Deconstructing the Step Load Response Reveals a Wealth of Information

Paul Ho, Senior Engineering Specialist, AEi Systems
Steven M. Sandler, Chief Engineer, AEi Systems
Charles E. Hymowitz, Managing Director, AEi Systems

When analyzing power circuits, engineers routinely evaluate the stability using gain-phase measurements also known as bode plots. Many manufacturers of voltage and low-dropout regulators are now doing away with the bode assessment in favor of only the step load response. The two tests are related, however, an incorrect assessment can lead to incorrect performance conclusions and poor resulting system performance. This article will show what can be learned from the step load response and why we should care.

In many cases it can be difficult or impossible to measure the Bode response of a system, since this is an invasive measurement, and the control loop may be inaccessible. In many monolithic devices, the necessary connections many not be available. In these cases it is often possible to perform a "small-signal step load response" or an output impedance test. A specially designed, transconductance signal injector can support the measurement of both the small-signal step load response and the output impedance of a voltage regulator. One such injector is the Picotest J2111A solid state current injector.

Impacts on Different Types of Responses

Small-signal step load responses are used to determine the stability of a regulator as opposed to large-signal step load responses since the former can be directly compared to a bode plot of the open loop response, while large signal responses can easily impact the circuit response due to circuit nonlinearities.

Since analog simulators generally evaluate small-signal performance, small-signal step loads have to be considered if the two results are to be compared. Large signal step loads may result in nonlinear effects that are not consistent with a small-signal simulation, though it is possible to perform large signal frequency domain simulations using harmonic balance simulators if the model can support the nonlinear effects.

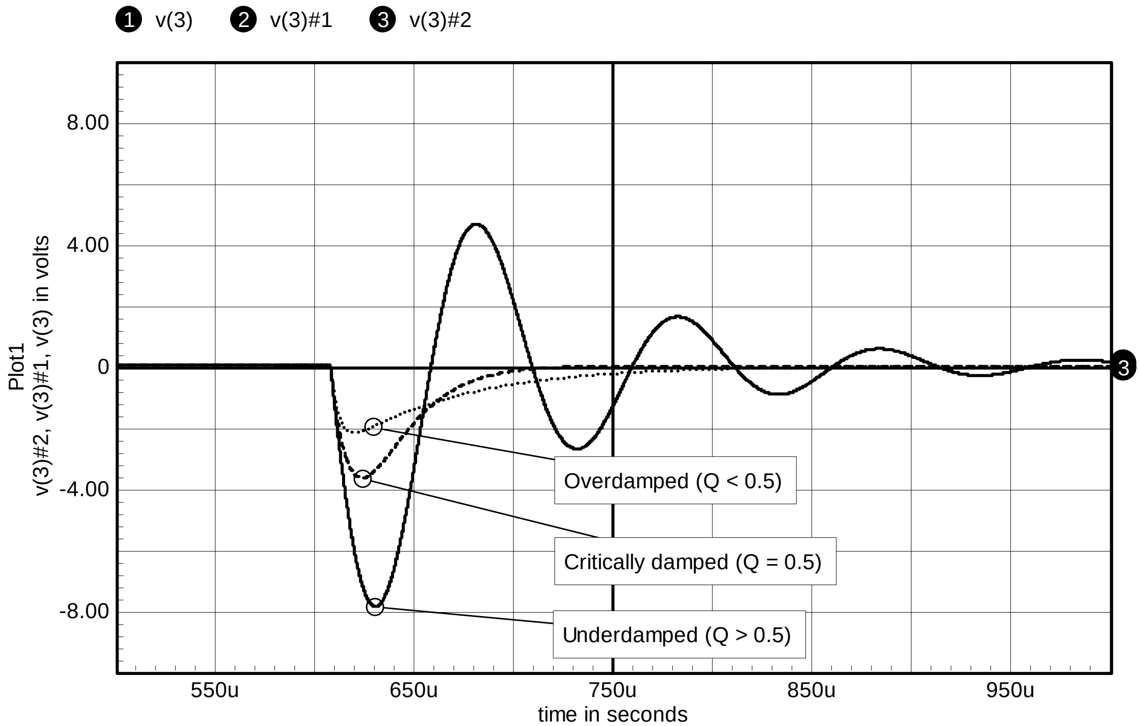


Figure 1 – Three types of step load responses

Figure 1 depicts examples of the three classifications of step load responses which are underdamped, critically damped, and overdamped. The underdamped response shows that the output oscillates with exponential damping. The critically damped response has the output settling to its steady state value without oscillating faster than any other response. While the overdamped response shows that the output does not oscillate, but takes a longer time to settle to its steady state value.

The output voltage during a step load rings if the control loop has a poor closed-loop performance, which is related to the open loop bode plot. The closed loop characteristics for a voltage regulator are impacted by its load capacitance, operating point dependent transconductance and output impedance (such as output capacitors). For most cases, the load capacitance has a large tolerance and the regulator is required to operate over a wide range of operating conditions. It is for these reasons that a regulator can be difficult to stabilize and one of the reasons why it is unwise to abandon the bode plot as a means of determining stability.

