Instrument Techniques That Reduce Effects of External Error Sources

Accurate measurements are required for process control, troubleshooting and quality assurance. Crucial to measurement accuracy is the ability to recognize and avoid potential sources of error. In general, test instruments account for about one half of the measurement uncertainty. The external test environment, ancillary hardware and measurement techniques account for the other half. With this in mind it is important that you not only select the proper instrumentation, but also configure it properly and use suitable test circuitry to avoid measurement errors. In this, the third of our five-part series, we present some of the more common external error sources and ways to minimize their effects on measurement integrity.

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MINIMIZING VOLTAGE MEASUREMENT ERRORS

Offset voltages – Significant errors may be introduced into DC voltage measurements by offset voltages, which appear as a non-zero reading on the voltmeter display. Typically this occurs when the instrument is connected to a low impedance circuit and no DC voltage is present. A number of error sources in the circuit may contribute to voltage offset. These include thermoelectric EMFs and offsets generated by rectification of RFI (radio frequency interference).

Thermoelectric EMFs: Thermoelectric EMFs generally have the most affect in low voltage measurements. These voltages are generated when different parts of a circuit are at different temperatures and when conductors of dissimilar materials are joined together. There are three primary methods to reduce these errors:

1. Use the same type of wire and connector materials throughout the circuit. Copper to copper connection is the best type of junction for low thermal emf.
2. Minimize the temperature gradients within the circuit. Shield the circuit from air flow with insulating foam or place the circuit with in an enclosure. Also allow the circuit to warm up to thermal equilibrium.
3. Reverse sources to cancel thermal EMFs. In this technique two voltage measurements are made. One in the positive polarity and one in the negative polarity. The thermal EMFs is the algebraic difference between the two measurements. With this known then the thermal EMFs can be cancelled out.

Since resistance measurements often apply a current source to the device under test (DUT) and measure voltage to calculate resistance, thermal EMFs can also be a source of error in these measurements. Likewise, non-ohmic contacts can rectify RFI and cause low resistance measurement errors. More details on correcting these errors are covered later under Resistance Measurements.

External noise sources – Significant errors can be generated by noise sources, which include AC line cycle noise, Johnson noise, magnetic fields and ground loops. Instrument programming to minimize AC line cycle noise was discussed in Part 1 of this series. The following sections discuss ways of minimizing voltage measurement errors from other common noise sources.

Johnson noise: The ultimate limit of resolution in an electrical measurement is defined by Johnson or thermal noise. This is the noise associated with the motion

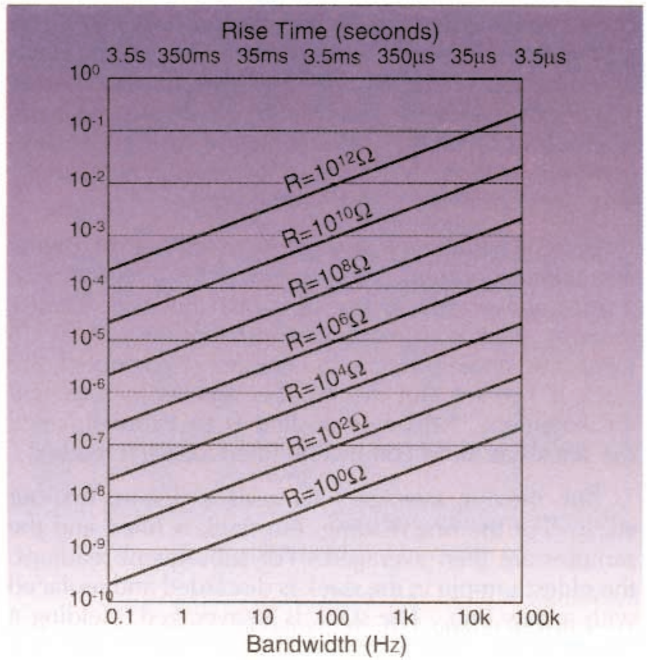


Figure 1. Noise voltage vs. bandwidth at various source resistances.

