Technical Article

Power Tips: How to Set up a Frequency Response Analyzer for Bode Plot

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Loop gain is an important parameter for characterizing a switch-mode power supply. Using a frequency analyzer to measure loop gain gives you a way to stabilize the power supply and optimize transient response.

Before measuring the Bode plot, you need to first break the loop and insert a small resistor at the breaking point, as shown in Figure 1. The frequency analyzer has a source that injects an AC disturbance, $\tilde{v}_{ds}$, across this small resistor.

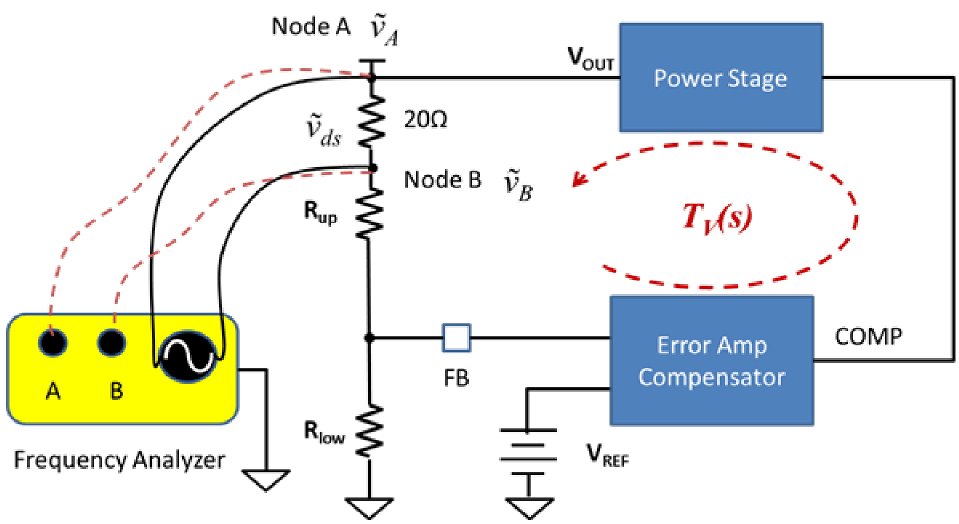

Figure 1. Typical Bode Plot Measurement Setup

As a result, AC fluctuation occurs at the two nodes, A and B, across the breaking point. The frequency analyzer has two receivers to measure signals at nodes A and B, $\tilde{v}_A$ and $\tilde{v}_B$. You can calculate the system loop gain, T_V, with Equation 1:

$$T_V = -\frac{\widetilde{v_A}}{\widetilde{v_B}} \tag{1}$$

To measure T_V accurately, the analyzer must measure $\tilde{v}_A$ and $\tilde{v}_B$ accurately. A frequency analyzer receiver has limited signal measurement resolution. In this post, I will use the AP300 from AP Instruments, a widely used frequency response analyzer, as a setup example. Figure 2 shows the AP300's receiver specifications and Figure 3 shows the source specifications.

RECEIVER

PARAMETER	TYPICAL SPEC.	MIN. / MAX. SPEC.
Dynamic Range [3,4] < 5 MHz	115 dB	100 dB min.
>= 5 MHz	95 dB	90 dB min.
B/A Mag Accuracy [3] < 1 MHz	+/- 0.025 dB	See appendix B
>= 1 MHz	+/- 0.05 dB	
Abs. Magnitude Accuracy < 1MHz	+/- 2 %	
>= 1MHz,< 5MHz	+/-5 %	
>= 5MHz	+/-10 %	
Phase Accuracy [3] < 1 MHz	+/- 0.2 degree	See appendix B
>= 1 MHz	+/- 0.8 degree	
Resolution (IF) Bandwidth	Depends on frequency and Bandwidth selection	0.01 Hz / 1 KHz
Input Signal Range(AC) [3]	5 uV to 1.77 V rms	17.7 uV / 1.77 V rms
Input Signal Range(AC+DC)	-5 / + 5 V Peak	-8 / + 8 V Peak
A to B Isolation < 5 MHz	115 dB	100 dB min.
>= 5 MHz	95 dB	90 dB min.
Input Imped., x1 probe	1 Megohm	
Input Imped., x10 probe	10 Megohm	
Input Cap., at BNC conn.	25 pF	
Absolute Maximum Safe Voltage at Receiver Input		+/- 15 V Peak

