Non-Invasive Assessment of Voltage Regulator Phase Margin without Access to the Control Loop

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Many voltage regulators are of the fixed output variety and include the voltage divider internal to the regulator. There are definite advantages to this approach, which allows active voltage trimming and also minimizes the physical space required. A disadvantage to this approach is that the voltage divider is not available for Gain-Phase or “Bode” measurement. This leads many to believe that it is not possible, or even necessary to evaluate the stability of such a regulator. Neither of these beliefs is true.

Digital systems often contain high-powered fast switching loads. Interconnects and load step repetition rates and times impact the power system’s stability. The loading can be difficult, if not impossible to replicate during the hardware development process and in simulation. Additionally, the stability varies throughout the system with varying impedances and filtering elements contributing to complex impedances presented to the power supply’s outputs.

While load step testing can be used to roughly indicate stability it does not provide an accurate phase margin number, and is subject to equipment issues and interactions with the circuit’s impedance, depending on where the load step is injected.

It would be useful to be able to measure the stability of switching and linear regulators in a system, with the actual loading applied, though without the need to physically cut into traces to get to the control loops.

In this article we demonstrate how to determine the phase margin of a voltage regulator’s control loop, without breaking any connections (non-invasively), and using only an inexpensive Vector Network Analyzer (VNA) and the Picotest J2111A Current Injector. In order to validate the method, an LM317 regulator is used so that the Bode measurement can be obtained for comparison with the proposed, non-invasive method. This measurement technique is also performed on a fixed output voltage regulator. Several output capacitors are used in order to obtain a wide range of phase margin solutions.

From the step load article discussed in (1), we determined the relationship between phase margin and Q as:

$$\varphi_m(Q) := \operatorname{atan}\left(\sqrt{\frac{1+\sqrt{1+4\cdot Q^4}}{2\cdot Q^4}}\right)\cdot\frac{180}{\pi} \quad \text{Degrees} \qquad \text{Eq. 1}$$

This implies that if we can measure the output impedance and determine the Q factor, we can determine the phase margin of the control loop.

