how it works

FAILING TO VERIFY AC-VOLTMETER ACCURACY BEFORE CONDUCTING RMS-NOISE MEASUREMENTS MAY CAUSE HIGHLY MISLEADING RESULTS.

Understanding and selecting rms voltmeters

Jim Williams and Todd Owen, Linear Technology Corp

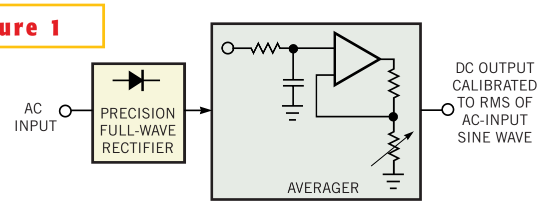
CHOOSING THE RIGHT ac voltmeter is crucial for meaningful noise measurements of low-noise, low-dropout regulators (see "Exacting noise test ensures low-noise performance of low-dropout regulators" on pg 149 in this issue). The ac voltmeter not only must have adequate bandwidth, but also must faithfully respond to the rms value of the measured noise. Similarly, the voltmeter must have the crest-factor capability to capture the noise signal's dynamic range. Crest factor is the ratio of the peak-to-rms value of the input signal. Unfortunately, most ac voltmeters, including digital voltmeters with ac ranges and instruments with "true- rms" ac scales, cannot be accurate under these measurement conditions. Thus, selecting an appropriate instrument requires care. The selection process begins with a basic understanding of ac-voltmeter types.

The basic ac-voltmeter types are rectify-and-average, analog-computing, and thermal. The thermal approach is the only one that is inherently accurate for all input waveshapes. This feature is relevant to determining the amplitude of rms noise. A fourth method for measuring the rms value of an input waveform—one that is uncommon for making noise measurements and therefore not part of this discussion—uses sampling techniques. This sampling technique involves taking a large number of samples of the input waveform and computing the rms value using digital techniques. Achievable accuracy for any given bandwidth varies with sampling rate and computational capability.

The rectify-and-average scheme applies the ac input to a precision rectifier (**Figure 1**). The rectifier output feeds a simple gain-scaled RC-averaging circuit to provide the output. In practice, you set the gain so that the dc output equals the rms value of a sine-wave input. If the input remains a pure sine wave, accuracy can be good. However, nonsinusoidal inputs cause large errors. This type of voltmeter is accurate only for sine-wave inputs with errors increasing as the input departs from sinusoidal.

Figure 2 shows a more sophisticated ac-voltmeter method. In this case, an analog computational loop (ideally) continuously computes the instantaneous value. The dc output follows the equation in the **figure**, resulting in much better accuracy than the rectify-and-average method when the input waveshape varies. Almost all commercial implementations of this approach use logarithmically based analog-computing techniques. Unfortunately, dynamic lim-

Figure 1



A rectify-and-average-based ac/dc converter works well only for sinusoidal inputs.

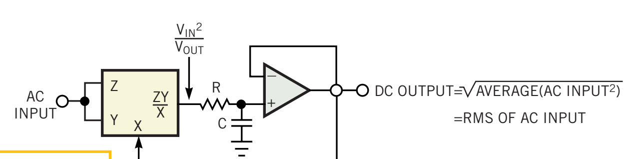


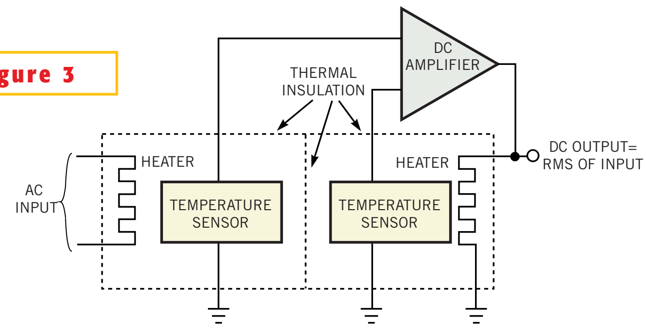
Figure 2

In an analog-computer-based, usually logarithmic, ac/dc converter, the loop continuously computes the input's rms value.

itations in the ZY/X block dictate bandwidth restrictions. These circuits typically develop significant errors beyond 20 to 200 kHz.

