# Keysight Technologies
## AC Voltage Measurement Errors in Digital Multimeters

Application Note

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights

# Introduction

When you make measurements with a digital multimeters (DMM), common errors will crop up. The following discussion will help you eliminate potential measurement errors and achieve the greatest accuracy with a DMM. This paper covers ac voltage measurement errors. For an overview of system cabling errors and dc voltage measurement errors, see Application Note 5988-5511EN. For a discussion of resistance; dc current; ac current; and frequency and period measurement errors, see Application Note 5988-5512EN.

Note: The Keysight True*volt* 34461A, a 6-1/2-digit, high-performance DMM with both benchtop and system features, will be used as an example throughout this article.

## Common Mode Errors

Errors are generated when the DMM's input LO terminal is driven with an ac voltage relative to earth. The most common situation where unnecessary common mode voltages are created is when the output of an ac calibrator is connected to the DMM "backwards." Ideally, a DMM reads the same regardless of how the source is connected. However, both source and DMM effects can degrade this ideal situation.

Because of the capacitance between the input LO terminal and earth (approximately 200 pF for the Keysight 34461A), the source will experience different loading, depending on how the input is applied. The magnitude of the error is dependent on the source's response to this loading.

The DMM's measurement circuitry, while extensively shielded, responds differently in the backward input case due to slight differences in stray capacitance to earth. The DMM's errors are greatest for high-voltage, high-frequency inputs. Typically, the DMM will exhibit about 0.06% additional error for a 100 V, 100 kHz reverse input. You can use the grounding techniques described for dc common mode problems to minimize ac common mode voltages (see Application Note 5988-5511EN).

## True RMS AC Measurements

True rms responding DMMs, like the Keysight Truevolt Series, measure the "heating" potential of an applied voltage. Power dissipated in a resistor is proportional to the square of an applied voltage, independent of the waveshape of the signal. This DMM accurately measures true rms voltage or current, as long as the wave shape contains negligible energy above the meter’s effective bandwidth.

The Keysight Truevolt Series uses the same techniques to measure true rms voltage and true rms current. The effective AC voltage bandwidth is 300 kHz, while the effective AC current bandwidth is 10 kHz.

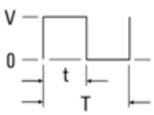
| Waveform Shape | Crest Factor (C.F.) | AC RMS | AC + DC RMS | Average Responding Error |
|---|---|---|---|---|
|   | 1.414 | $\frac{V}{1.414}$ | $\frac{V}{1.414}$ | Calibrated for 0 error |
|   | 1.732 | $\frac{V}{1.732}$ | $\frac{V}{1.732}$ | -3.9% |
|   | $\sqrt{\frac{T}{t}}$ | $\frac{V}{C.F.} \times \sqrt{1-\left(\frac{1}{C.F.}\right)^2}$ | $\frac{V}{C.F.}$ | -46% for C.F. = 4 |

Figure 1

The DMM's AC voltage and AC current functions measure the AC-coupled true rms value. In this DMM, the "heating value" of only the AC components of the input waveform are measured (dc is rejected). As seen in figure 1 above; for sine waves, triangle waves, and square waves, the AC–coupled and AC+DC values are equal, because these waveforms do not contain a DC offset. However, for non–symmetrical waveforms (such as pulse trains) there is a DC voltage content, which is rejected by Keysight’s AC–coupled true rms measurements. This can provide a significant benefit.

An AC–coupled true rms measurement is desirable when you are measuring small AC signals in the presence of large DC offsets. For example, this situation is common when measuring AC ripple present on DC power supplies. There are situations, however, where you might want to know the AC+DC true rms value. You can determine this value by combining results from DC and AC measurements, as shown below:

$$ac + dc = \sqrt{ac^2 + dc^2}$$

For the best AC noise rejection, you should perform the DC measurement using an integration time of at least 10 power–line cycles (PLCs).

## True RMS Accuracy and High–Frequency Signal Content

A common misconception is that because an AC DMM is true rms, its sine wave accuracy specifications apply to all waveforms. Actually, the shape of the input signal dramatically affects measurement accuracy for any DMM, especially when that input signal contains high–frequency the instrument's bandwidth.

For example, consider a pulse train, one of the most challenging waveforms for a DMM. The pulse width of that waveform largely determines its high–frequency content. The frequency spectrum of an individual pulse is determined by its Fourier Integral. The frequency spectrum of the pulse train is the Fourier Series that samples along the Fourier Integral at multiples of the input pulse repetition frequency (prf).

