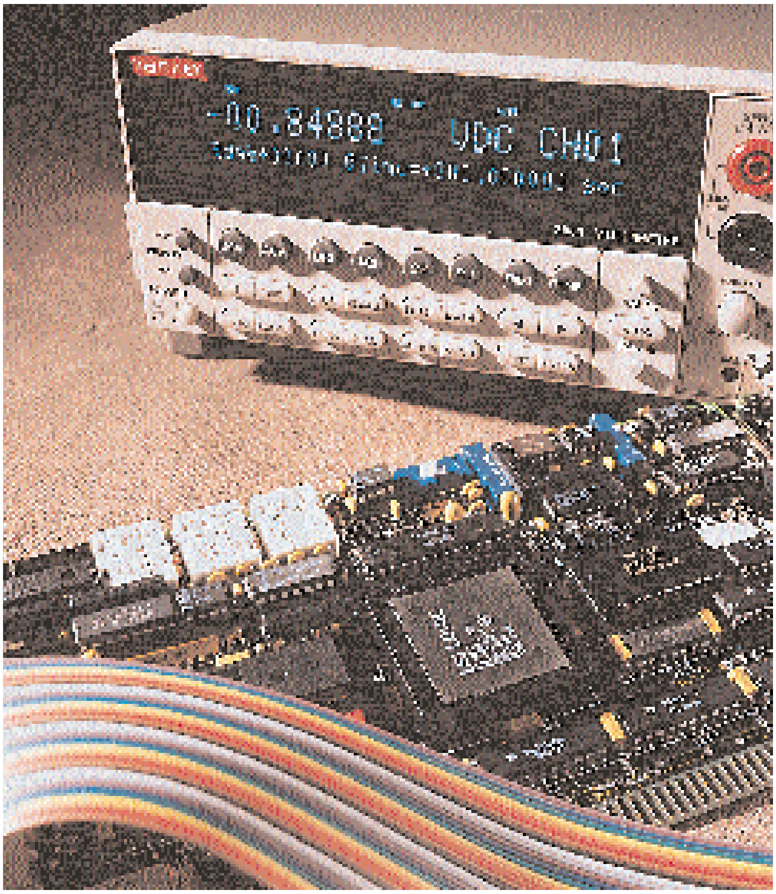
EQUIPMENT

by Thomas Hayden and John Yeager

Improving Measurements of Low-Level Voltage and Resistance

Imagine that a project requires precise measurements of a tiny voltage or resistance, maybe just a few billionths of a volt or a couple millionths of an ohm. Although you select and hook up a high-precision instrument—one seemingly perfect for the task—maybe you see offsets, drift, unstable readings and generally noisy measurements. Before cursing the manufacturer and returning the unit, you need to remember that many errors develop outside of the recording instrument.

In fact, making a sensitive measurement of voltage or resistance demands more than selecting an appropriate instrument from a supplier's catalog. The catalog may list awesome specifications for an instrument, but its performance covers only about one-third of the factors that affect low-level accuracy. The remaining two-thirds of the factors arise in the external environment, ancillary hardware or measurement techniques.



Measurements of low-level voltage and resistance can be made with a digital multimeter.

This article reveals some of the fundamental difficulties associated with measuring low-level voltage and resistance. It also provides techniques that will enable you to deal with problems that can generate errors in your measurements.

Low-level basics

In a low-level measurement, the size of a signal lies near the theoretical limit of sensitivity, which depends on the noise in the system. In other words, even a little interference can obscure such small signals. As a rule of thumb, this is a problem for voltages and resistances below 1 millivolt and 1 ohm, respectively. However, measurements in these ranges must be made in many applications, including microcalorimetry, resistance in electrical conductors and characterizing thermocouples. Measurements of low-level voltage and resistance can be made with a digital multimeter, nanovoltmeter or micro-ohmmeter, or by using two instruments—one called the stimulus, or source, which often produces a test current, and another for measuring a quantity, such as voltage. Each method suffers from inherent limitations. The choice of one approach over another depends on the signal's size and the required measurement accuracy.