The thermally based ac voltmeter is inherently insensitive to input waveshape, making it suitable for measuring the amplitude of rms noise. Additionally, thermally based meters can achieve high accuracy at bandwidths exceeding 100 MHz. **Figure 3** shows the classic thermal scheme. (See **references 1** and **2** for more background on thermal ac-to-dc conversion.) This thermal converter comprises matched heater-temperature sensor pairs and an amplifier. The ac input drives a heater, warming it. The temperature sensor associated with this heater responds by biasing the amplifier. The amplifier closes its feedback loop by driving the output heater to warm its associated temperature sensor. When the loop closes, the heaters are at the same temperature. As a result of this "force-balance" action, the dc output equals the input heater's rms heating value, which is the fundamental definition of rms. Changes in waveshape have no effect because the scheme effectively downconverts any waveshape into heat. This "first-principles" nature of operation makes thermally based ac voltmeters ideal for quantitative rms-noise measurement. (The fundamental definition of an rms value is "the equivalent heating in a load.")

Figure 3



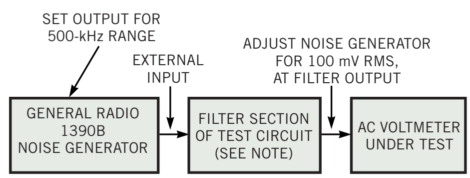
A thermally based ac/dc converter, which has extraordinarily low error, converts the ac input to heat and determines the dc output value necessary to produce identical heating.

NOISE-DRIVEN AC VOLTMETERS

The wide performance variation of these three conversion methods, even within a method, mandates caution in selecting an ac voltmeter. Comparing ac voltmeters intended for use in rms-noise measurements is illuminating. **Figure 4** shows a simple evaluation arrangement. The noise generator drives a filter circuit, which produces a suitably bandpass-filtered input at the voltmeter under test. (You can find a schematic for the filter circuit in "Exacting noise test ensures low-noise performance of low-dropout regulators," pg 150.) In this application, you attach the noise generator, instead of a regulator under test, to the filter input. (For more information on noise generators, see **references 3** and **4**.)

Table 1 shows noise-test results for 20 voltmeters. Four of the voltmeters are thermal types; the remainder use logarithmic analog computing or rectify-and-average ac-to-dc conversion. The four thermal types agreed well within 1%. Three of the thermal types were within 0.2%. The fourth (the HP3400A), a metered instrument, is readable only to 1%. The other 16 voltmeters showed maximum errors of 48% relative to the thermal group. The errors cause lower readings than are warranted. In other words, a poorly chosen voltmeter gives unfairly optimistic readings.

The lesson here is clear: It is essential to verify ac-voltmeter accuracy before proceeding with rms-noise measurements. Failure to do so may cause highly misleading results.



NOTE: FOR FILTER SCHEMATIC, SEE **FIGURE 2** OF "EXACTING NOISE TEST ENSURES LOW-NOISE PERFORMANCE OF LOW-DROPOUT REGULATORS" ON PG 150 IN THIS ISSUE.

Figure 4 The setup for evaluating ac voltmeters includes a noise generator and a filter.