of electrons due to their thermal energy at temperatures above absolute zero (0 ºK). Figure 1 shows the thermal noise voltage as a function of resistance and bandwidth. Johnson noise is defined by the equation V = square root of 4kTBR, where:

V = rms noise voltage developed in the source resistance

k = Boltzman's constant (1.38 e-23 joule/ºK)

T = absolute temperature of the source in ºK

B = Noise bandwidth in hertz

R = Resistance of the source in ohms

Johnson noise can be minimized by lowering the temperature of the DUT and by decreasing the noise bandwidth of the measurement. In high resistance measurement circuits, noise bandwidth is often limited by the RC time constant (rise time) created by the resistance of the DUT and signal source output, combined with the measuring instrument's input capacitance.

Noise bandwidth can be artificially reduced by programming the instrument to average a number of digital readings (discussed later) and by using an analog low-pass filter ahead of the voltmeter. However, there is a practical limit to these methods as they slow down data collection, and very long measurements are susceptible to time and temperature drift errors.

Non-periodic noise: Typically, non-periodic noise levels randomly fluctuate above and below the acquired signal. Johnson noise is one example. When this is the case, a digital filter can be used to average a number of A/D conversions before displaying the result. This removes the random noise artifacts because their excursions above and below the signal level are about equal over a sufficient period of time. The greater the number of conversions averaged, the slower the measurement rate, but the lower the noise error. Trade offs between speed and noise are normally required to tailor the instrumentation to the measurement application. When random noise is not a problem, the digital filter can be turned off.

Some instruments also allow a choice of digital averaging algorithms, for example, either a repeating or a moving average. A repeating filter involves filling a memory stack with readings and taking an average to yield one reading. Once the reading is computed, the stack is flushed and the process repeats for the next measurement. This type of filter is the slowest, since the stack has to be completely filled for each reading.

The moving average filter uses a first-in, first-out stack. For the first reading, the stack is filled and the samples are then averaged. For subsequent readings, the oldest sample in the stack is discarded and replaced with a new one. The stack is re-averaged, yielding a new reading. This method is the faster of the two, but since not as many samples are taken, it is slightly less stable than the repeat averaging filter.

The test program algorithm should be written so it clears the filter memory stacks at appropriate times to avoid the problem of averaging an inappropriate set of readings. Averaging readings from multiple DUTs or readings at distinctly different voltage levels would be examples of this.

Magnetic fields: Magnetic fields generate spurious voltage in two circumstances: (a) the field is changing with time or (b) there is relative motion between the circuit and the field. The amount of voltage a magnetic field induces in a circuit is proportional to the rate of change in magnetic flux density and the area that circuit leads enclose. To minimize induced magnetic voltages, leads should be run close together and magnetically shielded. Also, fasten the leads to a solid stationary support to reduce movement. To further reduce the effects of nearby magnetic fields, use Mu metal shielding around the measurement circuit. (Mu metal is a special alloy with high permeability at low magnetic flux densities and low frequencies.)

Conductors carrying large currents should also be shielded or run as twisted pairs to prevent generating magnetic fields that can affect nearby measurement circuits. Keeping the measuring instrument physically separated from magnetic fields also is good practice in reducing such errors.

Ground loops: Noise and error voltages also arise from ground loops. When the voltage source and measuring instrument are both connected to a common ground bus, but at different locations, a loop is formed. A voltage between the source ground and instrument ground will cause a current to flow around the loop. This current creates an unwanted voltage in series with the source voltage. Frequently, ground loop are formed when a number of instruments and sources are plugged into power strips on different instrument racks.

