

Resistance Measurement Handbook



Introduction

This paper focuses on resistance (R) as represented in the basic electrical equation $V = IR$ and offers precautions for measurement based on the properties of measurement targets. Such targets range from highly stable resistors to unstable insulation resistance, making it necessary to consider specific precautions that apply to each. Additionally, measurement methods and key considerations differ significantly depending on whether the resistance value is measured in kiliohms (or less) or in megaohms (or more).

It is our hope that this paper will prove to be a useful tool as you develop an understanding of appropriate resistance measurement methods.

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1. What is resistance?

-1. Causes of resistance

For the purposes of this paper, resistance refers to electrical resistance. As a property, it expresses the difficulty with which an electrical current flows, and it is expressed using the ohm (Ω). The reciprocal of resistance ($1/\Omega$) is conductance, which is expressed in siemens (S). With the exception of certain fields such as electrochemistry, conductance is rarely used.

When a potential difference V arises between two terminals, the electrical charge (in the form of either electrons or holes) moves toward the electrode with the opposite polarity. Resistance acts to oppose this movement. According to Ohm's law, the current I can be given by

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

This equation indicates that as the potential difference V increases, and as the resistance R decreases, the current I will increase.

The resistance R can be given by

$$R = \rho \frac{l}{S}$$

where ρ is the resistivity, l is the length and S is the cross-sectional area.

This equation indicates that resistance increases with length and thinness. In this way, resistance values vary with physical size, but they can be reasonably assumed to conform to the range described in Figure 3.

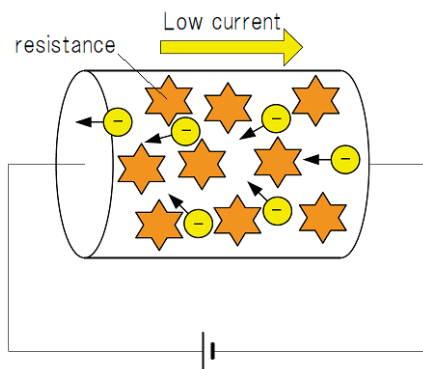


Figure 1 High Resistance

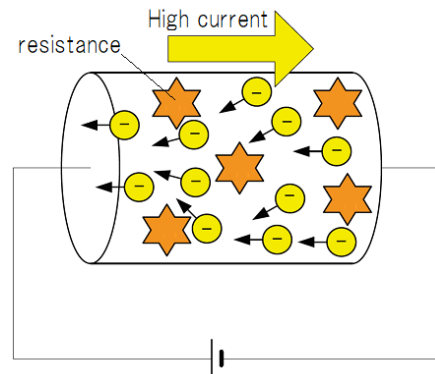


Figure 2 Low Resistance

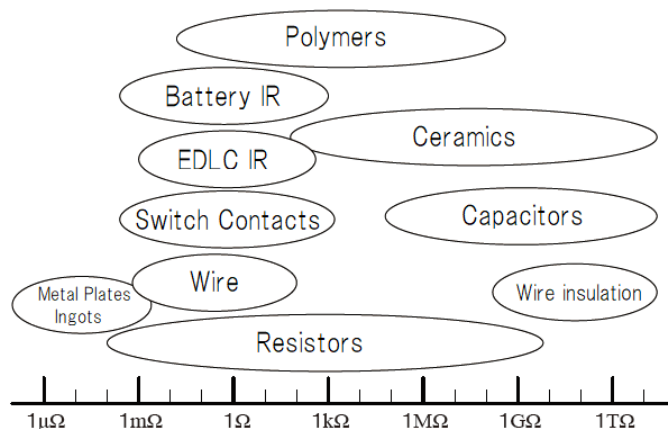


Figure 3 Various Measurement Targets and Their Resistance Values

-2. Resistance of Various Objects and Materials

➤ Resistors

The resistors commonly found in familiar electric products generally range from 1 Ω to 10 M Ω . Shunt resistors used as a special application to detect the current in batteries and motors range from about 0.1 m Ω to 1 Ω , while those used in circuits that handle high voltages are about 1 G Ω due to the need to avoid heat generation, which is given by V^2/R .

➤ Wire

Since the resistance value of wire increases with length, the unit Ω/m is used to express conductor resistance. AWG24 (0.2sq) wire such as that used inside devices has high resistance—90 m Ω/m —while the AWG6 (14sq) wire used for power cables has much lower resistance—about 1.3 m Ω/m (and 0.13 m Ω/m for 150sq).

Wire insulation must be made of material that resists the flow of current. Since leak current routes increase in number as a wire becomes longer, the unit Ωm is used to express the resistance of wire insulation. Materials used to manufacture insulation include polyvinyl chloride (PVC), polyethylene (PE), and Teflon (TE). Typical insulation resistance is 10 G Ω/m or higher for wires insulated with polyvinyl chloride, 100 G Ω/m or higher for wires insulated with polyethylene, and 1,000 G Ω/m or higher for wires insulated with Teflon.

➤ Switch and relay contact resistance

Wired circuits that carry current of dozens of amperes consume power on the order of several watts with a resistance of just 1 m Ω . Consequently, circuit breakers and other switch contacts on high-current wired circuits have resistance values that are much lower than 1 m Ω . Power relays, circuit breakers, and other components are designed to be used in high-current wired circuits. For that reason, their contacts will gradually corrode until eventually continuity is lost entirely if the energization current falls to a microampere-order current, necessitating caution.

Since the switches used in standard electronic circuits carry an energization current of 1 A or less, their contact resistance is on the order of dozens of milliohms. Their contacts are typically plated with gold so that stable contact can be obtained with energization currents that are measured in microamperes.

The resistance value of switches that use conductive rubber varies significantly depending on the amount of pressure applied. Contact resistance is fairly high at around 1 k Ω , but they are characterized by an extremely high level of contact durability.

When in the open state, switch resistance is 10 M Ω or higher. The initial insulation resistance is largely determined by the case's insulating properties but declines with use due to bits and pieces of the contact material that rub off over time and accumulated dust from the surrounding environment.

➤ Connector resistance

As with switch and relay contact resistance, the requirements for high-current wired circuits and signaling connectors differ. The emphasis when designing connectors for high-current contacts is on lowering the contact resistance. By contrast, signaling contacts are plated with gold, and the emphasis is on stability under minuscule loads. Materials used to manufacture connector housings include polyamides (PAs, or nylons) and polybutylene terephthalate (PBT). Since polyamides have low insulating performance, caution is necessary when measuring high resistance.

