Understanding Power Supply Loop Stability and Compensation—Part 2: Unusual or Problematic Bode Plots

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Abstract

Part 2 of this article series discusses examples of unusual or problematic Bode plots and their corresponding root causes. The previous article "Understand Power Supply Loop Stability and Loop Compensation—Part 1: Basic Concepts and Tools" reviews the critical concepts and importance of loop stability, from the Nyquist plot criterion to Bode plots.

Introduction

It is always important to design a stable power supply with good dynamic response. Bode plots have been the standard way to quantify the loop bandwidth and stability margins of a feedback system such as a closed-loop power supply. However, occasionally, engineers may encounter unusual or problematic power supply Bode plots and may be unsure whether the loop has sufficient stability margins. In such situations, the Nyquist criterion and plot provide an alternative way for analysis and can sometimes be more helpful in explaining the concept and determining loop stability.

Typical Power Supply Loop Bode Plots and Design Considerations

Figure 1 shows a typical step-down switching mode power converter control loop Bode plots in the frequency domain, and its time domain load transient responses. They are modeled in the LTpowerCAD® design tool. In this example, the solid line plots are for a design with ~32 kHz bandwidth and 70° phase margin. In general, for a buck switching mode converter, a phase margin greater than 45° is usually acceptable and greater than 60° is sufficient. However, people may question this example phase plots. At around 8 kHz while the loop gain is much higher than 0 dB, the corresponding phase is about 38°, which is below 45°. Is there a potential stability issue to have low phase value while the gain magnitude is still high?

The answer is no. It can be better explained by applying the Nyquist criterion concept reviewed in a previous study.[1] Figure 2 shows the conceptual corresponding Nyquist plot of the solid line Bode plots in Figure 1a. As shown, before the T(jω) plot crosses the unit circle, its phase angle can be less than 45°, while the T(jω) plot is far away from the (-1, 0) point. Therefore, according to the Nyquist criterion, the system is indeed very stable.

In fact, it is possible to increase the phase of the design at the lower frequency range below the loop bandwidth, though it may not improve the supply dynamic response performance. In this example, a simple Type 2 compensation network is used with a resistor R_{TH} in series with a capacitor C_{TH} of the feedback error amplifier circuit. We can increase the compensation capacitor C_{TH} value from 510 pF to 1500 pF. The corresponding Bode plots are dotted line plots shown in Figure 1a. The larger C_{TH} moves the compensation zero to lower frequency, therefore helping to increase the lower frequency range phase to be over 60°. However, this phase improvement does not improve the supply dynamic performance. Instead, as shown in Figure 1a, the larger C_{TH} value reduces the lower frequency gain amplitude, resulting in longer V_{OUT} settling time after the load transient as shown in the dotted line waveform in Figure 1b. The total V_{OUT} undershoot and overshoot amplitudes remain unchanged. In conclusion, the original design (solid line in Figure 1) is a better choice, despite its lower phase value at lower frequency.

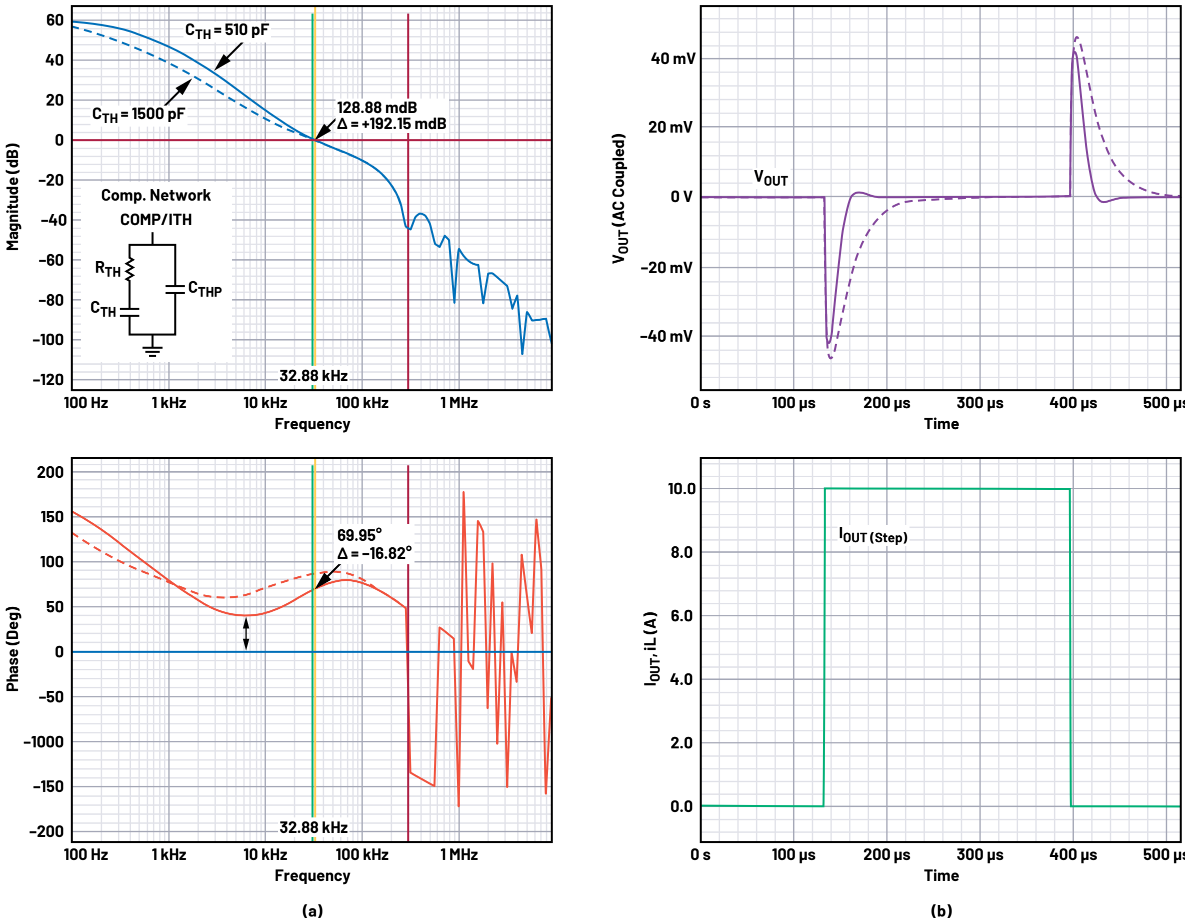


Figure 1. A typical LTC3833 buck converter Bode plots and load transient responses in LTpowerCAD (with different compensation capacitor C_{TH} values: solid line: 510 pF, dotted line: 1500 pF): (a) loop gain Bode plots; (b) load transient response.

