Killing the Bode Plot

Steve Sandler, (Picotest)
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Steve Sandler, Picotest
Steve Sandler has more than 35 years’ experience in the design, analysis, and troubleshooting of power conversion and system level equipment for commercial, military, and space applications.

Steve is the CEO of Picotest.com, a company that designs and distributes test equipment accessories designed for test and troubleshooting power systems.

Steve is also the founder and chief engineer of AEi Systems, a leading analysis and modeling company specializing in worst case analysis of high reliability systems.

Steve has authored several books related to power electronics including most recently the book entitled "Power Integrity - Measuring, Optimizing and Troubleshooting Power Systems."
The Bode Plot’s Days are Numbered ….

R.I.P.

The world’s most popular stability assessment test

Rest in Peace

1947-2017?
So What’s Wrong with Bode Plots

What’s RIGHT might be a better question

The first problem is that the Bode plot is a POOR indicator of RELATIVE stability – this is well known and well published. It means that Bode Plot results can be inaccurate and misleading.

Another problem is that the measurement requires us to inject a signal into the loop. Many devices simply don’t provide access to the loop.

We’ll show some examples...
Stability STILL Matters – A LOT

Closed Loop Performance is directly related to the Stability Performance.

That is why you DO need to assess Stability, maybe even more than ever – it’s essential to optimum, low noise, performance.

Stability assessment isn’t going away, only the Bode plot will, fortunately, better methods are currently available......
Why are Bode Plots Becoming Irrelevant

1. Poor or No Control Loop Access

3.3V/1.5A LDO

Fixed regulators/references don’t allow access to the control loop

In other cases, we might not have physical space to inject into the loop or their might be a large number of power supplies

6 output power supply

8.5mm

8.5mm

More power supplies

Or we might not want to gain access because it requires cutting a trace or a wire
High Frequency Injection is Impractical

500MHz Bandwidth eGaN Linear Regulator

FEATURES

- 3.8nV/√Hz Input Noise Voltage
- 3.7mA Supply Current
- 200MHz Gain Bandwidth
- Low Total Harmonic Distortion: −85dBc at 1MHz
- 70V/μs Slew Rate
- 400μV Maximum Input Offset Voltage
- 300nA Maximum Input Bias Current
- Unity-Gain Stable
- Capacitive Load Stable Up to 100pF
- 23mA Minimum Output Current
- Specified at ±5V and Single 5V
- Low Profile (1mm) SOT-23 (ThinSot™) Package
2. Many new devices have multiple internal loops
   - All need to be accounted for
     — Digital Control Loops
Why are Bode Plots Becoming Irrelevant

3. You can have both good phase margin and good gain margin and yet have poor stability
   - There may be multiple crossovers
   - Control loops can be high order
   - Multiple or non-linear loops
   - SM provides the most accurate measure of stability

ONLY this one point is **UNSTABLE**
What is RELATIVE Stability & Why Bode Plots Can Mislead

A **STABLE**

control loop is one that doesn’t oscillate

\[
\text{Closed Loop} = \frac{\text{Open Loop}}{1 + T}
\]

This is the gain/phase vector

Unity gain negative feedback results in a denominator of zero = unstable

The minimum magnitude of the denominator provides the RELATIVE measure – also known as the ‘Stability Margin’

Nyquist is a better assessment tool for Stability than Bode
A DC-DC Converter Example

What’s Interesting

• Bode & Nyquist - same data
• Bode didn’t indicate stability
• Scope Owners: load step ringing may or may not indicate a stability issue
• Must use a Closed Loop Test → Nyquist, Impedance, etc.

78 degrees phase margin
6.7dB gain margin

But it Rings Severely
Output Impedance is as Good as Nyquist

PM = 50 Deg, 658 Hz

Impedance Peak, 860Hz

Ringing at 860Hz

Flyback Converter

Flyback Converter

Distance from (1,0)
So How Can We Easily and Accurately Assess Stability?

- Non-Invasive Stability Measurement – ‘NISM’

No Control Loop – No Problem
Stability Margin can be determined from a **single** output impedance measurement!
The NISM Concept is Simple

Yes. You can measure phase margin from a single measurement.

