Measurement Techniques for Evaluating Current Range Extenders from 1 Ampere to 3000 Amperes

Marlin Kraft

Abstract: When measuring standard resistors at different ratios with a direct current comparator (DCC) incorporating current range extenders (CREs), it can be difficult to determine if the measurements are correct and to evaluate measurement uncertainty. This technical note discusses techniques developed at the National Institute of Standards and Technology (NIST) for measuring a set of low value resistors at the same current using different ratios. The design of modern automated DCCs allows measurement currents up to about 150 mA and DCCs can operate at 1:10 ratios with uncertainties well below one part in 10^6. Higher currents require CREs with ratios from 1:10 to 1:100,000 or more. The techniques described here allow low uncertainties to be obtained by measuring high quality medium current resistors at different power levels, so that they can be used as standards when measuring high current resistors. These techniques also allow you to determine if your CRE is functioning properly.

1. Introduction

In the early 1950s, scientists at the National Standards Laboratory (NSL) in Australia, the National Bureau of Standards (NBS) in the United States, the Physikalisch-Technische Brundesanstalt (PTB) in Germany, and the National Research Council (NRC) of Canada recognized that increased accuracy and stability that could be obtained in DC resistance ratio measurements by using transformers constructed with new high-permeability, low-loss magnetic materials. NRC initiated a study to improve the three-winding current transformer calibration techniques after an intercomparison with PTB.

The measurement technique used with three-winding current ratio transformers is similar to that used with the three-winding voltage ratio transformer, however the power source and the balancing detector are interchanged. The important difference is the current ratio transformer operates with zero flux in its magnetic core at balance and this, together with appropriate flux detection techniques, makes it possible to measure direct current. In 1961, Kusters and Moore of NRC collaborated with Miljanic of the University of Belgrade in Yugoslavia to develop the direct current comparator (DCC). A patent was granted in 1964 [1, 2, 3].

The DCC is essentially a magnetic flux detector, which can be used to determine the ratio between two currents with a high degree of accuracy. It operates on the principle that when the ampere turn equality is achieved between two windings of opposite polarity on a magnetic core, no flux will be induced in that core. With appropriate windings, this allows the bridge to pass a known ratio of current through a pair of resistors that have values that are in a ratio equal to the ratio of turns. A separate winding is used to detect minor corrections, and feedback is applied to the secondary to achieve zero DC flux in the core. When the primary and secondary ampere turns are equal and opposite then the voltage developed across each resistor is nearly the same.

A simplified schematic diagram of an early manual DCC resistance bridges is shown in Fig. 1 [4]. The bridge consists of an adjustable 1111.111 turn winding in the primary circuit, and a fixed 1000 turn and adjustable deviation windings in the secondary circuit. The resistor to be measured is connected in the primary circuit and a reference resistor, R_S is connected in the secondary circuit. If the deviation winding is set equal to the correction c_S of resistor R_S, the bridge becomes a direct reading in ohms. The reference resistors and low-power resistors are located in a constant temperature oil bath maintained at 25.00 ± 0.01 °C. The DCC resistance bridge is balanced by adjusting the primary turns ratio for a null condition on detector D using the reversal balancing procedure.

The fully adjustable ratio winding in the primary circuit of Fig. 1 can be replaced by a fixed winding of 100 turns, 10 turns, or 1 turn which will provide additional bridge ratios of 10:1, 100:1, and 1000:1. For these higher ratios, the adjustable fractional-turn section in the primary side is switched to the secondary side in order to balance the bridge. The bridge has a resolution of 0.1 parts per million (ppm) for all ratios. For resistance ratio measurements of 1:1 and 10:1, the adjustable 1 A internal power supply is connected in the primary circuit. When the bridge is used for ratio measurements of 100:1 and 1000:1, the internal power supply is replaced by an external, adjustable 100 A supply. The 100:1 and 1000:1 ratios have respective maximum current ratings of 20 A and 100 A.

Author

Marlin Kraft
National Institute of Standards and Technology*
100 Bureau Drive, Stop 8171
Gaithersburg, Maryland 20899-8171
marlin.kraft@nist.gov

In the late 1980s, work started on developments leading to automated DCCs, at the request of Sandia National Laboratories. By 1994 the first microprocessor controlled automated DCC was commercially available.

