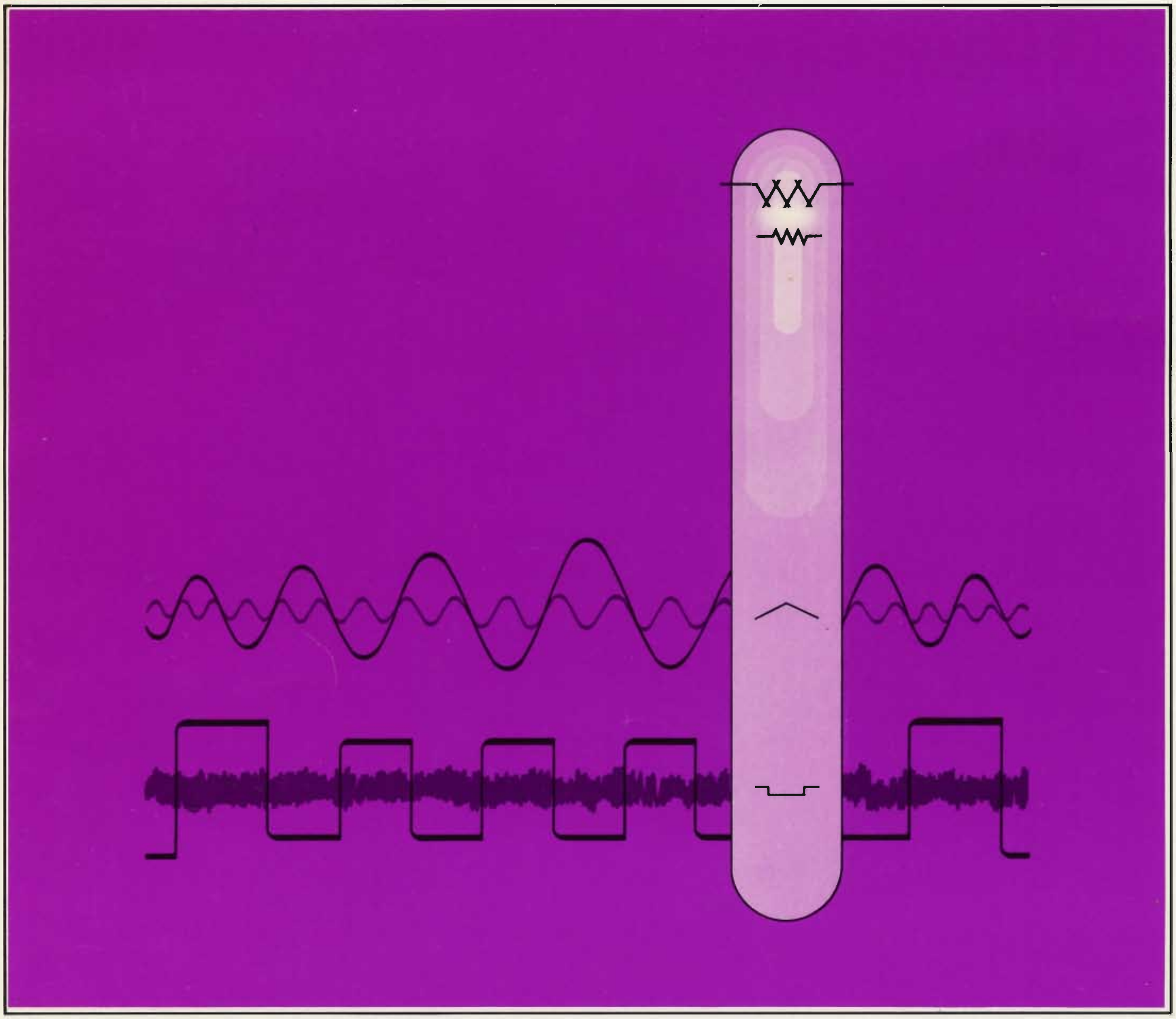
APPLICATION NOTE 124

True RMS Measurements



HEWLETT PACKARD

True RMS Measurements

June 5, 1970

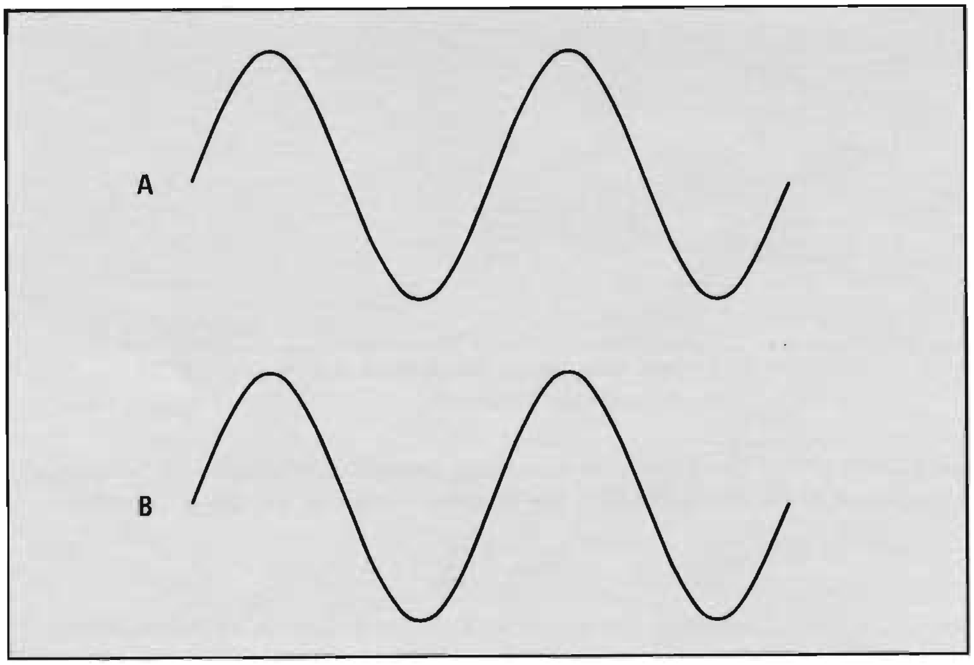


FIGURE 1.

Can you see any difference in the waveforms shown in Figure 1? Both waveforms were computer generated. One waveform is distorted by 1% 3rd harmonic in phase with the fundamental. The other waveform is a pure sine wave. 1% distortion is a typical specification for many good oscillators and is present in almost every sine wave used today. Would you be able to determine that waveform A in Figure 1 is distorted? Do you realize that if you measure the voltage level of this 1% distorted waveform with an average responding 4 digit DVM, only 3 digits are accurate, or with a 5 digit DVM, still only 3 digits are accurate? This AN will show that many measurements being made today are not "good enough".

EFFECTS ON MEASUREMENTS

The two major types of converters used with DVM's today are average responding and true rms responding. The average responding converter responds to the average value of the rectified waveform times a constant (constant ≅ 1.11 for a pure sine wave). If the waveform contains harmonics of the fundamental, the average value will vary depending on the amplitude and phase of the harmonics. Multiplying this varying average by a constant has to give a varying rms indication. Figure 2 is a plot of the error caused by the common 1% distorted waveform in Figure 1. Each harmonic was held to 1% of the fundamental and the phase of the harmonic varied from 0° to 360°.

