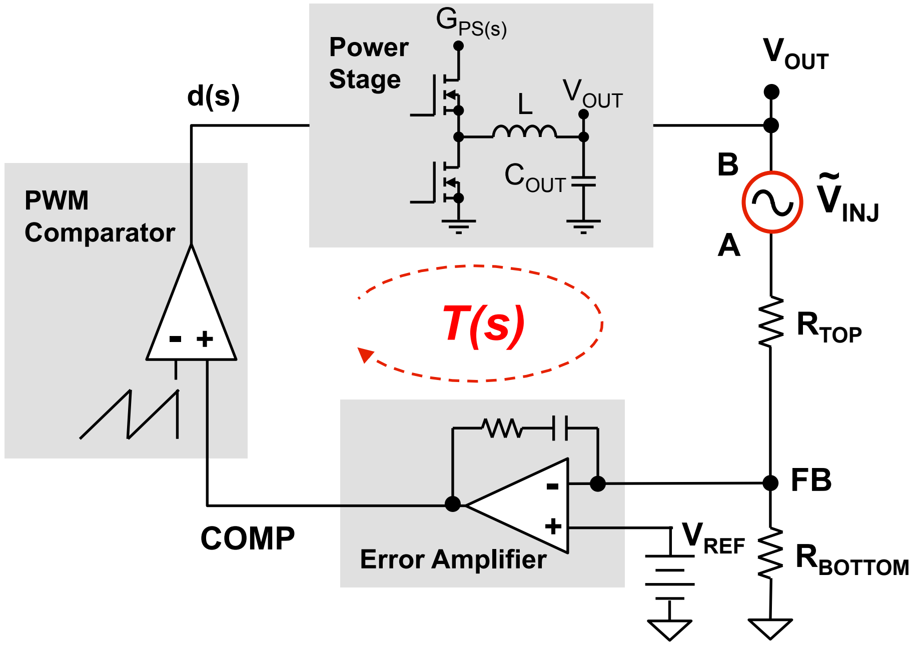
AP300 Specification:	Measurable Signal Range	5 µV to 1.77 V

System closed-loop response: $\tilde{V}_B(s) = \dfrac{T(s)}{1+T(s)}\tilde{V}_{INJ}(s) \quad \tilde{V}_A(s) = \dfrac{-1}{1+T(s)}\tilde{V}_{INJ}(s)$



- Both $\tilde{V}_A$ and $\tilde{V}_B$ should be of sufficient amplitude for loop gain measurement
- At f = 100 Hz, to have
  $\left|\tilde{V}_A\right| > 5\,\mu V, \left|\tilde{V}_{INJ}\right| > 5\,mV$
- At f = 300 kHz, to have
  $\left|\tilde{V}_B\right| > 5\,\mu V, \left|\tilde{V}_{INJ}\right| > 50\,\mu V$

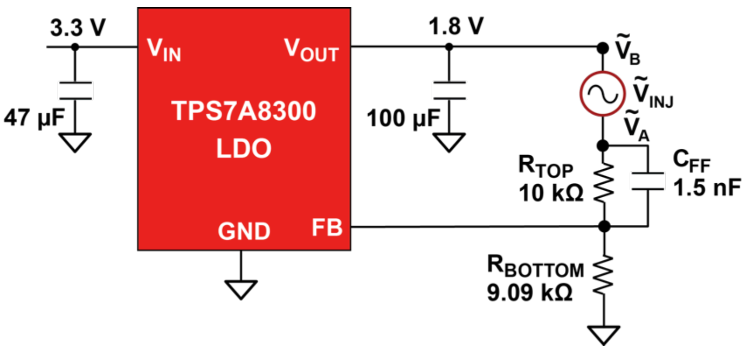
Excessive Voltage Injection Leads to Saturation



What could happen if voltage injection is excessive?

- Duty-cycle saturation
- Error amplifier saturation
- False triggering of over-current protection
- False triggering of over-voltage protection
- LDO driver and pass device saturation

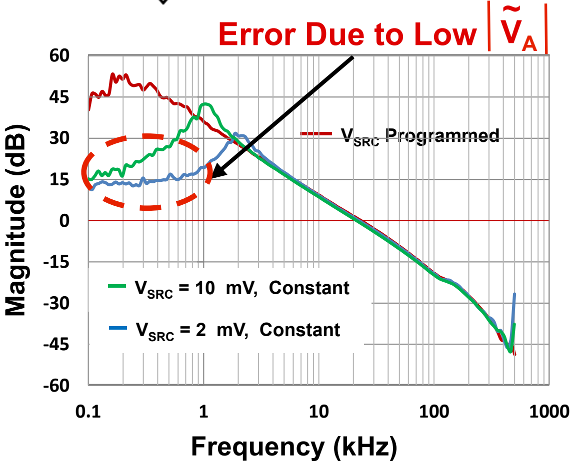
Programmable V_{SRC}

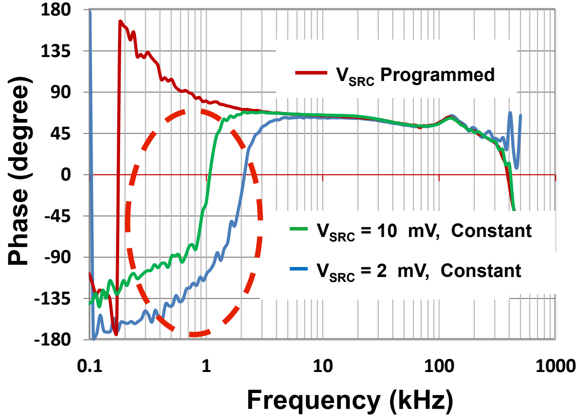


V_{SRC} is the voltage source of the frequency analyzer

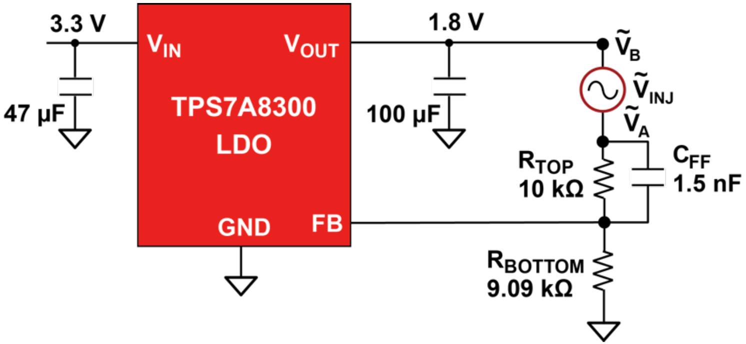
(Image reproduced with permission from Ridley Engineering Inc.)

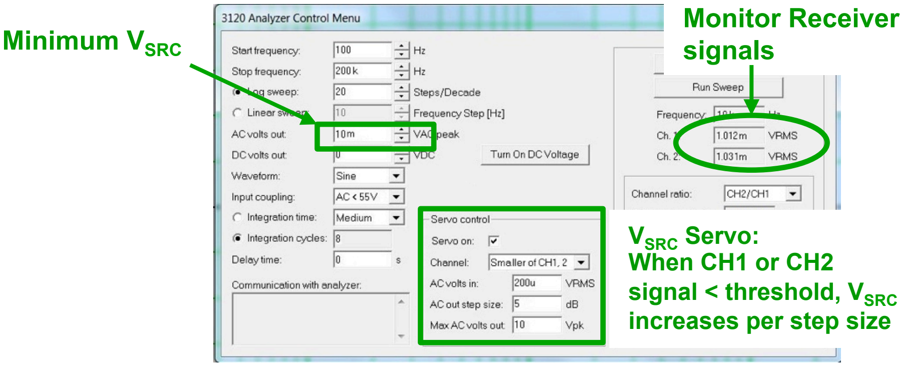
Loop Gain Measurement with Different V_{SRC}





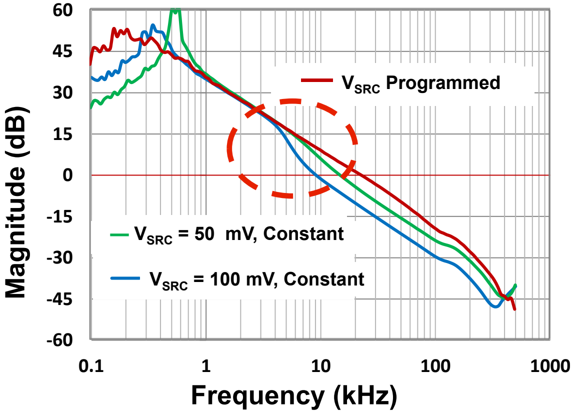
Servo Control V_{SRC}

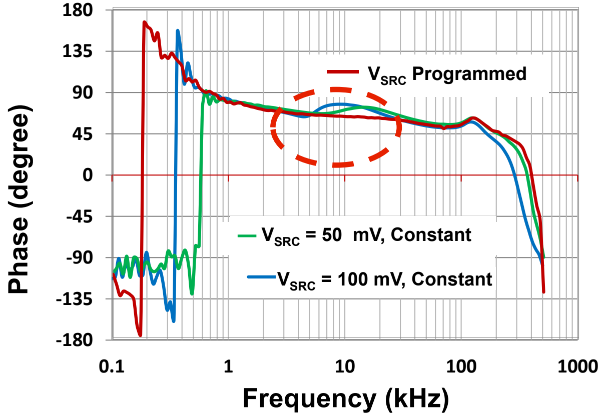




Generated by Venable Instruments' Stability Analysis Software and reproduced here with permission from Venable Instruments.