2. Comparator Current/Power Measurements

The DCC bridge produces a known ratio of currents in the two resistors, R_S and R_X. However, the greater power is dissipated in the smaller resistor. In the comparison of a 1 Ω standard and a 0.1 Ω unknown, with 1 A in the 0.1 Ω there will be only 0.1 A in the 1 standard. It is also possible to use a 10 Ω standard, (100:1 ratio) and a 100 Ω standard (1000:1 ratio). By taking a series of measurements at different current levels (which would dissipate insufficient power in the standard to cause self-heating errors), the power coefficient characteristics of the resistor that carries the higher current can be determined.

Extensive intercomparisons of the manual DCC bridge and the automated binary DCC bridge were performed at Sandia National Laboratories and results were presented in 2001 [5]. NIST still uses the manual DCC to quickly confirm results from time to time as do other several other laboratories. With the manual current comparator bridge, if something is wrong in the connections or settings, the bridge will not function or a bridge balance cannot be obtained. It is important to ensure that the internal power supplies and the primary and secondary galvanometers are in good working order. The automated DC current comparator bridges rely on many internal digital electronic components. They can still function when connections or settings are incorrect, but will produce erroneous results.

The results of an international comparison of low ohmic resistor measurements with NIST and Van Swinden Laboratories (VSL) in the Netherlands were published in 2012 [6]. This international intercomparison will later be expanded to include the Federal Office of Metrology (METAS) in Switzerland and the National Physical Laboratory (NPL) in England.

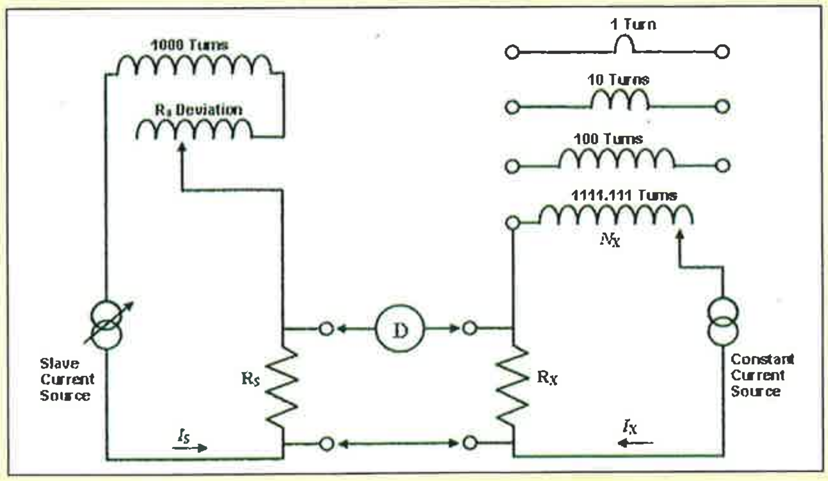

Figure 1. Simplified schematic diagram of the DCC resistance bridge.

Unknown Resistor R_x		DCC Setup	Standard Resistor R_s	
1 Ω	15 mA	Bridge only	0.1 Ω	150 mA
0.1 Ω	150 mA	Extender	1 Ω	15 mA
0.1 Ω	1 A		1 Ω	100 mA
0.1 Ω	1 A		10 Ω	10 mA
0.1 Ω	1 A		100 Ω	1 mA
0.01 Ω	1 A	Extender	0.1 Ω	100 mA
0.01 Ω	1 A		1 Ω	10 mA
0.01 Ω	1 A		10 Ω	1 mA
0.01 Ω	10 A		1 Ω	100 mA
0.01 Ω	10 A		10 Ω	10 mA
0.001 Ω	1 A	Extender	0.01 Ω	100 mA
0.001 Ω	1 A		0.1 Ω	10 mA
0.001 Ω	1 A		1 Ω	1 mA
0.001 Ω	10 A		0.1 Ω	100 mA
0.001 Ω	10 A		1 Ω	10 mA
0.0001 Ω	10 A	Extender	0.01 Ω	100 mA
0.0001 Ω	10 A		0.1 Ω	10 mA
0.0001 Ω	100 A		0.1 Ω	100 mA

Table 1. R_x and R_s resistance values used for range extender validation.

