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6th Edition

Low Level Measurements Handbook

Precision DC Current, Voltage, and Resistance Measurements

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KEITHLEY

A GREATER MEASURE OF CONFIDENCE

TABLE OF CONTENTS

SECTION 1 Low Level DC Measuring Instruments

SECTION 2 Measurements from High Resistance Sources

SECTION 3 Measurements from Low Resistance Sources

SECTION 4 Applications

SECTION 5 Low Level Instrument Selection Guide

APPENDIX A Low Level Measurement Troubleshooting Guide

APPENDIX B Cable and Connector Assembly

APPENDIX C Glossary

APPENDIX D Safety Considerations

INDEX

SECTION 1

Low Level DC Measuring Instruments

FIGURE 1-1: Standard Symbols Used in this Text

Prefixes

Symbol	Prefix	Exponent
y	yocto-	10^{-24}
z	zepto-	10^{-21}
a	atto-	10^{-18}
f	femto-	10^{-15}
p	pico-	10^{-12}
n	nano-	10^{-9}
μ	micro-	10^{-6}
m	milli-	10^{-3}
(none)	(none)	10^{0}
k	kilo-	10^{3}
M	mega-	10^{6}
G	giga-	10^{9}
T	tera-	10^{12}
P	peta-	10^{15}
E	exa-	10^{18}
Z	zetta-	10^{21}
Y	yotta-	10^{24}

Quantities

Symbol	Unit	Quantity
V	volts	EMF
A	amperes	current
Ω	ohms	resistance
C	coulombs	charge
s	seconds	time
W	watts	power
F	farads	capacitance
Hz	cycles/s	frequency
K	degrees	temperature

1.1 Introduction

DC voltage, DC current, and resistance are measured most often with digital multimeters (DMMs). Generally, these instruments are adequate for measurements at signal levels greater than 1μV or 1μA, or less than 1GΩ. (See **Figure 1-1** for standard symbols used in this text.) However, they don't approach the theoretical limits of sensitivity. For low level signals, more sensitive instruments such as electrometers, picoammeters, and nanovoltmeters must be used.

Section 1 offers an overview of the theoretical limits of DC measurements and the instruments used to make them. It includes instrument descriptions and basic instrument circuit designs. For easier reference, this information is organized into a number of subsections:

1.2 Theoretical Measurement Limits: A discussion of both the theoretical measurement limitations and instrument limitations for low level measurements.

1.3 Instrument Definitions: Descriptions of electrometers, DMMs, nanovoltmeters, picoammeters, source-measure units, SourceMeter® instruments, low current preamps, and micro-ohmmeters.

1.4 Understanding Instrument Specifications: A review of the terminology used in instrument specifications, such as accuracy (resolution, sensitivity, transfer stability), deratings (temperature coefficient, time drift), noise (NMRR and CMRR), and speed.

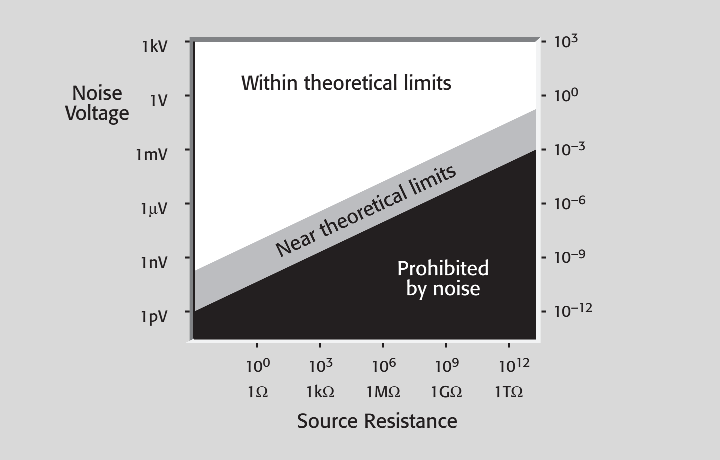
1.5 Circuit Design Basics: Describes basic circuit design for voltmeter circuits (electrometer, nanovoltmeter) and ammeter circuits (shunt ammeter, feedback picoammeter, high speed picoammeter, logarithmic picoammeter).

1.2 Theoretical Measurement Limits

The theoretical limit of sensitivity in any measurement is determined by the noise generated by the resistances present in the circuit. As discussed in Sections 2.6.5 and 3.2.2, voltage noise is proportional to the square root of the resistance, bandwidth, and absolute temperature. **Figure 1-2** shows theoretical voltage measurement limits at room temperature (300K) with a response time of 0.1 second to ten seconds. Note that high source resistance limits the theoretical sensitivity of the voltage measurement. While it's certainly possible to measure a 1μV signal that has a 1Ω source resistance, it's not possible to measure that same 1μV signal level from a 1TΩ source. Even with a much lower 1MΩ source resistance, a 1μV measurement is near theoretical limits, so it would be very difficult to make using an ordinary DMM.

In addition to having insufficient voltage or current sensitivity (most DMMs are no more sensitive than 1μV or 1nA per digit), DMMs have high

FIGURE 1-2: Theoretical Limits of Voltage Measurements



input offset current[1] when measuring voltage and lower input resistance compared to more sensitive instruments intended for low level DC measurements. These characteristics cause errors in the measurement; refer to Sections 2 and 3 for further discussion of them.

Given these DMM characteristics, it's not possible to use a DMM to measure signals at levels close to theoretical measurement limits, as shown in **Figure 1-3**. However, if the source resistance is 1MΩ or less, or if the desired resolution is no better than 0.1µV (with low source resistance), the signal level isn't "near theoretical limits," and a DMM is adequate. If better voltage sensitivity is desired, and the source resistance is low (as it must be because of theoretical limitations), a nanovoltmeter provides a means of measuring at levels much closer to the theoretical limits of measurement. With very high source resistance values (for example, 1TΩ), a DMM isn't a suitable voltmeter. DMM input resistance ranges from 10MΩ to 10GΩ—several orders of magnitude less than a 1TΩ source resistance, resulting in severe input loading errors. Also, input currents are typically many picoamps, creating large voltage offsets. However, because of its much higher input resistance, an electrometer can make voltage measurements at levels that approach theoretical limits. A similar situation exists for low level current measurements; DMMs generally have a high input voltage drop

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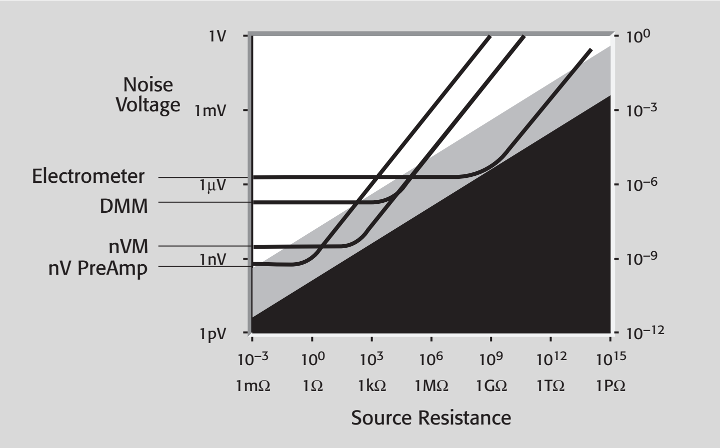
[1] Input current flows in the input lead of an active device or instrument. With voltage measurements, the *input current* is ideally zero; thus, any input current represents an error. With current measurements, the *signal current* becomes the *input current* of the measuring instrument. However, some background current is always present when no signal current is applied to the instrument input. This unwanted current is the *input offset current* (often called just the *offset current*) of the instrument.

The source and test connections can also generate unwanted *offset currents* and *offset voltages*.

A *leakage current* is another unwanted error current resulting from voltage across an undesired resistance path (called *leakage resistance*). This current, combined with the *offset current*, is the total error current.

FIGURE 1-3: Typical Digital Multimeter (DMM), Nanovoltmeter (nVM), Nanovolt Preamplifier (nV PreAmp), and Electrometer Limits of Measurement at Various Source Resistances



(input burden), which affects low level current measurements, and DMM resolution is generally no better than 1nA. Thus, an electrometer or picoammeter with its much lower input burden and better sensitivity will operate at levels much closer to the theoretical (and practical) limits of low current measurements.

1.3 Instrument Definitions

A number of different types of instruments are available to make DC measurements, including electrometers, DMMs, nanovoltmeters, picoammeters, SMUs (source-measure units), SourceMeter instruments, low current preamps, and micro-ohmmeters. The following paragraphs discuss and compare the important characteristics of these instruments.

1.3.1 The Electrometer

An electrometer is a highly refined DC multimeter. As such, it can be used for many measurements performed by a conventional DC multimeter. Additionally, an electrometer's special input characteristics and high sensitivity allow it to make voltage, current, resistance, and charge measurements far beyond the capabilities of a conventional DMM.

An electrometer must be used when any of the following conditions exist:

1. The task requires an extended measurement range unavailable with conventional instruments, such as for detecting or measuring:
    - Currents less than 10nA (10^{-8}A).
    - Resistances greater than 1GΩ (10^{9}Ω).

2. Circuit loading must be minimized, such as when:
    - Measuring voltage from a source resistance of 100MΩ or higher.
    - Measuring current when input voltage drop (burden) of less than a few hundred millivolts is required (when measuring currents from sources of a few volts or less).
3. Charge measurement is required.
4. Measuring signals at or near Johnson noise limitations (as indicated in **Figure 1-2**).

In addition to their versatility, electrometers are easy to operate, reliable, and rugged.