BUILD A THERMAL-VOLTMETER CIRCUIT

You may want to construct, rather than purchase, a thermal voltmeter. **Figure 5**'s circuit is applicable to noise measurement. As in **Figure 4**'s block diagram, the input to this circuit also comes from the previously mentioned filter circuit in "Exacting noise test ensures low-noise performance of low-dropout

TABLE 1—VOLTMETER COMPARISONS

Voltmeter	Reading (mV)	Error (%)	AC/DC-conversion method
HP3403C	100	0	Thermal
HP3400A	100	0	Thermal
Fluke 8920A	100	0	Thermal
Figure 5's circuit	100	0	Thermal
Bench DVM	84	-16	Log
Bench DVM	85	-15	Rectify-average
Bench DVM	84	-16	Rectify-average
Fluke 8800A	90	-10	Rectify-average
HP3455	100	0	Log
HP334	92	-8	Rectify-average
Handheld DVM	52	-48	Rectify-average
HP3478	100	0	Log
Inexpensive handheld DVM	56	-44	Rectify-average
HP403B	93	-7	Rectify-average
HP3468B	93	-7	Log
Bench DVM	80	-20	Rectify-average
Bench DVM	72	-28	Rectify-average
Bench DVM	62	-38	Rectify-average
Fluke 87	95	-5	Log
HP34401A	93	-7	Log

regulators," pg 150. IC_1's output biases IC_2, which provides additional ac gain. The LT1088-based rms/dc converter comprises matched pairs of heaters and diodes and a control amplifier. IC_2 drives R_1, producing heat, which lowers D_1's voltage. Differentially connected IC_3 responds by driving R_2 via Q_3 to heat D_2, closing a loop around the amplifier. Because the diodes and heater resistors match, IC_3's dc output is related to the rms value of the input regardless of input frequency or waveshape. In practice, residual LT1088 mismatches necessitate a gain trim, which you can implement using IC_4. IC_4's output is the circuit output.

Start-up or input overdrive can cause IC_2 to deliver excessive current to the LT1088 with resultant damage. Comparators IC_{5A} and IC_{5B} prevent this damage. Overdrive forces D_1's voltage to an abnormally low potential. IC_{5A} triggers low under these conditions, pulling IC_{5B}'s negative input low. This action causes IC_{5B}'s output to go high, which puts IC_2 into shutdown and terminates the overload. After a time that the RC network at IC_{5B}'s input determines, the circuit enables IC_2. If the overload condition still exists, the loop almost immediately again shuts down IC_2 . This oscillatory action continues, protecting the LT1088 until the removal of the overload condition.

To trim this circuit, connect the input to a 10-mV rms, 100-kHz signal. Set the 500Ω zero-trim potentiometer for a dc output of exactly 100 mV. Next, apply a 100-kHz, 100-mV rms input and adjust the 10-kΩ full-scale-trim potentiometer for a dc output of 1V. Repeat this sequence until the adjustments do not interact. Two passes should be sufficient.□

