Technical Information

Low Voltage/Low Resistance Measurements

A voltmeter is an instrument for measuring the electrical potential difference between two points, calibrated in volts.

How to Select a Voltmeter

Many kinds of instruments can measure voltage, including digital multimeters (DMMs), electrometers, and nanovoltmeters. Making voltage measurements successfully requires a voltmeter with significantly higher input impedance than the internal impedance (source impedance) of the device under test (DUT). Without it, the voltmeter will measure less potential difference than existed before the voltmeter was connected. Electrometers have very high input impedance (typically in the order of 100TΩ [10^{14}Ω]), so they're the instrument of choice for high impedance voltage measurements. DMMs and nanovoltmeters can typically be used for measuring voltages from 10MΩ sources or lower. Nanovoltmeters are appropriate for measuring low voltages (microvolts or less) from low impedance sources.

Low Voltage Measurements

Significant errors may be introduced into low voltage measurements by offset voltage and noise sources that can normally be ignored when measuring higher signal levels. Steady offsets can generally be nulled out by shorting the ends of the test leads together, then enabling the instrument's zero (relative) feature. The following paragraphs discuss non-steady types of error sources that can affect low voltage measurement accuracy and how to minimize their impact on the measurements.

Thermoelectric EMFs

The most common sources of error in low voltage measurements are thermoelectric voltages (thermoelectric EMFs) generated by temperature differences between junctions of conductors (**Figure 1**).

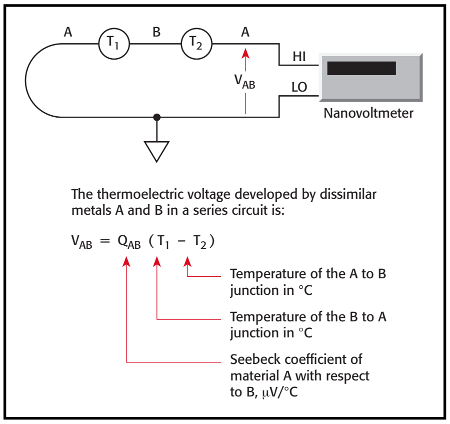

Figure 1. Thermoelectric EMFs

Constructing circuits using the same material for all conductors minimizes thermoelectric EMF generation. For example, connections made by crimping copper sleeves or lugs on copper wires results in cold-welded copper-to-copper junctions, which generate minimal thermoelectric EMFs. Also, connections must be kept clean and free of oxides.

Minimizing temperature gradients within the circuit also reduces thermoelectric EMFs. A way to minimize such gradients is to place all junctions in close proximity and provide good thermal coupling to a common, massive heat sink. If this is impractical, thermally couple *each pair* of corresponding junctions of dissimilar materials to minimize their temperature differentials which will also help minimize the thermoelectric EMFs.

Johnson Noise

The ultimate limit to how well the voltmeter can resolve a voltage is defined by Johnson (thermal) noise. This noise is the voltage associated with the motion of electrons due to their thermal energy. All sources of voltage will have internal resistance, and thus produce Johnson noise. The noise voltage developed by any resistance can be calculated from the following equation:

$$V = \sqrt{4kTBR}$$

k = Boltzmann's constant (1.38×10^{-23} J/K)
T = absolute temperature of the source in Kelvin
B = noise bandwidth in Hz
R = resistance of the source in ohms

From this equation, it can be observed that Johnson noise may be reduced by lowering the temperature and by decreasing the bandwidth of the measurement. Decreasing the bandwidth of the measurement is equivalent to increasing the response time of the instrument; thus, *in addition to increasing filtering*, the bandwidth can be reduced by increasing instrument integration (typically in multiples of power line cycles).

