Beyond Non-Invasive Phase Margin – Extracting Bode Plots from Output Impedance

There are many applications where it is not possible to access the feedback loop in order to measure a bode plot. This is true for applications such as fixed voltage three terminal regulators, for many packaged converters and also for Point of Load (POL) switching converters. In other applications, such as integrated satellite electronics or production hardware, it is not possible or acceptable to lift wires or cut traces, so that if provisions were not made for stability testing it is not possible to measure the Bode plot of the regulator using traditional transformer based, or solid-state Bode box based signal injection methods.

There are many articles and application notes describing the extraction of phase margin, using a non-invasive technique that extracts the phase margin from an output impedance measurement[i ii]. The term non-invasive comes from the fact that this type of measurement can be made "in system", without breaking the control loop and in parallel with any and all loading. By combining the Picotest Signal Injectors with the OMICRON-Lab Bode 100 VNA, this measurement is a simple, automated measurement with cursor based readout. However, the measurement can be made with any network analyzer that can display group delay.

One of the frequent questions our customers ask is that while they appreciate being able to quantitatively measure the phase margin, how do they obtain the corresponding control loop's Bode plot? . The method was never intended to create a Bode plot, only to assess the overall stability of the control loop.

Though not possible in all cases, it is quite feasible to extract the Bode plot of a linear regulator, or at least a significant portion of it, using the same measurement system used for the non-invasive phase margin measurement. Interestingly, we have found that some component vendors use this same technique for extracting data curves, though not specifically for the extraction of the Bode plot.

The devices that we are interested in measuring are fully encased or packaged devices only allowing access to the input, output and ground pins. Given this limitation, it would seem impossible to extract a Bode plot, however, consider the well known relationship between the closed loop and open loop responses of a feedback system.

$$Closed_{Loop} = \frac{Open\_Loop}{1+T} \qquad \text{Eq. 1}$$

In this representation, T is the frequency dependent gain vector, containing BOTH magnitude and phase information. It is not uncommon to use this relationship to determine component characteristics, such as the open loop opamp output resistance from closed loop measurements. Since there are three variables in this relationship, it is possible to solve for any one variable, if the other two are known. Our goal is to obtain the Bode plot, so it follows that we must know both the open loop and closed loop responses; then it is possible to solve for the third variable, which is the frequency dependent gain vector, T. T, represents both the gain and phase curves of the Bode plot.

In order to clearly show how this is possible, let us consider the case of a simple linear voltage regulator. Figure 1 shows a simplified model of a typical voltage regulator, using the Agilent ADS simulator. This simulator allows us to easily perform the vector math in order to compute T; though this can also be done in some SPICE programs.