Figure 2. AP300 Frequency Response Analyzer Receiver Specifications

Image Source: AP Instruments

SOURCE

PARAMETER	TYPICAL SPEC.	MIN. / MAX. SPEC.
Frequency Accuracy		100 ppm +/- 0.01 Hz
Frequency Resolution	0.01 Hz	
Frequency Range		0.01 Hz – 30 MHz
Flatness, DC to 1 MHz [2]	+/- 0.2 dB	
1 to 30 MHz	+/- 1 dB	
Harmonics	- 40 dBc	
Spurious, Exc. Harmonics	- 55 dBc	
AC Output Level Range		1.25 mV / 1.77V rms (into 1M Ohm), 5mV / 7.08V rms in high level mode
AC Output Level Error [2]		+/- 15 %
DC Offset Range		-10 / +10 V Peak
DC Offset Error		+/- 2 %
Residual DC Offset		+/- 30 mV
Maximum Peak Current Output	500 mA	
Output Impedance	50 Ohms (2 Ohms in high level mode)	
Absolute Maximum Safe Voltage at Source Output		+/- 15 Volts Peak

Figure 3. AP300 Frequency Response Analyzer Source Specifications

Image Source: AP Instruments

Disturbance Injection Signal Amplitude

According to the receiver specs, the measurable signal should be greater than 5µV. To measure voltages, $\tilde{v}_A$ and $\tilde{v}_B$, accurately, the two signals should be of amplitude greater than that measurable by the frequency response analyzer.

Voltages $\tilde{v}_A$ and $\tilde{v}_B$ are related to both the disturbance injection signal and the loop gain itself (Equation 2):

$$\widetilde{v_{ds}} = \widetilde{v_A} - \widetilde{v_B} \tag{2}$$

Solving Equation 1 and Equation 2 results in Equation 3 and Equation 4:

$$\widetilde{v_A} = \frac{T_V \times \widetilde{v_{ds}}}{1 + T_V} \tag{3}$$

$$\widetilde{v_B} = \frac{-\widetilde{v_{ds}}}{1 + T_V} \tag{4}$$

At frequencies lower than the crossover, the magnitude of loop gain, $|T_V|$, is much greater than 1. Signal $\tilde{v}_B$ is approximated by $\tilde{v}_{ds}/|T_V|$. To guarantee that signal $\tilde{v}_B$ is greater than the measurable amplitude of 5µV, the disturbance signal $\tilde{v}_{ds}$ should be greater than 5µV × $|T_V|$. A power converter with tight regulation usually has DC gain greater than 60dB. As a rule of thumb, $\tilde{v}_{ds}$ starts from 50mV at 100Hz.

Another important specification is the output impedance of the source. The AP300 has 50Ω output impedance. To ensure the delivery of sufficient energy, it's best to insert a 50Ω matching resistor at the breaking point. Using a smaller resistor is acceptable if you adjust the injection signal amplitude to compensate for the loss of signal strength, but don't choose too small a resistor. I recommend using a resistor of value greater than one-fifth the output impedance of the frequency response analyzer source output port.

If you inserted a small resistor, use Equation 5 to adjust the disturbance signal amplitude. For example, for a 20Ω resistor, $\tilde{v}_{ds}$ should start from 88mV at 100Hz.

$$K = \frac{1}{2}\times\left(1+\frac{50\Omega}{R_{ds}}\right) \tag{5}$$

It is not a good idea to keep large constant disturbance signal amplitude over the whole frequency range. As frequency increases, the magnitude of $|T_V|$ decreases, which then makes signal $\tilde{v}_B$ increase. For some applications, a large disturbance at crossover might saturate the error amplifier or the duty cycle. To keep the signal as small as possible, the disturbance signal should decrease with frequency.

Figure 4 shows the AP300 interface, which provides a programmable source. The green trace in the graph shows the disturbance signal amplitude over frequency.

