**FOR SENSITIVE VOLTAGE MEASUREMENTS, KNOW YOUR DUT—
IT DETERMINES THE RIGHT INSTRUMENT TO USE**

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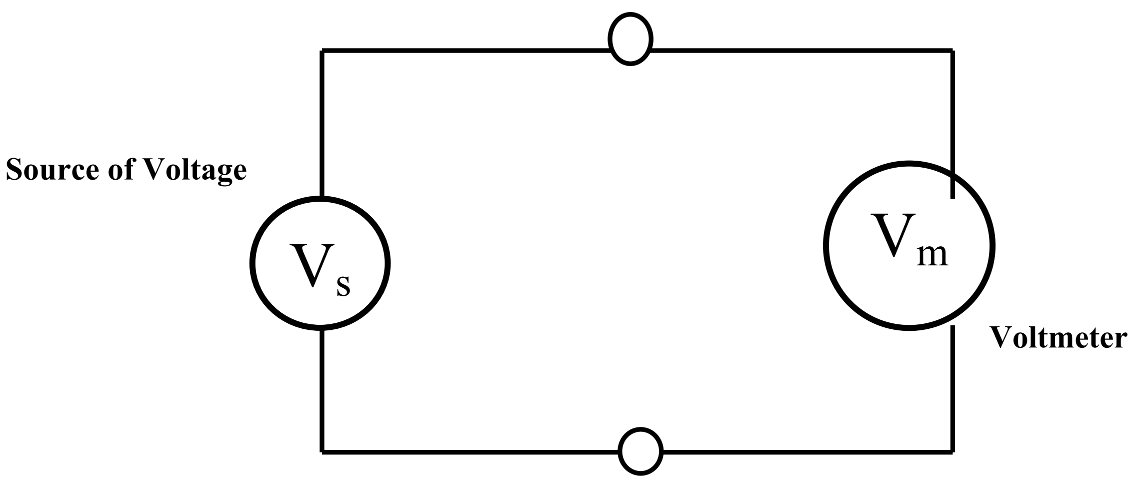
If you have a source of DC voltage with a value V_s, the expectation is that a voltmeter connected to the source will display a reading, V_m, that is essentially equal to V_s (see Figure1). And often this is the case. However*, when the source of voltage acts very differently from an ideal voltage source*, *measuring the voltage adequately can be a challenge*. When a voltage measurement is non-trivial, choosing the right voltmeter can make a significant difference in your results.



$$V_m = V_s$$

Figure 1. Ideal voltmeter measuring an ideal voltage source.

There are two fundamental problems that may prevent V_m from being acceptably close to V_s. First, the source of voltage is not an ideal voltage source; second, the voltmeter is not an ideal voltmeter.

Ideal voltage sources do not exist; that is, V_S will change with the load. An ideal voltmeter has infinite input impedance, thus acting as an open circuit. Because *real* voltmeters have finite input impedance, they load the voltage source being measured, and consequently V_S will change as you try to measure it. How much it changes depends on how close the source and voltmeter are to being ideal.

Voltage Source Model

Any real source of voltage can be modeled by a Thevenin model, an ideal voltage source in series with a source resistance (Figure 2.). As long as the source is made up of linear elements, this model should act as a real source of voltage.

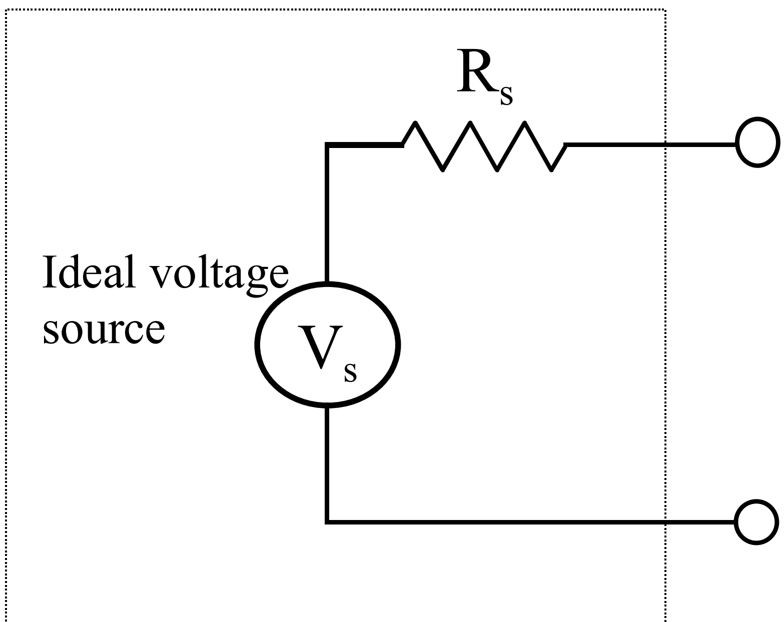


Figure 2. Model of a DC voltage source

The source resistor R_S creates non-ideal behavior in a source of voltage. The value of R_S determines how much the source output voltage drops for a given load placed across it.

Because any resistance generates voltage noise, the source resistance also places a fundamental limit on how well the voltmeter can *resolve* V_S. The voltage noise generated by a resistor is called Johnson noise, and its magnitude is given by:

$$V_n = \sqrt{4kTR_sB}$$

k = Boltzmann’s constant (1.38 x 1023 J/K)

T = absolute temperature in K

B = noise bandwidth in Hz

The larger R_s is, the larger V_n will be. This noise is NOT part of the voltage signal you are trying to measure. At a given temperature and bandwidth, there is nothing a voltmeter can do to differentiate between V_n and V_s. Figure 3 shows the theoretical voltage measurement limits at room temperature with an instrument response time of 0.1 seconds to 10 seconds. If the voltages you want to measure (or *changes* in V_s) are smaller than V_n, you are operating in the dark area of Figure 3, and V_s cannot be properly observed with the voltmeter.