Consequences of the Step Load Response

A lower open loop phase margin (PM) is associated with a higher closed loop Q, which occurs at the bandwidth frequency. The Q can be observed in an output impedance plot of the regulator. Q is defined as the magnitude of the ratio of the resonant output impedance to the characteristic impedance of the regulator:

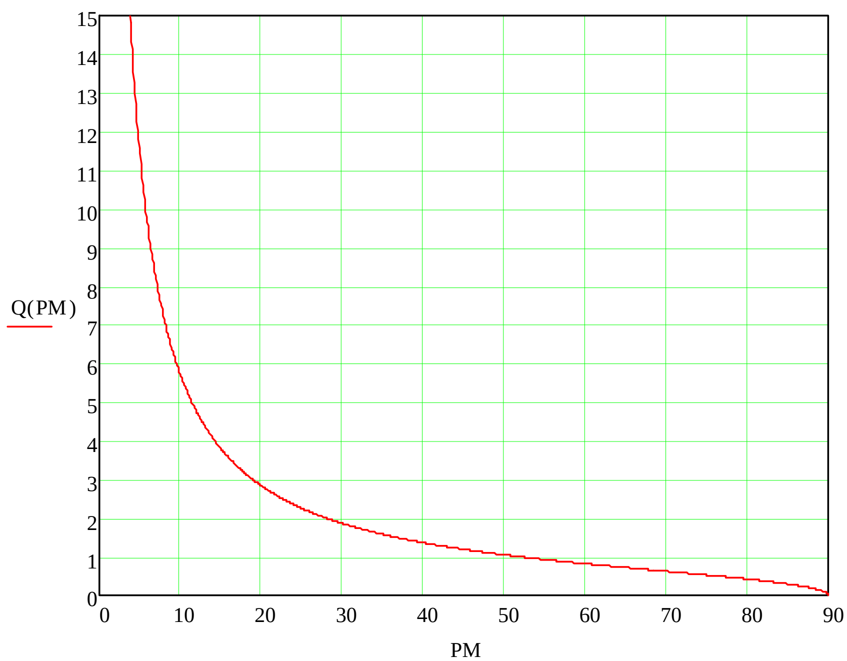
$$Q = \frac{Z_r}{Z_0} \qquad \text{Eq. 1}$$

Q is also defined as the resonant frequency divided by the -3dB bandwidth, defined as the difference between the higher and lower frequencies, where the magnitude of the impedance is -3dB less than the resonant impedance:

$$Q = \frac{f_r}{f_{-3dB\ BW}} \qquad \text{Eq. 2}$$

The mathematical relationships between the PM and Q can be expressed as[1]:

$$Q(\varphi_m) := \frac{\sqrt{\cos\left(\varphi_m \cdot \frac{\pi}{180}\right)}}{\sin\left(\varphi_m \cdot \frac{\pi}{180}\right)}$$ in degrees Eq. 3



[1] Erickson, Robert W. and Dragan Maksimovic. *Fundamentals of Power Electronics.* Second Edition. Springer, 2001.

Figure 2 – Q as a function of phase margin.

$$\varphi_m(Q) := \operatorname{atan}\left(\sqrt{\frac{1+\sqrt{1+4\cdot Q^4}}{2\cdot Q^4}}\right)\cdot\frac{180}{\pi}$$ (PM is in degrees) Eq. 4

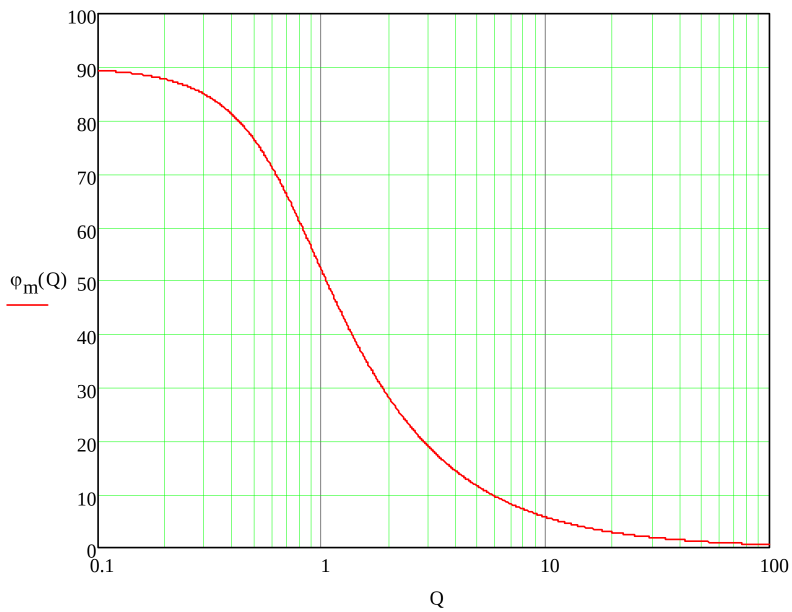


Figure 3 – Phase margin as a function of Q.

The following circuit can be used to confirm the relationship between PM and Q. The configuration shown is to make the open loop bode plot. LOL is a large inductor which acts as an open circuit in the AC simulation and the large value capacitor COL is used to couple the AC signal into the circuit and acts as a short in the AC simulation. LOL and COL also allow the correct DC bias to be calculated.

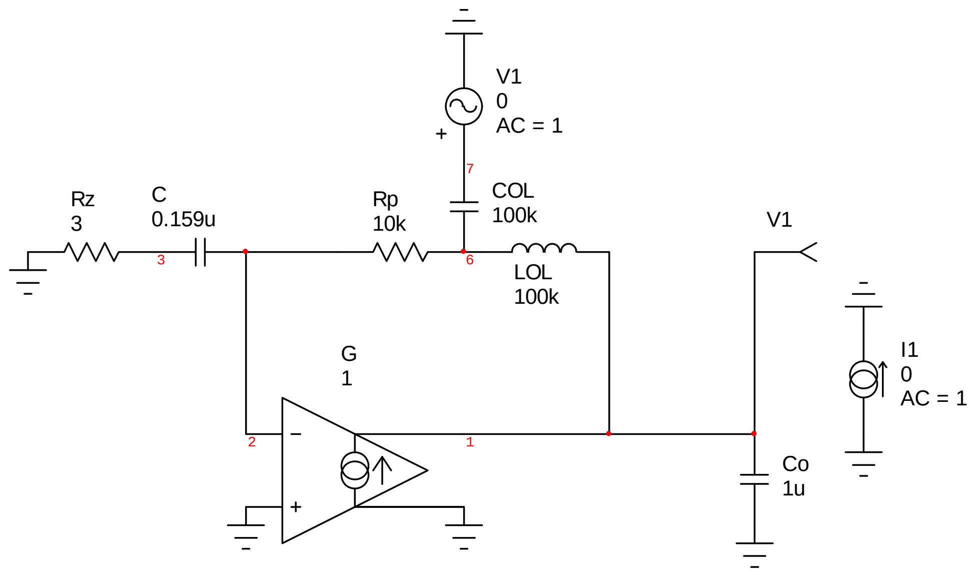


Figure 4 – AC model of a voltage regulator.