Loop Gain Measurement with Different V_{SRC}





Frequency Analyzer– IF Bandwidth (Integration Time)

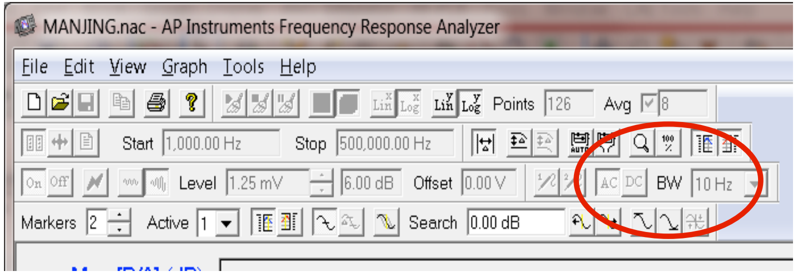
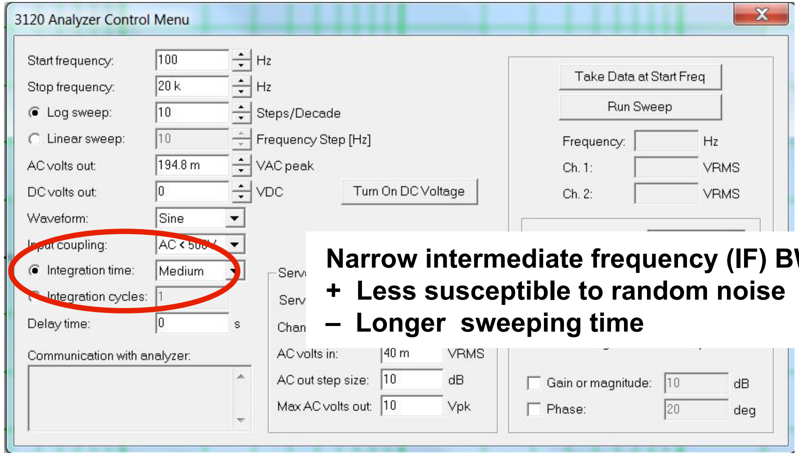
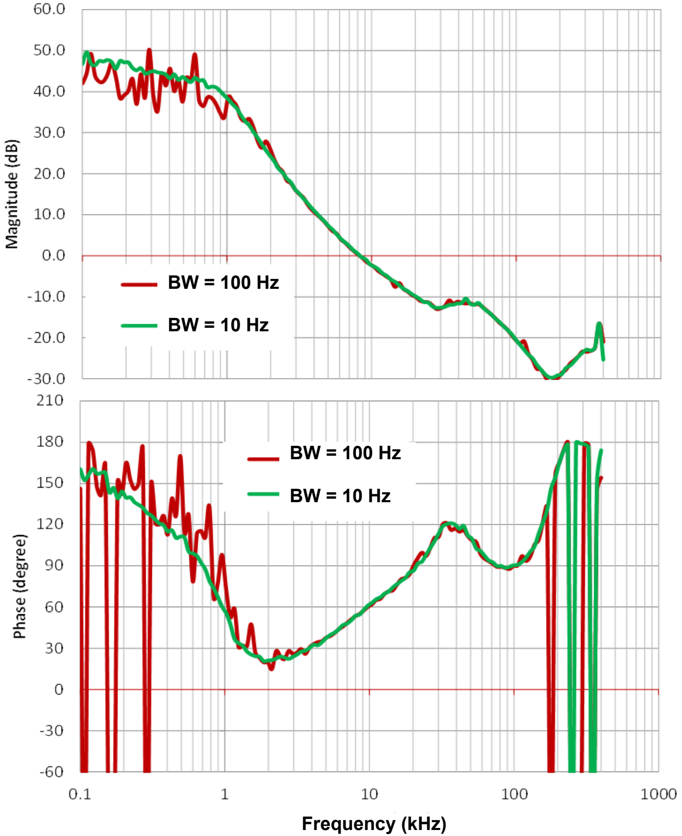


Image reproduced with permission from Ridley Engineering Inc.



Narrow intermediate frequency (IF) BW:
+ Less susceptible to random noise
– Longer sweeping time

Generated by Venable Instruments' Stability Analysis Software and reproduced here with permission from Venable Instruments.



Using Injection Isolator with Correct Frequency Range

Injection Isolator

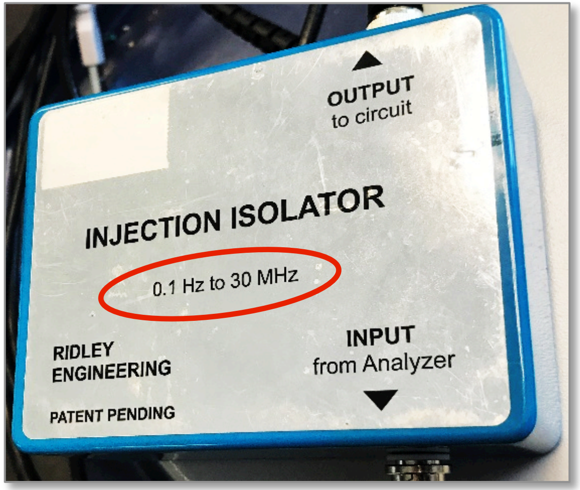


Image reproduced with permission from Ridley Engineering Inc.

BODE BOX™: Injection Isolator + Pre-Connected Signal Receiver

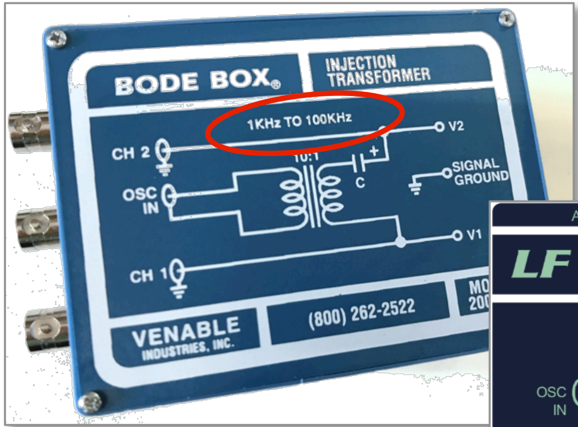


Image used with permission from Venable Instruments.

Active BODE BOX™

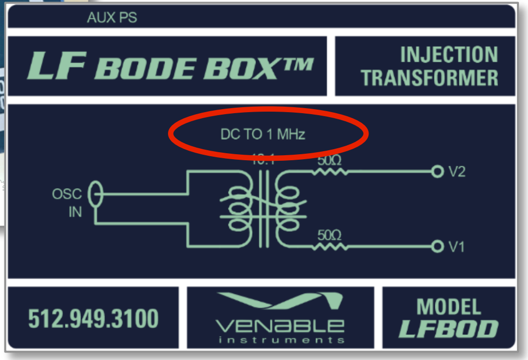


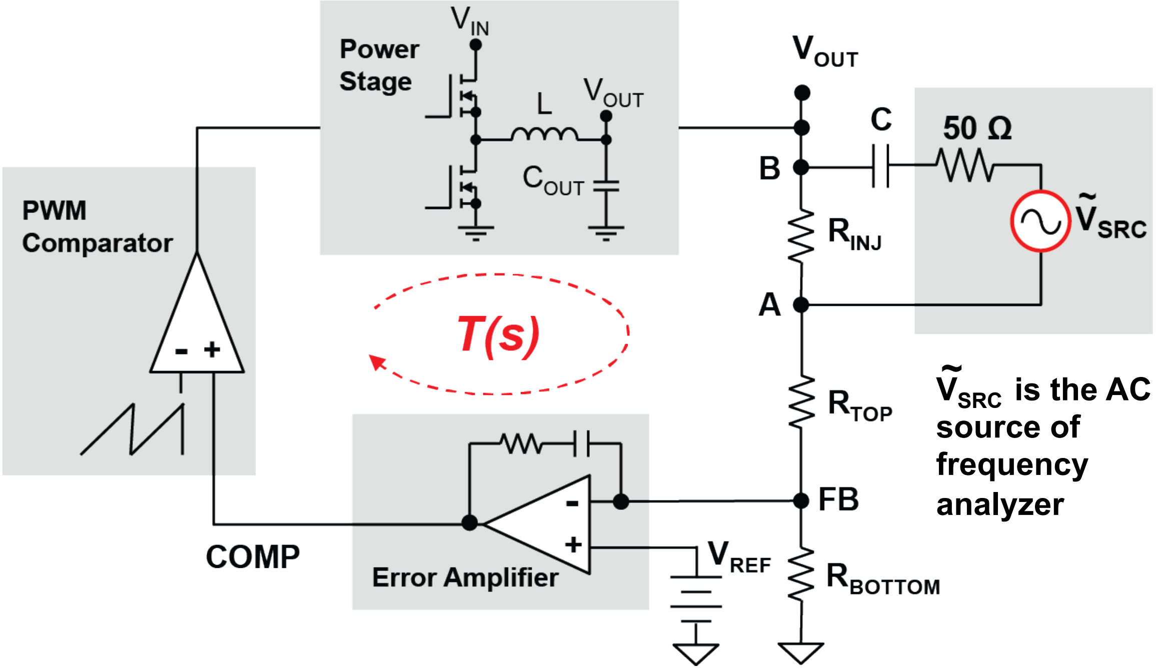
Image used with permission from Venable Instruments.