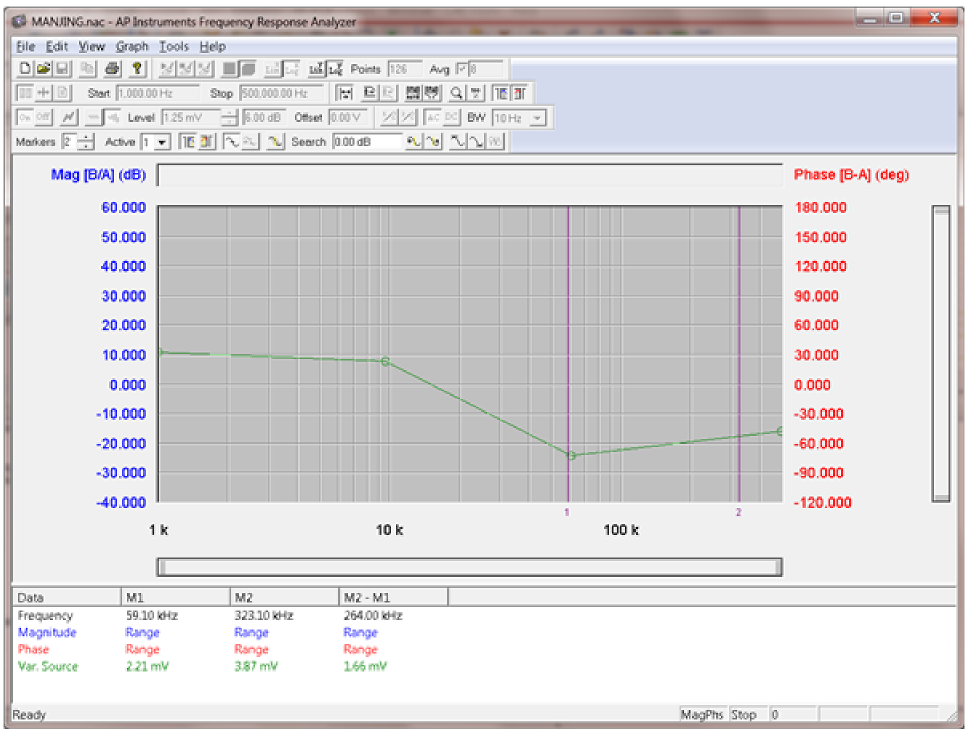

Figure 4. The AP300 Bode Plot Graphical User Interface, GUI

Figure 5 shows a Bode plot measured with a constant disturbance signal of 25mV. The measured Bode plot shows a gain of only 50dB at 100Hz, while I estimated over 70dB gain at 100Hz from the high-performance controller, TPS53661. DC gain is an important indicator for regulator output DC regulation.

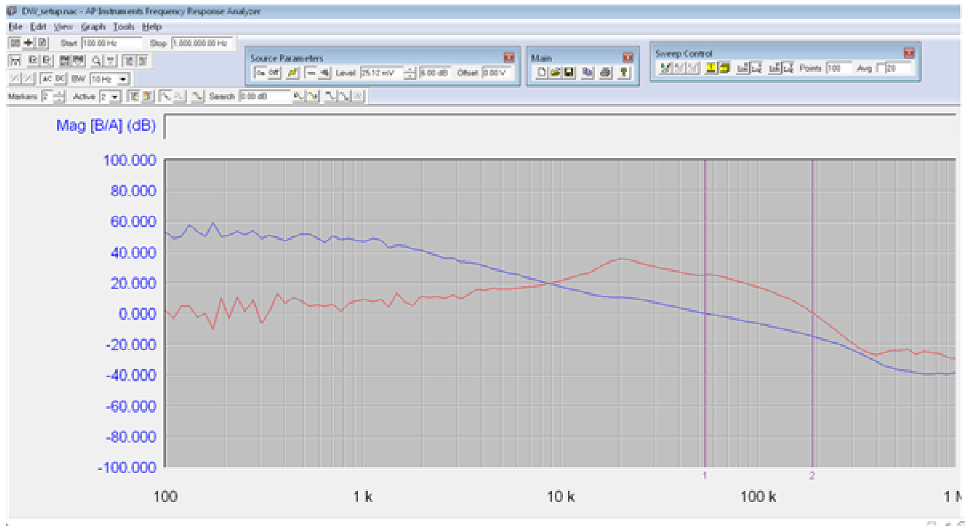

Figure 5. Bode Plot of a Step-down Converter with the TPS53661 Controller, with a Constant Disturbance Signal of 25mV

I adjusted the disturbance signal accordingly and measured the Bode plot again. The measured Bode plot shows a much higher gain at 100Hz, as shown in Figure 6.

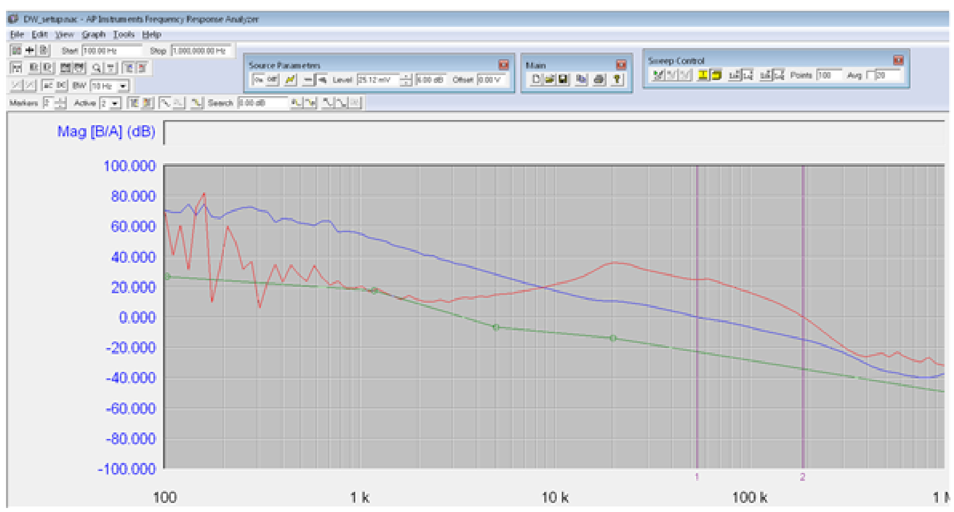

Figure 6. Bode Plot of a Step-down Converter with the TPS53661 Controller, with a Programmable Disturbance Signal

Measurement IF-bandwidth Selection

The intermediate frequency, IF-bandwidth, reducing the IF receiver bandwidth reduce the effect of random noise on the measurement. It takes the frequency analyzer longer to complete the measurement.

