APPLICATION NOTE

Make Better AC RMS Measurements with your Digital Multimeter

KEYSIGHT

Introduction

If you use a digital multimeter (DMM) for AC voltage measurements, it is important to know what type of reading your meter is giving you so that you can properly interpret the results. Is your meter is giving you peak value, average value, root-mean-square (RMS) value, or something else? If the answer is “something else,” you may be in trouble, and the trouble usually happens with AC rms measurements. This application note will help you understand the different techniques DMMs use to measure rms values, how the signal affects the quality of your measurements, and how to avoid common measurement mistakes.

Measuring AC RMS

Measuring AC rms values is more complicated than it appears at first glance. If it is complicated, why do we bother? Because true rms is the only AC voltage reading that does not depend on the signal's shape. It is often the most useful measurement for real-world waveforms.

Often, rms is described as a measure of equivalent heating value, with a relationship to the amount of power dissipated by a resistive load driven by the equivalent DC value. For example, a 1Vpk sine wave will deliver the same power to a resistive load as a 0.707Vdc signal. A reliable rms reading on a signal will give you a better idea of the effect the signal will have on your circuit.

Figure 1 shows four common voltage parameters. Peak voltage (Vpk) and peak-to-peak voltage (Vpk-pk) are simple. Vavg is the average of all the instantaneous values in one complete waveform cycle. You will learn how we calculate Vrms below.

For sine waves, the negative half of the waveform cancels out the positive half and averages to zero over one cycle. This type of average would not provide much insight into the signal’s effective amplitude, so most meters compute Vavg based on the absolute value of the waveform. For a sine wave, this works out to Vpk x 0.637 (Figure 2).

You can derive Vrms by squaring every point in the waveform, finding the average (mean) value of the squares, then finding the square root of the average. You can take a couple of shortcuts with pure sine waves: just multiply Vpk x 0.707 or Vavg x 1.11. Inexpensive peak-responding or average-responding meters rely on these scaling factors.

The scaling factors apply only to pure sine waves. For every other type of signal, using this approach produces misleading answers. If you are using a poorly designed meter for the task, you can easily end up with significant errors—as high as 40 percent or more—depending on the meter and the signal.

The ratio of Vpk to Vrms, known as the crest factor, is important to measurement accuracy. The crest factor measures how high the waveform peaks relative to its RMS value. The higher the crest factor, the more difficult it is to accurately measure AC.

Two measurement challenges are associated with high crest factors. The first involves input range. Imagine a pulse train with a very low duty cycle but a relatively high peak amplitude. Signals like this force the meter to simultaneously measure a high peak value and a much lower rms value, possibly creating overload problems on the high end and resolution problems on the low end.

The second challenge is the amount of higher-frequency energy in the signal. High crest factors generally indicate more harmonics, which can cause trouble for all meters. Peak- and average-responding meters trying to measure rms have a particularly hard time.