Ground Loops

When both the signal source and the measurement instrument are connected to a common ground bus, a ground loop is created (**Figure 2a**). This is the case when, for instance, a number of instruments are plugged into power strips on different instrument racks. Frequently, there is a difference in potential between the ground points. This potential difference—even though it may be small—can cause large currents to circulate and create unexpected voltage drops. The cure for ground loops is to ground the entire measurement circuit at only one point. The easiest way to accomplish this is to isolate the DUT (source) and find a single, good earth-ground point for the measuring system, as shown in **Figure 2b**. Avoid grounding sensitive measurement circuits to the same ground system used by other instruments, machinery, or other high power equipment.

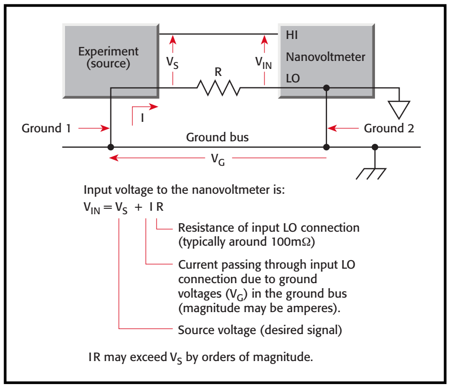

Figure 2a: Multiple Grounds (Ground Loops)

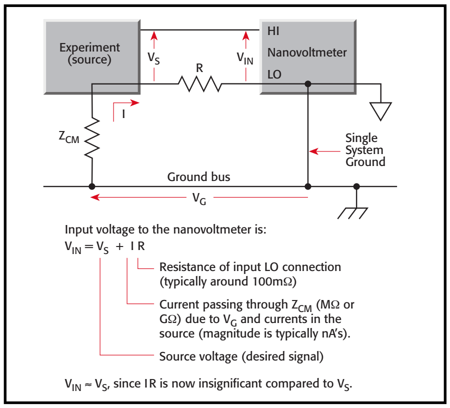

Figure 2b: Single System Ground

Magnetic Fields

Magnetic fields generate spurious voltages in two circumstances: 1) if the field is changing with time, and 2) if there is relative motion between the circuit and the field (**Figure 3a**). Changing magnetic fields can be generated from the motion of a conductor in a magnetic field, from local AC currents caused by components in the test system, or from the deliberate ramping of the magnetic field, such as for magnetoresistance measurements.

To minimize induced magnetic voltages, leads must be run close together and should be tied down to minimize movement. Twisted pair cabling reduces the effects of magnetic fields in two ways: first, it reduces the loop area through which the magnetic field is interfering; second, a magnetic field will create voltages of opposite polarities for neighboring loops of the twisted pair that will cancel each other. (**Figure 3b**)

Low Resistance Measurements

Low resistances (<10Ω) are typically best measured by sourcing current and measuring voltage. For very low resistances (micro-ohms or less) or where there are power limitations involved, this method will require measuring very low voltages, often using a nanovoltmeter. Therefore, all the low voltage techniques and error sources described previously also apply here. Low resistance measurements are subject to additional error sources. The next sections describe methods to minimize some of these.

