KEITHLEY

5th Edition

Low Level Measurements

Precision DC Current, Voltage and Resistance Measurements

3.1 Introduction

Section 1 described instruments for making both low voltage and low resistance measurements. This section provides information on how to use these instruments and make accurate low voltage and low resistance measurements. This includes various error sources and ways to minimize their effect on measurement integrity.

3.2 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. The following paragraphs discuss factors that can affect low voltage measurement accuracy.

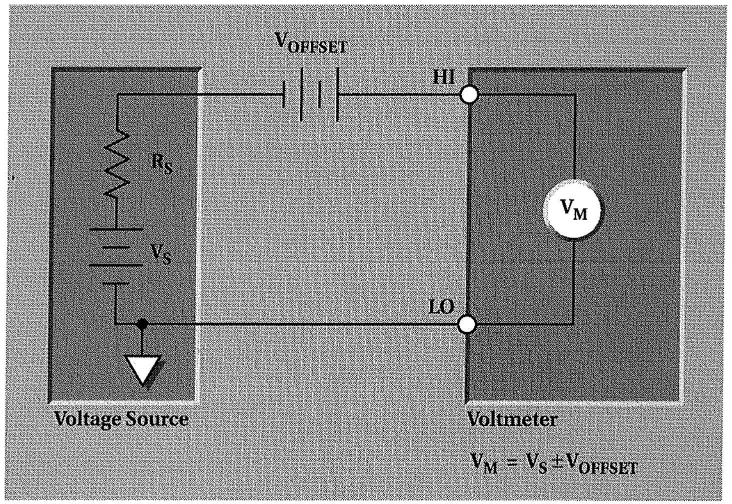
3.2.1 Offset Voltages

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. 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:

$$V_M = V_S \pm V_{OFFSET}$$

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



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:

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

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

$$V_M = 4.75\mu V \text{ (an error of } -5\%)$$

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.

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**.

Constructing circuits using the same material for all conductors minimizes thermoelectric EMF generation. For example, connections

FIGURE 3-2: Thermoelectric EMFs

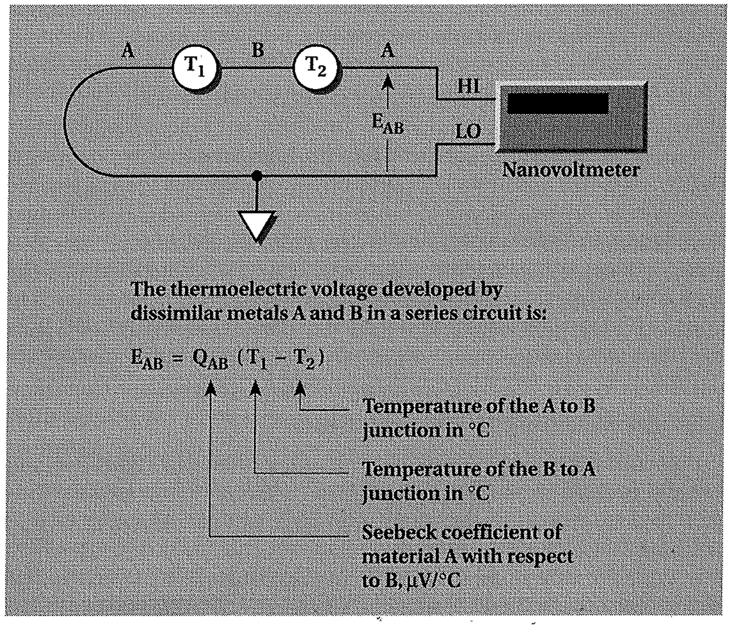


TABLE 3-1: Seebeck Coefficients

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

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. For example, clean Cu-Cu connections may have a Seebeck coefficient of ≤0.2μV/°C, while Cu-CuO connections may have a coefficient as high as 1mV/°C.