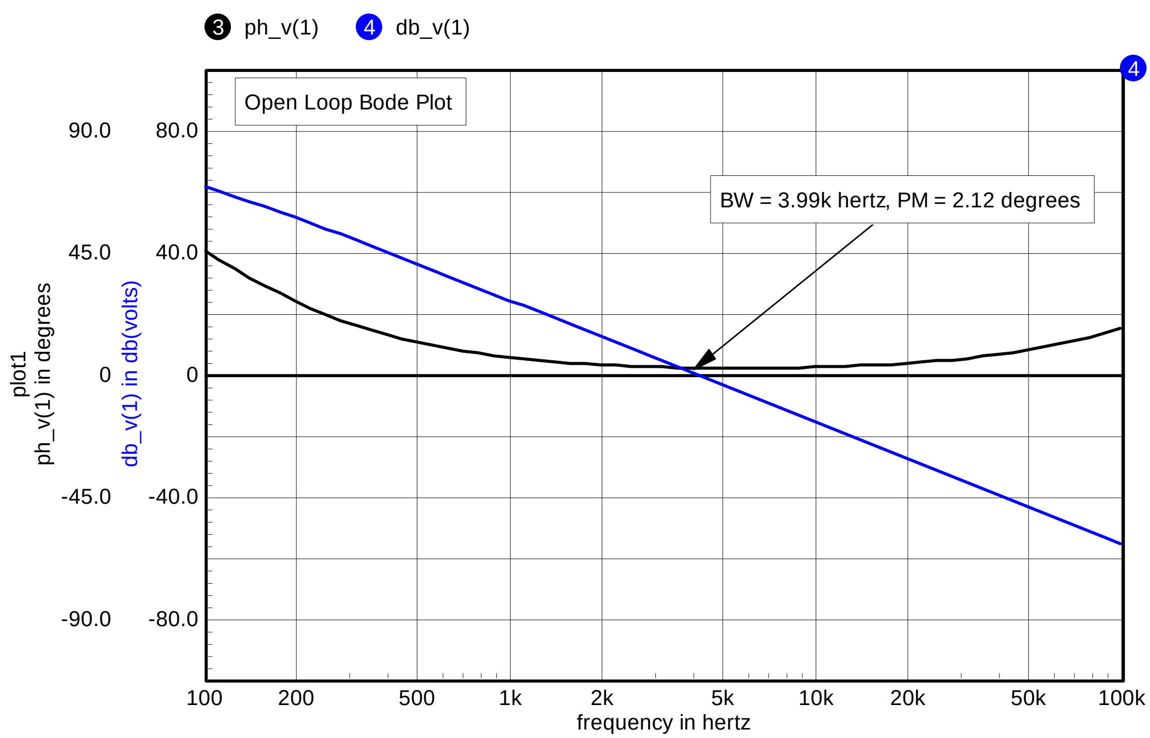


Figure 5 – The bode plot of the AC model of the regulator; the phase margin is 2.12 degrees.

The closed loop output impedance can be simulated by setting the COL and LOL values to 1p, effectively closing the loop, while these very small values result in a negligible effect on the circuit at our frequencies of interest. The AC current source, I1, is then connected from node 1 to ground. The voltage on node 1 is observed for the output impedance.

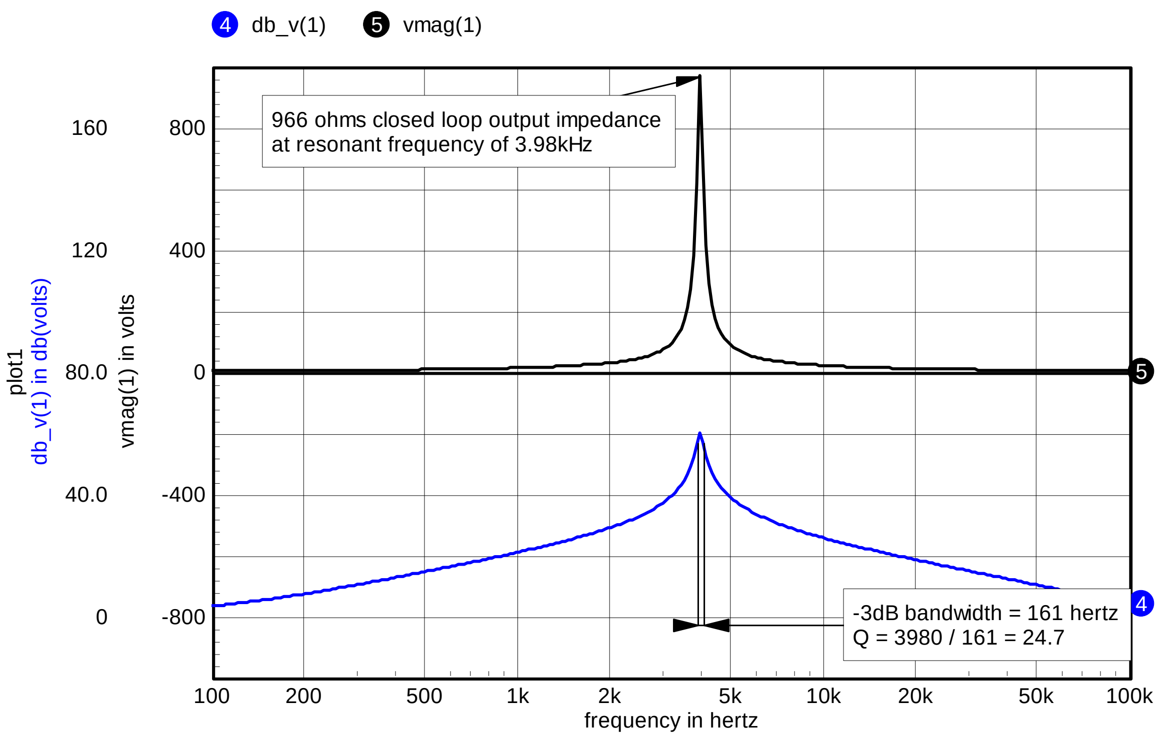


Figure 6 – Output impedance plot of the AC model of the regulator, the Q is 24.7.