Low Voltage/Low Resistance Measurements

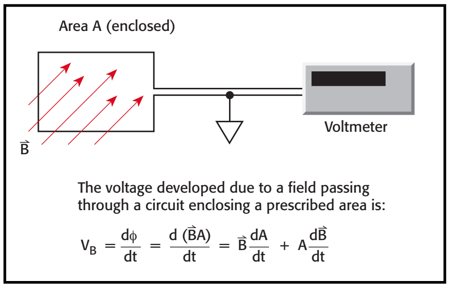

Figure 3a: Voltages generated by magnetic fields

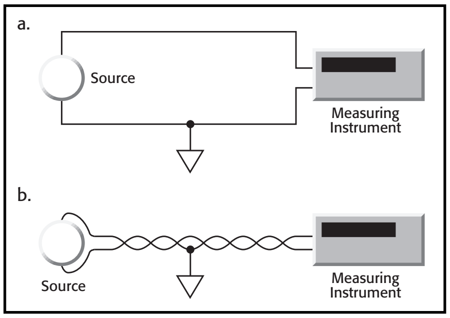

Figure 3b: Minimizing interference from magnetic fields with twisted leads

Lead Resistance and Four-Wire Method

Resistance measurements in the normal range (>10Ω) are generally made using the two-wire method shown in **Figure 4a**. The main problem with the two-wire method for low resistance measurements (<10Ω) is the error caused by lead resistance. The voltage measured by the meter will be the sum of the voltage directly across the test resistance and the voltage drop across the leads. Typical lead resistances lie in the range of 1mΩ to 100mΩ. Therefore, the four-wire (Kelvin) connection method shown in **Figure 4b** is preferred for low resistance measurements. In this configuration, the test current is forced through the DUT through one set of test leads while the voltage is measured using a second set of leads called the sense leads. There is very little current running through the sense leads, so the sense lead resistance has effectively been eliminated.

Thermoelectric EMFs

Thermoelectric voltages can seriously affect low resistance measurement accuracy. Given that resistance measurements involve *controlling* the current through the DUT, there are ways to overcome these unwanted offsets in addition to those mentioned in the low voltage measurement section, namely, the offset-compensated ohms method and the current-reversal method.

1) **Offset Compensation Technique** (**Figure 5a**) applies a source current to the resistance being measured only for part of the measurement cycle.

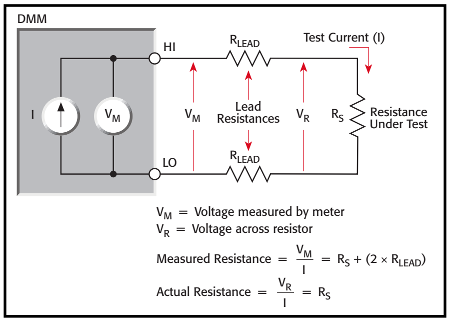

Figure 4a: 2-wire Resistance Measurement: Lead Resistance Error

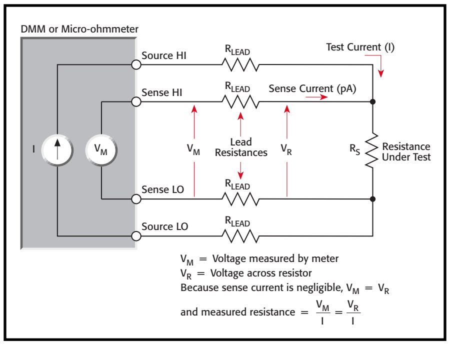

Figure 4b: 4-wire Resistance Measurement

When the source current is on, the total voltage measured by the instrument is the sum of the voltage due to the test current and any thermoelectric EMFs present in the circuit. During the second half of the measurement cycle, the source current is turned off and the only voltage measured is that due to the thermoelectric EMF. This unwanted offset voltage can now be subtracted from the voltage measurement made during the first half of the delta mode cycle.

- **Current Reversal Technique/Delta Mode** (**Figure 5b**).

  Thermoelectric EMFs can also be cancelled by taking two voltages with test currents of opposite polarity. The voltage due to the test current can now be calculated using the formula shown in **Figure 5b**. This method provides better noise immunity and, therefore, better accuracy than the offset compensation technique. (*This is the method employed by the Model 2182 Nanovoltmeter/Model 2400 SourceMeter instrument combination.*)

For these methods to be effective, the consecutive measurements need to be made rapidly when compared with the thermal time constant of the circuit under test. If the instruments' response speed is too low, changes in the circuit temperature during the measurement cycle will cause changes in the thermoelectric EMFs, with the result that the thermoelectric EMFs are no longer fully cancelled.

Dry Circuit Testing

Applications that involve measuring contact resistance may require that existing oxide layers remain unbroken during the measurement. This can be done by limiting the test current to less than 100mA and the voltage drop across the sample to no more than 20mV. Most low resistance meters have this "dry circuit" measurement technique built in.

