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Techniques for Reducing Resistance Measurement Uncertainty: DC Current Reversals vs. Classic Offset Compensation

By Chris Miller
Project Manager
Keithley Instruments, Inc.

Introduction

Device manufacturing, quality assurance, and research groups often make resistance measurements (force current/measure voltage) to monitor, evaluate, or study the quality of their devices and materials. These device manufacturers could be relay, connector, or MR head suppliers. While the device manufacturer would likely employ contact resistance measurements, under dry circuit test conditions, for a life cycle test, a quality assurance test group would measure resistance to evaluate an automotive connector in a salt environment test. Similarly, a materials researcher might measure resistance to study metal lattice structures under very high compression forces.

These resistance measurement applications require the ability to source a given test current that allows sufficient voltage sensitivity to yield reliable, repeatable results. The typical industrial practice for measuring resistance of <1Ω is to force 100mA and measure the voltage drop across the contact. Repeatability of <100µΩ (or <10µV) is the norm.

Many evaluators of these devices have found that 100mA of test current is decades higher than the current that the device will undergo in actual use. One example of this would be an automotive connector that is used to link a sensor on an engine back to a microprocessor. This connector is intended to carry only low levels of current, not 100mA. This high level of test current has resulted in erroneous data that is used to evaluate the device's performance at a much lower current level, typically <100µA. This means that, to have the same <100µΩ repeatability when using 100µA test currents, a voltage sensitivity of 10nV is required.

Keithley Instruments, Inc.
28775 Aurora Road
Cleveland, Ohio 44139
(440) 248-0400
Fax: (440) 248-6168
www.keithley.com

This paper discusses compensating for the errors, such as DC offset voltages, random and unpredictable “white noise,” and heating effects, that occur when making measurements down to the 10nV level in an experiment or test procedure. In particular, the advantages of DC Current Reversals of the new Keithley Model 2182 Nanovoltmeter will be discussed over classic offset compensation techniques.

Measurement Errors

Noise is defined as any unwanted signal imposed on a desired signal or the variations in one data point to the next, over a given time period. This noise has three major components; 1/f (drift) noise from DC offset voltages, random and unpredictable “white noise” (with a Gaussian distribution) and thermoelectric effects due to variable heating of a device. For the majority of measurements, DC offset voltages come from connections composed of dissimilar metals that are at different temperatures. Inherent to any resistance measurement is the Johnson noise of the resistor under test, along with test equipment, which contribute to the random, unpredictable “white noise.”

Compensating for Errors

Two methods for compensating for unwanted voltages include the offset compensation method and the DC current reversal method.

Classic Offset Compensation Method

Offset compensation method, used by some DMMs and ηV/μΩ meters to eliminate voltages caused by thermoelectric EMF from a measurement, requires a full scale test current (I_{FS}) and a near zero current (I_Z). See **Figure 1**. If the thermoelectric EMF is constant over the I_{FS} and I_Z test measurements, then the error due to the thermoelectric EMF can be eliminated by using the following formula:

$$V_{Ocomp} = (V_{IFS} + V_{EMF}) - (V_{IZ} + V_{EMF})$$

$$V_{Ocomp} = V_{IFS} - V_{IZ}$$

Thus the offset voltage is extracted from the measured voltage.

The “white noise” is the remaining noise component. The total noise of the measurement is the noise at the I_{FS} rms summed with the noise at the I_Z current. If the noise has a Gaussian distribution, there is a $\sqrt{2}$ increase in noise, where:

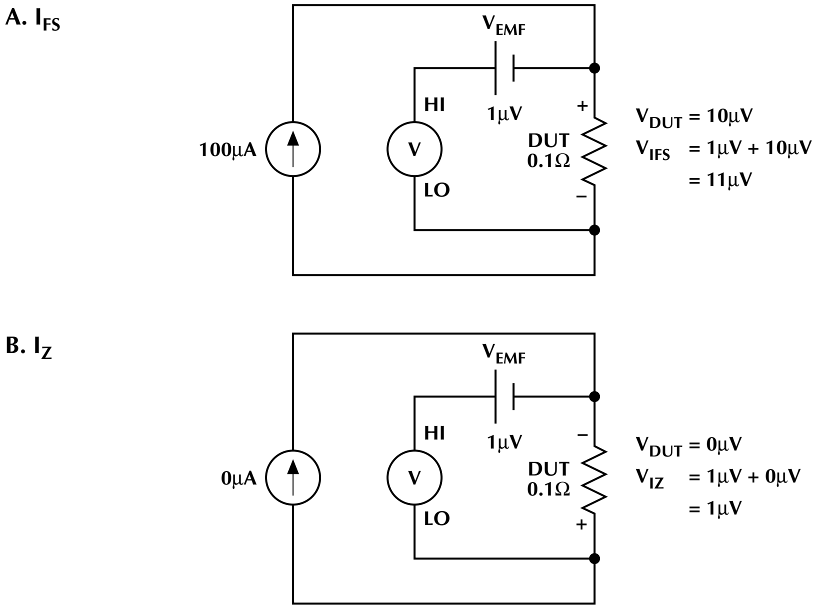
$$V_{\text{Ocomp\_Noise}} = V_{\text{Noise IFS}} \oplus V_{\text{Noise IZ}}$$

$$V_{\text{Ocomp\_Noise}} = [(V_{\text{Noise IFS}})^2 + (V_{\text{Noise IZ}})^2]^{1/2}$$

If $V_{\text{Noise IFS}} = V_{\text{Noise IZ}}$ then

$$V_{\text{Ocomp\_Noise}} = \sqrt{2} \cdot (V_{\text{Noise IFS}})$$

Figure 1



DC Current Reversal Method

In contrast, the DC current reversal method uses two I_{FS} currents to cancel the thermoelectric EMFs (**Figure 2**). These currents are equal in magnitude, but have opposite polarities. This method has a main advantage over offset compensation; there is lower “white noise.” Therefore, this technique eliminates the effects of V_{EMF}.

$$V_{\text{DC Rev}} = [(V_{\text{IFSp}} + V_{\text{EMF}}) - (V_{\text{IFSn}} + V_{\text{EMF}})]/2$$

If $V_{\text{IFSp}} = -(V_{\text{IFSn}})$ then

$$V_{\text{DC Rev}} = (V_{\text{IFSp}} - V_{\text{IFSn}})/2$$

$$V_{\text{DC Rev}} = 2(V_{\text{IFSp}})/2$$

$$V_{\text{DC Rev}} = V_{\text{IFSp}}$$

The “white noise” is reduced by a factor of 2 when using this method from:

$$V_{\text{DC Rev Noise}} = (V_{\text{Noise IFSp}} \oplus V_{\text{Noise IFSn}})/2$$

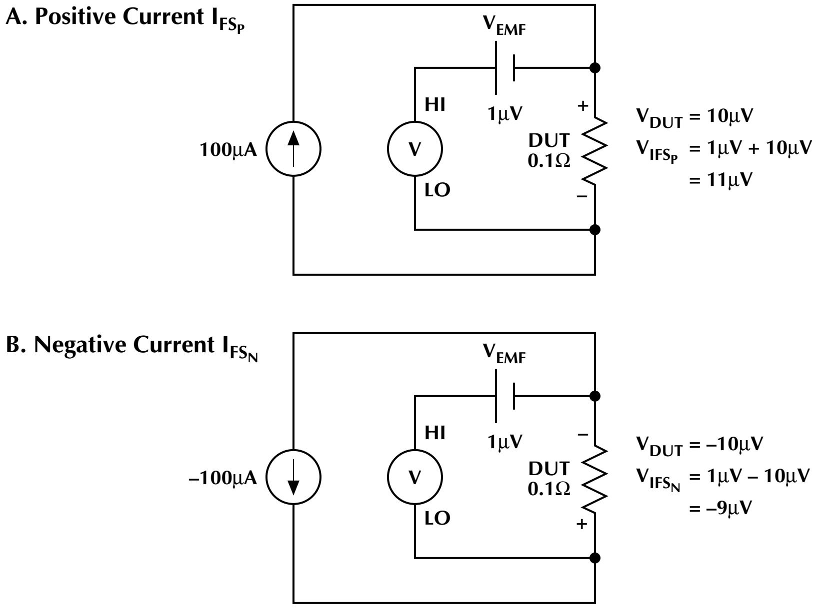
$$V_{\text{DC Rev Noise}} = \{[(V_{\text{Noise IFSp}})^2 + (V_{\text{Noise IFSn}})^2]^{1/2}\}/2$$

