

Power Supply Design Seminar

# Considerations for Measuring Loop Gain in Power Supplies

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# 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

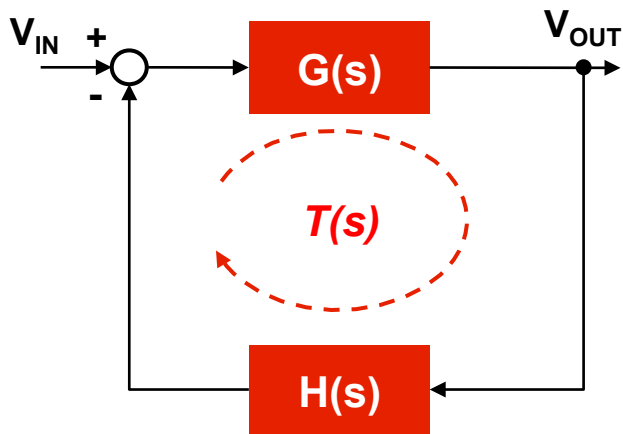
# Introduction – Loop Gain Overview

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

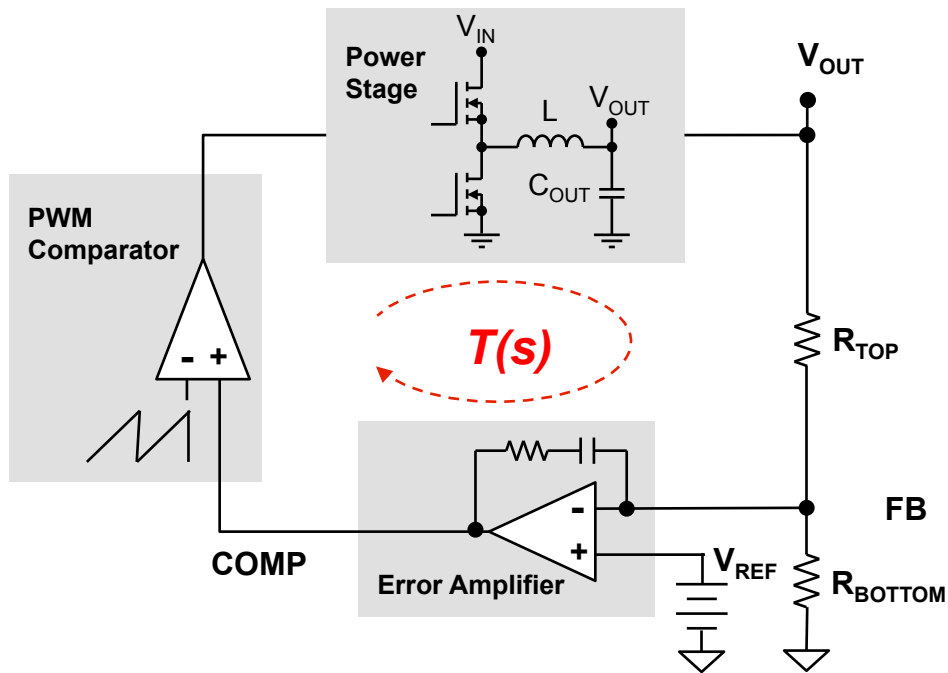
# Introduction – What Is Loop Gain?

Loop gain: product of all gains around feedback loop

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



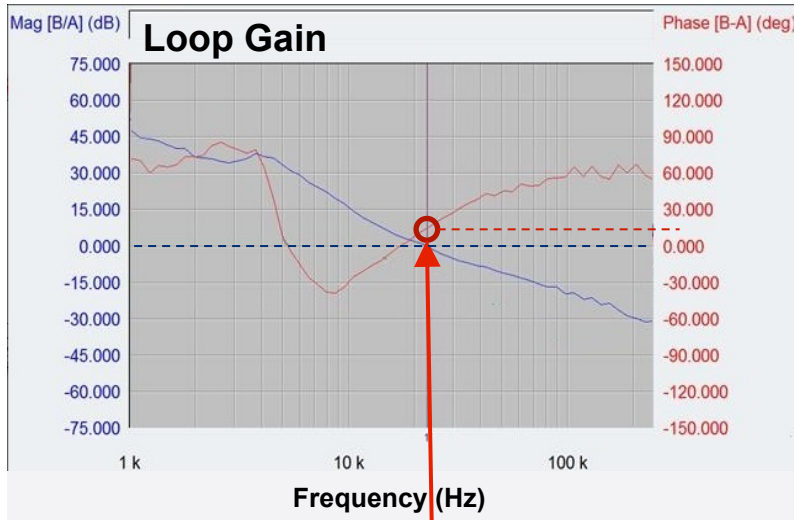
Simple Feedback System



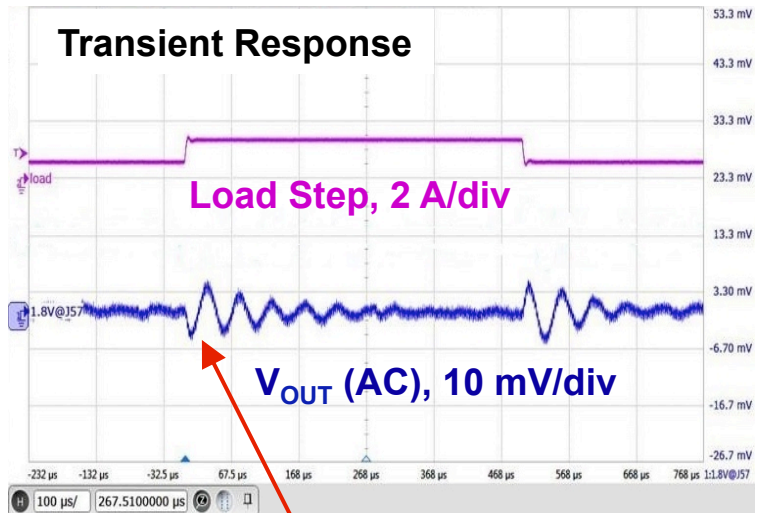
DC/DC Converter Control System

# Why Do We Measure Loop Gain?

## 1) Loop gain is good indicator of stability



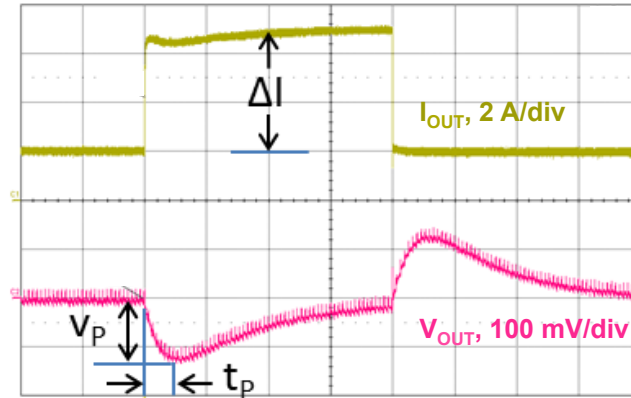
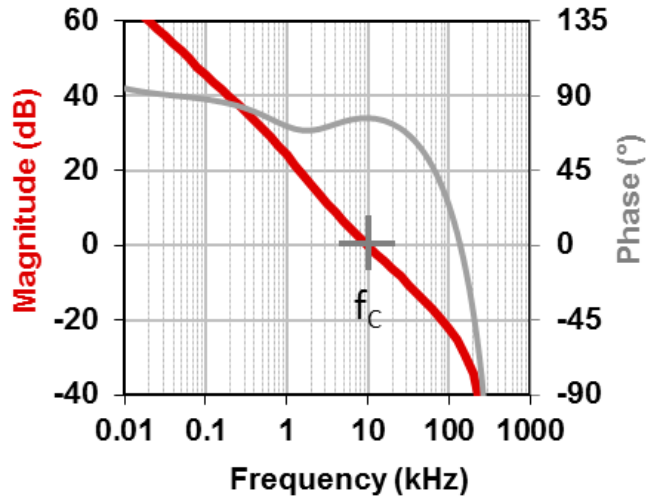
$f_c = 22.4 \text{ kHz}$   
Phase Margin =  $15^\circ$



Output Oscillates at about 20 kHz

# Why Do We Measure Loop Gain?

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



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

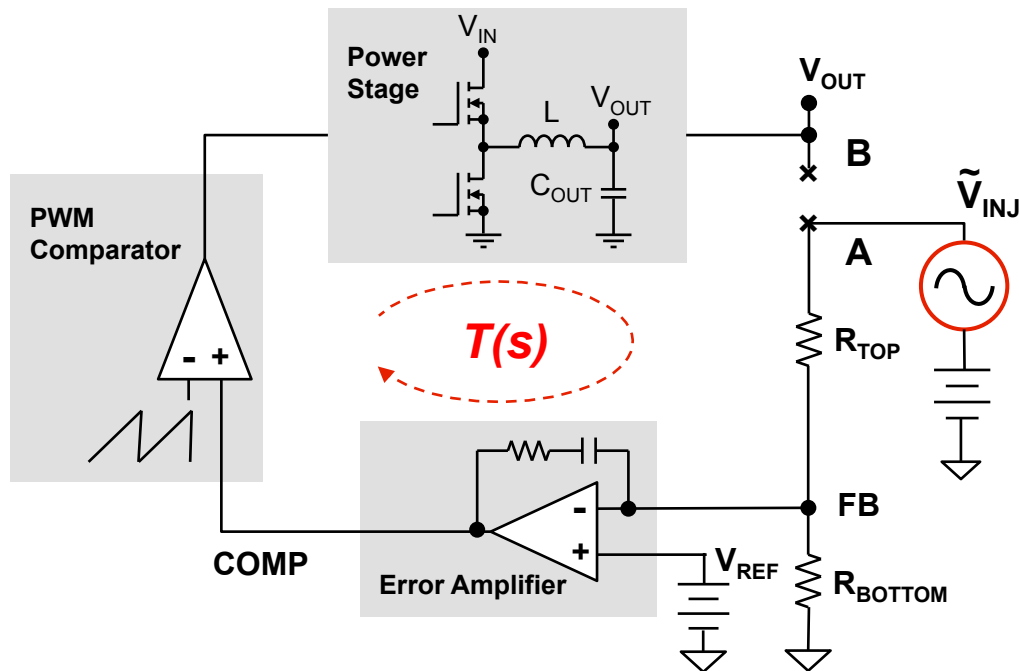
$$V_P = \frac{\Delta I}{8 \cdot f_C \cdot C_{OUT}}$$