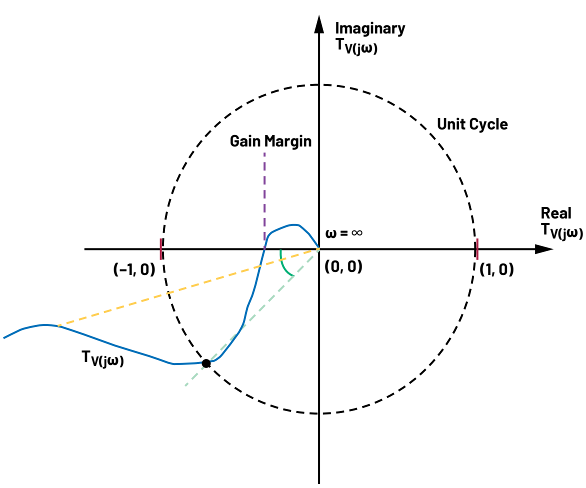


Figure 2. Conceptual Nyquist plot of Figure 1a solid line Bode plots.

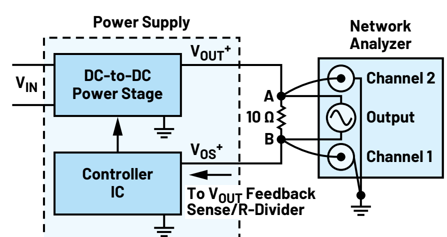
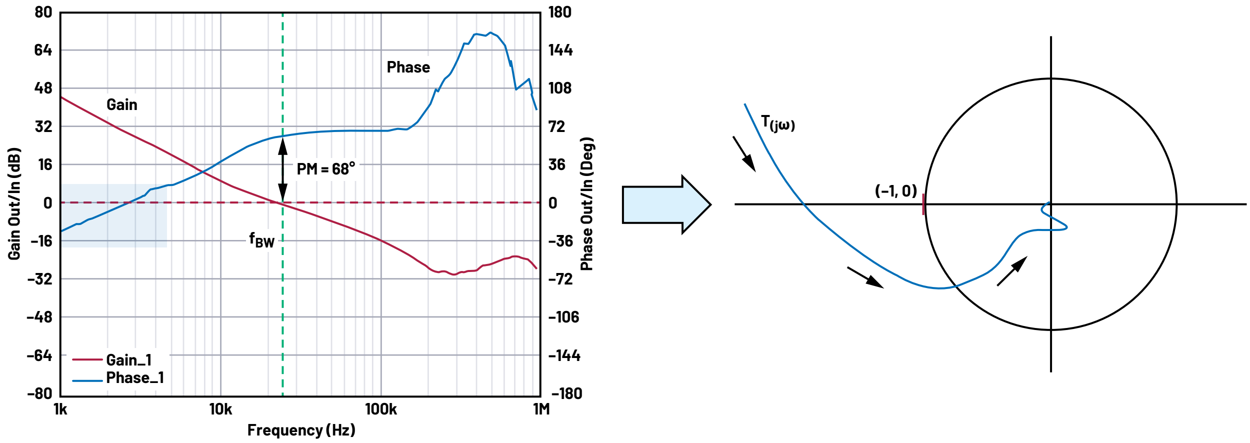


Figure 3. Standard power supply feedback loop Bode plots test setup.

Figure 3 shows the standard test setup to measure a power supply feedback loop Bode plots. A small value 10 Ω to 50 Ω resistor is inserted in the output voltage feedback path between V_{OUT} (Node A) and controller Vout_sense input (Node B), which is usually on top of the internal feedback resistor divider. The network analyzer applies a small signal (usually ≤ 50 mV pp) AC signal across this 10 Ω resistor over a wide frequency range. The loop gain Bode plots are measured by sensing and calculating the AC signal ratio of VA(s)/VB(s) over a range of frequency by the network analyzer.



(a) (b)

Figure 4. Measured supply Bode plots with a strange negative low frequency phase plot and its conceptual Nyquist plot: (a) measured Bode plots; (b) conceptual Nyquist plot.

Next, let's look at a few typical cases of unusual Bode plots:

Case 1: Measured Bode Plots Have Low or Even Negative Phase at Lower Frequency While the Loop Gain Is High

Figure 4a shows lab-measured Bode plots with even negative phase values at very low frequency range well below the loop bandwidth frequency. However, with increased frequency, the measured phase increased, resulting in a large, positive phase margin at the crossover frequency f_{BW}. Is this system stable?

