Testing LDOs requires you to have adequate instrument bandwidth

Most electronic systems contain at least one voltage regulator, with many systems requiring several regulators, each providing a different voltage. The performance of these regulators is critical to the performance of the downstream circuits that they power. Many important characteristics of these voltage regulators are either not specified by the manufacturer or worse, the data is incomplete or misleading. The latter is often due to the limited bandwidth of the test equipment used by the device manufacturers in their testing.

In this article, we will look at the role that fidelity (i.e. signal accuracy and quality) plays in the regulator characterization process and also compare the correct performance with that specified in the datasheet for a sample device. These are low cost, high-fidelity instruments, meaning that the ability to make these measurements is within almost all of our budgets. The equipment used is an Agilent E5061B Network Analyzer in conjunction with the Picotest J2100A series of signal injectors and a Picotest G5100A function/arbitrary wave generator.

First we will evaluate a regulator’s stability using Bode (phase-gain) plots, output impedance, step load response, PSRR and reverse transfer characteristics. The LM317 voltage regulator was chosen for demonstration purposes, as it provides access to the feedback divider and is widely used in industry. Many other regulators will provide similar results.

Stability

There is no universally recognized standard for assessing the stability (or instability) of a voltage regulator. Some companies have specific guidelines, such as a 45 degree phase margin and a 12 dB gain margin in order to be considered acceptable. Others believe that a circuit is stable if it is not oscillating. This may be true though the ramifications of poor phase margin are far reaching and often difficult to quantify.

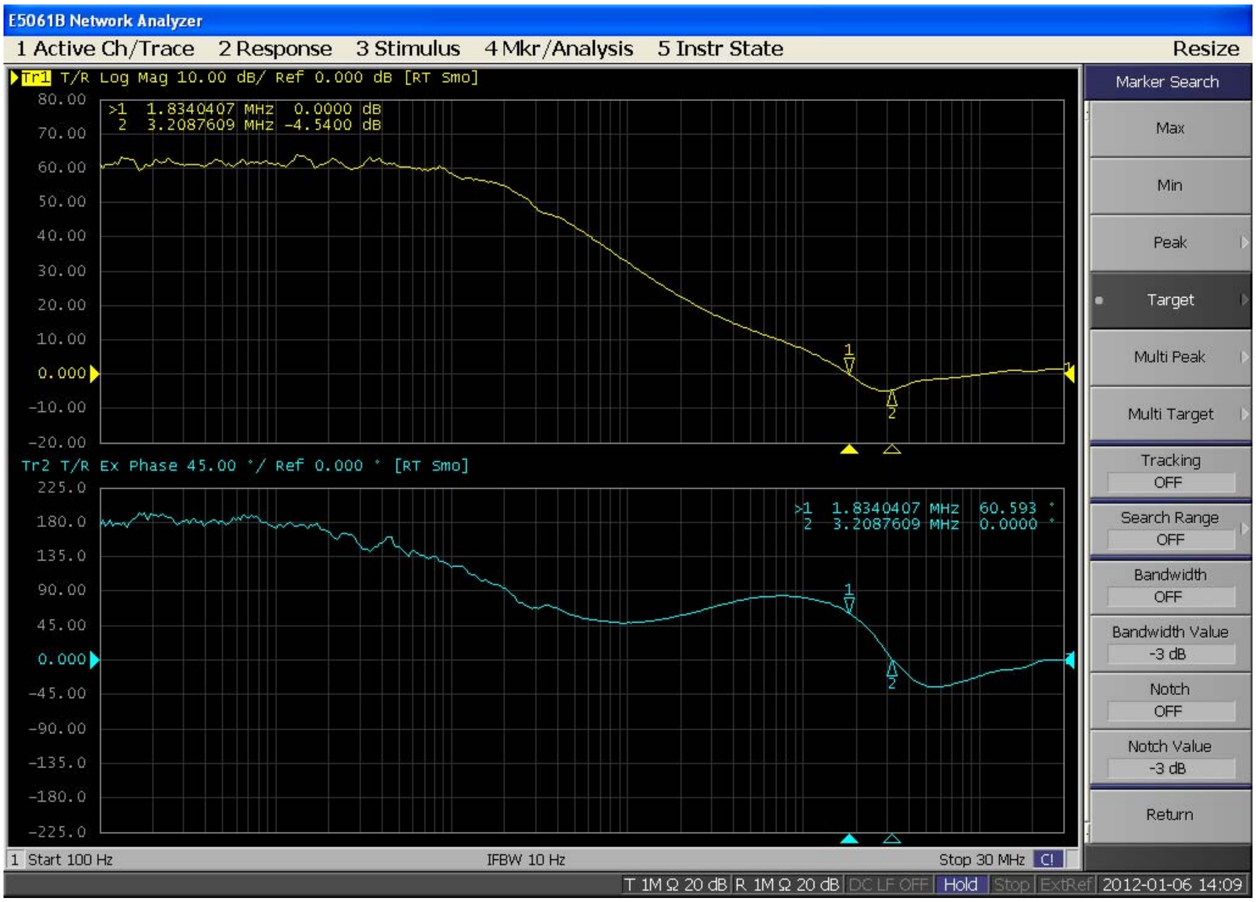
In many cases the connections required to measure the stability of a voltage regulator are not available. This is always true in the case of fixed voltage regulators, since the output voltage divider is internal to the device and, therefore, not accessible. In such cases the “fallback” measurement is usually a step load response, which is *believed* to be related to stability, in order to perform some form of stability assessment. (See section "Step Load Response" below).