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

# Loop Gain Measurement Method



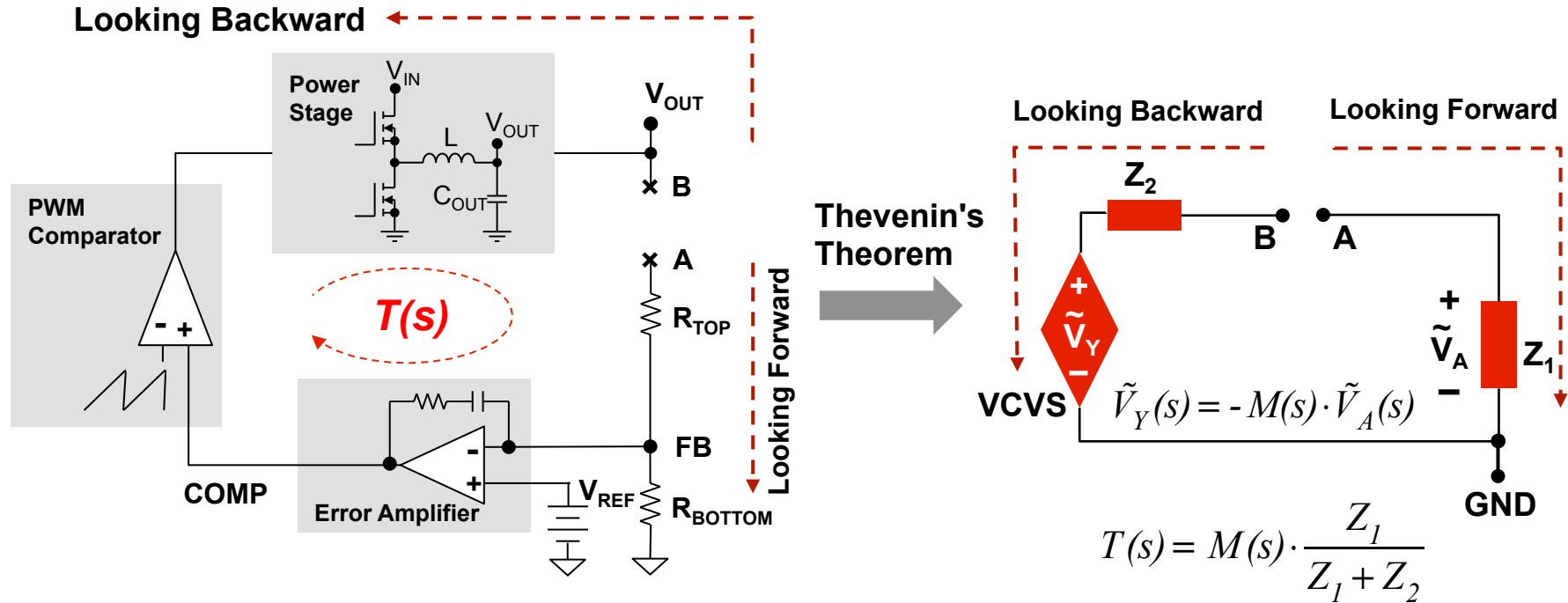
# Loop Gain Measured in Open-Loop Setup



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

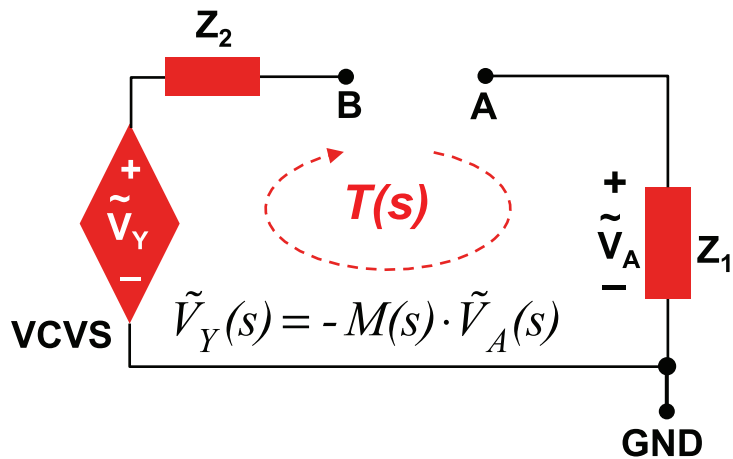
**X It is not practical to measure loop gain in open-loop setup**

# Equivalent Circuit of Feedback System

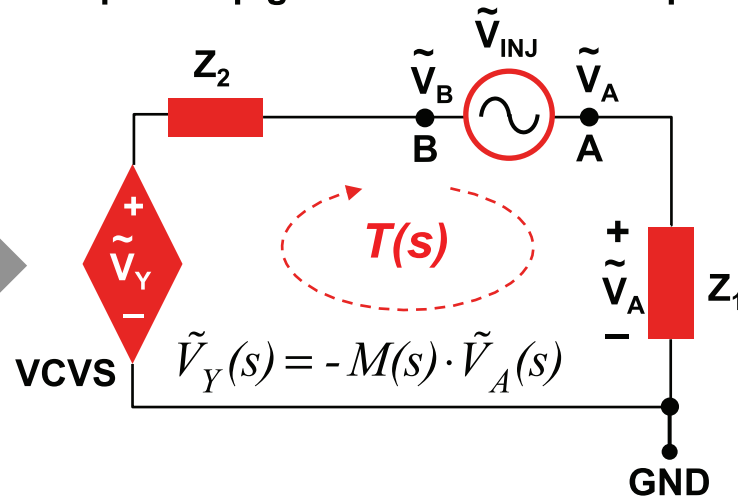


# Loop Gain Measurement – Voltage Injection Method

When  $Z_2 = 0 \Omega$ ,  $T(s) = M(s)$



Measure open loop gain with feedback loop closed



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

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

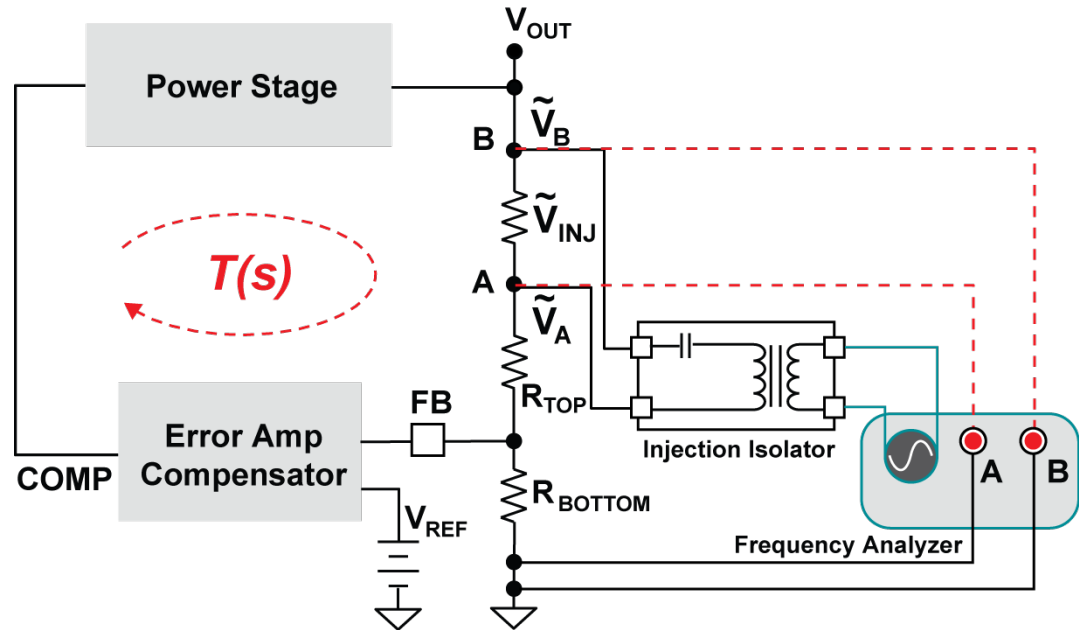
Derivation

# 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:  $T(s) = -\frac{\tilde{V}_B}{\tilde{V}_A}$

**Voltage Source**  
 **$R_{OUT} = 50 \Omega$**

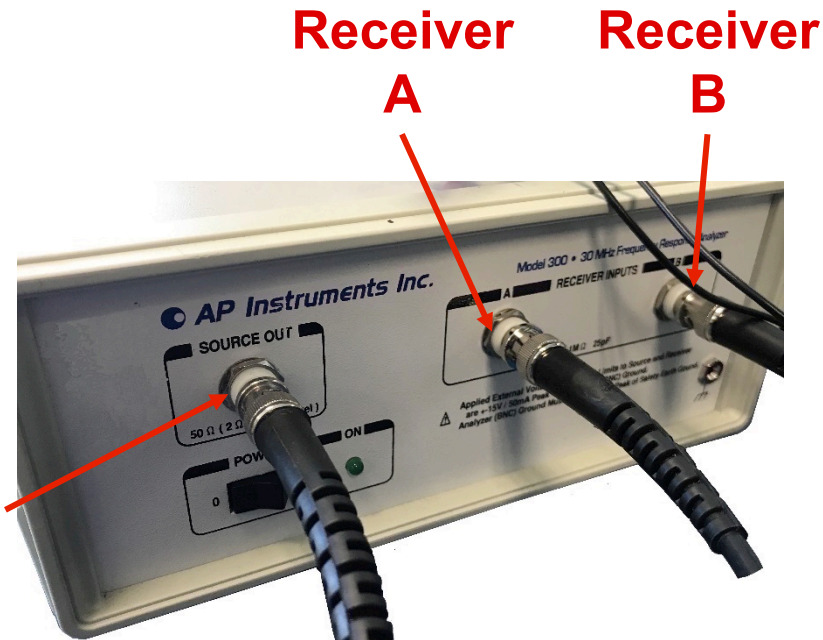


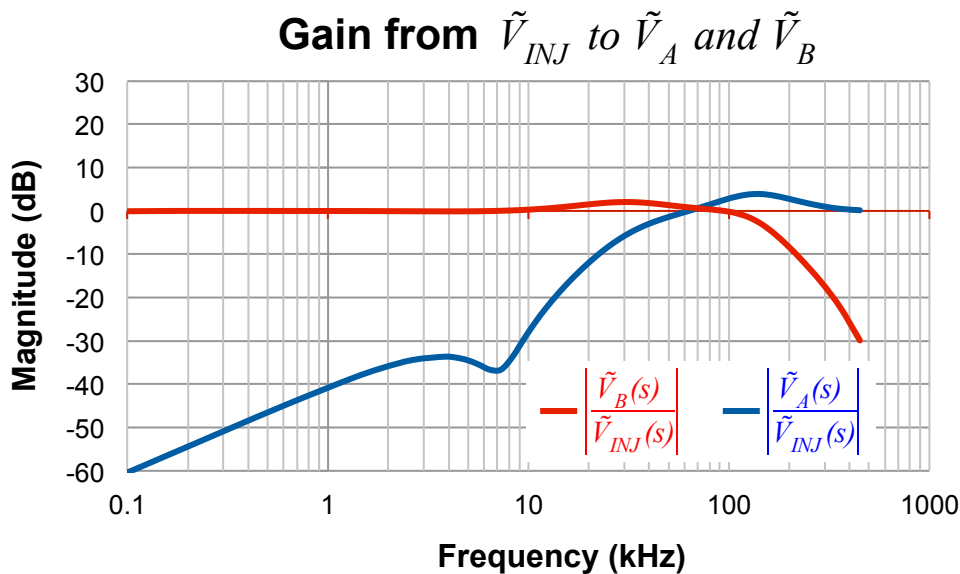
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# Injecting Sufficient AC Voltage