➤ Battery and electric double-layer capacitor (EDLC) internal resistance (IR)

The internal resistance (IR) of batteries and electric double-layer capacitors is correlated with the ease with which large currents can be obtained from these components. Whereas the internal resistance of a battery that produces a large current of 10 A might be extremely low at around 1 m Ω , it would not be unusual for the internal resistance of a lithium-ion button cell to exceed 100 Ω .

Because the internal resistance of batteries exhibits frequency characteristics, and because the voltage and current phases differ, a diagramming method known as a Cole-Cole plot such as that shown in Figure 4 is used to evaluate the property. In shipping inspections carried out as part of manufacturing processes, effective resistance (the real axis component) at 1 kHz provides a simple way to manage internal resistance.

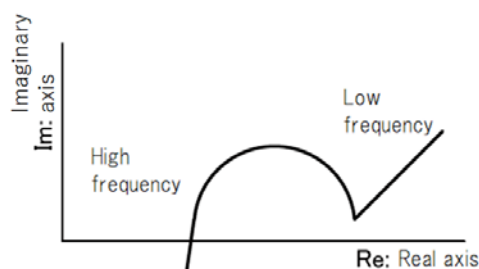


Figure 4 Battery Impedance

➤ Capacitors

Since capacitors store an electrical charge between electrodes, the higher the resistance value between electrodes, the better. Consequently, the resistance between the electrodes of a capacitor is known as the insulation resistance.

Typically, insulation resistance is at least 10 G Ω for ceramic capacitors and 100 k Ω for electrolytic capacitors.

2. Methods for measuring resistance

Methods for measuring resistance can be classified according to the method used to connect the voltmeter, ammeter, or other instrument, as well as the frequency used to make the measurement.

-1. Classification on the Basis of Connection Method

Generally speaking, the bridge method and fall-of-potential method are used to measure resistance.

➤ Bridge Method

The bridge method was the most common means of measuring resistance prior to 1980, a period during which various electronic circuit technologies had not yet been developed (see Figure 5). This approach, which did not require any complex electronic circuitry, could be implemented easily with a high-sensitivity galvanometer and a high-precision standard resistor. Engineers developed a variety of bridge method variants, including the Kelvin double bridge method (see Figure 6), which is well suited for measuring low resistance values, and the AC impedance method, which can be used with inductors and capacitors. Today, these methods have been replaced with low-resistance meters and LCR meters.

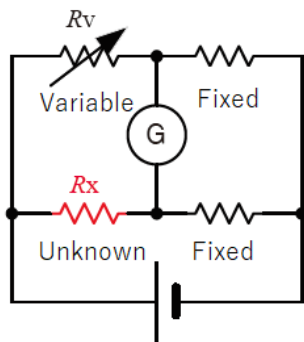


Figure 5 Wheatstone Bridge

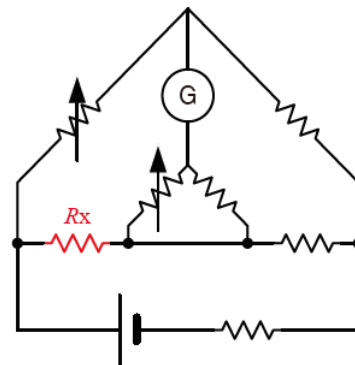


Figure 6 Kelvin Double Bridge

➤ Fall-of-potential method

This method, which is also known as the voltmeter-ammeter method, came to prominence with the development of electronic circuits. The current I is measured with a high-precision ammeter, and the voltage V is measured with a voltmeter. Then the resistance can be calculated using Ohm's law ($R = V / I$).

Figure 7 illustrates the connections used to measure low resistance. In low-resistance measurement, the error component due to the voltage drop caused by the ammeter can become problematic. The voltage is detected across the measurement target R_X so that the ammeter's voltage drop is not detected.

Figure 8 illustrates the connections used to measure high resistance. In high-resistance measurement, the leak current flowing to the voltmeter can become problematic. To prevent this leak current from affecting the measurement results, the ammeter is connected in series with the measurement target R_X , and the voltmeter measures the voltage drop from R_X as well as the ammeter.

High-precision digital multimeters (DMMs) are used as the ammeter and voltmeter in the fall-of-potential method, while instruments designed exclusively for resistance measurement (known as ohmmeters) integrate both functions into a single device. Instruments designed to measure resistance values of less than 1 k Ω consist of a constant-current source and voltmeter to avoid fluctuations in the detected voltage due to factors such as fluctuations in contact resistance. By contrast, use of a constant current to measure high resistance values of 1 M Ω or greater results in extremely long stray

capacitance charging times, making it more desirable to use an instrument that consists of a constant-voltage source and an ammeter. General-purpose LCR meters consist of a power source with an output resistance on the order of dozens of ohms along with an ammeter and voltmeter so that they can accommodate a broad range of measurement targets.

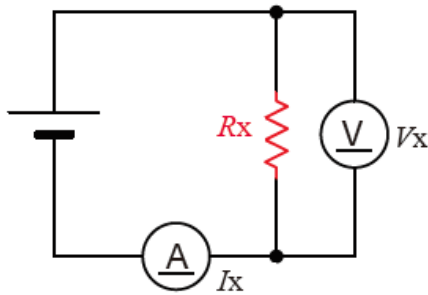


Figure 7 Fall-of-potential Method (Low Resistance)

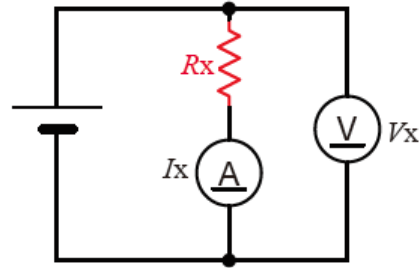


Figure 8 Fall-of-potential Method (High Resistance)

Reference: *Electrical Engineering Handbook*, The Institute of Electrical Engineers of Japan

-2. Classification on the Basis of Measurement Frequency

The power source, ammeter, and voltmeter may either use a DC signal (see Figure 9) or an AC signal (see Figure 10). Measuring instruments that use the DC method include digital multimeters (DMMs), DC low-resistance meters, and insulation resistance meters, while those that use the AC method include LCR meters and AC low-resistance meters.

