

Signal Injection Transformers

Steven M. Sandler, Chief Engineer, AEi Systems
Charles E. Hymowitz, Managing Director, AEi Systems

An injection transformer is a special type of transformer that is connected between a network analyzer and a DC-DC converter or voltage regulator in order to both inject a perturbing signal into the control loop and to record the response of the loop over a wide frequency range. The purpose for using a transformer is to measure the phase-gain response of the control loop while minimally impacting the loop performance.

An example of a voltage regulator stability test setup is shown in Figure 1. The output of a network analyzer (Source), an oscillating signal of small amplitude and varying frequency, stimulates the voltage regulator's control loop across R1, via the transformer. R1 is generally referred to as the injection resistor. It effectively breaks the regulator's control loop allowing the two channels of the analyzer to compare and generate the magnitude and phase the loop, i.e. V_{out}/V_{in} . The circuit response is monitored on either side of R1 via the CH1 and CH2 connections, again, through the transformer. The undistorted transmission of these signals, their levels and the proper setup and connection of the circuit are paramount to a successful outcome.

There is not much written about injection transformers, which is easily verified via a quick internet search. Much of what is published discusses why an expensive transformer is not necessary. Much of what is written, even by manufacturers of the voltage regulators and other power ICs is remarkably incorrect.

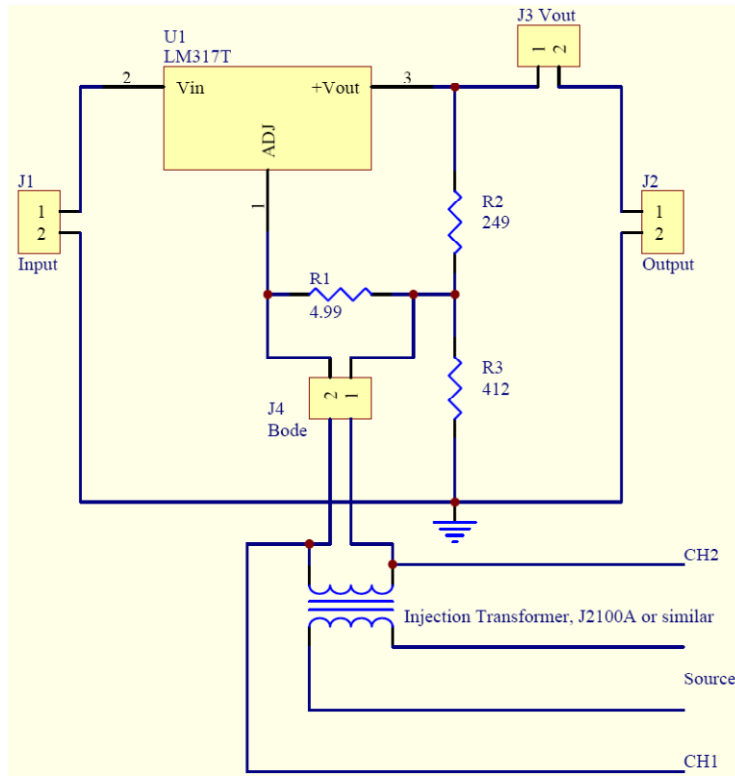
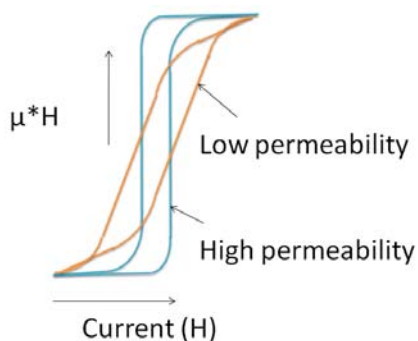


Figure 1: Example schematic showing the test setup connectivity for measuring the Bode response of a voltage regulator. The transformer connects to a network analyzer.

An incomplete understanding of signal injection transformers can easily result in incorrect test data and/or damaged equipment. In this article we'll take a look at what makes the signal injection transformer special, why an audio or video transformer is not a suitable alternative for most applications and why the injection transformer is not suitable for measuring input ripple rejection (PSRR) or other measurements that allow DC current to flow through the transformer.