AP300 Specification: Measurable Signal Range

5  $\mu$ V to 1.77 V

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



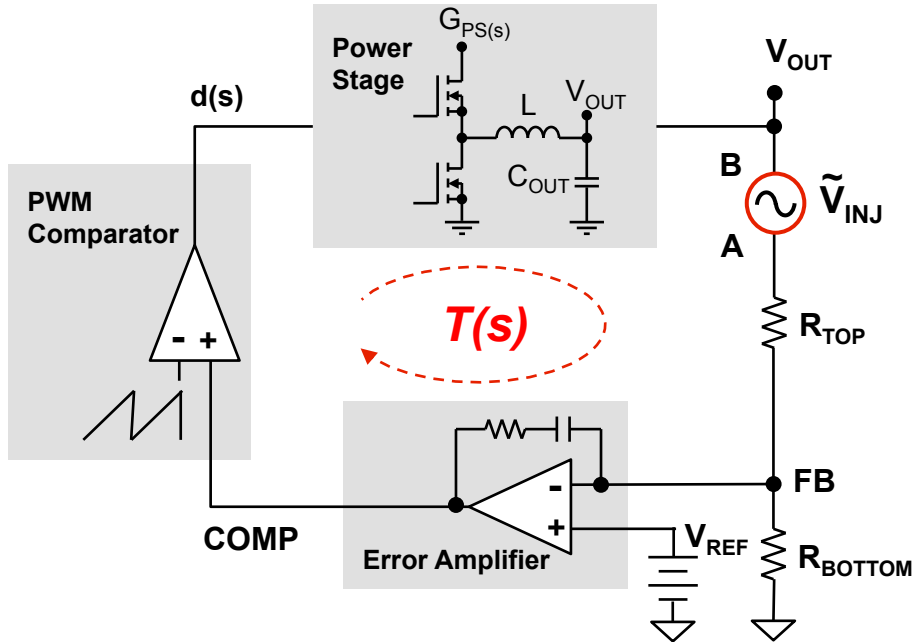
- Both  $\tilde{V}_A$  and  $\tilde{V}_B$  should be of sufficient amplitude for loop gain measurement

- At  $f = 100$  Hz, to have  $|\tilde{V}_A| > 5 \mu V$ ,  $|\tilde{V}_{INJ}| > 5 mV$

- At  $f = 300$  kHz, to have

$$|\tilde{V}_B| > 5 \mu V, |\tilde{V}_{INJ}| > 50 \mu V$$

# Excessive Voltage Injection Leads to Saturation

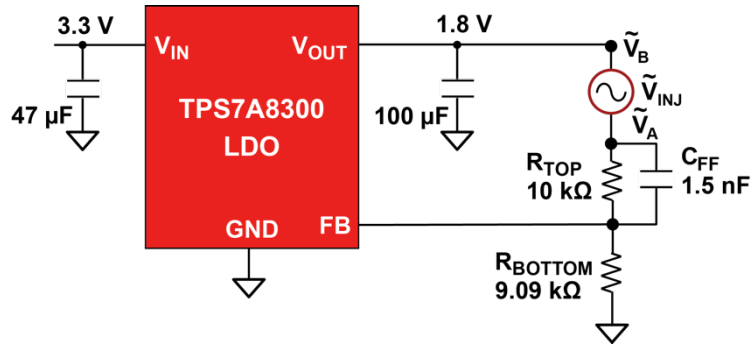


**What could happen if voltage injection is excessive?**

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

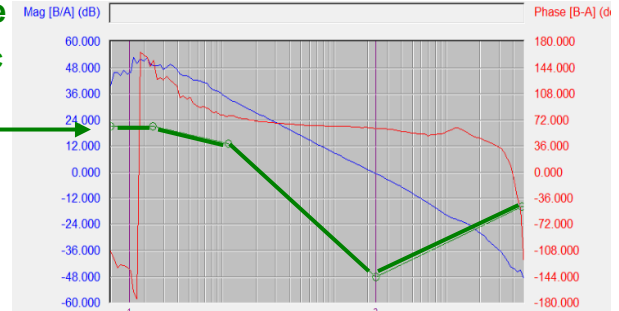


# Programmable $V_{SRC}$



Programmable  $V_{SRC}$

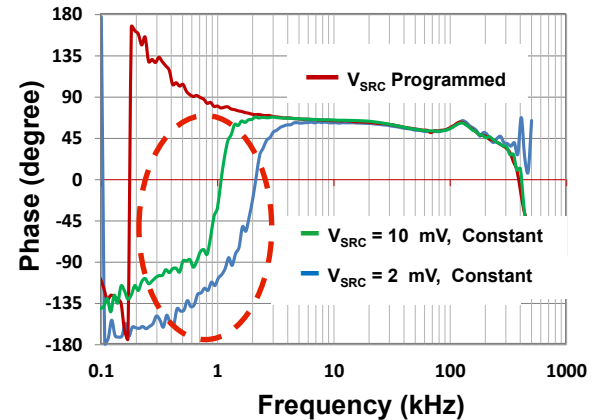
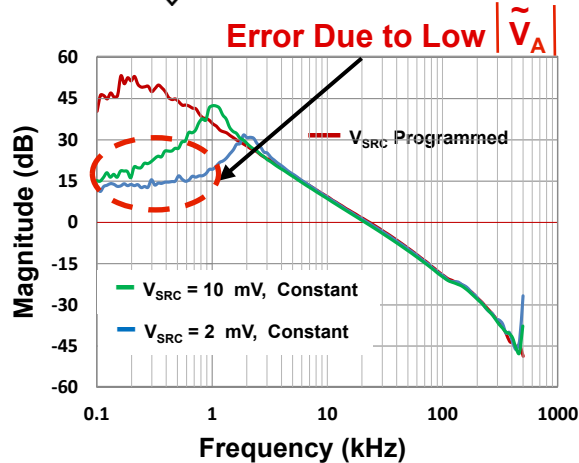
High  $V_{SRC}$  at Low Frequencies



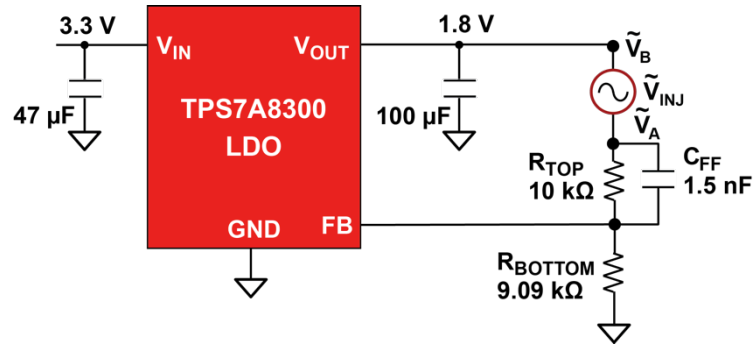
$V_{SRC}$  is the voltage source of the frequency analyzer

(Image reproduced with permission from Ridley Engineering Inc.)

Loop Gain Measurement with Different  $V_{SRC}$



# Servo Control $V_{SRC}$



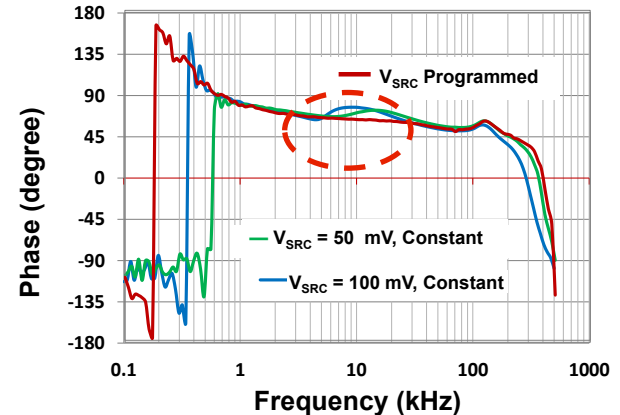
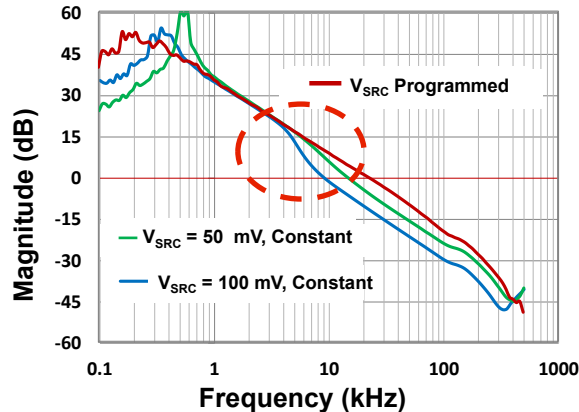
Minimum  $V_{SRC}$

Monitor Receiver signals

$V_{SRC}$  Servo:  
When CH1 or CH2 signal < threshold,  $V_{SRC}$  increases per step size

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## Loop Gain Measurement with Different $V_{SRC}$



# Frequency Analyzer– IF Bandwidth (Integration Time)

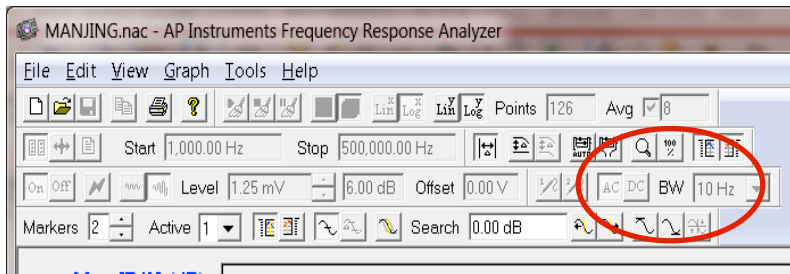
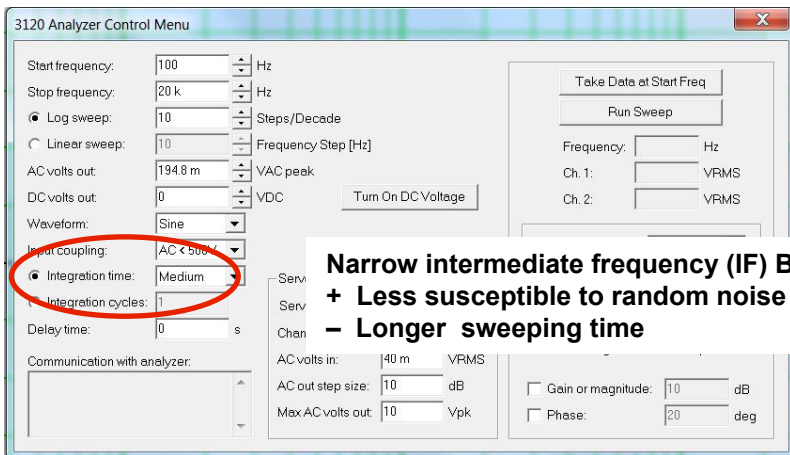
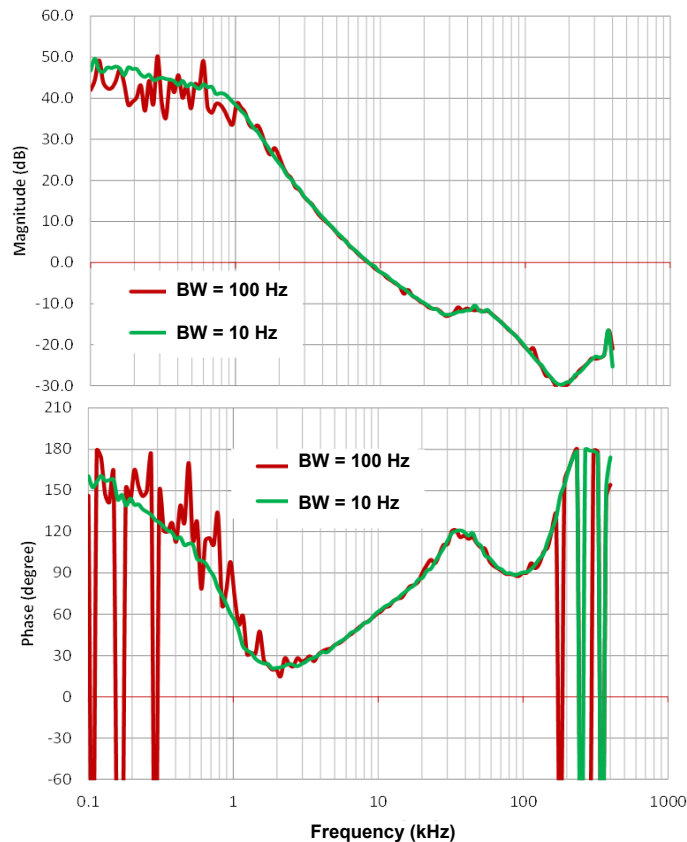