Generally speaking, the DC method allows for higher-precision measurement. In addition to the fact that the reference voltage sources, reference resistors, and amplifiers that make up measurement circuits can be operated at a higher level of stability in the DC domain, the standards used to calibrate measuring instruments exhibit higher precision with DC signals. Additionally, much of the current flows to stray capacitance when measuring insulation resistance using an AC signal, causing a dramatic deterioration in precision.

The AC method is used in applications where measurement using a DC signal is not an option. For example, since it is not possible to pass a DC current through a capacitor, capacitance (i.e., the capacitor's impedance) cannot be measured using a DC current. Similarly, the AC method is used in situations where DC electromotive force is present, for example when measuring the internal resistance of batteries.

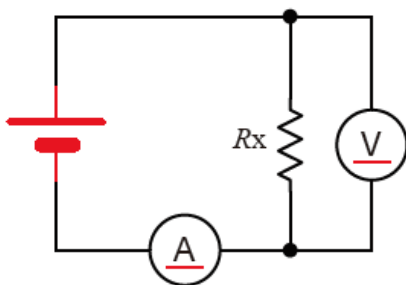


Figure 9 DC method

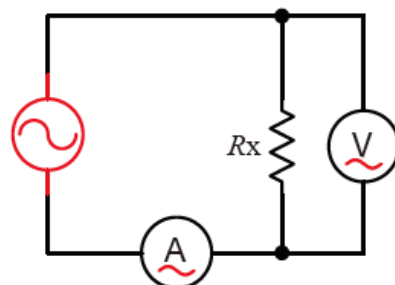


Figure 10 AC method

3. Sources of Error in Resistance Measurement

In order to measure resistance in a stable manner, a variety of potential impediments must be addressed. These include:

- Effects of wiring resistance
- Effects of electromotive force
- Effects of thermal noise
- Effects of leak current
- Effects of dielectric absorption
- Effects of friction noise
- Delicate measurement targets
- Effects of external noise
- Effects of temperature, humidity, and air movements
- Probing method

-1. Effects of Wiring Resistance

To make a measurement, it is necessary to wire the measuring instrument to the measurement target. Table 1 provides an example of wiring resistance. Since factory-supplied measurement leads from measuring instrument manufacturers use AWG20 to AWG24 wire, they yield round-trip resistance values on the order of hundreds of milliohms. Copper wire is usually employed, and copper wire exhibits temperature dependence of $0.4\%/^{\circ}\text{C}$. Consequently, we can conclude that it is impossible to keep the effects of wiring resistance below $10\text{ m}\Omega$. Contact resistance occurs where the measurement probes make contact with the measurement target. If you use new gold-plated probes and press down on them with sufficient force, it is possible to keep the contact resistance under $1\text{ m}\Omega$. However, since the surfaces of probes become contaminated with solder, oil, rust, dust, and other substances with use over time, it is not unusual for contact resistance to exceed $1\text{ }\Omega$ by the end of a probe's service life. With measurement targets such as conductive rubber, the contact resistance may even reach or exceed $1\text{ k}\Omega$.

In the two-wire resistance measurement setup illustrated in Figure 11, the wiring resistance (or contact resistance) values R_{C1} and R_{C2} are added to the measurement target's resistance value R_X . For the above reasons, it would be difficult to measure a resistance value of less than $1\text{ }\Omega$ in a stable manner using this two-wire method.

Measured value = $R_{C1} + R_X + R_{C4}$ when two-wire method is used.

The four-wire method illustrated in Figure 12 can be used to dramatically reduce the impact of wiring resistance. Ordinarily, the voltmeter has an extremely high input resistance, so the measurement current will not flow to R_{C2} and R_{C3} . The measurement current I flows from R_{C1} and from R_X to R_{C4} . Since the voltmeter detects the voltage drop across the measurement target R_X , measurement can be performed without being affected by R_{C1} to R_{C4} . High-precision ohmmeters have a voltmeter input resistance of $100\text{ G}\Omega$ or greater.

Measured value = R_X when four-wire method is used.

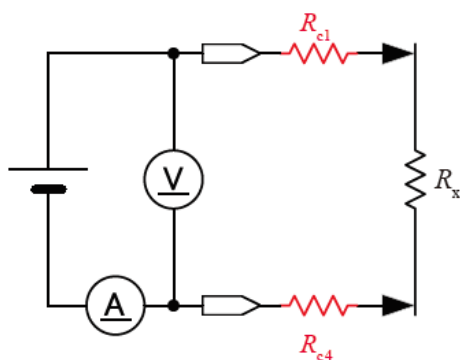


Figure 11 Two-wire Resistance Measurement

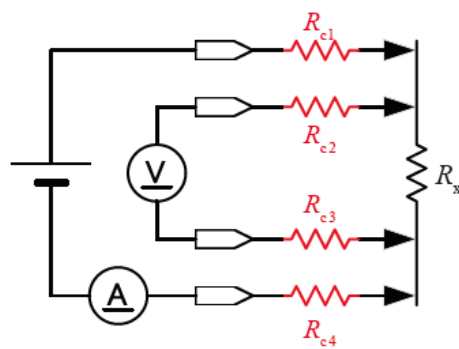


Figure 12 Four-wire Resistance Measurement

Table 1 Example Resistance Values for Different Wire Gauges

AWG	sq	Resistance
AWG28	0.08sq	220mΩ/m
AWG26	0.12sq	140mΩ/m
AWG24	0.2sq	90mΩ/m
AWG22	0.3sq	58mΩ/m
AWG20	0.5sq	38mΩ/m
AWG18	0.75sq	23mΩ/m
AWG16	1.25sq	15mΩ/m

-2. Effects of Electromotive Force

➤ Measuring error

In resistance measurement, the measurement current I_X flows to the measurement target R_X , and the voltage drop $R_X I_X$ across the measurement target is detected. When electromotive force exists on the path along which this voltage is detected, the measured value will include an error component (see Figure 13). Examples of electromotive force include the following:

- Thermal electromotive force
- Battery electromotive force
- The voltmeter's offset voltage