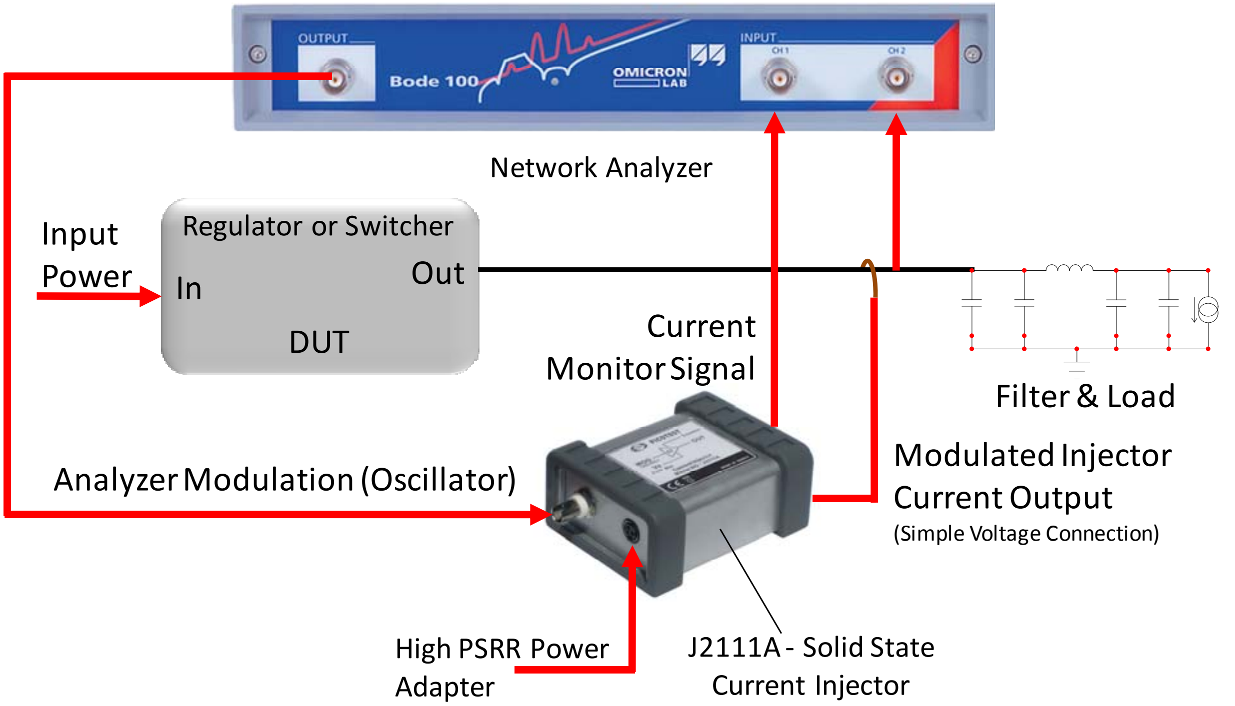


Figure 1: Generic test setup used for the non-invasive phase margin measurement based on output impedance. A network analyzer, in this case the OMICRON LAB Bode 100 is used to modulate the Picotest Solid State Current injector. The resulting plot at the output of the power supply is the output impedance.

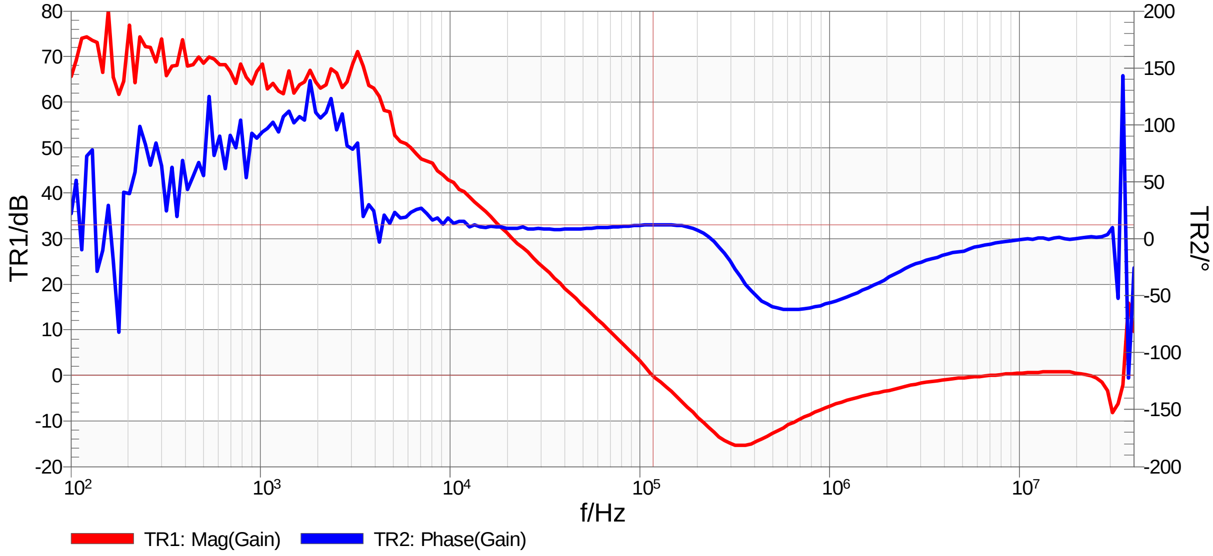
Figure 1 shows a generic test setup for the output impedance measurement. It should be noted that this method works using a simple clip lead on the output of the power supply. The measurement point can also be positioned anywhere along the voltage path allowing assessment of the stability as the load impedance changes with layout.