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**Narrow intermediate frequency (IF) BW:**  
+ Less susceptible to random noise  
- Longer sweeping time

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# Using Injection Isolator with Correct Frequency Range

## Injection Isolator

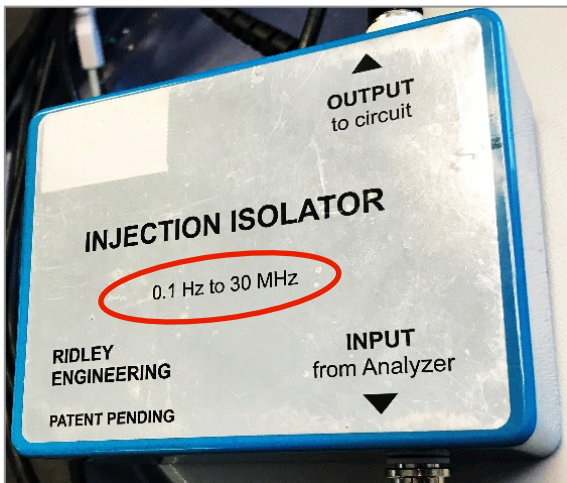


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## BODE BOX™: Injection Isolator + Pre-Connected Signal Receiver

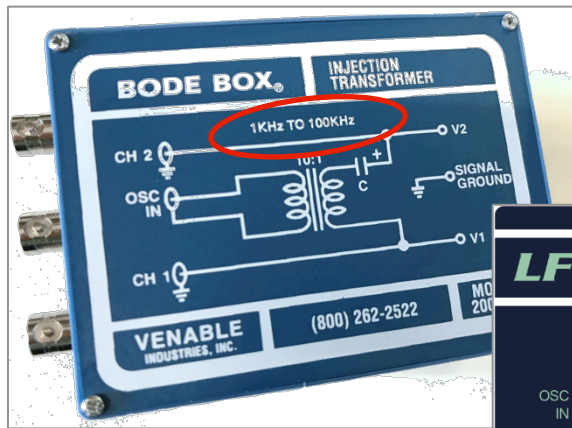


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## Active BODE BOX™

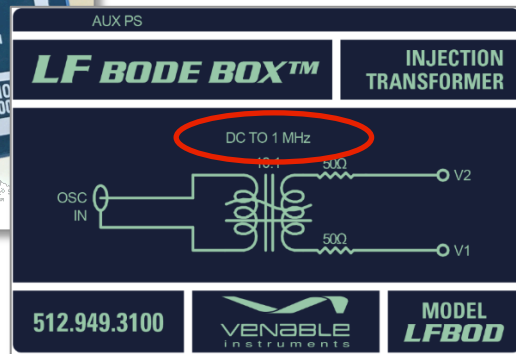


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# Setting Up Circuit for Loop Gain Measurement

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

# Maintaining DC Static Operating Point

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

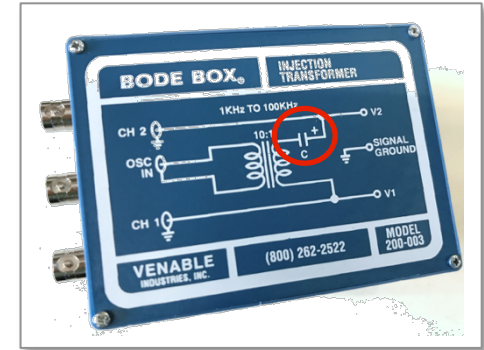
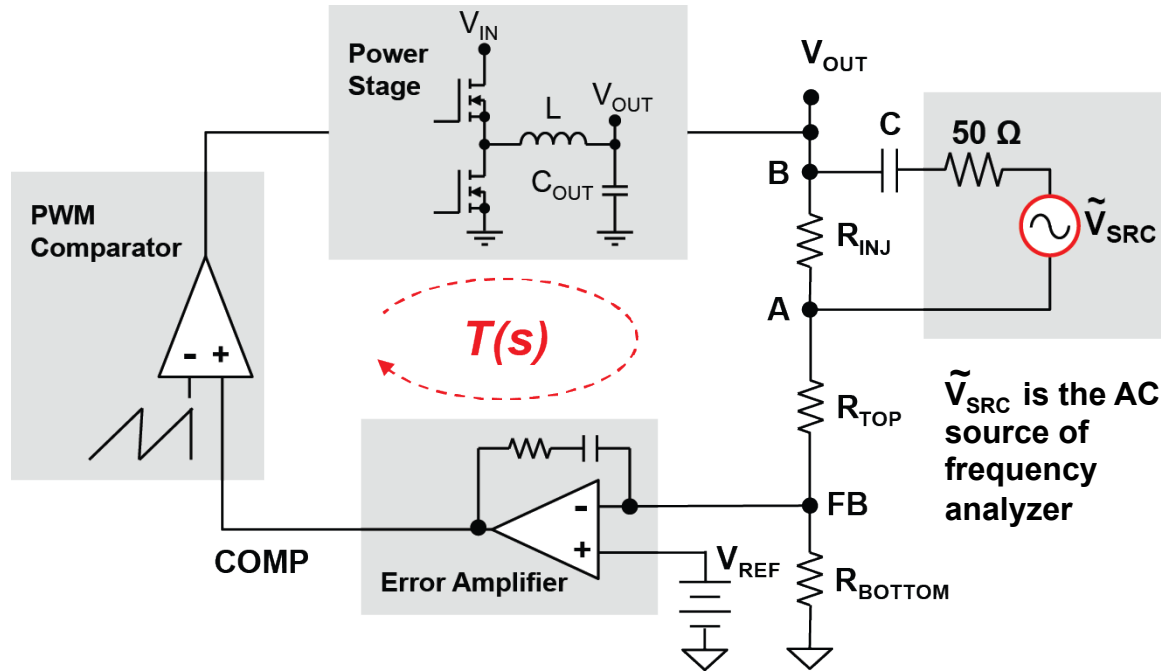


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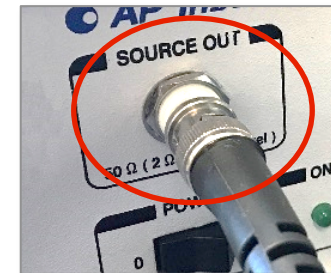
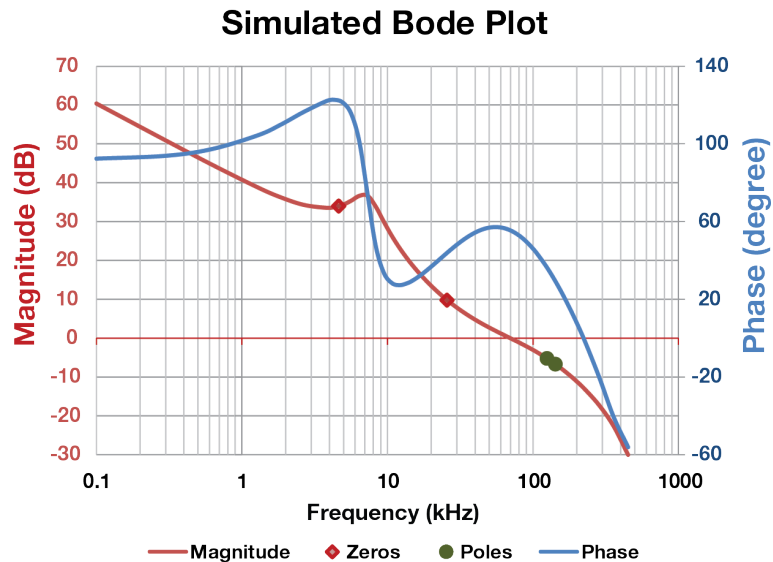
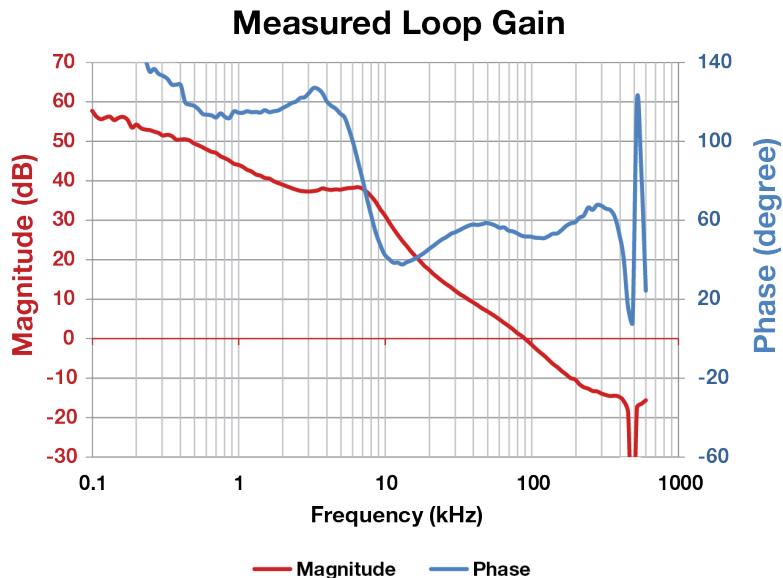


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**Source  $R_{OUT} = 50 \Omega$**