The phase margin computed as a function of the Q value (24.7) is 2.319 degrees which is very close to the one measured in the bode plot simulation.

Most datasheets that show step load data are in response to a single step load event (pulse with effectively infinite period) where the output is allowed to completely settle. The plot may not be small-signal and sometimes may not indicate if it is small or large signal. If the step load data is small-signal then the resulting plot is the regulator's "natural" response to a step load. While this response is a proper way to relate performance to the bode plot, the datasheet graph is not necessarily the response to step loads of varying frequencies. If the voltage excursions are the most important metric of a step load response, the worst case maximum excursions occur when the step load <u>frequency</u> is equal to the open loop bandwidth with a 50% duty cycle. This is the "forced" response to the dynamic load.

A simple way to observe the step load response is a parallel RLC circuit which represents the closed loop output impedance of the regulator. This simplified circuit only represents the output impedance, so other parameters cannot be determined with this simplification, but it allows us to easily relate the Q of the RLC circuit to the Q of the regulator. This also allows us to mathematically connect the PM of the regulator to its Q.

The following parallel RLC circuit has a Q of 3 with R = 300 Ω, L = 1.59 mH, and C = 0.159µF. This is the equivalent of a regulator with a PM of 19°. The current is stepped with two types of stimuli, one is an increasing step (pulse) and the other is a 50% duty cycle square wave with a frequency equal to $\frac{1}{2\pi\sqrt{LC}}$. The first response is the natural response and the second response is the forced response. The magnitude of the forced response can be easily derived using Fourier analysis for the dynamic load current and multiplying the fundamental Fourier coefficient by the impedance of the parallel RLC circuit. SPICE simulation results for these values of RLC are shown below.

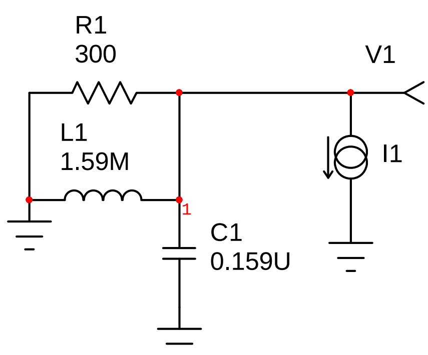


Figure 7 – Simplified output impedance model of a regulator.

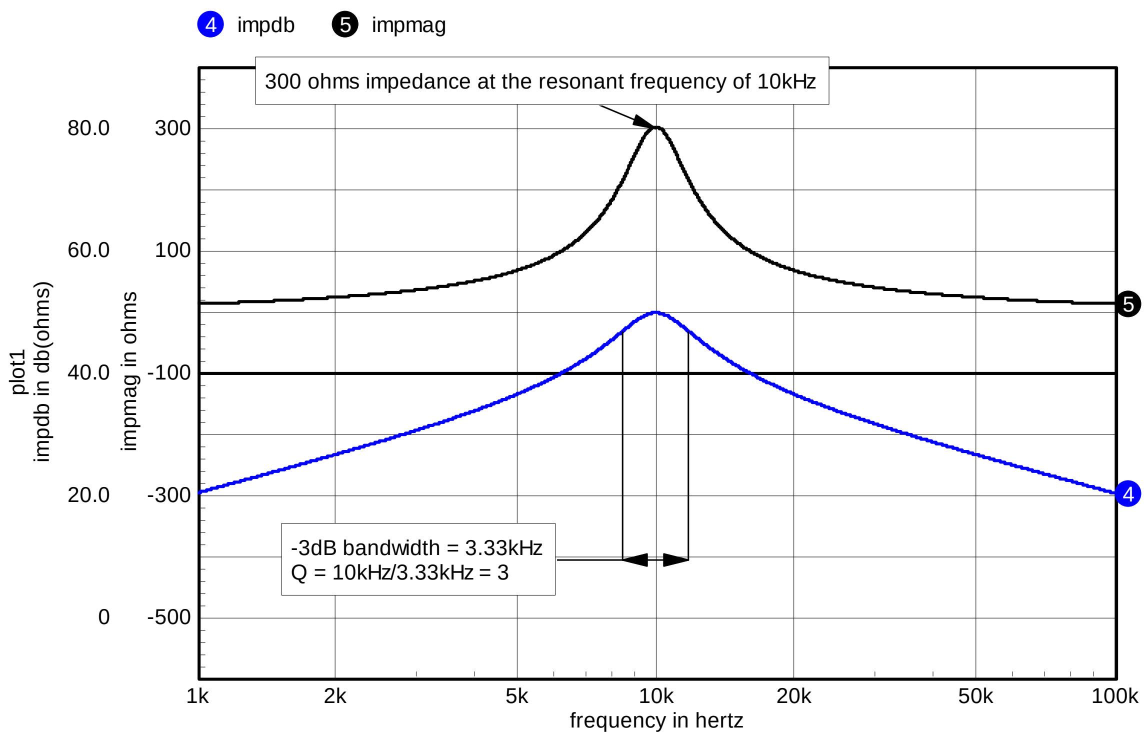


Figure 8 – Output impedance plot of the simplified output impedance model of the regulator.