First, we noticed this type of Bode plot is usually only observed in lab-measured results, while the corresponding small signal model tool of the same supply using LTpowerCAD does not show this. There are some practical considerations to be considered: (1) the measurement result can be inaccurate at lower frequency, as the Bode plot is measured as VA(s)/VB(s). At lower switching frequency, the loop gain amplitude is very high. As a result, for a small AC inject signal from the network analyzer, the resulting VB(s) signal is very small. For example, Figure 4a shows the loop gain is about 48 dB (~251) at 1 kHz. If the inject AC signal is 100 mV, the signal at V(B) is estimated at 100 mV/251=0.4 mV at 1 kHz. Therefore, it is easy for measurement noises to pollute the VB(s) signal resulting an inaccurate phase result. (2) Sometimes, it is found out that the grounding connection of the DUT power ground, signal ground and network analyzer ground connection can noticeably affect the measurement results, especially phase plot at very low frequency. (3) There may be other details of the power supply not modeled in the simplified LTpowerCAD model. For example, the clock-synchronization phase lock loop circuit is usually not modeled due to its complexity. (4) Most importantly, Bode plots at the frequency range far lower than the supply crossover frequency does not determine the supply stability, even if the measurement result is real and accurate. This can be explained by the corresponding Nyquist plot as shown in Figure 4b though the T(jω) plot intersects the x-axis (that is phase < -180°), it does not encircle the (-1, 0) point clockwise. Actually, the T(jω) plot always keeps a good distance from (-1, 0) point, therefore the system is very stable according to the Nyquist stability criterion. To further support this statement, Figure 5 shows this converter's time-domain load transient response waveform. It demonstrates a load transient response of a very stable system.

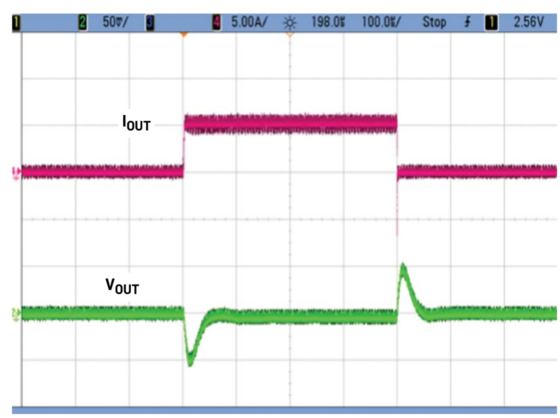


Figure 5. Measured load transient response of the supply in Figure 4a.

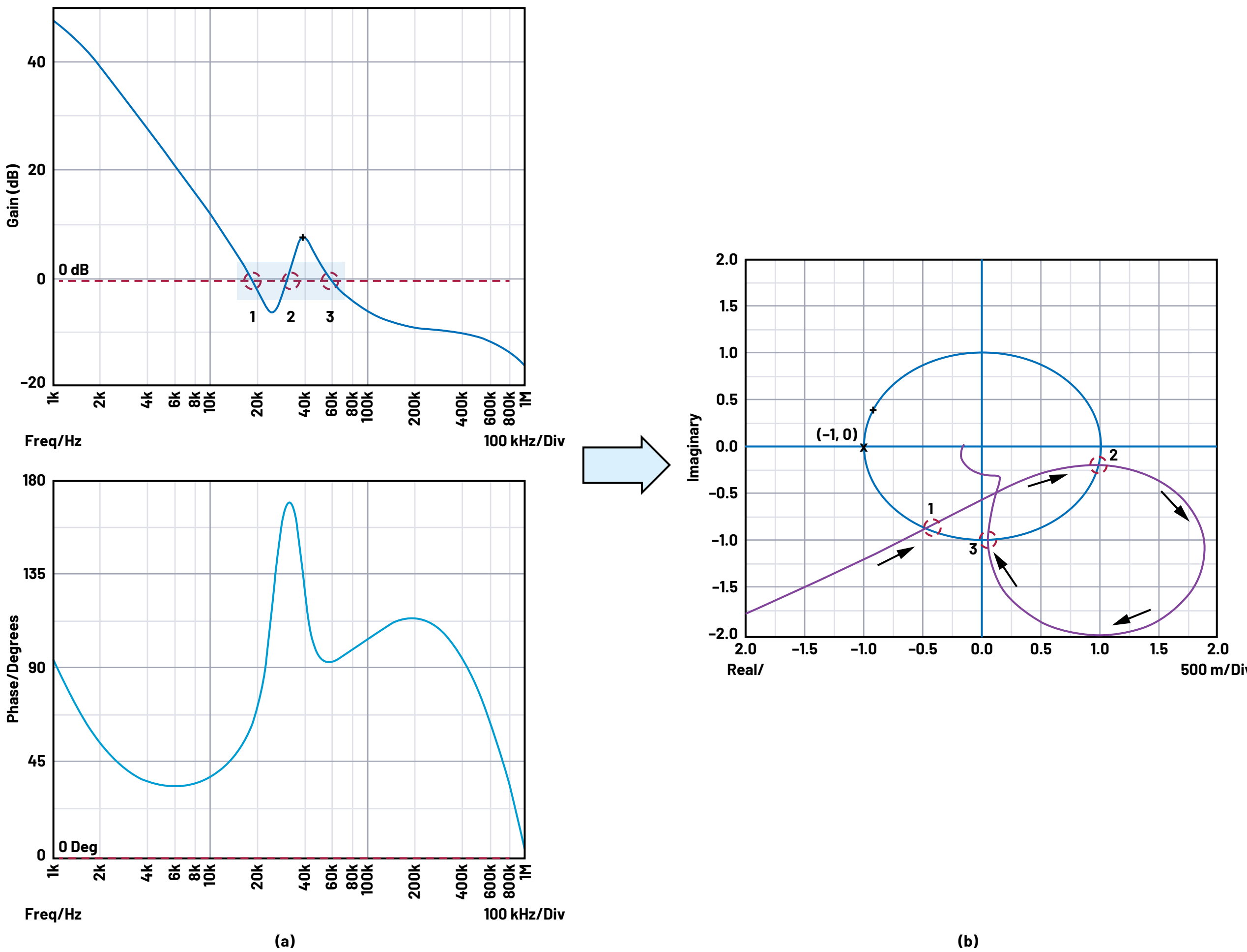


Figure 6. Bode plots with strange gain plot after the crossover frequency (generated with Simplis tool) and its corresponding Nyquist plot proving a stable systems: (a) loop Bode plots; (b) corresponding Nyquist plot.

