KEITHLEY

Application Note Series

Number 200

Understanding Low Voltage Measurements

Introduction

Techniques for making precision, accurate voltage measurements are fairly well known. But a lot of these methods fall short when resolution must be extended below one microvolt, which is often the case when measuring physical parameters in industry such as temperature, pressure, force, etc.

For example, industrial temperature measurements often require resolution of 0.1°C. But data for such measurements must be recorded to 0.01°C or 0.001°C to ensure measurement precision. Temperature changes of this magnitude correspond to voltage changes on the order of one microvolt or less, since most thermocouples have sensitivities of about 40µV/°C.

Error Sources

Significant errors may be introduced in these extremely low voltage measurements by noise sources that can be ignored at higher levels. These sources include Johnson noise, thermoelectric EMFs, magnetic fields, and ground loops. Taking steps to understand and minimize these factors is crucial for meaningful measurements at low voltages.

Thermoelectric EMFs and Johnson Noise

Thermoelectric or Johnson noise voltage limits the ultimate resolution of any electrical measurement. It is caused by thermal agitation within circuit resistances.

This noise voltage $E_{rms} = \sqrt{4kTBR}$

where: k is Boltzmann's constant, 1.38×10^{-23} joule/K
T is temperature in °K
R is resistance in Ω
B is the noise bandwidth in Hz

This equation shows that reducing temperature, resistance, or noise bandwidth will reduce circuit noise.

Reducing noise bandwidth through appropriate filtering reduces thermal noise. However, it also increases the measurement time required to obtain a given accuracy.

Reducing circuit resistance can reduce noise in some instances. However, it does not diminish problems when sensing current since it reduces the signal more than the thermal noise. For example, reducing the resistance of a current-measuring shunt by a factor of 100 cuts noise by a factor of 10. But from Ohm's law, reducing resistance by 100 also cuts the voltage to be measured by 100, thus making the noise voltage proportionally larger.

Thermoelectric voltages are the most common source of errors in low voltage measurements. These voltages arise when different parts of a circuit are at different temperatures or when conductors made of dissimilar materials are joined together, as in an ordinary solder joint. For example, the thermoelectric EMF of lead-tin solder with respect to copper is 3µV/°C.

Constructing circuits using the same material for conductors minimizes the thermoelectric EMF. Other steps can also be taken to minimize thermoelectric EMFs. For example, connections made by crimping copper sleeves and lugs result in cold-welded copper-to-copper junctions that generate minimal thermoelectric EMF.

Minimizing temperature gradients within the circuit also reduces thermoelectric EMFs. A typical practice is to place all junctions in close proximity and provide good thermal coupling to a common massive heat sink. This coupling must take place through electrical insulators having high thermal conductivity. Since most electrical insulators do not conduct heat well, special insulators such as hard anodized aluminum, beryllium oxide, specially filled epoxy resins, sapphire, or diamond often must be used to couple junctions to the heat sink.

In addition, allowing test equipment to warm up and reach thermal equilibrium in a constant ambient temperature also minimizes thermoelectric EMF effects. Any remaining thermoelectric EMF generated is relatively constant and can generally be compensated by zero controls provided on the measuring instrument. To keep ambient temperatures constant, equipment should be kept away from direct sunlight, exhaust fans, and similar sources of hot or cold air.

Magnetic Fields

In addition to thermal noise, the motion of circuit leads in magnetic fields also generates spurious voltages. Even the earth's relatively weak magnetic field can generate nanovolt noise levels in dangling leads, so leads must be kept short and rigidly tied down.

Basic physics shows that the amount of voltage a magnetic field induces in a circuit is proportional to the area the circuit leads enclose. Thus, leads must be run close together or be shielded to minimize induced magnetic voltages. One commonly used magnetic shielding material is mu-metal, a special alloy with high permeability at low magnetic flux densities. Current-carrying conductors should also be shielded or run as twisted pairs to prevent generating magnetic fields that affect other circuits.

Ground Loops

Noise and error voltages also arise from so-called ground loops. These loops are often created when numerous instruments used in a test are grounded at several different points. A typical example is a number of instruments plugged into power strips on different instrument racks. Frequently, there is a small difference in potential among the ground points. This potential difference can cause large noise currents to circulate and create unexpected voltage drops.

The cure for ground loops is to ground all equipment at one point. The easiest way of accomplishing this is to use isolated power sources and instruments, then find a single, good earth-ground point for the entire system.

A number of digital multimeters are available with 1µV sensitivity for such measurements. These instruments often have isolated inputs and sensitivities as low as 100nV. But this equipment tends to have uncertainties of a few microvolts and is slow at 100nV resolution.

Digital nanovoltmeters are also available that have noise and drift of a few hundredths of a microvolt. These instruments are designed to make readings within 15nV noise levels in a single digital conversion.

Test System Safety

Many electrical test systems or instruments are capable of measuring or sourcing hazardous voltage and power levels. It is also possible, under single fault conditions (e.g., a programming error or an instrument failure), to output hazardous levels even when the system indicates no hazard is present.

These high voltage and power levels make it essential to protect operators from any of these hazards at all times. Protection methods include:

- Design test fixtures to prevent operator contact with any hazardous circuit.
- Make sure the device under test is fully enclosed to protect the operator from any flying debris.
- Double insulate all electrical connections that an operator could touch. Double insulation ensures the operator is still protected, even if one insulation layer fails.
- Use high reliability, fail-safe interlock switches to disconnect power sources when a test fixture cover is opened.
- Where possible, use automated handlers so operators do not require access to the inside of the test fixture or have a need to open guards.
- Provide proper training to all users of the system so they understand all potential hazards and know how to protect themselves from injury.

It is the responsibility of the test system designers, integrators, and installers to make sure operator and maintenance personnel protection is in place and effective.

For further information on low voltage measurements, refer to the Model 2182 Nanovoltmeter data sheet, Keithley's Low Level Measurements *handbook, and "Techniques for Reducing Resistance Measurement Uncertainty: DC Current Reversals vs. Classic Offset Compensation," a white paper authored by Chris Miller.*

KEITHLEY

Keithley Instruments, Inc. 28775 Aurora Road • Cleveland, Ohio 44139 • 440-248-0400 • Fax: 440-248-6168
1-888-KEITHLEY (534-8453) www.keithley.com

No. 1132
8012KIKN