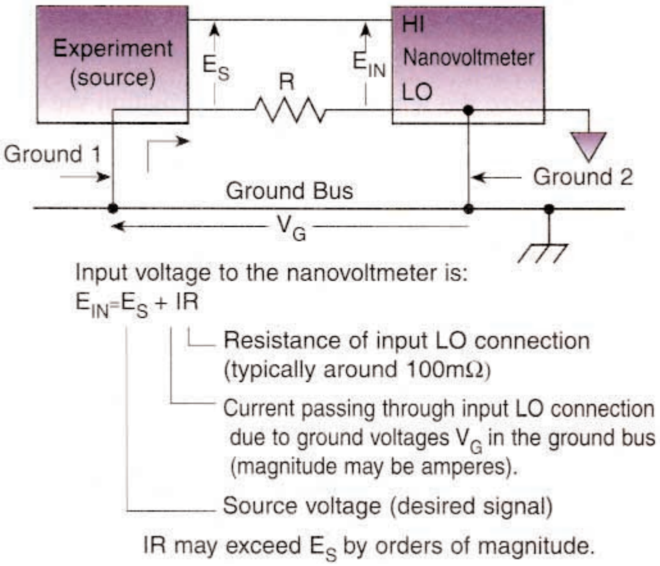
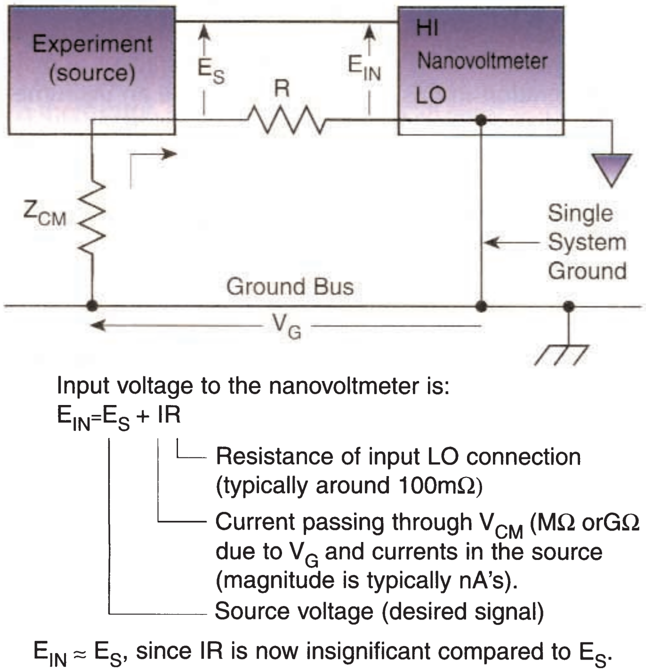


Figure 2. Formation of a ground loop in a measurement circuit.

A good way to eliminate ground loops is to ground all the test equipment at a single point. The easiest way to do this is use isolated power sources and instruments, then find a single, good, earth ground point for the entire system. However, if an instrument is particularly sensitive, avoid connecting it to the same ground system used by other instruments, machinery or high-power equipment.

RESISTANCE MEASUREMENTS

Commonly, errors in resistance measurements arise from test lead resistance, thermoelectric EMFs, nonohmic contacts and device heating (thermal effects). Some instrument come with standard features or options that help reduce these errors.



Input voltage to the nanovoltmeter is:
$E_{IN}=E_S + IR$

Resistance of input LO connection (typically around 100mΩ)

Current passing through V_{CM} (MΩ orGΩ due to V_G and currents in the source (magnitude is typically nA's).

Source voltage (desired signal)