The control loop of the regulator determines many of the performance characteristics of the voltage regulator, including the PSRR, step load response and output impedance to name a few. The LM317 datasheet does not define stability regions, nor does it provide any data or specifications for phase margin or gain margin as a function of the input and loading.
Most datasheets neglect specific stability information, though depending on the manufacturer of the device, there may or may not be a paragraph describing the selection of output capacitors. This is generally in the form of some subjective text about selection of output capacitors and

considerations for dielectrics and ESR. The ESR parameter is itself often poorly specified, uncontrolled and has a very large tolerance.

Since many of the manufacturers datasheets include measured data (though not of stability) with no output or adjustment capacitors, the Bode plots in this article is measured with no output or adjustment capacitors.

The Bode measurement in Figure 1 is made using a Picotest J2101A wideband injection transformer along with the Agilent E5061B Network Analyzer. The regulator loading is provided by a Picotest J2111A solid state current injector, since that will also be used for the output impedance and the step load response measurements and presents negligible capacitance to the regulator. Electronic loads can present substantial capacitance, defeating the no load capacitance measurement



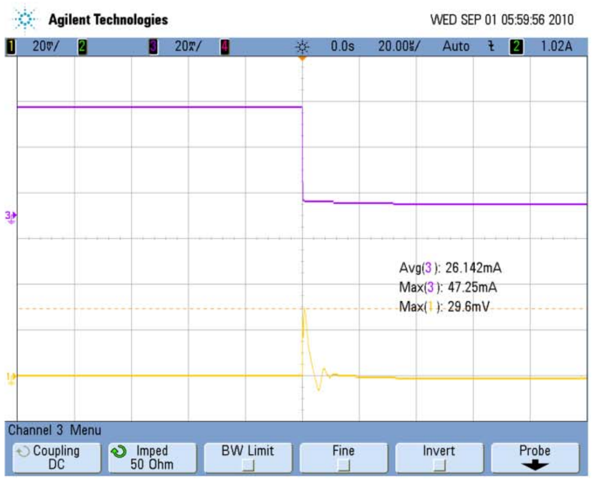
The results of the Bode plot indicate that the bandwidth of the regulator is approximately 2MHz at this operating current and the phase crossover is approximately 3 MHz, requiring the measurement bandwidth to exceed this latter frequency.

The addition of output capacitors will reduce the bandwidth, though any stability improvement will be dependent primarily on the ESR of the capacitors.

