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Voltage References Behaving Badly: Output Caps Are Key Source Of Poor Stability

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The purpose of a voltage reference is to provide a very precise dc voltage level, which in turn will be used by other circuitry within a variety of applications. In some cases it could be for monitoring comparisons, while in other cases it might provide the reference for a voltage regulator or an ADC. Each application has specific needs, but in general the goal is to develop a very precise, low-noise voltage source. By its very nature, a voltage reference is quite susceptible to control loop issues. This is due in part to the low dc output resistance of the reference and its low power circuitry, which generally results in a relatively high effective output inductance. Typically, the lower the operating current the higher the inductance.

Furthermore, the low dc output resistance results in this output inductor being a high Q inductor that is very sensitive to external capacitance. Despite this susceptibility, many voltage reference manufacturers recommend the use of an output capacitor. The following measurements highlight a few of the issues resulting from the addition of the output capacitor to the voltage reference circuit or, in some cases, the selection of an inappropriate output capacitor value. In each example, the capacitor is the source of poor control loop stability, which can manifest itself as a noise problem in the application, if not as an outright oscillation.

The measurements presented in this article were obtained using a variety of instruments and each of the specific models is identified in the descriptions of the measurements. However, in each measurement, the Picotest one-port, transmission line probe was used to probe the output of the voltage reference. The controlled 50-Ω impedance and variable lead pitch of this probe enable higher bandwidth, lower noise measurements than would typically be possible with other probe types.[1] Fig. 1 shows an example of how the probe contacts a voltage reference device under test. In addition, a Picotest P2130 dc block was used to ac couple the transmission line probe in all measurements.

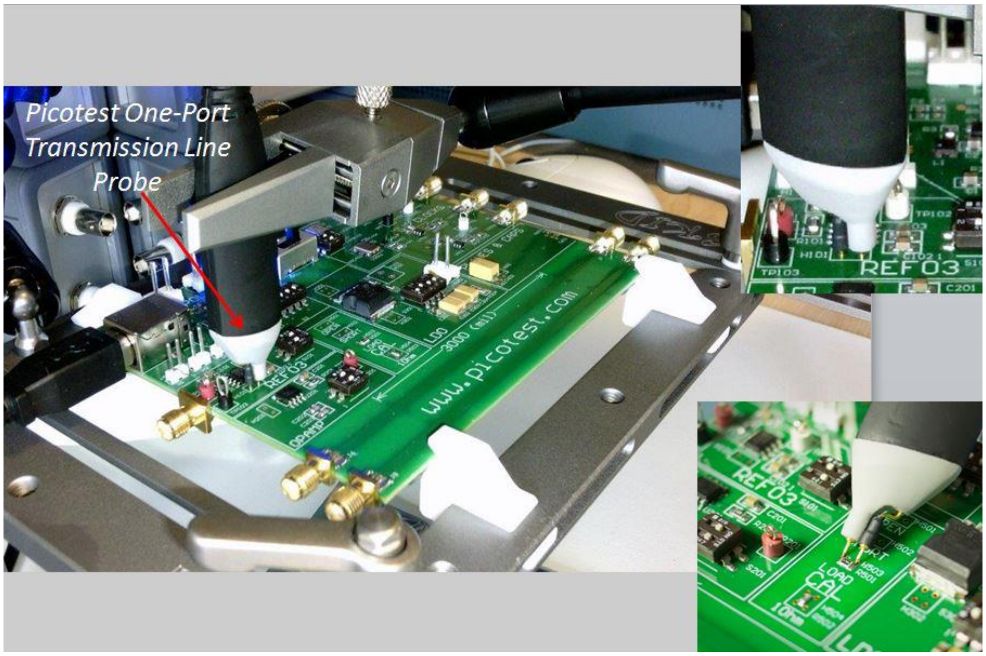
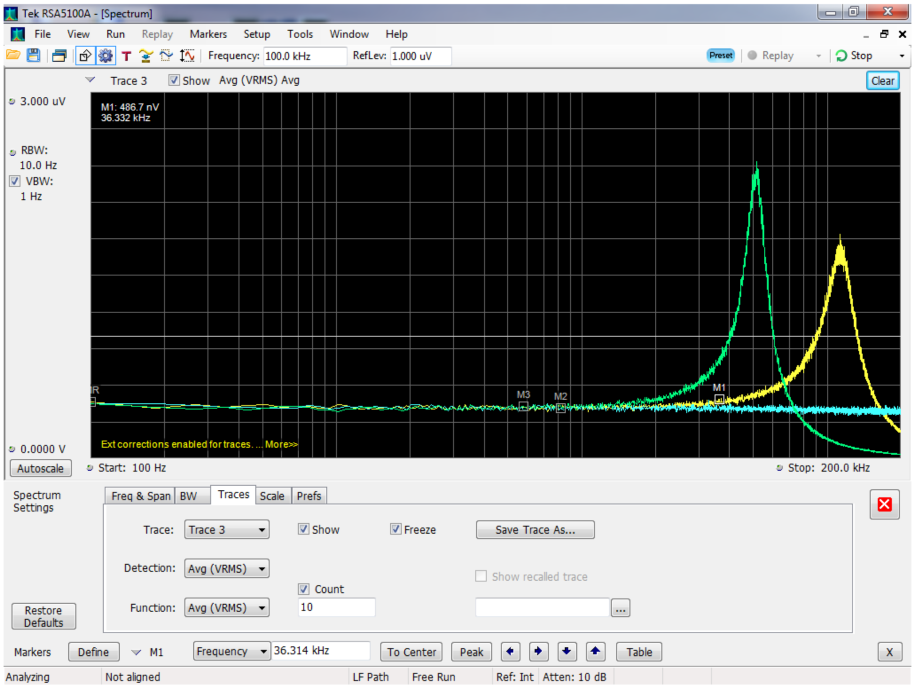