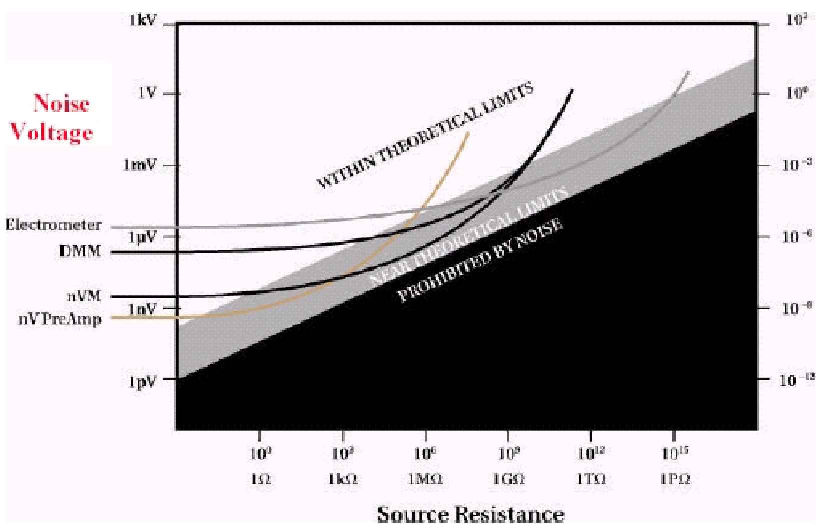
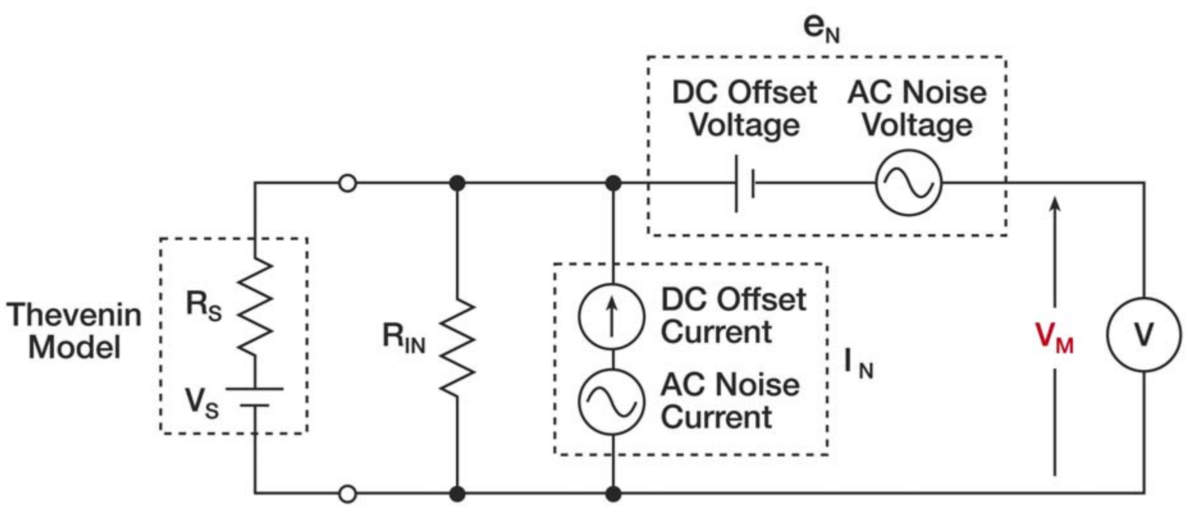


Figure 3. Johnson noise is the ultimate limitation on measurement sensitivity (dark area of the graph). Measurement performance in the presence of noise varies by type of instrument used and the signal source resistance.

Voltmeter Model

The input of an ideal voltmeter essentially is an open circuit and draws no current from the voltage source. The simplest model of a *real* voltmeter is an ideal voltmeter in parallel with a resistance R_{in} (modeling the input resistance of a real voltmeter). As long as R_{in} is much larger than R_s, the voltmeter will display a voltage reading V_m close to V_s. A more advanced model (Figure 4) incorporates other non-ideal voltmeter characteristics such as generated DC current and voltage offsets, and AC current and voltage noise. These error terms are captured in the model shown in Figure 4 by I_n and E_n.



$$V_M = V_S^* \left[\frac{R_{IN}}{R_S + R_{IN}} \right] + e_N + I_N^* \left[\frac{R_S R_{IN}}{R_S + R_{IN}} \right]$$

Figure 4. Model of a voltmeter reading a DC signal source.

The equation for the voltmeter reading, V_m, appears below the circuit in Figure 4. In real instrument designs, I_n and E_n cannot be minimized simultaneously. Either term can only be minimized *at the expense* of increasing the other. These tradeoffs distinguish different types of instrument designs and where they are best employed.

Pick the Right Instrument Based on DUT Characteristics

Clearly, the source resistance of a DUT plays a pivotal role in how successfully you measure V_s, and is the principal variable in deciding which instrument to use. The performance of typical instruments when measuring voltage sources with different values of R_s is illustrated in Figure 3.

When measuring a voltage source with small R_s (typically less than 100kΩ to 1MΩ), most benchtop voltmeters and DMMs have sufficiently large R_{in} so that *loading errors* will not be a limiting factor. For very low voltages (less than 1µV), a nanovoltmeter having a small E_n allows you to measure voltage levels close to the theoretical limits.

In order to measure voltages with high R_s (typically *higher* than 100kΩ to 1MΩ), you need an instrument with very high input impedance and small I_n, such as an electrometer, SourceMeter® instrument, or Source-Measure Unit (SMU).

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