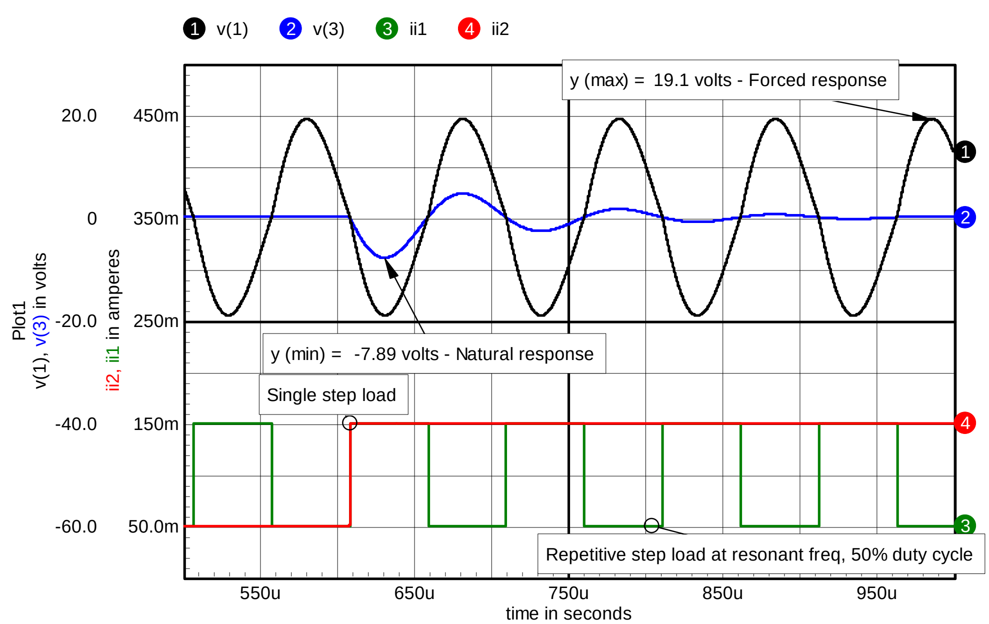


Figure 9 – Natural and forced step load responses of the simplified output impedance model of the regulator.

The magnitude of the forced response is 19.1V since the Fourier of the fundamental of the step load square wave is $\frac{4}{\pi} \cdot 50\ \text{mA} = 64\ \text{mA}$ which is multiplied by the impedance of 300 Ω at the resonant frequency. The result of 19.1V is greater than the product of the current and the impedance.

Simulations can be repeated with different values of R to adjust Q and PM.

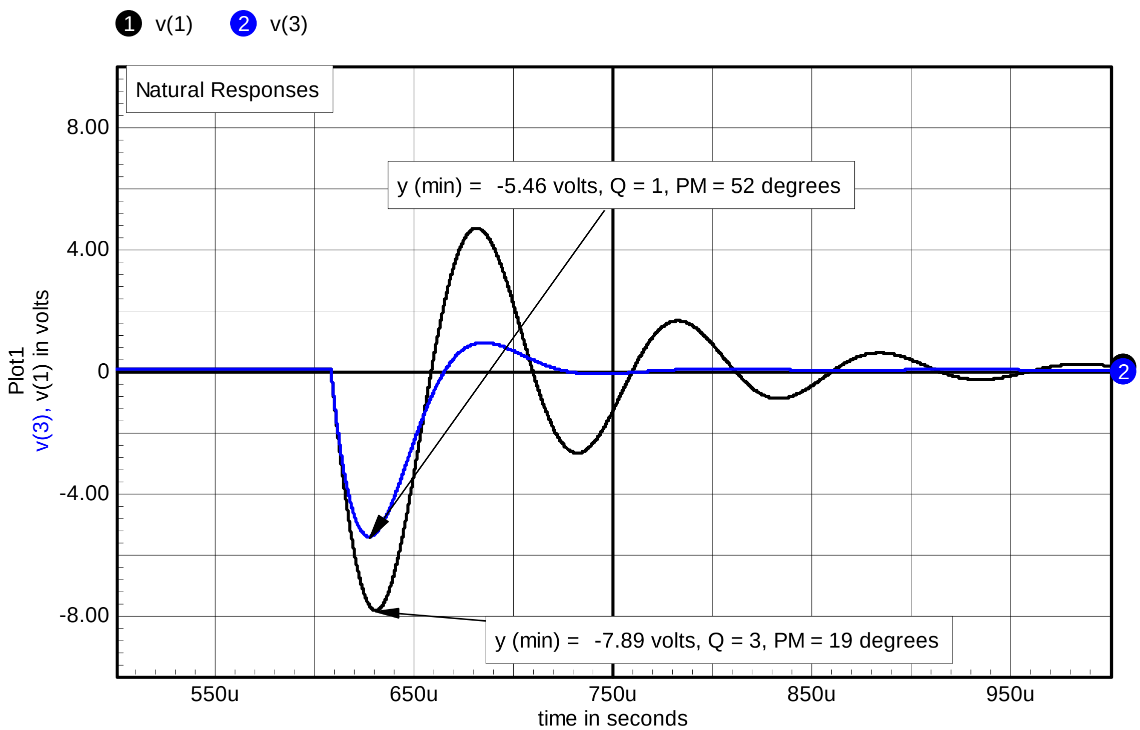


Figure 10 – Natural responses as a function of Q/PM. The number of rings and their amplitude increase with increasing Q and decreasing PM.

The affect on the worst case maximum magnitude of the forced response can be seen as a function of Q and PM.