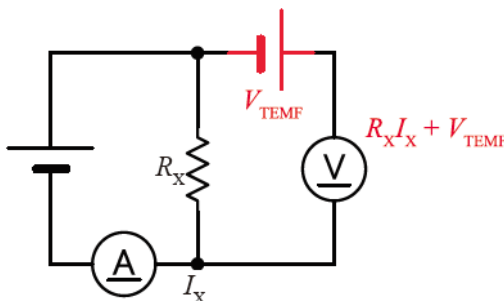


Figure 13 Addition of Electromotive Force to a Detected DC Voltage

Electromotive force refers to a potential difference that occurs at the point of contact between two different metals (see Figure 14). Specifically, it occurs at points where probes contact the measurement target, and at connections between the

measuring instrument and the measurement leads. The magnitude of the electromotive force varies with the temperature of the measurement environment, with electromotive force increasing as the temperature difference grows. Generally speaking, measurement probes and measurement targets are made of different materials, and the measuring instrument and measurement target are not at the same temperature. Holding a measurement target will cause its temperature to rise, and body heat from your hands will also warm probes. Even if you exercise caution concerning these effects, it would be extremely difficult to limit electromotive force to 1 μV or less. Additionally, when using a single stable relay to switch among multiple measurement targets, the relay coil will warm the relay contacts, generating an electromotive force of around 10 μV at the contacts. As an example, a measuring instrument being used to measure a measurement target with a true resistance value of 1 Ω with an electromotive force of 10 μV using a measurement current of 1 mA would indicate the following value:

$$\frac{1\ \Omega \times 1\ \text{mA} + 10\ \mu\text{V}}{1\ \text{mA}} = 1.01\ \Omega$$

As you can see, the reading includes an error component of 1% relative to the true resistance value.

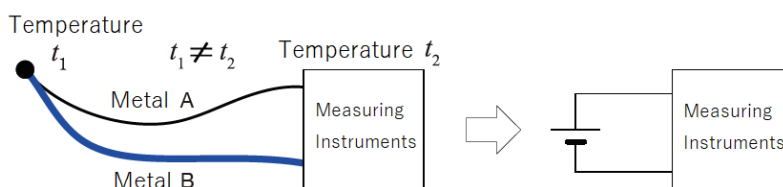


Figure 14 Generation of Electromotive Force

Voltmeter offset voltages vary from 1 μV to 10 mV. The measuring instrument's offset voltage can be excluded through regular use of its zero-adjustment function.

Internal resistance (IR) is an indicator of a battery's ability to supply current. When measuring the internal resistance of a battery, the electromotive force is much greater than the thermal electromotive force (Figure 15). The typical voltage of a dry cell battery is 1.5 V, while battery modules for EVs have an electromotive force of several hundred volts.

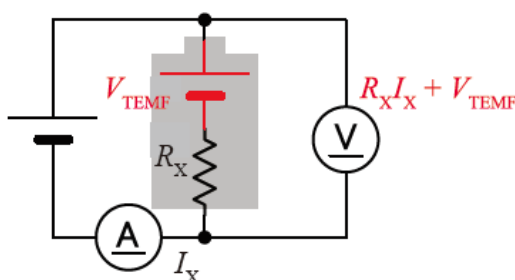


Figure 15 Effects of a Battery's Electromotive Force

➤ Methods for reducing electromotive force

The following methods can be used to reduce the effects of electromotive force:

- Increasing the detection voltage by using a large measurement current
- Using an AC detection signal

If we change the measurement current in the previous electromotive force example from 1 mA to 100 mA, the error component can be reduced to 0.01%:

$$\frac{1\ \Omega \times 100\ \text{mA} + 10\ \mu\text{V}}{100\ \text{mA}} = 1.0001\ \Omega$$

However, caution is necessary since this change will also subject the measurement target to the power as given by RI^2 .

As shown in Figure 16, the fundamental solution is to use an AC detection signal. Both thermal electromotive force and battery electromotive force are considered to act as stable DC for short periods of time on the order of several seconds, and they can be segregated by frequency region by using an AC detection signal. Measuring instruments with an offset voltage compensation (OVC) function can eliminate electromotive force by making the measurement current a pulse waveform, which can be created by either of two methods: toggling the measurement current on and off, or reversing the measurement current's polarity.

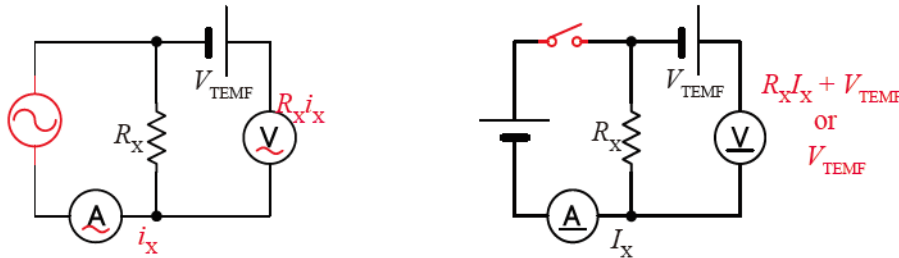


Figure 16 Using an AC Detection Signal

-3. Effects of Thermal Noise

Objects that have resistance have thermal noise by virtue of their properties. The magnitude of the thermal noise v_{TN} is given by

$$v_{\text{TN}} = \sqrt{4kTBR}$$

where k is the Boltzmann's constant (1.38×10^{-12} J/K), T is the absolute temperature, B is the bandwidth, and R is the resistance value.

When measuring resistance, the thermal noise v_{TN} is added to the detected voltage $R_x I_x$, as shown in Figure 17. The magnitude of the thermal noise with a measurement time of 1 sec. is as follows:

$$v_{\text{TN}} \approx 10\ \text{nV}_{\text{pp}} \text{ when } R \text{ is } 100\ \Omega.$$

$$v_{\text{TN}} \approx 1\ \mu\text{V}_{\text{pp}} \text{ when } R \text{ is } 1\ \text{M}\Omega.$$

$$v_{\text{TN}} \approx 0.1\ \text{mV}_{\text{pp}} \text{ when } R \text{ is } 10\ \text{G}\Omega.$$

As indicated by the defining equation, thermal noise can be reduced by means of the following two methods:

- Increasing the detected voltage so that it is sufficiently greater than the thermal noise by performing high-voltage (high-current) measurement
- Increasing the measurement time so as to reduce the bandwidth B

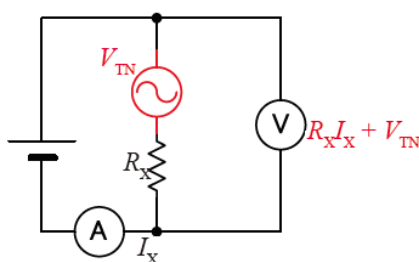


Figure 17 Effects of Thermal Noise

-4. Effects of Leak Current

When the voltmeter input resistance and measurement cable insulation resistance are low, current flows outside the measurement target, introducing another error component (see Figure 18).