# Measuring Loop-Gain for VMC

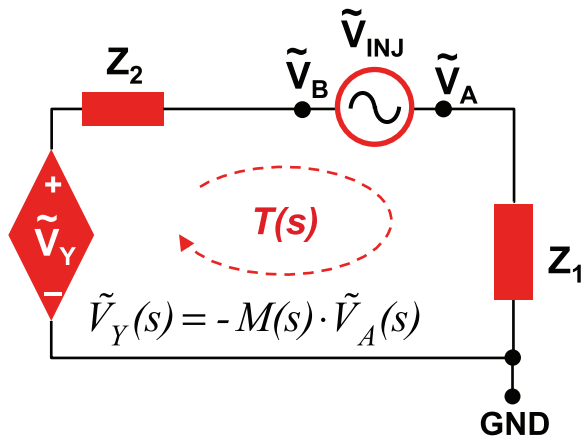
## TPS40425, Dual-Phase Buck Converter



**Measured crossover frequency and phase margin match simulation well!**

# Correct Voltage Injection Point

## Impedance Requirement

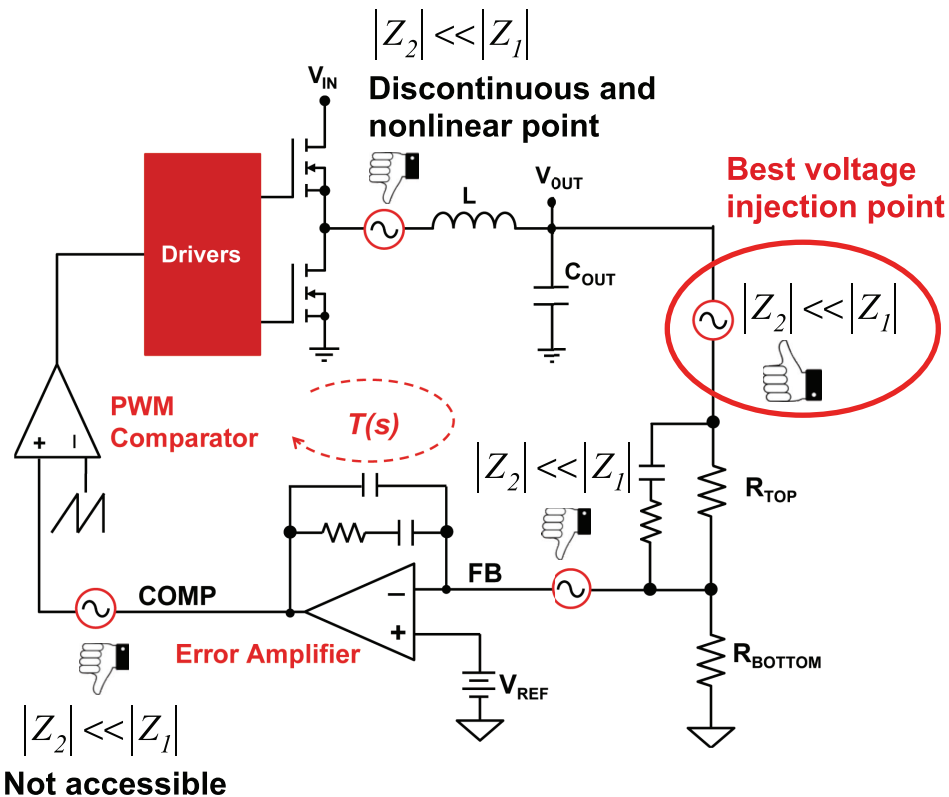


Measured loop gain:

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

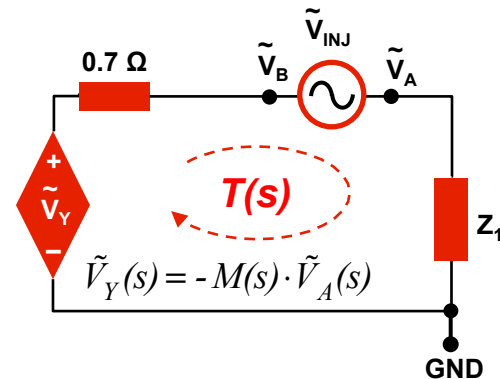
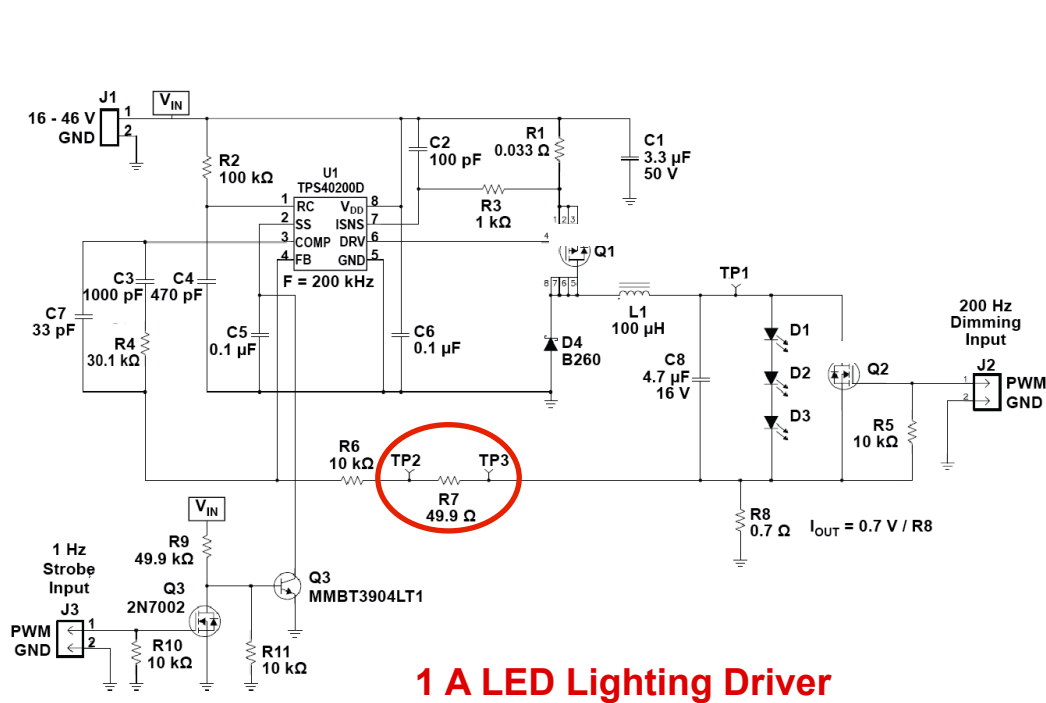
Injection point should have:

$$|Z_2| \ll |Z_1|$$

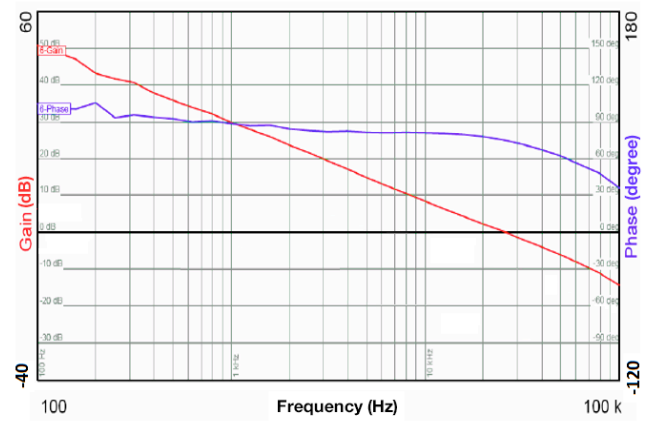




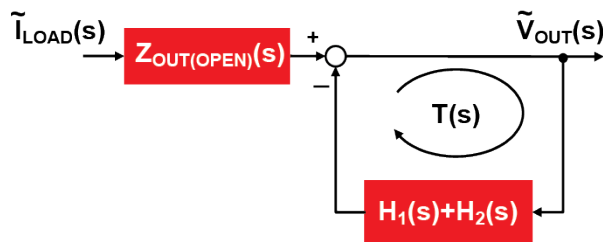
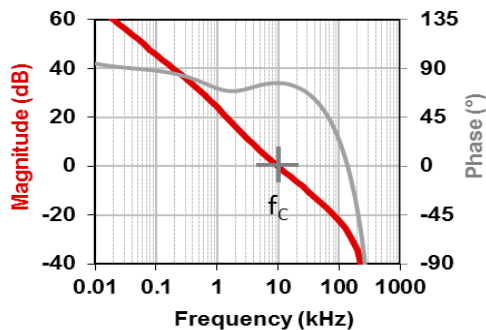
# Measuring Loop Gain for LED Driver



Measured Loop Gain



# Multiple Feedback Paths



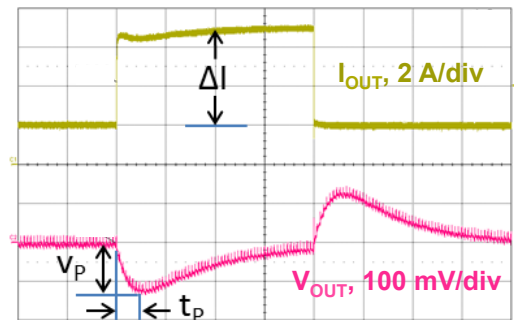
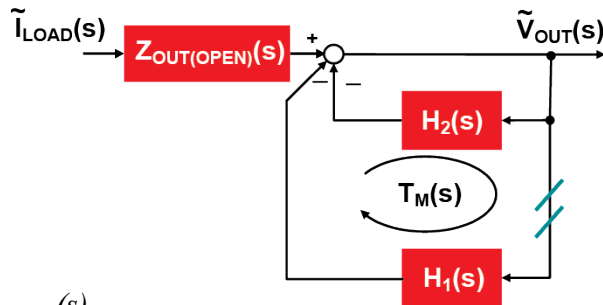
$$T(s) = H_1(s) + H_2(s)$$

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

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

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

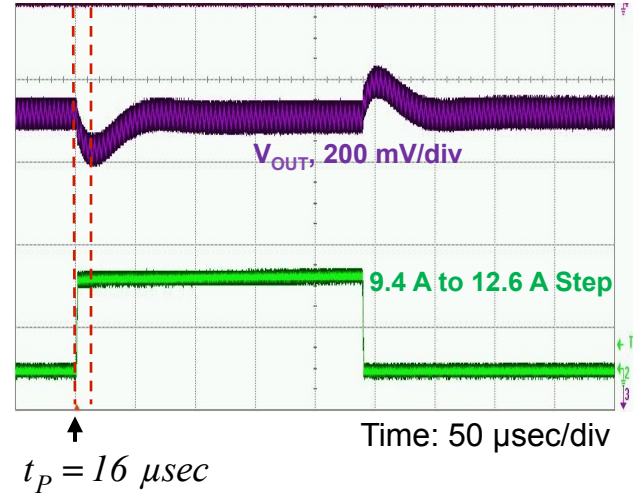
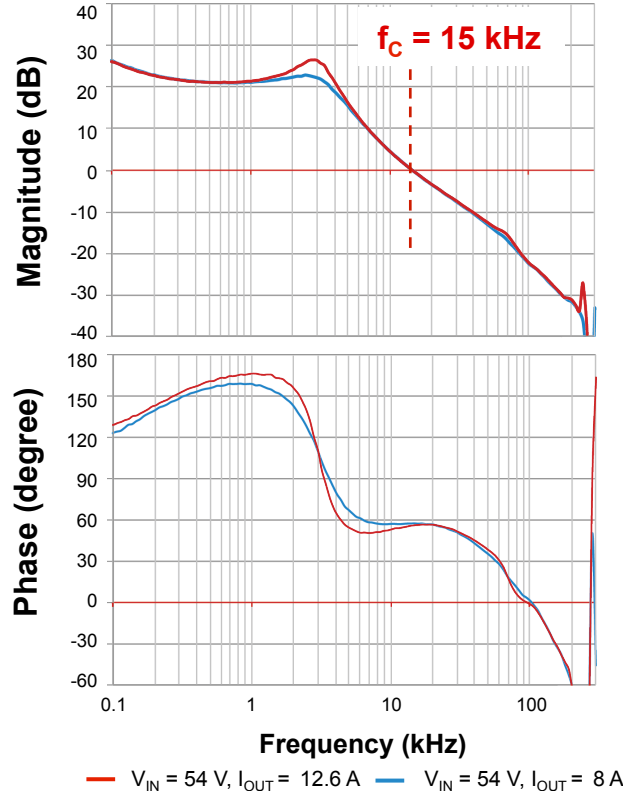
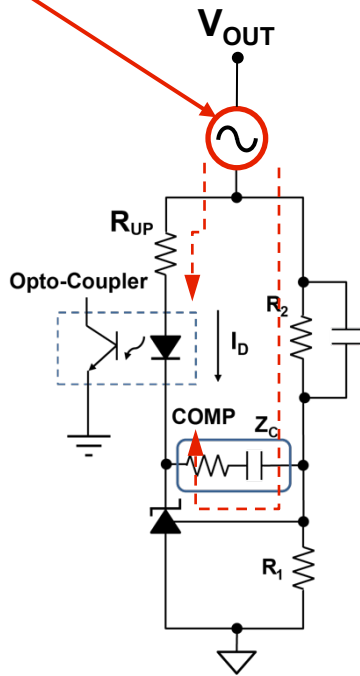
- Bandwidth of  $T_M(s)$  might not tell how transient response performs