Some simple transformer theory

The BH loop of a magnetic element relates to the transformer impedance. If the vertical axis is the product of permeability and current, which is also the integral of the applied Volts and seconds, then a vertical line is a very high impedance and a horizontal line is a short circuit. A very high permeability material is nearly vertical, while a cut, gapped or low permeability core is more diagonal, meaning lower impedance.



The three frequency ranges, low, mid and high

If a vertical line is a high impedance, then in the frequency domain, we mean high inductance. The lower -3dB point occurs at the frequency at which the impedance of the transformer is equal to the parallel resistance across the

transformer, or the injector termination resistance. For this reason, we need very high inductance to operate at very low frequency. It is also clear from this reasoning that the lower the injection resistance, the lower the inductance required for a given frequency of operation (Figure 2).

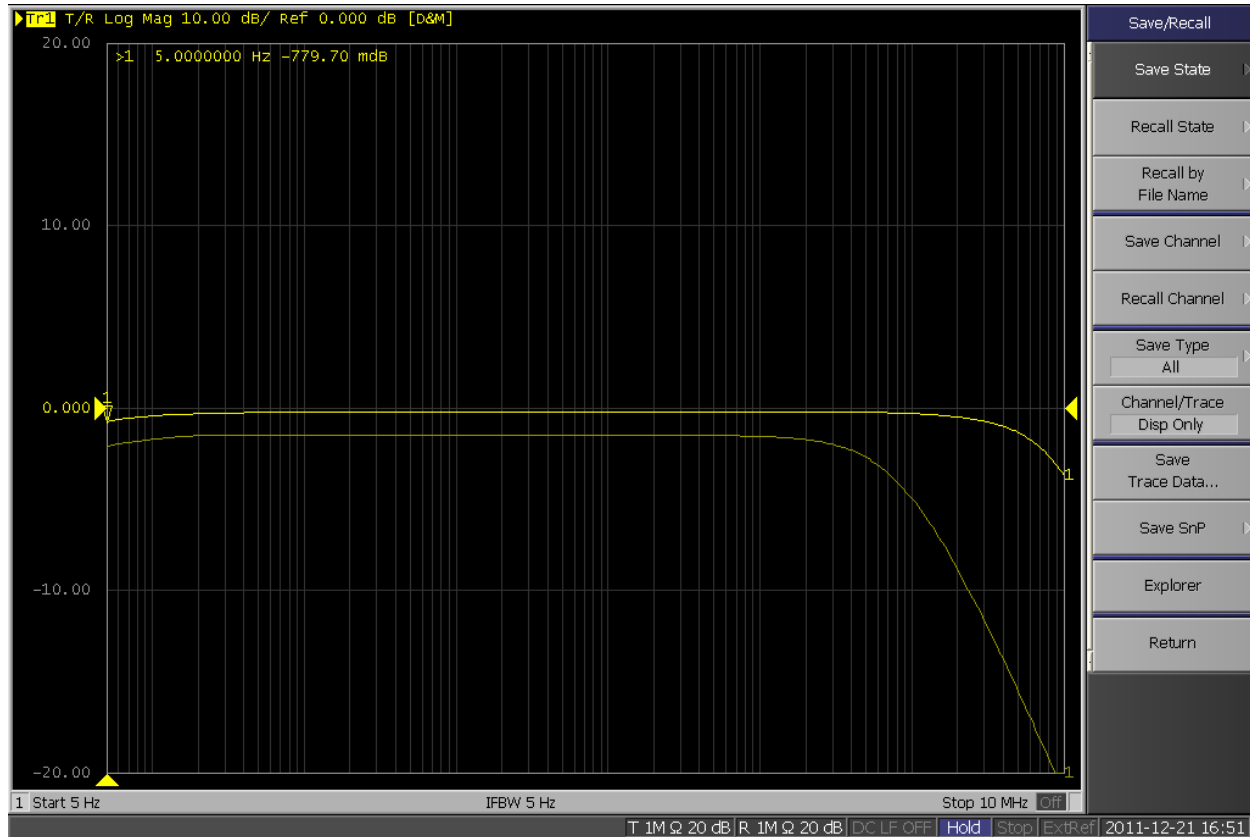


Figure 2: Injection transformer with 5 Ohm (thin trace) and 50 Ohm (thick trace) terminations showing that the terminating resistor is an integral part of determining the transformer frequency response. (Measured using the Agilent E5061B Network Analyzer).