Fig 1. In the main photo seen here, Picotest's one-port transmission-line probe connects to the REF03 voltage reference on one of Picotest's test instrument evaluation boards. The inset photo in the upper righthand corner shows a closeup of the probe as it connects to the board. The inset photo in the lower righthand corner shows a similar probe attached to a calibrator. The angle in this last image offers a better view of the probe tip.

Peaks In Noise Density

In Fig. 2, the noise density of an LT1009 shunt voltage reference is measured on a Tektronix RSA5100A real-time spectrum analyzer. The measurement is taken with a 0.1-µF capacitor installed on the output (yellow trace) and also with a 0.47-µF capacitor installed (green trace). The peaks in these measurements are an indication of the very poor control loop stability that results from the inclusion of the output capacitor.



Tek RSA5100A - [Spectrum]

Frequency: 100.0 kHz
RefLev: 1.000 uV

Trace 3 ☑ Show Avg (VRMS) Avg

M1: 486.7 nV
36.332 kHz

RBW: 10.0 Hz
☑ VBW: 1 Hz

Ext corrections enabled for traces. ... More>>

Start: 100 Hz
Stop: 200.0 kHz

Trace: Trace 3
☑ Show
☑ Freeze
Detection: Avg (VRMS)
Function: Avg (VRMS)
☑ Count 10
☐ Show recalled trace

Markers M1 Frequency 36.314 kHz

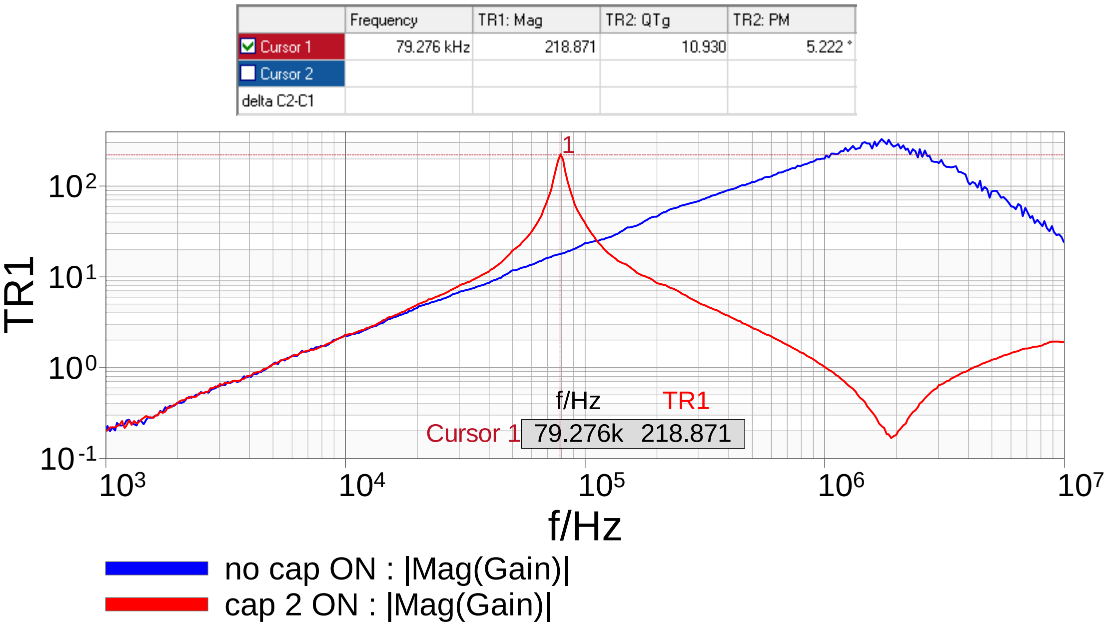
Analyzing | Not aligned | LF Path | Free Run | Ref: Int | Atten: 10 dB