Voltmeter Function

The input resistance of an electrometer voltmeter is extremely high, typically greater than 100TΩ ($10^{14}\Omega$). Furthermore, the input offset current is less than 3fA (3×10^{-15}A). These characteristics describe a device that can measure voltage with a very small amount of circuit loading.

Because of the high input resistance and low offset current, the electrometer voltmeter has minimal effect on the circuit being measured. As a result, the electrometer can be used to measure voltage in situations where an ordinary multimeter would be unusable. For example, the electrometer can measure the voltage on a 500pF capacitor without significantly discharging the device; it can also measure the potential of piezoelectric crystals and high impedance pH electrodes.

Ammeter Function

As an ammeter, the electrometer is capable of measuring extremely low currents, limited only by theoretical limits or by the instrument's input offset current. It also has a much lower voltage burden than conventional DMMs.

With its extremely low input offset current and minimal input voltage burden, it can detect currents as low as 1fA (10^{-15}A). Because of this high sensitivity, it's suitable for measuring the current output of photomultipliers and ion chambers, as well as very low currents in semiconductors, mass spectrometers, and other devices.

Ohmmeter Function

An electrometer may measure resistance by using either a constant-current or a constant-voltage method. If using the constant-current method, the electrometer's high input resistance and low offset current enables measurements up to 200GΩ. When using the constant-voltage method, the electrometer applies a constant voltage to the unknown resistance, measures the current, and then calculates the resistance. This is the preferred method because it allows the unknown resistor to be tested at a known voltage. An electrometer can measure resistances up to 10PΩ ($10^{16}\Omega$) using this method.

Coulombmeter Function

Current integration and measurement of charge are electrometer coulombmeter capabilities not found in multimeters. The electrometer coulombmeter can detect charge as low as 10fC (10^{-14}C). It's equivalent to an active integrator and, therefore, has low voltage burden, typically less than 100μV.

The coulombmeter function can measure lower currents than the ammeter function can, because no noise is contributed by internal resistors. Currents as low as 1fA (10^{-15}A) may be detected using this function. See Section 2.3.8 for further details.

1.3.2 The DMM

Digital multimeters vary widely in performance, from low cost handheld 3½-digit units to high precision system DMMs. While there are many models available from a wide variety of manufacturers, none approaches the theoretical limits of measurement discussed previously. These limitations don't imply that DMMs are inadequate instruments; they simply point out the fact that the vast majority of measurements are made at levels far from theoretical limits, and DMMs are designed to meet these more conventional measurement needs.

Although low level measurements are by definition those that are close to theoretical limits, and are thus outside the range of DMMs, advances in technology are narrowing the gap between DMMs and dedicated low level instruments. For example, the most sensitive DMMs can detect DC voltages as low as 10nV, resolve DC currents down to 10pA, and measure resistances as high as 1GΩ. While these characteristics still fall far short of the corresponding capabilities of more sensitive instruments like the electrometer described previously, all the measurement theory and accuracy considerations in this book apply to DMM measurements as well as to nanovoltmeter, picoammeter, electrometer, or SMU measurements. The difference is only a matter of degree; when making measurements close to theoretical limits, all measurement considerations are vitally important. When measuring at levels far from theoretical limits, only a few basic considerations (accuracy, loading, etc.) are generally of concern.

1.3.3 The Nanovoltmeter

A nanovoltmeter is a very sensitive voltage meter. As shown in **Figure 1-3**, this type of instrument is optimized to provide voltage measurements near the theoretical limits from low source resistances, in contrast to the electrometer, which is optimized for use with high source resistances. Compared to an electrometer, the voltage noise and drift are much lower, and the current noise and drift are much higher. Input resistance is usually similar to that of a DMM and is much lower than that of an electrometer.

As is the case with electrometers, nanovoltmeters are just as reliable and easy to operate as DMMs. Their distinguishing characteristic is their voltage sensitivity, which can be as good as 1pV. Most nanovoltmeters aren't multifunction instruments and are correspondingly less complex than electrometers.

1.3.4 The Picoammeter

A picoammeter is an ammeter built along the lines of the ammeter function of an electrometer. When compared with an electrometer, a picoammeter has a similar low voltage burden, similar or faster speed, less sensitivity, and a lower price. It may also have special characteristics, such as high speed logarithmic response or a built-in voltage source.

1.3.5 The Source-Measure Unit

As its name implies, a source-measure unit (SMU) has both measuring and sourcing capabilities. Adding current and voltage sourcing capabilities to a measuring instrument provides an extra degree of versatility for many low level measurement applications. For example, very high resistance values can be determined by applying a voltage across a device and measuring the resulting current. The added sourcing functions also make a SMU more convenient and versatile than using separate instruments for such applications as generating I-V curves of semiconductors and other types of devices.

The typical SMU provides the following four functions:

- Measure voltage
- Measure current
- Source voltage
- Source current

These functions can be used separately or they can be used together in the following combinations:

- Simultaneously source voltage and measure current, or
- Simultaneously source current and measure voltage.

SMUs have a number of electrometer-like characteristics that make them suitable for low level measurements. The input resistance is very high (typically 100TΩ or more), minimizing circuit loading when making voltage measurements from high impedance sources. The current measurement sensitivity is also similar to that of the electrometer picoammeter—typically as low as 10fA.

Another important advantage of many source-measure units is their sweep capability. Either voltage or current can be swept across the desired range at specified increments, and the resulting current or voltage can be measured at each step. Built-in source-delay-measure cycles allow optimizing measurement speed while ensuring sufficient circuit settling time to maintain measurement integrity.

1.3.6 The SourceMeter® Instrument

The SourceMeter instrument is very similar to the source-measure unit in many ways, including its ability to source and measure both current and voltage and to perform sweeps. In addition, a SourceMeter instrument can display the measurements directly in resistance, as well as voltage and current.

The typical SourceMeter instrument doesn't have as high an input impedance or as low a current capability as a source-measure unit. The SourceMeter instrument is designed for general-purpose, high speed production test applications. It can be used as a source for moderate to low level measurements and for research applications.

Unlike a DMM, which can make a measurement at only one point, a SourceMeter instrument can be used to generate a family of curves, because it has a built-in source. This is especially useful when studying semiconductor devices and making materials measurements.

When used as a current source, a SourceMeter instrument can be used in conjunction with a nanovoltmeter to measure very low resistances by automatically reversing the polarity of the source to correct for offsets.

1.3.7 The Low Current Preamp

Some SMUs and SourceMeter instruments may have a remote low current preamp. With this design, the sensitive amplifier circuitry is separate from the SMU or SourceMeter instrument. This makes it possible to place the most sensitive part of the instrument very close to the device being tested, thereby eliminating a major source of error, the noise and leakage from the cables themselves.

1.3.8 The Micro-ohmmeter

A micro-ohmmeter is a special type of ohmmeter designed especially for making low level resistance measurements. While the techniques used for making resistance measurements are similar to those used in a DMM, micro-ohmmeter circuits are optimized for making low level measurements. The typical micro-ohmmeter can resolve resistances as low as $10\mu\Omega$.

Measurements made using the micro-ohmmeter are always performed using the four-wire technique in order to minimize errors caused by test leads and connections. The typical micro-ohmmeter also has additional features such as offset compensation and dry circuit testing to optimize low resistance measurements. Offset compensation is performed by pulsing the test current to cancel offsets from thermoelectric EMFs. The dry circuit test mode limits the voltage across the unknown resistance to a very small value (typically <20mV) to avoid puncturing oxides when testing such devices as relay contacts, connectors, and switches.

1.4 Understanding Instrument Specifications

Knowing how to interpret instrument specifications properly is an important aspect of making good low level measurements. Although instrument accuracy is probably the most important of these specifications, there are several other factors to consider when reviewing specifications, including noise, deratings, and speed.

1.4.1 Definition of Accuracy Terms

This section defines a number of terms related to instrument accuracy. Some of these terms are further discussed in subsequent paragraphs. **Table 1-1** summarizes conversion factors for various specifications associated with instruments.

SENSITIVITY - the smallest *change* in the signal that can be detected.

RESOLUTION - the smallest *portion* of the signal that can be observed.

REPEATABILITY - the closeness of agreement between *successive* measurements carried out under the same conditions.

REPRODUCIBILITY - the closeness of agreement between measurements of the same quantity carried out with a stated *change in conditions*.

ABSOLUTE ACCURACY - the closeness of agreement between the result of a measurement and its true value or accepted *standard value*. Accuracy is often separated into gain and offset terms.

RELATIVE ACCURACY - the extent to which a measurement accurately reflects the *relationship* between an unknown and a *reference value*.

ERROR - the *deviation* (difference or ratio) of a measurement *from its true value.* Note that true values are by their nature indeterminate.

RANDOM ERROR - the *mean* of a large number of measurements influenced by random error *matches the true value*.

SYSTEMATIC ERROR - the *mean* of a large number of measurements influenced by systematic error *deviates from the true value*.

UNCERTAINTY - an estimate of the *possible* error in a measurement, i.e., the estimated possible deviation from its actual value. This is the opposite of accuracy.

"Precision" is a more qualitative term than many of those defined here. It refers to the freedom from uncertainty in the measurement. It's often applied in the context of repeatability or reproducibility, but it shouldn't be used in place of "accuracy."

