

# THE AC VOLT

By Ron Nepton

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In the US, the DC volt is legally defined by the Josephson array — a superconducting quantum device with a highly repeatable output voltage. (The DC Volt, *Nuts & Volts*, Jan. '97.) Banks of standard cells and

D1 conducts. Thus, A1 is just a unity gain inverter. This signal is summed with the original input by A2, but because R4 is only 10K ohms, the A1 output is amplified by twice as much as the original input. When the input is negative, D1 is off and D2 conducts. This holds the

becomes the basis for defining an RMS volt.  $V_{RMS} = 0.707 V_{PEAK}$ . By taking the ratio of  $V_{RMS}/V_{AV} = 0.707/0.636 = 1.1116$ , we get a value of 22.2K ohms for R5 to make the Figure 1 circuit RMS responding (for sinewaves).

Crest factor is the ratio of peak-to-RMS values. This is 1.414 for sinewave inputs (1/0.707), but can be as high as five or more for random noise. Average responding voltmeters are calibrated for sinewave inputs, but loose accuracy when used for other input wave forms (including distorted sinewaves).

There are many other precision rectifier circuits; some use opamps only and no diodes. One or

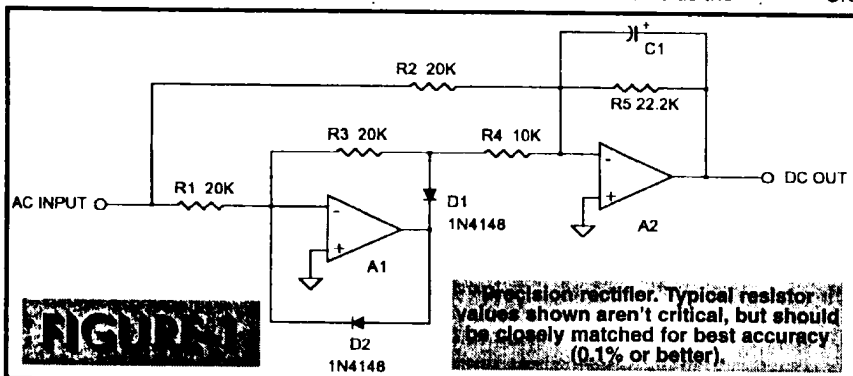
two new designs or variations are published each year, and this is an indication of just how useful and widespread this function has become. Good places to look for new circuits are the "Design Ideas" section in *EDN* magazine and "Ideas for Design" in *Electronic Design*.

## RMS CONVERTERS

An ideal RMS converter computes the average of the squared input over some averaging time interval and then takes the square root. That is:

$$E_{RMS} = \sqrt{\frac{1}{T} \int_0^T v_{in}^2 dt} = \sqrt{V_{in}^2}$$

This looks worse than it really is because we can perform this



temperature-stabilized zener diode references are used by the National Institute of Science and Technology (NIST) to calibrate DC meters for scientific and industrial customers. So how is the AC volt defined?

As it turns out, there is no "standard" AC volt in the same way there is a standard DC volt. Instead, the AC volt is defined by conversion to DC and comparison with a DC voltage standard.

The evolution of this conversion is another fascinating story in the quest for ever higher measurement accuracy. And, along the way, I'll give you some pointers on building low-cost AC calibration equipment for your own shop or lab.

## PRECISION RECTIFIERS

Although not as accurate as the thermal converters we'll look at shortly, precision rectifiers are widely used. The circuits are inexpensive and quite good enough for "everyday" measurements. Many commercial AC meters are of this type.

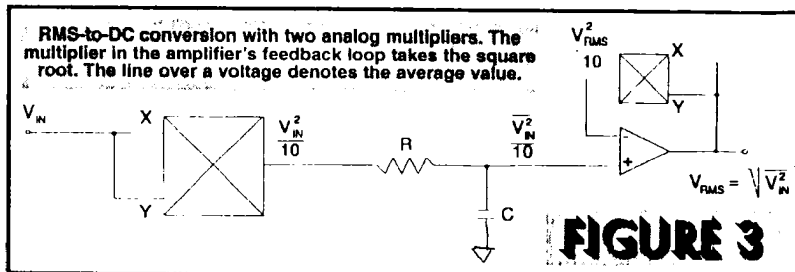
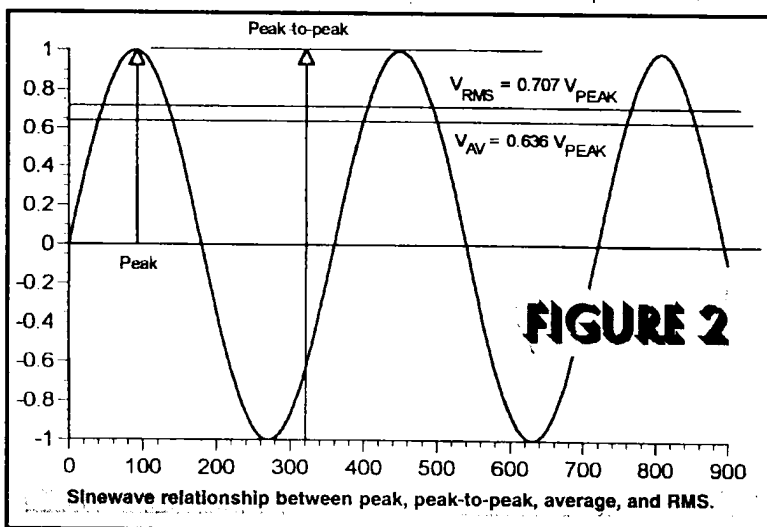
The circuit in Figure 1 has been around for many years, but it can be made to perform very well. So how does it work? For positive input signals, diode D2 is off and