Fig. 2. This noise density measurement shows the impact of a 0.1-µF (yellow) or 0.47- µF (green) output capacitor on an LT1009 shunt voltage reference operating with a 1-mA bias current. The noise density peaks are an indication of the very poor control loop stability resulting from the inclusion of the output capacitor.

Peaks In Output Impedance

Fig. 3 presents two measurements of output impedance for a REF03 series voltage reference. The measurements, which were taken on a Bode 100 vector network analyzer (VNA) from Omicron Lab, were taken with a 0.1-µF capacitor installed on the reference's output (red trace) and with no capacitor installed on the reference's output (blue trace).

The effective output inductance of the reference can be seen in the blue trace as a 0.6-dB/octave increasing impedance slope. A datapoint at 20 Ω and 80 kHz indicates the effective inductance is nearly 40 µH. This 40-µH inductance resonates with the 0.1-µF capacitor at 80 kHz, evident from the high Q impedance peak in the red curve.



	Frequency	TR1: Mag	TR2: QTg	TR2: PM
☑ Cursor 1	79.276 kHz	218.871	10.930	5.222 °
☐ Cursor 2				
delta C2-C1				

Fig. 3. Output impedance of a REF03 series voltage reference with a 0.1-µF ceramic capacitor on the output (red trace) and with no output capacitor (blue trace). The effective inductance can be seen in the blue trace as a 0.6-dB/octave increasing impedance slope. A datapoint at 20 Ω and 80 kHz indicates the effective inductance is nearly 40 µH. This 40-µH inductance resonates with the 0.1-µF capacitor at 80 kHz, evident from the high Q impedance peak in the red curve.

The stability of the control loop within the voltage reference can be extracted directly, using the noninvasive stability measurement (NISM) technique, which indicates approximately a 5.2° phase margin in the case where the output cap is installed. Surprisingly, this capacitor is "highly recommended" by the manufacturer. Yet, with the peak in the output impedance produced by the 0.1-µF capacitor at 80 kHz, a 100-nA rms noise current would result in an output noise signal exceeding the specified limits for the entire 10-Hz-to-10-kHz bandwidth at a single frequency.

A simple way to correct for this low phase margin is to reduce the Q of the circuit below unity. Given that the effective inductance is 40 µH, a resistance should be inserted between the capacitor and the reference or in series with the capacitor (ESR) or both. The combined resistance should be greater than or equal to

$$\sqrt{\frac{L}{C}}$$

or, for this reference, the resistance should be greater than or equal to

$$\frac{0.0063\Omega}{\sqrt{C}}\ .$$

Note that all references are different and it is important to determine the inductance of the reference you are using. Hint: A good rule of thumb here is that lower inductance is better.

Degraded PSRR

In Fig. 4, the Bode 100 is used to measure the PSRR of the REF03 voltage reference with the recommended 0.1-µF output capacitor installed (red trace) and with no capacitor installed (blue trace). In addition to the VNA, a Picotest J2111 current injector is used as it permits a non-invasive measurement of PSRR.[2] In this measurement, note the degradation in PSRR around 80 kHz when the capacitor is installed.

