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6th Edition

Low Level Measurements Handbook

Precision DC Current, Voltage, and Resistance Measurements

KEITHLEY

SECTION 3

Measurements from Low Resistance Sources

3.1 Introduction

Low voltage and low resistance measurements are often made on devices and materials with low source impedance. While Section 1 described instruments for measuring low voltage and low resistance, Section 3 describes how to use these instruments to make accurate measurements, including a discussion of various error sources and ways to minimize their effect on measurement integrity:

3.2 Low Voltage Measurements: Discussion of potential error sources and how to minimize their impact on low voltage measurement accuracy. These error sources include offset voltages, noise and common-mode current, and reversal errors.

3.3 Low Resistance Measurements: Topics include lead resistance, thermoelectric EMFs, non-ohmic contacts, device heating, dry circuit testing, and measuring inductive devices.

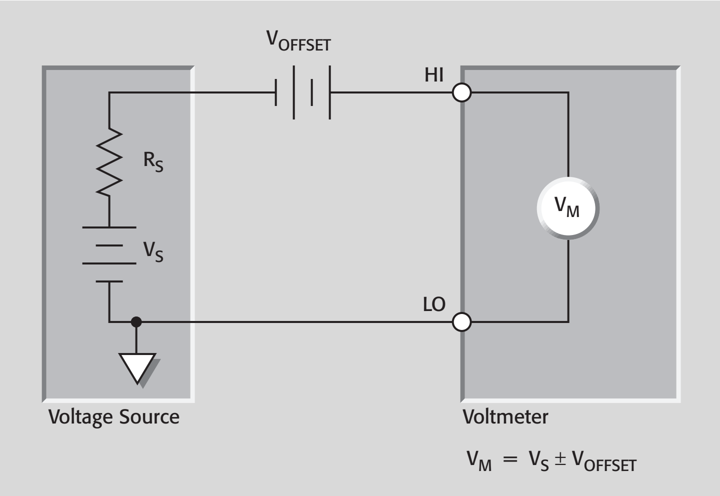
3.2 Low Voltage Measurements

Significant errors may be introduced into low voltage measurements by offset voltages and noise sources that can normally be ignored when measuring higher voltage levels. The following paragraphs discuss factors that can affect low voltage measurement accuracy.

3.2.1 Offset Voltages

Ideally, when a voltmeter is connected to a relatively low impedance circuit in which no voltages are present, it should read zero. However, a number of error sources in the circuit may be seen as a non-zero voltage offset.

FIGURE 3-1: Effects of Offset Voltages on Voltage Measurement Accuracy



These sources include thermoelectric EMFs, offsets generated by rectification of RFI (radio frequency interference), and offsets in the voltmeter input circuit.

As shown in **Figure 3-1**, any offset voltage (V_{OFFSET}) will add to or subtract from the source voltage (V_S) so that the voltage measured by the meter becomes:

$V_M = V_S \pm V_{OFFSET}$

The relative polarities of the two voltages will determine whether the offset voltage adds to or subtracts from the source voltage.

For example, assume $V_S = 5\mu V$ and $V_{OFFSET} = 250nV$. If the voltage polarities are in opposition, the voltmeter reading will be:

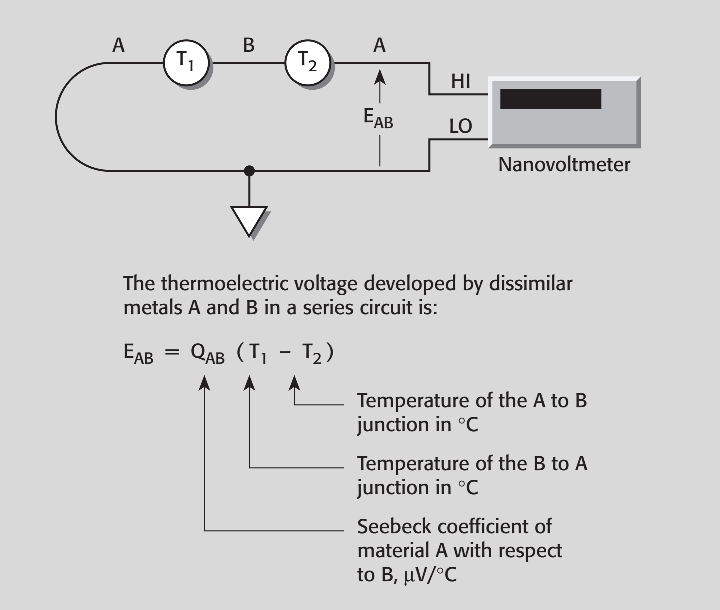
$V_M = (5 \times 10^{-6}) - (250 \times 10^{-9})$

$V_M = 4.75 \times 10^{-6}$

$V_M = 4.75\mu V$ (an error of –5%)

Steady offsets can generally be nulled out by shorting the ends of the test leads together, then enabling the instrument's zero (relative) feature. Note, however, that cancellation of offset drift may require frequent rezeroing, particularly in the case of thermoelectric EMFs.

FIGURE 3-2: Thermoelectric EMFs



The thermoelectric voltage developed by dissimilar metals A and B in a series circuit is:

$E_{AB} = Q_{AB} (T_1 - T_2)$

Temperature of the A to B junction in °C

Temperature of the B to A junction in °C

Seebeck coefficient of material A with respect to B, µV/°C

Thermoelectric EMFs

Thermoelectric voltages (thermoelectric EMFs) are the most common source of errors in low voltage measurements. These voltages are generated when different parts of a circuit are at different temperatures and when conductors made of dissimilar materials are joined together, as shown in **Figure 3-2**. The Seebeck coefficients (Q_{AB}) of various materials with respect to copper are summarized in **Table 3-1**.

TABLE 3-1: Seebeck Coefficients

Paired Materials*	Seebeck Coefficient, Q_{AB}
Cu - Cu	≤0.2 µV/°C
Cu - Ag	0.3 µV/°C
Cu - Au	0.3 µV/°C
Cu - Pb/Sn	1–3 µV/°C
Cu - Si	400 µV/°C
Cu - Kovar	~40–75 µV/°C
Cu - CuO	~1000 µV/°C

* Ag = silver   Au = gold   Cu = copper   CuO = copper oxide
Pb = lead   Si = silicon   Sn = tin

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 copper-to-copper junctions, which generate minimal thermoelectric EMFs. Also, connections must be kept clean and free of oxides. Crimped copper-to-copper connections, called “cold welded,” do not allow oxygen penetration and may have a Seebeck coefficient of ≤0.2µV/°C, while Cu-CuO connections may have a coefficient as high as 1mV/°C.

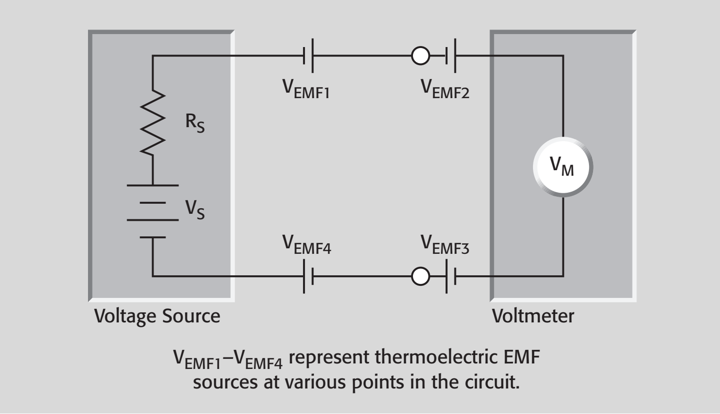
Minimizing temperature gradients within the circuit also reduces thermoelectric EMFs. A technique for minimizing such gradients is to place corresponding pairs of junctions in close proximity to one another and to provide good thermal coupling to a common, massive heat sink. Electrical insulators having high thermal conductivity must be used, but, since most electrical insulators don’t conduct heat well, special insulators such as hard anodized aluminum, beryllium oxide, specially filled epoxy resins, sapphire, or diamond must be used to couple junctions to the heat sink.