Figure 2 below shows the Fourier Integral of two very different pulses: one of broad width (200 µs); the other narrow (6.7 µs). The bandwidth of the ACV path in the DMM is 300 kHZ; therefore, frequency content above 300 kHz is not measured.

Notice that the sin(πfT)/πfT spectrum of the narrow pulse significantly exceeds the effective bandwidth of the instrument. The net result is a less accurate measurement of the narrow, high–frequency pulse.

In contrast, the frequency spectrum of the broad pulse has fallen off significantly below the DMM's 300 kHz (approximately) bandwidth, so measurements of this pulse are more accurate.

Reducing the prf increases the density of lines in the Fourier spectrum, and increases the portion of the input signal's spectral energy within the DMM's bandwidth, which improves accuracy.

In summary, error in rms measurements arise when there is significant input signal energy at frequencies above the DMM's bandwidth.

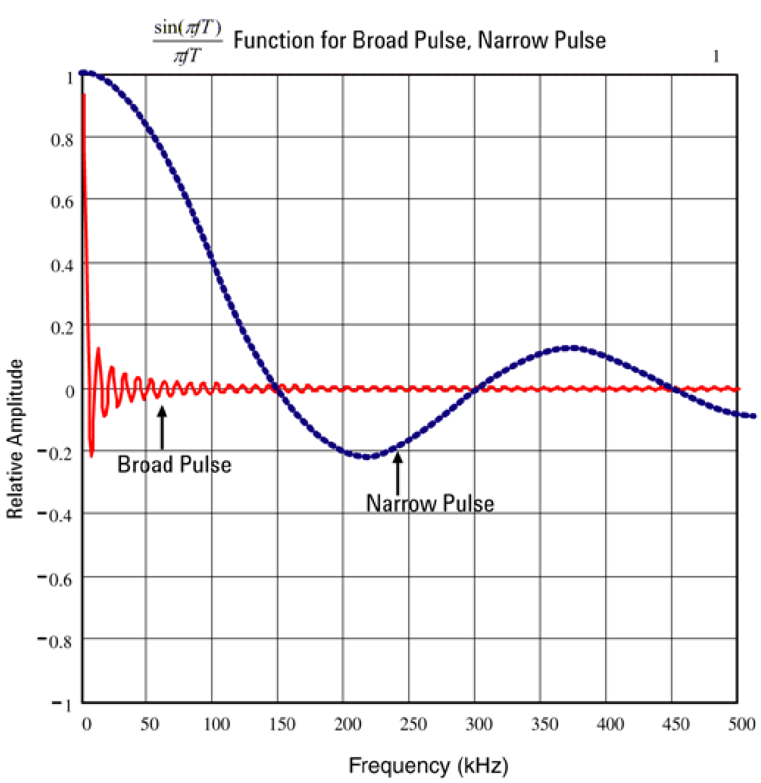



Figure 2. Fourier integral of two different pulses

## Estimating High–Frequency (Out–of–Band) Error

A common way to describe signal waveshapes is to refer to their **Crest Factor**. Crest factor is the ratio of the peak value to rms value of a waveform. For a pulse train, for example, the crest factor is approximately equal to the square root of the inverse of the duty cycle.

$$CF = \frac{1}{\sqrt{d}} = \frac{1}{\sqrt{\frac{t_p}{T}}} = \frac{1}{\sqrt{prf \times t_p}}$$

Notice that crest factor is a composite parameter, dependent upon the pulse width and repetition frequency; crest factor alone is not enough to characterize the frequency content of a signal.

Traditionally, DMMs include a crest factor derating table that applies at all frequencies. The measurement algorithm used in the Truevolt Series DMMs is not inherently sensitive to crest factor, so no such derating is necessary. With this DMM, as discussed in the previous section, the focal issue is high–frequency signal content which exceeds the DMM's bandwidth.

For periodic signals, the combination of crest factor and repetition rate can suggest the amount of high– frequency content and associated measurement error. The first zero crossing of a simple pulse occurs at $f_1 = 1/t_p$.