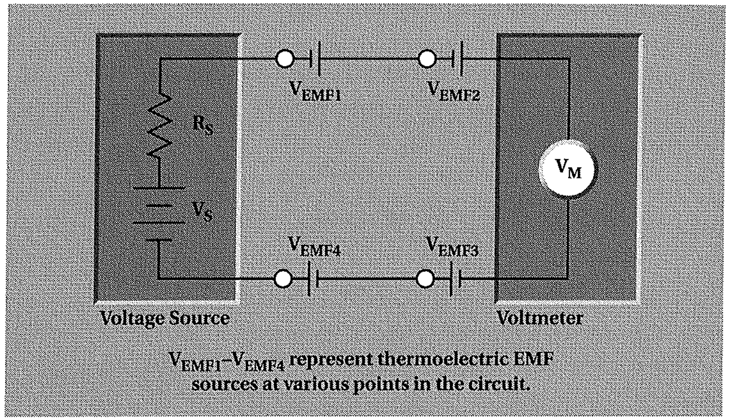
Minimizing temperature gradients within the circuit also reduces thermoelectric EMFs. A technique for minimizing such gradients is to place all junctions in close proximity to one another and to provide good thermal coupling to a common, massive heat sink. Electrical insulators having high thermal conductivity must be used, but, since most electrical insulators do not 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. Any remaining thermoelectric EMF, provided it is relatively constant, can be compensated for by using the instrument zero feature. 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 instru-

FIGURE 3-3: Connections from Voltage Source to Voltmeter



ment does not interfere with the reading. The following paragraphs provide tips on making good connections to minimize thermoelectric voltages.

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. By matching the composition of the wires between the cryostat and the voltmeter and keeping all dissimilar metal junction pairs at the same temperature, very low voltage measurements can be made 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 cancelled 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:

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

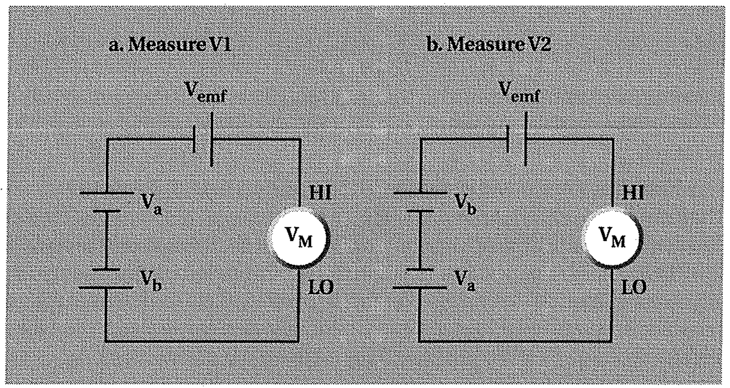
The two cells are reversed in **Figure 3-4b** and the measured voltage is:

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

The average of the difference between these two measurements is:

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

FIGURE 3-4: Reversing Sources to Cancel Thermoelectric EMFs



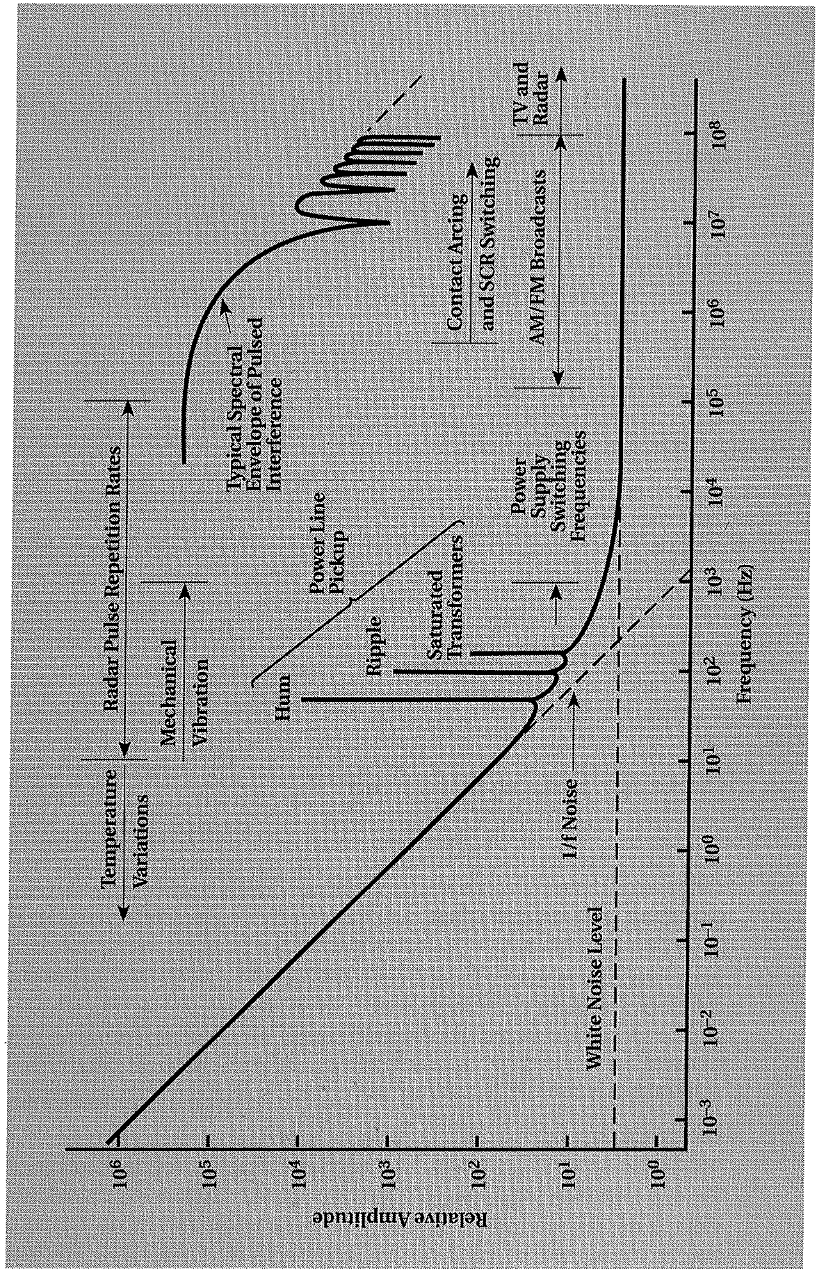
Notice that this measurement technique effectively cancels out the thermoelectric EMF term (V_{emf}), which represents the algebraic sum of all thermoelectric EMFs in the circuit. If the measured voltage is the result of a current source flowing through the unknown resistance, then either the current-reversal 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 frequency 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.

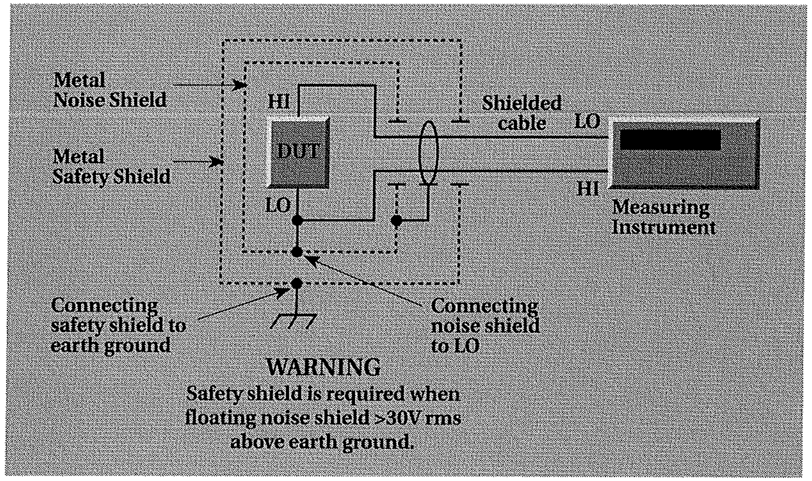
FIGURE 3-5: Voltage Noise Frequency Spectrum



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. Normally, noise shields should be connected to input LO, but if the RFI/EMI is earth-ground based, connecting shields to LO may not reduce the interference. 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