Allowing test equipment to warm up and reach thermal equilibrium in a constant ambient temperature also minimizes thermoelectric EMF effects. The instrument zero feature can compensate for any remaining thermoelectric EMF, provided it is relatively constant. To keep ambient temperatures constant, equipment should be kept away from direct sunlight, exhaust fans, and similar sources of heat flow or moving air. Wrapping connections in insulating foam (e.g., polyurethane) also minimizes ambient temperature fluctuations caused by air movement.

Connections to Avoid Thermoelectric EMFs

Connections in a simple low voltage circuit, as shown in **Figure 3-3**, will usually include dissimilar materials at different temperatures. This results in a number of thermoelectric EMF sources, all connected in series with the voltage source and the meter. The meter reading will be the algebraic sum of all these sources. Therefore, it is important that the connection between the signal source and the measuring instrument doesn't interfere with the reading. The following paragraphs provide tips on making good connections to minimize thermoelectric voltages.

FIGURE 3-3: Connections from Voltage Source to Voltmeter



If all the connections can be made of one metal, the amount of thermoelectric EMF added to the measurement will be negligible. However, this may not always be possible. Test fixtures often use spring contacts, which may be made of phosphor-bronze, beryllium-copper, or other materials with high Seebeck coefficients. In these cases, a small temperature difference may generate a large enough thermoelectric voltage to affect the accuracy of the measurement.

If dissimilar metals cannot be avoided, an effort should be made to reduce the temperature gradients throughout the test circuit by use of a heat sink or by shielding the circuit from the source of heat.

Measurements of sources at cryogenic temperatures pose special problems since the connections between the sample in the cryostat and the voltmeter are often made of metals with lower thermal conductivity than copper, such as iron, which introduces dissimilar metals into the circuit. In addition, since the source may be near zero Kelvin while the meter is at 300K, there is a very large temperature gradient. Matching the composition of the wires between the cryostat and the voltmeter and keeping all dissimilar metal junction pairs at the same temperature allows making very low voltage measurements with good accuracy.

Reversing Sources to Cancel Thermoelectric EMFs

When measuring a small voltage, such as the difference between two standard cells or the difference between two thermocouples connected back-to-back, the error caused by stray thermoelectric EMFs can be canceled by taking one measurement, then carefully reversing the two sources and taking a second measurement. The average of the difference between these two readings is the desired voltage difference.

In **Figure 3-4**, the voltage sources, V_a and V_b, represent two standard cells (or two thermocouples). The voltage measured in **Figure 3-4a** is:

$$V_1 = V_{emf} + V_a - V_b$$

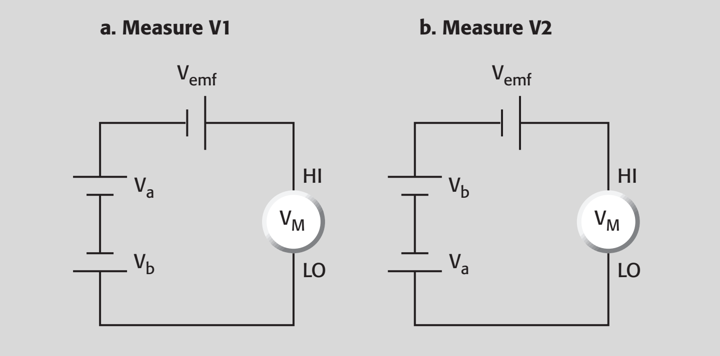
The two cells are reversed in **Figure 3-4b** and the measured voltage is:

$$V_2 = V_{emf} + V_b - V_a$$

The average of the difference between these two measurements is:

$$\frac{V_1 - V_2}{2} = \frac{V_{emf} + V_a - V_b - V_{emf} - V_b + V_a}{2} \text{ or } V_a - V_b$$

FIGURE 3-4: Reversing Sources to Cancel Thermoelectric EMFs

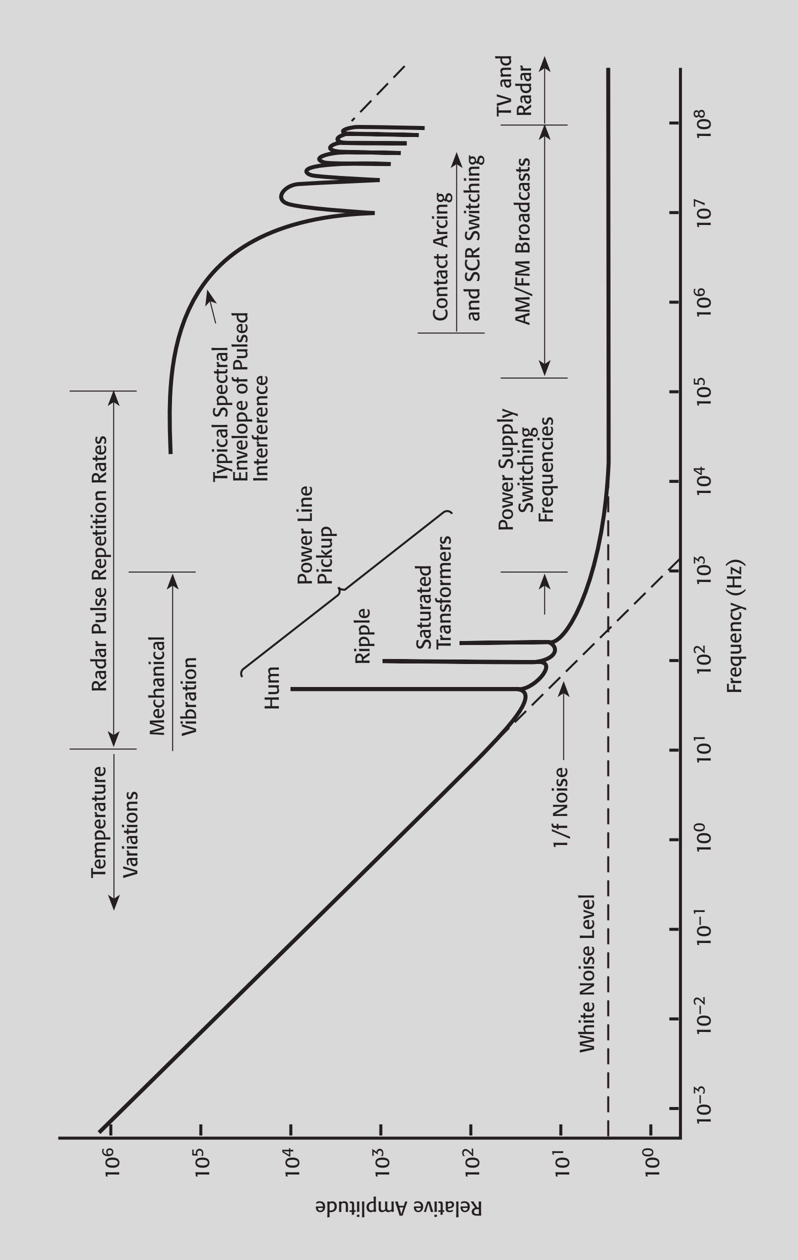


Notice that this measurement technique effectively cancels out the thermoelectric EMF term (V_{emf}), which represents the algebraic sum of all thermoelectric EMFs in the circuit except those in the connections between V_a and V_b. If the measured voltage is the result of a current flowing through an unknown resistance, then either the current-reversal method or the offset-compensated ohms method may be used to cancel the thermoelectric EMFs. These methods are described in Section 3.3.2.