References

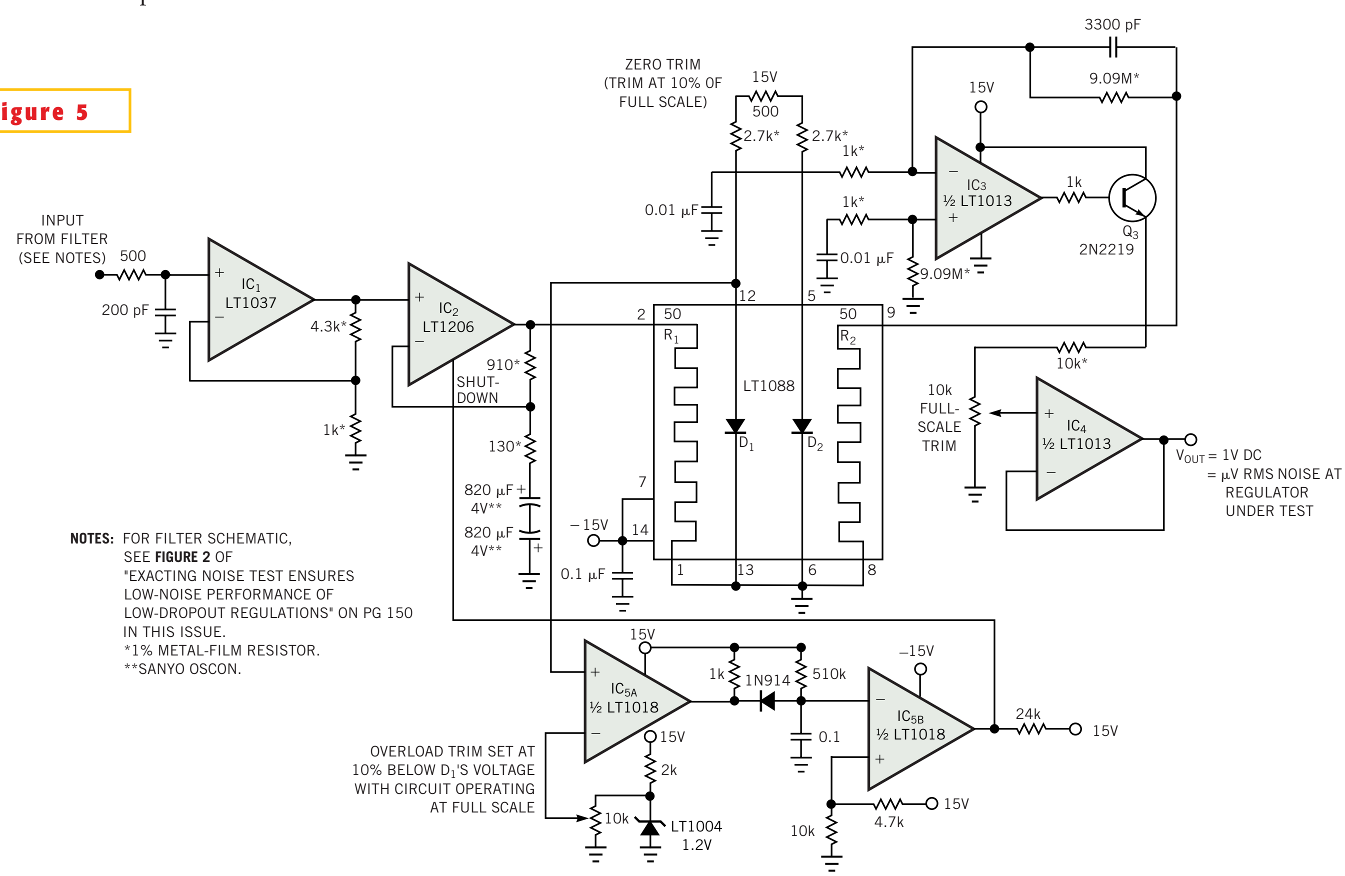
1. "1968 Instrumentation. Electronic—Analytical—Medical," AC voltage Measurement, Hewlett-Packard Co, pg 197.
2. Williams, Jim, "A monolithic IC for 100-MHz rms/DC conversion," Application Note 22, Linear Technology Corp, September 1987.
3. Williams, Jim, "Practical circuitry for measurement and control problems;" "Broadband random noise generator;" "Symmetrical white Gaussian noise;" Appendix B, Application Note 61, Linear Technology Corp, August 1994, pg 24 and 38.
4. General Radio Co, Type 1390B, Random-noise-generator operating instructions, October 1961.

Authors' biographies

Jim Williams is a staff scientist at Linear Technology Corp (Milpitas, CA, www.linear-tech.com), where he specializes in analog-circuit and instrumentation design. He has served in similar capacities at National Semiconductor, Arthur D Little, and the Instrumentation Laboratory at the Massachusetts Institute of Technology (Cambridge, MA). A former student at Wayne State University (Detroit), Williams enjoys art, collecting antique scientific instruments, and restoring old Tektronix oscilloscopes.

Todd Owen is a design engineer at Linear Technology, where he has worked for six years. He designs low-dropout linear regulators and has a BSEE from California Polytechnic State University (San Luis Obispo, CA). He enjoys skydiving with his wife.

Figure 5



This inexpensive thermally based rms voltmeter circuit is suitable for low-dropout-regulator noise measurements.