If $V_{\text{Noise IFSp}} = V_{\text{Noise IFSn}}$ then

$$V_{\text{DC Rev Noise}} = (\sqrt{2} \cdot V_{\text{Noise IFSp}})/2$$

Therefore, the DC current reversal technique has 50 percent less noise than the offset compensation technique.

Figure 2

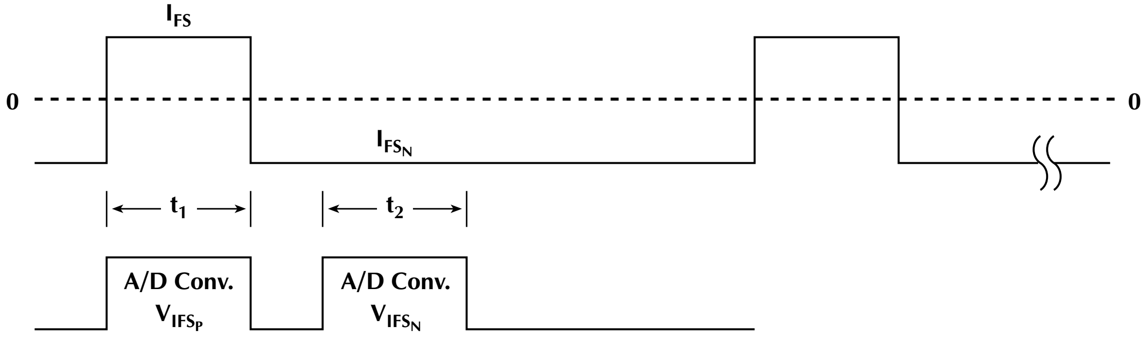


Keeping Offset Voltages Constant

The DC current reversal and offset compensation techniques both require the V_{EMF} to be constant in each measurement phase (t_1 and t_2) in order to remove the V_{EMF} noise contribution (**Figure 3**). For copper (Cu) and tin/lead (Sn / Pb) contacts, V_{EMF} of 1–3µV/°C are common. To achieve 1nV to 3nV of V_{EMF} repeatability from t_1 to t_2, the temperature must be held to within 0.001°C. This requires either a well designed thermal shield with heavy heat sinking and foam insulation around all the contacts or to have a small time duration between t_1 and t_2. If the time duration between t_1 and t_2 is limited to one-tenth of the thermal time constant of the thermal shielding, then V_{EMF} will be eliminated properly.

Figure 3

DC Current Reversal Timing



Using a Model 2182 Nanovoltmeter with a 2400 SourceMeter

The Keithley Model 2182 Nanovoltmeter has the ability to make measurements at both positive and negative test current (t1 and t2 measurements) in just 110ms (60Hz operation) or 130ms (50Hz) with power line integration rejection with <35nVp-p noise. This rapid reversal allows V_{EMF} to be removed properly because the temperature cannot change in such a short interval.

This approach limits the “white noise” to a frequency bandwidth of 9–30Hz, where it has a flat frequency noise spectrum. See **Figure 4**. Any additional post digital averaging filter of the readings can narrow the bandwidth of measurement and provide a $\sqrt{n}$ reduction in noise, where n is the filter size.