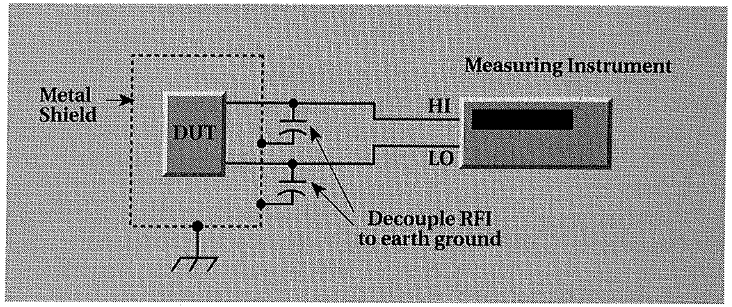


If all else fails, external filtering of the device input paths may be required, as shown in **Figure 3-7**. In many cases, a simple one-pole filter may be sufficient; in more difficult cases, multiple-pole notch or band-stop filters may be required. In particular, multiple capacitors of different values 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.

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

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



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 resulting from the flow of current, 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 resulting voltage drop will be indicated by the instrument.

In some applications, the voltage to be measured is always present and the preceeding 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."

Zero Drift

Zero drift is a change in the meter reading with no input signal (usually with the input shorted) as a function 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.

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 (0K). 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

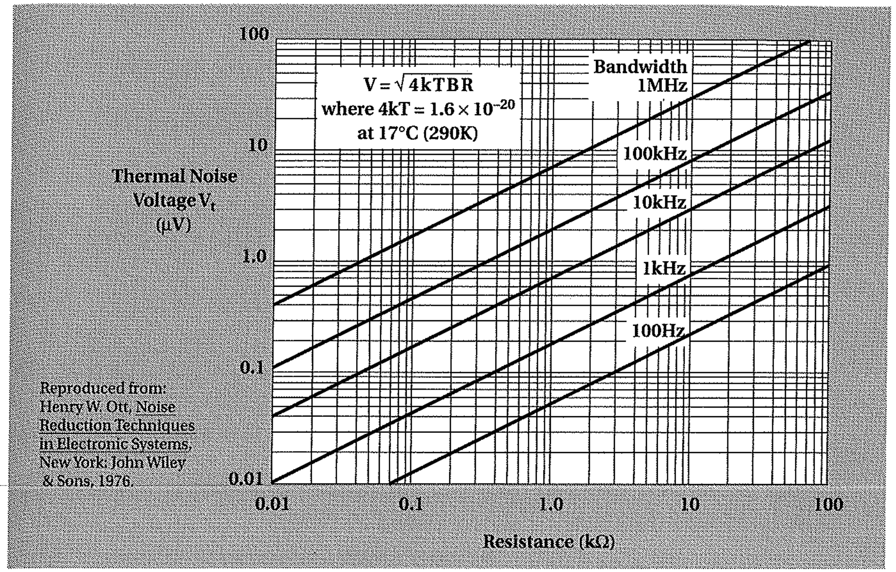
B = noise bandwidth in hertz

R = resistance of the source in ohms

For example, at room temperature (293K), a source resistance of 10kΩ with a bandwidth of 5kHz will have almost 1μV rms of noise.

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 (293K) to liquid nitrogen temperature (77K) decreases the voltage noise by approximately a factor of 2.

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



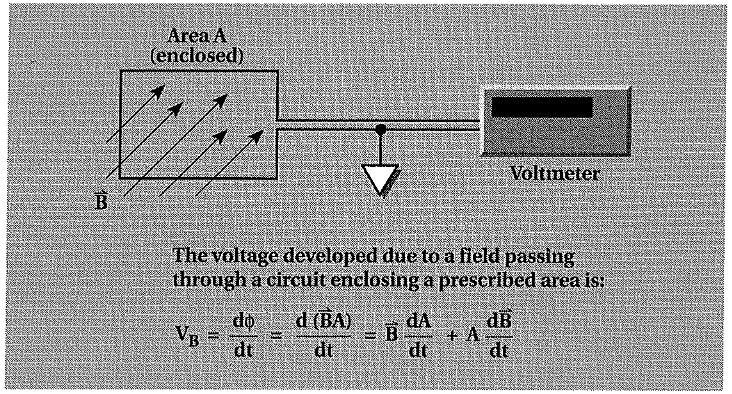
If the voltmeter has adjustable filtering and integration, the bandwidth can be reduced by increasing the amount of filtering and/or by integrating over multiple power line cycles. Decreasing the bandwidth of the measurement is equivalent to increasing the response time of the instrument, and as a result, 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 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. 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. Even the earth's relatively weak magnetic field can generate nanovolts in dangling leads, so leads must be kept short and rigidly tied down.