Step Load Response

The step load response is often used as a secondary assessment of the relative stability of the voltage regulator. In cases where the output voltage divider is not accessible, this is often used as the primary evaluation of the regulator's stability. A few words of caution are warranted here. First, the data is often shown for large load step (large signal) excursions, from zero or light load to near maximum load. This measurement technique often includes large signal effects and not the control loop, so it is preferable to measure the small-signal step response if one is interested in stability. The results are also impacted by many other measurement limitations, with the most significant being the sampling rate of the oscilloscope, the oscilloscope time-base, and the slew rate of the step load. In many cases, electronic loads do not provide acceptable slew rates, and may also present a significant capacitive load to the regulator.

The figures below show the step load response for different oscilloscope time base settings. This demonstrates how easily a step load response can be misinterpreted if wrong settings are chosen. The J2111A current injector is used for this measurement, since it offers negligible capacitance, up to 40MHz bandwidth and the current signal offers 20nS rise and fall times. A Picotest G5100A frequency/arbitrary generator is used to drive the current injector. An Agilent 1 GHz DSO60104A oscilloscope is used, since it offers a 4GHz sampling rate, assuring that no data is lost in the measurement. An Agilent 1157A 2GHz active probe is used to ensure the probe does not limit the measurement as well.



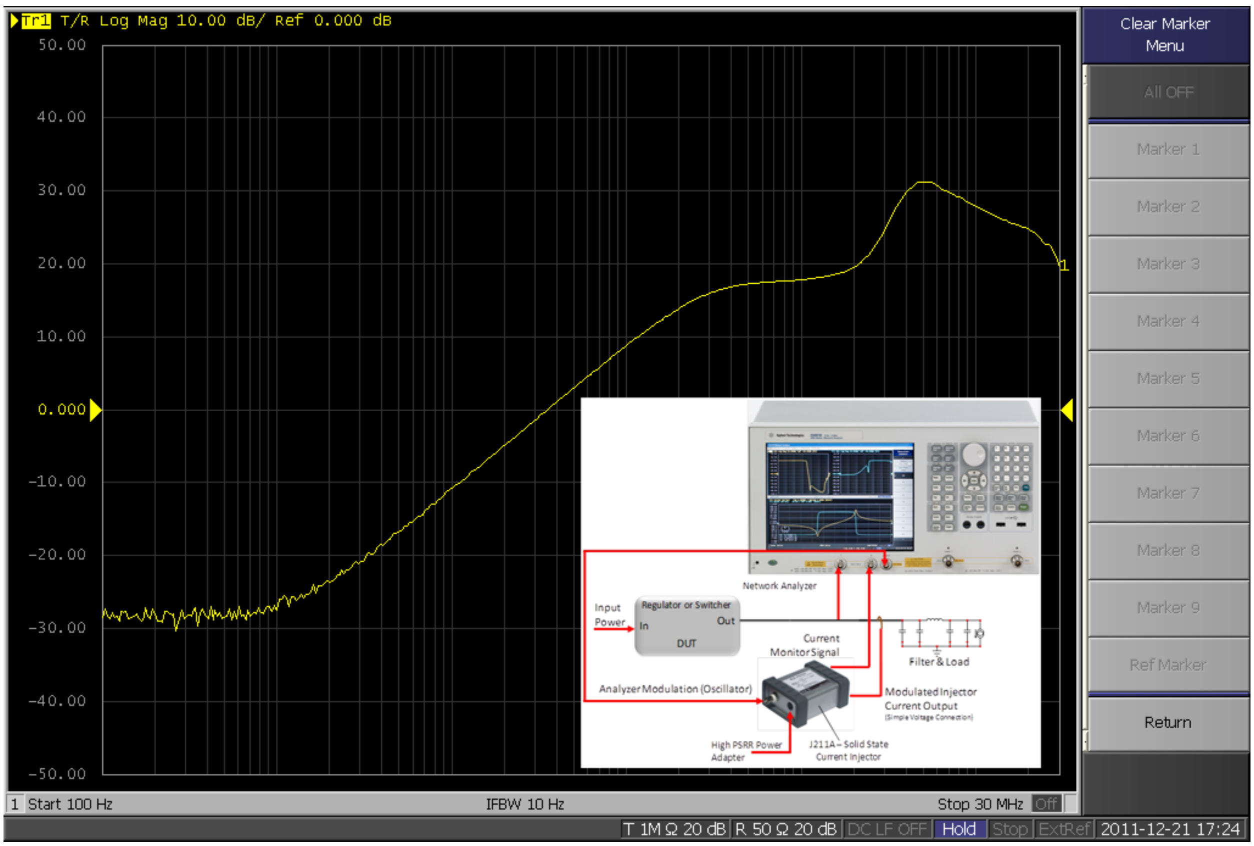
The transient response measurement is not a reliable indicator of stability, since the result is heavily dependent on many other parameters, and as evident here, it is quite simple to obtain an incorrect result, which can then lend itself to an incorrect assessment of the regulator performance and stability.