1.4.2 Accuracy

One of the most important considerations in any measurement situation is reading accuracy. For any given test setup, a number of factors can affect accuracy. The most important factor is the accuracy of the instrument itself, which may be specified in several ways, including a percentage of full scale,

TABLE 1-1: Specification Conversion Factors

Percent	PPM	Digits	Bits	dB	Portion of 10V	Number of time constants to settle to rated accuracy
10%	100000	1	3.3	–20	1 V	2.3
1%	10000	2	6.6	–40	100mV	4.6
0.1%	1000	3	10	–60	10mV	6.9
0.01%	100	4	13.3	–80	1mV	9.2
0.001%	10	5	16.6	–100	100 μV	11.5
0.0001%	1	6	19.9	–120	10 μV	13.8
0.00001%	0.1	7	23.3	–140	1 μV	16.1
0.000001%	0.01	8	26.6	–160	100 nV	18.4
0.000001%	0.001	9	29.9	–180	10 nV	20.7

a percentage of reading, or a combination of both. Instrument accuracy aspects are covered in the following paragraphs.

Other factors such as input loading, leakage resistance and current, shielding, and guarding may also have a serious impact on overall accuracy. These important measurement considerations are discussed in detail in Sections 2 and 3.

Measurement Instrument Specifications

Instrument accuracy is usually specified as a percent of reading, plus a percentage of range (or a number of counts of the least significant digit). For example, a typical DMM accuracy specification may be stated as: ±(0.005% of reading + 0.002% of range). Note that the percent of reading is most significant when the reading is close to full scale, while the percent of range is most significant when the reading is a small fraction of full scale.

Accuracy may also be specified in ppm (parts per million). Typically, this accuracy specification is given as ±(ppm of reading + ppm of range). For example, the DCV accuracy of a higher resolution DMM might be specified as ±(25ppm of reading + 5ppm of range).

Resolution

The resolution of a digital instrument is determined by the number of counts that can be displayed, which depends on the number of digits. A typical digital electrometer might have 5½ digits, meaning five whole digits (each with possible values between 0 and 9) plus a leading half digit that can take on the values 0 or ±1. Thus, a 5½-digit display can show 0 to 199,999, a total of 200,000 counts. The resolution of the display is the ratio of the smallest count to the maximum count (1/200,000 or 0.0005% for a 5½-digit display).

For example, the specification of ±(0.05% + 1 count) on a 4½-digit meter reading 10.000 volts corresponds to a total error of ±(5mV + 1mV) out of 10V, or ±(0.05% of reading + 0.01% of reading), totaling ±0.06%. Generally, the higher the resolution, the better the accuracy.

Sensitivity

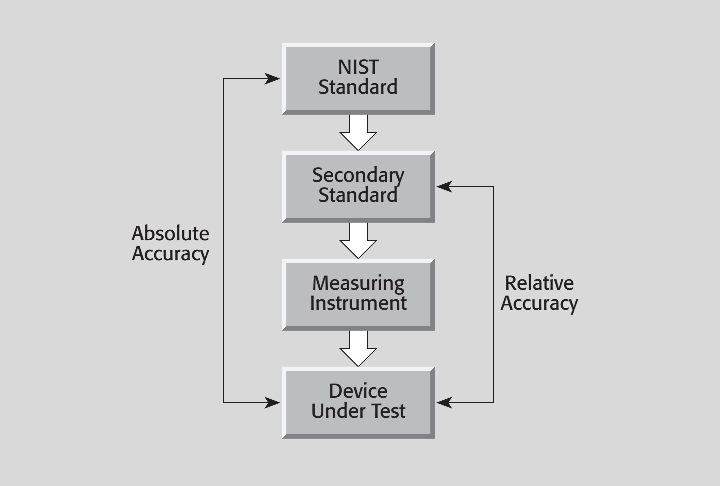
The sensitivity of a measurement is the smallest change of the measured signal that can be detected. For example, voltage sensitivity may be 1µV, which simply means that any change in input signal less than 1µV won't show up in the reading. Similarly, a current sensitivity of 10fA implies that only changes in current greater than that value will be detected.

The ultimate sensitivity of a measuring instrument depends on both its resolution and the lowest measurement range. For example, the sensitivity of a 5½-digit DMM with a 200mV measurement range is 1µV.

Absolute and Relative Accuracy

As shown in **Figure 1-4**, absolute accuracy is the measure of instrument accuracy that is directly traceable to the primary standard at the National Institute of Standards and Technology (NIST). Absolute accuracy may be specified as ±(% of reading + counts), or it can be stated as ±(ppm of reading + ppm of range), where ppm signifies parts per million of error.

FIGURE 1-4: Comparison of Absolute and Relative Accuracy



Relative accuracy (see **Figure 1-4**) specifies instrument accuracy to some secondary reference standard. As with absolute accuracy, relative accuracy can be specified as ±(% of reading + counts) or it may be stated as ±(ppm of reading + ppm of range).

Transfer Stability

A special case of relative accuracy is the transfer stability, which defines instrument accuracy relative to a secondary reference standard over a very short time span and narrow ambient temperature range (typically within five minutes and ±1°C). The transfer stability specification is useful in situations where highly accurate measurements must be made in reference to a known secondary standard.

Calculating Error Terms from Accuracy Specifications

To illustrate how to calculate measurement errors from instrument specifications, assume the following measurement parameters:

Accuracy: ±(25ppm of reading + 5ppm of range)
Range: 2V
Input signal: 1.5V

The error is calculated as:

$$\begin{aligned}\text{Error} &= 1.5(25 \times 10^{-6}) + 2(5 \times 10^{-6}) \\ &= (37.5 \times 10^{-6}) + (10 \times 10^{-6}) \\ &= 47.5 \times 10^{-6}\end{aligned}$$

Thus, the reading could fall anywhere within the range of 1.5V ± 47.5μV, an error of ±0.003%.

1.4.3 Deratings

Accuracy specifications are subject to deratings for temperature and time drift, as discussed in the following paragraphs.

Temperature Coefficient

The temperature of the operating environment can affect accuracy. For this reason, instrument specifications are usually given over a defined temperature range. Keithley accuracy specifications on newer electrometers, nanovoltmeters, DMMs, and SMUs are usually given over the range of 18°C to 28°C. For temperatures outside of this range, a temperature coefficient such as ±(0.005 % + 0.1 count)/°C or ±(5ppm of reading + 1ppm of range)/°C is specified. As with the accuracy specification, this value is given as a percentage of reading plus a number of counts of the least significant digit (or as a ppm of reading plus ppm of range) for digital instruments. If the instrument is operated outside the 18°C to 28°C temperature range, this figure must be taken into account, and errors can be calculated in the manner described previously for every degree less than 18°C or greater than 28°C.

Time Drift

Most electronic instruments, including electrometers, picoammeters, nanovoltmeters, DMMs, SMUs, and SourceMeter instruments, are subject to changes in accuracy and other parameters over a long period of time, whether or not the equipment is operating. Because of these changes, instrument specifications usually include a time period beyond which the instrument's accuracy cannot be guaranteed. The time period is stated in the specifications, and is typically over specific increments such as 90 days or one year. As noted previously, transfer stability specifications are defined for a much shorter period of time—typically five or 10 minutes.

1.4.4 Noise and Noise Rejection

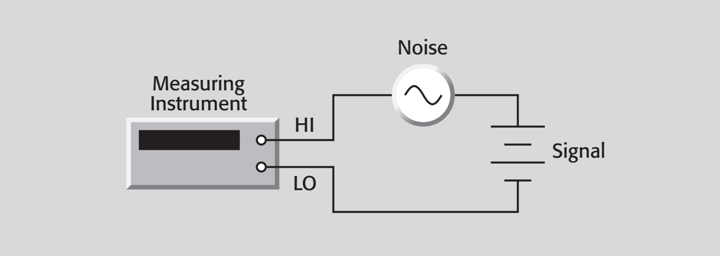
Noise is often a consideration when making virtually any type of electronic measurement, but noise problems can be particularly severe when making low level measurements. Thus, it's important that noise specifications and terms are well understood when evaluating the performance of an instrument.

Normal Mode Rejection Ratio

Normal mode rejection ratio (NMRR) defines how well the instrument rejects or attenuates noise that appears between the HI and LO input terminals. Noise rejection is accomplished by using the integrating A/D converter to attenuate noise at specific frequencies (usually 50 and 60Hz) while passing low frequency or DC normal mode signals. As shown in **Figure 1-5**, normal mode noise is an error signal that adds to the desired input signal. Normal mode noise is detected as a peak noise or deviation in a DC signal. The ratio is calculated as:

$$\text{NMRR} = 20 \log \left[\frac{\text{peak normal mode noise}}{\text{peak measurement deviation}} \right]$$

FIGURE 1-5: Normal Mode Noise

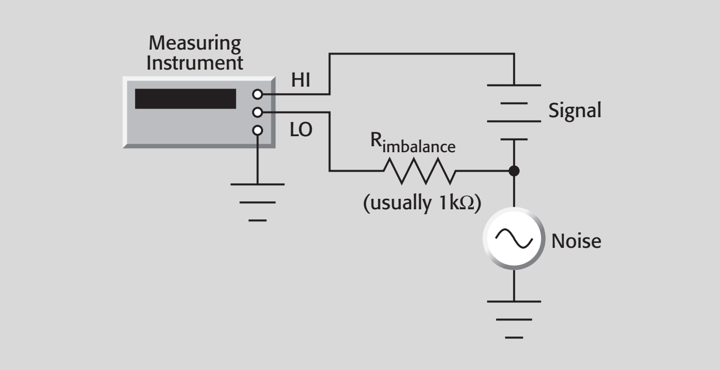


Normal mode noise can seriously affect measurements unless steps are taken to minimize the amount added to the desired signal. Careful shielding will usually attenuate normal mode noise, and many instruments have internal filtering to reduce the effects of such noise even further.

