Technical Article

Understand Power Supply Loop Stability and Loop Compensation—Part 1: Basic Concepts and Tools

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Introduction

Loop design and stability tests are important tasks for a power engineer. A power supply, either switch mode or linear mode, should be designed with fast transient response and a sufficient stability margin. An unstable or marginally stable power supply can oscillate and cause increased ripples, voltage, current, and thermal stresses, and possibly damage the supply and its critical load devices.

To check power supply feedback loop bandwidth and stability, loop Bode plots are widely used to provide accurate and quantified values of loop performances. This article will review the critical concepts and importance of loop stability, from the Nyquist plot criterion to Bode plots. It then provides examples of Bode plots and tools, along with lab measurements to generate Bode plots, to demonstrate how to best assess loop stability. Practical loop measurement setup considerations will be explained as well.

Basic Feedback Loop Concept Review: Stability Criterion and Bode Plot

Nyquist Plot and Nyquist Criterion

To assess a linear negative feedback loop system stability, one basic and original concept is the Nyquist criterion using the Nyquist plot. It was named after Harry Nyquist, an engineer with Bell Telephone Laboratories, who published a classic paper on stability of feedback amplifiers in 1932. His Nyquist stability criterion can now be found in all textbooks on feedback control theory.

Assuming a feedback system open-loop gain transfer function is T(s), its Nyquist plot is a plot of the T(s) with $s = j\omega = j2\pi f$ in the complex plane of Re(T(s)) and IM(T(s)), as the frequency ω is swept as a parameter that goes from 0 to infinity. The plot can be described using polar coordinates, where the magnitude of the loop is the radial coordinate, and the phase of the transfer function is the corresponding angular coordinate from point (0, 0). The loop stability is determined by looking at the number of encirclements of the (-1, 0) point on this plot. For a typical analog feedback loop power supply, its open-loop transfer function is typically stable (that is, without RHP). In this case, the closed-loop system is stable if the $T(j\omega)$ plot does not encircle the (-1, 0) point clockwise as frequency increases, as shown in Figure 1. On the other side, if the $T(j\omega)$ Nyquist plot encircles the (-1, 0) point clockwise as frequency increases, as shown in Figure 4, the system is unstable.

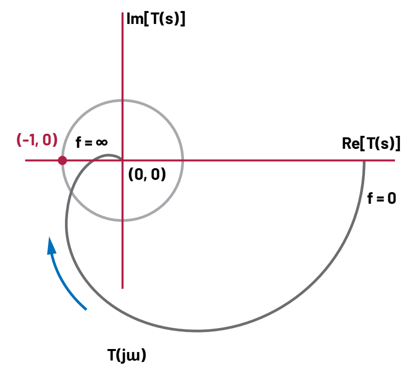


Figure 1. A typical Nyquist plot of a stable negative feedback linear system (power supply).

To have some margin of stability, it is important to keep the $T(j\omega)$ plot away from the critical (-1, 0) point. Therefore, using the Nyquist criterion and plot, the power supply feedback system stability margin is determined by the distance of the $T(j\omega)$ plot from the (-1, 0) point. Strictly speaking, the minimum distance between the (-1, 0) point to the $T(j\omega)$ plot should be used to quantify the stability margin, as represented by the value dm in Figure 2. However, to simplify the task of frequency domain analysis (using Bode plots), the phase margin (PM) is defined as the corresponding phase angle of the point where the $T(j\omega)$ plot intersects with the unit circle ($|T(j\omega)| = 1$, or 0 dB), and the gain margin (GM) is determined by the $|T(j\omega)|$ value, where the $T(j\omega)$ plot intersects with the real axis (that is, phase = $-180°$), as shown in Figure 2.

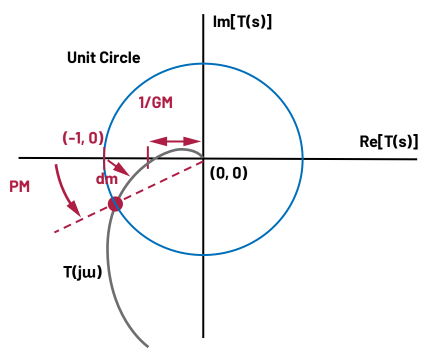


Figure 2. Stability margins (phase margin (PM) and gain margin (GM)) on the Nyquist plot.