FIGURE 3-9: Low Voltages Generated by Magnetic Fields



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

ϕ = $\vec{B}A$ = magnetic flux

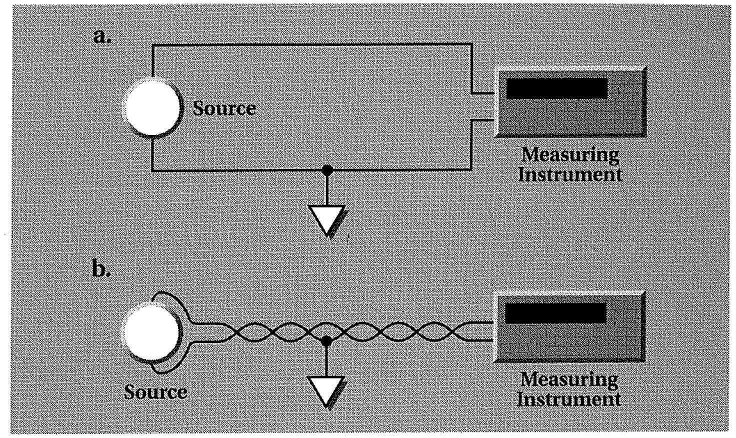
Since the induced voltage is proportional both to the magnitude of A and $\vec{B}$, as well as to the rate of change in A and $\vec{B}$, the amount of induced voltage can be minimized in two ways:

- 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 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**, much less area is enclosed because the leads are twisted together, which minimizes the voltage.

FIGURE 3-10: Minimizing Interference from Magnetic Loops



Conductors that carry large currents should also be shielded or run as twisted pairs to prevent generating magnetic fields that can affect nearby circuits. Specially constructed, shielded twisted-pair cables are available to maximize shielding.

In addition to these techniques, AC signals from magnetic fields can be filtered at the input of the instrument, and , if possible, the instrument should be physically relocated further from the source of an interfering magnetic field.

Ground Loops

Noise and error voltages also arise from ground loops. 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:

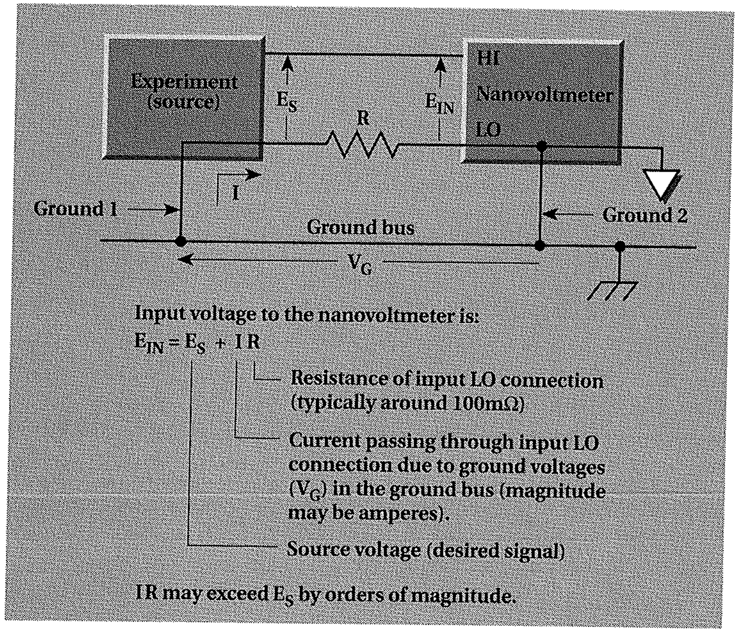
$$E = IR$$

where E = 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.