It is also evident that there are two distinct transient response outcomes, the “natural” response and the “forced” response. The natural response is the response obtained when the stimulus is well below the control loop bandwidth while the forced response is the response obtained when the stimulus occurs at the frequency of the bandwidth. The forced response is generally much larger than the natural response, while the datasheet generally shows the natural response. A final observation is that the ringing frequency and amplitude are dependent on the load current. A variation in load current can produce a amplitude and frequency modulated step load response, which sensitive circuits, like LNA’s and oscillators may not like. The amplitude and frequency modulation may also appear in the EMI signature of the system.

Output Impedance

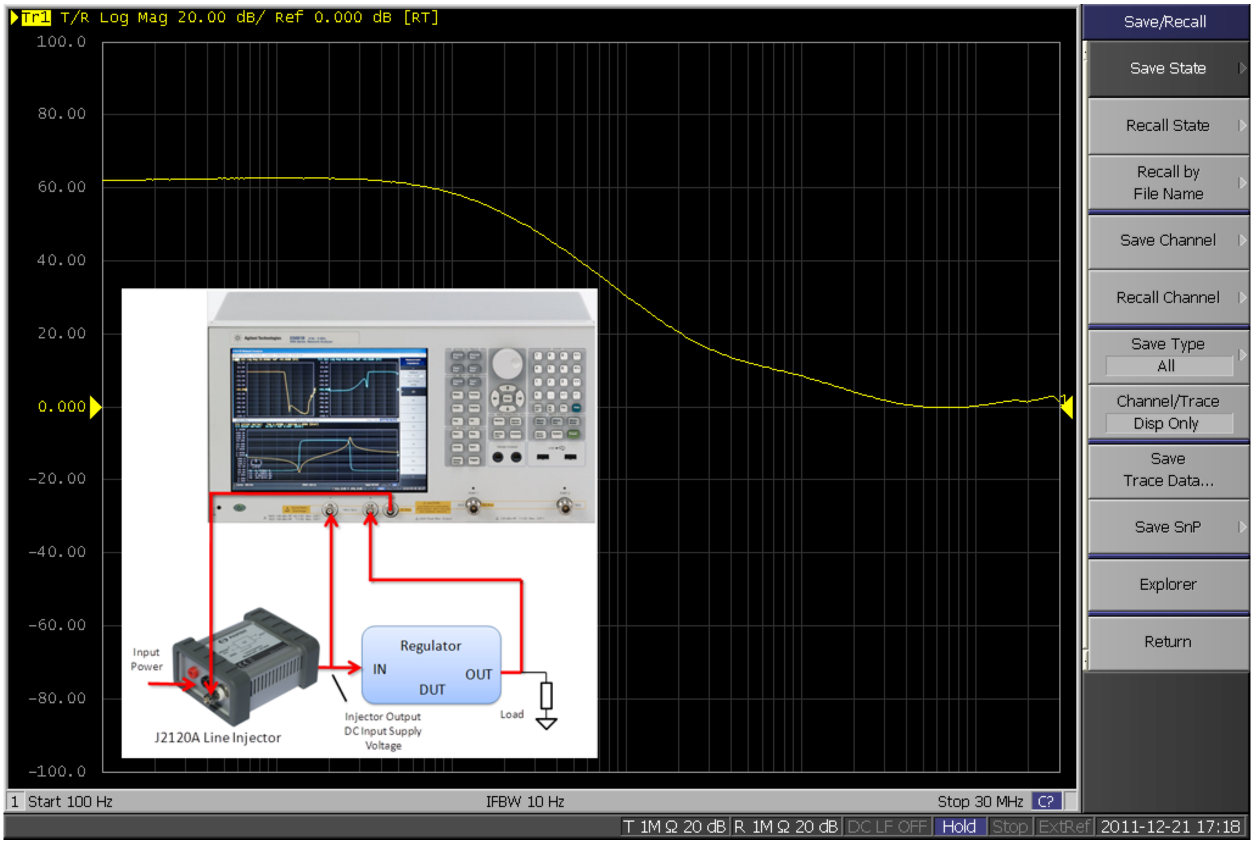
Output impedance is related to the transient response, though the transient response is assessed in the time domain, while the output impedance is assessed in the frequency domain. The output impedance is much less subject to interpretation, since there are fewer dependencies. There is no slew rate, sampling rate or time base dependencies to mask the true results.