➤ Voltmeter input resistance

The input resistance of a typical voltmeter is 10 M Ω , although it may be as high as about 10 G Ω in some instruments. In high-resistance measurement where the voltmeter's input resistance may become problematic, it is effective either to insert the ammeter at a location where the voltmeter's leak current will have no effect, as shown in Figure 8, or to measure the current after applying a constant voltage, as shown in Figure 19.

➤ Cable insulation resistance

A cable's insulation resistance varies greatly depending on the material used and on the extent to which it absorbs moisture. The insulation resistance of cable insulation that is typically used varies as follows:

Fluorocarbon resin (PTFE) > Polyethylene (PE) > Polyvinyl chloride (PVC) > Nylon (PA)

When using cables with polyvinyl chloride insulation to measure high resistance values in excess of 1 G Ω , contact with the cables will introduce a large error. Even if there is no direct contact between cables, a similarly large error component can be introduced by placing low-insulation cables on a conductive mat or metal frame or holding them in your hands. To counteract issues involving cables' insulation resistance, it is important not only to use well-insulated cables, but also to guard (shield) the current detection lines (see Figure 19). Inflow of leak current from the insulation resistance R_C to the ammeter can be prevented by routing it to the guard line. Use of guarding is an extremely effective way to counteract noise.

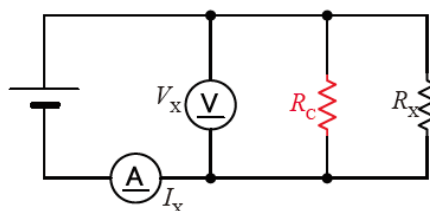


Figure 18 Effects of Leak Current

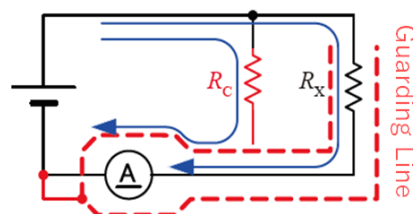


Figure 19 Dealing with Leak Current

-5. Effects of Dielectric Absorption

When measuring high resistance, the measured value may continue to increase for a period of time ranging from dozens of seconds to several minutes. For example, consider an application in which a capacitor with a high dielectric constant is measured using cables sheathed in polyvinyl chloride insulation. One cause of this phenomenon is the absorption current caused when charges inside the insulator polarize at different speeds (see Figure 20).

When the cable is the cause, the issue can be resolved by using cables with Teflon or polyethylene insulation, which has a lower absorption current. It is also extremely effective to use cables guarding the current detection lines. It is also important to measure current after applying a voltage as described in the previous section.

When the measurement target itself has a high dielectric absorption, as is the case with a high-dielectric capacitor, the only option is to use an adequately long measurement time.

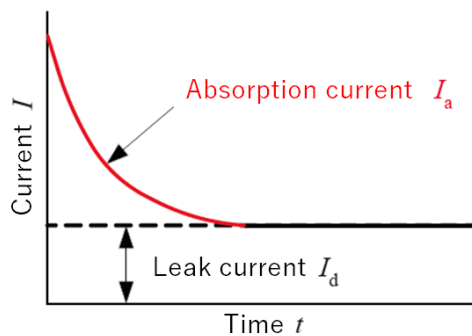


Figure 20 Change in Leak Current Due to Dielectric Absorption

Source: Namba, Noriyuki and Kaneko, Fumitaka (1980) *Electrical materials*, Science and engineering books

-6. Effects of Friction Noise

Simply moving a measurement cable slightly can cause the measured value to fluctuate greatly. This phenomenon is caused by static electricity resulting from friction between the cable conductor and its insulation. The charge generated by this friction flows as current to areas of low impedance, as shown in Figure 21. If the friction-induced current I_F flows to resistance R_x , the noise voltage $R_x I_F$ will result, making this phenomenon especially pronounced during high-resistance measurement.

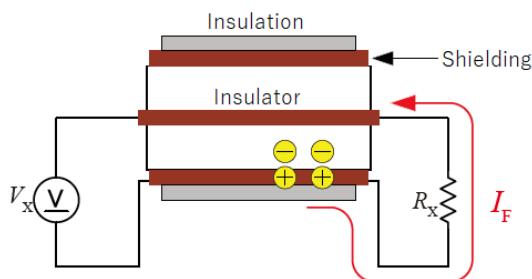


Figure 21 Generation of Friction Noise

To reduce friction noise, it is necessary above all else to avoid vibration and bending. As a cable-related measure, a semiconducting layer can be added on the inside of the shielding, as shown in Figure 23. By adding a soft

semiconducting layer, the shielding layer can be prevented from rubbing against the insulating layer, which has a large frictional charge effect, thereby suppressing the generation of friction noise.

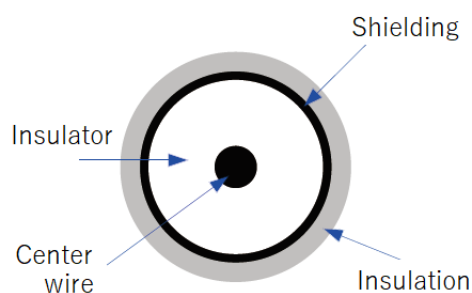


Figure 22 Normal Shielded Wire

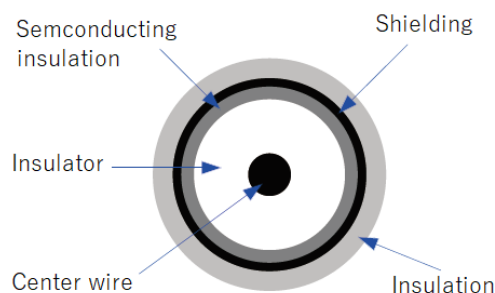


Figure 23 Example of a Low-noise Cable

Figure 24 compares noise for a cable with polyethylene insulation with that for a low-noise cable when each is bent as illustrated in the wiring shown in Figure 21. Since the end of the cable is terminated with 100 M Ω , the current caused by friction should be approximately equal to the generated voltage divided by 100 M Ω . Whereas the standard polyethylene cable carries a noise current of 200 pA to 300 pA, virtually no noise is observed for the low-noise cable.