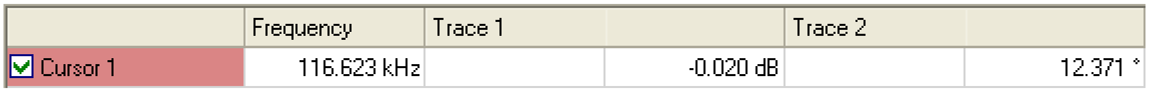
The best overall fit to the Erickson/Maksimovic solution is found as:

$$PM\ (Deg) = 50.363 * Q^{-0.907} \qquad \text{Eq. 2}$$

The result is within the greater of 3 degrees or 5%, which is useful in that the greatest accuracy is where it matters the most, which is at low phase margin. The equation breaks down at Q=0.5 (72 degrees), since there are no longer imaginary roots, therefore, at Q=0.6 or 71.183 degrees, the VNA software screen reports the phase margin as “> 71 Deg.”

In order to demonstrate and validate the method, the first measurement uses an LM317 voltage regulator. This regulator is an adjustable type, allowing us to measure the control loop’s Bode response (Figure 2) and also derive it from the output impedance (Figure 3).





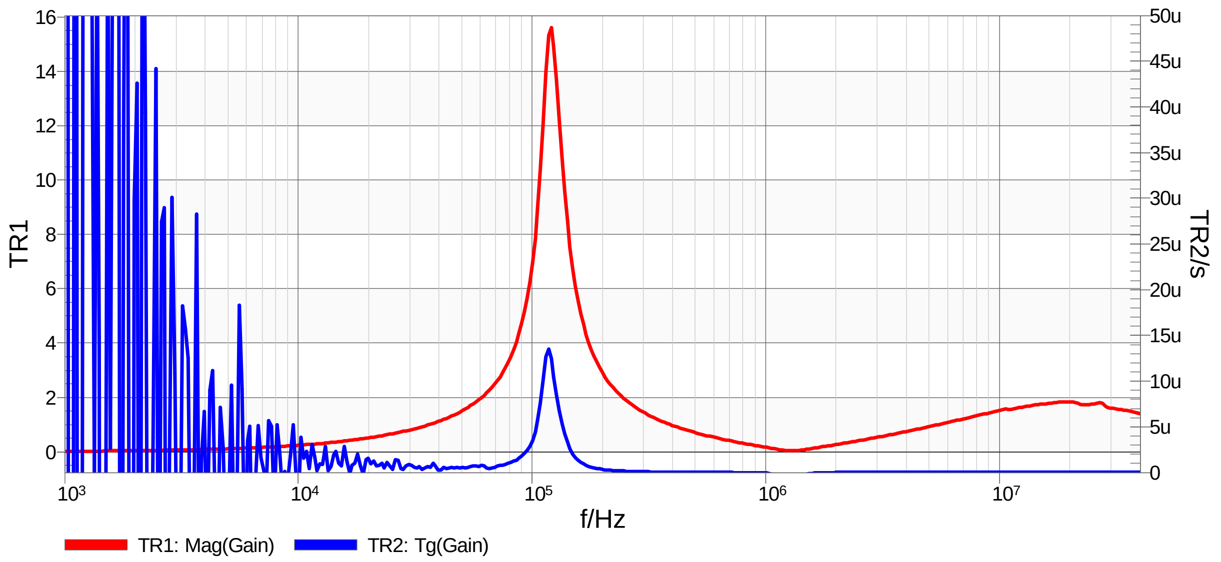
	Frequency	Trace 1		Trace 2	
☑ Cursor 1	116.623 kHz		-0.020 dB		12.371 °