The effect of signal amplitude on the frequency response

If the signal gets large enough, the BH Loop will enter its non-linear region, reducing permeability and impacting frequency response (Figure 3). This begins where the BH loop starts to curve. This is much more abrupt in a high permeability material than in a low permeability material.

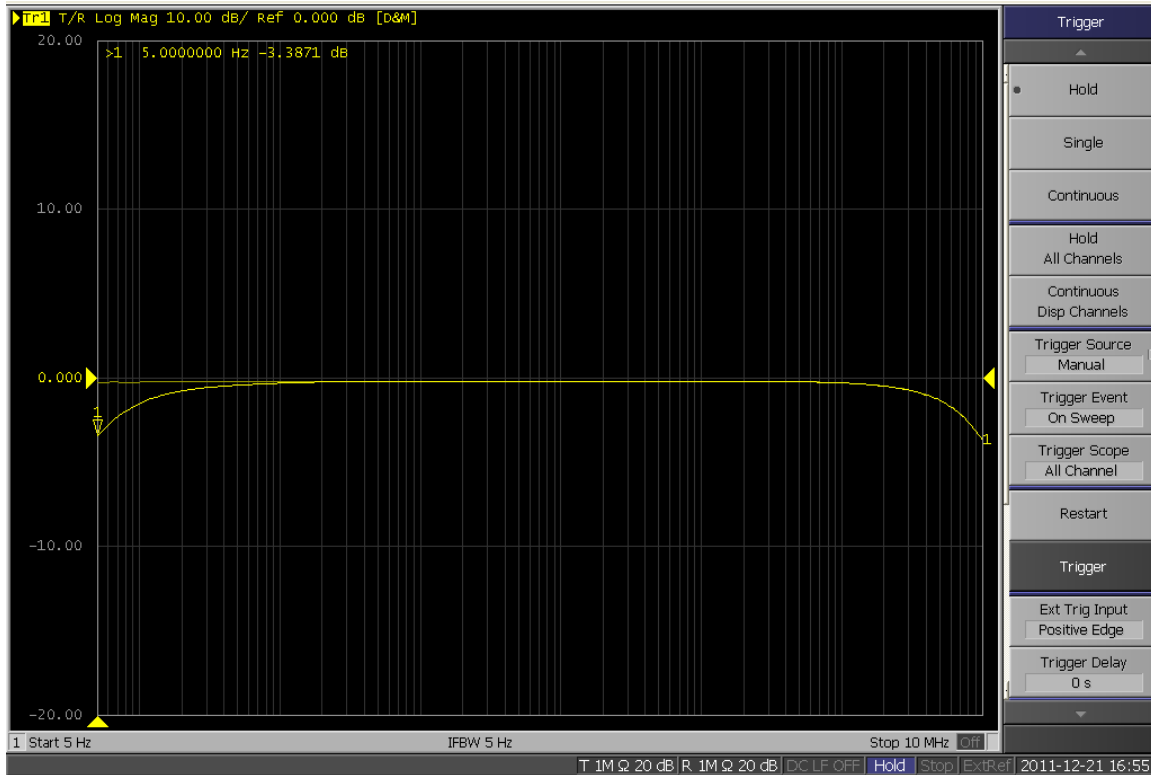


Figure 3: Injection transformer with -10dBm (thin trace) and +5dBm (thick trace) inputs showing the impact of the amplitude reaching the curve in the BH Loop.