A digital multimeter works well for measurements that require resolution as low as 1 microvolt or 10 milliohms. If the multimeter accommodates a sensitive preamp, these measurements can be pushed down to about 1 picovolt or 1 pico-ohm. A nanovoltmeter, as its name implies, resolves voltage measurements as low as 1 nanovolt. Micro-ohmmeters are appropriate for resistances as low as 10 micro-ohms. Even lower resistances, down to approximately 1 nano-ohm, can be measured with a combination of a programmable current source and a nanovoltmeter.

Taking a test

Identifying potential problem areas and avoiding them constitute the keys to making accurate low-level measurements. The types of errors that may affect a specific measurement system can be predicted from a so-called test-envelope grid. This grid, plus estimated noise levels from various sources, points toward potential measurement problems.

Percentage	Parts per Million	Decades
10	100,000	1
1	10,000	2
0.1	1,000	3
0.01	100	4
0.001	10	5
0.0001	1	6
0.00001	0.1	7

Table 1. Measurement resolution conversion factors.

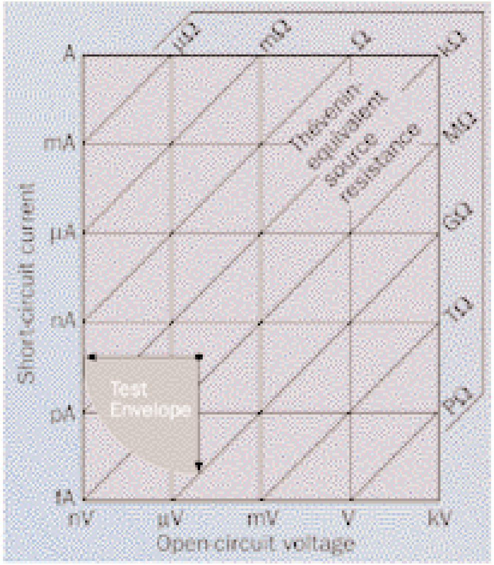


Figure 1. Test-envelope grid.

To create such a grid, you begin by applying the Thévenin network theorem to your measuring system. According to this theorem, any two-terminal network can be modeled as a voltage source in series with a Thévenin-equivalent resistance, R_S. The value of R_S can be calculated from the open-circuit voltage (V_O), short-circuit current (I_S) and Ohm's law, such that $R_S = V_O/I_S$. If the device being tested is, for example, a voltage source that produces 10 μV, and it is being measured with a voltmeter that has an input bias current of 100 picoamperes, then $R_S = 10\ \mu\text{V}/100\ \text{pA} = 100$ kilo-ohms. The point (10 μV, 100 pA) gets plotted as a beginning of a test-envelope grid for this voltage source (figure 1).

The size of a test envelope depends on the desired resolution of a measurement. To generate a test envelope, resolution should be quantified in decades—the number of places to the right of the decimal point when resolution is given as a percentage of a measurement. A resolution of 0.1 percent, for instance, equals 0.001, or three decades. Several levels of resolution are given in decades in table 1.

Continuing with the envelope for the voltage-source example, imagine that this application requires a resolution of 0.01% (or 0.0001), which translates into four decades. From the point (10 μV, 100 pA), draw a horizontal line that is four decades long and extends to the left. Then draw a vertical line, also four decades long but extending below the same point. Complete the test envelope by connecting the ends of the two lines with an arc.

This envelope depicts several characteristics of the device being tested. The three corners of the envelope represent important resistances, which can be calculated by using Ohm's law or read from the resistance axis of the test grid. The envelope's beginning point (10 μV, 100 pA) represents the Thévenin-equivalent resistance. The left end of the horizontal line represents the maximum resistance that can be placed in series with the device. The bottom of the vertical line represents the minimum resistance that can be placed in parallel with it. Finally, any sources that produce noise levels that lie inside the test envelope can create problems in measurement accuracy.

