Watch Out for Those Thermoelectric Voltages!

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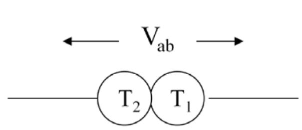
What are Thermal EMFs?

Thermoelectric voltages (EMFs) are the most common source of errors in low-voltage measurements. Thermal EMFs result from temperature differences within a measuring circuit at junctions between conductors made of dissimilar materials. The magnitude of a thermal EMF generated by a material junction depends on the thermoelectric coefficient of the two materials. For example, when connecting test leads to a voltmeter, at the point where the leads connect to the measurement terminals is a natural point where a thermoelectric voltage is created. The leads are rarely at the same temperature as the terminals when they are connected. Over time they should stabilize to a common temperature point. This time might be seconds, a few minutes, or many minutes or longer. There are many influences over this stabilization time.

Regarding the amount of this voltage, it has two main influences: the different materials that are in contact, which determines the Seebeck coefficient; and the temperature difference between the two materials. Mathematically, the temperature between materials is shown in the equation below.



Material A ↔ Material B

$$V_{ab} = Q_{ab} (T_1 - T_2)$$

Q_{ab} is the Seebeck Coefficient of material A with respect to material B [1].

Paired Materials	μV/°C (Q_{ab})
Copper-Copper	<0.2
Copper-Cadmium/Tin Solder	0.2
Copper-Gold	0.3
Copper-Silver	0.3
Copper-Brass	3
Copper-Lead-Tin Solder	5
Copper-Aluminum	5
Copper-Nickel	10
Copper-Kovar	40
Copper-Copper Oxide	>1000

Table 1. Various Seebeck coefficients Q_{ab} for different materials that might be connected to copper. Copper is the common material used for electrical conductors, so the Seebeck coefficients relative to copper describe the most common conditions that are found in electrical test and measurement applications [1].

You can see from Table 1, copper to copper has the lowest coefficient. Gold and silver are also low, so you often see gold flashed copper in connections. The advantage here is gold does not oxidize as readily as copper. You can see oxidized copper has an extremely high coefficient (1000uV/degree)—so it is important to have clean copper connections. A common soldier connection uses tin/lead solder. Its connection with copper is shown here. At 5uV per degree it has about 25 times the effect as better materials, so a lower thermal soldier such as cadmium-tin soldier is better, having effects similar to the best materials.

How to Avoid EMF Errors

The best measurement practices to minimize thermal EMFs include zeroing the measurement device. It is important to zero the digital multimeter (DMM) to

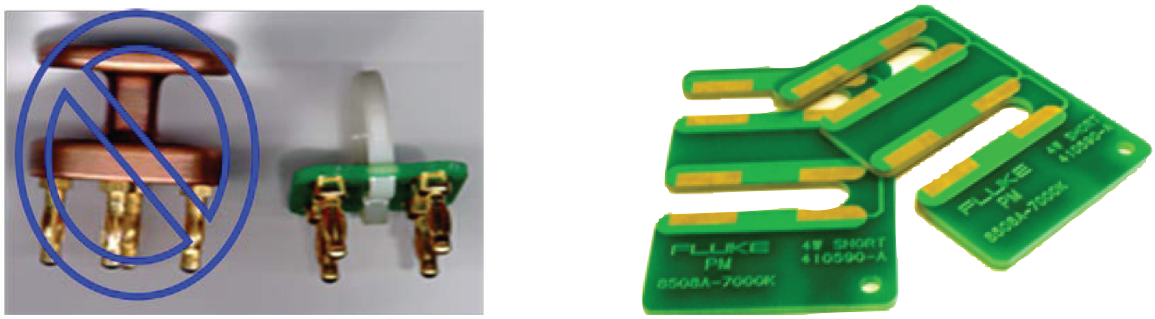


Figure 1. Small shorting devices are shown here. Specially made circuit boards, supplied with Fluke's 8508A DMM, provide both ohmic and thermal zeros for quick stabilization.

eliminate internal offsets that occur naturally in circuits over both time and changing temperature conditions. The best practice for doing such a zero is to apply both an "ohmic" zero and a "thermal" zero to the DMM. Ohmic zeros have very small actual resistance so the measurement value is truly a zero without any unwanted offsets caused by I times R losses based on the current supplied by the meter and the physical resistance of the shorting device. (For example, milliamps of current through milliohms of resistance create microvolts of unwanted measurement voltage.)

Thermal zeros are short circuits that also have a low physical mass (or thermal mass). This permits a fast thermal equalization between the shorting device and the meter terminals. A low thermal mass enables the temperatures of the meter and shorting device to equalize to a common point and, as a result, have only insignificant thermal EMFs. Remember that any appreciable thermal emf will cause offset voltages. In Figure 1 you can see an example of a large mass shorting bar that is not satisfactory due to its size. Using such a large device would cause a very large delay before proper thermal equilibrium is reached between the terminals and such a large shorting bar. A thermally better shorting device with a smaller mass is also shown for comparison. You can appreciate the mass differences between the two shorting devices.