RFI/EMI

RFI (Radio Frequency Interference) and EMI (Electromagnetic Interference) are general terms used to describe electromagnetic interference over a wide range of frequencies across the spectrum. **Figure 3-5** shows the general fre-

FIGURE 3-5: Voltage Noise Frequency Spectrum



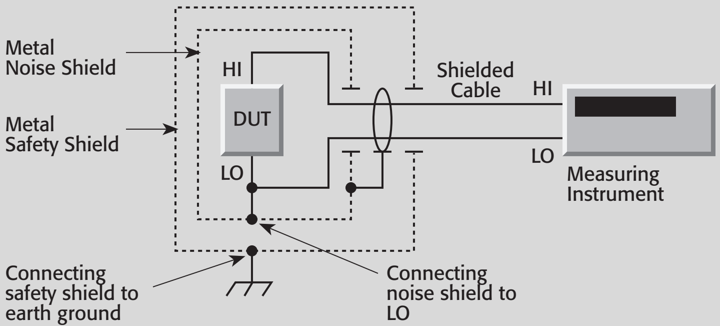
quency spectrum of these interference sources in comparison with other noise signals such as 1/f and thermal noise.

RFI or EMI can be caused by sources such as TV or radio broadcast signals or it can be caused by impulse sources, as in the case of high voltage arcing (see **Figure 3-5**). In either case, the effects on the measurement can be considerable if enough of the unwanted signal is present.

RFI/EMI interference may manifest itself as a steady reading offset or it may result in noisy or erratic readings. A reading offset may be caused by input amplifier overload or DC rectification at the input.

RFI and EMI can be minimized by taking several precautions when making sensitive measurements. The most obvious precaution is to keep all instruments, cables, and DUTs as far from the interference source as possible. Shielding the test leads and the DUT (**Figure 3-6**) will often reduce interference effects to an acceptable level. Noise shields should be connected to input LO. In extreme cases, a specially constructed screen room may be necessary to attenuate the troublesome signal sufficiently.

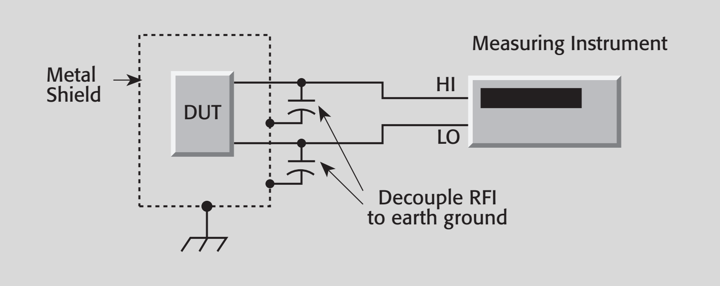
FIGURE 3-6: Shielding to Attenuate RFI/EMI Interference



WARNING
Safety shield is required when the noise shield is more than 30V DC or rms off earth ground.

If all else fails to prevent RF interference from being introduced into the input, external filtering of the device input paths may be required, as shown in **Figure 3-7**. In many cases, a simple one-pole filter may be sufficient; in more difficult cases, multiple-pole notch or band-stop filters may be required. In particular, multiple capacitors of different values may be connected in parallel to provide low impedance over a wide frequency range. Keep in mind, however, that such filtering may have other detrimental effects, such as increased response time on the measurement.

FIGURE 3-7: Shielded Connections to Reduce Inducted RFI/EMI



Internal Offsets

Nanovoltmeters and nanovolt preamplifiers will rarely indicate zero when no voltage is applied to the input, since there are unavoidable voltage offsets present in the input of the instrument. A short circuit can be connected across the input terminals and the output can then be set to zero, either by front panel zero controls or by computer control. If the short circuit has a very low thermoelectric EMF, this can be used to verify input noise and zero drift with time. Clean, pure copper wire will usually be suitable. However, the zero established in this manner is useful only for verification purposes and is of no value in the end application of the instrument.

If the instrument is being used to measure a small voltage drop resulting from the flow of current through a resistor, the following procedure will result in a proper zero. First, the instrument should be allowed to warm up for the specified time, usually one to two hours. During this time, the connections should be made between the device under test and the instrument. No current should be supplied to the device under test to allow the temperature gradients to settle to a minimum, stable level. Next, the zero adjustment should be made. In some instruments, this is done by pressing REL (for Relative) or ZERO button. The instrument will now read zero. When the test current is applied, the instrument will indicate the resulting voltage drop.

In some applications, the voltage to be measured is always present and the preceding procedure cannot be used. For example, the voltage difference between two standard cells is best observed by reversing the instrument connections to the cells and averaging the two readings. This same technique is used to cancel offsets when measuring the output of differential thermocouples. This is the same method used to cancel thermoelectric EMFs and is described in more detail in the paragraph entitled, “Reversing Sources to Cancel Thermoelectric EMFs.” See **Figure 3-4**.

Zero Drift

Zero drift is a change in the meter reading with no input signal (measured with the input shorted) over a period of time. The zero drift of an instrument is almost entirely determined by the input stage. Most nanovoltmeters use some form of chopping or modulation of the input signal to minimize the drift.

The zero reading may also vary as the ambient temperature changes. This effect is usually referred to as the temperature coefficient of the voltage offset.

In addition, an instrument may display a transient temperature effect. After a step change in the ambient temperature, the voltage offset may change by a relatively large amount, possibly exceeding the published specifications. The offset will then gradually decrease and eventually settle to a value close to the original value. This is the result of dissimilar metal junctions in the instrument with different thermal time constants. While one junction will adjust to the new ambient temperature quickly, another changes slowly, resulting in a temporary change in voltage offset.

To minimize voltage offsets due to ambient temperature changes in junctions, make measurements in a temperature controlled environment and/or slow down temperature changes by thermally shielding the circuit.

3.2.2 Noise

Significant errors can be generated by noise sources, which include Johnson noise, magnetic fields, and ground loops. An understanding of these noise sources and the methods available to minimize them is crucial to making meaningful low voltage measurements.

Johnson noise

The ultimate limit of resolution in an electrical measurement is defined by Johnson or thermal noise. This noise is the voltage associated with the motion of electrons due to their thermal energy at temperatures above absolute zero. All voltage sources have internal resistance, so all voltage sources develop Johnson noise.

A plot of thermal noise voltage as a function of resistance and bandwidth at a temperature of 290K is shown in **Figure 3-8**. This voltage is related to the temperature, noise bandwidth, and the source resistance. The noise voltage developed by a metallic resistance can be calculated from the following equation:

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

where: V = rms noise voltage developed in source resistance

k = Boltzmann's constant, 1.38×10^{-23} joule/K

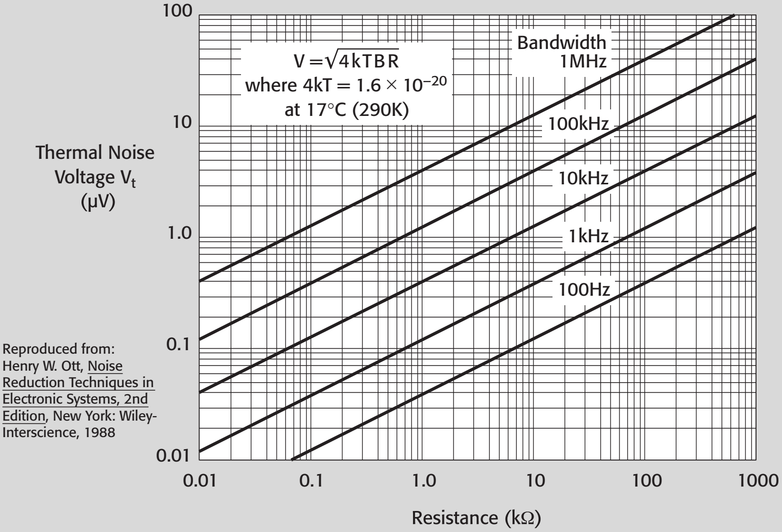
T = absolute temperature of the source in kelvin

B = noise bandwidth in hertz

R = resistance of the source in ohms

For example, at room temperature (290K), a source resistance of 10kΩ with a measurement bandwidth of 5kHz will have almost 1μV rms of noise.