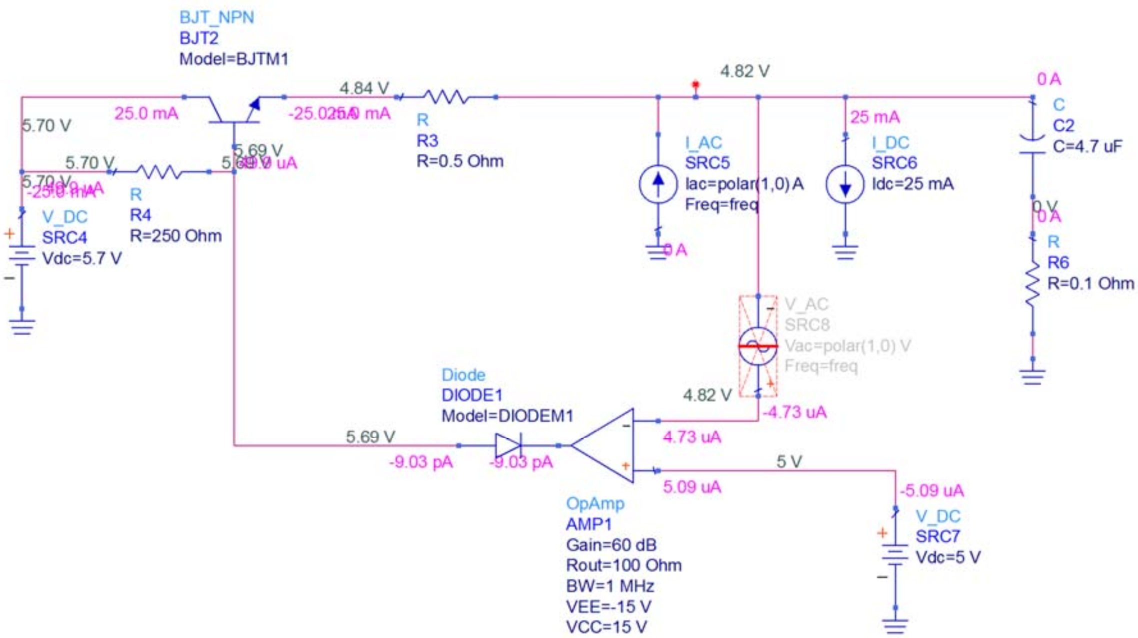

Figure 1 Agilent ADS simulation model of a simple voltage 5V regulator.

In this simplified model, the input voltage has been reduced below the regulation voltage (headroom) and so the output voltage is not 5V, but rather is 4.82V. This low output voltage is because the regulator is not in regulation. In this state any responses, such as PSRR or output impedance that we measure represent the open loop responses. The output impedance simulation result from this model represents the open loop output impedance. Increasing the input voltage allows the control loop to become active, thereby generating the closed loop output impedance.

Figure 2 shows the output impedance magnitude in both the open loop and closed loop operating conditions. The simulation result also includes phase information, though we have not displayed it for the sake of simplicity.

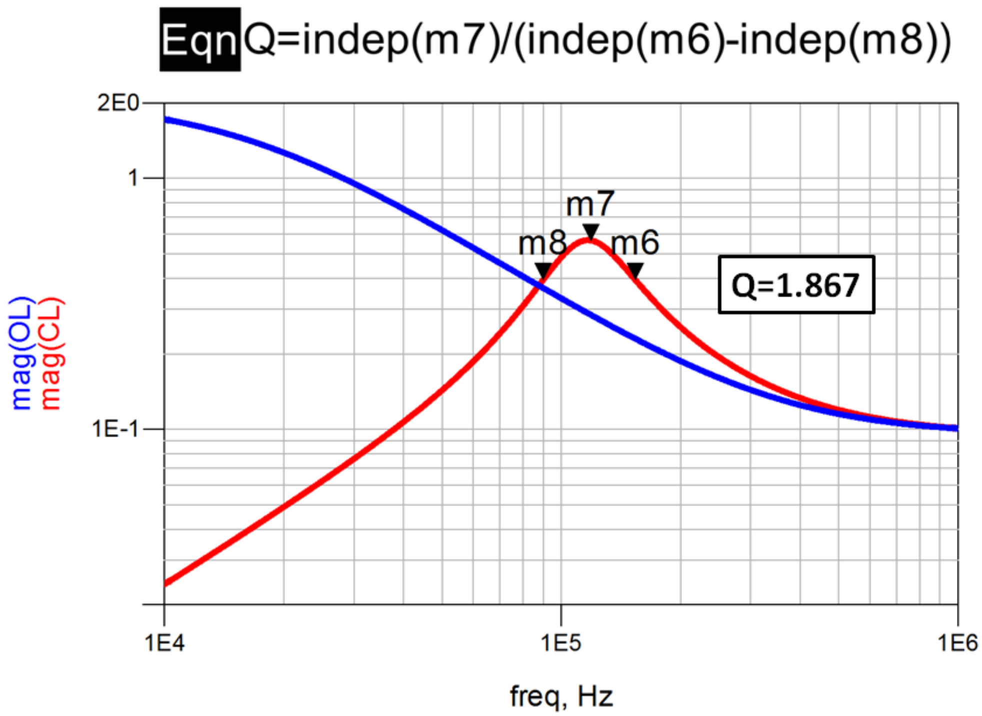

Figure 2 – Open Loop (red) and Closed Loop (blue) output impedances from the circuit in Figure 1

The Q of the closed loop impedance plot (red trace) as measured from the 3dB points is approximately 1.9, translating to approximately 30 degrees of phase margin. Solving Equation 1 for loop gain vector T as a function of the open loop and closed loop impedances in ADS results in Figure 3 as per equation 2.