Setting Up Circuit for Loop Gain Measurement

- Identify correct voltage injection point
- Connect equipment to circuit under test

Maintaining DC Static Operating Point

Insert small resistor (10 Ω to 100 Ω) between point A and B to maintain ~ same static operating point



$\tilde{V}_{SRC}$ is the AC source of frequency analyzer

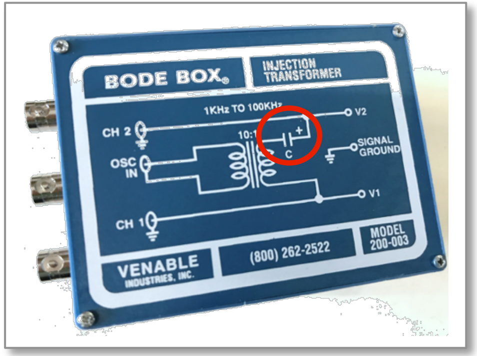


Image used with permission from Venable Instruments.

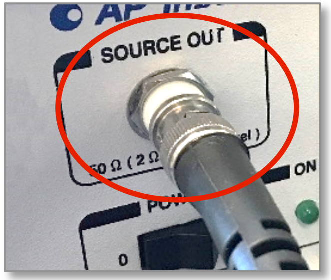
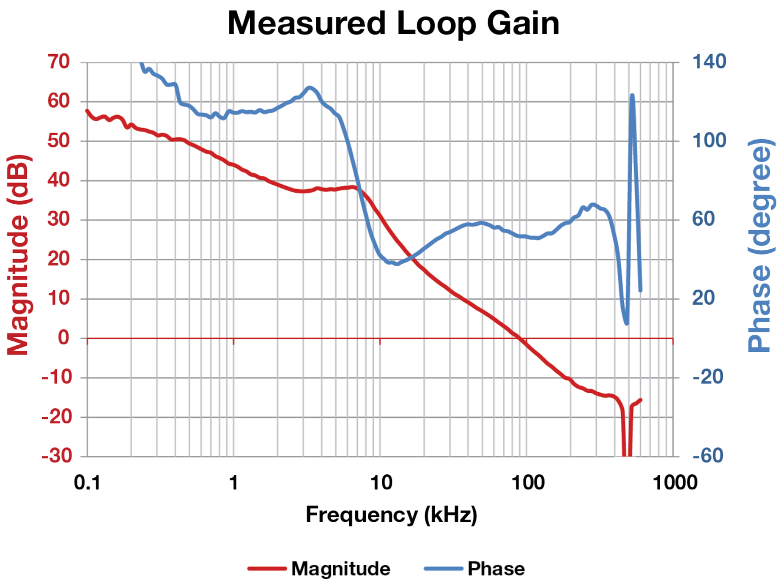


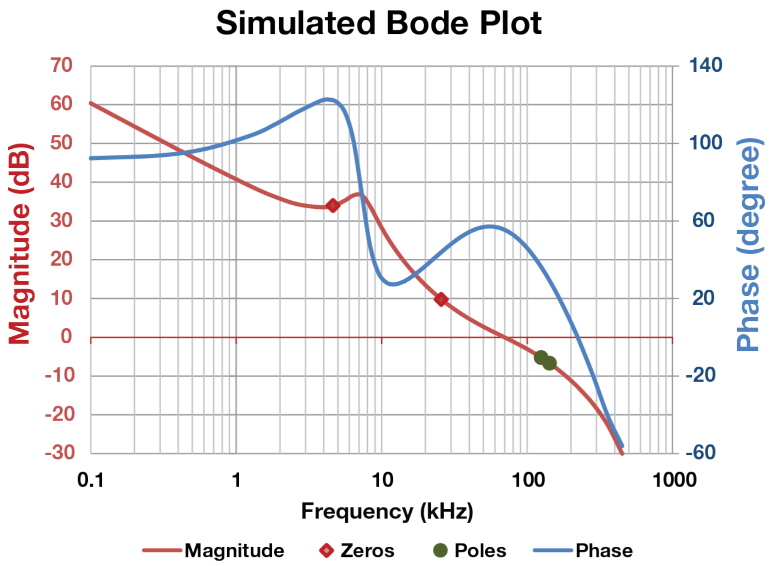
Image reproduced with permission from AP Instruments, Inc.

Source R_{OUT} = 50 Ω

Measuring Loop-Gain for VMC

TPS40425, Dual-Phase Buck Converter

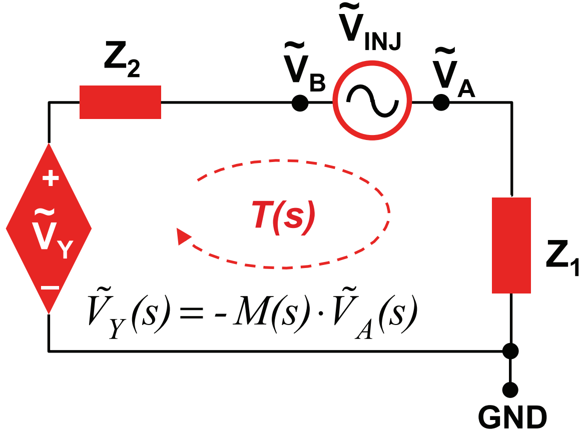




Measured crossover frequency and phase margin match simulation well!

Correct Voltage Injection Point

Impedance Requirement

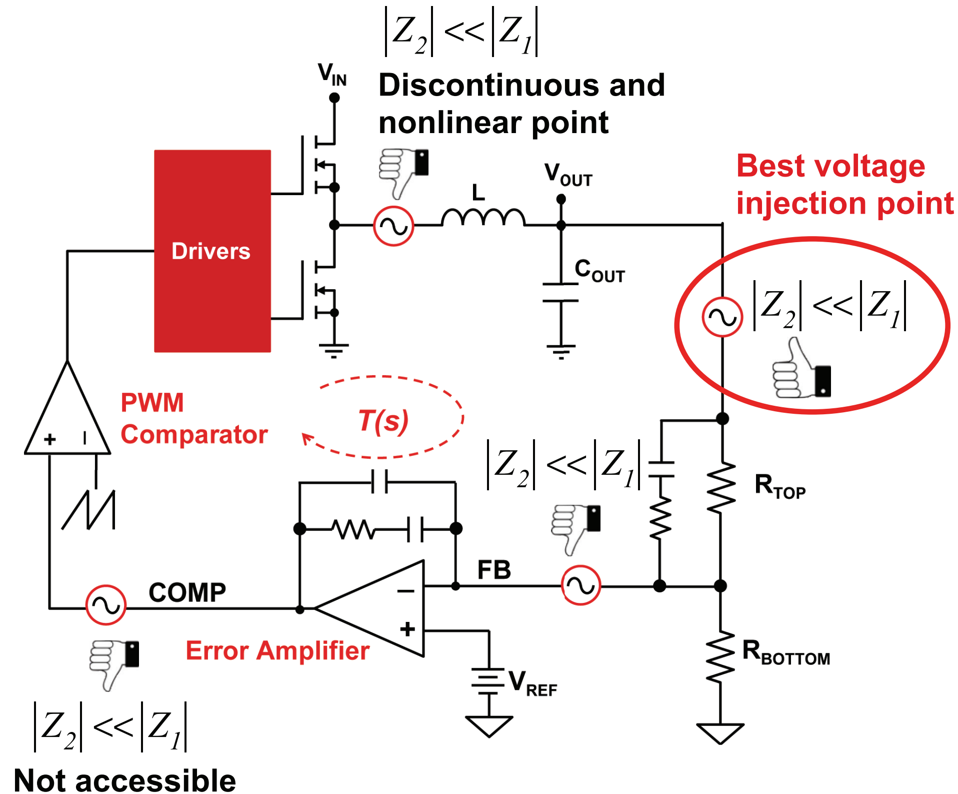


Measured loop gain:

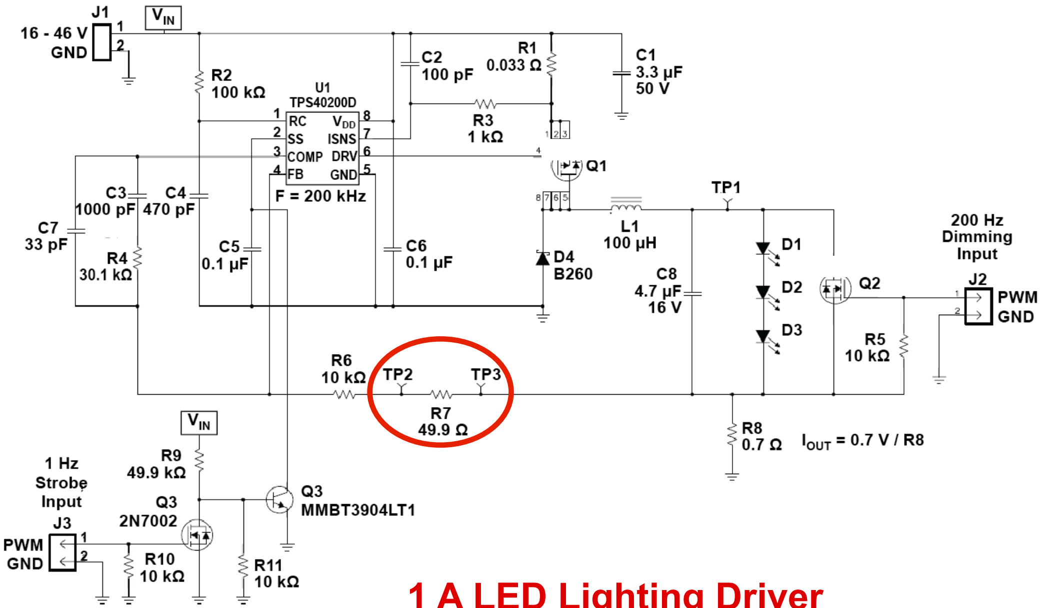
$$T_m(s) = T(s)\cdot\left(1+\frac{Z_2}{Z_1}\right)+\frac{Z_2}{Z_1}$$

Injection point should have:

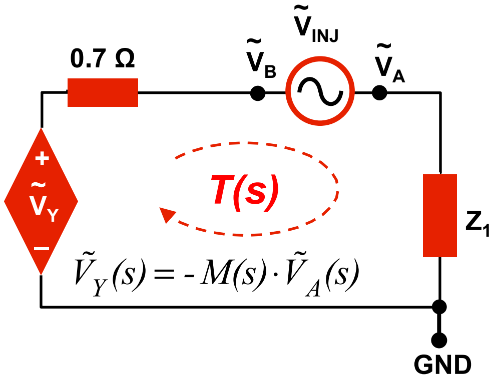
$$|Z_2| << |Z_1|$$



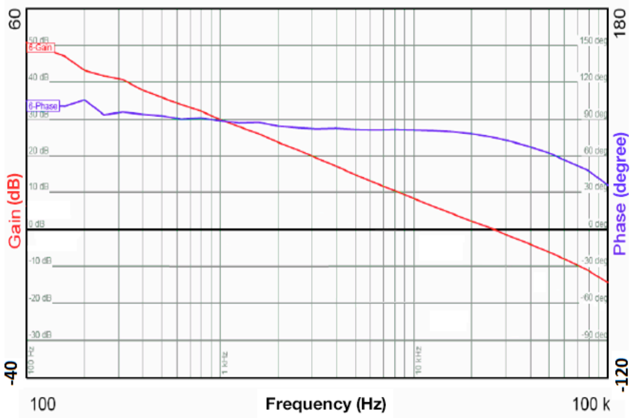
Measuring Loop Gain for LED Driver



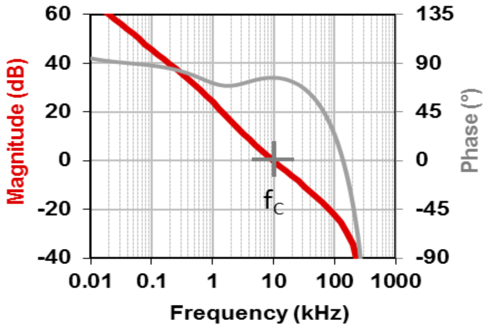
1 A LED Lighting Driver

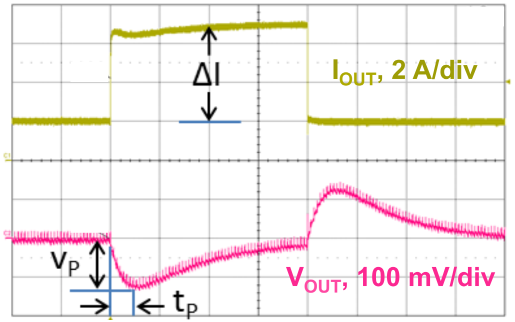


Measured Loop Gain



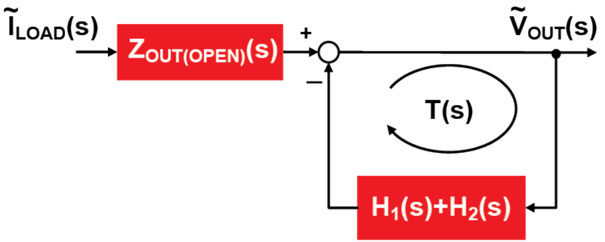
Multiple Feedback Paths

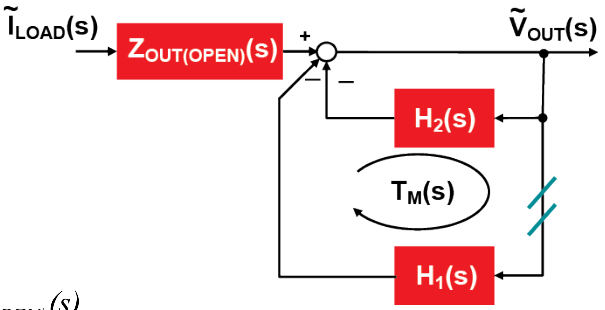




$$V_P = \frac{\Delta I}{8 \cdot f_C \cdot C_{OUT}}$$

$$Z_{OUT(CLOSED)}(s) = \frac{Z_{OUT(OPEN)}(s)}{1 + T(s)}$$





$$T(s) = H_1(s) + H_2(s)$$

$$Z_{OUT(CLOSED)}(s) = \frac{Z_{OUT(OPEN)}(s)}{1 + H_1(s) + H_2(s)}$$

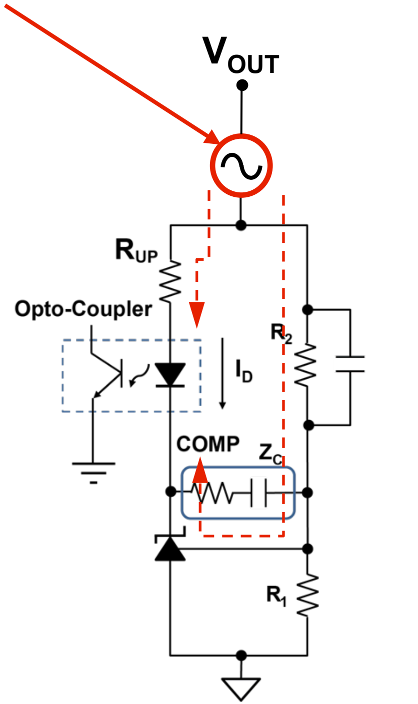
- **Bandwidth of T(s) can predict transient performance**
- **Loop gain with feedback path 2 closed:**

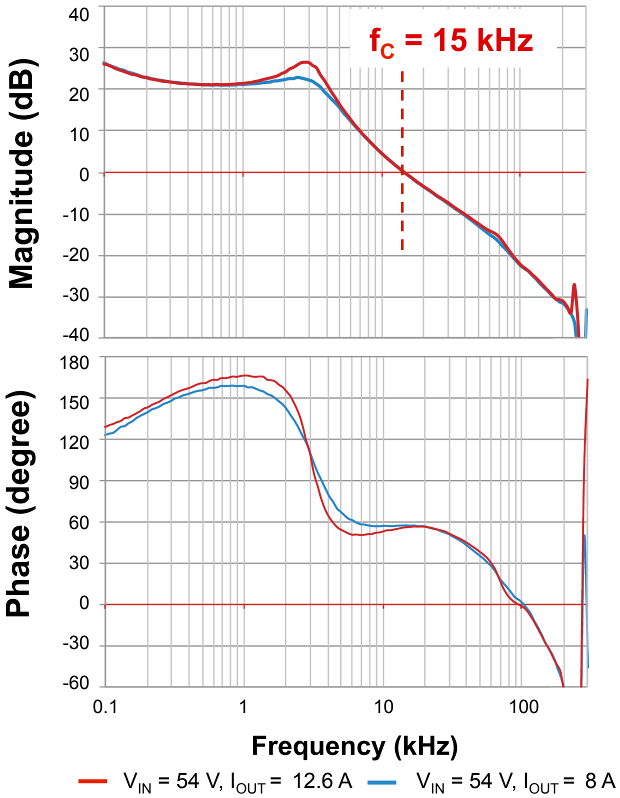
$$T_M(s) = \frac{H_1(s)}{1 + H_2(s)}$$

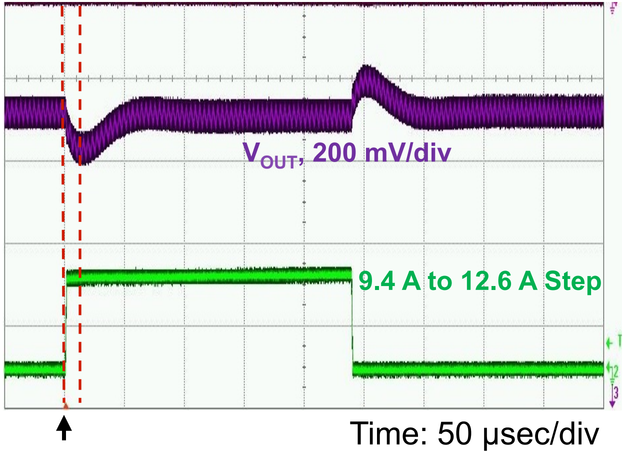
- **Bandwidth of $T_M(s)$ might not tell how transient response performs**