FIGURE 3-8: Thermal Noise Voltage as a Function of Resistance and Bandwidth



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Johnson noise may be reduced by lowering the temperature of the source resistance and by decreasing the bandwidth of the measurement. Cooling the sample from room temperature (290K) to liquid nitrogen temperature (77K) decreases the voltage noise by approximately a factor of two.

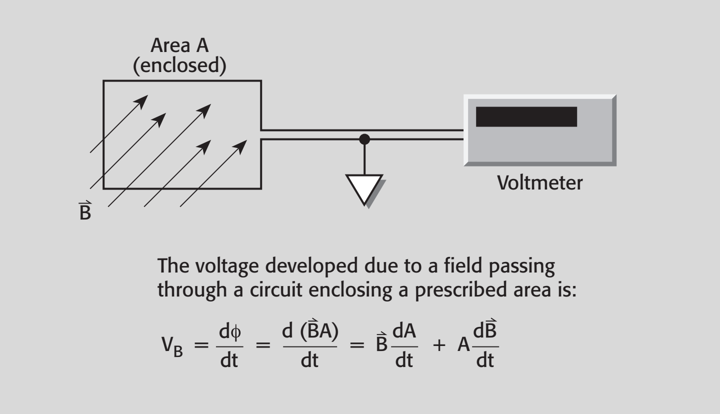
If the voltmeter has adjustable filtering and integration, the bandwidth can be reduced by increasing the amount of filtering and/or by integrating over multiple power line cycles. Decreasing the bandwidth of the measurement is equivalent to increasing the response time of the instrument, and as a result, the measurement time is much longer. However, if the measurement response time is long, the thermoelectric EMFs associated with the temperature gradients in the circuit become more important. Sensitive measurements may not be achieved if the thermal time constants of the measurement circuit are of the same order as the response time. If this occurs, distinguishing between a change in signal voltage and a change in thermoelectric EMFs becomes impossible.

Johnson noise is discussed in more detail in Section 2.6.5.

Magnetic Fields

Magnetic fields generate error 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. Voltages in conductors 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

FIGURE 3-9: Low Voltages Generated by Magnetic Fields



field, such as for magneto-resistance measurements. Even the earth's relatively weak magnetic field can generate nanovolts in dangling leads, so leads must be kept short and rigidly tied down.

Basic physics shows that the amount of voltage a magnetic field induces in a circuit is proportional to the area the circuit leads enclose and the rate of change in magnetic flux density, as shown in **Figure 3-9**. The induced voltage (V_B) is calculated as follows:

$$V_B = \frac{d\phi}{dt} = \frac{d(\vec{B}A)}{dt} = \vec{B}\frac{dA}{dt} + A\frac{d\vec{B}}{dt}$$

where: V_B = induced voltage

A = loop area

$\vec{B}$ = magnetic flux density

$\phi = \vec{B}A$ = magnetic flux

The induced voltage is proportional both to the magnitude of A and $\vec{B}$, as well as to the rate of change in A and $\vec{B}$, so there are two ways to minimize the induced voltage:

- Keep both A and $\vec{B}$ to a minimum by reducing loop area and avoiding magnetic fields, if possible; and
- Keep both A and $\vec{B}$ constant by minimizing vibration and movement, and by keeping circuits away from AC and RF fields.

To minimize induced magnetic voltages, leads must be run close together and magnetically shielded and they should be tied down to minimize movement. Mu-metal, a special alloy with high permeability at low magnetic flux densities and at low frequencies, is a commonly used magnetic shielding material.

FIGURE 3-10: Minimizing Interference from Magnetic Fields

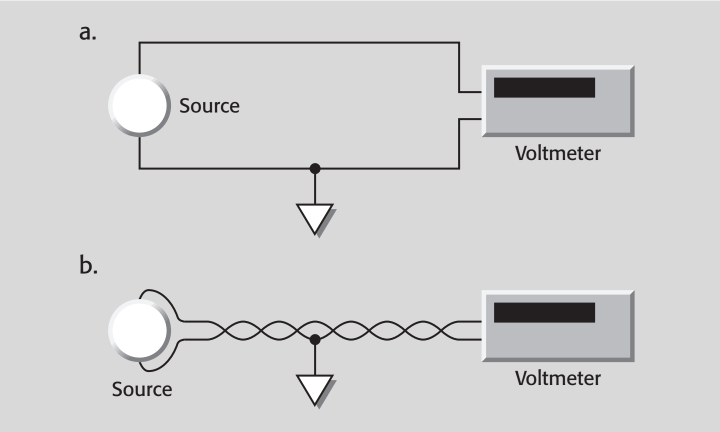


Figure 3-10 shows two ways of locating the leads from the source to the voltmeter. In **Figure 3-10a**, a large area is enclosed; thus, a large voltage is developed. In **Figure 3-10b**, a much smaller area is enclosed because the leads are twisted together, and the voltage induced is considerably reduced. Twisted pair also cancels magnetically induced voltages because each adjacent twist couples a small but alternating polarity (equal) voltage.

Conductors that carry large currents should also be shielded or run as twisted pairs to avoid generating magnetic fields that can affect nearby circuits. In addition to these techniques, AC signals from magnetic fields can be filtered at the input of the instrument. If possible, the signal source and the instrument should be physically relocated further away from the interfering magnetic field.

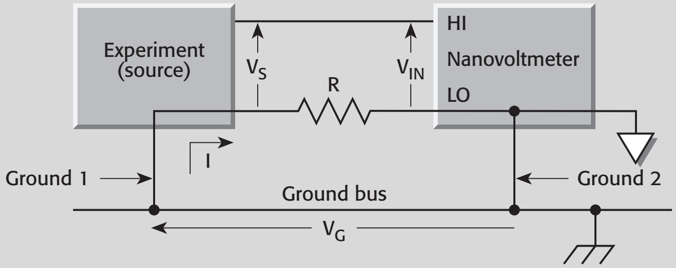
Ground Loops

Noise and error voltages also arise from ground loops. When there are two connections to earth, such as when the source and measuring instruments are both connected to a common ground bus, a loop is formed as shown in **Figure 3-11a**. A voltage (V_G) between the source and instrument grounds will cause a current (I) to flow around the loop. This current will create an unwanted voltage in series with the source voltage. From Ohm's Law:

$$V_G = IR$$

where V_G = ground loop interfering voltage, R = the resistance in the signal path through which the ground loop current flows, and I = the ground loop current. A typical example of a ground loop can be seen when a number of instruments are plugged into power strips on different instrument racks. Frequently, there is a small difference in potential between the ground points. This potential difference can cause large currents to circulate and create unexpected voltage drops.

FIGURE 3-11a: Multiple Grounds (Ground Loops)



Input voltage to the nanovoltmeter is:

$V_{IN} = V_S + V_G$

where V_G = IR, and

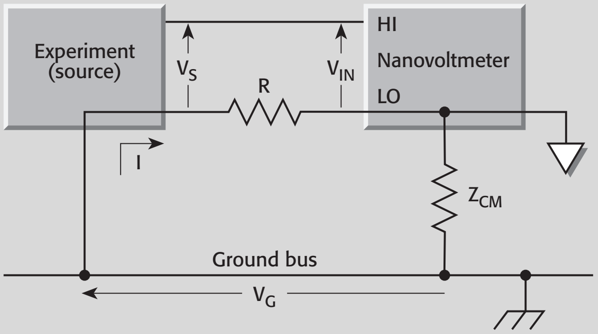
R = Resistance of input LO connection (typically around 100mΩ)

I = Current passing through input LO connection due to ground voltages (V_G) in the ground bus (magnitude may be amperes)

V_S = Source voltage (desired signal)

V_G may exceed V_S by orders of magnitude.