Common Mode Rejection Ratio

Common mode rejection ratio (CMRR) specifies how well an instrument rejects noise signals that appear between both input high and input low and chassis ground, as shown in **Figure 1-6**. CMRR is usually measured with a 1kΩ resistor imbalance in one of the input leads.

FIGURE 1-6: Common Mode Noise



Although the effects of common mode noise are usually less severe than normal mode noise, this type of noise can still be a factor in sensitive measurement situations. To minimize common mode noise, connect shields only to a single point in the test system.

Noise Specifications

Both NMRR and CMRR are generally specified in dB at 50 and 60Hz, which are the interference frequencies of greatest interest. (CMRR is often specified at DC as well.) Typical values for NMRR and CMRR are >80dB and >120dB respectively.

Each 20dB increase in noise rejection ratio reduces noise voltage or current by a factor of 10. For example, a rejection ratio of 80dB indicates noise reduction by a factor of 10^4, while a ratio of 120dB shows that the common mode noise would be reduced by a factor of 10^6. Thus, a 1V noise signal would be reduced to 100μV with an 80dB rejection ratio and down to 1μV with a 120dB rejection ratio.

1.4.5 Speed

Instrument measurement speed is often important in many test situations. When specified, measurement speed is usually stated as a specific number of readings per second for given instrument operating conditions. Certain factors such as integration period and the amount of filtering may affect overall instrument measurement speed. However, changing these operating modes may also alter resolution and accuracy, so there is often a tradeoff between measurement speed and accuracy.

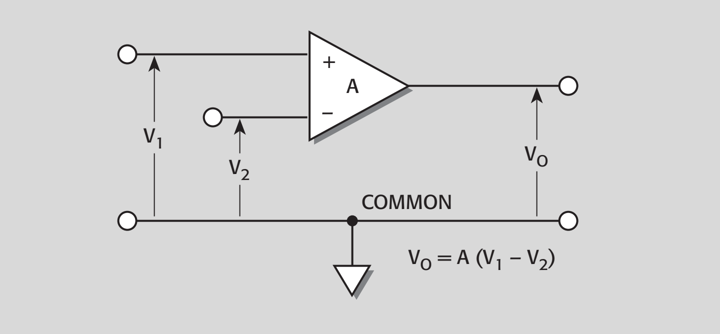
Instrument speed is most often a consideration when making low impedance measurements. At higher impedance levels, circuit settling times become more important and are usually the overriding factor in determining overall measurement speed. Section 2.6.4 discusses circuit settling time considerations in more detail.

1.5 Circuit Design Basics

Circuits used in the design of many low level measuring instruments, whether a voltmeter, ammeter, ohmmeter, or coulombmeter, generally use circuits that can be understood as operational amplifiers. **Figure 1-7** shows a basic operational amplifier. The output voltage is given by:

$$V_O = A\,(V_1 - V_2)$$

FIGURE 1-7: Basic Operational Amplifier



The gain (A) of the amplifier is very large, a minimum of 10^4 to 10^5, and often 10^6. The amplifier has a power supply (not shown) referenced to the common lead.

Current into the op amp inputs is ideally zero. The effect of feedback properly applied is to reduce the input voltage difference ($V_1 - V_2$) to zero.

1.5.1 Voltmeter Circuits

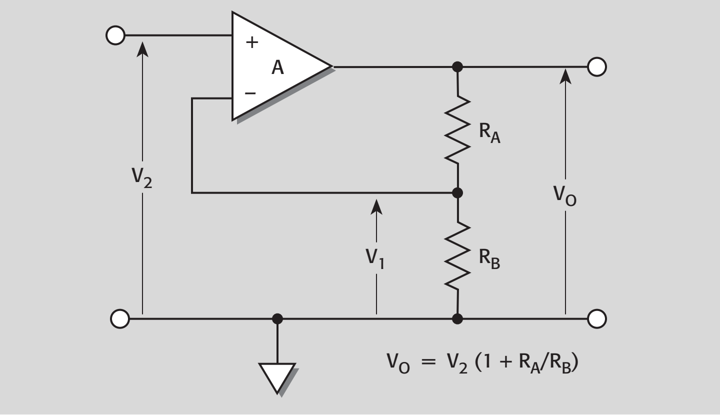
Electrometer Voltmeter

The operational amplifier becomes a voltage amplifier when connected as shown in **Figure 1-8**. The offset current is low, so the current flowing through R_A and R_B is the same. Assuming the gain (A) is very high, the voltage gain of the circuit is defined as:

$$V_O = V_2\,(1 + R_A/R_B)$$

Thus, the output voltage (V_O) is determined both by the input voltage (V_2), and amplifier gain set by resistors R_A and R_B. Given that V_2 is applied to the amplifier input lead, the high input resistance of the operational amplifier is the only load on V_2, and the only current drawn from the source is the very low input offset current of the operational amplifier. In many electrometer voltmeters, R_A is shorted and R_B is open, resulting in unity gain.

FIGURE 1-8: Voltage Amplifier



Nanovoltmeter Preamplifier

The same basic circuit configuration shown in **Figure 1-8** can be used as an input preamplifier for a nanovoltmeter. Much higher voltage gain is required, so the values of R_A and R_B are set accordingly; a typical voltage gain for a nanovoltmeter preamplifier is 10^3.

Electrometer and nanovoltmeter characteristics differ, so the operational amplifier requirements for these two types of instruments are also somewhat different. While the most important characteristics of the electrometer voltmeter operational amplifier are low input offset current and high input impedance, the most important requirement for the nanovoltmeter input preamplifier is low input noise voltage.

1.5.2 Ammeter Circuits

There are two basic techniques for making current measurements: these are the shunt ammeter and the feedback ammeter techniques. DMMs and older electrometers use the shunt method, while picoammeters and the AMPS function of electrometers use the feedback ammeter configuration only.

Shunt Ammeter

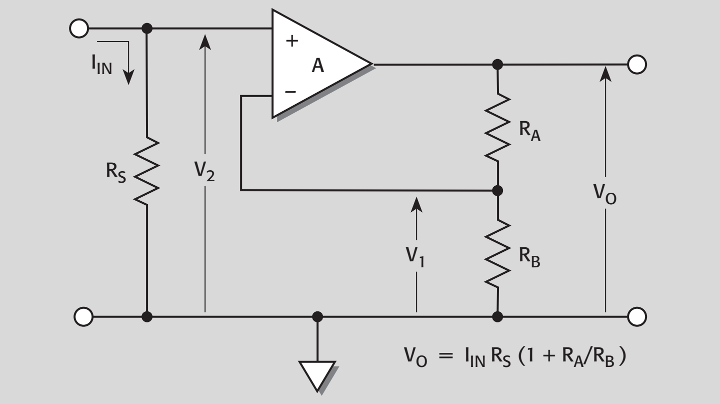
Shunting the input of a voltmeter with a resistor forms a shunt ammeter, as shown in **Figure 1-9**. The input current (I_{IN}) flows through the shunt resistor (R_S). The output voltage is defined as:

$$V_O = I_{IN} R_S (1 + R_A/R_B)$$

For several reasons, it's generally advantageous to use the smallest possible value for R_S.

First, low value resistors have better accuracy, time and temperature stability, and voltage coefficient than high value resistors. Second, lower resistor values reduce the input time constant and result in faster instrument response time. To minimize circuit loading, the input resistance (R_S) of an ammeter should be small, thus reducing the voltage burden (V_2). However, note that reducing the shunt resistance will degrade the signal-to-noise ratio.

FIGURE 1-9: Shunt Ammeter



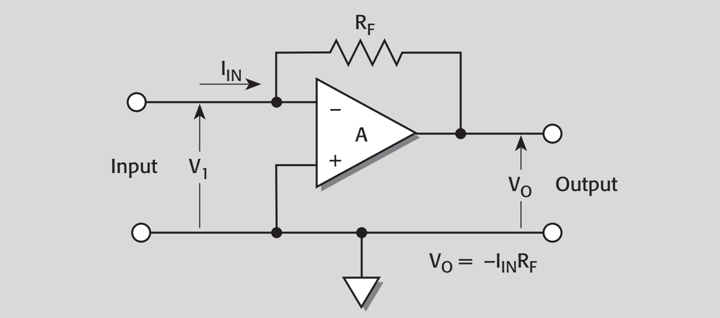
Feedback Ammeter

In this configuration, shown in **Figure 1-10**, the input current (I_{IN}) flows through the feedback resistor (R_F). The low offset current of the amplifier (A) changes the current (I_{IN}) by a negligible amount. The amplifier output voltage is calculated as:

$$V_O = -I_{IN}R_F$$

Thus, the output voltage is a measure of input current, and overall sensitivity is determined by the feedback resistor (R_F). The low voltage burden (V_1) and corresponding fast rise time are achieved by the high gain op amp, which forces V_1 to be nearly zero.