Multiple Feedback Paths – Isolated Converter

The correct injection point includes all feedback paths





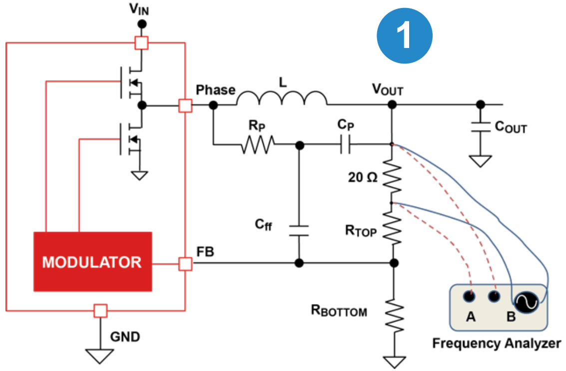


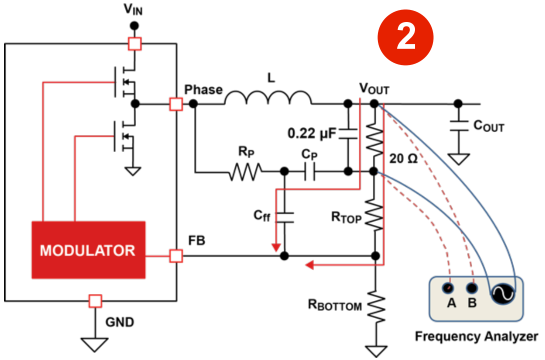
$t_P = 16\ \mu sec$

Measured loop gain correlates well with transient response

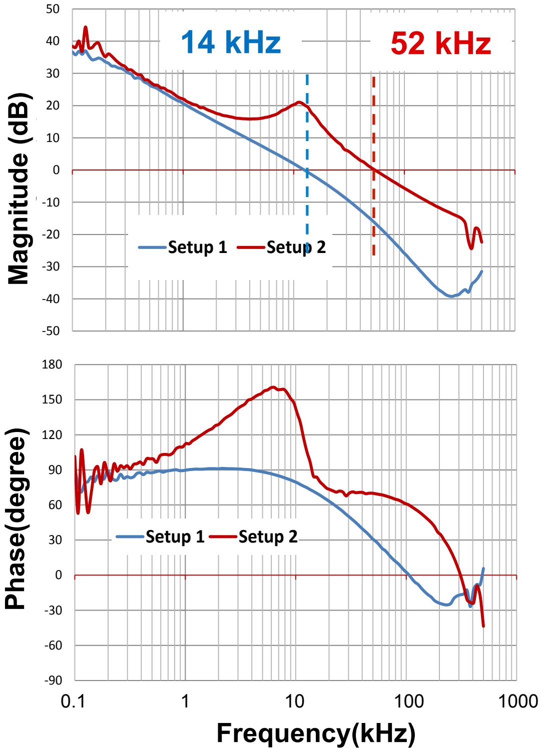
$$t_P \cong \frac{1}{4 \cdot f_C} = 16.7\ \mu sec$$

Multiple Feedback Paths – D-CAP™ Control

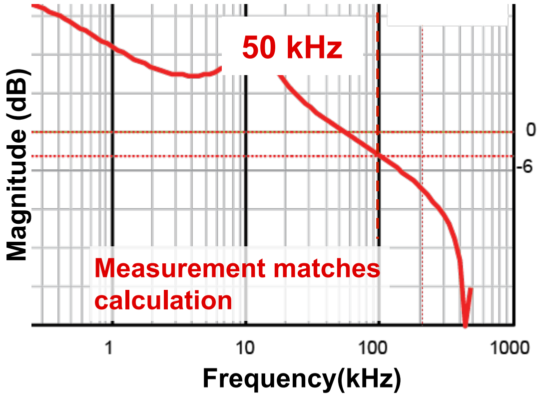


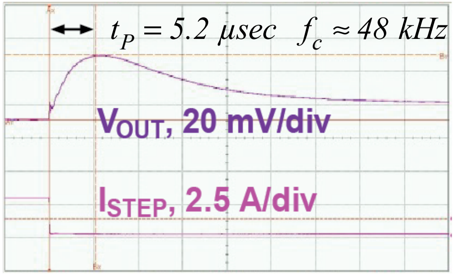


Measured Loop Gain



Calculated Loop Gain

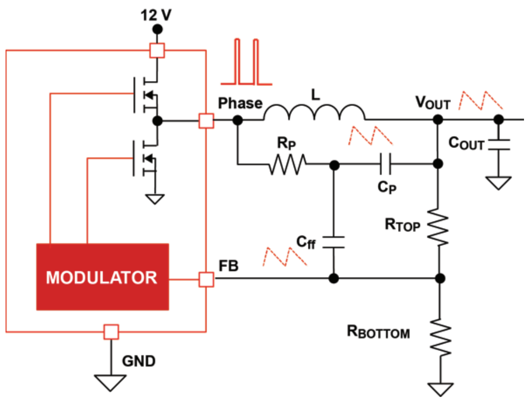




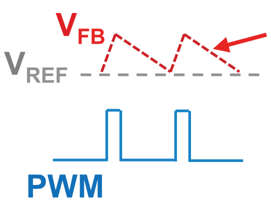
Measurement matches transient response

Maintaining AC Operating Point – DCAP™ Control

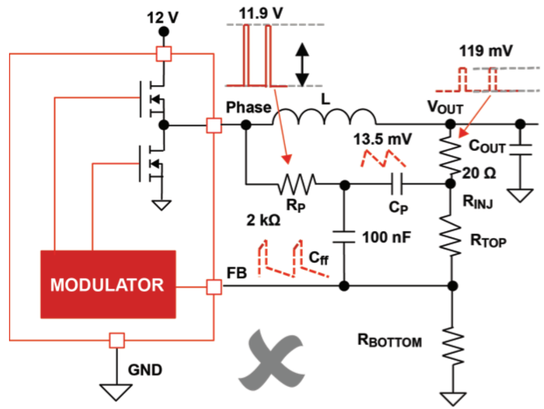
A DCAP™ regulator block diagram

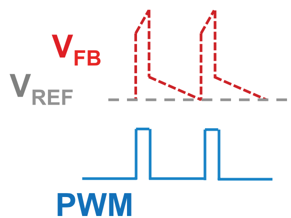


F_{SW} = 400 kHz, D = 10%

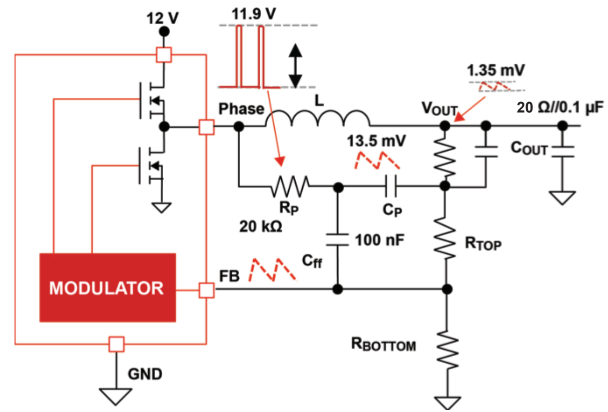


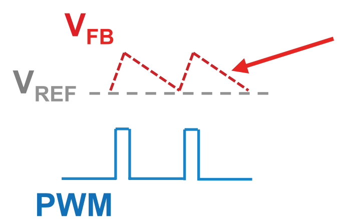
Falling slope of FB pin ripple determines PWM modulation gain





Ripple at FB pin is distorted



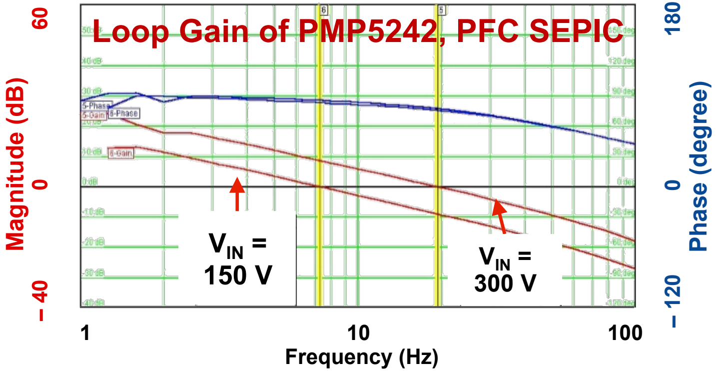


FB pin ripple is similar to that at normal operation

Measuring Loop Gain for PFC Converter

Challenges of measuring loop gain for power factor correction converter

- Low control bandwidth
- High output voltage
- Use DC input



Isolator of correct frequency range

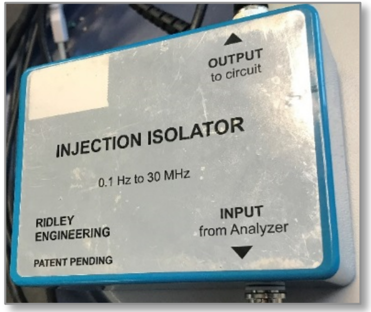
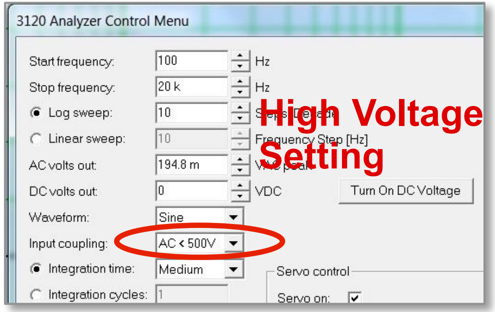


Image used with permission from Ridley Engineering Inc.