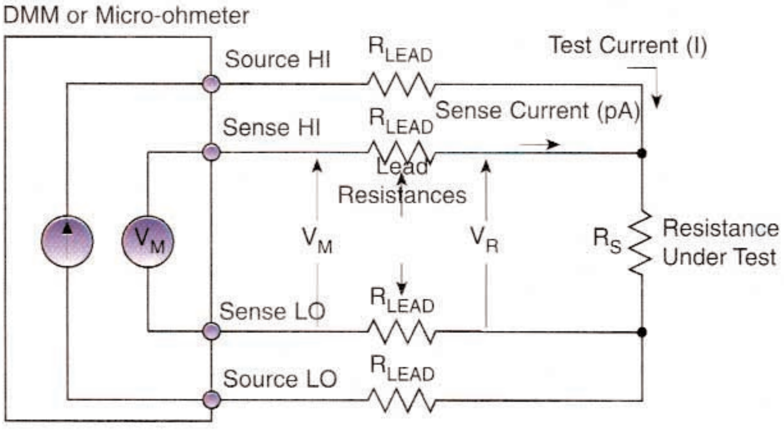
$E_{IN} \approx E_S$, since IR is now insignificant compared to E_S.

Figure 3. Single system ground minimizes ground loop effects.

Lead Resistance – One of the most common sources of error in relatively low resistance measurements is the test lead resistance. This is the resistance in the leads from the meter to the circuit and it is added to the overall resistance measurement. There are two ways to eliminate this error: (a) periodically short the ohmeter's two-wire measurement leads to zero the instrument or (b) use a four-wire (Kelvin) lead arrangement if available on the instrument.

Zeroing the instrument: Shorting the ohmeter's two-wire measurement leads is good for short term "re-zeroing" but can drift over time. The drift can be severe, for example, from reading to reading, but usually is a longer term problem.

Four-wire resistance measurement: This is the industry standard for minimizing test lead errors; this feature is available on a large number of ohmeters and DMMS. With this method, the instrument forces a test current through the DUT resistance using two source leads. The meter reads the voltage developed across the DUT resistance with another set of leads. (See Figure 4.) Since the voltage sensing part of this circuit (voltmeter) has a high input impedance(typically on the order of 109 ohms), almost no test current flows into the meter and almost all of the current flows into the DUT resistance. Only the voltage at the DUT is measured. Therefore no "test lead" resistance is part of the measuring circuit.



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

Figure 4. Four-wire resistance measurements minimize lead resistance errors.

Since this method involves two additional leads, many instruments provide the convenience of input connections for a Kelvin probe or clip assembly. Typically, this type of assembly provides two test electrodes in one clip-on connection (Figure 5). With two electrodes per probe and two probes per assembly, there really are four wires with only two connections. There still can be offset error if zero verification is not performed before taking measurements. Typically, zero verification tests are performed when:

1. The ohmeter or DMM has not been used for several hours or more

2. The test configuration has changed

3. There has been a significant change in DUT characteristics

4. Uncertainty or change has been introduced into the test envi-

ronment, such as power outage/fluctuation, temperature change, etc.

Thermoelectric EMFs – Thermoelectric voltages can be a source of error in resistance measurements. The two methods most commonly used to overcome these unwanted offsets are the current reversal method and offset compensated ohms measurement.

Current reversal method: Current reversal can be used to cancel the effect of thermoelectric potentials by making two measurements of opposite polarity. As shown in Figure 6, you force a test current with one polarity and take a voltage measurement across the DUT. Then you force the same test current with the opposite polarity and take another voltage measurement. Next, you calculate the difference of the two voltages by algebraically subtracting the two measurements, which cancels out the thermoelectric potentials in series with the desired voltage. Finally, you divide this algebraic difference by two, which averages the two measurements, using the result to calculate the DUT resistance.