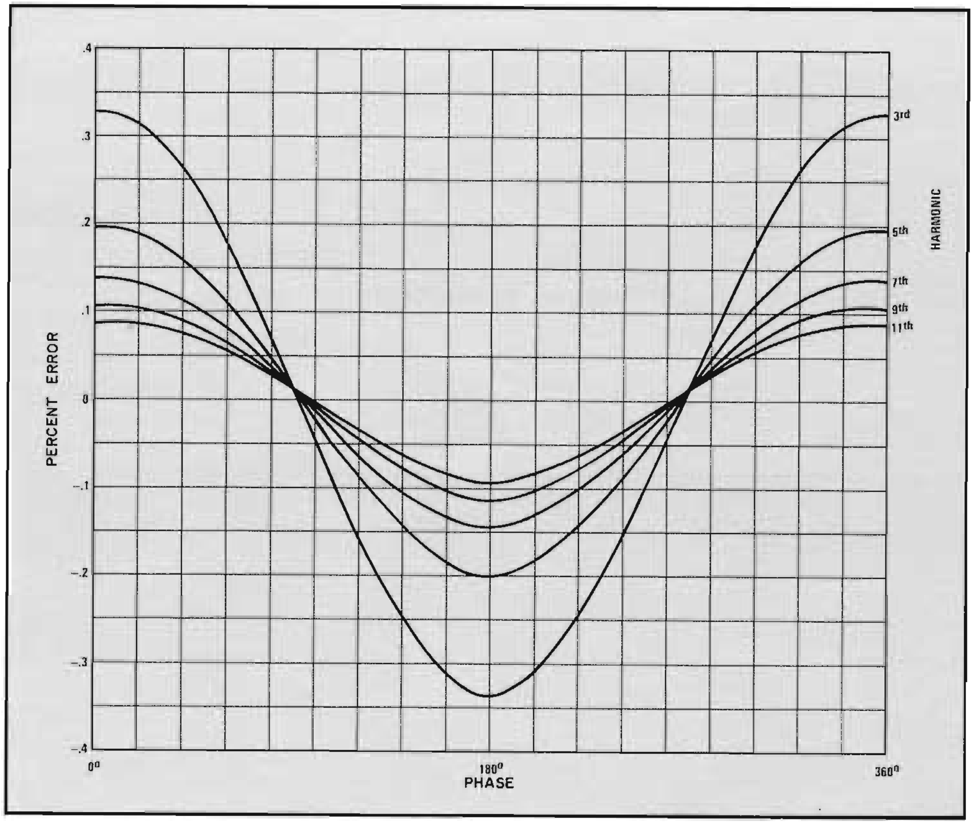


FIGURE 2. Percent Error versus Phase. Each harmonic is 1% of the fundamental magnitude.

Figure 3 is a plot of the % error in an average responding converter as a function of the magnitude of the distortion. This can be approximated by the simple equation:

$$\text{Error} \cong \frac{E_h}{NE_f}$$

where E_h is the magnitude of the harmonic, E_f is the magnitude of the fundamental, and N is the order of the odd harmonic.

Table 1 gives the equations for both average responding rms calibrated voltage and true rms voltage. Note that only the average responding equation contains a phase term.

TABLE 1.

$$F(t) = A + B\sin\omega t + C\sin(3\omega t + \phi) + \cdots Z\sin(n\omega t + \theta)$$

$$E_{AVG} = \frac{1}{T}\int_0^{t_o}\left[A + B\sin\omega t + C\sin(3\omega t + \phi) + \cdots\right]dt$$

$$E_{TRMS} = \frac{1}{\sqrt{2}}\sqrt{A^2 + B^2 \cdots}$$

The 1% 3rd harmonic can add an additional ±0.33% error to the basic accuracy of an average responding converter. In a 4 digit DVM, this amounts to an additional 33 counts of error, or the last digit is meaningless. In a 5 digit DVM, 333 counts of error can be added, or the last 2 digits are meaningless. In both cases, only 3 digits are meaningful with the typical 1% distorted waveform.