- From 1 Impedance Measurement - 3 data points
  - Impedance Magnitude, Phase, and Group Delay

- The NISM software extracts data from output impedance and the ‘Q’ via group delay and allows the $Z_S$ and $Z_L$ to be mathematically determined so they can be converted to Stability Margin

- Phase margin is determined by setting $|T_m| = 1$ and solving for phase.
What is NISM and Why It’s a Critical Technology

- Nyquist solves our problem, but is not always simple to compute
- NISM accomplishes the same thing more simply thru closed loop output impedance
- NISM determines control loop margins without needing access to the feedback loop
- NISM is based on proven Minor Loop Gain Theory
  - Similar to assessing Load Step ‘Q’
- The NISM technology is licensed and promoted by Picotest.com
- The measurement capability can be found on various VNAs
  - OMICRON Lab, Keysight, Copper Mountain
NISM is Based on Fundamentals

- Dr. R.D. Middlebrook popularized the topic of *Minor Loop Gain, $T_m$* with his introduction of the extra element theorem which allowed us to assess the stability of power supplies and input filters
- Minor loop gain, based on Nyquist criteria, is now one of the most researched electronics topics
- Many articles can be found with an internet search of “forbidden region stability criteria”

Today this is a highly researched university topic and many papers will be found using the search term “Minor Loop Gain”.

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<tbody>
<tr>
<td>Dynatron</td>
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<td>Dr. Lee</td>
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How Do I Make a NISM Measurement

- Step 1: Measure Impedance
- Step 2: Set Cursors

Practically speaking, output impedance is measured with a suitable probe in a 1 or 2 port configuration.

The software converts the impedance to group delay and Q.

The user positions waveform cursors on the impedance and Q waveforms and the conversion to phase margin is read out on the instrument’s screen.
NISM on the OMICRON Lab Bode 100
NISM on the Keysight E5061B
NISM – Just as Accurate as a Bode Plot

- Accurate to within 1 degree
- Accurate even when Bode Plots are not
- Accurate up to 65 degrees

Lab comparisons of 7 regulators/capacitors
Bode plot and the NISM methods were within ±0.9 degrees

Phase Margin Experimental Comparisons

Noise free simulation results were within ±0.3 degrees, attributable to cursor resolution
LT1086 Linear Regulator

Vin 5V

N = 500mA

Min = 25mA

Max = 1A

Vin 3.28% 45.24% 45.24%

Vout ±0.5V

R1 249 3.28%

R2 110 3.28%

C1 0.1uF 45.24%

C2 0.1uF 45.24%

R3 1

Cout

TR1: Mag(Gain)

TR2: Qtg(Gain)
LP2998 DDR Termination Regulator

28.9 deg

29.43 deg
TPS7A4501 Linear Regulator 5mA

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<th>Bode Plot</th>
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<tr>
<td>Measured</td>
<td>51 deg</td>
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A low-noise, fast-transient-response 1.5-A low-dropout (LDO) voltage regulator

VRG8666 (RH3080) Linear Regulator

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<tr>
<td>Measured</td>
<td>20 deg</td>
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Measured data includes:

- **TR1 (dB)**: Measured at various frequencies with a range of ±60 dB.
- **TR2 (°)**: Measured at various frequencies with a range of ±180°.

Connectors and components include:
- X1
- VRG8666
- V1
- C2 330u
- C3 330u
- R1 250k
- C1 1u
- R2 19

The circuit diagram shows the connection of these components and their respective parameters.
High Speed Opamp

- Using the Keysight E5061B VNA, with the NISM software, we were able to test the stability of this 245 MHz op-amp.
- The big WOW is that we obtained the (very poor) phase margin from the impedance measurement using NISM (just about 2 degrees).
- This is a great capability; to be able to accurately assess stability at 100's of MHz or higher without lifting any wires (which would interfere with the measurement).
Applications for NISM

• Op-amps
• Voltage Regulators – including LDOs, POLs, VRMs….  
• Voltage References
• Audio Amplifiers – including switching types
• Input Filter Stability
• System Level Box-to-Box Stability
• Current Regulator Stability (electronic load, LED, etc.)
• Almost any control loop
A New Path To Stability Testing is Here

- Technology, Integration, Shrinking Form Factors Have Forced the Issue
  - Reduced the practical application of Bode Plot measurement
  - The load (impedance and current) are critical to an accurate stability assessment
  - What’s needed is an in-circuit measurement

- NISM – Non-Invasive Stability Measurement
  - The final nail in the Bode Plot coffin is the availability of an alternative assessment
  - Available on popular VNAs
  - Included with the Instrument or available as a software add-on
Thank you!

QUESTIONS?