Low-level measurements of voltage and resistance may suffer from several common sources of noise, some of which are listed in table 2. Generally, you need to apply solutions outside of the instrument to minimize these errors. Once you have created a test envelope for a measurement system, refer to figure 2a for voltage measurements or figure 2b for resistance ones. These illustrations reveal the potential sources of error that can affect different parts of the test grid. By recognizing these potential problem areas, you can develop strategies to avoid or minimize errors.

Minimizing thermal emfs

In measurements of low-level dc voltage, the most common errors arise from thermal electromotive forces, also known as thermoelectric voltages or thermal offsets. These thermal emfs result from temperature differ-

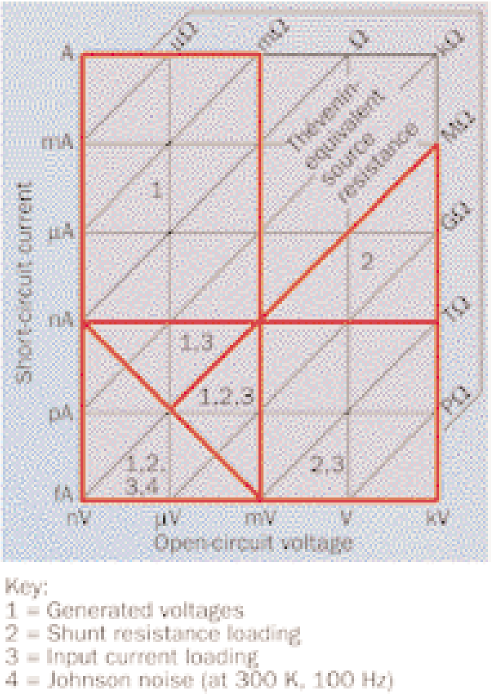


Figure 2a. Voltage measurement errors.

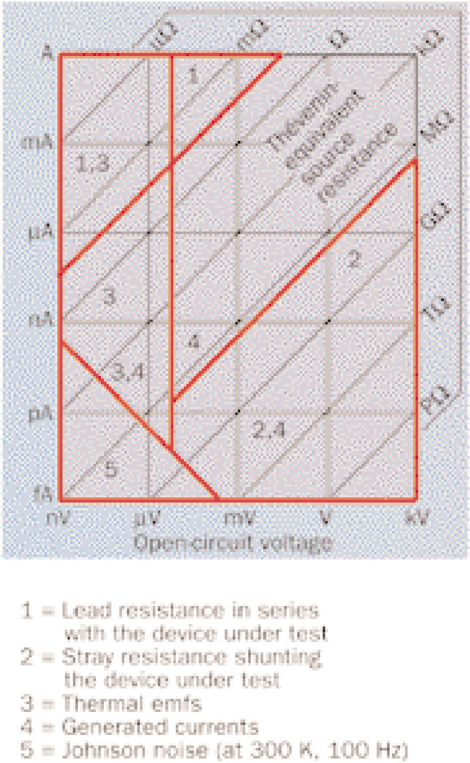


Figure 2b. Resistance measurement errors.

Error symptoms	Likely causes	Typical error/ noise levels	How to avoid this type of error
Offset voltage	Thermal emf	100 nV to 5 µV	Use only crimped Cu–Cu connections. Minimize temperature gradients.
Noise voltage	1. RFI rectification 2. Magnetic coupling (50/60 Hz) (normal mode noise; common mode noise)	1. 100 nV to 100 mV 2. 1 nV to 10 mV	1. Use voltage reversal/ zeroing method (offset compensation). Use shielding; remove source of interference. 2. Use shielding; connect shields at only one point; move test equipment away from magnetic field.
Offset resistance	Lead resistance	1 mΩ to 1 Ω	Use 4-wire method.
Noisy readings	1. Ground loops 2. Johnson noise	mV to V	1. Ground all equipment at one point. 2. Use filter or averaging.
Long time stabilize	Shunt capacitance loading	ms to seconds	Use guard circuit.
Unstable readings	Thermal emf	1–50 µV	Keep connections at same temperature.