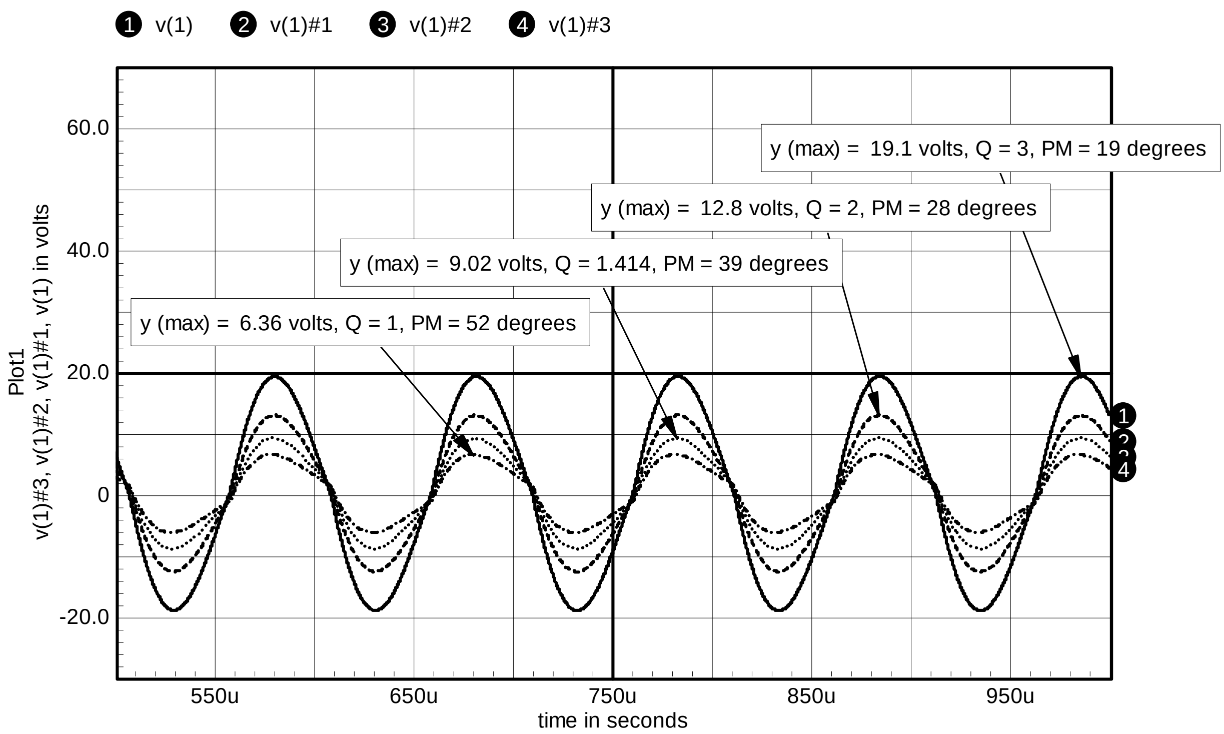


Figure 11 – Several forced responses as functions of Q and PM. The magnitude increases in the same manner as the natural response.

Bench measurements of an LM117linear regulator are also obtained to relate the closed loop output impedance, open loop bode plot, and step load responses to each other.

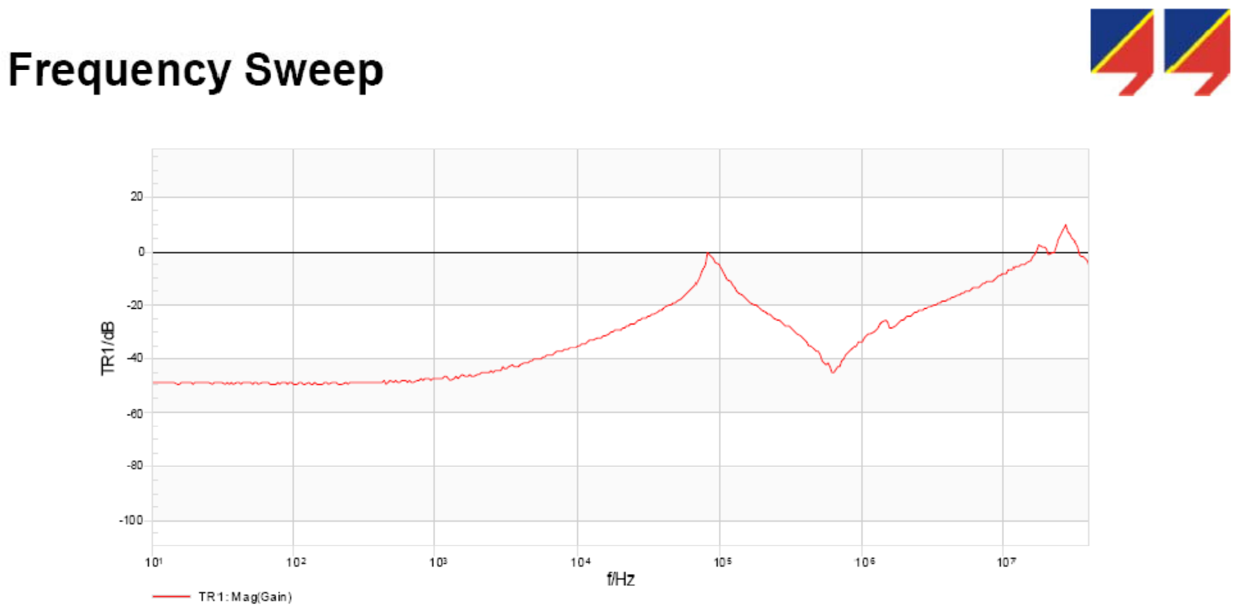


Figure 12 – Closed loop output impedance bench measurement of the regulator. Note that there is a resonant frequency at 80kHz with a Q of approximately 5.4. (Plot courtesy of Omicron Bode 100).