Case 2: Measured Gain Plot Intersects 0 dB Multiple Times, While the Phase Is Greater Than -180°

Figure 6a shows another example of loop Bode plots on which the gain plot crosses the 0 dB axis three times, while phase value remains very positive. What may cause this strange Bode plot? Is it a stable system?

The Figure 6a Bode plot is usually caused by an additional post L/C filter at the supply output side after the supply local output capacitor, as illustrated in Figure 7. In noise-sensitive applications, to further attenuate switching ripples on the output voltage, sometimes an additional inductor L_S (or ferrite bead) is added. The inductor L_S can be a real inductor or the parasitic inductance of output cables or long PCB traces. The resonance of local capacitor, remote capacitors C_{CF} and C_{BF}, and additional filter inductor L_S creates this unusual Bode plot. To understand this, Figure 8 shows the supply local C/L/C impedance Z1(s) analysis from the supply local output V_{OUT} sense point in this case. This Z1(s) impedance has a resonant valley and a resonant peak on its gain plot, resulting in valley and peak in the loop gain plot.

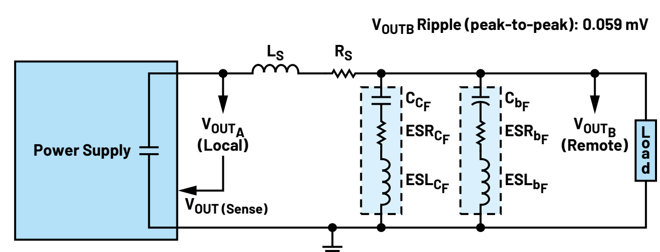


Figure 7. Power supply with additional output L/C filter.

Is this supply stable, as its loop gain plot crosses the 0 dB line multiple times while its phase remains high? Again, it can be checked with the corresponding conceptual Nyquist plot, as shown in Figure 6b. It shows the T(jω) plot crosses the unit circle multiple times, but it does not encircle the (-1, 0) point with a good distance. Therefore, according to the Nyquist criterion, it is a very stable system. The steady state and load transient time-domain simulations further verify the system is stable, as shown in Figure 9.

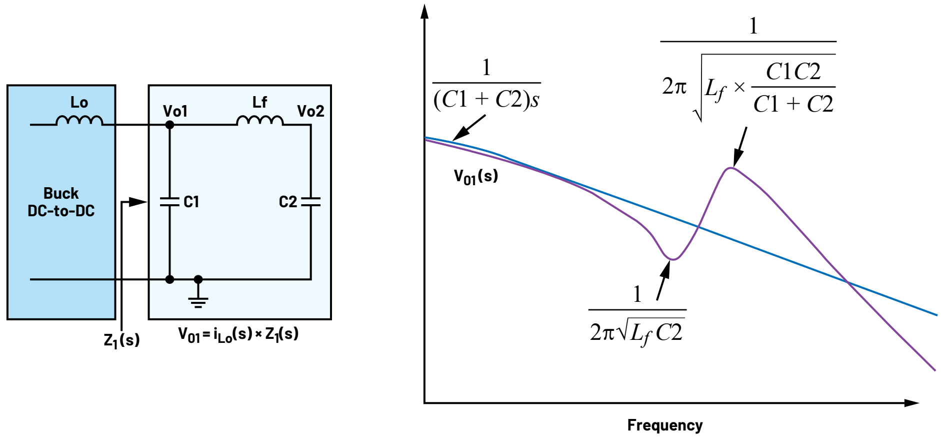


Figure 8. Output capacitor and L/C network impedance Z1(s) analysis from the supply local output side.