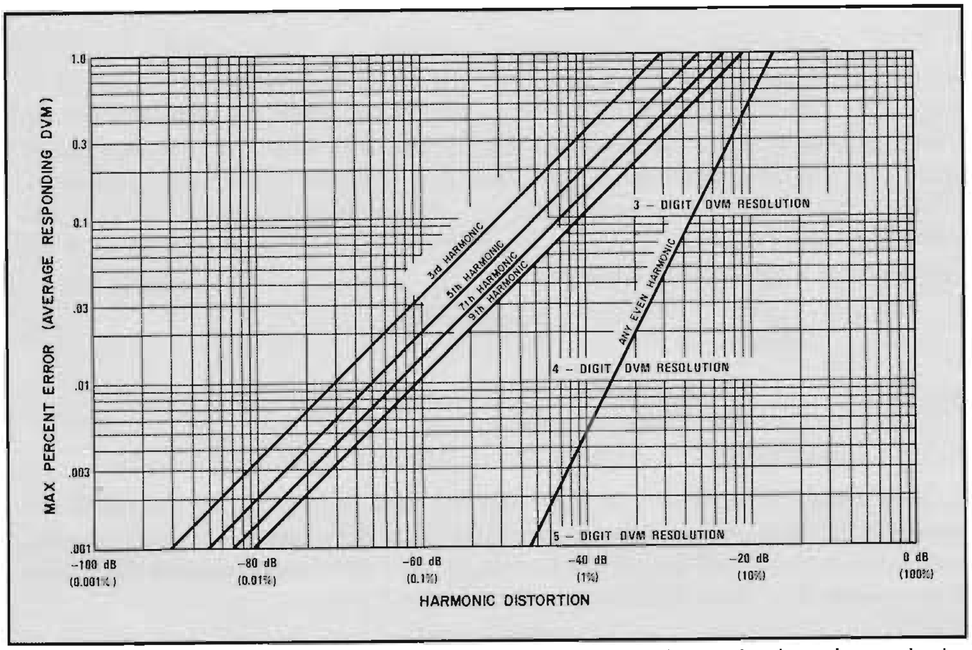


FIGURE 3. Maximum % Error versus Harmonic Magnitude. Harmonic phase is constant.

So far, worst case has been assumed. This need not be done if the magnitude and phase of the harmonics can be determined. Determining the magnitude of the harmonics would not be too difficult, but determining the phase relationship is next to impossible. It would be possible to analyze the signal using the wave analysis technique where each harmonic is isolated and measured by an average responding converter. After the fundamental and all the harmonics have been measured and recorded, they could be summed together by the square root of the sum of the squares method. This process eliminates the phase relationship problem, but requires expensive instrumentation and a great deal of time.

On the other hand, the true rms converter responds to the effective dc heating value of the waveform. The fundamental and each harmonic contribute to the total heating value. The true rms converter in essence takes each component of the waveform and sums them by the square root of the sum of the squares technique. The converter does the job of the wave analysis and computing in a very economical way. Harmonic phase relationships have no effect on the response of the converter. The true rms conversion is a correct indication of the distorted waveform and is usable with 4 and 5 digit DVM's.

The following example is used to exemplify the problems encountered with the average responding converter. The gain of an amplifier is determined by comparing the relative input voltage E_1 to the relative output voltage E_2.

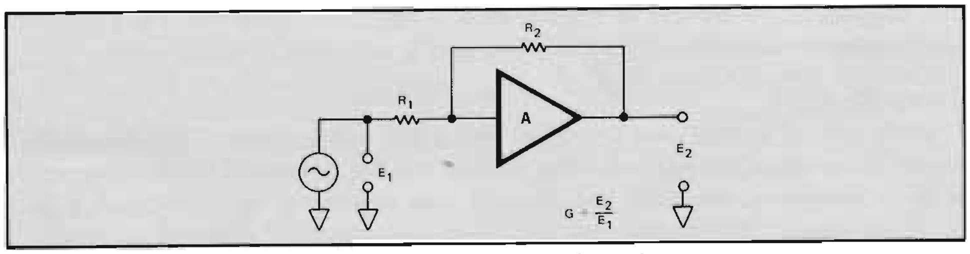


FIGURE 4. Amplifier Example

E_1 contains the typical 1% harmonic distortion. Since it is difficult to determine which components are present, assume the worst case in which all of the distortion is contained in the in-phase 3rd harmonic. The total error in an average responding converter will be the converter's inherent error plus the 33 counts of error due to the harmonic content of the waveform. A typical average converter specification is ±0.1%, or the total worst case error of +43 counts for a 4 digit DVM.

If the amplifier adds no harmonic phase or amplitude distortion to the signal, the +43 counts will be present on the E_2 voltage and the errors will cancel, but amplifiers are not pure. The amplifier, being a reactive device, will affect the phase relationship of the harmonics to some extent. Since it is impossible to determine how much effect the amplifier will have, worst case of 180° phase shift of the harmonics must be assumed. The measurement of E_2 will be in error by −23 counts (+10 counts inherent −33 counts due to the harmonic—Refer to Figure 2). If in our example the gain of the amplifier is unity, the following can occur:

$$E_1 = 1.0043$$
$$E_2 = .9973$$
$$\frac{E_2}{E_1} = .9930$$

This represents an error of 70 counts in the determination of the amplifier gain.