The Model 2182 Nanovoltmeter has integrated the DC current reversal technique into a “Delta” function. This function is used to communicate with an external current source, such as the Keithley Model 2400 SourceMeter® or Model 220 Current Source, which employ digital hardware triggering. This function measures V_{t1} at I_{FSp}, then triggers the current source to change to I_{FSn} and makes a second measurement at V_{t2}. The displayed result is:

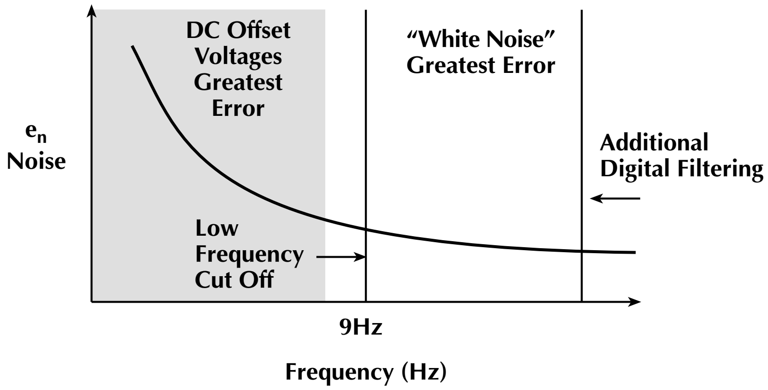
$$V = (V_{t1} – V_{t2})/2$$

No additional computer controller is required to perform the measurement or current reversals.

Digital Filtering to Lower Noise

Most measurement instruments have a voltage noise per $\sqrt{Hz}$ ($e_n/\sqrt{Hz}$). To reduce noise further, some test equipment companies would typically advise customers to increase

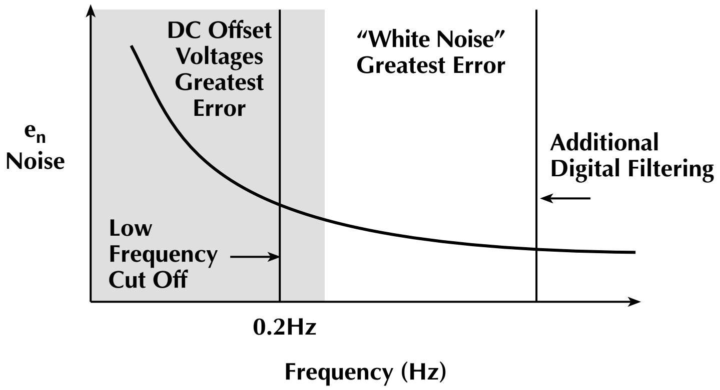
Figure 4



Noise vs. Frequency (2182 Nanovoltmeter)

the integration time of each measurement or add more digital filtering to reduce the bandwidth of the measurement. While this recommendation limits the bandwidth of the measurement, it also puts the measurement bandwidth at a very low frequency where V_{EMF} and drift are the greatest noise component. See **Figure 5**.