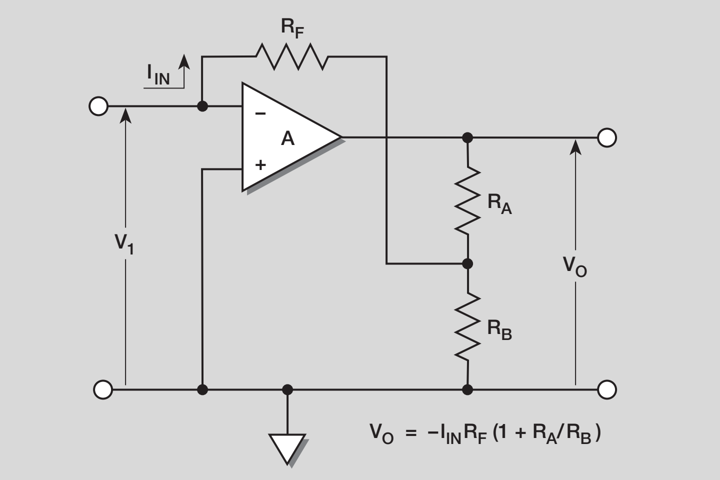
FIGURE 1-10: Feedback Ammeter



Picoammeter amplifier gain can be changed as in the voltmeter circuit by using the combination shown in **Figure 1-11**. Here, the addition of R_A and R_B forms a "multiplier," and the output voltage is defined as:

$$V_O = -I_{IN}R_F\ (1 + R_A/R_B)$$

FIGURE 1-11: Feedback Ammeter with Selectable Voltage Gain



High Speed Picoammeter

The rise time of a feedback picoammeter is normally limited by the time constant of the feedback resistor (R_F) and any shunting capacitance (C_F). A basic approach to high speed measurements is to minimize stray shunting capacitance through careful mechanical design of the picoammeter.

Remaining shunt capacitance can be effectively neutralized by a slight modification of the feedback loop, as shown in **Figure 1-12**. If the time constant R_1C_1 is made equal to the time constant R_FC_F, the shaded area of the circuit behaves exactly as a resistance R_F with zero C_F. The matching of time constants in this case is fairly straightforward, because the capacitances involved are all constant and aren't affected by input capacitances.

Logarithmic Picoammeter

A logarithmic picoammeter can be formed by replacing the feedback resistor in a picoammeter with a diode or transistor exhibiting a logarithmic voltage-current relationship, as shown in **Figure 1-13**. The output voltage (and the meter display) is then equal to the logarithm of the input current. As a result, several decades of current can be read on the meter without changing the feedback element.

FIGURE 1-12: Neutralizing Shunt Capacitance

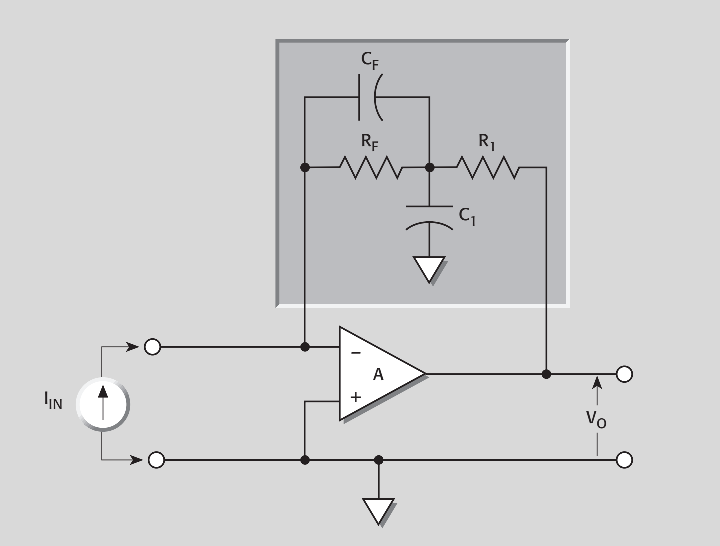
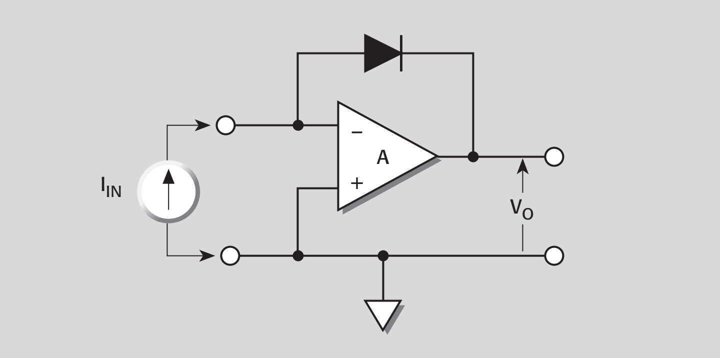


FIGURE 1-13: Logarithmic Picoammeter



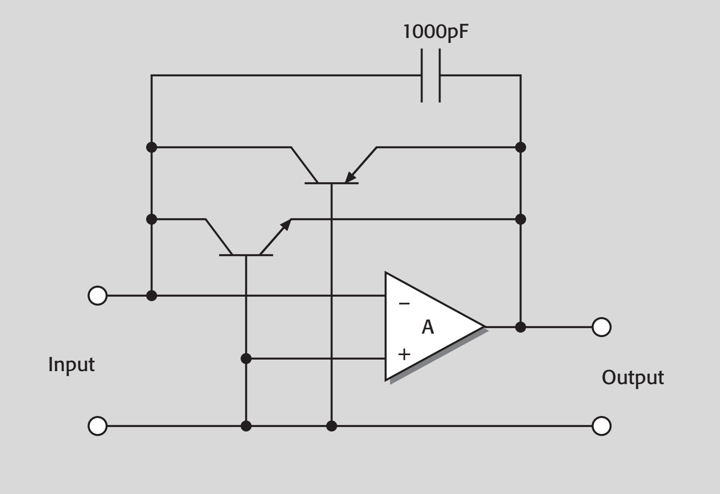
The main advantage of a logarithmic picoammeter is its ability to follow current changes over several decades without range changing.

The big disadvantage is the loss of accuracy and resolution, but some digital picoammeters combine accuracy and dynamic range by combining autoranging and digital log conversion.

If two diodes are connected in parallel, back-to-back, this circuit will function with input signals of either polarity.

Using a small-signal transistor in place of a diode produces somewhat better performance. **Figure 1-14** shows an NPN transistor and a PNP transistor in the feedback path to provide dual polarity operation.

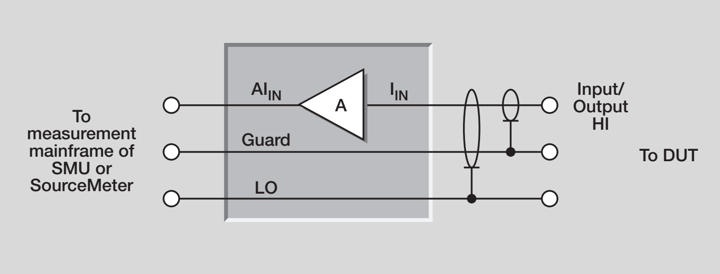
FIGURE 1-14: Dual Polarity Log Current to Voltage Converter



Remote Preamp Circuit (Source V, Measure I Mode)

Figure 1-15 illustrates a typical preamp circuit. In the Source V, Measure I mode, the SMU applies a programmed voltage and measures the current flowing from the voltage source. The sensitive input is surrounded by a guard, which can be carried right up to the DUT for fully guarded measurements. The remote preamp amplifies the low current signal passing through the DUT; therefore, the cable connecting the remote preamp to the measurement mainframe carries only high level signals, minimizing the impact of cable noise.

FIGURE 1-15: Remote Preamp in Source V, Measure I Mode



1.5.3 Coulombmeter Circuit

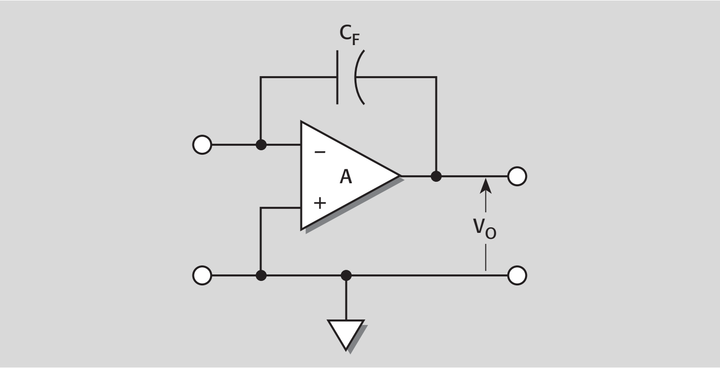
The coulombmeter measures electrical charge that has been stored in a capacitor or that might be produced by some charge generating process.

For a charged capacitor, $Q = CV$, where Q is the charge in coulombs on the capacitor, C is the capacitance in farads, and V is the potential across the capacitor in volts. Using this relationship, the basic charge measuring scheme is to transfer the charge to be measured to a capacitor of known value and then measure the voltage across the known capacitor; thus, $Q = CV$.

The electrometer is ideal for charge measurements, because the low offset current won't alter the transferred charge during short time intervals and the high input resistance won't allow the charge to bleed away.

Electrometers use a feedback circuit to measure charge, as shown in **Figure 1-16**. The input capacitance of this configuration is AC_F. Thus, large effective values of input capacitance are obtained using reasonably sized capacitors for C_F.

FIGURE 1-16: Feedback Coulombmeter



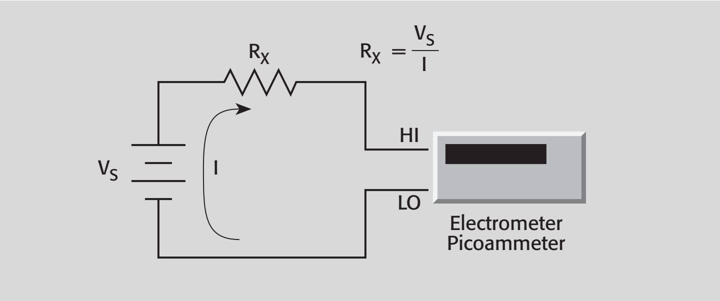
1.5.4 High Resistance Ohmmeter Circuits

Electrometer Picoammeter and Voltage Source

In this configuration (**Figure 1-17**), a voltage source (V_S) is placed in series with an unknown resistor (R_X) and an electrometer picoammeter. The voltage drop across the picoammeter is small, so essentially all the voltage appears across R_X, and the unknown resistance can be computed from the sourced voltage and the measured current (I).