3. Description of Range Extender Validation Process

Comparing results for several different ratios and current levels using range extenders is likely to reveal any errors that exist. Range extenders of 1000 A, 2000 A, and 3000 A can be checked with this same measurement technique using a well characterized 10 μΩ high current resistor to achieve less than 1×10^{-6} expanded uncertainties ($k = 2$). To test a range extender, a series of comparisons can be performed using standard resistors of the four-terminal design that have a well-known predictable drift, and known temperature coefficients which are directly proportional to the power coefficients. The validation process test requires a combination of at least seven resistors, including four of the Reichsanstalt [7, 8] design having nominal values of 0.1 Ω, 0.01 Ω, 0.001 Ω and 0.0001 Ω. We used two resistors at each nominal value giving a total of 14 resistors used in the following process.

The reference resistors and unknown resistors are all placed in a constant temperature oil bath maintained at 25.00 ± 0.005 °C. This is critical to achieve the desired uncertainties because the temperature coefficients of the resistors are in the range of 1×10^{-6}/°C to 5×10^{-6}/°C. Given that the power

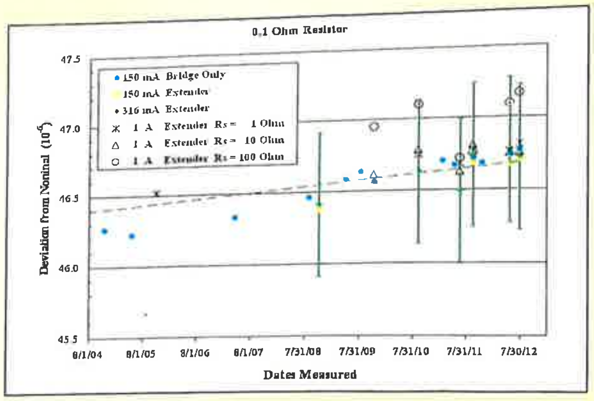

Figure 2. Measurement results for a 0.1 Ω resistor.

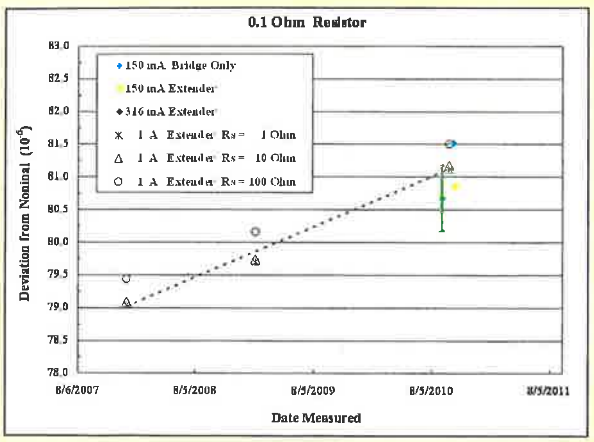

Figure 3. Measurement results for another 0.1 Ω resistor.

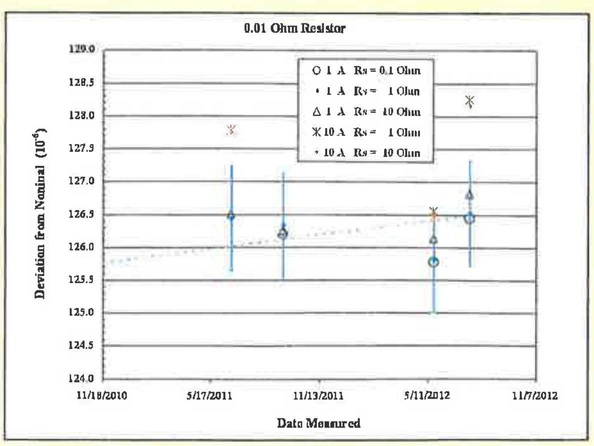

Figure 4. Measurement results for a 0.01 Ω resistor.

dissipation is as much as 1 W, presumably even state of the art air baths will have difficulties maintaining the temperature stability required to achieve relative uncertainties at or below 0.5×10^{-7} uncertainty ($k = 2$). Shunts of the same nominal values could be used as well in an oil bath, but the size of large current shunts makes this impractical.