The output impedance measurement is made using a J2111A current injector and the Agilent E5061B network analyzer to assess the output impedance from 5Hz to 30MHz. The figure below shows the output impedance of the LM317 in dBOhms from 100Hz to 30MHz.



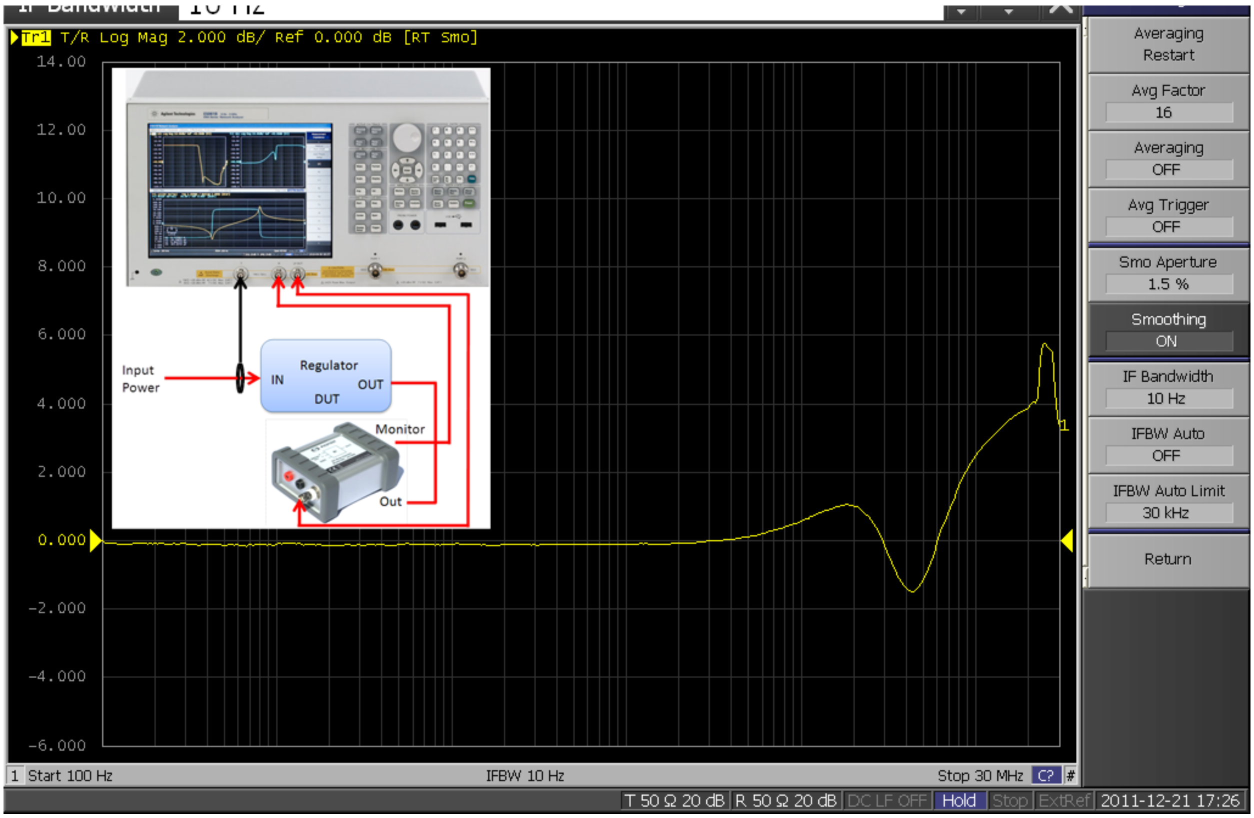
PSRR

One measurement that many engineers have trouble making is power supply rejection ratio, or PSRR, since there are few if any signal injectors made for this measurement. Some of the more common methods we have seen are to use an injection transformer or an audio amplifier. Neither of these methods is acceptable and will produce erroneous data. The injection transformer is a very sensitive device, which saturates at very low current, offers limited bandwidth and has the potential to become permanently biased, destroying a very expensive transformer and/or damaging the driving amplifier as a result of the transformer saturation. An audio amplifier eliminates the transformer saturation, but also offers very limited bandwidth. The following PSRR measurement was made using a Picotest J2120A Line Injector, which offers a usable bandwidth of 1Hz-40MHz. For comparison purposes, a measurement of the Texas Instrument TPS7A8001 High PSRR regulator is included.



Reverse Transfer

One parameter that is often overlooked and rarely even mentioned in relation to the voltage regulator is reverse transfer. Reverse transfer is the ratio of the input current to the output current. This is a significant parameter for several reasons. One is that it leads to the conducted emissions presented to the input bus, and more importantly, many systems include several regulators, which may be powered from the same input. The reverse transfer, in conjunction with the input source impedance, results in a voltage signal superimposed on the input voltage. This signal then travels, by way of this input signal, through to the other voltage regulators in the system, in much the same way as crosstalk.



Conclusions

We have seen that even older voltage regulators, like the LM317 can have a bandwidth of 5MHz and require a network analyzer measurement of more than 20 MHz Some newer regulators have bandwidths that are greater than 10MHz, requiring a measurement bandwidth of 30MHz or greater.