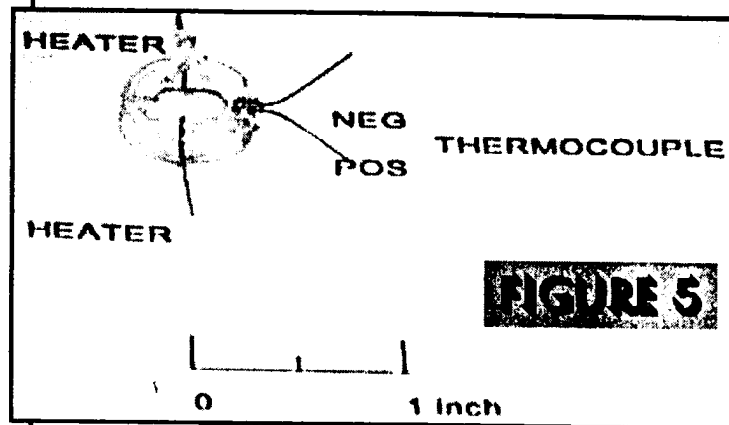
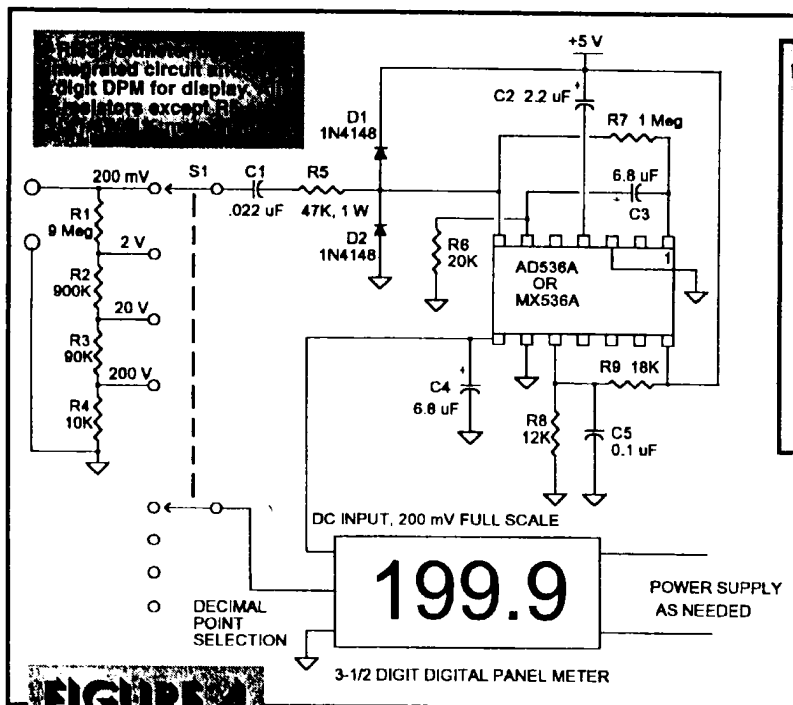
inverting input of A1 at virtual ground and effectively removes A1 from the circuit. So A2 is an inverter producing a positive output of the same voltage as during the positive half-cycle input. R5 is chosen so that one-volt RMS at the input gives a one volt DC output. And this brings up the interesting subject of average, root mean square (RMS), and peak value measurements.

Figure 2 illustrates these relationships; the peak and peak-to-peak values are easy to see and understand.

If all the instantaneous values are averaged over a half-cycle, the result is the average voltage. For a sinewave,  $V_{AV} = 0.636 V_{PEAK}$ . With R5 in Figure 1 equal to 20K ohms, the DC output would be the average value. But we usually find the RMS value to be more useful because it is a measure of the energy in the signal. Virtually all AC voltmeters read RMS volts although many are actually average responding (those that use rectifiers).

An AC RMS ampere flowing through a resistance produces the same amount of heat as a DC ampere, so this





Model U-1 vacuum thermal converter from Best Technologies, Inc.; 5 mA through the 90-ohm heater generates a thermocouple output of about 7 mV.

Of course, in practice, there are many pitfalls and NIST is continually studying the various uncertainties and new converter designs. For example, the thermocouple voltage changes slightly when switched between DC and AC current. Also, the direction of the DC current can produce a small voltage difference. But these uncertainties amount to no more than 0.00005% (0.5 ppm) and are only of concern in maintaining the National AC standards.

heater power can produce 0.1% of rated output voltage in a typical five-milliampere thermal converter. They are rather sensitive to electromagnetic interference (EMI), especially at FM and TV frequencies. Short leads and short printed circuit traces will help minimize EMI pickup. Figure 6 graphs the AC-DC calibration uncertainty vs. frequency as posted on the NIST Web site at [www.nist.gov](http://www.nist.gov)

Even at relatively low frequencies — 50 KHz and up — shunt capacitance can cause measurable error. NIST has found that coaxial mounts for thermal converters and series voltage-dropping resistors are stable and

operation electronically in a number of ways.