Bode Plots and Stability Criterion

Though the Nyquist plot provides an accurate stability criterion of a feedback system, it does not visually show the frequency values on the T(jω) plot. It is not easy to use this plot for transfer function analysis and designs with poles and zeros in the frequency domain. In the 1930s, another Bell Labs engineer, Hendrik Wade Bode, devised a simple method for graphing gain and phase shift plots. They are known as a pair of Bode plots, including the corresponding gain plot and phase plot as functions of frequency. In a more intuitive way, one Nyquist plot can be redrawn with a pair of Bode plots, as shown in Figure 3. The Bode magnitude plot is the graph of the function |T(s = jω)| of frequency value ω = 2πf. Here, the horizontal x-axis of frequency is logarithmic. The magnitude (gain) is given in decibels—that is, a value for the magnitude |T| is plotted on the axis at 20log10|T|. The Bode phase plot is the graph of the phase, commonly expressed in degrees, of the transfer function arg(T(s = jω)) of frequency value ω. The value for phase is plotted on a linear vertical axis. Using Bode plots, the frequency at which the gain plot reaches 0 dB (x-axis) is defined as the closed-loop bandwidth f_{BW} of the system. This is the same point that the T(jω) Nyquist plot crosses the unit circle. Therefore, at f_{BW}, the phase difference between the phase plot and –180° is the phase stability margin (PM) shown in the Nyquist plot—that is, PM = 180 + arg(T(jω)) at f_{BW}. Note that PM ≤ 0 indicates an unstable system. As frequency increases, the power supply phase may further decrease. At the point where phase reaches –180°, it is the same point where the T(jω) Nyquist plot intersects the Re axis, where the gain margin (GM) is defined by 1/|T(jω)|. In summary, the Bode stability criterion is the simplified Nyquist criterion represented in Bode plots.

As an example, Figure 4 shows a typical unstable system and its Nyquist and corresponding Bode plots. In its Nyquist plot, the loop T(jω) trajectory encircles the (–1, 0) point clockwise as frequency increases. The plot intersects with the x-axis even before the |T(jw)| magnitude—that is, the distance to the (0, 0) point—drops to 1. The T(jω) plot intersects the unit circle with a negative phase angle. Correspondingly, on its bode plots, the phase plot reaches –180° while the gain plot is still greater than 0 dB. At the crossover frequency f_{BW}, the phase value is below –180°. From Bode plots, it is easy to tell that it is an unstable system with PM < 0°.

Another major benefit of Bode plots comes from the very visible representations of a transfer function and its poles and zeros, with their exact frequency locations and effects on gain and phase plots. This makes loop compensation design a standard engineering process.

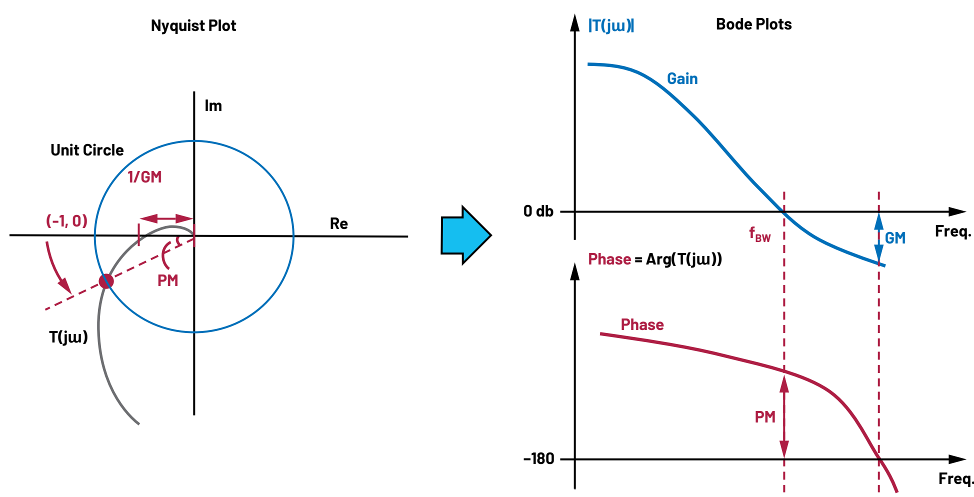


Figure 3. A typical stable system: Nyquist plot to Bode plots and corresponding bandwidth, phase margin (PM), and gain margin (GM).