The advantages of this method are that it's fast and, depending on the power supply voltage and insulating materials, it allows measuring extremely high resistance. Also, with an adjustable voltage source, the voltage dependence of the resistance under test can be obtained directly.

FIGURE 1-17: High Resistance Measurement Using External Voltage Source

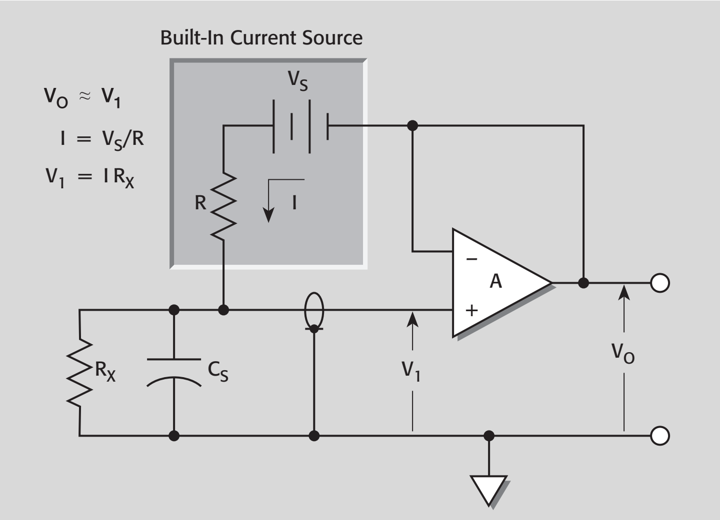


Usually, this method requires two instruments: a voltage source and a picoammeter or electrometer. Some electrometers and picoammeters, however, have a built-in voltage source and are capable of measuring the resistance directly.

Electrometer Ohmmeter Using Built-In Current Source

Figure 1-18 shows the basic configuration of an alternative form of electrometer ohmmeter. A built-in constant-current source, formed by V_S and R, forces a known current through the unknown resistance (R_X). The resulting voltage drop is proportional to the unknown resistance and is indicated by the meter as resistance, rather than voltage.

FIGURE 1-18: Electrometer Ohmmeter with Built-In Current Source

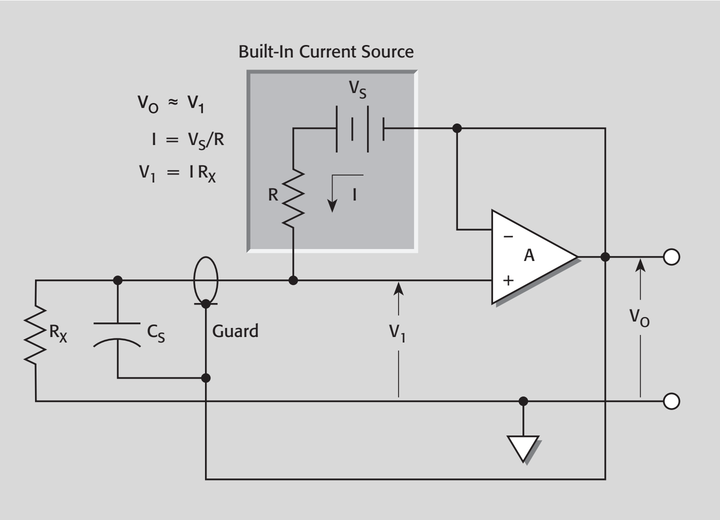


The disadvantage of this method is that the voltage across the unknown is a function of its resistance, so it cannot be easily controlled. Very high resistances tend to have large voltage coefficients; therefore, measurements made with a constant voltage are more meaningful. In addition, the response speed for resistances greater than 10GΩ will be rather slow. This limitation can be partially overcome by guarding.

Electrometer Ohmmeter with Guarded Ohms Mode

Figure 1-19 shows a modification of the circuit in **Figure 1-18** in which the HI input node is surrounded with a guard voltage from the operational amplifier output. The amplifier has unity gain, so this guard voltage is virtually the same potential as V_1 and the capacitance (C_S) of the input cable is largely neutralized, resulting in much faster measurements of resistances greater than 10GΩ.

FIGURE 1-19: Electrometer Ohmmeter with Guarded Ohms

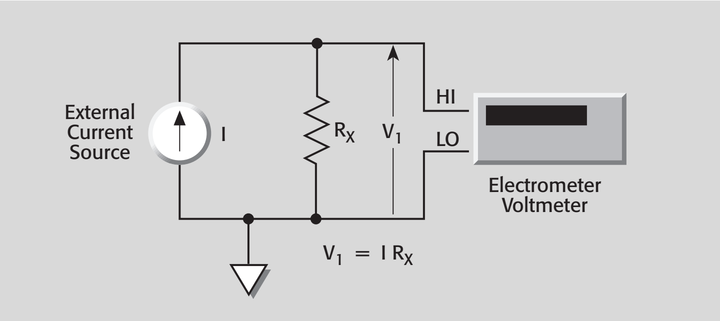


The guarded mode also significantly reduces the effect of input cable leakage resistance, as discussed in Section 2.4.2.

Electrometer Voltmeter and External Current Source

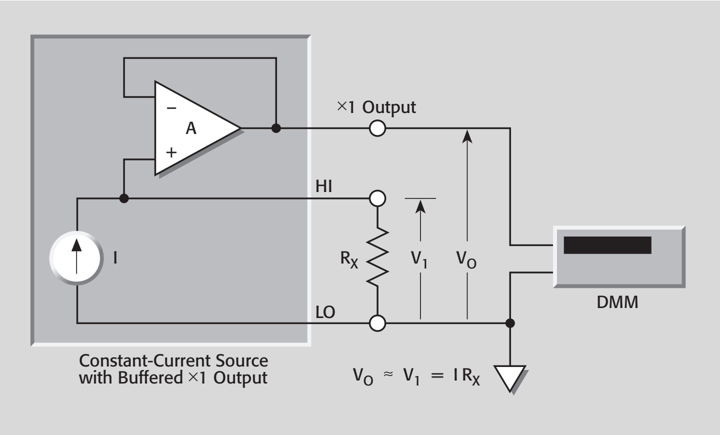
In this method, shown in **Figure 1-20**, a current source generates current (I), which flows through the unknown resistor (R_X). The resulting voltage drop is measured with an electrometer voltmeter, and the value of R_X is calculated from the voltage and current.

FIGURE 1-20: High Resistance Measurement Using External Current Source with Electrometer Voltmeter



If the current source has a buffered ×1 output, a low impedance voltmeter, such as a DMM, may be used to read the voltage across R_X. This arrangement is shown in **Figure 1-21**.

FIGURE 1-21: High Resistance Measurement Using a True Current Source with a DMM



1.5.5 Low Resistance Ohmmeter Circuits

Nanovoltmeter and External Current Source

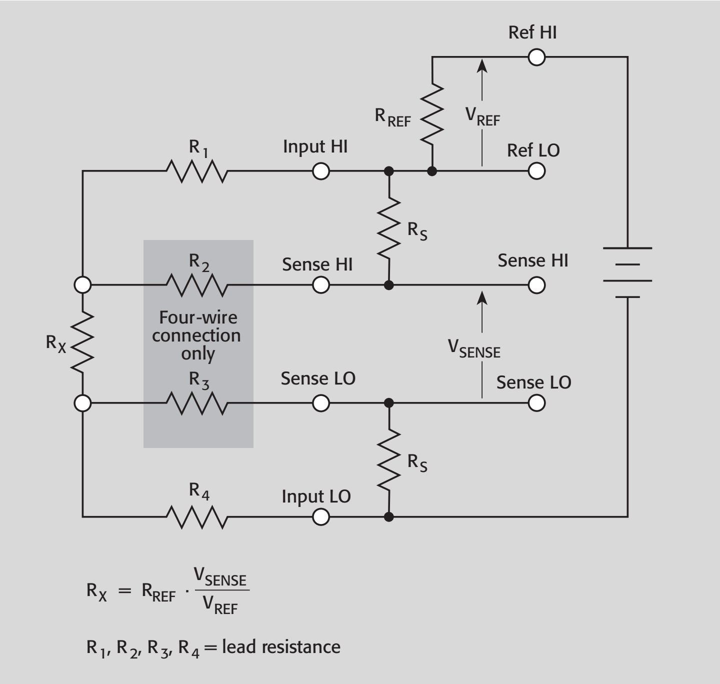
If the electrometer in **Figure 1-20** is replaced with a nanovoltmeter, the circuit can be used to measure very low resistances ($<\mu\Omega$). Using a four-wire method eliminates any lead resistance from the measurement. A current source that can automatically change polarity can be used to correct for offsets. First, a voltage measurement is taken with positive test current, then another voltage measurement is taken with negative test current. Averaging the difference between the two readings cancels the offsets.