Table 2 Low-level voltage and resistance measurement error sources and how to avoid them.

ences within a measuring circuit at junctions between conductors composed of dissimilar materials. The magnitude of a thermal emf generated by a material junction depends on the thermoelectric coefficient of the two materials. This can range from less than 0.2 μV/° C for copper-to-copper junctions up to 1000 μV/° C for copper-to-copper-oxide junctions.

Thermal emf errors can be avoided in several ways. First, use only clean, crimped copper-to-copper connections. Avoid soldered connections because of the use of other metals. Second, reduce temperature gradients by placing all junctions close together, using heat-sink blocks at all junctions and using insulators with high thermal conductivity, such as beryllium oxide, to isolate your system from external sources. Finally, allow all equipment to reach its thermal equilibrium before making measurements.

Although some test conditions rule out these avoidance strategies, alternative solutions exist. A copper–constantan thermocouple, for instance, requires using two different metals. Nevertheless, the wires can be connected in a manner called series-opposing polarity (figure 3), in which a constantan–constantan connection results in no error, and two copper leads are available for connecting a measuring instrument.

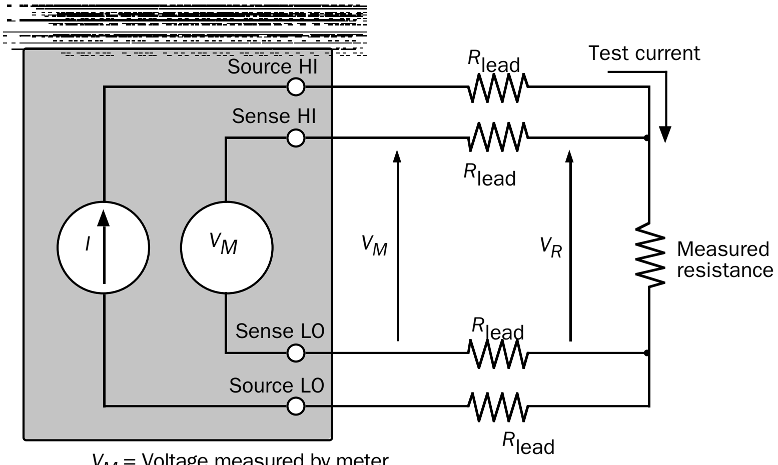
Tempering temperature

An instrument's specifications for accuracy normally apply to a specified temperature range for a thoroughly warmed-up instrument, for example, 18–28°C. Outside that range the manufacturer will typically specify a temperature coefficient, such as ±(0.005% + 1 count)/°C. Ambient-temperature effects can be minimized in several ways: keep the instrument away from sunlight and other heat sources; protect the instrument from fan exhausts and other drafts; wrap connections in insulating foam; zero the instrument on the range that will be used for a measurement and rezero the instrument often.

Also recognize the fundamental limit on the accuracy of any measurement—Johnson noise. This broadband noise is caused by the thermal agitation of charged particles in any resistive component. All voltage and current sources, for example, contain internal resistance and exhibit Johnson noise. As might be expected, higher temperatures produce higher levels of Johnson noise. So lowering the temperature of the device being tested reduces this noise. Also, you can further reduce the effects of Johnson noise by averaging a number of readings.

Magnetism and line noise

A measuring system can also pick up interference from magnetic fields or ac sources, such as power lines or fluorescent lights. A magnetic field passing through a conductive loop in a test circuit will generate a magnetic emf that is proportional to the



V_M = Voltage measured by meter
V_R = Voltage across resistor
Because sense current is negligible,
$V_M = V_R$ and measured resistance is $\frac{V_M}{I} = \frac{V_R}{I}$

Figure 4. Four-wire resistance measurement.

strength of the field, the loop's area and the rate at which these variables change. Even Earth's relatively weak magnetic field can generate nanovolts in dangling leads. Nevertheless, ac pickup (line-cycle noise) represents the most common source of interference. You can verify noise coming from ac fields by monitoring the analog output of an instrument with an oscilloscope.