Another best practice recommendation is to use low thermal leads for connection between the UUT and DMM. It is best to use copper wires by itself, or with crimp attached copper lugs as connectors. Alternatively, low thermal solder is good, to attach lugs to wires. It is imperative to clean the connections to remove oxidation. If clean, non-oxidized copper is not practical, use gold flashed copper terminals as this will prevent oxidation and still maintain a low thermal EMF condition. Of course, controlling the environment is important. Keep the ambient temperature constant and avoid sources of heat such as sunlight or exhaust fans. Insulating or covering the sensitive connections is important and is a good practice to use in various situations.

A Demonstration

The following is a demonstration of how you can inadvertently introduce thermal EMF errors when zeroing a High Precision DMM.

The DMM is set to the most sensitive range to easily illustrate the effect. In this case, we set the 8508A reference multimeter to measure DC volts, on the 200 mV range. The filter is enabled and the resolution is set to 7.5 digits for a reasonable speed, yet accurate, measurement setup. The shorting PCB is connected to the input of the meter. This provides a zero condition with an easily usable, quality short, which is supplied with the meter.

For reference, the terminals of the meter are low thermal material—beryllium copper. The shorting PCB uses gold flashed copper on the connection surface, minimizing oxidation problems. It should be noted that the terminals of the DMM are at a higher temperature than room temperature, so there will always be a thermal condition to be aware of. In this case, the input thermals measured about 29 °C. Due to the relatively low thermal mass of the shorting PCB the short temperature comes to temperature equilibrium within about a minute. After thermal stabilization a zero is performed on the DMM. Excluding measurement environment noise, over a twenty minute period, the stability of the zero should be six least significant digits in this particular setup.

Now, let's compare how other devices, commonly found in the lab and possibly used to perform an instrument zero, compare to the zero we set with the shorting PCB. One simple test is to take a common test lead, and plug it into the meter so it shorts the high and low terminals with a low resistance 'zero.' You see the measurement on the DMM shows a number much different than the PCB. This is due to the fact the material on the banana plugs is comprised of nickel. It also is at a different temperature. This will create a thermal EMF that is often on the order of hundreds of counts.

Using this technique to zero a measurement instrument is not satisfactory when making measurements with sensitivities in the micro volt or several micro volt levels.

A dual banana plug with a shorting wire between the terminals is often found (and used) in labs.

The problem is not small, as the Seebeck effect between nickel and the copper beryllium terminals of the DMM is very measurable. Also, the thermal mass of the plug is moderately large, so stabilization will take longer than a short with less mass.

This short was found in a box of connection devices in a lab. Could this be a good device to use as a short? The terminals are better than nickel plated terminals, and should exhibit lower thermal EMF characteristics. It should have a very low ohmic resistance, given that the shorting bar is massive and is copper. It has a huge mass, so its thermal mass is also huge. It would require a very long time to thermally settle with the measurement instrument.

Given this short would be at room temperature, and the measurement instrument is several degrees higher than room temperature, the equalization/stabilization time is not practical. The bottom line is this: While this short is an ohmic zero, it definitely is not a zero for a thermal EMF voltage.

Some manufacturers and experienced measurement technicians find that simple copper wire is very satisfactory. This is often called bell wire (a simple wire that has historically been used for telephone connections). When a small solid copper wire is connected to the terminals, you will see this measured zero is very consistent with the performance of the shorting PCB.

The benefit here is both a low Seebeck coefficient and a low thermal mass.

If we re-examine the DMM's measurement zero by reattaching the shorting PCB, the zero should be within 6 LSD once it is settled.

The measured voltage is within 2 counts of the original zero. This confirms the voltages observed with the other shorting devices are EMF related.

Another best measurement practice to minimize thermal EMFs and various offsets is to make multiple measurements using lead reversal techniques. Diagram 1 illustrates an application where a single reference is measured by a DMM [1]. It models the thermal EMF voltage that is caused by different metals involved in connecting the cables to the UUT and DMM with associated temperature differences between the cables and terminals.

The leads are configured in a forward configuration for one measurement and reversed for a second measurement. The equivalent thermal EMF is constant in both cases. Mathematically, the thermal EMF is eliminated through taking half of the difference of the two measurements: $V_{Ref} = (+\text{Forward} - \text{Reverse})/2$ [1].

There are other offsets which can come into play in such measurements. Also, when you make a null measurement between two standards, there are possibly some common mode signals which cause errors. More thorough reversing techniques will eliminate these errors very effectively. In practice, Fluke switches leads at both the DMM terminals (for forward and reverse conditions), and at the UUT (for positive and negative polarity conditions). Several measurements are taken at each lead configuration.