Your calculated amplifier gain is already 70 counts in error due to a phase distortion caused by the amplifier. If the amplifier adds 1% to the magnitude of the harmonics, the measurement of E_2 will be in error by −56 counts (+10 counts inherent −66 counts due to the distortion. Refer to Figure 3). The calculated gain is

$$\frac{E_2}{E_1} = \frac{.9944}{1.0043} = .9901$$

or the calculated gain is in error by 89 counts.

By using a true rms converter, you don't have to worry about the errors caused by distortion. All of the digits remain useful and the reading is affected only by the basic accuracy of the instrument. Distortion does not cause errors in true rms converters. Distortion is part of the total power of the waveform and the converter responds to the power, not the average of the waveform. Distortion would have to be less than 0.1% to use all 4 digits of a 4 digit DVM and less than 0.01% to use all 5 digits of a 5 digit DVM. Signals just are not pure enough for you to gamble with average responding measurements.

TRUE RMS MEASUREMENTS

Besides being the only accurate way to make everyday ac voltage measurements, the true rms converter allows you to accurately measure signals containing very high distortion such as square waves, pulse trains, and even noise. This section discusses some of these unique measurement capabilities.

Square Wave

A square wave can be generated by summing together sine waves of the appropriate frequency and amplitude. The harmonic content of a square wave is so great that the average responding converter calibrated to respond to the rms of a sine wave cannot even make an approximate measurement of the rms value. The true rms converter responds to the effective dc heating value of the square wave and is independent of the number or magnitude of the harmonics used to generate the square wave.

AC plus DC

Until now, all signals were ac coupled into a true rms converter. To measure the rms value of an ac voltage plus a dc offset voltage, you had to measure the ac component and the dc component separately and then add them together as the square root of the sum of the square. Today, true rms converters are capable of accepting dc coupled signals and measuring the rms value in one step. (Note Figure 5.)

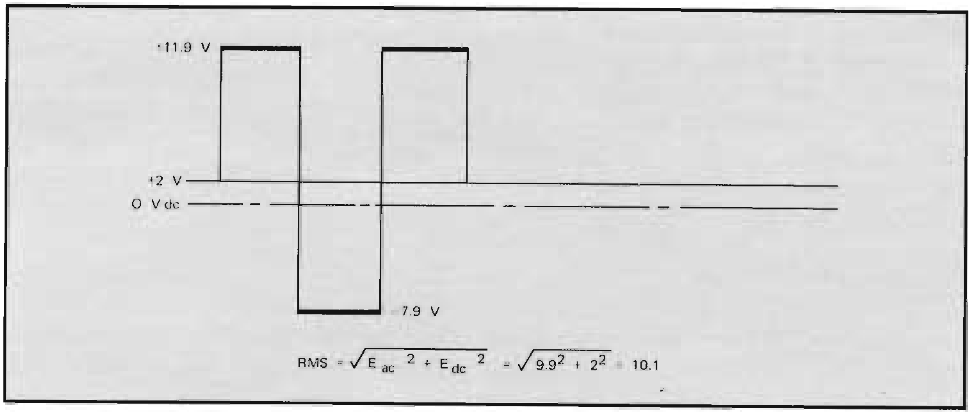


FIGURE 5. AC plus DC

Pulse Trains and Crest Factor

A pulse train in essence is a non-symmetrical square wave. Only a true rms converter can respond to a pulse train.

The term crest factor is used to describe a physical characteristic of any waveform. Basically crest factor is a ratio of the peak value of the signal to its rms value, or the square root of the inverse duty cycle minus one. Figure 6 shows both definitions.