You can take several precautions to limit noise from a magnetic field. First, keep the test circuit away from sources of magnetic noise, including motors and transformers. Second, avoid movement of leads and other parts of a test circuit. For instance, tape leads to a solid, stationary surface to minimize vibration. Third, minimize the loop area between leads by using short, twisted-wire pairs. Finally, use shielded cables.

When magnetic fields cannot be avoided, an entire circuit may require shielding. The extent of the shielding depends on the local environment and equipment configuration. The shielding may cover only the circuit being tested, both the test circuit and the measuring instrument or everything—the test circuit, measuring instrument and even the person doing the measuring. Some test configurations, however, rule out complete shielding. In those cases some form of filtering may be required, and filtering is particularly effective when the noise source is ac pickup.

Terminal measurements

Most measurements of low-level resistance require four-terminal measurements, also known as Kelvin connections. This test configuration uses two leads to supply a current to an unknown resistance and two other leads to measure the voltage drop across the resistance (figure 4). Ohm's law can be used to determine the unknown value.

This four-terminal technique minimizes the effects of lead resistance, which typically is in a range of 0.01–1 Ω. Keep test leads as short as possible to further minimize errors caused by lead resistance. Also, for some tests and devices, the current should be kept as low as possible to avoid heating and temperature-coefficient effects. On the other hand, current should be as high as possible to boost the voltage level and accuracy.

Although an instrument may have an internal source of current, using an external source often increases a measurement's accuracy and reduces its difficulty. Testing different devices may require drastically different currents, and external sources usually offer a wider range of currents and can be set to the precise level required. Also, some low-current applications, including thermistors, require a voltage clamp—often as low as 20

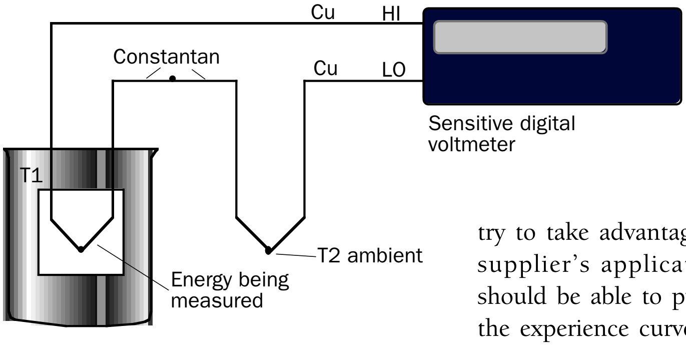


Figure 3. Micro-calorimeter with differential temperature measurement. The constantan wires are connected together, and the copper (Cu) wires are directly connected to the voltmeter, with result that there are no spurious junctions formed.

mV—on the current source. The clamp protects the device being tested from potentially damaging voltages. Although most digital multimeters do not possess such low-level voltage clamps, most external current sources do.

Despite the advantages of using separate source and measuring instruments, they must be properly grounded to avoid trouble. If both instruments are connected to a common ground bus, a loop is formed. A number of instruments plugged into power strips on different instrument racks is one example of this problem. The difference in potential between ground points can cause large currents to circulate and create unwanted drops in voltage. You can cure this problem by using isolated power sources and instruments, and then grounding the entire system at one earth–ground point.

In conclusion

As you can see, selecting the best instrument carries you only part way toward making the most accurate measurements. After shopping carefully for the proper device, you must face even more important problems, which lie in your overall measurement system and beyond. You can meet those challenges by applying configurations, connections and techniques that avoid or reduce the effects of many sources of errors. If those efforts are not successful, try to take advantage of your instrument supplier's application engineers, who should be able to push you rapidly along the experience curve for low-level voltage and resistance measurements.

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