FIGURE 3-11b: Reduced Ground Loops



$V_{IN} \approx V_S$, since V_G is now insignificant compared to V_S.

Z_{CM} = Common mode impedance of nanovoltmeter

The cure for such ground loops is to ground all equipment at a single point. The easiest way of accomplishing this is to use isolated power sources and instruments, then find a single, good earth-ground point for the entire system. Avoid connecting sensitive instruments to the same ground system used by other instruments, machinery, or other high power equipment. As shown in **Figure 3-11b**, ground loops can also be reduced by using a voltmeter with high common mode impedance (Z_{CM}), also known as common mode isolation.

3.2.3 Common-Mode Current and Reversal Errors

Excessive common-mode current can significantly affect low-level voltage measurements. Although common-mode currents are most often associated with noise problems, they can result in large DC offsets in some cases. In the following paragraphs, we will briefly discuss the basic principles behind errors generated by common-mode currents and ways to avoid lead reversal errors.

Common-Mode Current

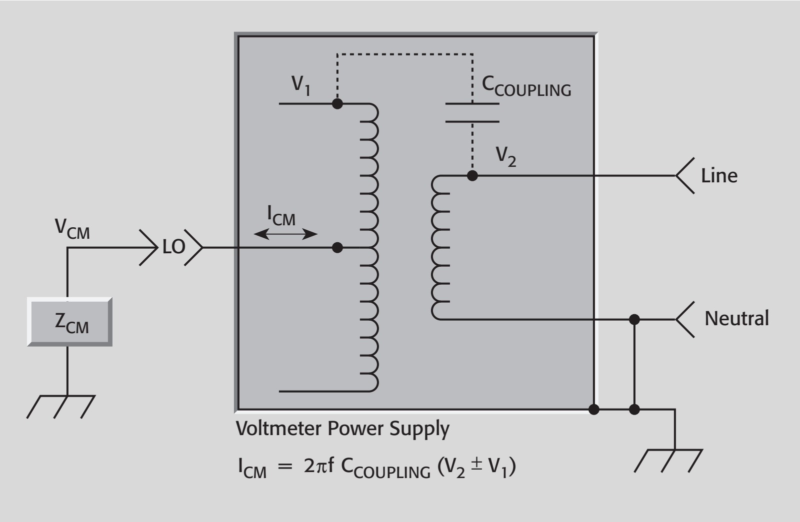
Common-mode current is the current that flows between the instrument's LO terminal and chassis or earth ground. As shown in **Figure 3-12**, common-mode current (I_{CM}) is caused by capacitive coupling ($C_{COUPLING}$) from the power line through the power transformer. The amplitude of the common-mode current is defined as:

$$I_{CM} = 2\pi f C_{COUPLING} (V_2 \pm V_1)$$

where f is the power line frequency.

Note that the common-mode current flows through the impedance (Z_{CM}), which is present between input LO and chassis ground. As a result, the amplitude of voltage (V_{CM}) depends on the magnitude of Z_{CM} as well as the value of I_{CM}.

FIGURE 3-12: Common Mode Current Generation by Power Line Coupling



Common-Mode Reversal Errors

Reversing leads can result in errors caused by common-mode currents. As shown in **Figure 3-13**, many low voltage sources have internal resistive dividers, which attenuate an internal voltage source to the desired level. For example, the output voltage from the source is defined as:

$$V_{OUTPUT} = V_S \left(\frac{R_2}{R_1 + R_2} \right)$$

With the correct connection scheme shown in **Figure 3-13a**, the low or chassis side of the voltage source is connected to input LO of the measuring instrument. Any common-mode current (I_{CM}) that may be present flows from the voltmeter input LO to instrument chassis common, through earth ground to voltage source ground. Note that no common-mode current flows through either of the two divider resistors of the voltage source when this connection scheme is used.

If the input leads of the voltmeter are reversed, we have the situation shown in **Figure 3-13b**. Now, the common-mode current (I_{CM}) flows through R_2, developing a voltage drop, which is added to the voltage to be measured. This added voltage is mainly power line frequency and its effect on the voltmeter reading will depend upon the normal-mode rejection capability of the meter. The reading may become noisy or it may have a constant offset. In some cases, the sensitivity of the meter may be reduced, because the input stages are overloaded.

To minimize common-mode reversal errors, choose an instrument with the lowest possible common-mode current. If possible, the voltage source being measured should be isolated from ground.

3.3 Low Resistance Measurements

Aside from all the low voltage measurement considerations described in Section 3.2, low resistance measurements are subject to additional error sources, including lead resistance, non-ohmic contacts, and device heating. This section describes these error sources and methods to eliminate or minimize them. Other measurement considerations, including dry circuit testing and testing inductive devices, are also described.

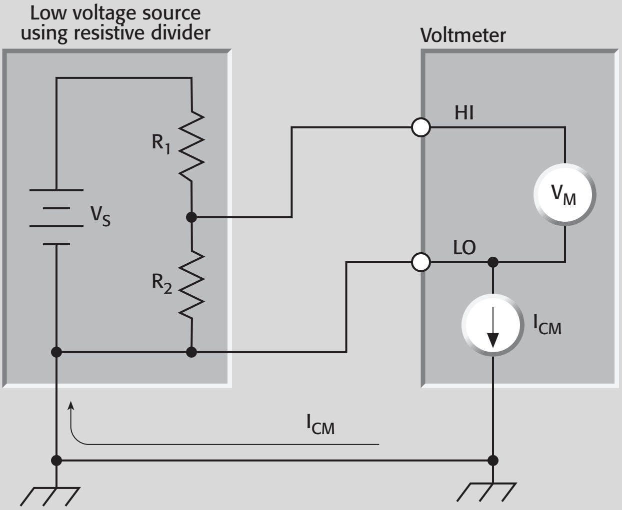
3.3.1 Lead Resistance and Four-Wire Method

Resistance measurements are often made using the two-wire method shown in **Figure 3-14**. The test current is forced through the test leads and the resistance (R) being measured. The meter then measures the voltage across the resistance through the same set of test leads and computes the resistance value accordingly.

The main problem with the two-wire method as applied to low resistance measurements is that the total lead resistance (R_{LEAD}) is added to the measurement. Since the test current (I) causes a small but significant volt-

FIGURE 3-13: Effects of Reversing Leads on Common Mode Errors

a. With proper connections, I_{CM} generates no noise or offset.



b. With reversed connections, I_{CM} generates noise and possible offset.

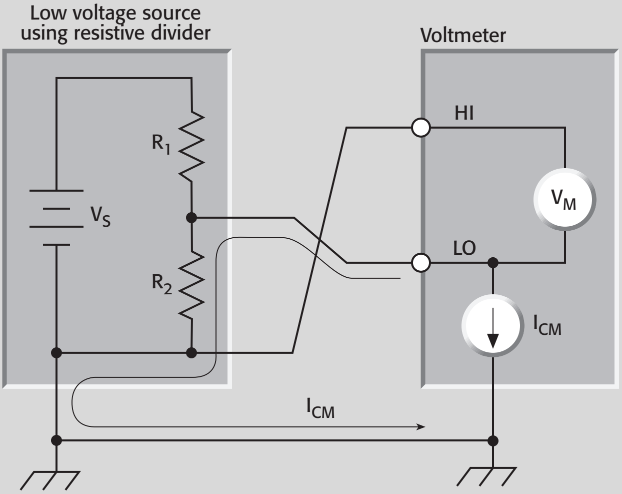
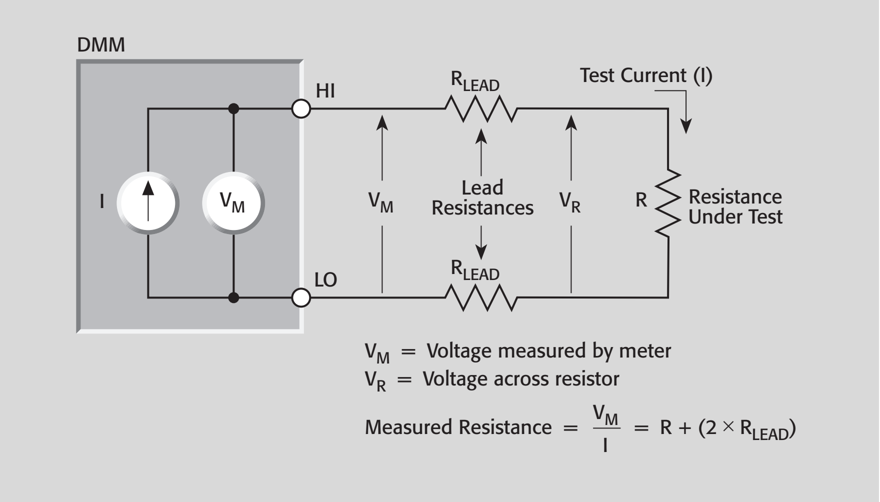