Eqn T=-(OL-CL)/CL   Eq. 2

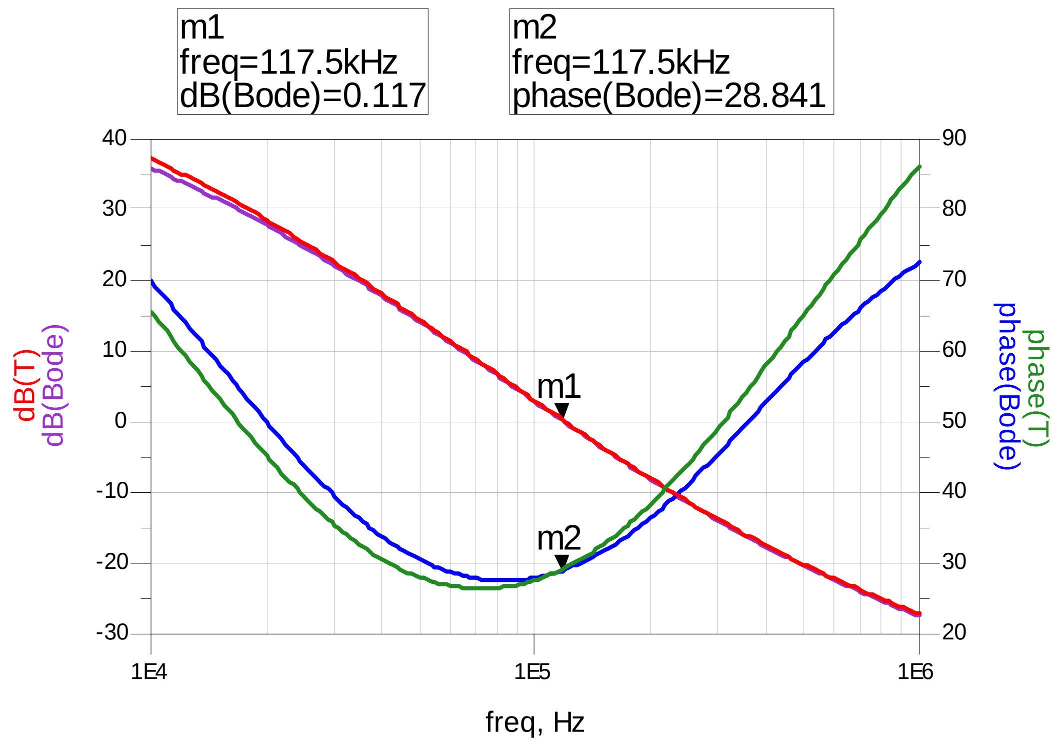

Figure 3 – ADS results of the extracted Bode plot (T) and the traditional Bode plot (Bode) using equation 2.

With the equation defined, ADS allows us to plot the extracted loop gain as "T" representing the Bode plot (Figure 3). We also simulated the bode plot using traditional methods and included the results in the same data display as "Bode" (purple and blue waveforms). The extracted Bode plot is in very good agreement until well beyond the gain crossing. The success of this method is dependent on the ability to obtain open loop and a closed loop plots and applies to nearly any performance characteristic, such as output impedance or PSRR. In some cases, it is possible to extract the Bode plot from a switching regulator, such as a POL, though in most cases it is not. The necessary requirement is the ability to obtain an open loop result without changing the control loop dynamics. In most switching converters, the loop gain is dependent on the duty cycle, so that reducing the input voltage alters the gain.

Putting this method into practice, the Bode plot is extracted from an LM317 regulator with a 100uF tantalum output capacitor, operating at 25mA load current. The LM317 was selected since it is very popular, but also because it allows us to directly measure the Bode plot for comparison with our extracted result. Figure 4 shows the non-invasive extracted Bode measurement and the direct Bode measurement. The correlation of the injection method and extracted is very good, especially near the zero crossing bandwidth.