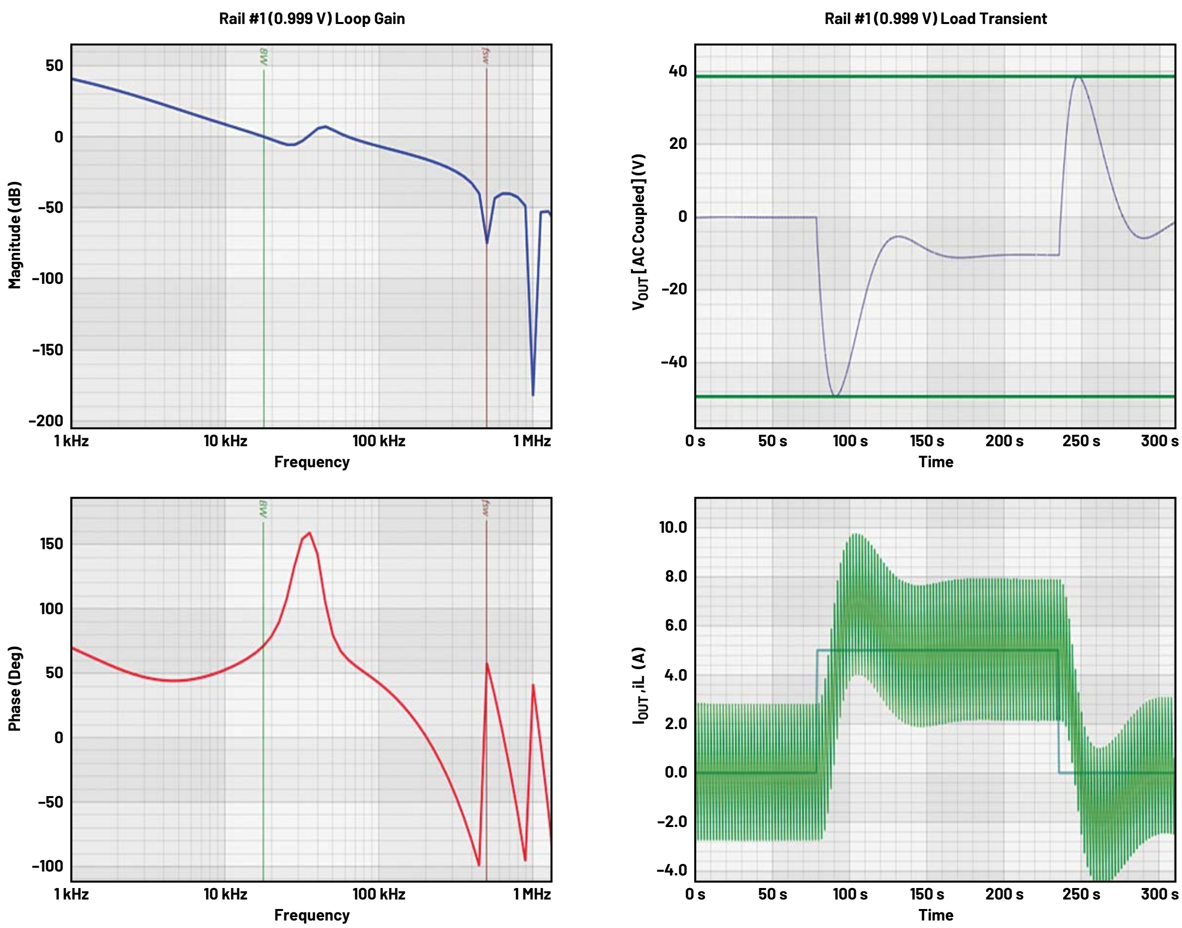


Figure 9. Loop Bode plots and load transient response of the power supply in Figure 6.

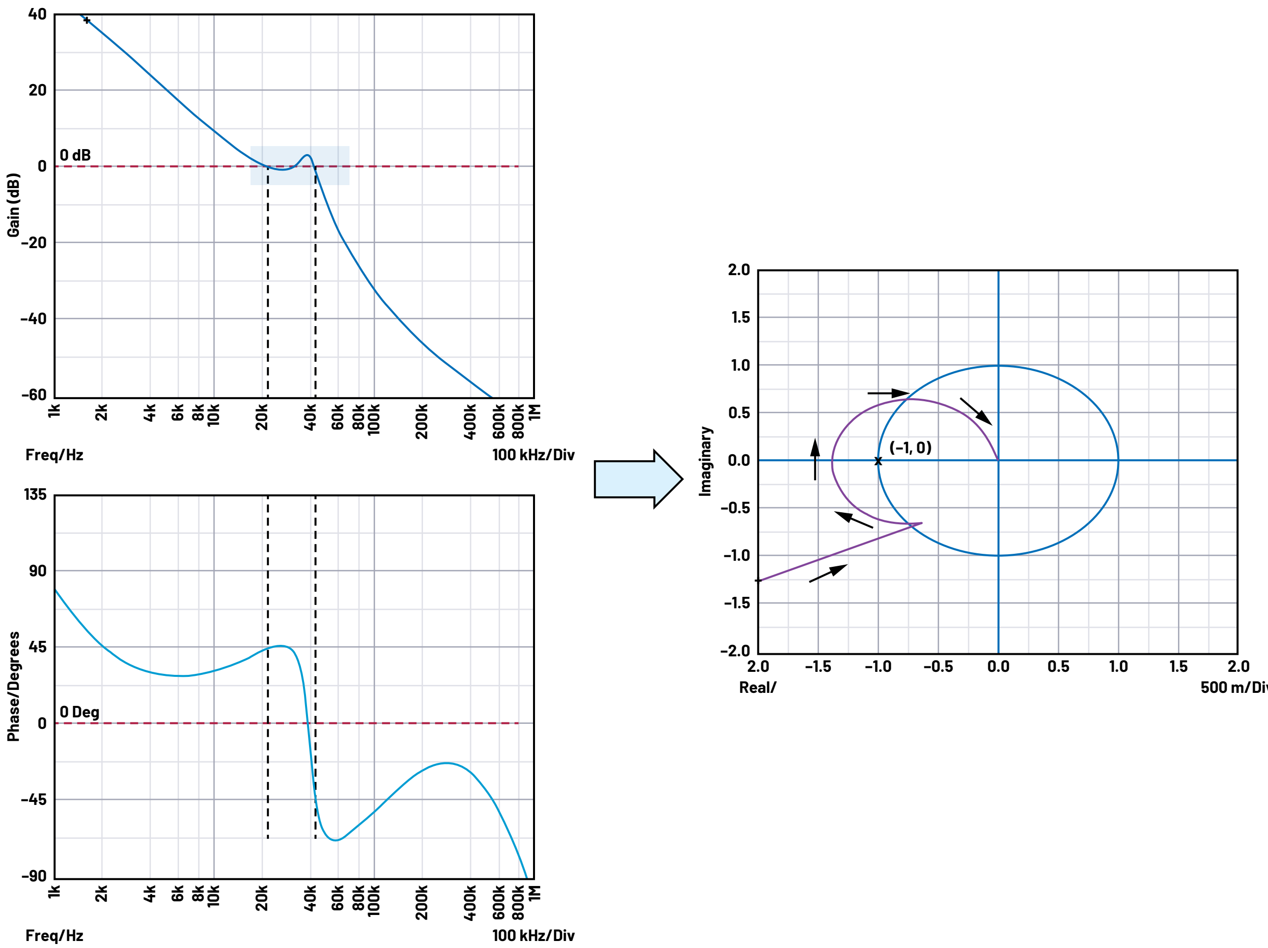


Figure 10. Example Bode plots and the corresponding Nyquist plot (generated with Simplis tool) showing an unstable system.

Case 3: Quick Bode Plot Phase Drop After the Supply Bandwidth

Figure 10 shows another power supply design with unusual Bode plots and its corresponding Nyquist plot. The gain plot crosses the 0 dB line first at ~20 kHz with a 45° phase margin. However, after the supply bandwidth, the gain goes down momentarily, then comes back close to the 0 dB line again at over 40 kHz. At the same time, the phase drops sharply. As shown in its conceptual corresponding Nyquist plot, the T(jω) path passes the (-1, 0) point on its path, ends up with an unstable system.