DMM Ohmmeter

The typical DMM uses the ratiometric technique shown in **Figure 1-22** to make resistance measurements. When the resistance function is selected, a series circuit is formed between the ohms voltage source, a reference resistance (R_{REF}), and the resistance being measured (R_X). The voltage causes a current to flow through the two resistors. This current is common to both resistances, so the value of the unknown resistance can be determined by measuring the voltage across the reference resistance and across the unknown resistance and calculating as:

$$R_X = R_{REF} \cdot \frac{\text{SENSE HI} - \text{SENSE LO}}{\text{REF HI} - \text{REF LO}}$$

FIGURE 1-22: Ratiometric Resistance Measurement

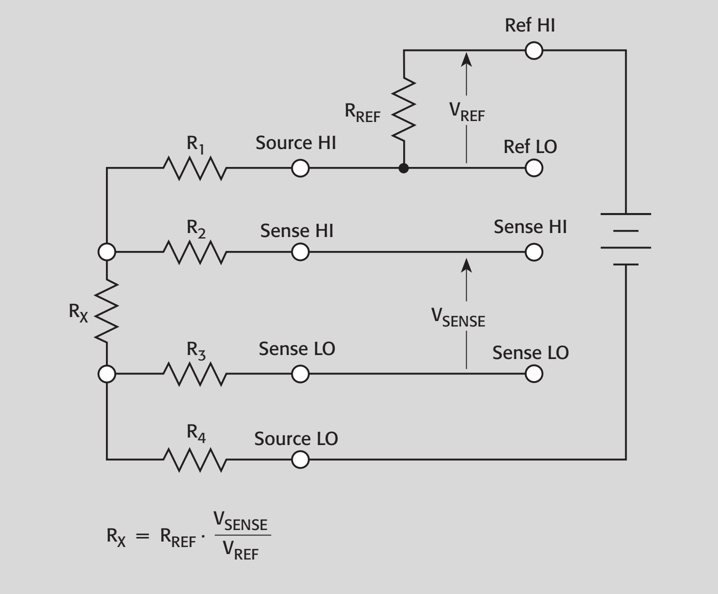


The resistors (R_S) provide automatic two-wire or four-wire resistance measurements. When used in the two-wire mode, the measurement will include the lead resistance, represented by R_1 and R_4. When the unknown resistance is low, perhaps less than 100Ω, the four-wire mode will give much better accuracy. The sense lead resistance, R_2 and R_3, won't cause significant error because the sense circuit has very high impedance.

Micro-ohmmeter

The micro-ohmmeter also uses the four-wire ratiometric technique, which is shown in **Figure 1-23**. It doesn't have the internal resistors (R_S), as in the DMM, so all four leads must be connected to make a measurement. Also, the terminals that supply test current to the unknown resistance are labeled Source HI and Source LO.

FIGURE 1-23: Micro-ohmmeter Resistance Measurement

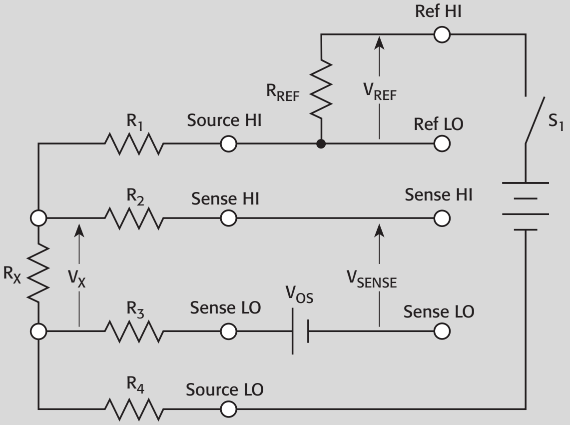


$$R_X = R_{REF} \cdot \frac{V_{SENSE}}{V_{REF}}$$

The pulsed drive mode, shown in **Figure 1-24**, allows the micro-ohmmeter to cancel stray offset voltages in the unknown resistance being measured. During the measurement cycle, the voltage across the unknown resistance is measured twice, once with the drive voltage on, and a second time with the drive voltage turned off. Any voltage present when the drive voltage is off represents an offset voltage and will be subtracted from the voltage measured when the drive voltage is on, providing a more accurate measurement of the resistance.

The dry circuit test mode, shown in **Figure 1-25**, adds a resistor across the source terminals to limit the open-circuit voltage to less than 20mV. This prevents breakdown of any insulating film in the device being tested and gives a better indication of device performance with low level signals. The meter must now measure the voltage across this resistor (R_{SH}), as well as the voltage across the reference resistor and the unknown resistor. See Section 3.3.5 for more information on dry circuit testing.

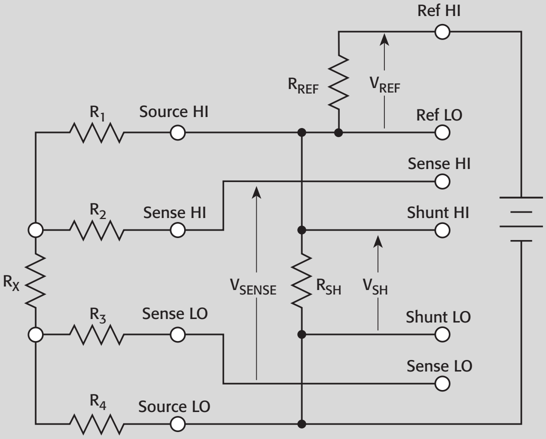
FIGURE 1-24: Micro-ohmmeter in Pulse Mode



$$R_X = R_{REF} \cdot \frac{V_{SENSE\ 1} - V_{SENSE\ 2}}{V_{REF}}$$

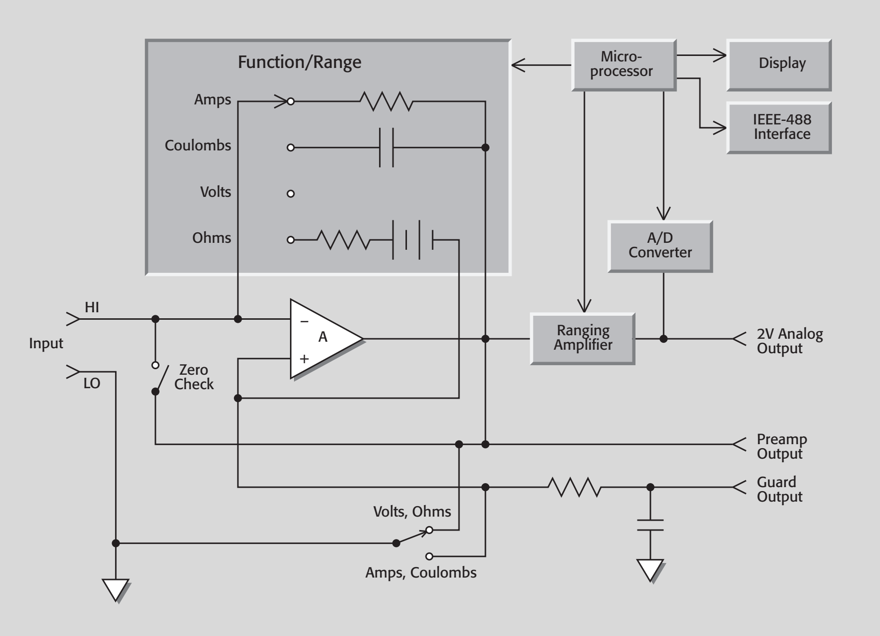
where $V_{SENSE\ 1}$ is measured with S_1 closed, and is equal to $V_X + V_{OS}$, and $V_{SENSE\ 2}$ is measured with S_1 open, and is equal to V_{OS}.

FIGURE 1-25: Micro-ohmmeter with Dry Circuit On



$$R_X = \frac{V_{SENSE}}{\frac{V_{REF}}{R_{REF}} - \frac{V_{SH}}{R_{SH}}}$$

FIGURE 1-26: Typical Digital Electrometer



1.5.6 Complete Instruments

Digital Electrometers

Figure 1-26 is a block diagram of a typical digital electrometer. The analog section is similar to the circuitry discussed previously. An electrometer preamplifier is used at the input to increase sensitivity and raise input resistance. The output of the main amplifier is applied to both the analog output and the A/D converter. Range switching and function switching, instead of being performed directly, are controlled by the microprocessor.

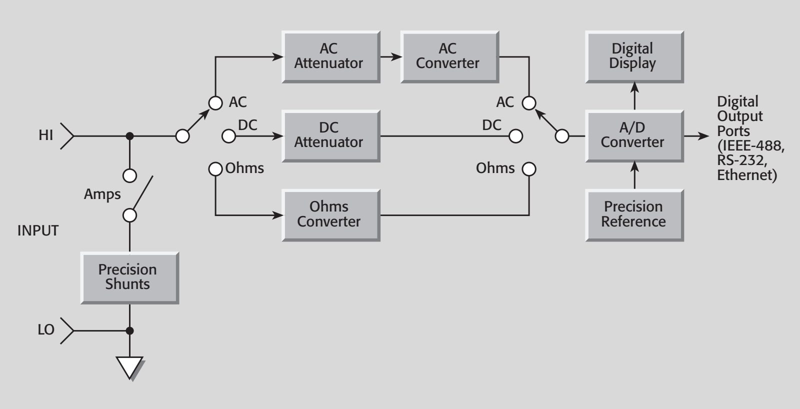
The microprocessor also controls the A/D converter and supervises all other operating aspects of the instrument. The input signal to the A/D converter is generally 0–2V DC. After conversion, the digital data is sent to the display and to the digital output port (IEEE- 488 or RS-232).

Digital Multimeters (DMMs)

Most DMMs include five measurement functions: DC volts, AC volts, ohms, DC amps, and AC amps. As shown in **Figure 1-27**, various signal processing circuits are used to convert the input signal into a DC voltage that can be converted to digital information by the A/D converter.