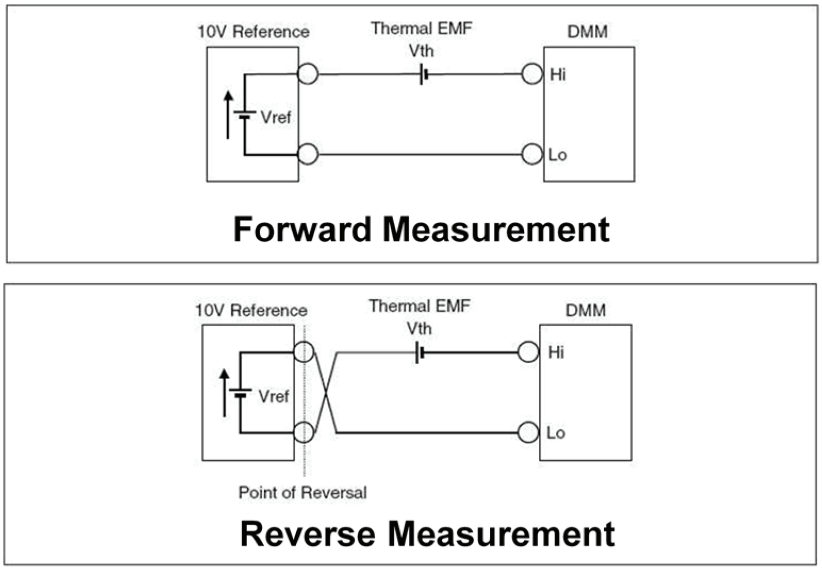


Diagram 1.

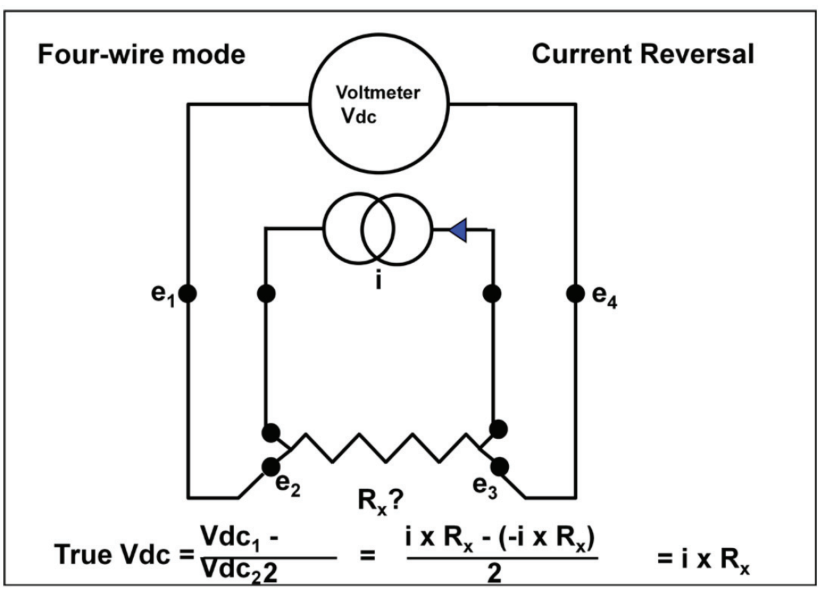


Diagram 2.

Another best measurement practice to minimize thermal EMFs and various offsets is to utilize instrument specific EMF reduction techniques. When measuring resistance with a high sensitivity, or at a low value, the four-wire ohms function is a technique that eliminates the unwanted effect of lead resistance and causing measurement error. Considering how a resistance measurement is done, a DMM usually has an internal precision current source which is used to stimulate the resistance being measured and uses its voltmeter capability to measure the voltage drop across the test resistor. In two wire connection mode, the additional resistance of the test leads can cause an error in the measurement. Making the measuring connection separate from the current source connection eliminates the lead resistance error. However, in the measurement circuit, there are four test lead connections. Each has a thermal EMF and these four thermal EMFs can also cause unwanted measurement errors.

Precision DMMs often have a technique to automatically remove the effects of thermal EMFs. In the 8508A, a technique called "Tru-ohms" can be used to easily remove EMFs. This technique is described in Diagram 2 [1]; it consists of making two measurements and adding the results. The direction of the source current is reversed in these two measurements and the mathematical combination of the two measurements removes the thermal EMF offset. The Tru-ohms method doubles the measurement time (as it takes twice as many measurements of the test resistance), but the thermal EMF errors become a non-issue.

Summary

Thermal EMFs can add unwanted errors to sensitive voltage and resistance measurements. Proper application practices can be used to minimize these errors:

- Use low thermal EMF cables & connections.
- Use proper zero techniques on measurement instruments.
- Use reversal techniques whenever possible.
- Take advantage of EMF limiting techniques found in precision instrumentation.

References

[1] Jack Somppi, "How to Avoid Surprising Errors from Thermal EMFs," Fluke Calibration How To Seminar.

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