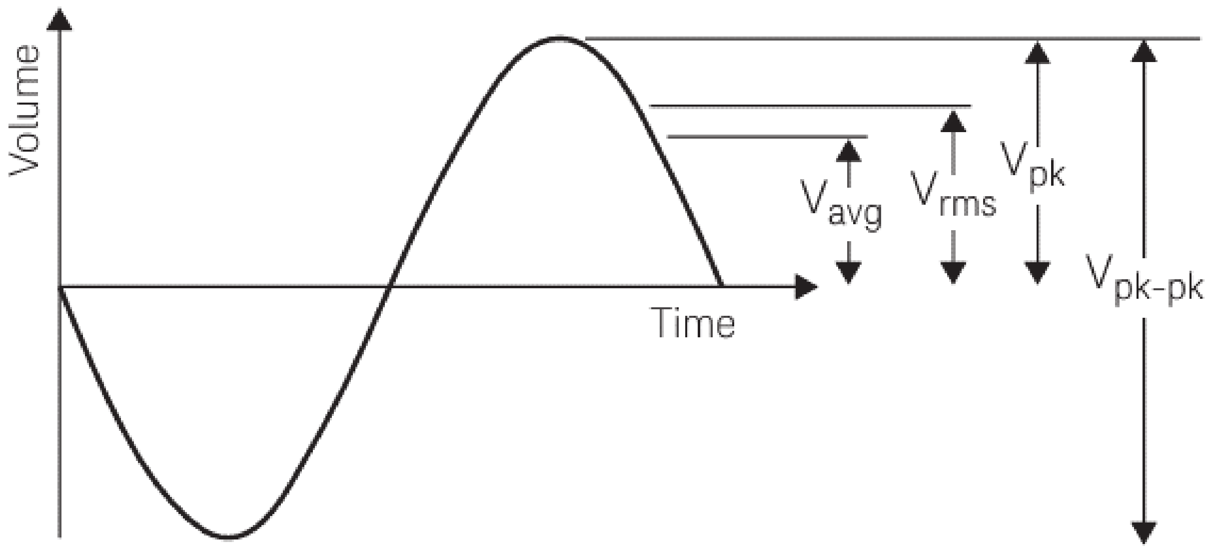

Figure 1. Common voltage parameters.

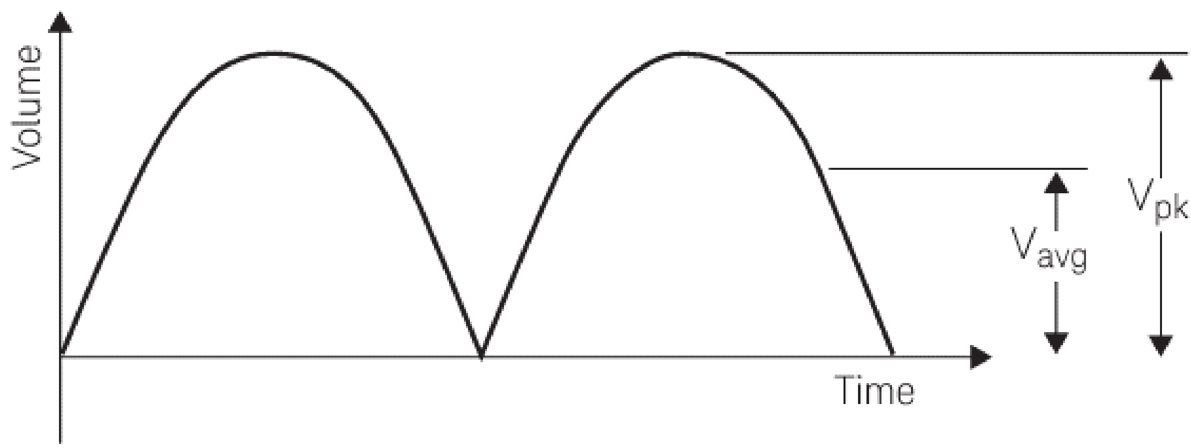

Figure 2. Vavg is calculated based on the absolute value of the waveform.

Tips for Making Better AC RMS Measurements

Given the importance—and difficulty—of measuring rms, what is the best way to proceed with your day-to-day measurement tasks? The following tips will help you achieve better results.

Tip 1: Understand how your DMM measures RMS

When it comes to measuring rms values, multimeters are not created equal. A general understanding of the technology your multimeter uses to measure rms will help you decide if it meets your needs. Here is a summary of four common multimeter technologies' operational advantages and disadvantages. The first three operate by converting AC to DC; the last digitizes the analog input signal and then computes rms.

Thermal AC-to-DC converters

This older technology for rms measurements uses the equivalent heating-value approach. The AC signal heats a thermocouple, and then the DC section of the meter reads the thermocouple output. Advantages include wide bandwidth and the ability to handle very high crest factors, meaning this approach can deliver true rms for various real-world signals.

The disadvantages of the thermal approach are cost and lack of flexibility in trading off measurement speed with low-frequency accuracy. For these reasons, the technique is not used in the latest-generation DMMs.

If you need to measure high-bandwidth and high-crest-factor signals with great accuracy, you may want to search for one of these thermal models. If high accuracy is important to you, you may want to investigate multimeters that use the digital sampling method.