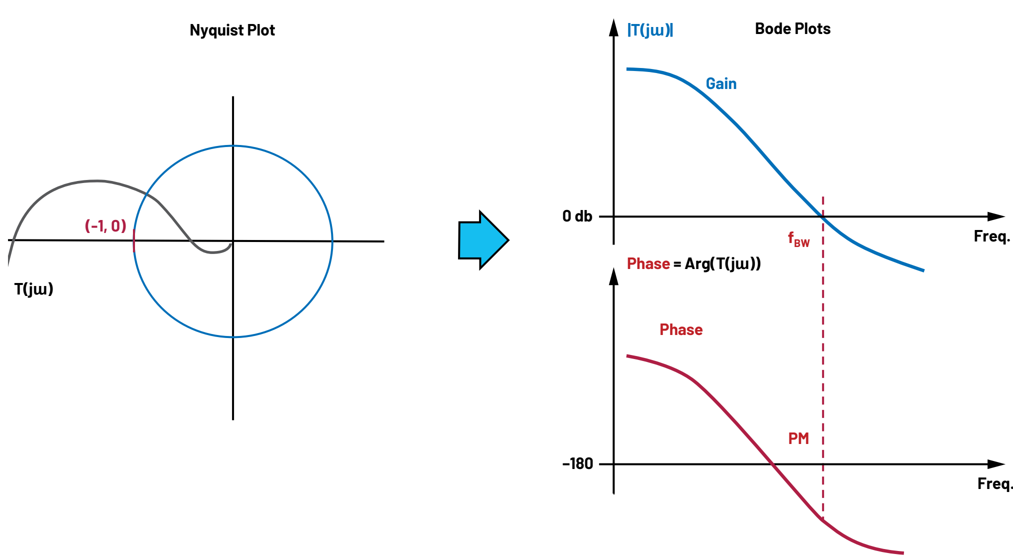


Figure 4. A typical unstable system Nyquist plot and its corresponding Bode plots.

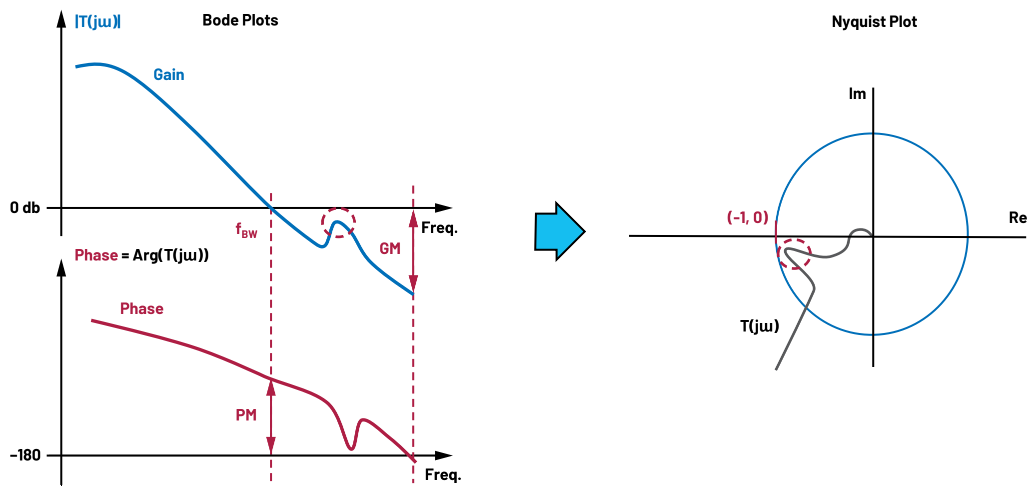


Figure 5. A conceptual system with good PM and GM, but at risk of being unstable.

Finally, though the Bode plot gain and phase margins are classical robustness measures that have been used in control system design for a long time, please note the Bode plot interpretation of stability margins can be incorrect or inaccurate if there are multiple points (frequencies) that the Nyquist plot crosses or approaches the unit circle (that is, the Bode gain plot crosses 0 dB). For example, Figure 5 shows an example of a system with good phase and gain margins on Bode plots. However, the Nyquist plot shows it is dangerously close to the (-1, 0) point with the risk being unstable. In this example, the system is not robust. So even on Bode plots, it is important to look at whole plots instead of just focusing on two points of PM (at f_{BW}) and GM.