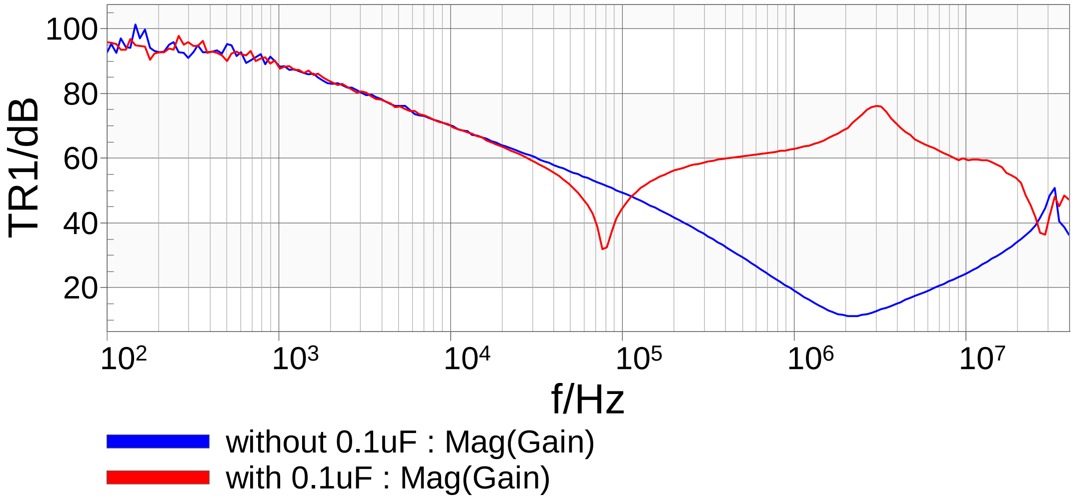
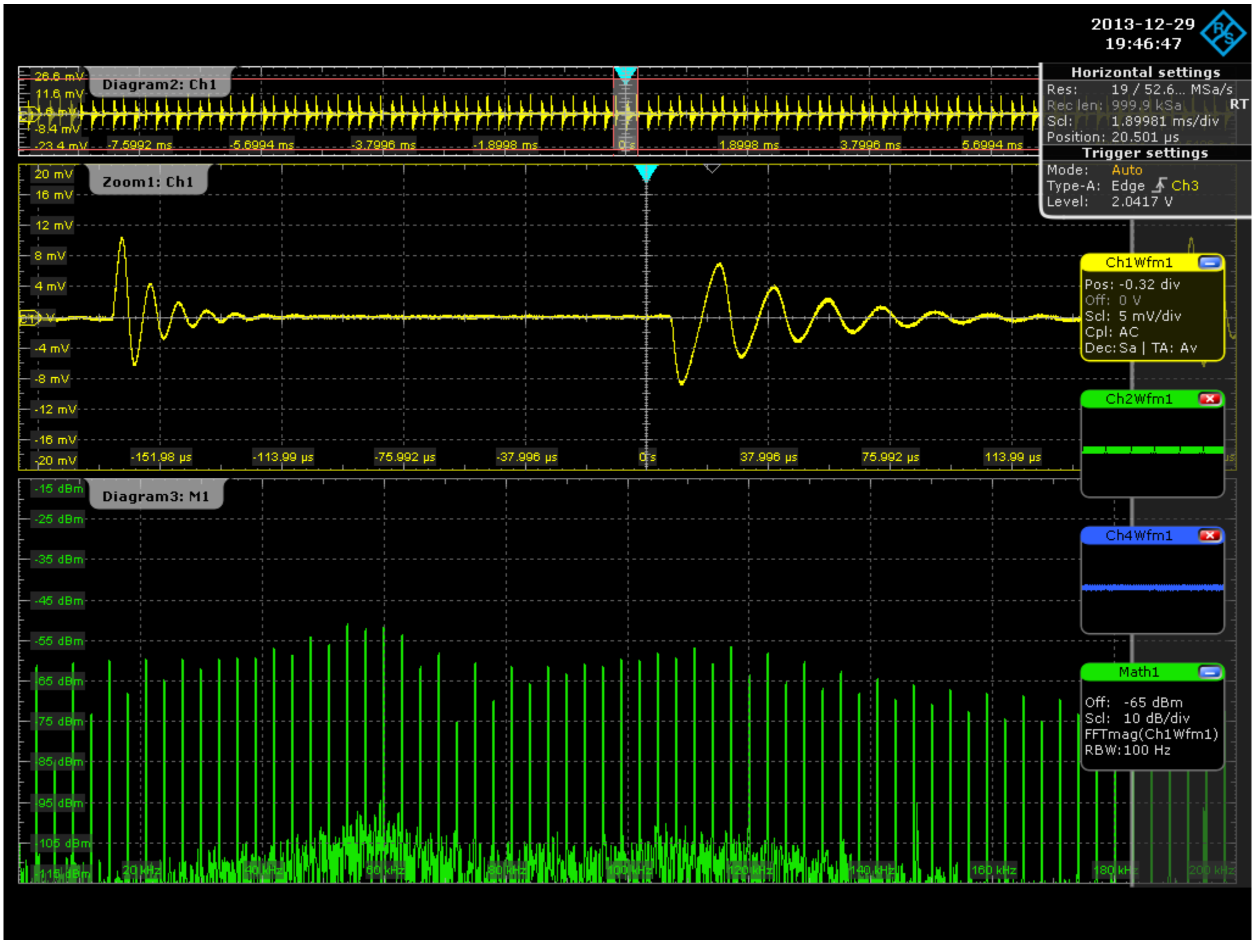