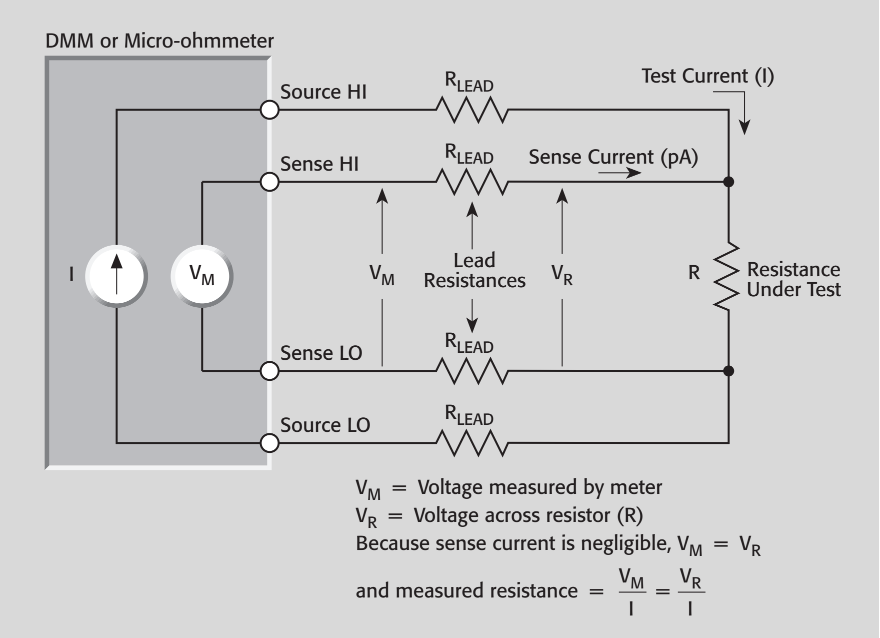
FIGURE 3-14: Two-Wire Resistance Measurement



V_M = Voltage measured by meter
V_R = Voltage across resistor

$$\text{Measured Resistance} = \frac{V_M}{I} = R + (2 \times R_{LEAD})$$

FIGURE 3-15: Four-Wire Resistance Measurement



V_M = Voltage measured by meter
V_R = Voltage across resistor (R)
Because sense current is negligible, $V_M = V_R$

$$\text{and measured resistance} = \frac{V_M}{I} = \frac{V_R}{I}$$

age drop across the lead resistances, the voltage (V_M) measured by the meter won't be exactly the same as the voltage (V_R) directly across the test resistance (R), and considerable error can result. Typical lead resistances lie in the range of 1mΩ to 10mΩ, so it's very difficult to obtain accurate two-wire resistance measurements when the resistance under test is lower than 10Ω to 100Ω (depending on lead resistance).

Due to the limitations of the two-wire method, the four-wire (Kelvin) connection method shown in **Figure 3-15** is generally preferred for low resistance measurements. These measurements can be made using a DMM, micro-ohmmeter, or a separate current source and voltmeter. With this configuration, the test current (I) is forced through the test resistance (R) through one set of test leads, while the voltage (V_M) across the DUT is measured through a second set of leads called sense leads. Although some small current may flow through the sense leads, it is usually negligible and can generally be ignored for all practical purposes. The voltage drop across the sense leads is negligible, so the voltage measured by the meter (V_M) is essentially the same as the voltage (V_R) across the resistance (R). Consequently, the resistance value can be determined much more accurately than with the two-wire method. Note that the voltage-sensing leads should be connected as close to the resistor under test as possible to avoid including the resistance of the test leads in the measurement.

3.3.2 Thermoelectric EMFs and Offset Compensation Methods

Thermoelectric voltages, as described in Section 3.2.1, can seriously affect low resistance measurement accuracy. The current-reversal method, the delta method, and the offset-compensated ohms method are three common ways to overcome these unwanted offsets.

Current-Reversal Method

Thermoelectric EMFs can be canceled by making two measurements with currents of opposite polarity, as shown in **Figure 3-16**. In this diagram, a voltmeter with a separate bipolar current source is used. With the positive current applied as in **Figure 3-16a**, the measured voltage is:

$$V_{M+} = V_{EMF} + IR$$

Reversing the current polarity as shown in **Figure 3-16b** yields the following voltage measurement:

$$V_{M-} = V_{EMF} - IR$$

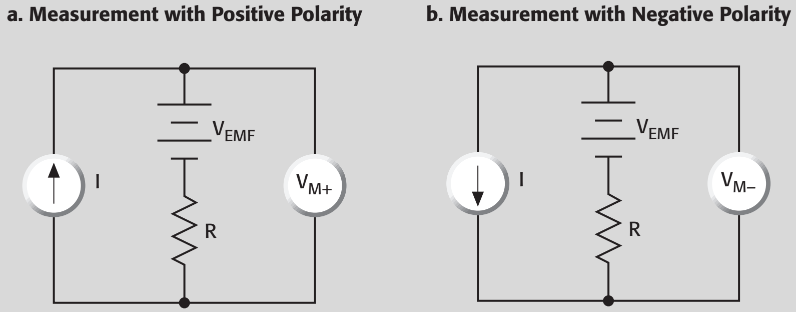
The two measurements can be combined to cancel thermoelectric EMFs:

$$V_M = \frac{V_{M+} - V_{M-}}{2} = \frac{(V_{EMF} + IR) - (V_{EMF} - IR)}{2} = IR$$

The measured resistance is computed in the usual manner:

$$R = \frac{V_M}{I}$$

FIGURE 3-16: Canceling Thermoelectric EMFs with Current Reversal



$$V_{M+} = V_{EMF} + IR \qquad V_{M-} = V_{EMF} - IR$$

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

Note that the thermoelectric voltage (V_{EMF}) is completely canceled out by this method of resistance calculation.

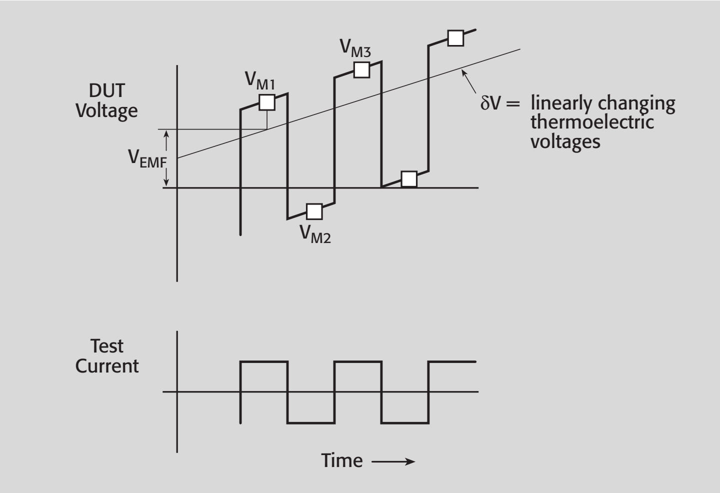
For the current-reversal method to be effective, it's important to use a low noise voltmeter with a response speed that is fast compared with the thermal time constant of the circuit under test. If the response speed is too slow, any changes in the circuit temperature during the measurement cycle will cause changes in the thermoelectric EMFs that won't be completely canceled, and some error will result.