In conclusion, the Bode plot method has been easy and successful for loop stability analysis. Therefore, it has been widely used for linear feedback systems, including power supplies. Engineers just love the simplicity (who doesn't?) to use the phase margin to determine and quantify the loop stability. Many field engineers may have forgotten the original Nyquist concept from school textbooks. It is necessary to point out that the concepts from the Nyquist criterion and the Nyquist plot are still useful, especially when there are unusual and confusing Bode plots.

Power Supply Loop Stability

There are two major types of power supplies: linear mode power supplies and switch-mode power supplies (SMPS). Linear mode power supplies are relatively simple. Their compensation network is usually integrated inside an IC; therefore, users just need to follow the data sheet guideline of minimum and maximum output capacitance requirements. SMPS usually have higher efficiency, therefore a higher power level than linear power supplies. Many SMPS controllers allow users to externally adjust the compensation loop for optimum stability and transient performance.

SMPS are nonlinear, time varying systems, due to the switching actions. However, they can be modeled with an averaged small signal, linearized model, which is valid up to the power supply switching frequency $f_{SW}/2$. Therefore, the linear control loop stability analysis using Nyquist and Bode plots can be applied. Usually, the maximum bandwidth of an SMPS is about 1/10 to ~1/5 of the switching frequency f_{SW}. Usually a 45° phase margin is acceptable, especially for buck step-down converters. A 60° phase margin is preferred, not only as a conservative value, because it also helps to flatten the closed-loop output impedance plot for a good power distribution network (PDN) design. An 8 dB to ~10 dB gain margin is usually desired, though one should keep in mind that the average model and its Bode plots are only valid up to $f_{SW}/2$. In addition, to attenuate switching noises in the feedback compensation loop, ≥8 dB gain attenuation at $f_{SW}/2$ is desired, as another gain margin or gain attenuation design guideline. For more details on small signal modeling and loop compensation design, see Analog Devices' app note AN149.[1]

Tools to Generate Power Supply Loop Bode Plots

Bode plot analysis is the standard and required method to quantify a power supply loop stability. There are many design and measurement tools to generate Bode plots.

LTpowerCAD Design Tool

The LTpowerCAD® design tool by ADI (free to download at analog.com/LTpowerCAD) is a powerful tool for power supply design and optimization tasks. It allows an engineer to design an SMPS in five simple steps,[2] including part search/selection, power stage design, efficiency optimization, loop and load transient design, and generating a design summary report. A complete paper design can be done in just a few minutes. Inside LTpowerCAD, real-time loop Bode plots are generated with small signal linear models of ADI power products. The loop model of each product was verified with ADI's demo board for good accuracy. The real-time Bode plots and transient waveform allow an engineer to quickly design and optimize a feedback loop.

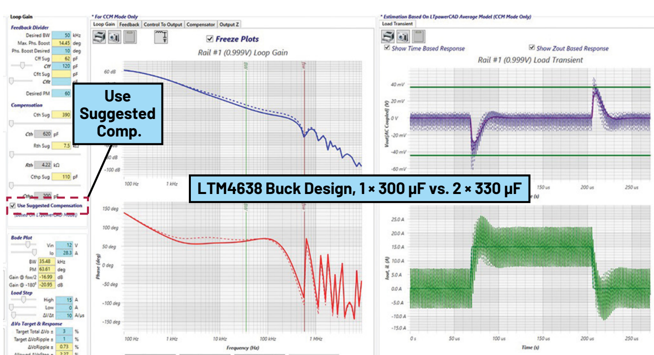
Figure 6a shows the LTpowerCAD tool start page. Users can start a power supply design by clicking the **Supply Design** icon. Figure 6b shows an example of the LTpowerCAD loop Bode plots and load transient using the LTM4638, a high density 20 V_{IN}/15 A μModule® step-down regulator. The LTM4638 is a fully integrated buck regulator including control IC, FETs, inductor, and some input and output capacitors, in a tiny 6.25 mm × 6.25 mm × 4 mm package. It has an option to allow external loop compensation to flexibly adjust the loop for different operating conditions, especially with different output capacitor values. Therefore, the loop and its transient performance can always be optimized as needed.