Figure 11 shows the circuit feedback loop setup while the power supply Bode plots are generated in Figure 10. In this case, the supply still has an additional post filter L/C network. However, different from the circuit diagram in Figure 7, in Figure 11 the output voltage is sensed from the remote load side (V_{OUTB}), after the post filter network.

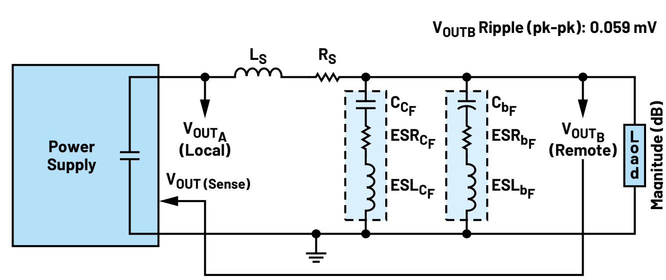


Figure 11. Power supply with post filter and remote V_{OUT} sense at node V_{OUTB}.

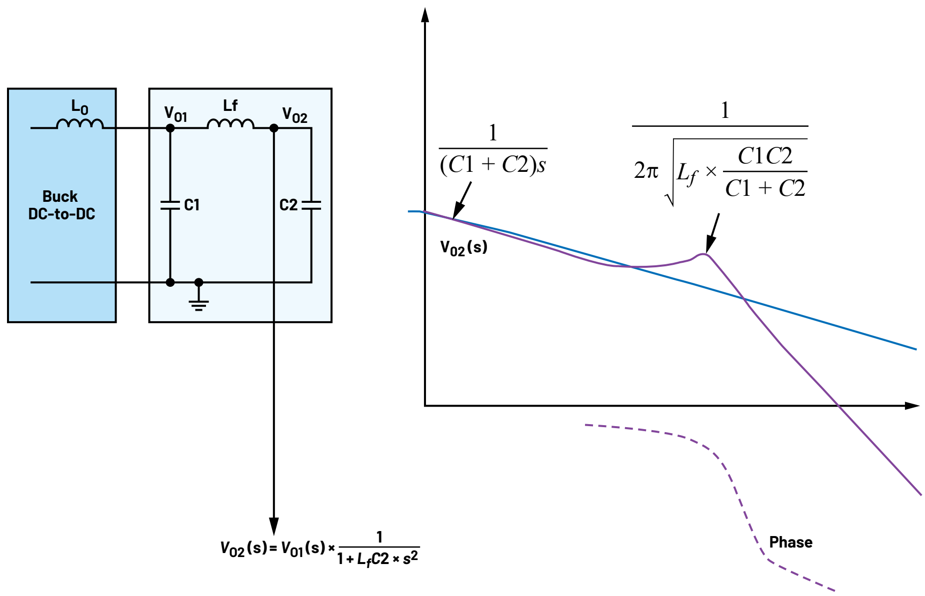


Figure 12. Analysis of the output L/C network with remote load side V_{OUT} sense.

Remote V_{OUT} sensing is used here to improve DC regulation accuracy as it compensates the DC voltage drop in the conduction path from the power supply output A to the remote load B. However, as shown in Figure 12, the additional post L/C is a second-order filter and adds significant (up to 180°) phase delay after the Lf/C1/C2 resonant frequency at the gain peak point of the Bode plot.

Figure 13 shows the time domain load transient response waveform of the system in Figure 12. The output voltage oscillates during steady state and load transient events, further demonstrating that the system is unstable.

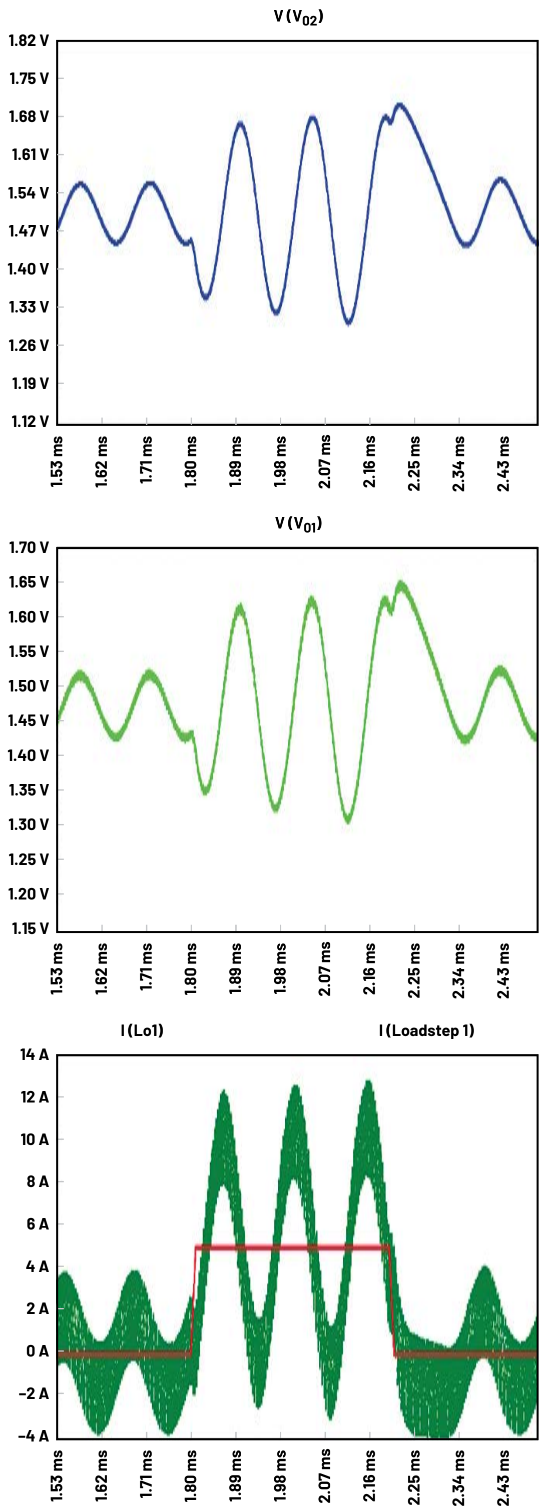


Figure 13. Unstable simulation waveforms at steady state and transient of Figure 10.