Delta Method

When the thermoelectric voltages are constant with respect to the measurement cycle, the current-reversal method will successfully compensate for these offsets. However, if changing thermoelectric voltages are causing inaccurate results, then the delta method should be used. The delta method is similar to the current-reversal method in terms of alternating the current source polarity, but it differs in that it uses three voltage measurements to make each resistance calculation. This method can best be explained through an illustration and mathematical computations.

Figure 3-17 shows the voltage drop of a DUT as a function of time with an alternating polarity current applied. A voltage measurement (V_{M1}, V_{M2}, V_{M3}, etc.) is taken each time the polarity is changed. Each voltage measurement includes a constant thermal voltage offset (V_{EMF}) and a linearly changing voltage offset (δV). The thermal voltage drift may be approximated as a linear function over short periods, so the rate of change of voltage as a function of time (δV) can also be treated as a constant. The first three voltage measurements include the following voltages:

FIGURE 3-17: Canceling Thermoelectric EMFs with Delta Method



$$V_{M1} = V_1 + V_{EMF}$$

$$V_{M2} = V_2 + V_{EMF} + \delta V$$

$$V_{M3} = V_3 + V_{EMF} + 2\delta V$$

where: V_{M1}, V_{M2}, and V_{M3} are voltage measurements

V_{M1} is presumed to be taken at time = 0

V_1, V_2, and V_3 are the voltage drop of the DUT due to the applied current

V_{EMF} is the constant thermoelectric voltage offset at the time the V_{M1} measurement is taken

δV is the thermoelectric voltage change

Cancellation of both the thermoelectric voltage offset (V_{EMF}) term and the thermoelectric voltage change (δV) term is possible through mathematical computation using three voltage measurements. First, take one-half the difference of the first two voltage measurements and call this term V_A:

$$V_A = \frac{V_{M1} - V_{M2}}{2} = \frac{(V_1 + V_{EMF}) - (V_2 + V_{EMF} + \delta V)}{2} = \frac{(V_1 - V_2)}{2} - \frac{\delta V}{2}$$

Then, take one-half the difference of the second (V_{M2}) and third (V_{M3}) voltage measurements and call this term V_B:

$$V_B = \frac{V_{M3} - V_{M2}}{2} = \frac{(V_3 + V_{EMF} + 2\delta V) - (V_2 + V_{EMF} + \delta V)}{2} = \frac{(V_3 - V_2)}{2} - \frac{\delta V}{2}$$

Both V_A and V_B are affected by the drift in the thermoelectric EMF, but the effect on V_A and V_B is equal and opposite. The final voltage reading is the average of V_A and V_B and is calculated as:

$$V_{Final} = \frac{V_A - V_B}{2} = \frac{(V_1 + V_3 - 2V_2)}{4}$$

Notice that both the V_{EMF} and δV terms are canceled out of the final voltage calculation.

In the delta method, each data point is the moving average of three voltage readings. This additional averaging of the voltage measurements means that the data resulting from the delta method has lower noise than the data derived when the current-reversal method is used to calculate it, even when both sets of data are taken over the same time period.

The success of the delta method depends on the linear approximation of the thermal drift, which must be viewed over a short period. Compensating successfully for changing thermoelectric voltages dictates that the measurement cycle time must be faster than the thermal time constant of the DUT. Therefore, an appropriately fast current source and voltmeter must be used for the delta method to be successful. Refer to Section 4.7.2 for information on specific test equipment.

Offset-Compensated Ohms Method

Another offset-canceling method used by micro-ohmmeters and many DMMs is the offset-compensated ohms method. This method is similar to the current-reversal method except that the measurements are alternated between a fixed source current and zero current.

As shown in **Figure 3-18a**, the source current is applied to the resistance being measured during only part of the cycle. When the source current is on, the total voltage measured by the instrument (**Figure 3-18b**) includes the voltage drop across the resistor as well as any thermoelectric EMFs, and it is defined as:

$$V_{M1} = V_{EMF} + IR$$

During the second half of the measurement cycle, the source current is turned off and the only voltage measured by the meter (**Figure 3-18c**) is any thermoelectric EMF present in the circuit:

$$V_{M2} = V_{EMF}$$

Given that V_{EMF} is accurately measured during the second half of the cycle, it can be subtracted from the voltage measurement made during the first half of the cycle, so the offset-compensated voltage measurement becomes:

$$V_M = V_{M1} - V_{M2}$$

$$V_M = (V_{EMF} + IR) - V_{EMF}$$

$$V_M = IR$$

and,

$$R = \frac{V_M}{I}$$

Again, note that the measurement process cancels the thermoelectric EMF term (V_{EMF}).

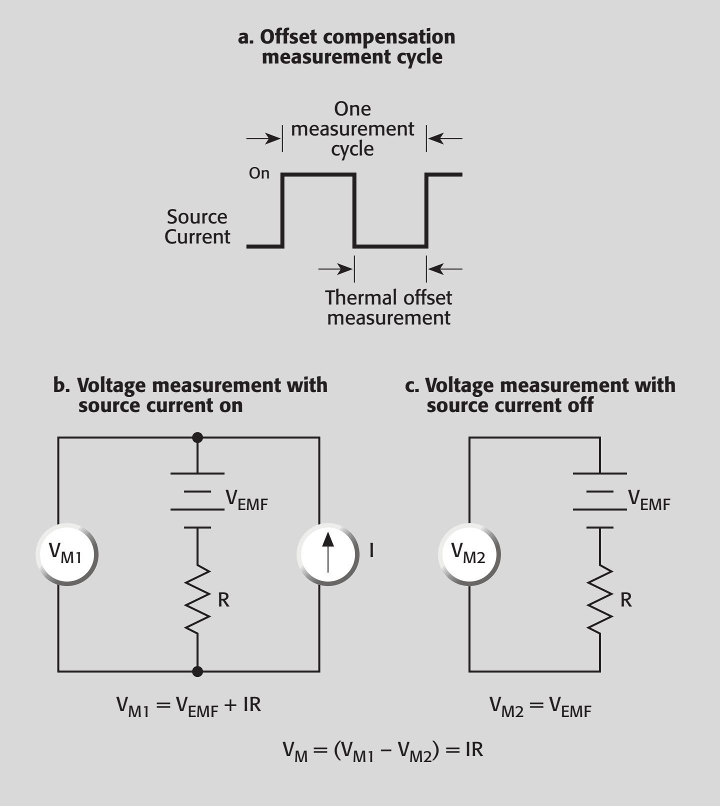


FIGURE 3-18: Offset-Compensated Ohms Measurement

3.3.3 Non-Ohmic Contacts

Non-ohmic contacts are evident when the potential difference across the contact isn't linearly proportional to the current flowing through it. Non-ohmic contacts may occur in a low voltage circuit as a result of oxide films or other non-linear connections. A non-ohmic connection is likely to rectify any radio frequency energy (RFI) present, causing an offset voltage to appear in the circuit. (A further discussion on RFI can be found in Section 3.2.1.) There are several ways to check for non-ohmic contacts and methods to reduce them.

If using a micro-ohmmeter or DMM to make low resistance measurements, change the range to check for non-ohmic contacts. Changing the measurement range usually changes the test current as well. A normal condition would indicate the same reading but with higher or lower resolution, depending on whether the instrument was up or down ranged. If the reading is significantly different, this may indicate a non-ohmic condition.