Fig. 4. This is a PSRR measurement for the same REF03 voltage reference used above and again the reference is measured with (red trace) and without (blue trace) the recommended 0.1-µF capacitor. Note the greatly degraded PSRR at about 80 kHz with the output capacitor installed.

Ringing In The Load Step Response

A small current step applied to a voltage reference with an output capacitor will produce ringing as a result of the peak in the reference's output impedance as demonstrated in Fig. 5. The two measurements shown here were taken using a Rohde & Schwarz RTO1044 digital oscilloscope with spectrum analysis mode. As with the previous measurement, the Picotest J2111 current injector is used here, in this case to generate a high-speed load step.[2]


2013-12-29
19:46:47

Horizontal settings
Res: 19 / 52.6... MSa/s
Rec len: 999.9 kSa
Scl: 1.89981 ms/div
Position: 20.501 µs

Trigger settings
Mode: Auto
Type-A: Edge Ch3
Level: 2.0417 V

Ch1Wfm1
Pos: -0.32 div
Off: 0 V
Scl: 5 mV/div
Cpl: AC
Dec: Sa | TA: Av

Ch2Wfm1

Ch4Wfm1

Math1
Off: -65 dBm
Scl: 10 dB/div
FFTmag(Ch1Wfm1)
RBW: 100 Hz

Fig. 5. A small current step applied to a voltage reference with an output capacitor will produce ringing as a result of the peak in the reference's output impedance. On channel 1, this ringing is measured at two different current levels with higher amplitude peaks seen in the measurement on the left and lower amplitude peaks produced in the measurement on the right.

Note the significant difference in the ringing responses on Channel 1 at the two load current levels, indicating the extreme sensitivity of the control loop stability to load current. Also note the spectral response of the reference ringing is a harmonic comb, with noise at many frequencies that can be propagated throughout a system. Interestingly, the "tines" of the comb are spaced at the step-load repetition frequency, so counterintuitively, the lower the repetition rate the more frequencies are generated over a given measurement bandwidth.

Output Resistance As A Function Of Output Voltage

Some voltage reference datasheets include an output impedance graph showing the impedance for various output capacitors. Fig. 5 is from the National (TI) datasheet for the LM4040 voltage reference. While the capacitor ESR is not stated it appears to be approximately 500 mΩ.

The low-frequency output resistance is relatively high in this device, and is shown to be significantly dependent on the programmed output voltage. In general, the higher the reference voltage the higher the inductance and resistance. Again, each reference is different and so should be considered carefully.