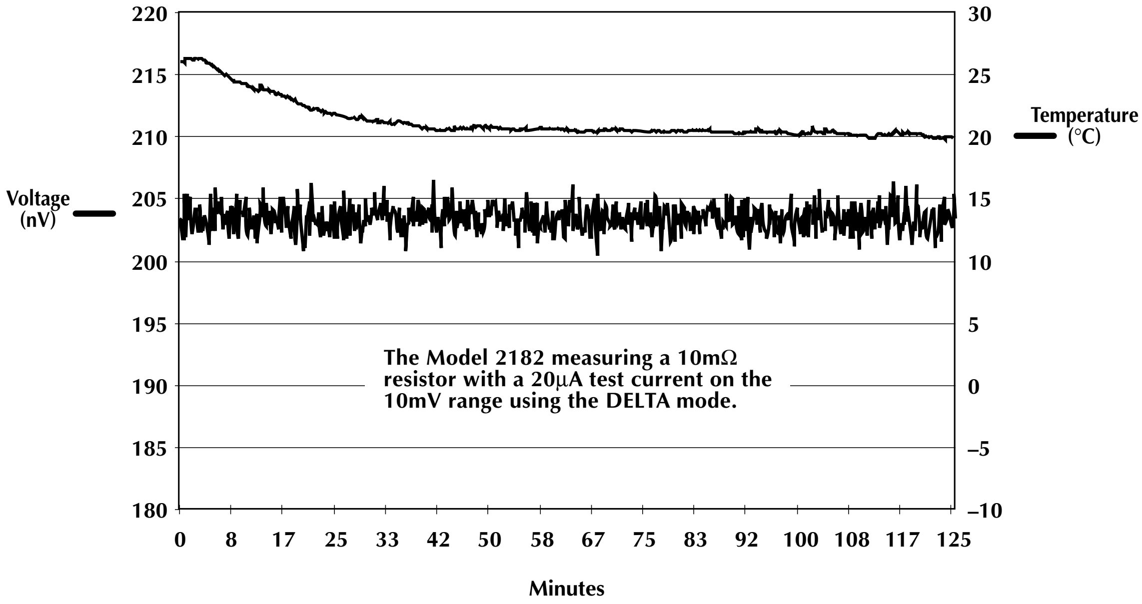
Figure 5



Noise vs. Frequency (older test equipment)

The Model 2182's DC current reversal method reduces the noise about 9Hz, not at "true DC." There is virtually no V_{EMF} or drift noise component in this measurement, even during large temperature changes. See **Figure 6**. When this technique has been performed with a computer, the current reversal can't be done until the reading has been taken from the nanovoltmeter. This will slow down the measurement time and increase V_{EMF} noise in the measurement.

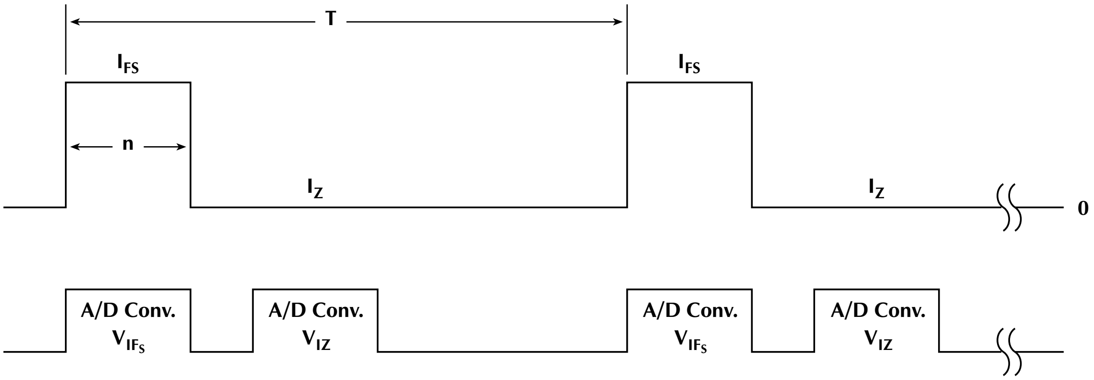
Figure 6



The Model 2182 measuring a 10mΩ resistor with a 20µA test current on the 10mV range using the DELTA mode.