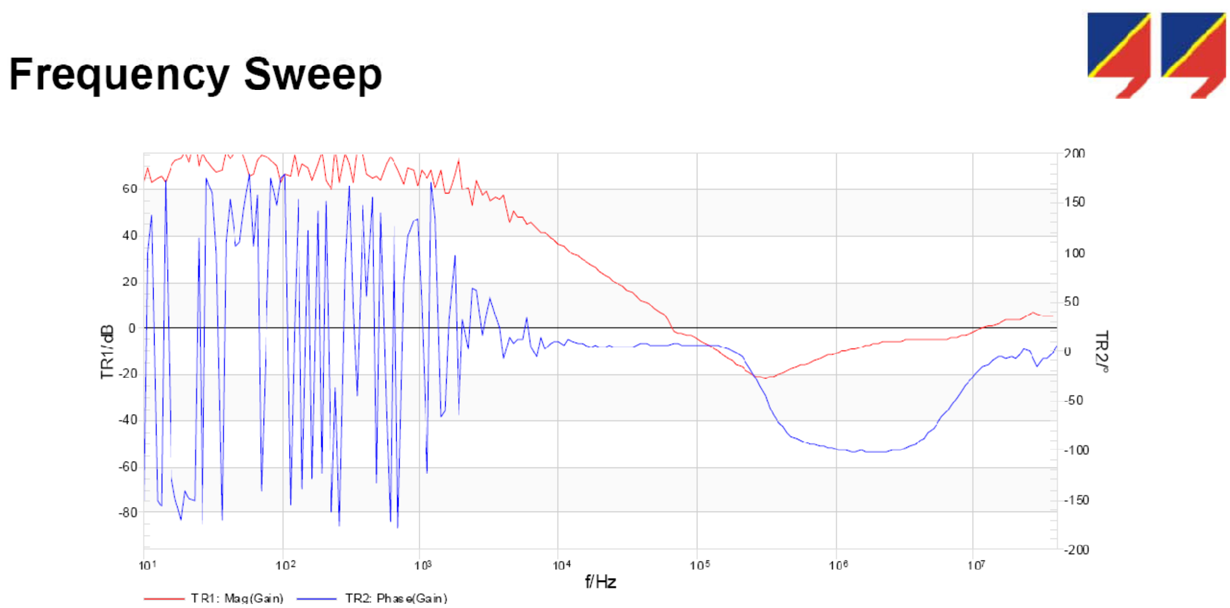


Figure 13 – Open loop bode plot of the regulator. The phase margin is approximately 7.5 degrees. The estimated phase margin from the Q value is 10.6 degrees which is close to the bode plot value.

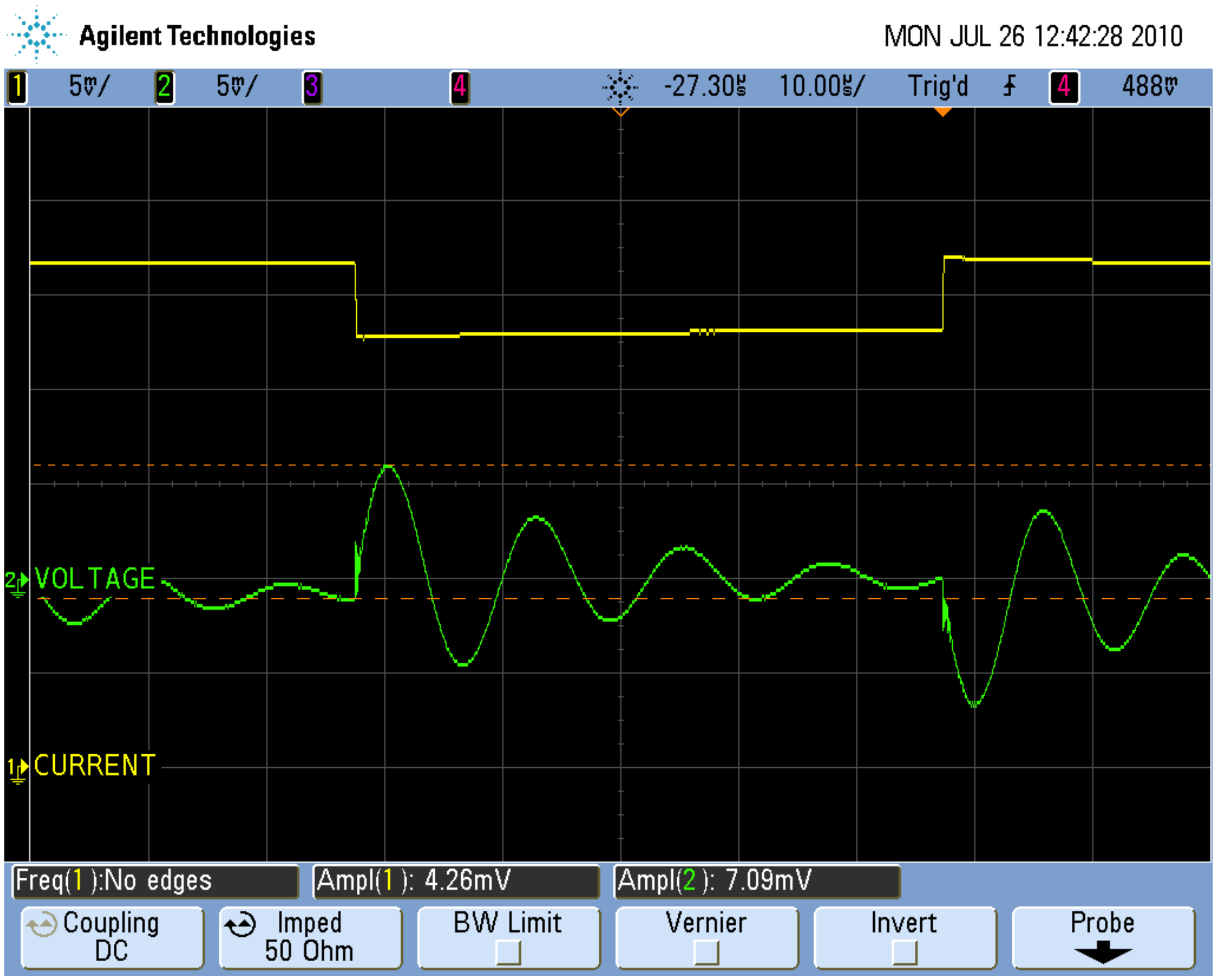


Figure 14 – The output voltage natural response to a current step load. The output rings at the resonant frequency of the closed loop output impedance. The peak amplitude is 7.09mV.