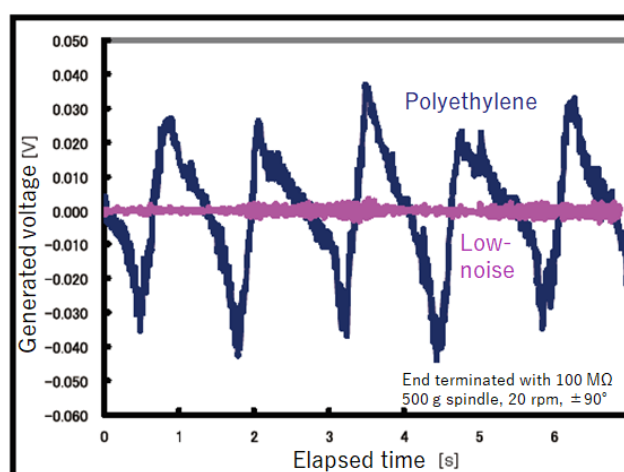


Figure 24 Friction Noise When Cables Are Bent

-7. Delicate Measurement Targets

Because the characteristics of components such as magneto-resistance elements (MR elements) used in hard disk heads, signal contacts, ferrite beads used to counteract EMI, and airbag inflators vary in response to slight measurement currents and voltages, special care is required during measurement of these components.

A small, 3.5-inch hard disk drive can store 1 terabyte of data in the form of magnetic information that is read by an MR element that has a microwatt-order allowable power. For this reason, measuring the component with a current in excess of 1 mA could easily damage the element.

Contamination on signal contacts (consisting of oxide films and other contaminants) is easily destroyed by voltages in excess of 100 mV. For this reason, measuring degraded contacts that have been used over an extended period of time with a high voltage may cause even defective contacts that are close to an insulated state to exhibit continuity, yielding an erroneous pass result (see Figure 25).

Ferrite beads used to counteract noise on signal lines will not fail at currents of about 100 mA. However, current on the order of dozens of milliamps will magnetize the magnetic material they contain, changing their impedance characteristics. And the initiator of an airbag inflator will generate sparks if subjected to a current in excess of 100 mA.

To measure elements such as these, a measuring instrument whose voltage when the probes are not connected to the measurement target (known as its open-circuit voltage) is limited to 20 mV is used in a technique known as dry-circuit testing.

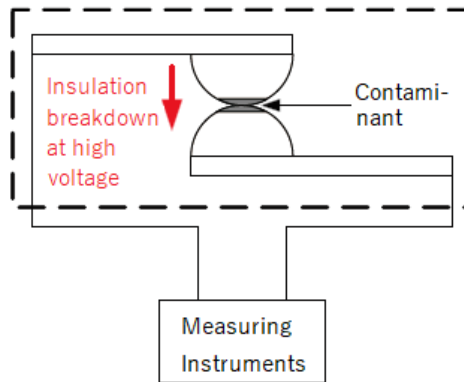


Figure 25 Measurement of Contaminated Signal Contacts with a High Voltage

-8. Effects of External Noise

Noise can be classified as shown in Figure 26. This section will focus on inductive noise and conductive noise, which often cause problems in practice.

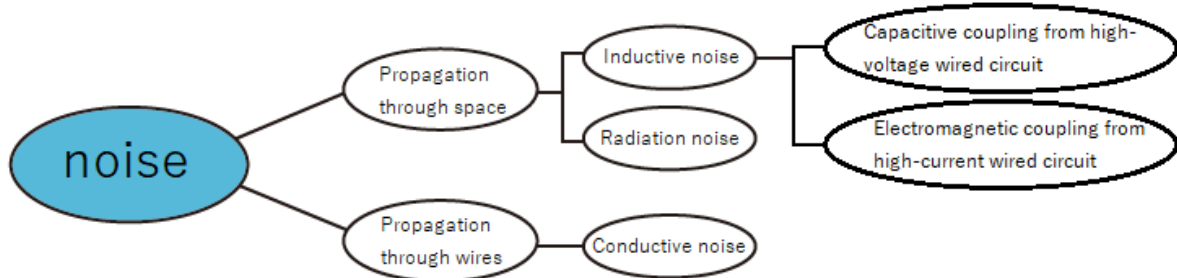


Figure 26 Types of Noise

(1) Effects of Inductive Noise

Large amounts of noise are emitted from components such as power cords, fluorescent light bulbs, solenoid valves, and computer displays. The following noise sources can impact resistance measurement:

- Capacitive coupling from high-voltage wired circuits
- Electromagnetic coupling from high-current wired circuits

a. Capacitive Coupling from High-voltage Wired Circuits

The amount of current that flows in from a high-voltage wired circuit can vary greatly depending on the coupled capacitance. As an example, current of about 38 nA would be induced if a 100 V commercial power line and wiring used in resistance measurement underwent capacitive coupling at 1 pF.

$$I = \frac{V}{Z} = 2\pi \cdot 60 \text{ Hz} \cdot 1 \text{ pF} \cdot 100 \text{ V}_{\text{rms}} = 38 \text{ nA}_{\text{rms}}$$

When measuring a 1Ω resistor with a current of 100 mA, the effect of this phenomenon is only about 0.4 ppm and can be safely ignored. However, when measuring a $1 \text{ M}\Omega$ resistance with a current of $10 \mu\text{A}$, the effect reaches 0.38%. In this way, caution concerning capacitive coupling from high-voltage wired circuits should be exercised during high-resistance measurement. Keep in mind that electrostatic shielding for wiring and measurement targets is an effective countermeasure (see Figure 27).