Many years ago, Ballantine Laboratories designed their model 320 True RMS Voltmeter. It used a series of biased diodes to approximate the "square" relationship between average and RMS. This worked well, but meter calibration was probably too labor-intensive for today's market, so it has been replaced by other techniques. (There is an excellent discussion of how to approximate functions with diodes, including examples, in *Nonlinear Circuits Handbook*, published by Analog Devices.)

Now that multiplier ICs are common and fairly inexpensive, we can literally square, average, and then take the square root as shown in Figure 3. Analog Devices and Maxim Integrated Products have taken this approach one step further. Both companies make ICs that contain the whole RMS-to-DC converter, except for the averaging low-pass filter.

Figure 4 shows a complete RMS voltmeter using an AD536A (or MX536A) and an off-the-shelf digital panel meter (DPM) for display. The AD536A needs only +5 volts for operation, but the DPM I used needed a floating nine-volt supply, so I had to use two nine-volt batteries. The low-pass filtering (averaging) is done by C2 and C4.

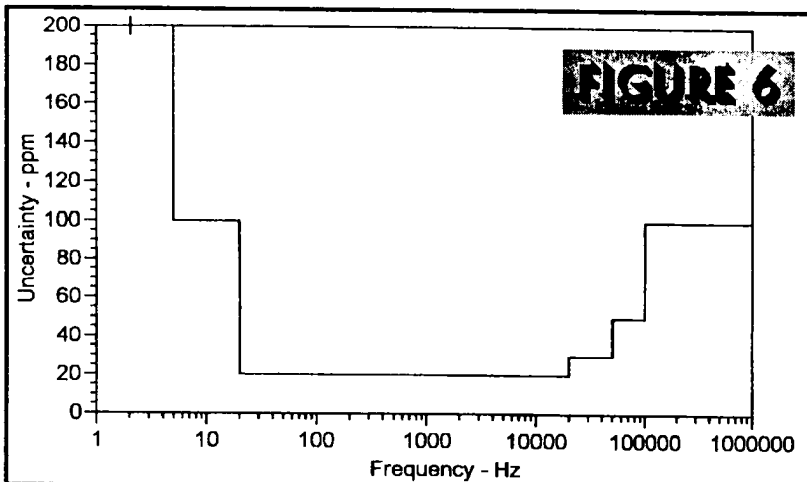
With the values shown, the DC error will be less than 1% of the reading down to about 10 Hz. The high-frequency response is set by the IC itself. The -3 dB bandwidth is 2 MHz for an input of one-volt RMS or larger, and 450 KHz at an input of 100 millivolts. For more details, ask the manufacturers for a

complete spec sheet. You will also find a wealth of information, including this voltmeter circuit, in the Analog Devices booklet *RMS-to-DC Conversion Application Guide*. (The AD536A is available from Jameco Electronic Components.)

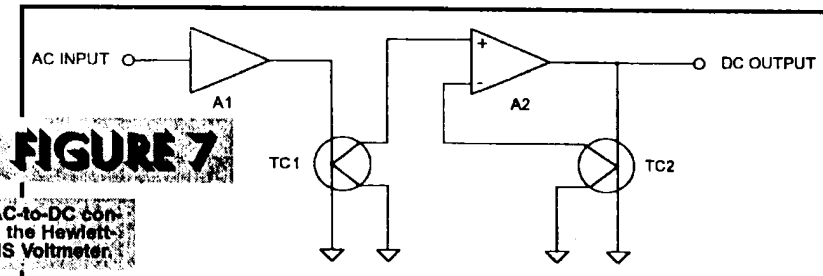
## THERMAL CONVERTERS

A thermal converter consists of a resistance heater in contact with a thermocouple enclosed in an evacuated glass bulb (for thermal insulation). A photo of a typical unit from Best Technology, Inc., is shown in Figure 5. Passing a current through the heater produces a voltage difference between the thermocouple leads. For this model, the output voltage is about seven millivolts for a five-milliampere heater current.

NIST uses thermal converters as "transfer" standards to calibrate AC voltage and current. In simplified terms, a known DC voltage is applied to a thermal converter's heater and the thermocouple voltage and the thermocouple voltage is read. Then, an AC voltage is connected to the heater and adjusted for the same thermocouple voltage. Thus, the RMS value of the AC voltage is equal to the original (calibrating) DC voltage. In a sense, the DC voltage is transferred to the AC voltage.



NIST AC-DC Calibration Uncertainty for voltages less than or equal to 100 volts, 1 ppm = 0.00001%.



Simplified diagram of thermal AC-to-DC converter. This circuit was used in the Hewlett-Packard Model 3403C True RMS Voltmeter.