$$V_P = \frac{\Delta I}{8 \cdot f_c \cdot C_{OUT}} \quad Z_{OUT(CLOSED)}(s) = \frac{Z_{OUT(OPEN)}(s)}{1 + T(s)}$$

# Multiple Feedback Paths – Isolated Converter

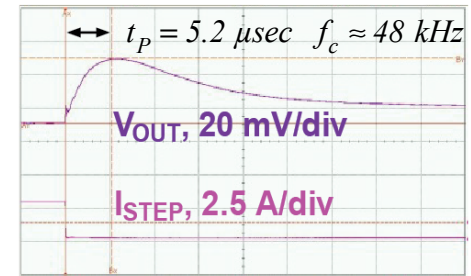
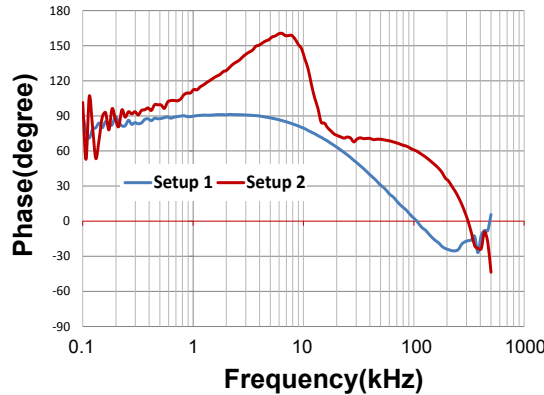
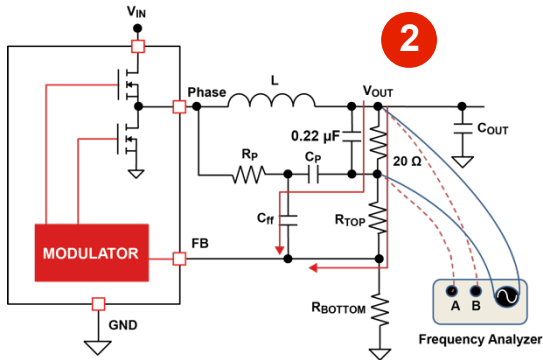
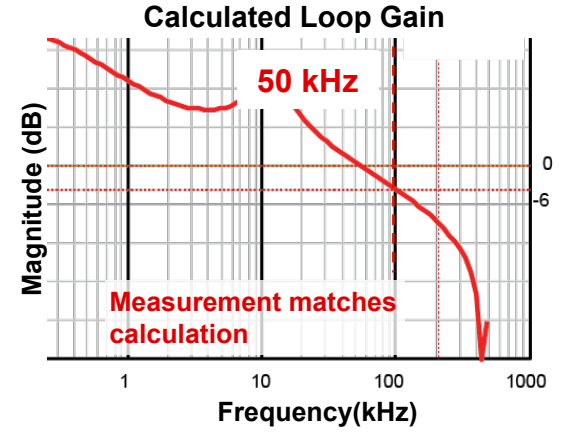
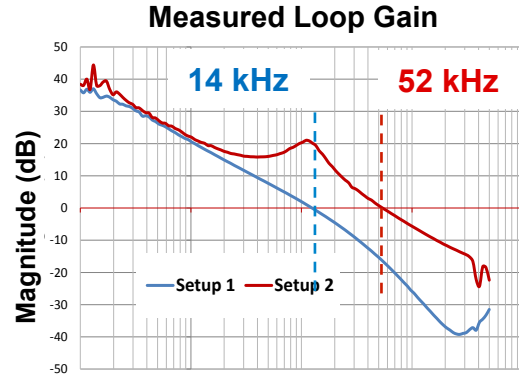
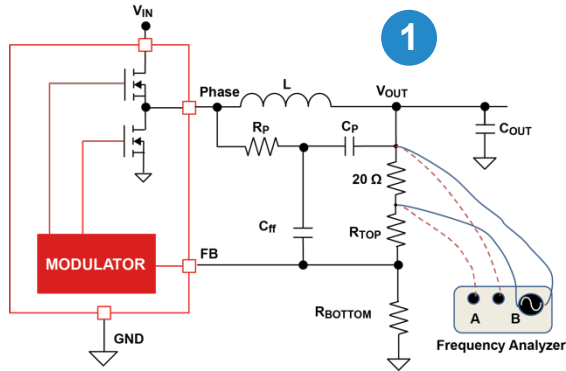
The correct injection point includes all feedback paths



Measured loop gain correlates well with transient response

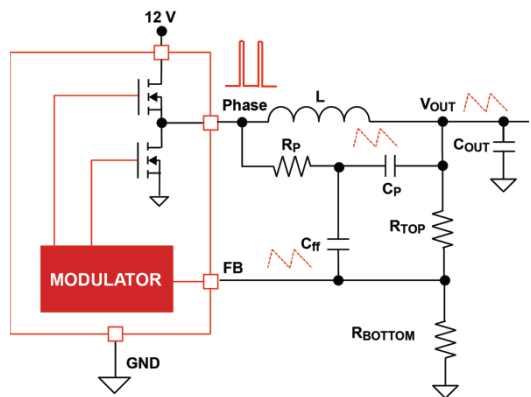
$$t_P \cong \frac{1}{4 \cdot f_C} = 16.7 \mu\text{sec}$$

# Multiple Feedback Paths – D-CAP™ Control

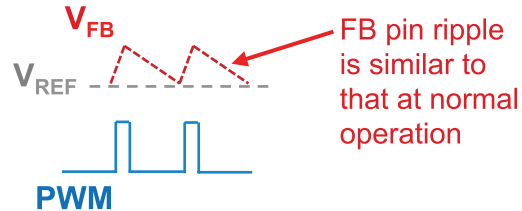
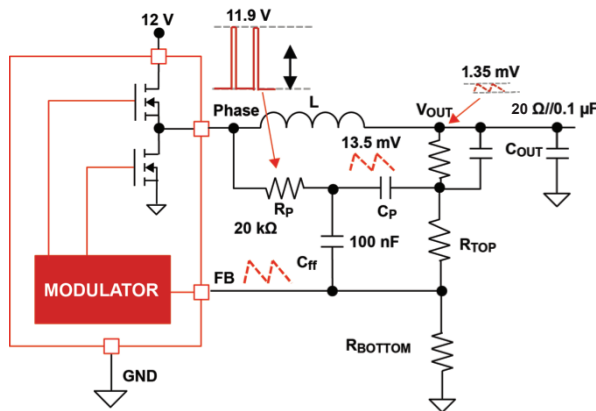
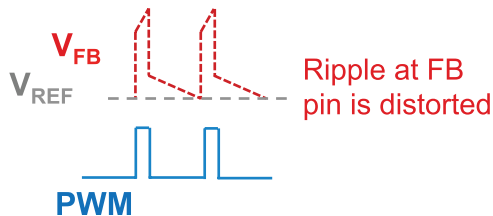
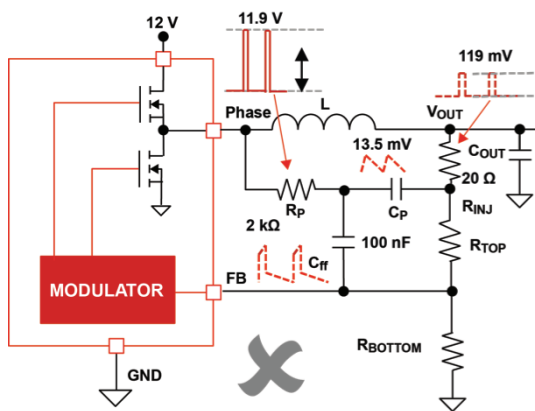
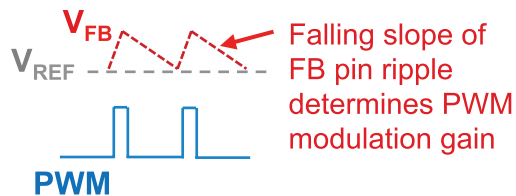


# Maintaining AC Operating Point – DCAP™ Control

A DCAP™ regulator block diagram



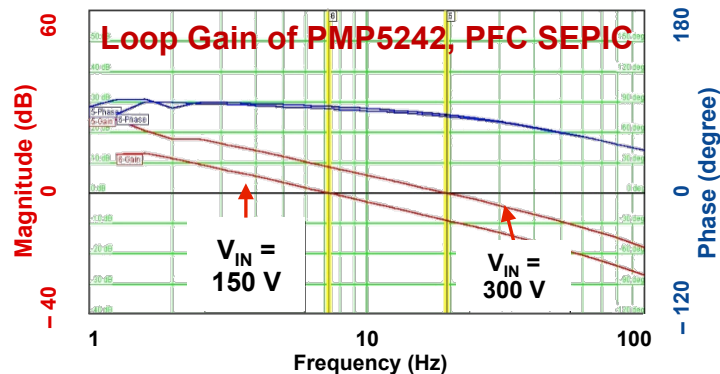
$F_{SW} = 400 \text{ kHz}, D = 10\%$



# 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

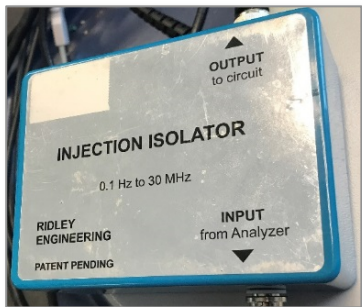
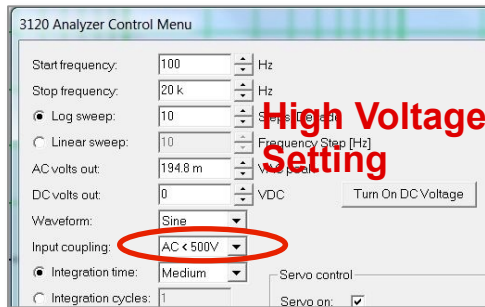