On the LTpowerCAD Bode plots in Figure 6b, the vertical green line indicates the supply bandwidth (crossover frequency). The phase plot is plotted as phase + 180°, for the convenience of reading phase margin. This is also a popular way for tools to plot phase. The vertical red line indicates the supply switching frequency. Since averaged small signal models are only valid up to $f_{SW}/2$, the strange zigzag gain and phase plots beyond f_{SW} are not meaningful anyway.

A user can simply enter/change the loop compensation network R/C values, or use the R/C value sliding bars, and click on the **Freeze Plots** checkbox to adjust and compare real-time Bode plot results. In addition, a user can also set a desired loop bandwidth (≤1/10 to ~1/5 f_{SW}) then click on the **Use Suggested Compensation** checkbox. The LTpowerCAD tool will automatically suggest a set of R/C compensation network values to optimize the loop with fast bandwidth and sufficient phase margin, regardless of the change in C_{OUT} in this example. This makes loop compensation design a simple, one-click action.

Finally, after the supply is designed in LTpowerCAD with optimal parameters, the design can be exported to the LTspice® simulation tool for time domain dynamic simulations.

(a) LTpowerCAD Design Tool Program Starting Page



(b) Loop Compensation (Bode Plots) Design and Load Transient Optimization

Figure 6. (a) The LTpowerCAD supply design tool and (b) its loop design page.

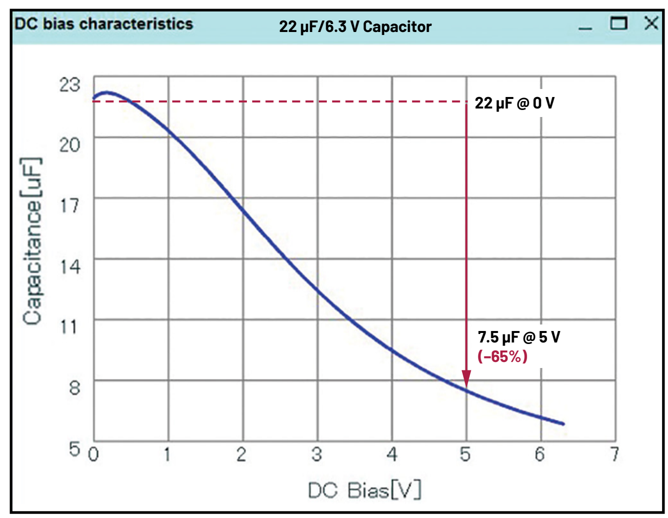
LTspice Circuit Simulation Tool

LTspice is a very popular circuit simulation tool by ADI. It can also be downloaded for free from analog.com/LTspice. LTspice can be used for time-domain steady-state and transient simulation of a power supply circuit, as well as simulating an AC circuit in the frequency domain. However, it does not yet offer a fast and convenient way to simulate switching supply Bode plots, unless a dedicated average small signal model circuit is developed for a given switch-mode supply circuit.[3,4,5] An engineer can use the LTpowerCAD tool for a supply design including loop compensation, then export the design to LTspice for more detailed circuit simulations.