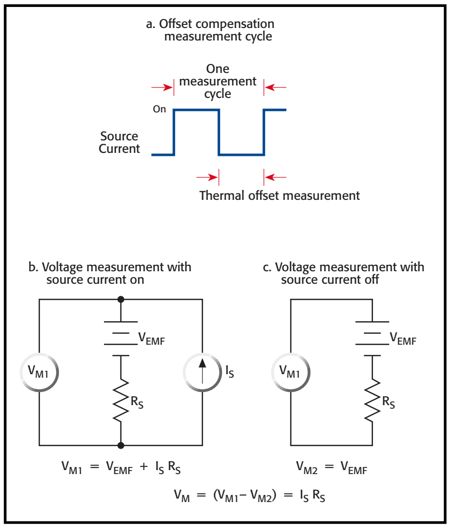

Figure 5a: Subtracting Thermoelectric EMFs with Offset Compensation

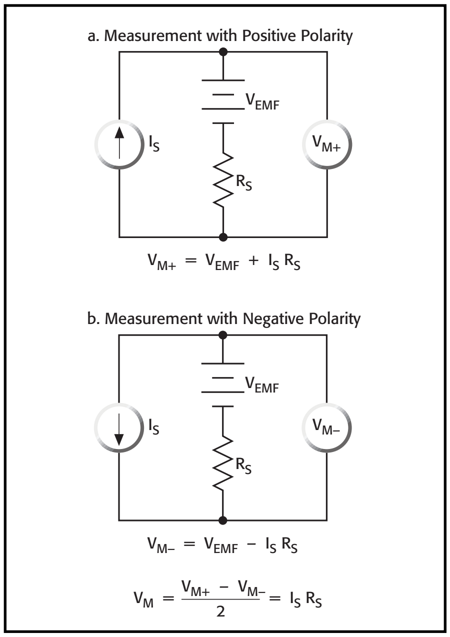

Figure 5b: Canceling Thermoelectric EMFs with Current Reversal

Selector Guide Low Voltage/Low Resistance Meters

MODEL	**2182A**	**1801 with 2001 or 2002**	**2002**	**2010**	**2750**
Page	229	235	27	29	238
VOLTAGE RANGE (Full Scale)					
From	10 mV	20 µV	200 mV	100 mV	100 mV
To	100 V	2 mV	1000 V	1000 V	1000 V
Input Voltage Noise	1.2 nV rms	0.12 nV rms	150 nV rms	100 nV rms	<1.5 µV rms
RESISTANCE RANGE					
From[1]	10 nΩ[3]	20 µΩ	1.2 mΩ	0.9 mΩ	0.4 mΩ
To[2]	100 MΩ[3]	200 Ω	1 GΩ	100 MΩ	100 MΩ
THERMOCOUPLE TEMPERATURE					
From	–200°C	–200°C	–200°C	–200°C	–200°C
To	1820°C	1820°C	1820°C	1372°C	1820°C
FEATURES					
IEEE-488	•	•	•	•	•
RS-232	•		•	•	•
CE	•		•	•	•
Input Connection	Special low thermoelectric w/copper pins. Optional 2187-4 Modular Probe Kit adds banana plugs, spring clips, needle probes, and alligator clips.	Copper nuts	Banana jacks (4)	Banana jacks (4)	Banana jacks (4)
Special Features	Delta mode and differential conductance with Model 6220 or 6221. Pulsed I-V with Model 6221. Analog output. IEEE-488. RS-232.	Multi-function. Temperature. IEEE-488. DMM.	8½ digits. DMM. Plug-in scanner cards.	Dry circuit. Offset compensation. DMM. IEEE-488. RS-232. Plug-in scanner cards.	Dry circuit. Offset compensation. DMM. IEEE-488. RS-232. Digital I/O. Plug-in modules.

1. Lowest resistance measurable with better than 10% accuracy.
2. Highest resistance measurable with better than 1% accuracy.
3. Delta mode, offset voltage compensation with external current source. 10nΩ if used with 5A test current with Model 2440.