Figure 6 shows the difference between measurements with different signal bandwidths. The Bode plot measured with a 10Hz bandwidth is clean and smooth. The Bode plot measured with a 100Hz bandwidth shows a lot of glitches for frequencies lower than 1 KHz. For applications with crossover below 10 KHz, I recommend use IF bandwidth less than 10Hz for a clean bode plot.

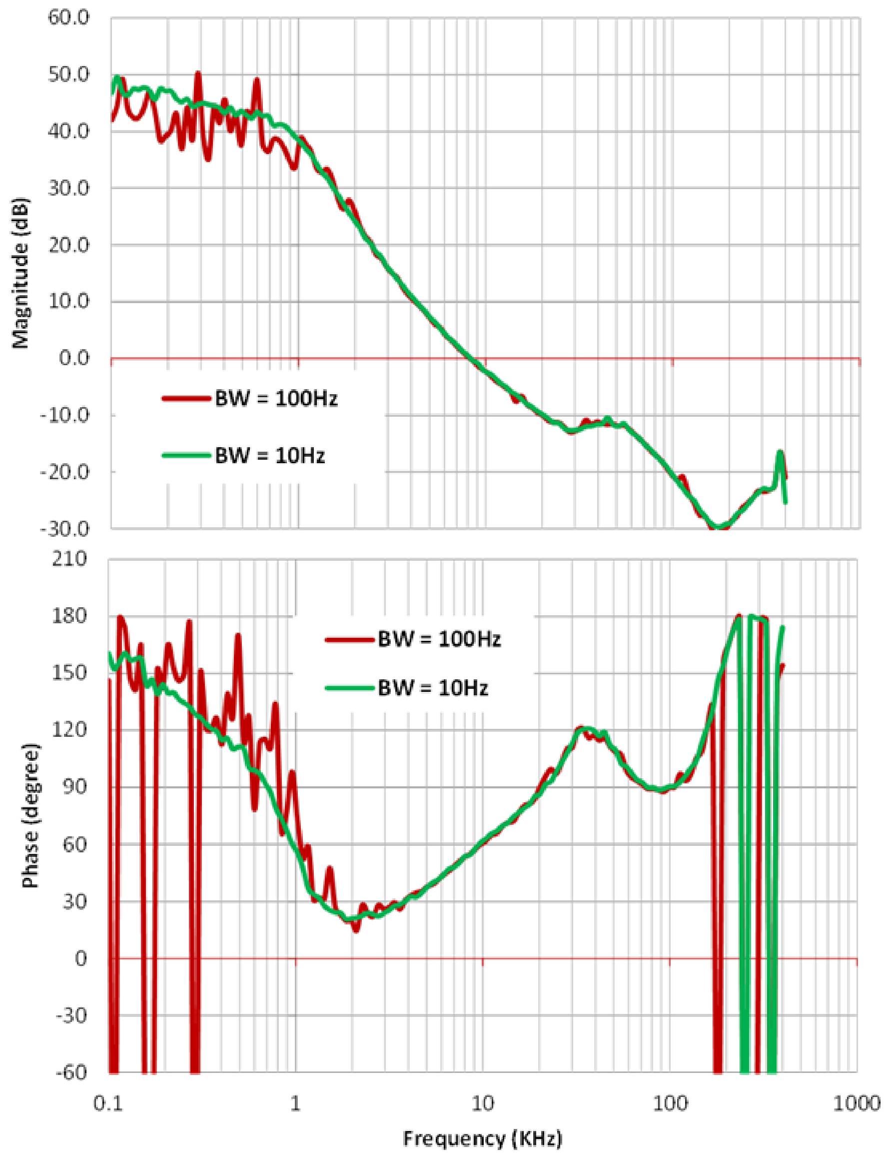

Figure 7. Bode Plots with Different Measurement Bandwidths

Setting disturbance signal at the correct amplitude is important for accurate Bode plot measurement. This post provides equations for engineer to estimate the proper disturbance signal amplitude. For applications with low crossover, the IF bandwidth should be small accordingly to provide a clean bode plot and accurate phase margin.

Additional Resources

- Read the application note, “How to Measure the Loop Transfer Function of Power Supplies”
- Read the AP300 frequency response analyzer manual
- Read more Power Tips blogs

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