Peak and averaging AC-to-DC converters

Inexpensive meters, particularly inexpensive hand-held meters, usually derive rms levels from either peak or average values. They deliver true rms only for pure, undistorted sine waves. If you need true rms measurements on real-world signals, these meters are not viable.

Analog AC-to-DC converters

Many mid-range DMMs use a chain of analog circuits to compute the square, mean, and square root of the mean to deliver true rms for nearly all signal types.

Digital sampling

This last method uses sampling techniques similar to those in digital oscilloscopes to create a set of data points sent through an rms algorithm. Synchronous sampling uses multiple passes to capture a signal, as shown in Figure 3. Each subsequent pass is delayed by a small amount, and with enough passes, the signal can be digitized with very high resolution.

This technique has several advantages: true rms on a wide range of signals, high accuracy, and the capability to create very fast, effective sampling rates and wider bandwidths, even with fairly slow analog-to-digital converters. However, this method only works with repetitive signals.

If accurate rms measurements are important to you and you are likely to run into pulse trains and other complicated signals, a true rms meter is the only solution. On the other hand, you can save some money with a peak—or average-responding meter. Just keep in mind what these meters can and cannot do.

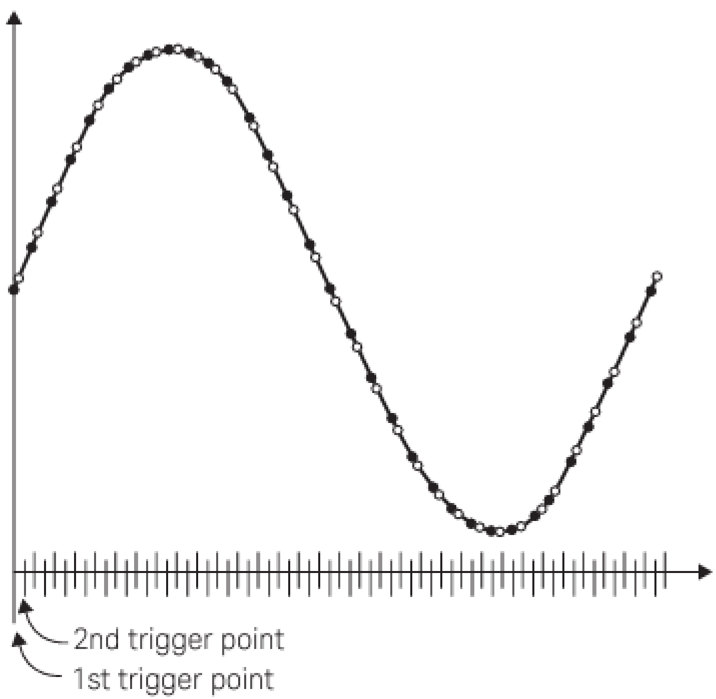

Figure 3. Digital sampling.

Tip 2: Understand how the signal affects the quality of your measurement

Let's look at several different signals, starting with a sine wave. The crest factor for a pure sine wave is 1.414, and a peak-responding meter can provide accurate rms simply by scaling the value of Vpk. With a Vpk value of 500 mV, we expect an rms value around 350 to 357 mV (the range accounts for the inaccuracy of the signal generator used). Sure enough, a true rms meter reads the signal as 353.53 mV. A less-expensive average responding meter reads the signal as 351 mV.

Unlike the pure sine wave, the triangle wave in Figure 4 has some higher frequency energy, so the crest factor of 1.732 is no surprise. Dividing the peak value by the crest factor yields an expected rms value of roughly 290 mV. Now, the average-responding meter starts to get into trouble, reading the signal as 276 mV, a 4 percent error compared to the true rms meter's reading of 288.68 mV. Let's look at pulse trains, where the crest factor depends on the duty cycle.