To stabilize such a system with a post second-stage filter and remote V_{OUT} sense, one solution is to reduce the supply bandwidth with a slower loop to push the post filter resonant peak much lower than 0 dB. As the expense of reduced loop bandwidth, the load transient response performance is compromised.

Case 4: Switching Supply Bode Plots with a 2nd Gain Peak at $f_{SW}/2$

Sometimes, even without an additional post filter, a switched-mode power supply may show a second gain peak at 1/2 of its switching frequency, which is usually much higher than the supply bandwidth frequency. An example is shown in Figure 14. Sometimes, for a supply with a fixed frequency, peak current mode control architecture, it can be the indicator that the inner current feedback loop is unstable, especially if the Bode plot gain peak increases with larger converter PWM duty cycle.

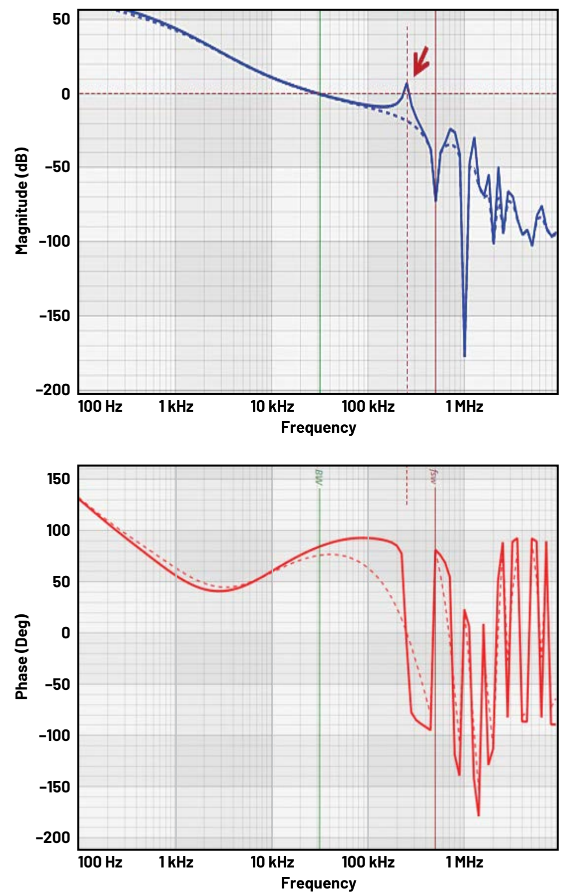
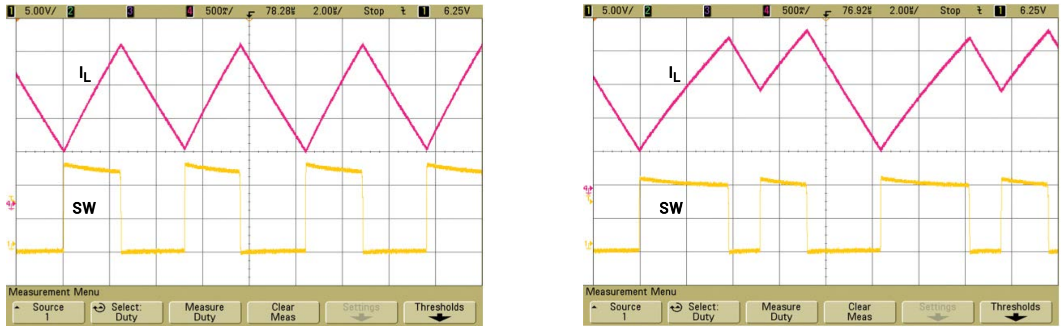


Figure 14. Switching supply with a second gain peak at the half of switching frequency (solid lines: duty cycle = 50%. Dashed lines: duty cycle = 40%).

Figure 15 shows the measured switching waveform of this peak-current mode step-down buck power supply. Figure 15a shows stable switching waveform of inductor current iL and switching node V_{SW}, at duty cycle = 41%. As the duty cycle is increased ≥50%, as shown in Figure 15b, the supply's switching waveform start to oscillate. V_{SW} waveform shows the repetitive large and small on-time pairs. This is called subharmonic oscillation with a pair of large and small on-time pulses, resulting in increased inductor current ripple.

A standard way to fix the subharmonic oscillation problem is to add a slope compensation ramp to the current comparator input of the converter. Figure 16 shows adding the slope compensation can eliminate the gain peak at $f_{SW}/2$. The amount of optimum slope compensation depends on duty cycle. The higher the duty cycle, the stronger the slope compensation is required. Note in most ADI's peak current mode regulators, an adaptive nonlinear slope compensation is integrated in the controller IC to ensure stability over wide duty cycle range, therefore, users don't have to worry about the risk of subharmonic oscillations.



(a) (b)

Figure 15. Switching waveform of a peak current buck converter at different duty cycle conditions: (a) normal operation (D = 41%, V_{IN} = 12 V, V_{OUT} = 5 V); (b) under subharmonic oscillation (D ≥ 50%, V_{IN} = 10 V, V_{OUT} = 5 V).

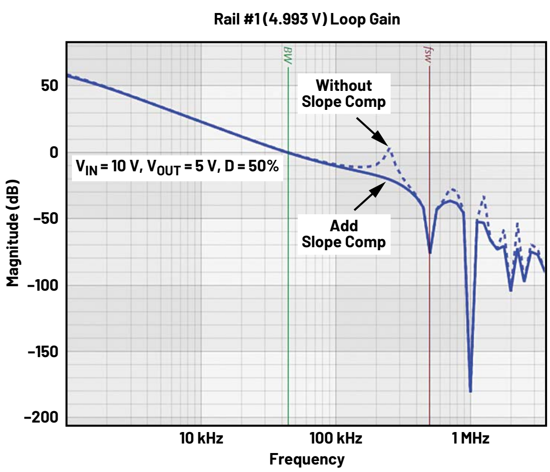


Figure 16. Bode plots of the converter in Figure 14 with and without additional slope compensation at duty = 50%.