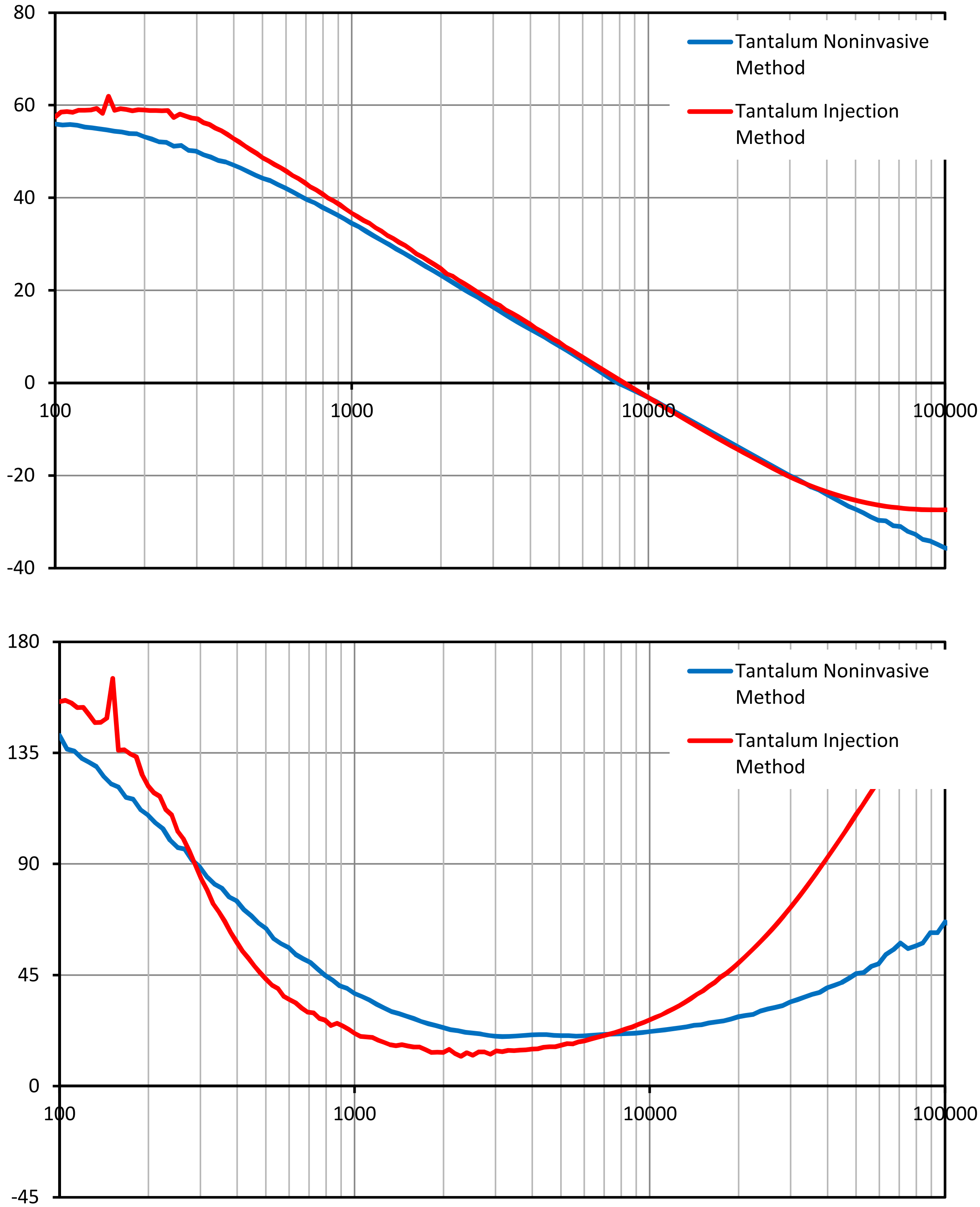

Figure 4 – LM317 Gain and phase comparison of injection method and non-invasive method.

While the method described here will not work in all applications, it has been shown that it is possible to extract a great deal more information using non-invasive methods than just the phase margin. In some cases, the control loop Bode plot can be extracted non-invasively just by examining the regulator's output impedance, as illustrated here.

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[i] New Technique for Non-Invasive Testing of Regulator Stability, Steven Sandler and Charles Hymowitz, AEi Systems, Power Electronics Technology, September 2011

[ii] "Invasive and Non-Invasive Stability Measurements", Picotest, 2010, https://www.picotest.com/blog/?p=312