Why this isn't just about frequency response

Large signal and DC currents reduce the apparent inductance of the transformer, primarily increasing the low frequency 3 dB point. Looking at the waveforms on an oscilloscope reveals a great deal of additional insight (Figure 4).

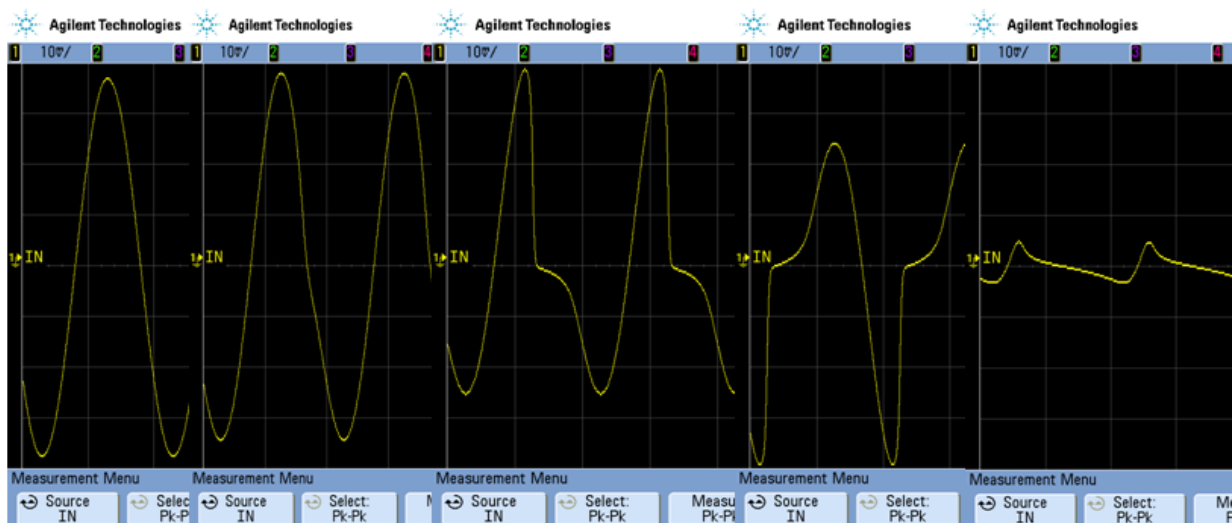


Figure 4: Transformer signal, 100Hz Sine wave, with 0, 5mA, 7.5mA, -7.5mA and 15mA DC bias current (Left to Right). The scaling is constant for all pictures.

The large harmonic content of the waveform can easily overload the A/D converter at the input of the analyzer, resulting in incorrect answers. The +7.5mA and -7.5mA bias conditions show the vertical symmetry of the transformer saturation. In one case saturating at the top of the BH loop and in the other case saturating at the bottom of the BH loop.

The apparent impedance can also be seen using the network analyzer to measure the primary impedance with and without DC bias current. The following measurement shows a 40dB change in apparent inductance in response to a 15mA DC bias current.

The application of DC bias current to the transformer can also result in damaged equipment (Figure 6). Prolonged or very high DC currents can lead to permanent magnetization of the core, yielding the transformer permanently biased and unusable. As seen in the above measurements, the saturated transformer presents a primary impedance which is very close to the DCR of the transformer. When connected to a pulse generator, the pulse generator is protected by an internal, 50 Ohm source resistor. When connected to a high power amplifier, as for a ripple rejection measurement, there is no such protection. The saturated core presents a short circuit across the amplifier, limited only by the DC or the transformer and the current limit protection within the amplifier.