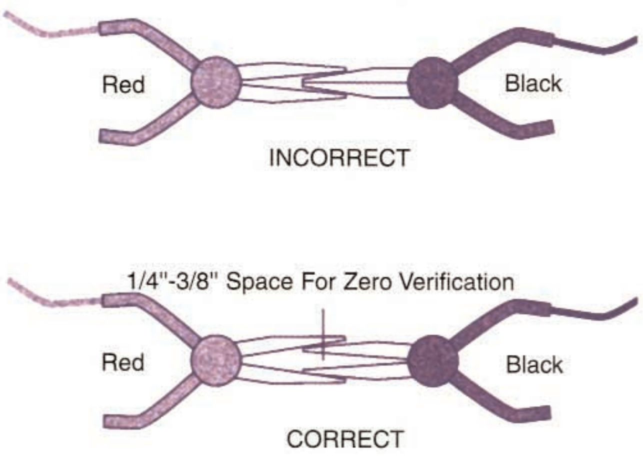
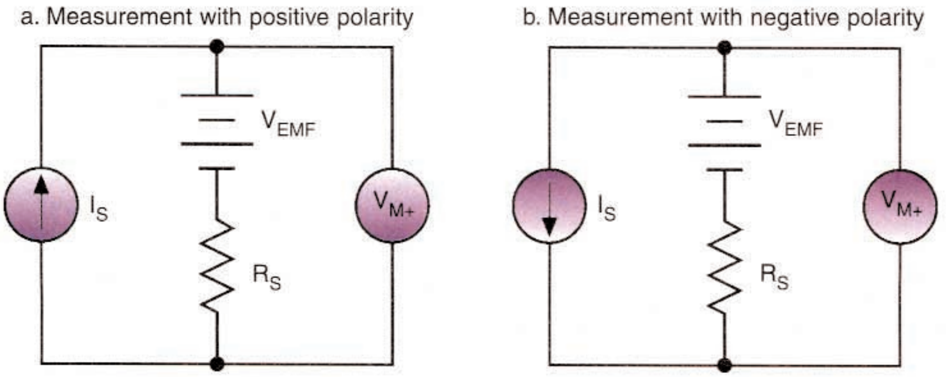


Figure 5. Kelvin probes and clip assemblies simplify and speed up four-wire measurements.

Offset compensated ohms: This offset canceling method also requires two measurements. In this technique (Figure 7), the test current is applied to the DUT and a voltage measurement is made. The test current is then turned off and another voltage measurement is made. This last voltage measurement is the measurement of the thermoelectric EMFs in the circuit. The voltage measurements are then algebraically subtracted. The result is an offset compensated voltage measurement, which is used to calculate the resistance. A major consideration in this technique is to have an instrument with adequate resolution and sensitivity to accurately measure the thermal EMF.

Both of these methods require two voltage readings and some internal calculations. Therefore, a complete measurement takes at least twice as much time as a standard measurement. However, some instruments are designed to make it easier to do these types of measurements and the required calculations. If thermal EMFs can not be eliminated or reduced with techniques mentioned earlier, then look for instruments that simplify and speed up current reversal or offset compensated ohms measurements.

Non-Ohmic Contacts – Frequently, switch and connector contacts are part of the measurement circuit, so you must guard against the effects of non-ohmic contacts. These contacts usually are the result of oxide films. They are manifested as a potential difference across the contact that is not linearly proportional to the current flowing through it. Non-ohmic contacts tend to rectify any RFI noise energy that is present, causing an offset to appear in the circuit. To prevent such errors, choose an appropriate contact material, such as indium or gold.


a. Measurement with positive polarity

b. Measurement with negative polarity

$$V_{M+} = V_{EMF} + I_S R_S \qquad V_{M-} = V_{EMF} - I_S R_S$$

$$V_M = \frac{V_{M+} - V_{M-}}{2} = I_S R_S$$

Figure 6. Canceling thermoelectric EMFs with current reversal.

Another precaution is to make sure the current source clamps the test voltage at a high enough level to avoid problems due to source contact non-linearity. (This is adjustable in most source-measurement instruments.) To reduce error due to voltmeter non-ohmic contacts, reduce AC pick-up by using shielding and appropriate grounding.

Device Heating – Some DUTs are temperature sensitive and prone to self-heating due to power dissipation when current is applied. This can change the DUT's resistance. A prime example is a thermistor. Limiting the test current is the best way to avoid errors when making resistance measurements on such devices. Depending on instrument design, this can be inconvenient. For example, when using a high resolution ohmmeter, you may need to change to a higher measurement range to force a smaller test current and therefore reduce power dissipation in the DUT. Some source-measurement instruments make this easier by providing an adjustable current limit or by applying the current as a short pulse to limit self-heating. Two pulses of opposite polarity can also compensate for thermal EMFs, as discussed earlier.