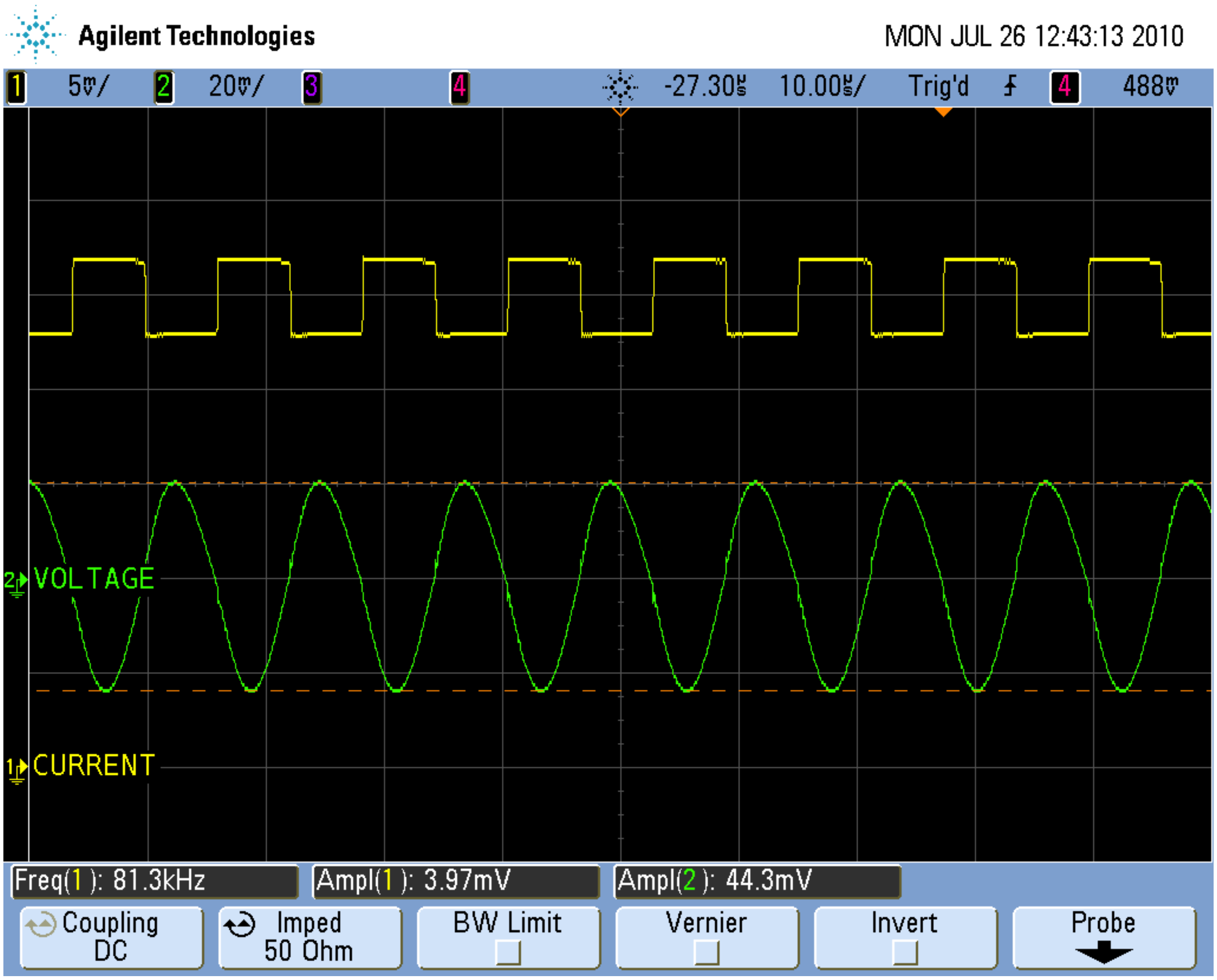


Figure 15 – The top yellow waveform is the step load current forcing function. The bottom green waveform is the output voltage forced response. The peak amplitude has increased 6.25 times because the current load stimulus frequency matches the closed loop output impedance resonant frequency.

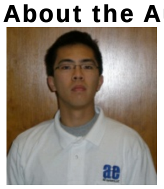
Conclusions

A small-signal step load response of a regulator can be used to determine the stability of the control loop and to complement the open loop bode plot or to substitute for it when the open loop measurement is not possible.

The natural response where the small signal step load occurs once and the output is allowed to settle is the response that is considered for stability. The worst case maximum excursion due to the step load occurs when the step load is repeated at the resonant frequency of the closed loop output impedance measurement or the bandwidth of the open loop bode plot. This is the forced response, and results in an output voltage that is greater than the product of the current multiplied by the peak impedance. The reason that the response is greater than the product is that the Fourier fundamental of a square wave is $\frac{4}{\pi}$, which is greater than 1.

Closed loop measurements of a regulator, such as the output impedance and step load natural responses, can be used to estimate its stability and the phase margin. The phase margin is related to a closed loop parameter Q, which is derived from the output impedance plot. The regulator can be simplified to passive elements once the closed loop output impedance is determined in order to simulate the small-signal step load response. The active feedback loops are not required since its effect is included in the output impedance plot. Linear regulators can be simplified to a parallel RLC circuit from the closed loop output impedance. The values of RLC can be adjusted to match the output impedance, Q, and phase margin.

About the Authors:



Paul Ho is an engineering scientist at AEi Systems, LLC. He is responsible for their reliability engineering related analyses.

Steve Sandler is the founder and CTO of AEi Systems, LLC. He is responsible for worst case circuit analysis of power, RF, and linear systems as well as the design of AEi Systems line of rad-hard dc-dc converters.

Charles Hymowitz is the Managing Director of AEi Systems where he is responsible for overall company operation. Previously Mr. Hymowitz was COO of Intusoft.