\+

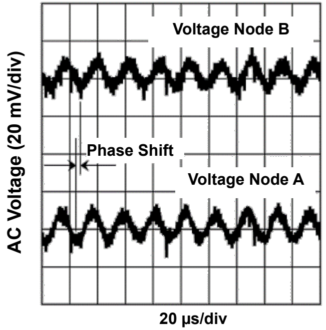
High-voltage frequency analyzer



Generated by Venable Instruments' Stability Analysis Software and reproduced here with permission from Venable Instruments.

OR

Oscilloscope for gain and phase measurement



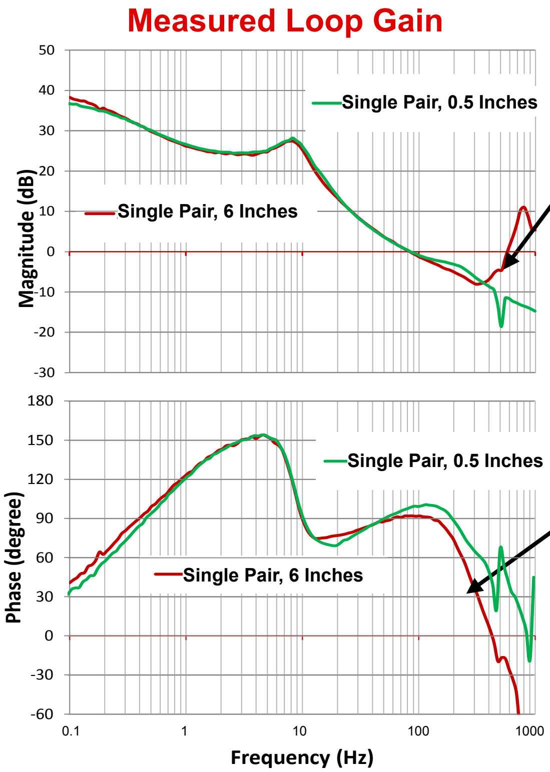
[5]

Connecting Equipment to Converter

- How connection wires affect loop gain measurement
- Where to connect reference leads of two receivers

Connection Wires Affect Loop Gain Measurement

TPS53355
V_{IN} = 12 V
V_{OUT} = 1.2 V
F_{SW} = 400 kHz



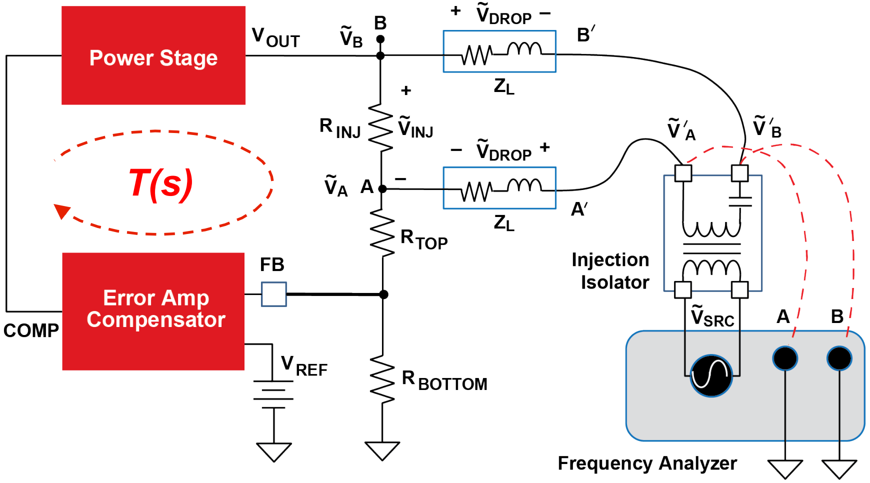
Bode plot measured with single-pair 6-inch long wires

Why does the gain increase at high frequency while the phase drops rapidly?

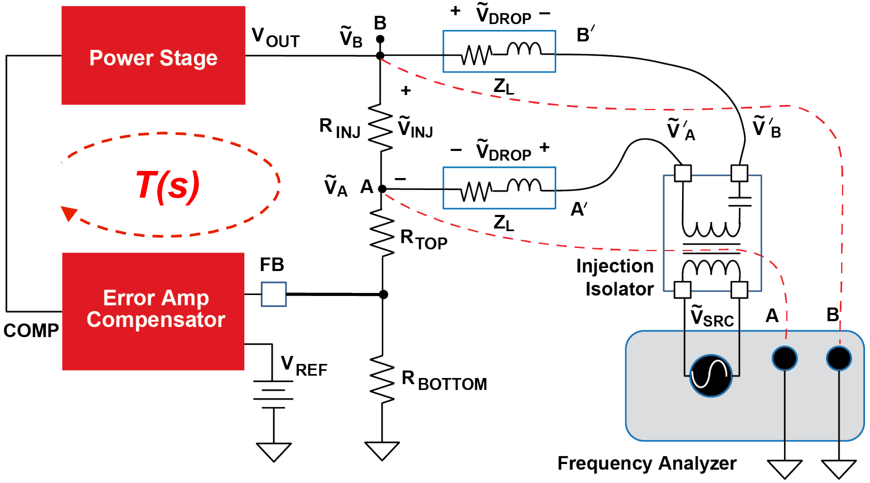
Bode plot with 0.5-inch short wires to connect receivers and adaptor to converter under test

How Connection Wires Affect Loop Gain Measurement

Receivers and adaptor share one pair of wires



Receivers and adaptor use separate wires



Measured loop gain:

$$T_M(s) = -\frac{\tilde{V}_B(s)}{\tilde{V}_A(s)} = \frac{T(s)+(1+T(s))\cdot\dfrac{Z_L(s)}{Z_{INJ}(s)}}{1+(1+T(s))\cdot\dfrac{Z_L(s)}{Z_{INJ}(s)}}$$

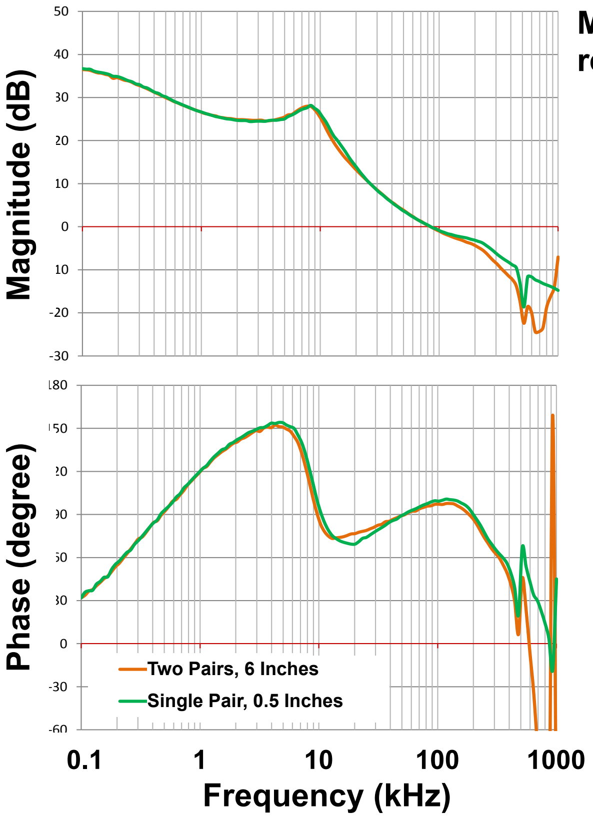
At high frequencies:

$$\left|T_M(+j\infty)\right| \approx \left|\frac{Z_L(+j\infty)}{Z_{INJ}(+j\infty)+Z_L(+j\infty)}\right|$$

Recommendation:

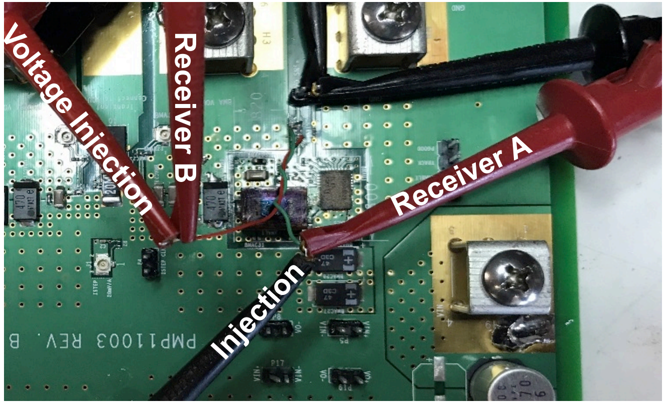
- **Use wires as short as possible**
- **Use separate wires for measurement and voltage injection**

Bench Verifications

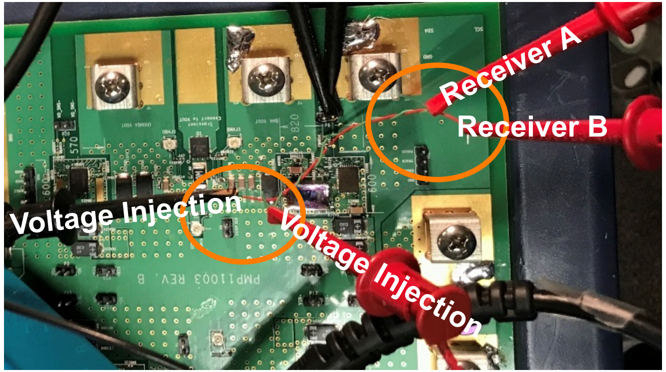


Measurement results are similar

One Pair of Wires

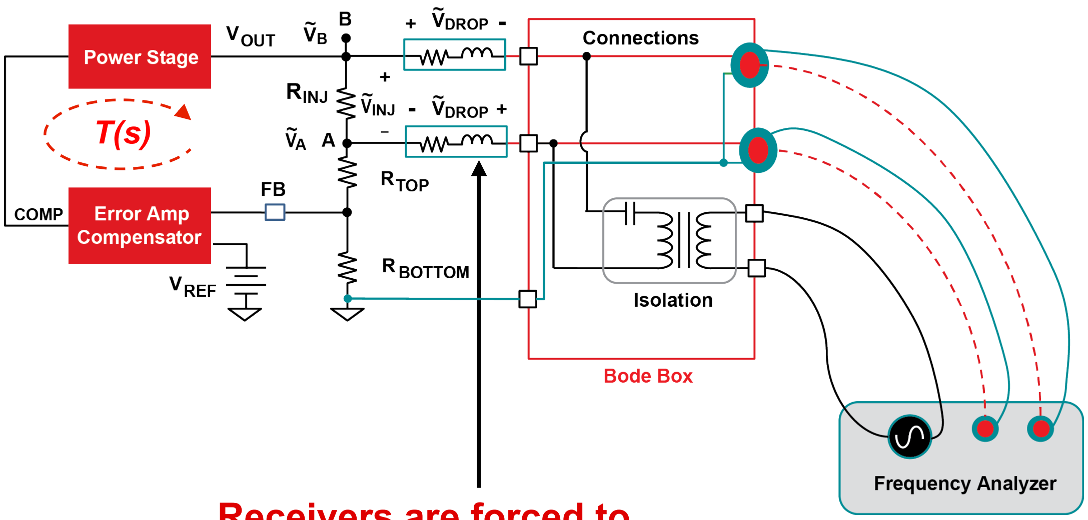


Two Pairs of Wires

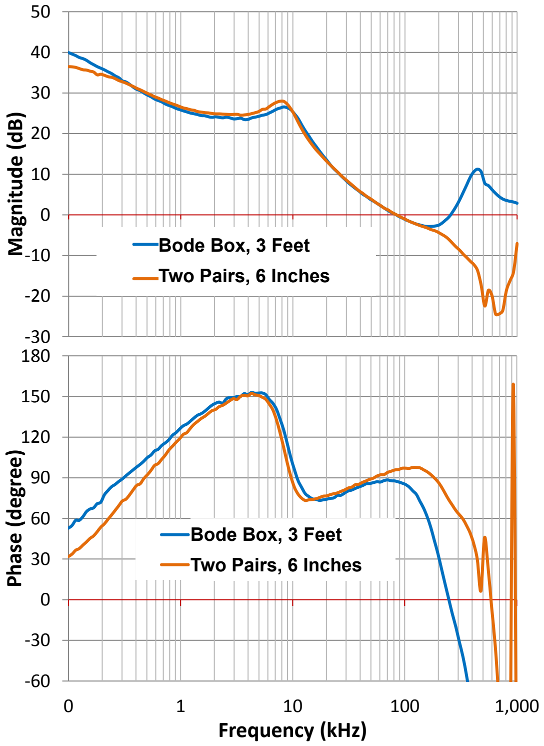


Considerations for Bode Box™

Receivers are pre-connected to output of injection isolator



Receivers are forced to sense voltage drops across connection cable



Which Is the Correct Reference Point?

Receiver A, B Coaxial Cables

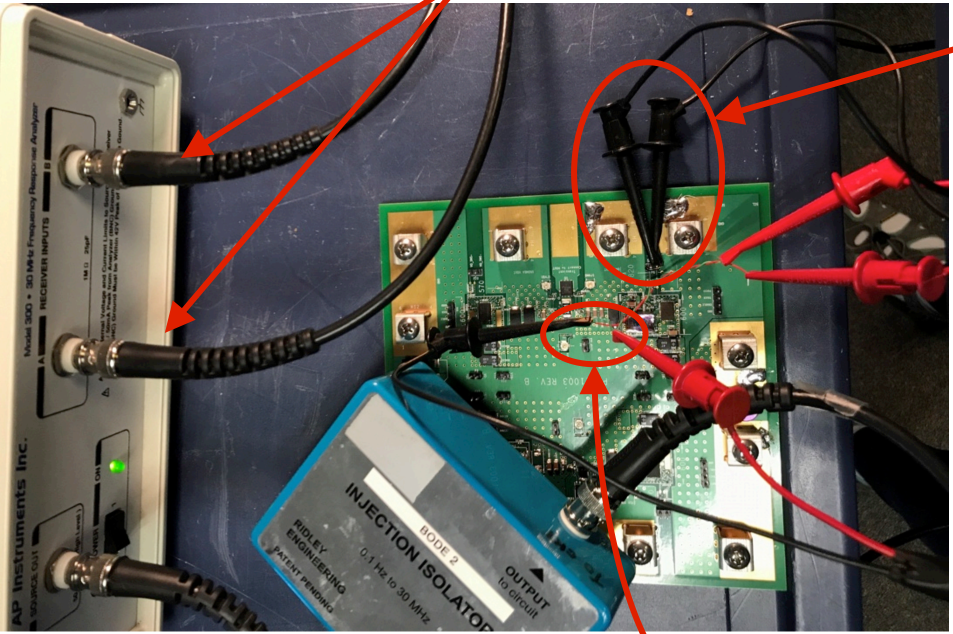


Image reproduced with permission from Ridley Engineering Inc. and AP Instruments, Inc.

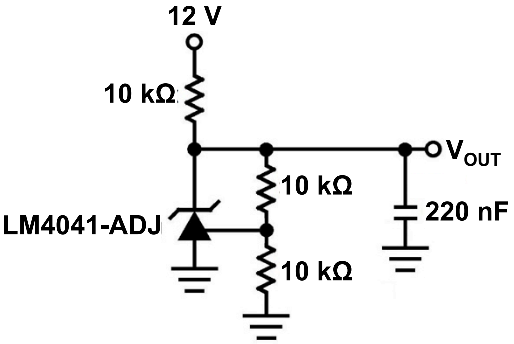
Reference Leads

Reference Clip

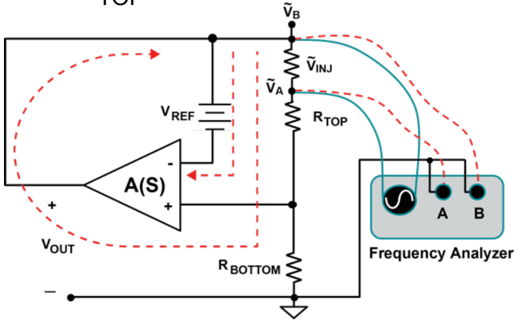
- For single-ended system, use controller signal ground for reference
- For converter with fully differential remote sensing, use remote negative sense for reference