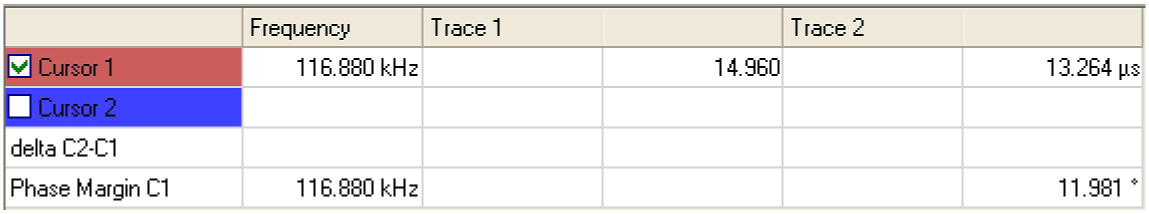
Figure 2: Bode Plot of the LM317 voltage regulator, Vout=3.3V, Iout=25mA, Cout=0.47uF X7R. (Measured with the OMICRON-Lab Bode 100 Analyzer and the Picotest J2100A injection transformer.) The phase margin is 12.4 degrees.

The output impedance corresponding to the same operating conditions in Figure 2 is shown in Figure 3. Note that the OMICRON-Lab Bode 100 can directly measure group delay, which is quite helpful, since the Q is directly related to the group delay, Tg as:

$$Q = Tg * Freq * \pi$$ Eq. 3

Zooming in on the resonant frequency we can determine that the frequency is 116.88kHz and the group delay is 13.26uS (Figure 3).





	Frequency	Trace 1		Trace 2	
☑ Cursor 1	116.880 kHz		14.960		13.264 µs
☐ Cursor 2					
delta C2-C1					
Phase Margin C1	116.880 kHz				11.981 °

Figure 3: The output Impedance and group delay for the LM317 voltage regulator whose Bode plot is shown in Figure 2.

Rearranging Eq. 1 to solve for the phase margin as a function of frequency and group delay results in:

$$\mathrm{PM}(\mathrm{Tg},\mathrm{Freq}) := \frac{180}{\pi}\cdot \mathrm{atan}\left[\sqrt{2\cdot\frac{1+\left(\sqrt{1+4\cdot \mathrm{Tg}^4\cdot \mathrm{Freq}^4\cdot\pi^4}\right)}{4\cdot \mathrm{Tg}^4\cdot \mathrm{Freq}^4\cdot\pi^4}}\right] \qquad \text{Eq. 4}$$

And solving for this particular measurement results in a phase margin of:

$\mathrm{PM}\left(13.26\,10^{-6},116.88\,10^{3}\right) = 11.726$ degrees

The result is very close to the Bode measurement (12.4 deg), and in fact it would be difficult to determine which result is more accurate, though the impedance measurement is arguably much less sensitive to parasitics within the measurement, and in particular does not have an injection transformer response to depend on.

The Bode 100 can display group delay and performs this mathematical conversion as part of a simple waveform cursor measurement. It is possible to perform this test using any network analyzer as long as you can extract the output impedance, convert it to group delay and evaluate equations 2 and 3 or 4.

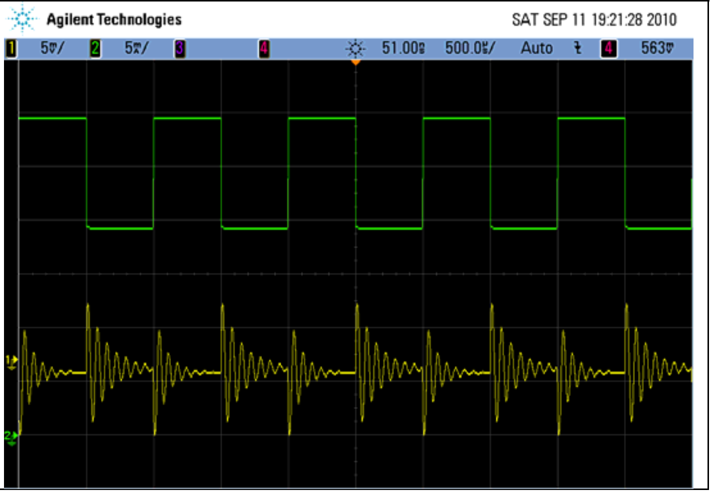
FIXED REGULATOR PHASE MARGN MEASUREMENTS