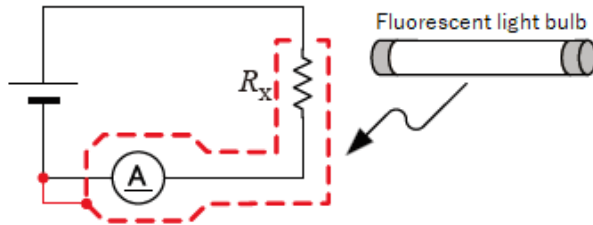


Figure 27 Electrostatic Shielding Close to High-voltage Wiring

b. Electromagnetic Coupling from High-current Wired Circuits

High-current wired circuits generate a magnetic field. Transformers with a large number of turns and choke coils emit even stronger magnetic fields. The voltage induced by such magnetic fields is affected by distance and surface area, but a voltage of about $0.75 \mu\text{V}$ will be induced in a 10 cm^2 loop lying 10 cm from a 1 A commercial power supply wire.

$$v = \frac{d\Phi}{dt} = \frac{d}{dt} \left(\frac{\mu_0 I S}{2\pi r} \right) = \frac{4\pi \cdot 10^{-7} f I}{r} = \frac{4\pi \cdot 10^{-7} \cdot 60 \text{ Hz} \cdot 0.001 \text{ m}^2 \cdot 1 \text{ A}_{\text{rms}}}{0.1 \text{ m}} = 0.75 \mu\text{V}_{\text{rms}}$$

When measuring a $1 \text{ m}\Omega$ resistor with a current of 1 A, the effect of this phenomenon is 0.07%. When performing high-resistance measurement, higher detection voltages mean that it does not generally become problematic. Effective means of minimizing the effects of electromagnetic coupling include segregating lines that emit noise from voltage detection wires used in resistance measurement and twisting each together (see Figure 28).

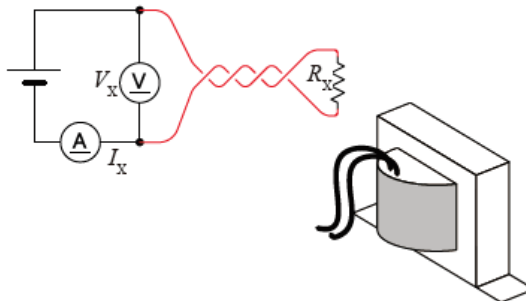


Figure 28 Twisting Lines Close to High-current Wires

(2) Effects of Conductive Noise

Conductive noise travels along a separate path than inductive noise, which is superposed on measurement targets and measurement leads. Conductive noise refers to noise that is superposed on power lines and USB or other control lines.

Power lines are connected to various types of equipment, including motors, welders, and inverters. While these devices are operating and each time they start and stop, a large spike current flows to the power supply. This spike current and the wiring impedance in the power lines causes a large spike voltage in the power lines and power supply grounding lines that has the potential to affect measuring instruments.

Similarly, noise can be injected into the measurement circuit from a controller's control lines. Noise from the controller's power supply and noise emitted from components such as the DC-DC converter inside the controller can disrupt a measuring instrument via its USB or external I/O wiring (see Figure 29).

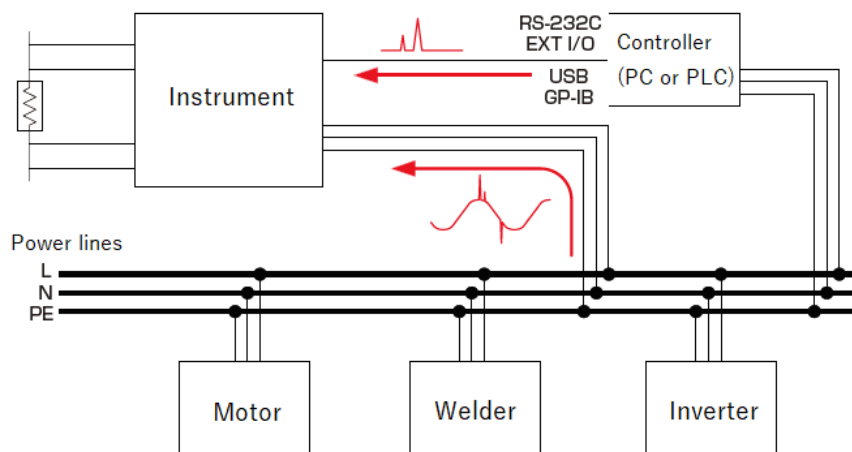


Figure 29 Encroachment of Conductive Noise

The following measures, illustrated in Figure 30, are effective once the path by which the noise is encroaching on the measurement circuit has been identified:

a. Segregate power lines.

It is desirable that power equipment, welders, and similar devices be powered by a different circuit than the measuring instrument.

b. Add a common-mode filter (EMI choke) to the path by which noise is gaining access to the circuit.

Use a common-mode filter with as high an impedance as possible. The more you add, the more effective they will be.

c. Isolate lines.

It is highly effective to optically isolate control lines. It is also effective to isolate power lines with a noise-cutting transformer. However, note that if you use a common grounding line on both sides of the isolation, the effectiveness of this measure will be diminished.

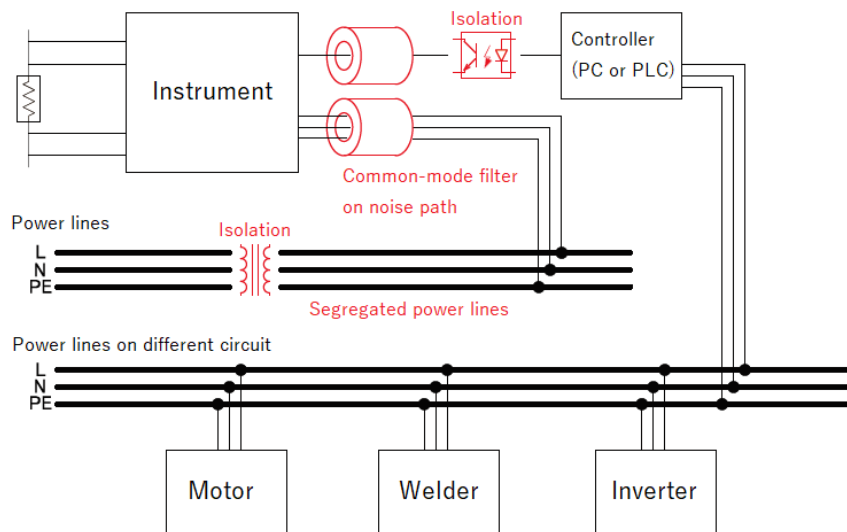


Figure 30 Conductive Noise Countermeasures

-9. Effects of Temperature, Humidity, and Air Movements

When a high degree of measurement precision is required, it is necessary to pay attention to the measurement environment as well.