When a traditional closed loop stability measurement is not available, the output impedance measurement provides a better closed stability assessment than the step load response, since there are far fewer dependencies that influence the result, and eliminates the need for an expensive oscilloscope and active probe.

The Picotest J21xxA series injectors, in conjunction with the Agilent E5061B Network Analyzer provide the necessary fidelity and bandwidth to obtain the correct results even at the high bandwidths that occur without the inclusion of an output capacitor.

A comparison between the data acquired in these measurements and those presented in the LM317 datasheet reveals that the datasheet measurements have many shortcomings. Specifically, the load step response is slew rate limited and large signal rather than small signal. The output impedance and the PSRR are both limited to 1MHz in the data sheet, which is below the bandwidth of the regulator and, therefore, does not include the negative impacts of the poor phase margin.

The datasheet does not include any stability data, however, measurements of the stability results in very poor phase margin, which is then reflected in all of the closed loop performance characteristics, including step load response, output impedance, PSRR and reverse transfer. This poor performance will then further propagate through the power system as EMI and also as crosstalk and may be further impacted by amplitude and frequency modulation of a dynamic load step.

In order to assure the system performance, it is essential that these measurements be assessed with a fidelity that extends at least to, and preferably beyond, the bandwidth of the regulator. Since the system level filtering also influences the performance of the voltage regulator, many of these measurements should be made "in circuit". Many of the J21xxA series injectors can be used in conjunction with the Agilent E5061B to make these "in-circuit" measurements (step load, output impedance, reverse transfer and in some cases PSRR), non-invasively.

More information is available in technical white papers and application notes at Picotest.com, AEiSystems.com and omicron-lab.com.

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