Voltage Injection Point A and B

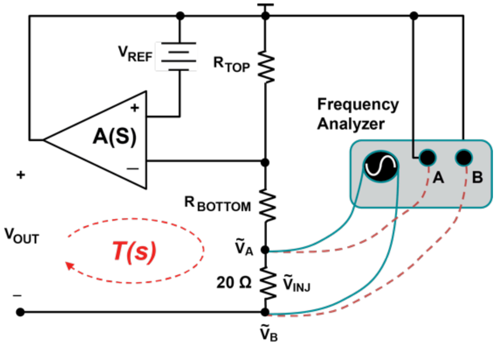
LM4041-N Shunt-Regulator



- GND is the reference point
- V_{INJ} is injected between V_{OUT} and R_{TOP}

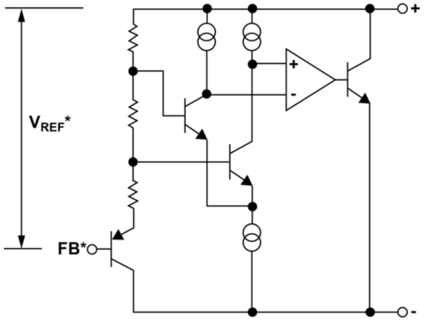


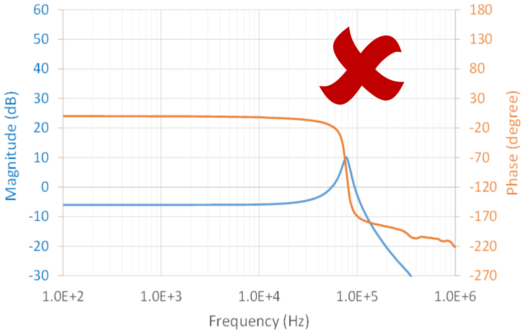
- V_{OUT} is the reference point
- V_{INJ} is injected between GND and R_{BOTTOM}

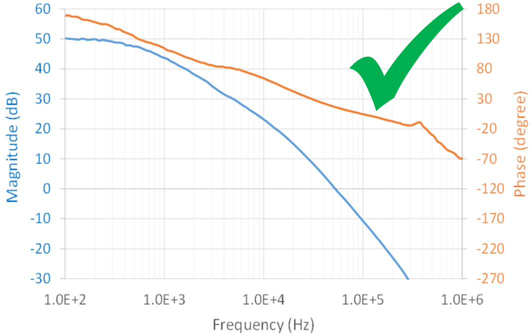


Block Diagram

V_{REF} Refers to V_{OUT}



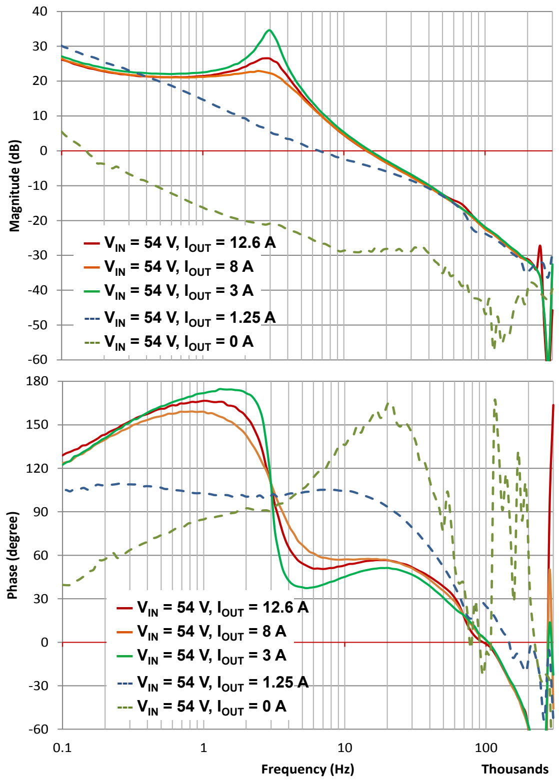




Check Stability Over All Conditions

Compensation network should be designed so that system is stable over all conditions:

- Over input voltage range
- Over output current range
- Over temperature range
- Over output voltage range



Summary

- Prepare circuit for test
  - Identify correct voltage injection point
    - Impedance looking backward should be as small as possible
    - Injection point should include all output feedback paths
  - Identify correct reference point
- Setup frequency analyzer with correct voltage source amplitude
- Select right injection isolator
- Maintain same DC and AC static operating point
- Receivers should not include voltage drops on connection wires
- Check stability over all conditions

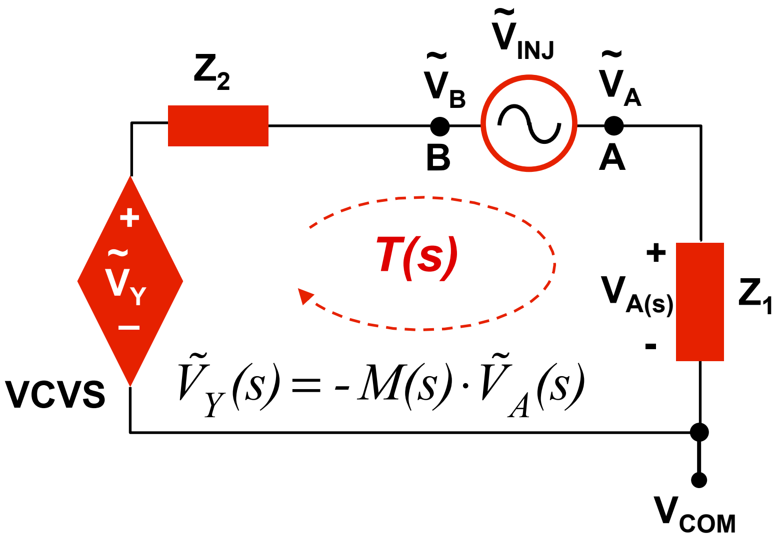
References

- [1] Bob Sheehan, “How to determine bandwidth from the transient-response measurement,” Power Tips Blog.
- [2]John Betten, “Calculating capacitance for load transients”, Power Tips, May 17th, 2015.
- [3] John Betten,“Control Loop Considerations for an LED Driver,” EETimes, August 17, 2007.
- [4] Datasheet of LM4041-N.
- [5] Application Note AN1889, “How to measure the loop transfer function of power supplies.”

Appendix

Derivation of Closed-Loop Responses

When Z_2 = 0 Ω, T(s) = M(s)



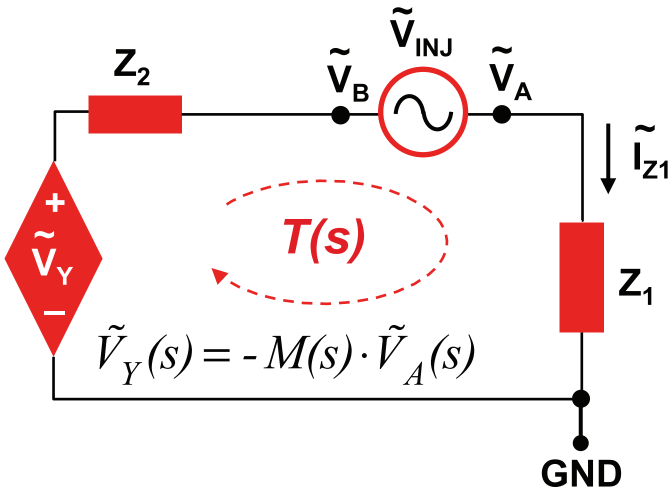
$$\tilde{V}_B(s) = -T(s) \cdot \tilde{V}_A(s)$$

$$\tilde{V}_{INJ}(s) = \tilde{V}_B(s) - \tilde{V}_A(s) = -\left(T(s)+1\right) \cdot \tilde{V}_A(s)$$

$$\Rightarrow \tilde{V}_A(s) = -\frac{1}{T(s)+1} \cdot \tilde{V}_{INJ}(s)$$

$$\Rightarrow \tilde{V}_B(s) = \frac{T(s)}{T(s)+1} \cdot \tilde{V}_{INJ}(s)$$

How Z_2 Affects Loop Gain Measurement



$$\tilde{I}_{Z1}(s) = \frac{\tilde{V}_A(s)}{Z_1(s)}$$

$$\tilde{V}_B(s) = -M(s) \cdot \tilde{V}_A(s) - \frac{Z_2(s)}{Z_1(s)} \cdot \tilde{V}_A(s) = -\left(M(s) + \frac{Z_2(s)}{Z_1(s)} \right) \cdot \tilde{V}_A(s)$$

Loop gain: $T(s) = M(s) \cdot \frac{Z_1(s)}{Z_1(s)+Z_2(s)}$

$$\Rightarrow M(s) = T(s) \cdot \left(1 + \frac{Z_2(s)}{Z_1(s)} \right)$$

Measured loop gain:

$$T_m(s) = -\frac{\tilde{V}_B(s)}{\tilde{V}_A(s)} = M(s) + \frac{Z_2(s)}{Z_1(s)}$$

$$T_m(s) = T(s) \cdot \left(1 + \frac{Z_2(s)}{Z_1(s)} \right) + \frac{Z_2(s)}{Z_1(s)}$$

TI Worldwide Technical Support

TI Support

Thank you for your business. Find the answer to your support need or get in touch with our support center at

www.ti.com/support

China:
http://www.ti.com.cn/guidedsupport/cn/docs/supporthome.tsp

Japan:
http://www.tij.co.jp/guidedsupport/jp/docs/supporthome.tsp

Technical support forums

Search through millions of technical questions and answers at TI's E2E™ Community (engineer-to-engineer) at

e2e.ti.com

China:
http://www.deyisupport.com/

Japan:
http://e2e.ti.com/group/jp/

TI Training

From technology fundamentals to advanced implementation, we offer on-demand and live training to help bring your next-generation designs to life. Get started now at

training.ti.com

China:
http://www.ti.com.cn/general/cn/docs/gencontent.tsp?contentId=71968

Japan:
https://training.ti.com/jp

Texas Instruments