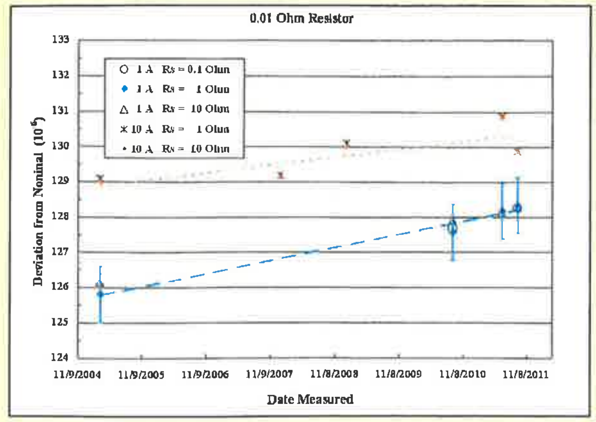

Figure 5. Measurement results for another 0.01 Ω resistor.

Table 1 shows the unknown resistor (R_X) and the current applied to it and the standard resistor (R_S) used with the appropriate current passing through it. The first step is to measure the 0.1 Ω resistor at 150 mA, and obtain a resistance value by putting 15 mA through a 1 Ω resistor using the current comparator bridge only. Two primary reference resistors were used at each of the four levels of measurement described in this technical note.

We connect the range extender and measure the same 0.1 Ω resistor at 150 mA against the same 1 Ω resistor and repeat the previous measurements. The fewer changes made in the test setup, the lower the probability of measurement errors. From this point on, the same 18 gauge shielded wires for the potential terminals were used on each of the R_X resistors. The current terminals of each of the R_X resistors were connected using the same 12 gauge wire up to 10 A. Above 10 A to 100 A, the same AWG 1/O gauge cables were used to connect to the R_X resistor's current terminals. The same number of readings and reversal rates were used in all of the measurements. The current is increased to 1 A on the 0.1 W resistor, which will put 100 mA through the 1 Ω standard. After making repeated measurements, change R_S to a 10 Ω resistor and repeat the 1 A measurements, then change R_S to a 100 Ω resistor and repeat the 1 A measurements. Figure 2 shows the results of the bridge and extender comparison at 150 mA and the 1 A measurements on all three current ranges. Figure 3 shows the same measurement results for another 0.1 Ω resistor. The green error bars in Figs. 2 and 3 are $\pm 0.5 \times 10^{-6}$, which is the published expanded uncertainty ($k = 2$) of a 0.1 W resistor measured at 10 mW [4].

The next level of testing utilizes a 0.01 Ω resistor as the R_X with 1 A applied, and R_S will now be a 0.1 Ω resistor with 0.1 A applied. The procedure continues with the 0.01 Ω resistor repeatedly measured using the same test parameters as in the previous tests. Figure 4 shows the results. As before, three well-characterized resistors were used for R_S. All three current ranges of the range extender agree at 1 A to within 0.1×10^{-6}. The 10 A measurement results agree within 0.05×10^{-6}. The blue error bars in Fig. 4 are $\pm 0.8 \times 10^{-6}$, which is the published expanded uncertainty ($k = 2$) of a 0.01 Ω resistor measured at 10 mW [4]. The difference between the 1 A value and the 10 A value is the heating effect of the resistor. The blue dashed line is the historical drift of this resistor for the last 10 years.

Figure 5 shows the results for another 0.01 Ω resistor. The 1 A data on the blue dashed line agree to within 0.5×10^{-6} and the 10 A

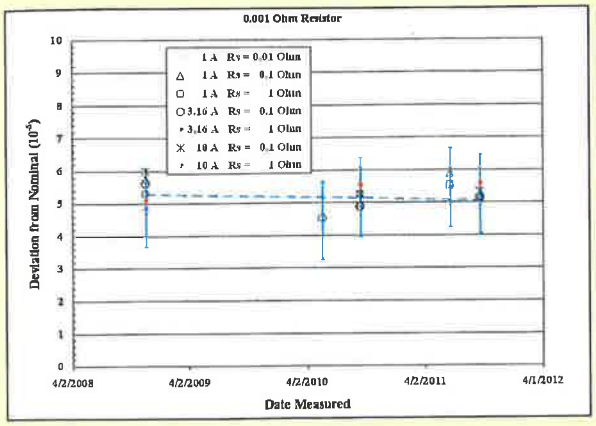

Figure 6. Measurement results for a 0.001 Ω resistor.