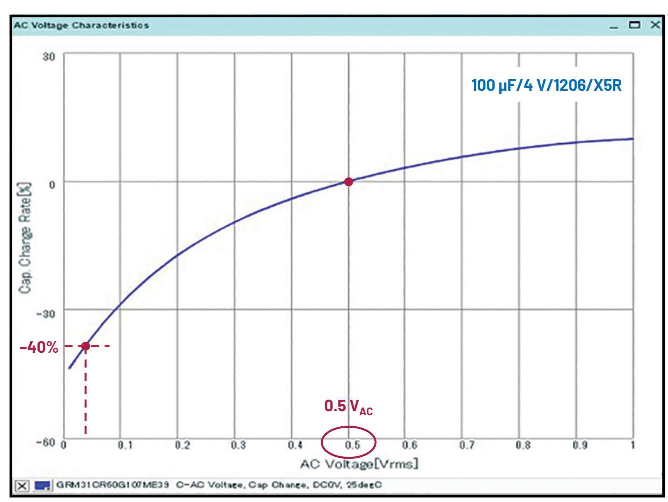
Bode Plot Lab Measurements

Why Perform a Lab Test? Considering Parameter Variations

Due to external component value inaccuracy and variations, modeled loop Bode plots can be good starting points but may not be very accurate. The most significant variations usually come from the output capacitor network. For example, Figure 7 shows a high capacitance multilayer ceramic capacitor (MLCC) value can vary significantly with its DC bias voltage or AC ripple voltage, resulting in 40% to ~60% capacitance value errors. The DC bias variation is built into the LTpowerCAD capacitor library, while the AC bias variation is not yet. Another popular type of capacitors are conductive polymer capacitors. They offer high capacitance but also have higher parasitic ESR resistance values than MLCCs. Unfortunately, the typical data sheet ESR value of polymer capacitors can be inaccurate. Even worse, many polymer capacitors are moisture sensitive (MSL3). The ESR value can change significantly over time if the part is not stored in a sealed dry pack bag.



(a) MLCC Capacitance vs. DC Bias Voltage

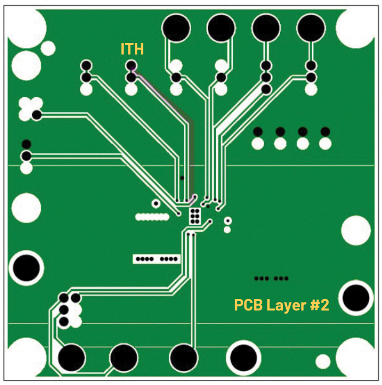


(b) MLCC Capacitance vs. AC Ripple Voltage

Figure 7. Large MLCC value variations vs. operating conditions.

Why Perform a Lab Test? Considering PCB Parasitics

Sometimes, the PCB trace parasitic inductance or capacitance can cause additional errors to loop Bode models as well. An example is shown in Figure 8, for a buck step-down converter demo board. A 3 cm long, 10 mil PCB trace of the compensation ITH pin can have 10 pF parasitic capacitance to ground. As a result, it causes a noticeable, ~10° phase margin drop. Similarly, keep in mind the supply feedback (FB) pin parasitic capacitance can cause the same effect.



(a) Eval Board PCB with 3 cm ITH Pin Trace

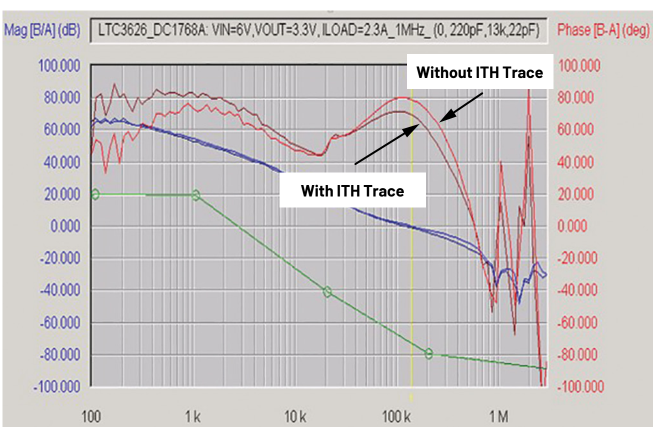


Figure 8. Compensation ITH pin PCB trace parasitic capacitance (~10 pF) affects loop phase plots.

In conclusion, the modeled loop Bode plots cannot be very accurate. Therefore, a bench Bode plot test is always a required step to qualify a power supply in the development stage.

Loop Bode Plot Measurement and Considerations

Typical Setup

A network (frequency) analyzer, such as the RidleyBox® by Ridley Engineering, or Bode 100 by Omicron Lab, is typical commercial equipment to measure supply Bode plots. Figure 9 shows a typical setup to measure a supply device under test (DUT) loop Bode plot. In addition to the standard feedback resistor, a small inject resistor Ro of 10 Ω to 50 Ω is inserted in the feedback path. The network analyzer injects a small 10 mV to 100 mV AC signal across Ro to "break" the loop. The network analyzer sweeps the AC signal frequency from low to high, then measures the signal on points A and B across Ro. The loop gain transfer function T(s) is measured at VA(s)/VB(s) (or ch2/ch1). The network analyzer computes the gain and phase of VA(s)/VB(s) at each frequency point, and therefore, generates the gain and phase Bode plots.