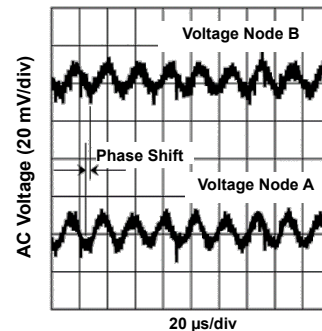
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High-voltage frequency analyzer



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Oscilloscope for gain and phase measurement

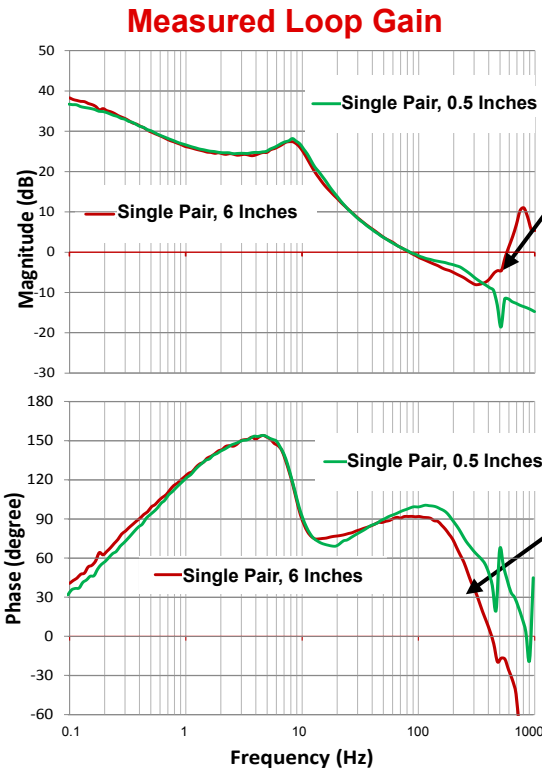


# Connecting Equipment to Converter

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

# Connection Wires Affect Loop Gain Measurement

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



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

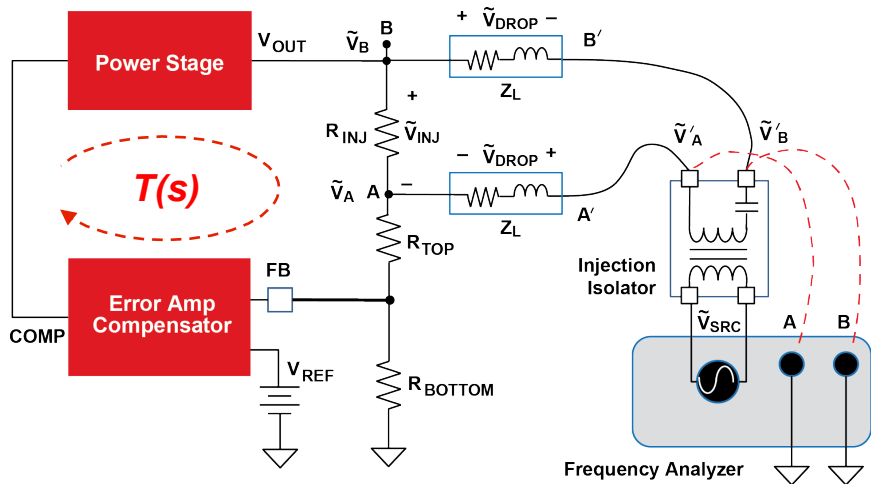
**Why does the gain increase at high frequency  
while the phase drops rapidly?**

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

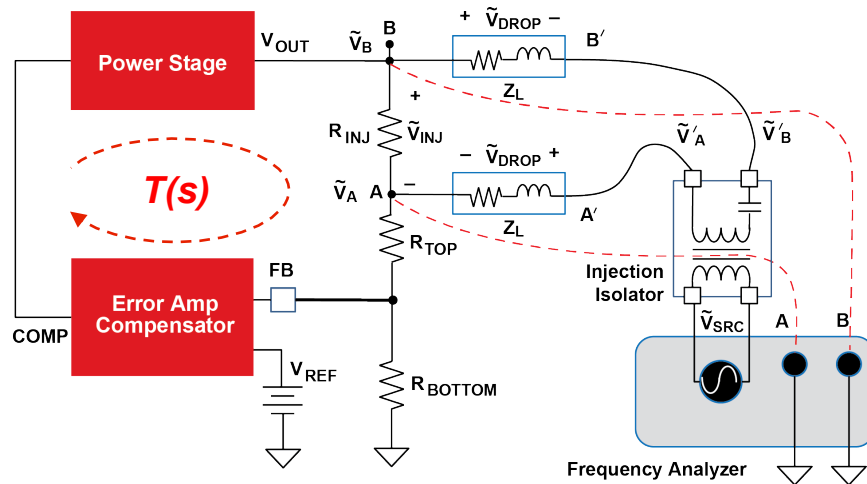


# How Connection Wires Affect Loop Gain Measurement

Receivers and adaptor share one pair of wires



Receivers and adaptor use separate wires



Measured loop gain:

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

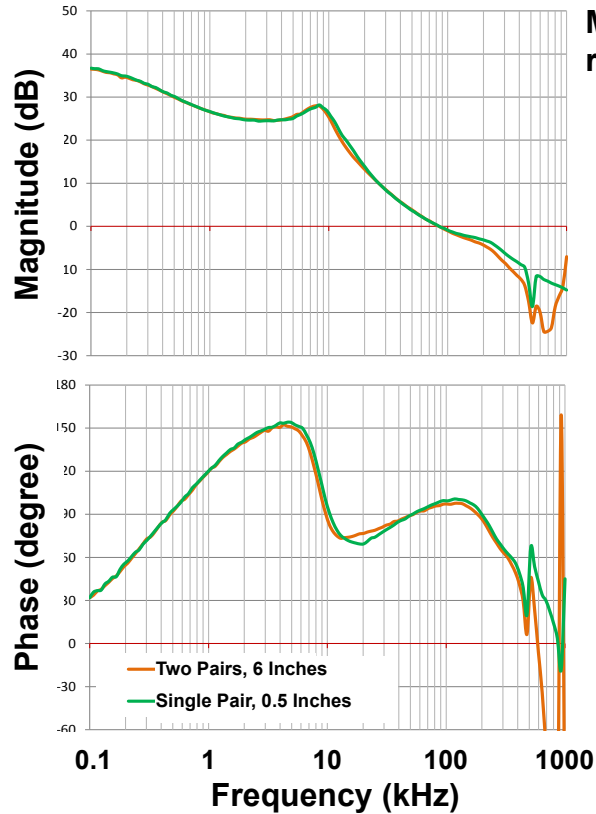
At high frequencies:

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

**Recommendation:**

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

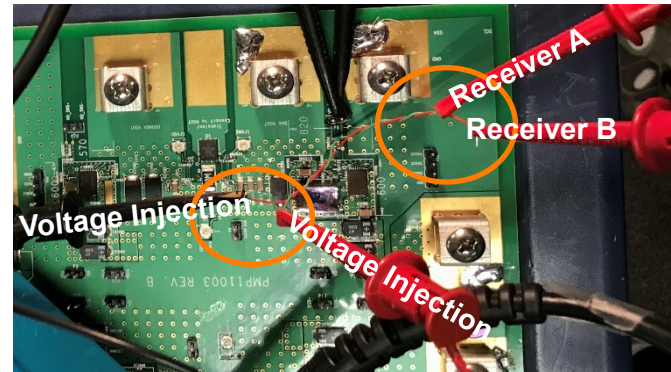
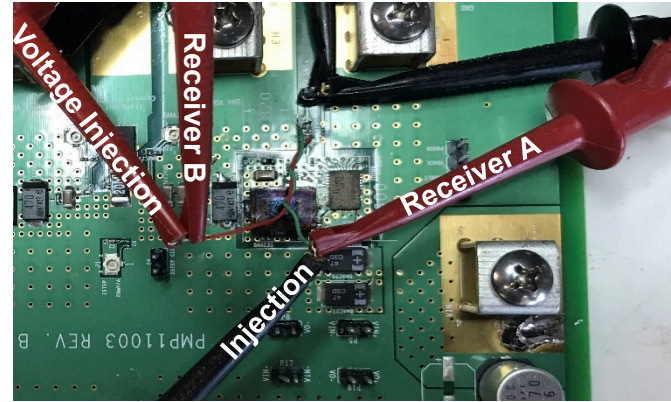
# Bench Verifications