You can get a close approximation of the crest factor with the formula: $\mathrm{CF} \cong \sqrt{\frac{T}{t}}$

where:

- CF = the crest factor
- T = the period of the waveform
- t = the on portion of that period

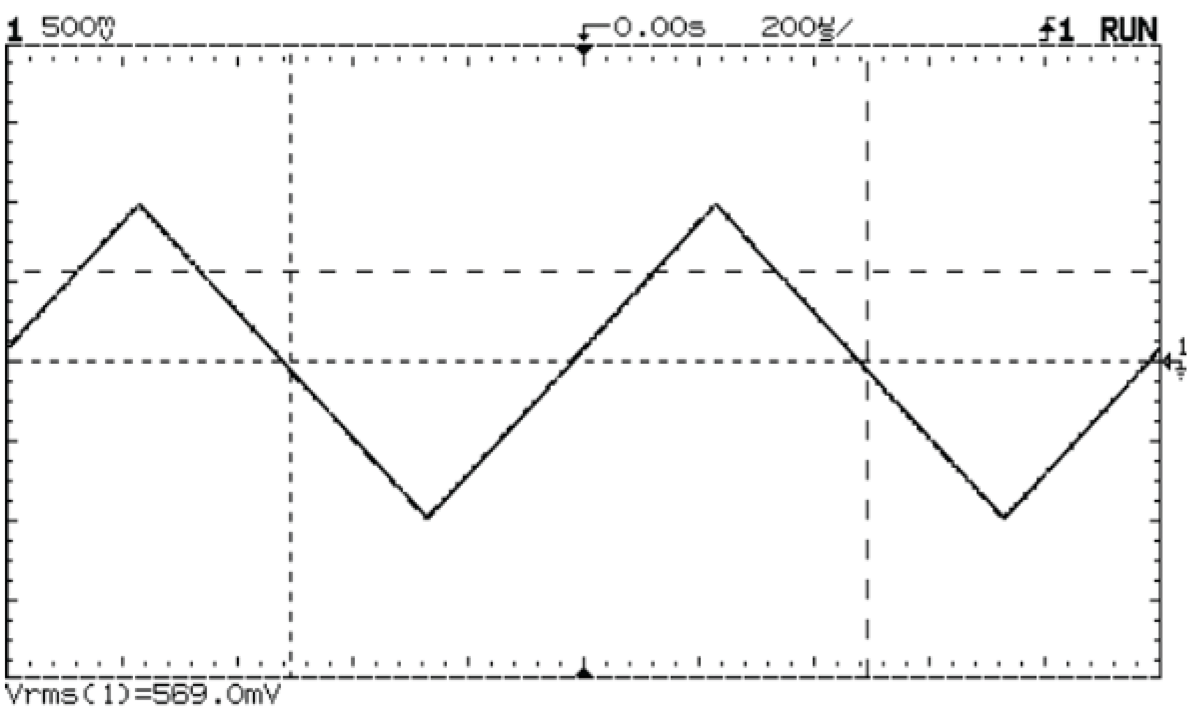

Figure 4. Measuring rms on a triangle wave.

This also is equal to the square root of the reciprocal of the duty cycle. So, for the pulse train in Figure 5, which has a 2 percent duty cycle, the crest factor is the square root of 50 or 7.071.

Computing the rms value for sines and triangles is quite simple; the rms value is Vpk divided by the crest factor. However, computing the AC rms value for a pulse train is a bit more complicated:

$$V_{rms} = \frac{V_{pk}}{CF} \times \sqrt{1 - \left(\frac{1}{CF}\right)^2}$$

Using the formula, the theoretical rms value of our 2-Vpk pulse train with a 2 percent duty cycle in Figure 5 is roughly 280 mV. Even in this case, which is outside its specified performance range, the true rms meter reads 275.9 mV. On the other hand, the average-responding meter reads 73 mV, a 74 percent error. This is an extreme example, but it clearly shows what high crest factors can do to your measurements.

Let's consider one more waveform—the noisy, messy sine wave shown in Figure 6. The true rms meter pegs it at 348.99 mV, which is close to the digital scope's measurement of 345 mV. The average responding meter puts the value at 273 mV, an error of more than 20 percent. This error is due to the limited bandwidth of the average-responding meter. The signal contains high-frequency energy that the average-responding meter does not consider.