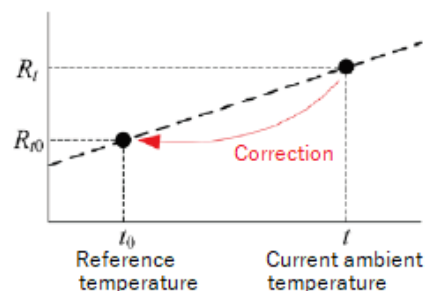
(1) Effects of Temperature

The copper wiring used in motors, transformers, solenoids, and other devices exhibits temperature dependence of about 0.4%/°C, meaning that measured values obtained during the summer and winter will differ by 5% to 10%. When measuring resistance values with temperature dependence such as those of copper wire, a technique known as temperature correction is used to correct measured values to resistance values for a specific temperature (the reference temperature). It is also necessary to manage winding wire resistance using temperature-corrected values in order to use the same judgment criteria when shipping and receiving products.

Means of measuring the temperature used in the temperature correction process include platinum resistance bulbs, thermocouples, and radiation thermometers that measure the temperature of the measurement target directly.

$$R_t = R_{t_0} \times \{ 1 + \alpha_{t_0} \times (t - t_0) \}$$

R_t	Observed resistance value	[Ω]
R_{t_0}	Corrected resistance value	[Ω]
t_0	Reference temperature	[°C]
t	Current ambient temperature	[°C]
α_{t_0}	Temperature coefficient at t_0	[1/°C]



(2) Effects of Air Movements

If the thermal time constants of the measurement target and thermometer differ, the movement of air, for example from an air-conditioner, will cause the thermometer's indicated value to differ from the temperature of the measurement target, as shown in Figure 31. For this reason, you may be unable to realize the expected benefits of temperature correction when measuring a large transformer.

Additionally, the thermal electromotive force caused by air movements will be unstable when making measurements with minuscule voltages.

In both cases, it is necessary to take into consideration the need to limit temperature variations by blocking air movements.

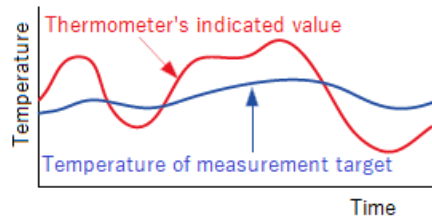


Figure 31 When the Measurement Target's Thermal Time Constant Is Large

(3) Effects of Humidity

Humidity is the enemy when measuring large resistance values in excess of $1\text{ M}\Omega$. Leakage may occur via a variety of routes, including the surface of the measurement target itself (see Figure 32), connectors (see Figure 33), and cables. Caution is necessary when using nylon connectors due to the need for flame resistance or polyvinyl chloride cables due to the need for weather resistance.

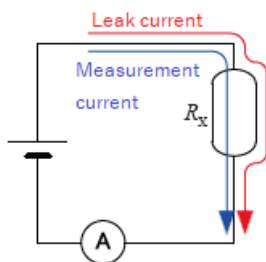


Figure 32 Leakage across the Measurement Target Surface

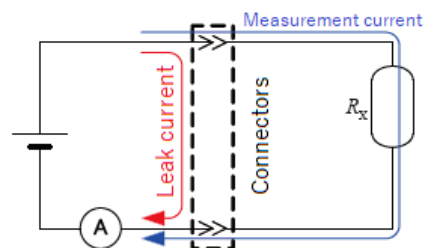


Figure 33 Connector Leakage

-10. Probing Methods

When the measurement target is an object with width and thickness, for example a plate or block, or a current detection resistor (shunt resistor) with a resistance of less than $100\text{ m}\Omega$, it becomes difficult to obtain an accurate measurement using clip- or pin-type leads. Use of such leads may cause measured values to vary by several percentage points to several dozens of percentage points depending on the contact pressure and contact angle. For example, measured values varied as follows in one attempt to measure a metal plate with dimensions of $300\text{ (W)} \times 370\text{ (L)} \times 0.4\text{ (t)}\text{ mm}$:

1.1 $\text{m}\Omega$ when using 0.2 mm pitch pin-type leads.

0.92 $\text{m}\Omega$ to 0.97 $\text{m}\Omega$ when using 0.5 mm pitch pin-type leads.

0.85 $\text{m}\Omega$ to 0.95 $\text{m}\Omega$ when using clip-type leads.

In addition, because resistance values for current detection resistors are defined for the components when they are mounted on a printed circuit board, taking measurements with a pin-type leads at the terminals of such a component will not yield the desired resistance value. This phenomenon is caused not by factors such as the contact resistance between the probe and measurement target, but rather by the distribution of current in the measurement target.

Figure 34 provides an example plot of equipotential lines for a metal plate. Current density is higher where the intervals between equipotential surfaces are closer and lower where they lie further apart, mirroring the relationship between wind and the pressure distribution charts used in weather forecasting. The figure illustrates how the potential gradient varies significantly near the point at which current is injected. This variation is due to the fact that the current is in the process of spreading out into the metal plate, increasing the current density in that area. For this reason, when the voltage detection terminals are placed close to the point at which current is injected, minute changes in the position of contact are associated with significant changes in the measured value.

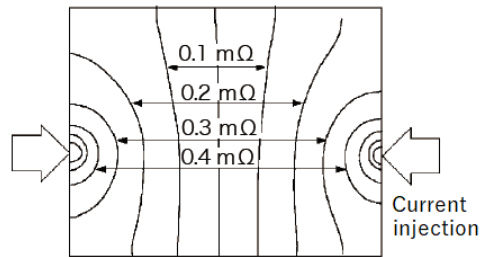


Figure 34 Equipotential Lines on a Metal Plate

(300 [W] × 370 [L] × 0.4 [t] mm)

*Equipotential lines were plotted every 50 μ V after injecting a current of 1 A at the endpoints.

To avoid this type of effect, it is desirable to detect voltage at a position that is located inside the current injection points. Generally speaking, current distribution will have become uniform at points that lie inside the current injection points by a factor of at least 3 times the measurement target's width (W) or thickness (t). As shown in Figure 35, it is desirable for the sense terminals to be positioned at least 3W or 3t inside the source terminals.

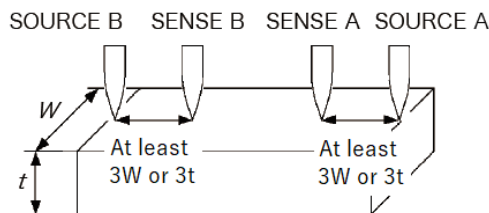


Figure 35 Probing Locations for a Measurement Target That Is Wide or Thick