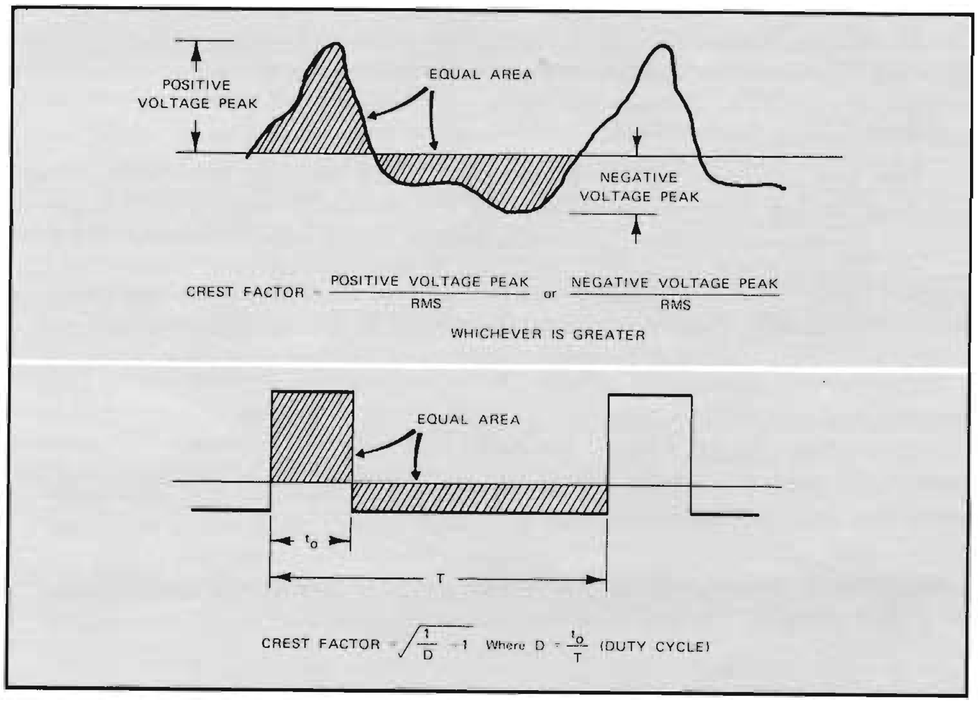


FIGURE 6. Definition of Crest Factor

An average responding converter that can measure only pure sine waves accurately has a crest factor of 1.414 (peak value of a sine wave to the rms value). True rms converters commonly have crest factors of 7:1. The crest factor that a true rms converter can respond to is a function of the dynamic range of the input amplifier and the operating point of the thermal converter. With a crest factor of 7:1, you can measure the rms value of a pulse train with a pulse width of 1/50 of the total period.

Also, to measure the rms value of a pulse that originates at 0 V dc, the signal must be dc coupled into the true rms converter. This is a direct application of $\sqrt{E_{ac}^2 + E_{dc}^2}$.

Noise

Noise is a limiting factor in any system. Thermal noise, transistor noise, and switch contact noise are examples of noise generated internally. This noise limits the sensitivity in measurement devices, distorts the purity of communication systems, and affects the output signals of all amplifiers. To effectively reduce noise, you must be able to measure noise. Since noise level is referenced to power, true rms is the only way to accurately measure the noise present in the system.

Mechanical to Electrical

Stress, strain, vibration, shock, temperature expansion and contraction are mechanical phenomena that are measured by converting mechanical motion into electrical signals. These signals are often noisy, non-periodic, and usually non-sinusoidal. In addition, the signals are usually superimposed on some dc level, thus making true rms the only way to measure these signals accurately. More importantly, mechanical movement is a form of energy. To measure total mechanical energy, you convert to electrical energy and measure the rms value of the electrical power. Only the thermal converter technique is a direct measurement of power.

THE USED-TO-BE'S

True rms measurements used to be slow. Today, 1 sec response time is possible. At frequencies below 20 Hz, measurement speed must be decreased to allow the converter time to respond to the signal. This is true for both average responding and true rms responding converters.

At high frequencies, true rms is faster than the majority of average responding converters. True rms can make accurate measurements at 1 reading a second on frequencies up to 1 MHz. Average responding converters are not capable of accurate 4 digit measurements above 100 kHz.

True rms converters used to be expensive. They still cost more than average converters but how expensive is an incorrect measurement? When 4 or 5 digits of accuracy are required, it's less expensive to make a correct measurement the first time than to correct a mistake caused by an inaccurate measurement.

SUMMARY

The true rms measurement technique is the most accurate available today. Besides accuracy, true rms allows a versatility in measurement capabilities unknown with previous techniques. Hewlett Packard has realized the importance of true rms measurements and is making a definite commitment to the development of instrumentation incorporating the advantages of true rms.

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