Case 5: Good Phase Margin and Gain Margin on Bode Plots, but Marginal Loop Stability

Bode plots offer a convenient way to quantity a system loop stability with its phase margin at its crossover frequency and gain margin at the point phase = -180°. However, sometimes we need to review the full plots in addition to just two points to ensure sufficient stability margins.

Figure 17 shows a pair of Bode plots which shows nice a 93° phase margin and a 13 dB gain margin. However, the shape of the gain plot after the crossover frequency f_{BW} looks risky. It remains flat over a frequency range, while the phase plot continues to drop. From its conceptual Nyquist plot, we can see the T(jω) plot is dangerously close to the (-1, 0) point after the T(jω) crosses the unit cycle. It indicates a potential risk of the T(jω) to encircle the (-1, 0) point with small component parameter variations. In this case, the loop should be redesigned to further keep the T(jω) plot away from the (-1, 0) point for increased stability margins.

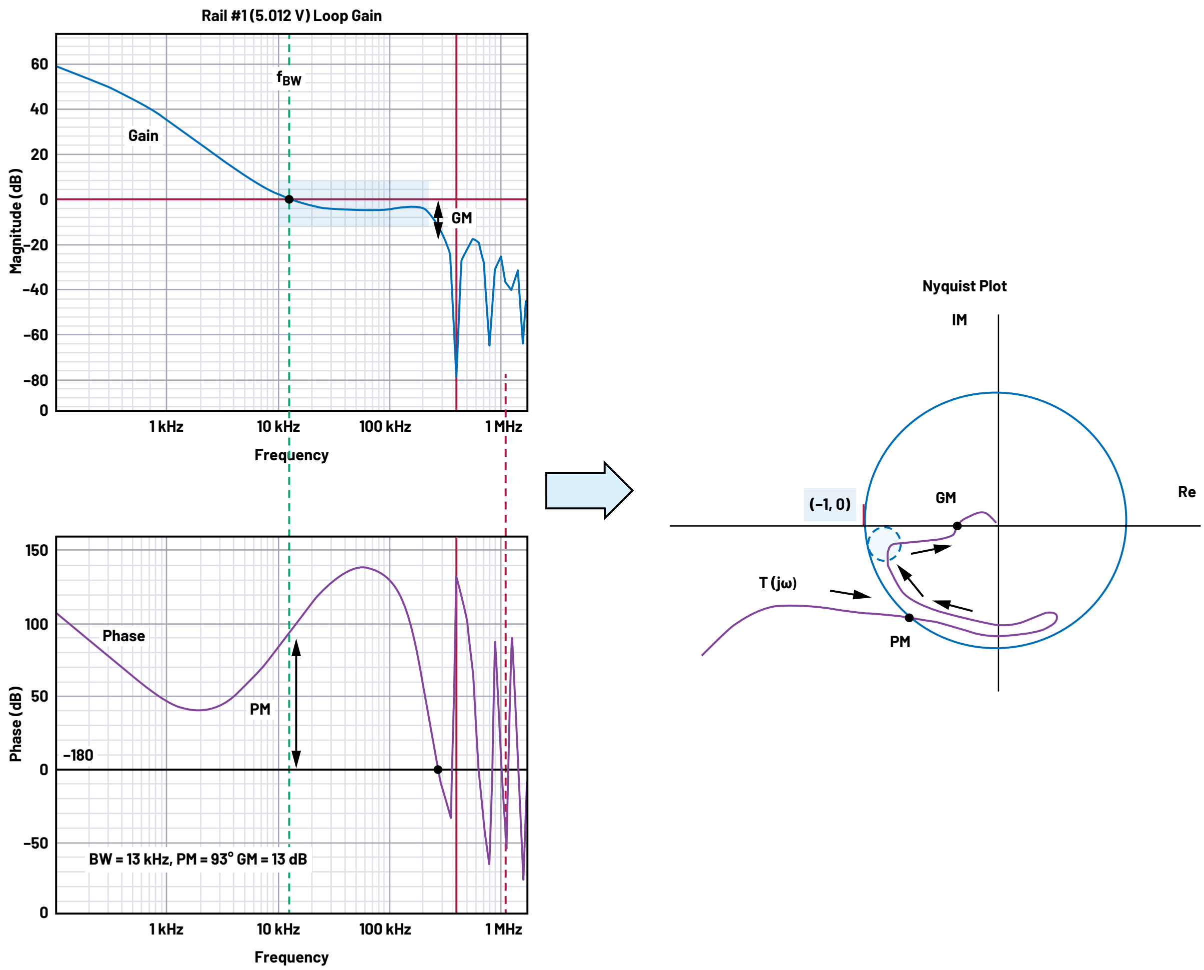


Figure 17. A power supply Bode plots with good phase margin and gain margin, but risky Nyquist plot.

Conclusion

In summary, the power supply loop gain Bode plot is the standard and a very effective method to quantify its stability margins. However, sometimes, some unusual or problematic Bode plots can be confusing. In this case, the corresponding Nyquist plot and Nyquist criterion can be applied to better understand the loop stability. This article provides a few typical examples and design considerations of system with unusual Bode plots.

References

[1] Henry Zhang. "Understand Power Supply Loop Stability and Loop Compensation – Part 1: Basic Concepts and Tools." Analog Devices, Inc., January 2022.

[2] Henry Zhang. "Modeling and Loop Compensation Design of Switching Mode Power Supplies." Application Note 149, Analog Devices, Inc., January 2015.

[3] Henry Zhang. "Designing Power Supply Parameters in Five Simple Steps with the LTpowerCAD Design Tool." Application Note 158, Analog Devices, Inc., September 2015.

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