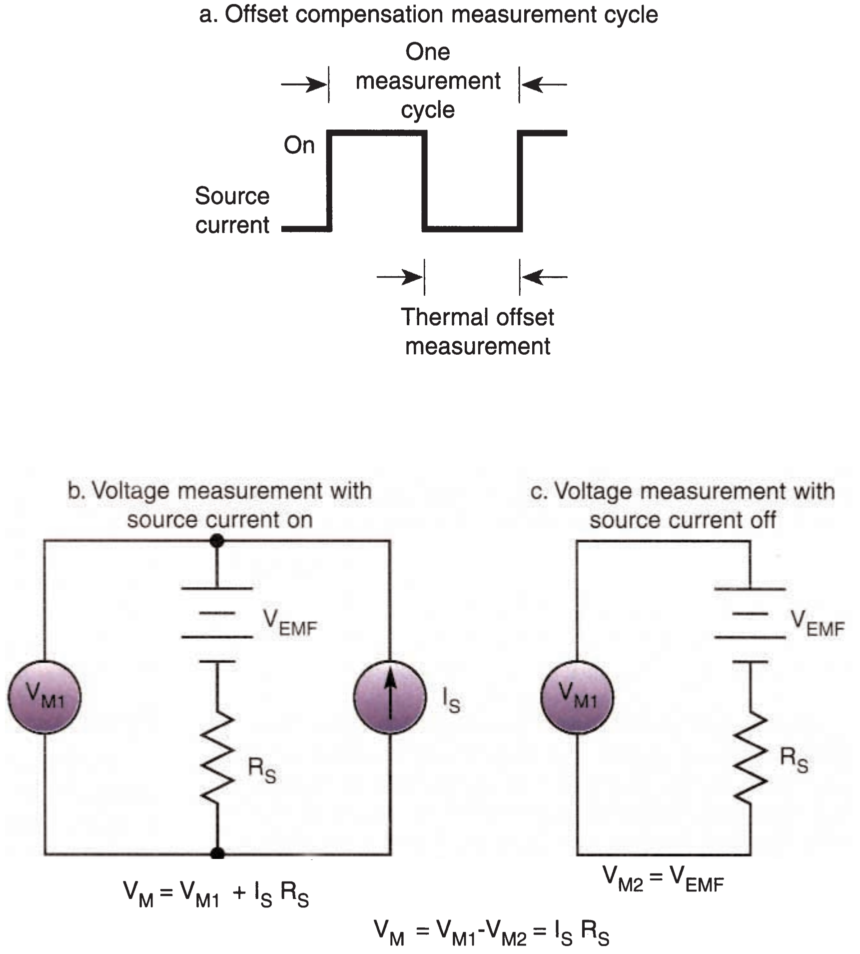


Figure 7. Offset compensated ohms measurement.

However, pulse techniques can present problems when measuring the resistance of inductive devices, such as transformers. Inductance may prevent current through the device from reaching its maximum value before a voltage measurement is taken. This will happen if the L/R time constant is greater than the pulse width, resulting in a resistance reading lower than would be the case with no inductance. If you suspect this type of pulse-mode measurement problem, make a second resistance measurement with a steady DC current applied. If the second reading is much higher than the first one, then pulse-mode measurements are probably causing inaccuracies. If the option is available, you can try programming the instrument for a longer pulse duration that is more suitable for the DUT's L/R time constant. Otherwise, steady DC measurements will probably provide better results.

These discussions point out that a high accuracy/high resolution instrument is not always enough to guarantee desired results. Paying attention to external measurement circuitry and noise sources can help avoid errors and provide more leeway in speed/accuracy trade-offs when programming the instrument. When noise sources can not be avoided, the techniques presented here help minimize their effects and improve results.

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