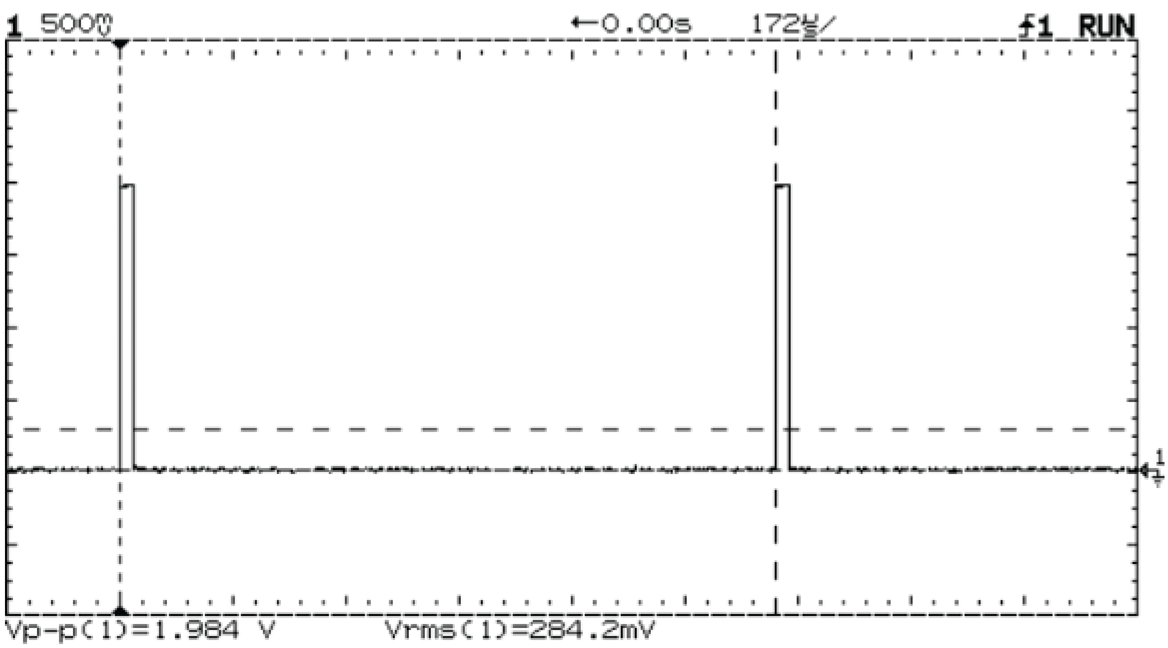

Figure 5. Measuring rms on a low-duty-cycle pulse train.