SNR Consideration

We need to consider the signal-to-noise ratio (SNR) in the loop measurement at a different frequency range. Particularly, a power supply loop usually has very high gain at very low frequency, to achieve high output DC regulation accuracy. As the frequency increases, the loop gain decreases. Since the loop gain is measured as VA(s)/VB(s), the VB(s) signal can be very small at very low frequency. As a result, the very low frequency loop gain plot can be noisy. This is why the measured phase plot usually is not very smooth at low frequency while gain is still high. To improve the SNR, sometimes it is helpful to have a variable injection AC signal over frequency. For example, the green line in Figure 8b shows a variable AC signal set with the network analyzer. The AC signal is higher at lower frequency and decreases linearly as frequency increases.

In addition, to minimize measurement noise, the network analyzer probe ground leads should be connected to a quiet signal ground trace near the power supply controller IC on the PCB.

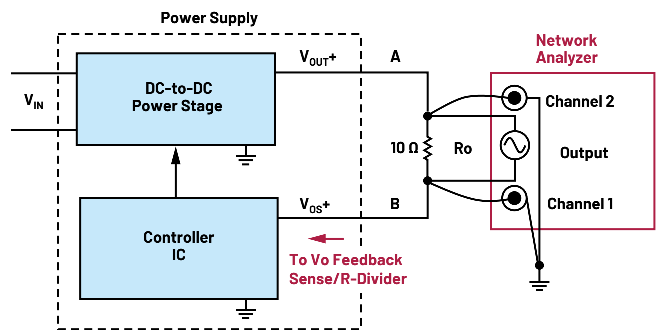
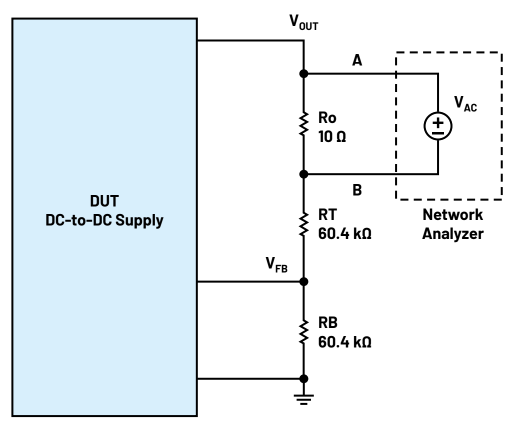
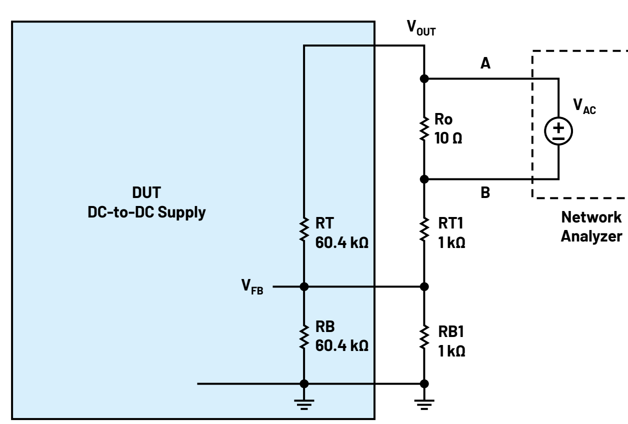


Figure 9. A typical setup to measure a power supply loop bandwidth (loop gain = ch2/ch1).



(a)



(b)

Figure 10. Typical power supply DUT Bode plot measurement setups: (a) supply with external feedback resistors and (b) power module with internal feedback resistors.

Measuring a Power Module with Integrated Feedback Resistors

Figure 10 shows two setup options for two typical power supply feedback resistors. Figure 10a is for a discrete power supply with the feedback resistor divider RT and RB accessible externally. So, its loop measurement setup is the same as the one in Figure 9. However, many integrated power supplies, such as ADI's LTM-series power modules, already have one or both feedback resistors inside the molded module connecting to V_{OUT}. Therefore, it is difficult to break the loop to insert the Ro resistor. Instead of breaking the original V_O sense path, an alternative way to measure the loop is shown in the paralleling method in Figure 10b, if the feedback (FB) pin is still accessible. In this case, a much smaller value (1 kΩ) external resistor pair creates the R-divider RT1/RB1 outside the module. Compared to Figure 10a, the outside resistors are now 1/60 of the previous value. Because of the lower resistance of the external parallel R-divider, most AC signal current flows through this external path instead of the internal path. Therefore, the injection resistor Ro can be inserted into the external R-divide RT1 and RB1. Figure 11 shows a gain and phase Bode plots comparison of a power supply measured with Figure 10a (Method 2) and Figure 10b (Method 1) setups. Two gain plots are overlapped with each other. Method 1 shows reduced inaccurate gain at lower frequency. Thankfully, it is not important, since we care mostly at higher frequency plots, especially at around the supply bandwidth frequency where stability margins are measured.