This gives an immediate impression of the high-frequency content by identifying where this crossing occurs as a function of crest factor: $f_1=(CF^2)(prf)$.

| | Typical error for square wave, triangle wave, and pulse trains of CF=3, 5, or 10 | | | | |
|---|---|---|---|---|---|
| **prf** | **square wave** | **triangle** | **CF=3** | **CF=5** | **CF=10** |
| 200 | -0.02% | 0.00% | -0.04% | -0.09% | -0.34% |
| 1000 | -0.07% | 0.00% | -0.18% | -0.44% | -1.71% |
| 2000 | -0.14% | 0.00% | -0.34% | -0.88% | -3.52% |
| 5000 | -0.34% | 0.00% | -0.84% | -2.29% | -8.34% |
| 10000 | -0.68% | 0.00% | -1.75% | -4.94% | -26.0% |
| 20000 | -1.28% | 0.00% | -3.07% | -8.20% | -45.7% |
| 50000 | -3.41% | -0.04% | -6.75% | -32.0% | -65.3% |
| 100000 | -5.10% | -0.12% | -21.8% | -50.6% | -75.4% |

Table 1. Typical error for various pulse waveforms as a function of input pulse frequency.

This is an additional error for each waveform, to be added to the value from the accuracy table provided in the instrument's data sheet

The specifications are valid for CF ≤ 10, provided there is insignificant signal energy above the 300 kHz bandwidth for voltage, or the 10 kHz bandwidth for current. DMM performance is not specified for CF > 10, or when significant out-of-band signal content is present.

### Example

A pulse train with level 1 Vrms, is measured on the 1 V range. It has pulse heights of 3 V (that is, a Crest Factor of 3) and duration 111 µs. The prf can be calculated to be 1000 Hz, as follows:

$$prf = \frac{1}{CF^1 \times t_p}$$

Thus, from Table 1, this AC waveform can be measured with 0.18% additional error.

## AC Loading Errors

In the ac voltage function, the input of the Keysight 34461A appears as a 1MW resistance in parallel with 100 pF of capacitance. The cabling used to connect signals to the DMM will also add additional capacitance and loading. Table 2 shows the DMM's approximate input resistance at various frequencies.

| Input Frequency | Input Resistance |
|---|---|
| 100 Hz | 1 MW |
| 1 kHz | 850 kW |
| 10 kHz | 160 kW |
| 100 kHz | 16 kW |

Table 2. Input resistance

For Low Frequencies:

$$Error(\%) = \frac{-100 \times R_s}{R_s + 1M\Omega}$$

Additional error for high frequencies:

$$Error(\%) = 100x\left[\frac{1}{\sqrt{1+(2p \times F \times R_s \times C_{in})^2}} - 1\right]$$

Where:

$R_S$ = Source Resistance
F = Input Frequency
$C_{in}$ = Input Capacitance
(100 pF) plus Cable Capacitance

Note: Be sure to use low-capacitance cable when measuring high-frequency signals.

## Low-Level AC Measurement Errors

When measuring ac voltages less than 100 mV, be aware that these measurements are especially susceptible to errors introduced by extraneous noise sources. An exposed test lead will act as an antenna and a properly functioning DMM will measure the signals received. The entire measurement path, including the power line, acts as a loop antenna. Circulating currents in the loop will create error voltages across any impedances in series with the DMM's input. For this reason, apply low-level ac voltages to the DMM through shielded cables, and connect the shield to the input LO terminal.

Connect the DMM and the ac source to the same electrical outlet whenever possible, and also minimize the area of any ground loops that cannot be avoided. A high-impedance source is more susceptible to noise pickup than a low-impedance source. To reduce the high-frequency impedance of a source, place a capacitor in parallel with the DMM's input terminals. There may be some experimentation involved to determine the correct capacitor value for the particular application.

Most extraneous noise is not correlated with the input signal. The equation below shows how to determine the error:

$$\text{Voltage Measured} = \sqrt{V_{in}{}^2 + Noise^2}$$

Correlated noise, while rare, is especially detrimental because it will always add directly to the input signal. Measuring a low-level signal with the same frequency as the local power line is a common situation where this error is likely to occur.

# Summary

When making high frequency or low voltage AC measurements it is important to minimize error mechanisms. When practical, use a low-impedance source, use proper cabling and minimize loops between cables. To determine AC measurement errors, it is important to include errors due to signal shape, noise and frequency.

For more information about the Keysight 34461A DMM, go to
**www.keysight.com/find/34461A**

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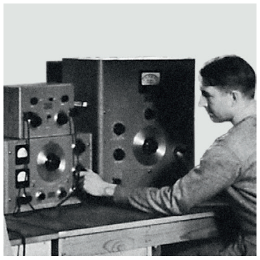

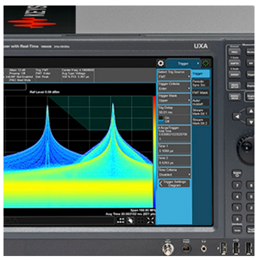

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Published in USA, December 1, 2017
5988-5513EN
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