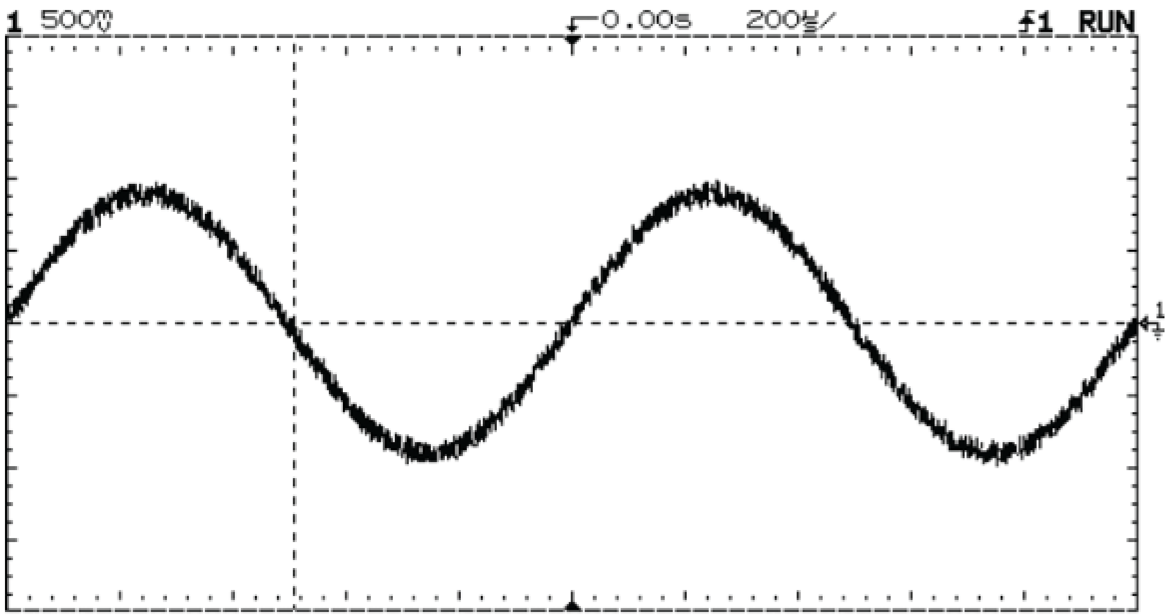

Figure 6. Measuring rms on a noisy sine wave.

Tip 3: Avoid common measurement traps

If an AC rms reading does not make sense, do not automatically assume something is wrong with your circuit—the trouble might be how you made the measurement. Below is a list of common traps that can affect rms measurements. We have touched on some of these already; you may have encountered many of them before.

Measurements below full-scale

Most meters specify AC inputs down to 5 percent or 10 percent of full scale (some go as low as 1 percent). For maximum accuracy, measure as close to full scale as you can. In some cases, you might need to override autoscaling if a manual setting will help maximize the input range.

AC and DC coupling

It is easy to overlook this simple issue when you are in a hurry. If your meter is AC coupled (or has selectable AC coupling), it inserts a capacitor in series with the input signal that blocks the DC component in your signal. This may or may not be desirable, depending on the signal and your goal.

If you expect to include the DC component, but the meter is AC coupled, the results can be dramatically wrong. As a side note, if you need to measure a small AC signal riding on a large DC offset but your meter doesn't provide AC + DC directly, you can measure the AC component using AC coupling and measure the DC component separately. Then add the two using rms addition:

$$AC + DC = \sqrt{(AC_{rms}2)^2 + DC^2}$$

Saturation problems with high-crest-factor signals

In addition to the problems, they cause with high-frequency content, high-crest-factor signals also can wreak havoc on your input range. Think back to that pulse train with a 2 percent duty cycle. Its 7+ crest factor means the peak value is more than seven times greater than the rms value. That means your meter needs to provide adequate amplitude resolution for the low rms value without saturating the high peak value. To make matters worse, you generally do not get an overload indication with crest-factor saturation. It is important to check your meter's specifications for maximum crest factor and to refrain from exceeding them.

Bandwidth errors

Signals rich in harmonics can produce low-reading measurements if the more significant of these components are not included in the measurement. Check the instrument's data sheet to see how much bandwidth you have to work with. Then, make sure your signals do not exceed it.

Self-heating errors

High voltages can heat up the meter's signal-conditioning components, leading to offset measurement values. Pay attention to the maximum input voltage; if you exceed it, allow the meter to cool down before making another measurement.

Settling time

By definition, rms measurements require time averaging over the measured lowest frequency over multiple periods. Consequently, switch to a faster filter if you are not concerned about low frequencies in a particular measurement and your DMM has selectable averaging filters.

Glossary

	Description
Crest factor	A measure of how high the waveform peaks, relative to its rms value
DMM	Digital multimeter
rms	An abbreviation for root-mean-square
True rms	The term “true” rms is used to distinguish meters that actually measure the rms value, from meters that derive rms levels from either peak or average values
Vavg	Average voltage, using the absolute value of the waveform (the negative portion of the cycle is treated as if it were positive)
Vpk	Peak voltage
Vpk-pk	Peak-to-peak voltage
Vrms	The rms value of AC voltage

Conclusion

While AC rms measurements are more complicated than they might seem at first glance, a little knowledge can help you deal with the complexity. If you have not already done so, verify the crest factor, bandwidth, and other limitations noted in your DMM's data sheet. As much as possible, stay within those limits.

A quality meter used within its limits should deliver consistently dependable measurements.

For more information

For more information about the Keysight Digital Multimeters, go to:
https://www.keysight.com/us/en/products/digital-multimeters-dmm.html

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