The cure for ground loops is to ground all equipment at a single point. The easiest way of accomplishing this is to use isolated power

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



sources and instruments, then find a single, good earth-ground point for the entire system, as shown in **Figure 3-11b**. Avoid connecting sensitive instruments to the same ground system used by other instruments, machinery, or other high-power equipment.

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.

FIGURE 3-11b: Single System Ground

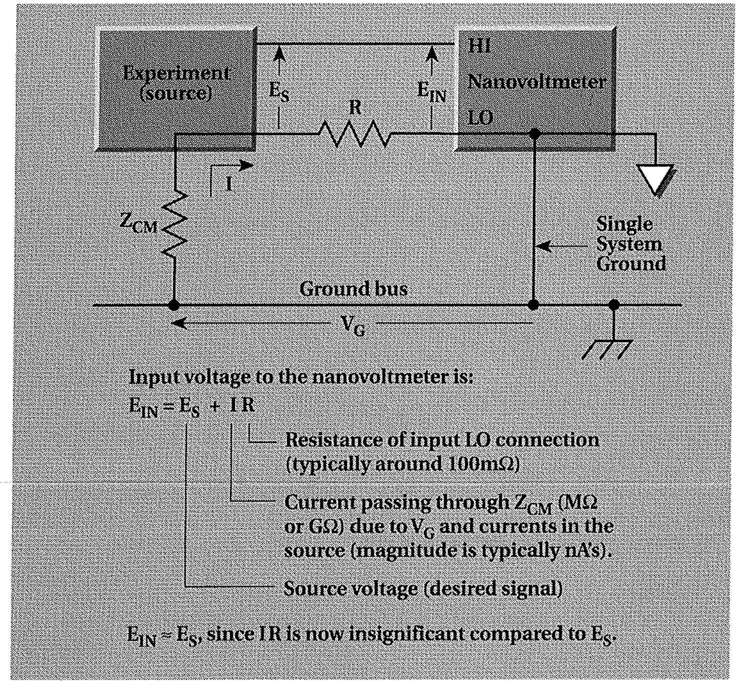
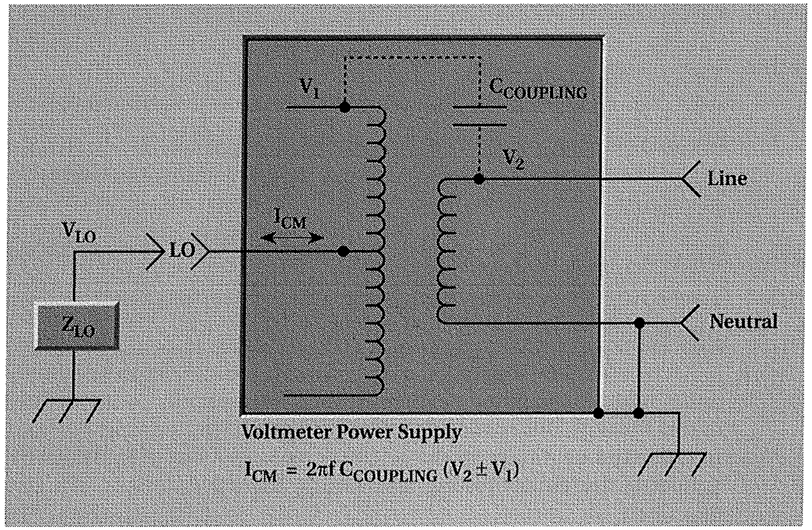


FIGURE 3-12: Common Mode Current Generation by Power Line Coupling



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

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 the 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 input LO to instrument chassis ground, through earth ground to 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 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 common-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.

Avoiding Common-Mode Reversal Errors

In some cases, it will be necessary to reverse the measuring leads. In such cases, 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.

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