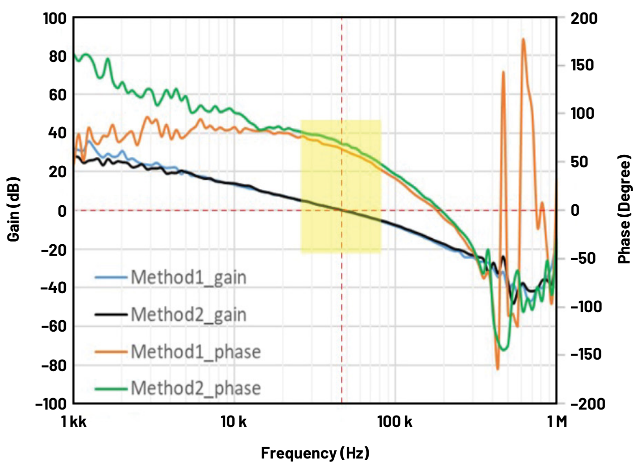


Figure 11. Example of Bode plots with Figure 10a and Figure 10b measurement methods on the same supply.

Furthermore, if the original feedback resistor network has a feedforward capacitor C_{FF}, in the paralleling R-divider method, the capacitor C_{FF} value should be increased proportionally to the ratio of RT/RT1, to keep the same R/C time constant value and pole/zero frequencies. Figure 12 shows the example.

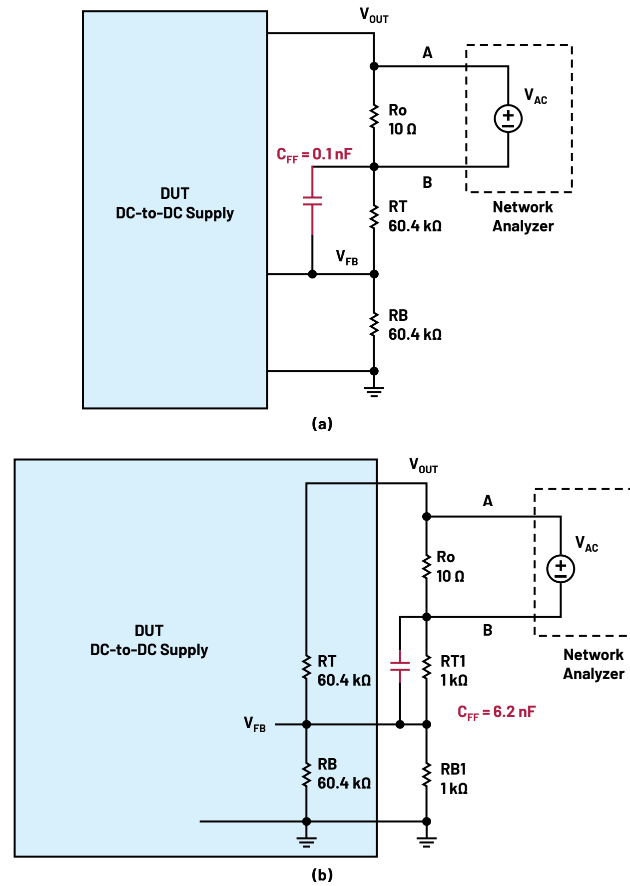


Figure 12. Proportional increased C_{FF} value with paralleling external R-divider.

Conclusion

The Nyquist criterion and the corresponding Bode loop stability criterion are important for an engineer to understand and design a fast and stable power supply. While Bode plots are widely used for loop stability, sometimes the Nyquist criterion can be used to explain unusual Bode plots. With clear loop stability concepts in mind, an engineer can use the LTpowerCAD design tool to quickly design and optimize a power supply. In addition, due to component variation and PCB parasitics, lab loop Bode measurement is a required step to fine tune the loop. Practical loop measurement and setup considerations should be considered for an accurate result.

References

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