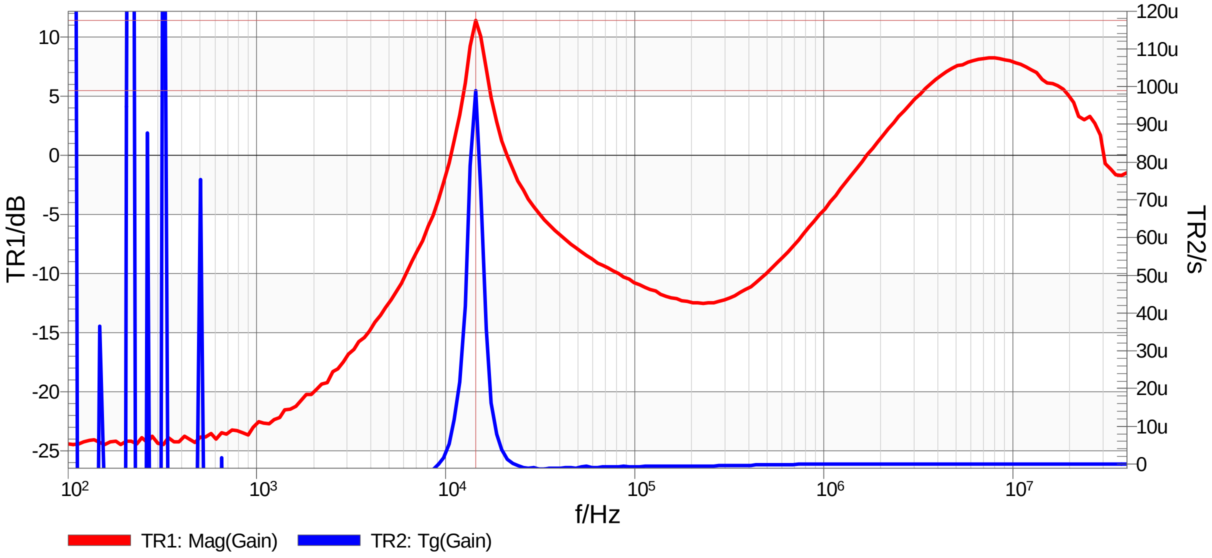
Using this same method, a TLV2217 fixed voltage regulator was tested in order to extract the phase margin. In this case, we cannot measure the actual phase margin for comparison using traditional Bode methods, so a small-signal transient step load measurement was used for correlation. The results of the step load test are shown in Figure 4 while the output impedance and phase margin are shown in Figure 5. The extracted phase margin is 13 degrees and consistent with the Q factor shown in the load step response.

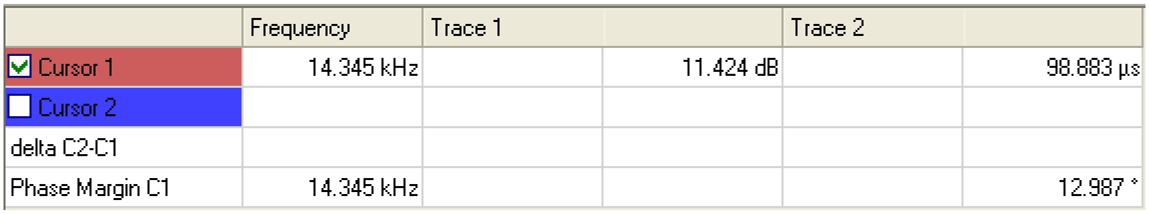
The step load was injected into the circuit using the same J2111A Current Injector used in the output impedance test. In this case, the Current Injector, essentially a Voltage Controlled Current source (similar to a “G” element in SPICE) is controlled by an arbitrary waveform generator. The Current Injector is capable of very small and fast load steps (20nS, 40MHz). It does not have the high input capacitive loading associated with an electronic load which otherwise can distort the load step measurement.