Measurement results are similar

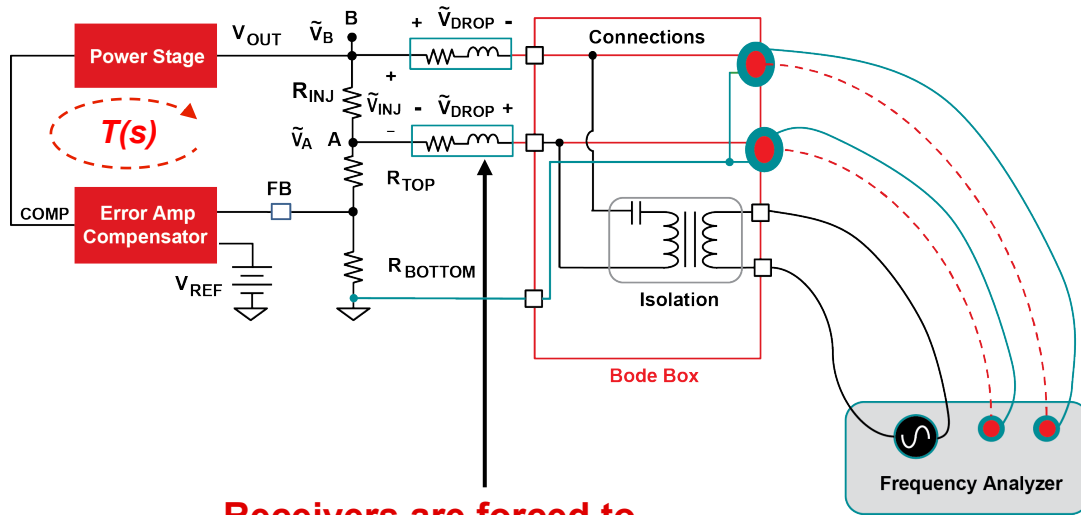
One Pair of Wires

Two Pairs of Wires

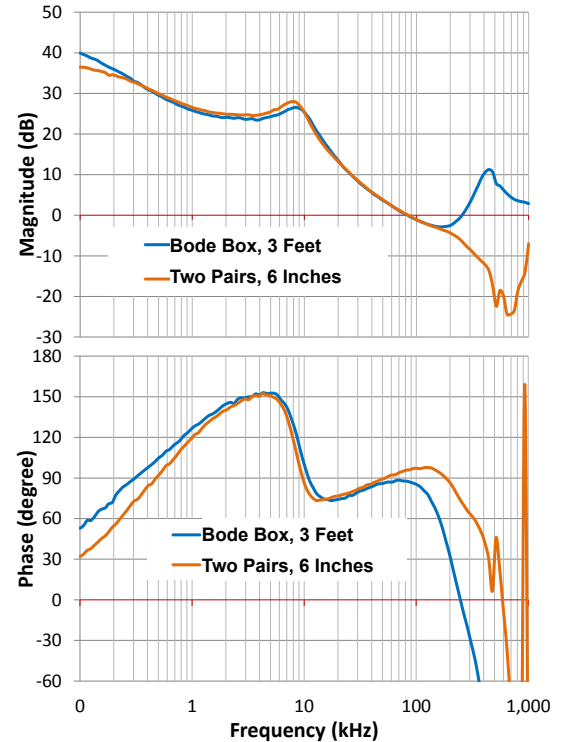


# Considerations for Bode Box™

Receivers are pre-connected to output of injection isolator

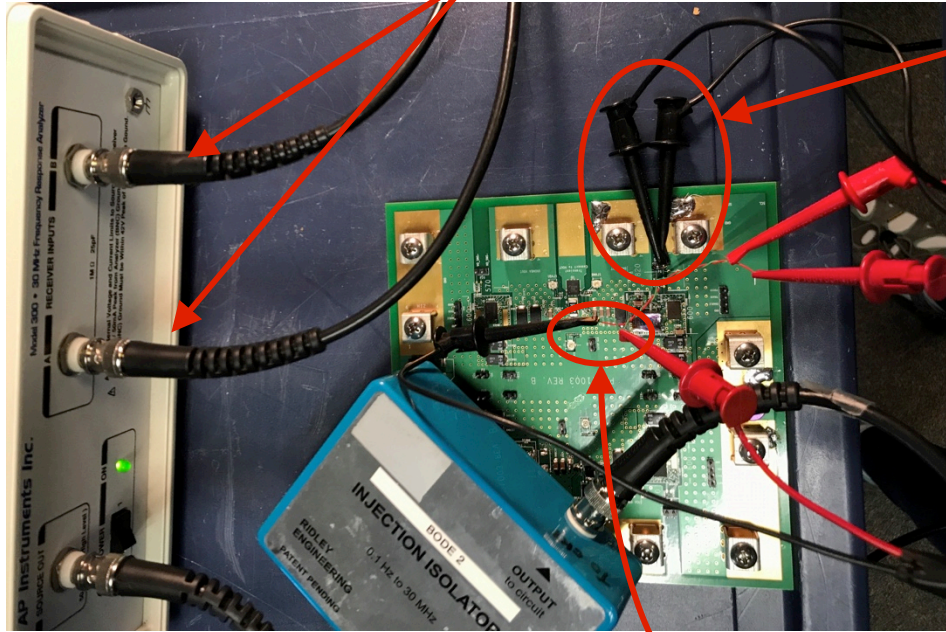


Receivers are forced to sense voltage drops across connection cable



# Which Is the Correct Reference Point?

Receiver A, B Coaxial Cables



Reference Leads



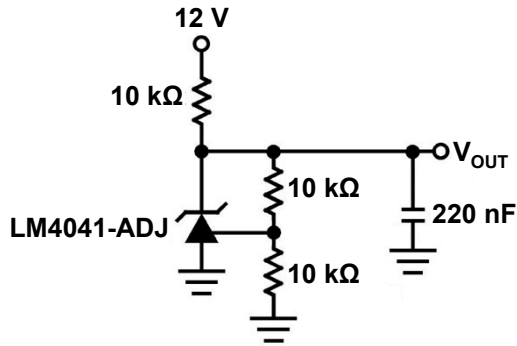
Reference Clip

- 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

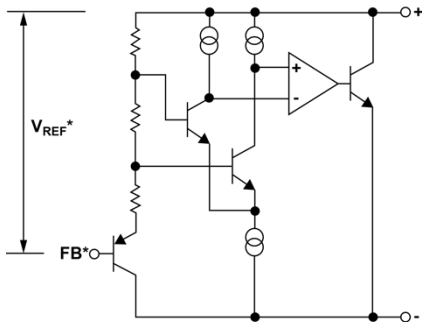
Image reproduced with permission from Ridley Engineering Inc. and AP Instruments, Inc.

# LM4041-N Shunt-Regulator

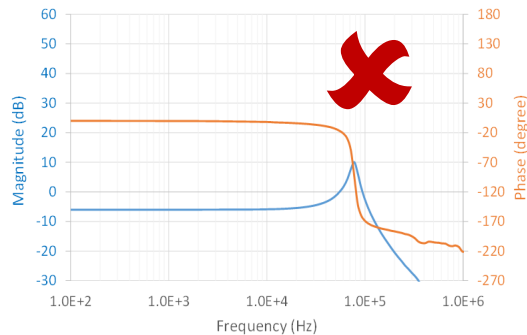
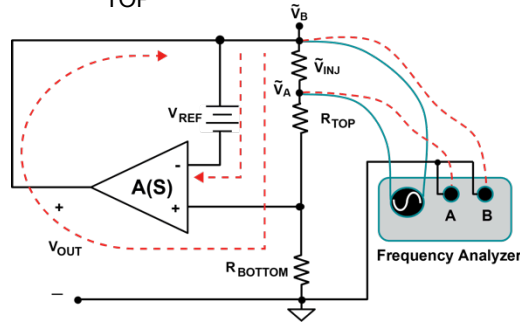


Block Diagram

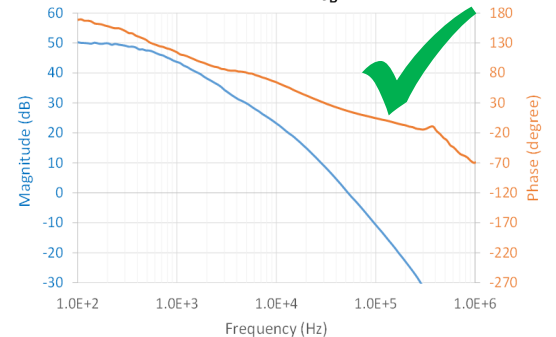
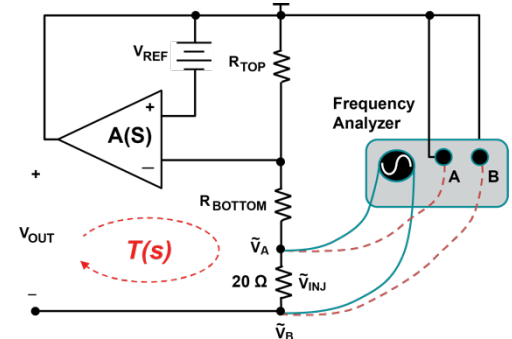
$V_{REF}$  Refers to  $V_{OUT}$



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



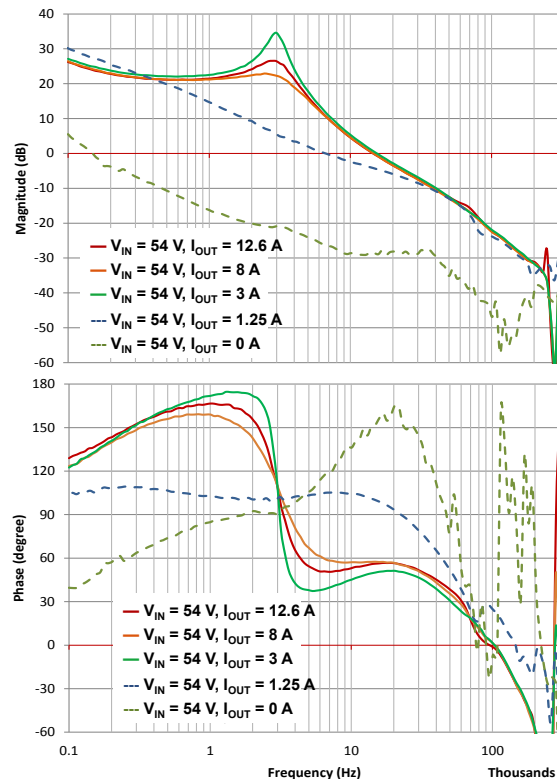
- $V_{OUT}$  is the reference point
- $V_{INJ}$  is injected between GND and  $R_{BOTTOM}$



# 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

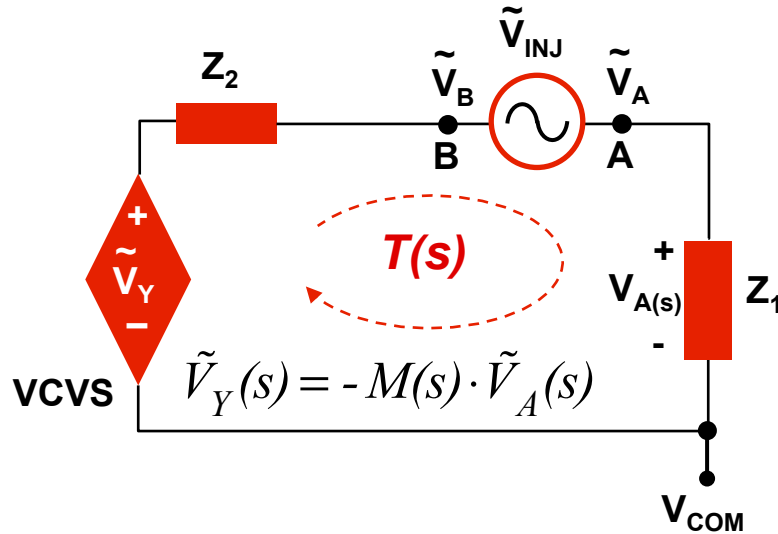
- [1] Bob Sheehan, “How to determine bandwidth from the transient-response measurement,” Power Tips Blog.
- [2] John Betten, “Calculating capacitance for load transients”, Power Tips, May 17th, 2015.
- [3] John Betten, “Control Loop Considerations for an LED Driver,” EETimes, August 17, 2007.
- [4] Datasheet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



# Appendix

# Derivation of Closed-Loop Responses

When  $Z_2 = 0 \Omega$ ,  $T(s) = M(s)$



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

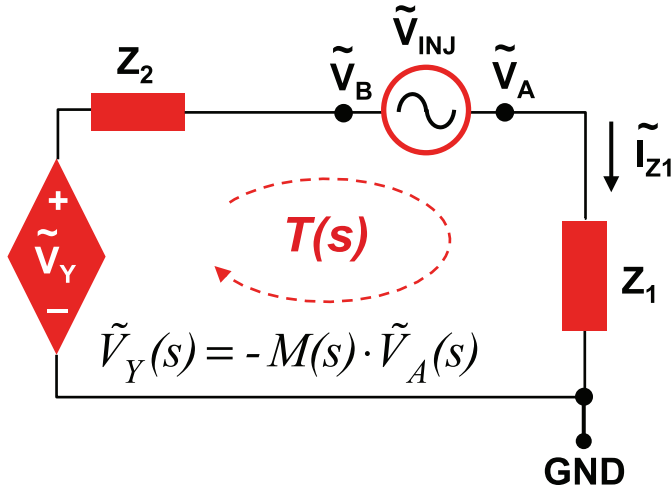
$$\tilde{V}_{INJ}(s) = \tilde{V}_B(s) - \tilde{V}_A(s) = - (T(s) + 1) \cdot \tilde{V}_A(s)$$

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

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



# How $Z_2$ Affects Loop Gain Measurement



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

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

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

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

**Measured loop gain:**

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

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



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