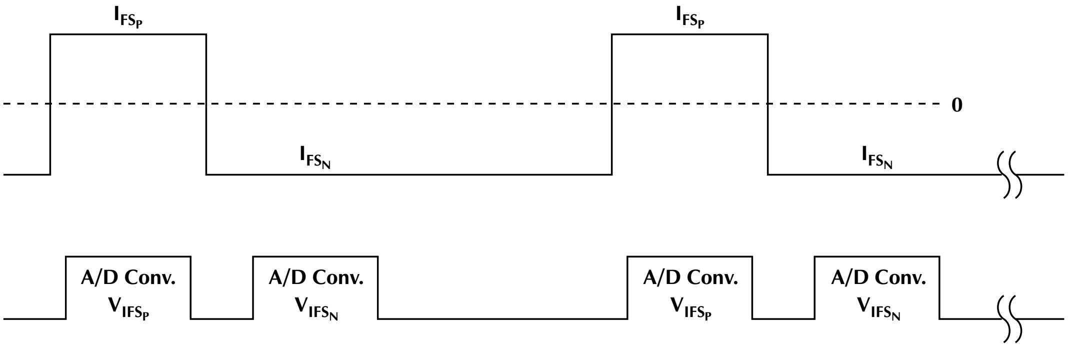
Figure 7

Power Variation



$P_{RMS} = I_{FS} \cdot V_{IF_S} \cdot \sqrt{n}$

DC Current Reversal



$P_{RMS} = I_{FS_P} \cdot V_{IFS_P}$

Older nanovoltmeters would reverse the current at a 1 to 5-second rates and use digital filtering at each t_1 and t_2 data point. While this would reduce higher frequency noise, it would not allow the V_{EMF} to be properly removed because the temperature would not be stable to 0.001°C over that time interval.

Avoiding Unwanted Heating Error

With offset compensation method, there is a variable power that is applied through the DUT. Some devices, such as copper conductors that have small dimensions and mass, can have variations in resistance on the order of 1% /mW. The power at the I_{FS} can have a variable duty cycle depending on how fast the measurement is acquired. See **Figure 7**. If the measurement acquisition time has 50% variability, then there is 40% variability in power and 40% variability in resistance.

With the DC current reversal method, a constant level of power is maintained on the Device Under Test (DUT). The power is the same at I_{FSp} and I_{FSn}. This avoids any error due to variability in acquiring the data from the DUT.

Conclusion

The Model 2182 Nanovoltmeter's fast speed has better than a 2-to-1 noise advantage over the offset compensation technique. With the use of the Model 2182's Delta function, components can now be studied at current levels closer to actual use, while still achieving repeatable, reliable, low noise results. This DC current reversal method removes unwanted offset voltages better, has lowered random noise and better predictability of each measurement, and has no error due to variations in test current heating due to the variations in reading acquisition time.

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

BELGIUM:	**Keithley Instruments B.V.**	Bergensesteenweg 709 • B-1600 Sint-Pieters-Leeuw • 02/363 00 40 • Fax: 02/363 00 64
CHINA:	**Keithley Instruments China**	Yuan Chen Xin Building, Room 705 • 12 Yumin Road, Dewai, Madian • Beijing 100029 • 8610-62022886 • Fax: 8610-62022892
FRANCE:	**Keithley Instruments Sarl**	B.P. 60 • 3, allée des Garays • 91122 Palaiseau Cédex • 01 64 53 20 20 • Fax: 01 60 11 77 26
GERMANY:	**Keithley Instruments GmbH**	Landsberger Strasse 65 • D-82110 Germering • 089/84 93 07-40 • Fax: 089/84 93 07-34
GREAT BRITAIN:	**Keithley Instruments Ltd**	The Minster • 58 Portman Road • Reading, Berkshire RG30 1EA • 0118-9 57 56 66 • Fax: 0118-9 59 64 69
INDIA:	**Keithley Instruments GmbH**	Flat 2B, WILOCRISSA • 14, Rest House Crescent • Bangalore 560 001 • 91-80-509-1320/21 • Fax: 91-80-509-1322
ITALY:	**Keithley Instruments s.r.l.**	Viale S. Gimignano, 38 • 20146 Milano • 02/48 30 30 08 • Fax: 02/48 30 22 74
NETHERLANDS:	**Keithley Instruments B.V.**	Postbus 559 • 4200 AN Gorinchem • 0183-635333 • Fax: 0183-630821
SWITZERLAND:	**Keithley Instruments SA**	Kriesbachstrasse 4 • 8600 Dübendorf • 01-821 94 44 • Fax: 01-820 30 81
TAIWAN:	**Keithley Instruments Taiwan**	1 Fl. 85 Po Ai Street • Hsinchu, Taiwan, R.O.C. • 886-3572-9077• Fax: 886-3572-9031

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