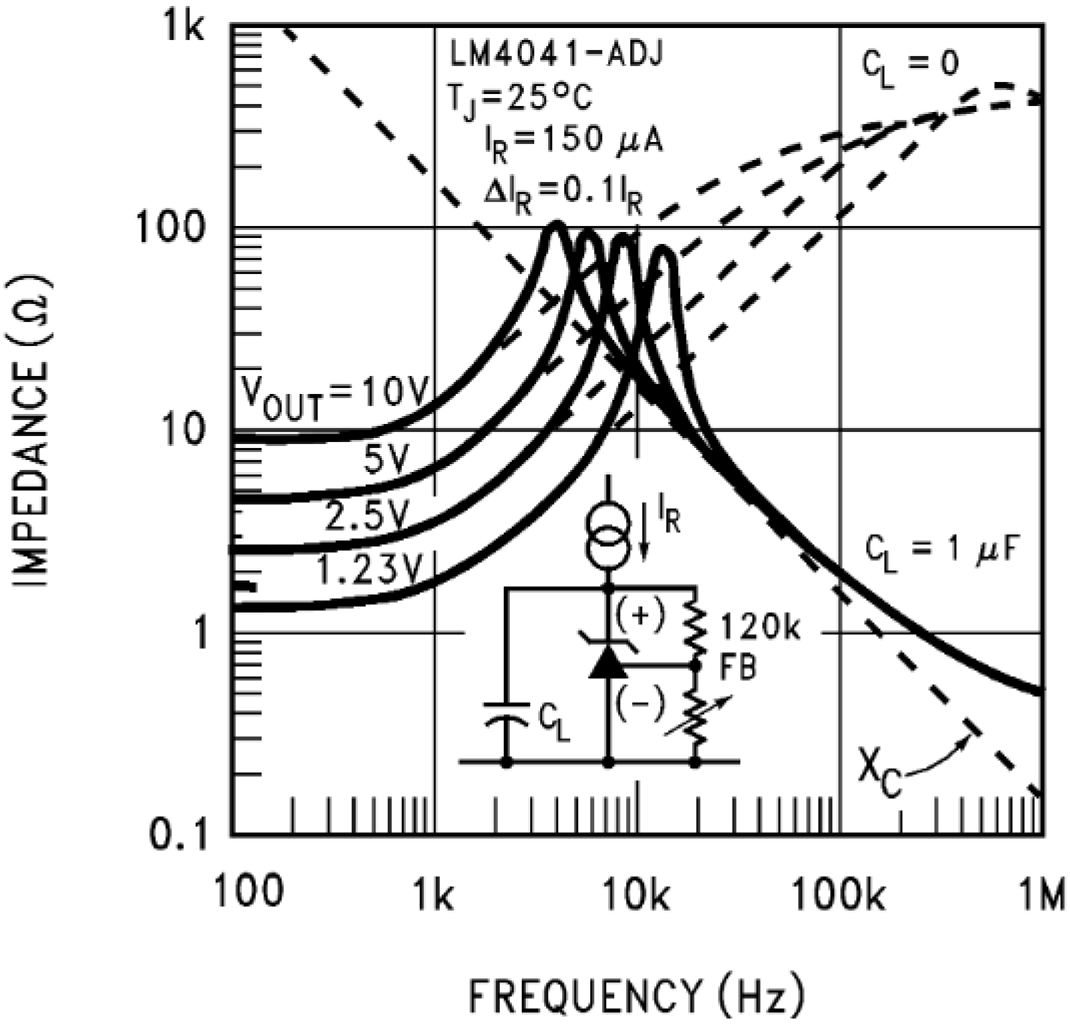


Fig. 5. The specified output impedance for an LM4040 shunt voltage reference from Texas Instruments.

Note that measuring the output impedance of a voltage reference can be quite difficult. The REF03 output impedance measurement shown previously indicates a low-frequency resistance of less than 200 mΩ and a peak impedance of 218 Ω. This low impedance is below the recommended minimum for a 1-port VNA impedance measurement[3], while the 218 Ω is greater than the recommended maximum for the 2-port VNA impedance method.[4] Special techniques are required to accurately measure this output impedance over a wide frequency range. Perhaps this will be the basis for a future article on the subject of measuring the impedance of a voltage reference.

References

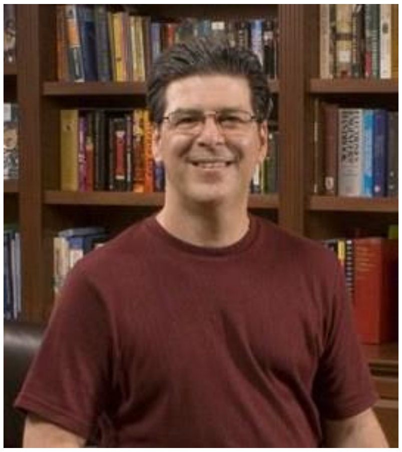
1. "Transmission Line Probes Enable Higher Bandwidth, Lower Noise Measurements For PDNs," November 2014 issue of How2Power Today.

2. "Troubleshooting Distributed Power Systems (Part 5): Using Current Injectors," October 2013 issue of How2Power Today.

3. "Troubleshooting Distributed Power Systems (Part 3): Measuring Impedance Using VNAs (1 Port)," August 2013 issue of How2Power Today.

4. "Troubleshooting Distributed Power Systems (Part 4): Measuring Impedance using VNAs (2 Port)," September 2013 issue of How2Power Today.

About The Author



Steven Sandler is the managing director of Picotest, a company specializing in precision test and measurement equipment. Sandler is also 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. His latest book, "Power Integrity: Measuring, Optimizing and Troubleshooting Power Related Parameters in Electronics Systems," was recently published by McGraw-Hill Education.

For further reading on voltage references, see the How2Power Design Guide and do a keyword search for "voltage reference."