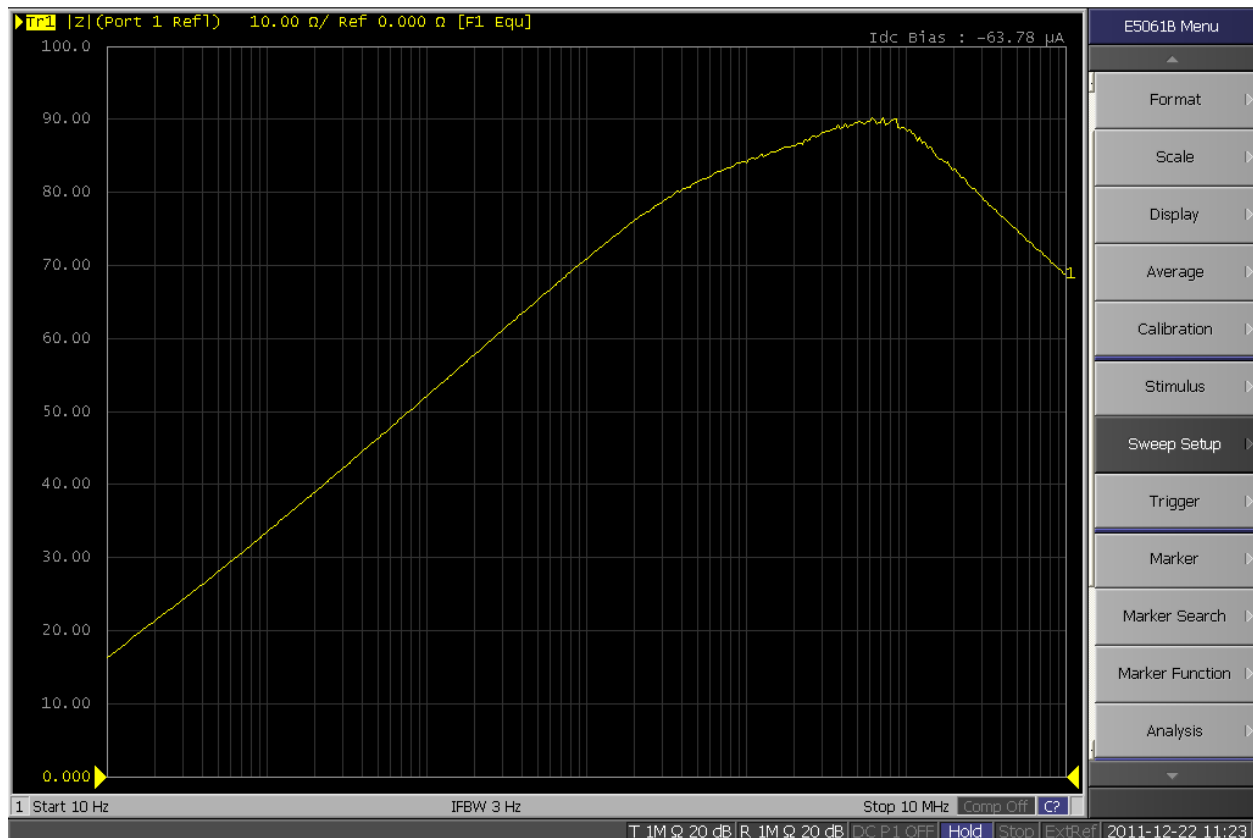


Figure 5: Transformer primary inductance with 0mA DC bias current.