The DC and AC attenuator circuits provide ranging for the AC and DC functions. The AC converter changes AC signals to DC, while the ohms con-

FIGURE 1-27: DMM Block Diagram



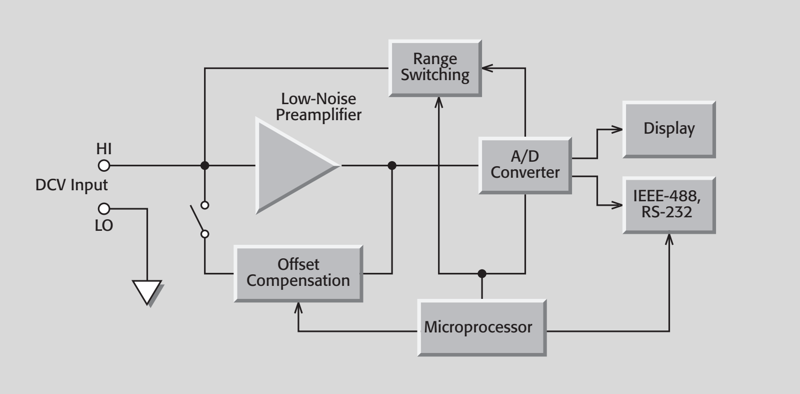
verter provides a DC analog signal for resistance measurements. Precision shunts are used to convert currents to voltages for the amps functions.

Once the input signal is appropriately processed, it's converted to digital information by the A/D converter. Digital data is then sent to the display and to the digital output port (IEEE-488, RS-232, or Ethernet).

Nanovoltmeters

A nanovoltmeter is a sensitive voltmeter optimized to measure very low voltages. As shown in **Figure 1-28**, the nanovoltmeter incorporates a low noise preamplifier, which amplifies the signal to a level suitable for A/D conversion (typically 2–3V full scale). Specially designed preamplifier circuits ensure that unwanted noise, thermoelectric EMFs, and offsets are kept to an absolute minimum.

FIGURE 1-28: Typical Nanovoltmeter



In order to cancel internal offsets, an offset or drift compensation circuit allows the preamplifier offset voltage to be measured during specific phases of the measurement cycle. The resulting offset voltage is subsequently subtracted from the measured signal to maximize measurement accuracy.

Once the preamplifier amplifies the signal, it's converted to digital information by the A/D converter. Digital data is then sent to the display and the IEEE-488 interface.

SMUs

The SMU provides four functions in one instrument: measure voltage, measure current, source voltage and source current. Generally, such instruments can simultaneously source voltage and measure current or simultaneously source current and measure voltage.

When configured to Source I and Measure V (as shown in **Figure 1-29**), the SMU will function as a high impedance current source with voltage measure (and voltage limit) capability.

Selecting either local or remote sense determines where the voltage measurement will be made. In local sense, the voltage is measured at the output of the SMU. In remote sense, the voltage is measured at the device under test, eliminating any voltage drops due to lead resistance.

The driven guard (×1 Buffer) ensures that the Guard and Output HI terminals are always at the same potential. Proper use of Guard virtually eliminates leakage paths in the cable, test fixture, and connectors. When configured to Source V and Measure I (as shown in **Figure 1-30**), the SMU will function as a low impedance voltage source with current measure (and current limit) capability.

SourceMeter Instrument

Like an SMU, a SourceMeter instrument can source current, source voltage, measure current and measure voltage. However, the SourceMeter instrument also has a sixth terminal, guard sense, which allows making more accurate measurements of networks. When configured to source current as shown in **Figure 1-31**, the SourceMeter unit functions as a high impedance current source with voltage limit capability and it can measure current, voltage, or resistance.

For voltage measurements, the sense selection (two-wire local or four-wire remote) determines where the measurement is made. In local sense, voltage is measured at the IN/OUT terminals of the instrument. In four-wire remote sense, voltage is measured directly at the device under test using the Sense terminals. This eliminates any voltage drops due to lead resistance.

When configured to source voltage as shown in **Figure 1-32**, the SourceMeter instrument functions as a low impedance voltage source with current limit capability and it can measure current, voltage, or resistance.

FIGURE 1-29: Source I Mode of SMU

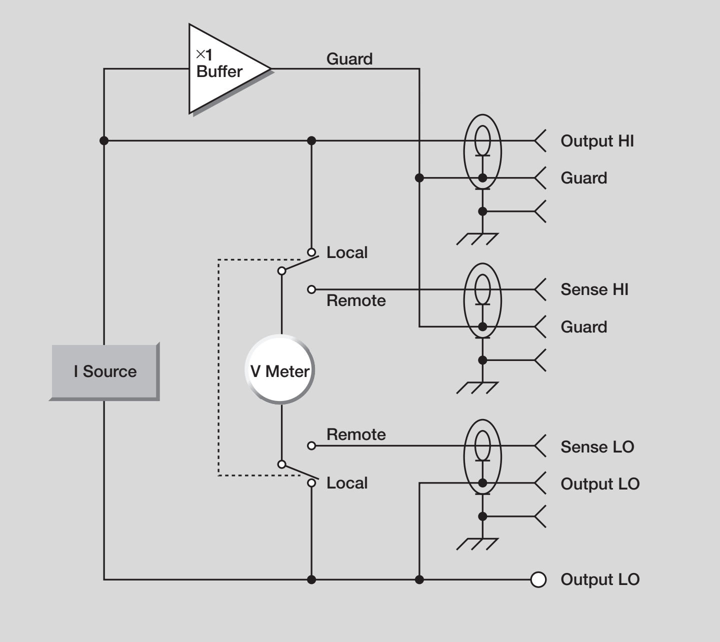
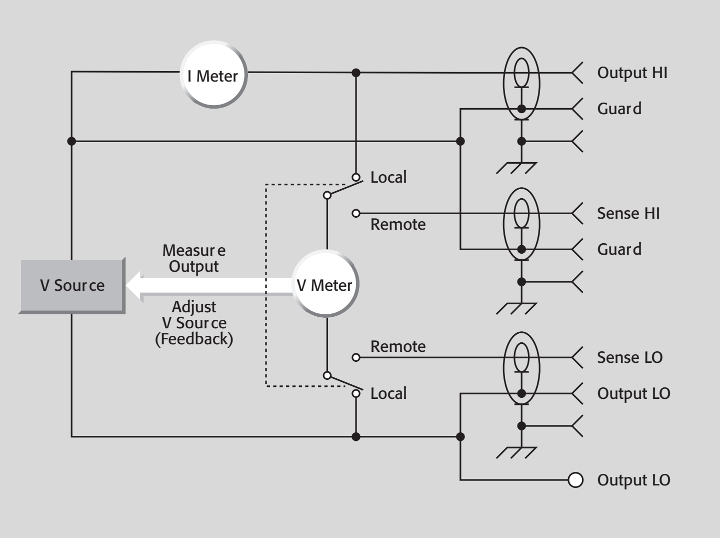


FIGURE 1-30: Source V Mode of SMU



Sense circuitry is used to monitor the output voltage continuously and adjust the V Source as needed.

FIGURE 1-31: Source I Mode of a SourceMeter Instrument

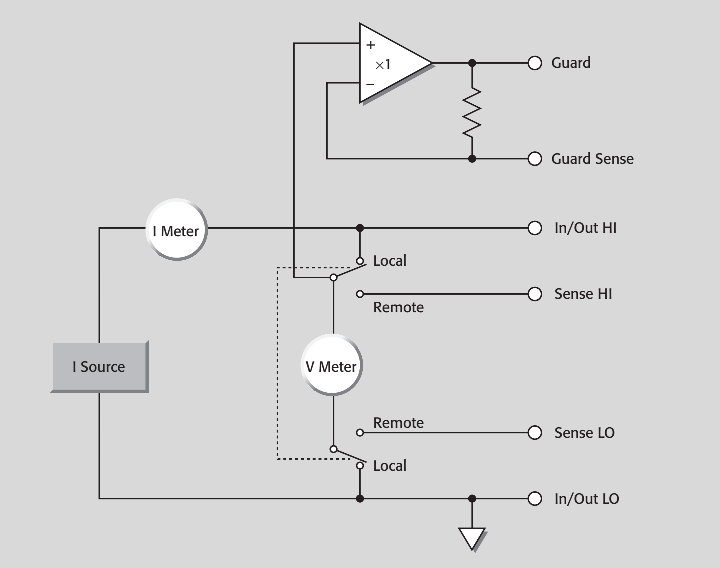
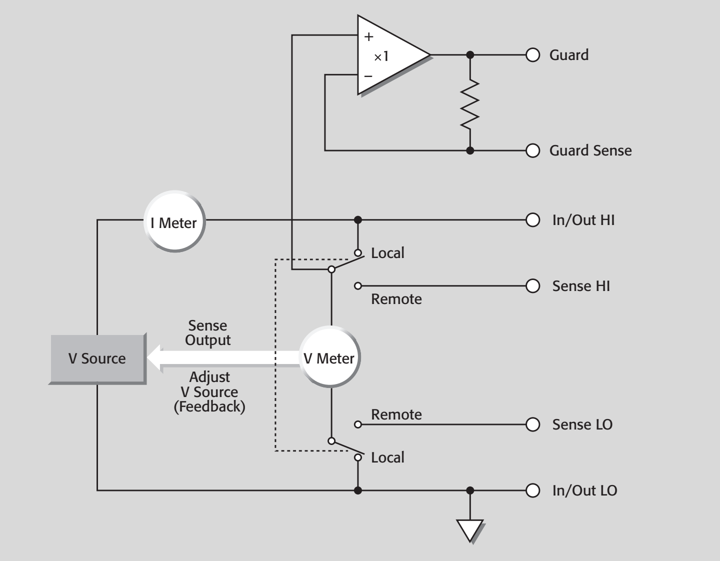


FIGURE 1-32: Source V Mode of a SourceMeter Instrument

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