If using a separate current source and voltmeter to make low resistance measurements, each instrument must be checked for non-ohmic contacts. If the current source contacts are non-ohmic, there may be a significant difference in the compliance voltage when the source polarity is reversed. If the voltmeter contacts are non-ohmic, they may rectify any AC pickup present and cause a DC offset error. If this is the case, the offset compensated ohms method is preferred to the current-reversal method for canceling offsets.

To prevent non-ohmic contacts, choose an appropriate contact material, such as indium or gold. Make sure the compliance voltage is high enough to avoid problems due to source contact non-linearity. To reduce error due to voltmeter non-ohmic contacts, use shielding and appropriate grounding to reduce AC pickup.

3.3.4 Device Heating

Device heating can be a consideration when making resistance measurements on temperature-sensitive devices such as thermistors. The test currents used for low resistance measurements are often much higher than the currents used for high resistance measurements, so power dissipation in the device can be a consideration if it is high enough to cause the device's resistance value to change.

Recall that the power dissipation in a resistor is given by this formula:

$$P = I^2R$$

From this relationship, we see that the power dissipated in the device increases by a factor of four each time the current doubles. Thus, one way to minimize the effects of device heating is to use the lowest current possible while still maintaining the desired voltage across the device being tested. If the current cannot be reduced, use a narrow current pulse and a fast responding voltmeter.

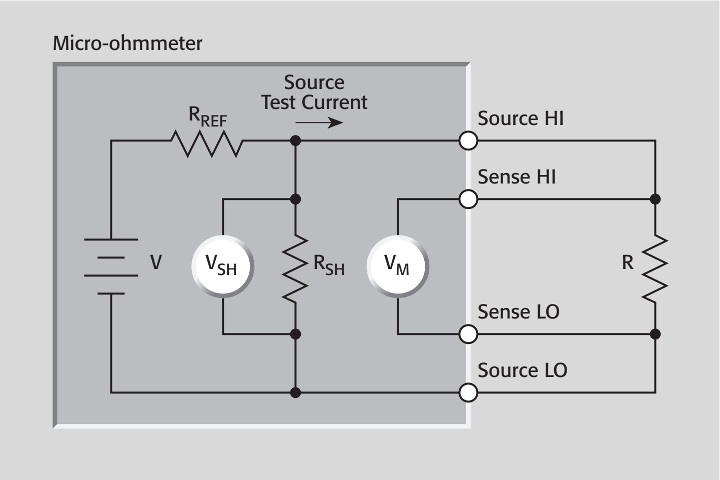
Most micro-ohmmeters and DMMs don't have provisions for setting the test current. It is generally determined by the range. In those cases, alternate means must be found to minimize device heating. One simple but effective way to do so is to use the instrument's one-shot trigger mode during measurements. While in this mode, the instrument will apply only a single, brief current pulse to the DUT during the measurement cycle, thereby minimizing errors caused by device heating.

3.3.5 Dry Circuit Testing

Many low resistance measurements are made on devices such as switches, connectors, and relay contacts. If these devices are to be used under "dry-circuit" conditions, that is, with an open-circuit voltage less than 20mV and a short-circuit current less than 100mA, the devices should be tested in a manner that won't puncture any oxide film that may have built up on the contacts. If the film is punctured, the measured contact resistance will be lower than if the film remains intact, compromising the validity of the test results.

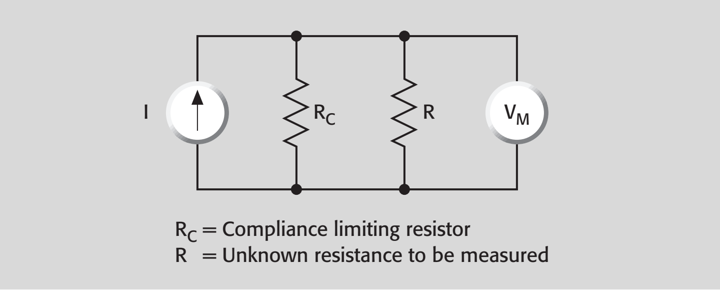
To avoid oxidation puncture, such measurements are usually made using dry circuit testing, which typically limits the voltage across the DUT to 20mV or less. Some micro-ohmmeters and DMMs have this capability built in, as shown in **Figure 3-19**. In this micro-ohmmeter, a precision shunt resistor (R_{SH}) is connected across the source terminals to clamp or limit the voltage across the DUT to <20mV. The remaining aspects of the circuit are very similar to the conventional four-wire measurement method: V and R_{REF} make up the current source, which forces current through the unknown resistance (R). This current should be no more than 100mA. The value of the unknown resistance is computed from the sense voltage (V_M), the voltage across clamping resistor (V_{SH}), the known value of R_{SH}, and the source current. Refer to Section 1.4.4 for more detailed circuit information.

FIGURE 3-19: Dry Circuit Testing



If dry circuit testing is to be done with a separate current source and voltmeter, the compliance voltage on the current source must be limited to 20mV or less. If it isn't possible to limit the compliance voltage to this level, a compliance limiting resistor must be used, as shown in **Figure 3-20**. In

FIGURE 3-20: Dry Circuit Testing Using Current Source and Voltmeter



this circuit, R_C is the resistor used to limit the voltage to 20mV and R is the unknown resistance.

The value of R_C must be chosen to limit the voltage at a given test current. For example, if the voltage limit is 20mV and the test current is 200μA, R_C can be calculated as:

$$R_C = 20\text{mV}/200\mu\text{A} = 100\Omega$$

If the unknown resistance (R) is 250mΩ, then R_C will cause a 0.25% error in the measured resistance.

The exact value of the unknown resistance (R) can then be calculated by the following equation:

$$R = \frac{(R_{\text{MEASURED}} \times R_C)}{(R_C - R_{\text{MEASURED}})}$$

where R_{MEASURED} is the calculated resistance measurement from the measured voltage (V_M) and the source current (I).

3.3.6 Testing Inductive Devices

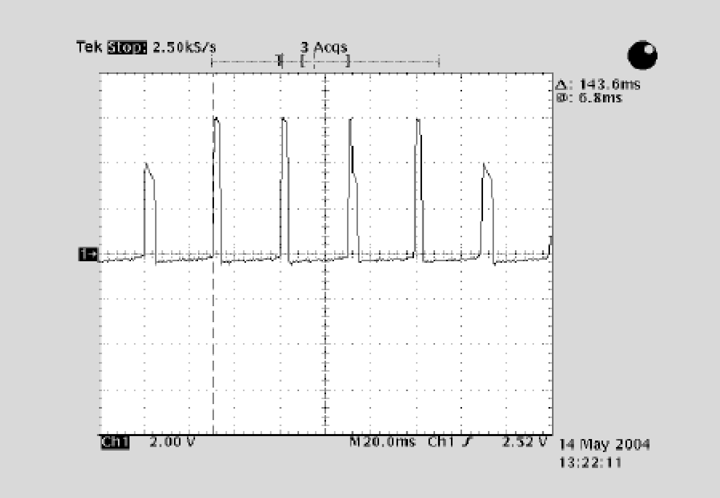
Inductive devices usually have a small resistance in addition to the inductance. This small resistance is normally measured with a DMM or a micro-ohmmeter. However, the measurements are often difficult because of the interaction between the inductance and the measuring instrument. This is particularly true with high L/R ratios.

Some of the problems that may result include oscillations, negative readings and generally unstable readings. An oscilloscope picture of an unstable measurement of a 200H inductor is shown in **Figure 3-21**.

When problems occur, try to take measurements on more than one range and check if the values correspond.

If possible, do not use offset compensation (pulsed current) because inductive reaction to the current pulse may cause unstable measurements or make autoranging difficult. Try using a higher resistance range when possible.

FIGURE 3-21



Check for oscillations by connecting an oscilloscope in parallel with the device and the meter. Sometimes, a diode across the inductor may settle down the oscillations by reducing the inductive kick.

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