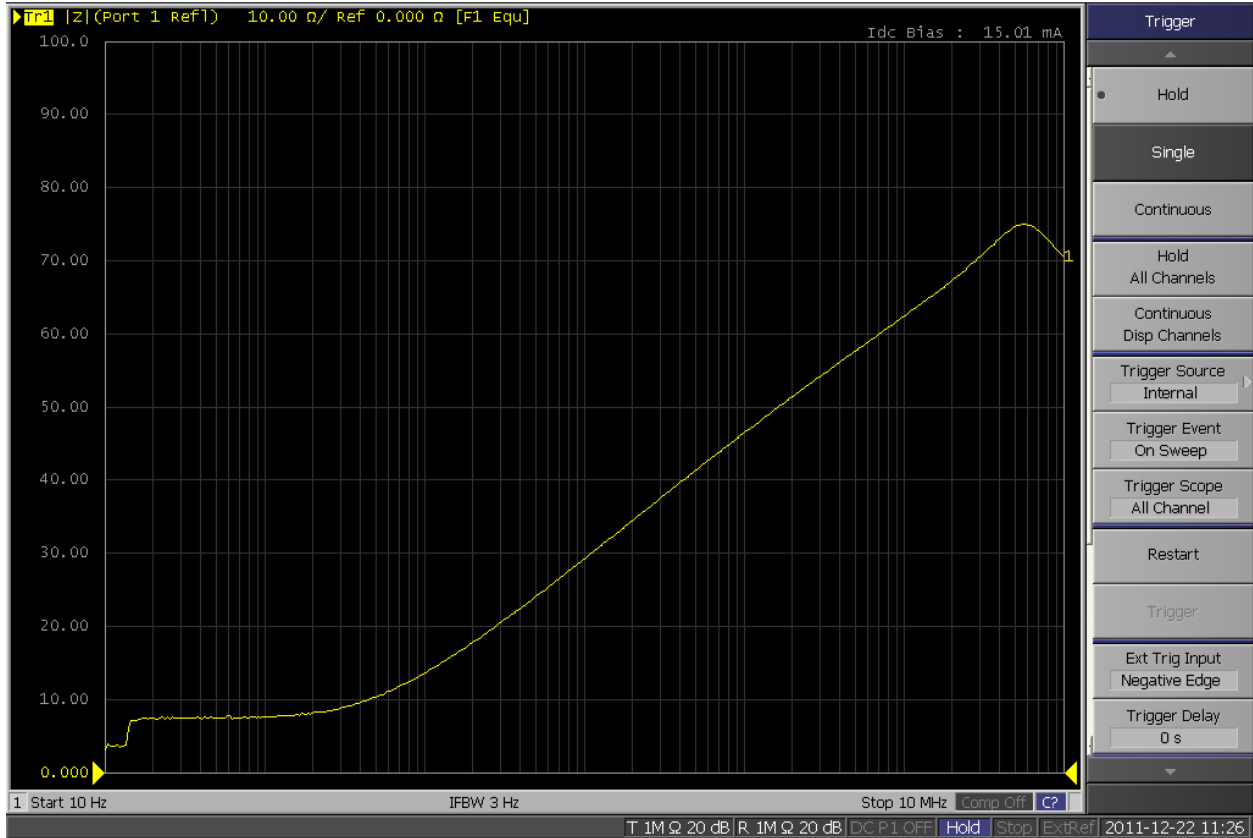


Figure 6: Transformer primary inductance with 15mA DC bias current.

Be wary of application notes

One common myth is that the transformer is outside of the stability measurement. Since the signals are measured on both sides of the transformer, the transformer itself does not significantly contribute to the measurement. In application note 1889 from National Semiconductor they recommend the use of a 60Hz AC power transformer. The use of such a transformer seems very suspect and the results are almost guaranteed to be incorrect.

Here is how the manufacturers sometimes train us to get wrong answers. In this case, a 60HZ power transformer is recommended for the injection transformer. The application note then suggests twisting the leads to minimize the inductance. Did they forget how high the leakage of such a transformer is? The application note teaches us that the transformer is OUTSIDE the measurement. Again, this is untrue. The measurements shown in Figure 7 are made using an LM317T voltage regulator as shown in Figure 1. One measurement (thick trace) is made using a high quality audio transformer, which offers much better performance than a 60Hz AC transformer. The other measurement (thin trace) is made using the Picotest J2100A injection transformer. Note the significant difference in the results, even at lower frequencies.