Of particular interest in the measurement of the TLV2217 with a 22uF chip tantalum capacitor shown in Figure 4 is the fact that the sensitivity of the Q factor to the load current is clearly shown. While we cannot clearly see the ringing frequencies, the two levels of the load step result in two different frequencies, as well as different Q. For this reason it is important that the measurement be made using the smallest possible load step signals.

Figure 4: Step load response for the TLV2217 fixed voltage regulator. The phase margin was found using the output impedance as shown above (see Figure 5). The step load was also performed with the J2111A Current Injector).

Capacitor	Freq, Tg	Extracted Phase Margin (Deg)	Scope Picture
22uF Chip Tantalum	97uS, 14.4 kHz	13°	





	Frequency	Trace 1		Trace 2	
☑ Cursor 1	14.345 kHz		11.424 dB		98.883 µs
☐ Cursor 2					
delta C2-C1					
Phase Margin C1	14.345 kHz				12.987 °

Figure 5: Output impedance and group delay plot of the TLV2217 voltage regulator showing the phase margin, Vout=3.3V Iout=25mA Cout=22uF Chip Tantalum.

Conclusion

We have shown that it is possible to extract the phase margin of a linear or switching voltage regulator using a Picotest J2111A Current Injector and a network analyzer simply by examining the output voltage terminals and measuring the output impedance.

This extraction works for circuits and ICs where the control loop is not accessible. The measurement is non-invasive, meaning that no components need to be lifted nor any wires disconnected to assess the phase margin.

Applying the J2111A Current Injector - Application Example

QUESTION: Our motherboard voltage regulator applications cover a very wide range of load rise times, depending on topology and application, with the fastest in the neighborhood of 250nS and the slowest in the several uS range. The load step sizes also vary greatly depending on the topology and application, anywhere from 1A to 90A or more.

From the attached files, it looks like the Picotest Current Injector product is designed more for testing very light load regulators at extremely high frequencies and slew rates. (Such as RF or Microwave applications requiring LDOs that would be placed directly next to their points of load)

Do you have an app note that would show the usefulness of the current injection product in testing a motherboard processor or memory regulator? For example, say a 4 phase switcher, running at 500kHz, with bandwidth of approximately 100-150kHz, and a step size requirement of 90A? In our application, would injecting such a small current really give us meaningful impedance information?

ANSWER: I think you are missing the intended value of the Current Injector and the important characteristics it was designed to expose. There is no question that the Current Injector is applicable to this application. In answer to your question, the answer is absolutely yes, you just need to think outside the box a little.

The Current Injector is not meant for testing large signal load steps as you noted, it is meant for determining stability and impedance over a wide frequency range. Large signal load steps can only be tested in your system with the real circuitry. There is no other way to test this as electronic loads are also generally too slow and too capacitive to provide accurate results.

Large signal load steps are only useful is assessing the dynamic voltage regulation or the regulator’s/interconnect’s ability to provide the current. The drawbacks are that the results can easily be incorrect, due to the sampling rate of the oscilloscope, and the speed and dynamic capacitance of the electronic load.

The point of the Current Injector is to test more critical aspects like stability, through either a small-signal load step or more robustly through an output impedance measurement. The Current Injector is non-invasive (very low capacitance) and has a very high bandwidth allowing the measurement of the multiple resonances occurring on a motherboard due to the traces and multiple decoupling capacitors. We frequently see resonances in the 2.5MHz to 30MHz range where none are expected. These higher frequencies can be killers for downstream RF or digital circuitry and are often hidden by large signal load step tests.

Since the load impacts the overall stability, it is essential that stability be measured with the production hardware. In systems where the control loop cannot be easily accessed or broken people often disregard the stability, either not performing the measurement or by using a large signal step which does not accurately convey the phase margin, overloads the oscilloscope, or due to the limited sampling rate provides incorrect results. Even a 1GHZ oscilloscope can easily provide incorrect results.

The answer to assessing this critical performance aspect is the J2111A Current Injector. With it you can measure the output impedance non-invasively and check the system’s stability.