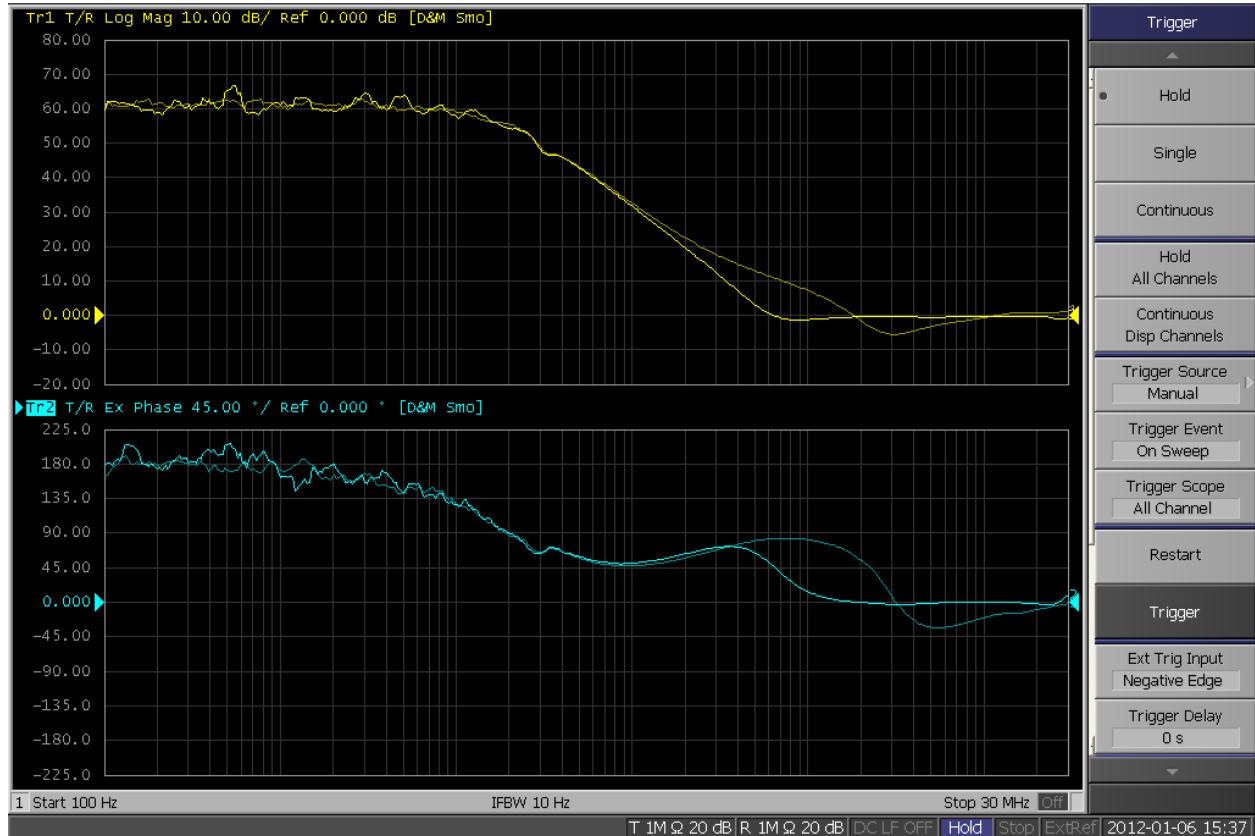


Figure 7: Comparing the correct J2100A injection transformer measurement (thin trace) with a high quality audio transformer measurement (thick trace) for the test setup in Figure 1, LM317 25mA 3.3Vout 5.8Vin no output capacitor.

Common power applications require accurate measurements from 1Hz (as in PFC circuits) to several MHz or more for the typical LDO. The transformer is an integral part of the measurement, and while less expensive transformers are available, they will often produce incorrect results.

To learn more about Picotest, or for help in selecting the appropriate signal injector, please visit www.picotest.com/injectors.

References

1. How to Measure the Loop Transfer Function of Power Supplies, National Semiconductor Application Note 1889, Frederik Dostal, October 14, 2008

About the Authors

Steve Sandler is the founder and chief engineer of AEi Systems, where he leads development of high-fidelity simulation models for all types of simulators as well as the design and analysis of both power and RF systems. Sandler has over 30 years of experience in engineering and is a recognized author, educator and entrepreneur in the areas of power, RF and instrumentation.



Charles Hymowitz is the managing director of AEi Systems. Hymowitz guides all aspects of the company's operations including technical services, product quality, sales and a staff of over 30 in-house and consulting engineers. As a technologist, marketer and business executive, Hymowitz has over 25 years of experience in the engineering services and EDA software markets.