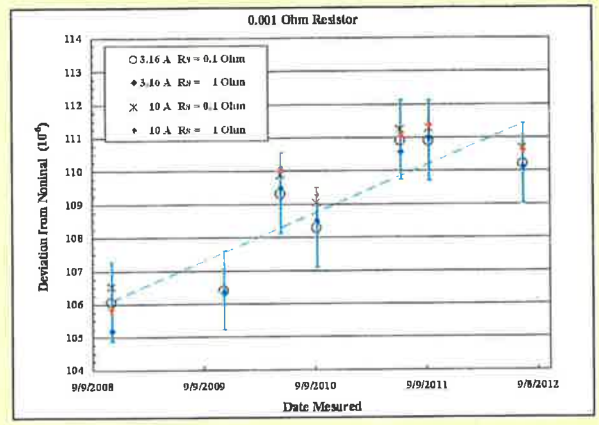

Figure 7. Measurement results for another 0.001 Ω resistor.

data agree to within 0.1 × 10^{-6}. The blue error bars in Fig. 5 are again ±0.8 × 10^{-6}, which is the published expanded uncertainty (k = 2) of a 0.01 Ω resistor measured at 10 mW [4]. The difference between the 1 A value and the 10 A value is the heating effect of the resistor.

The next level of testing utilizes a 0.001 Ω resistor as the R_X with 1 A applied, and R_S will now be a 0.01 Ω resistor with 0.1 A applied. The 0.001 Ω resistor is measured repeatedly with the same test parameters as in the previous tests. As before, three well-characterized resistors were used for R_S. Figures 6 and 7 show the measurement results for two different 0.001 Ω resistors.

The 1 A and 3.16 A measurement results of all three current ranges of the range extender agree to within 0.1 × 10^{-6}. The 10 A results agree to within 0.05 × 10^{-6}. The difference between the 1 A value and the 10 A value is small because there is very little heating effect of the resistor. The small change is because of the temperature coefficient, which is about 1 × 10^{-6}/°C. The blue dashed line is the historical drift of this resistor. The blue error bars in Figs. 6 and 7 are ± 1.2 × 10^{-6}, which is the published expanded uncertainty (k = 2) of a 0.001 Ω resistor measured at 10 mW [4].

The final level of testing listed in Table 1 utilizes a 0.0001 Ω resistor as the R_X with 10 A applied, and R_S will now be a 0.01 Ω resistor with 0.1 A applied. The 0.0001 Ω resistor is measured repeatedly with the same test parameters as in the previous tests. As before, well-characterized resistors were used for R_S. Figure 8 shows the results. The blue error bars in Fig. 8 are ±4 × 10^{-6}, which is the published expanded uncertainty (k = 2) of a 0.0001 Ω resistor measured at 10 mW [4].

It is critical that the current cables be changed from American wire gauge (AWG) 12 gauge to AWG 1/0 gauge cables for the 10 A currents that will be used in the next level of testing. The next three figures will show how the full range of the range extender was checked. Figure 9 shows a 0.0001 W resistor with a temperature coefficient of +2 × 10^{-6} / °C that peaks around 25 °C. This makes it ideal for a full range check. The error bars are 1 s at each current level. The change in value from 10 A to 100 A is small and in the positive direction, which agrees with the temperature coefficient.

Figure 10 shows a 0.0001 Ω resistor with a temperature coefficient of -5 × 10^{-6}/ °C. The change in value from 10 A to 100 A is small and in the negative direction, which agrees with the temperature coefficient.

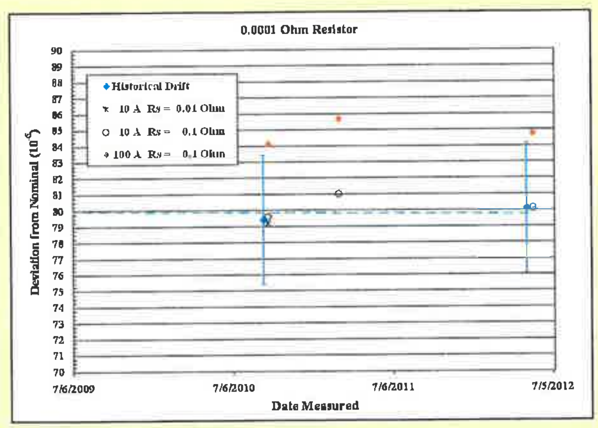

Figure 8. Measurement results for a 0.0001 Ω resistor.

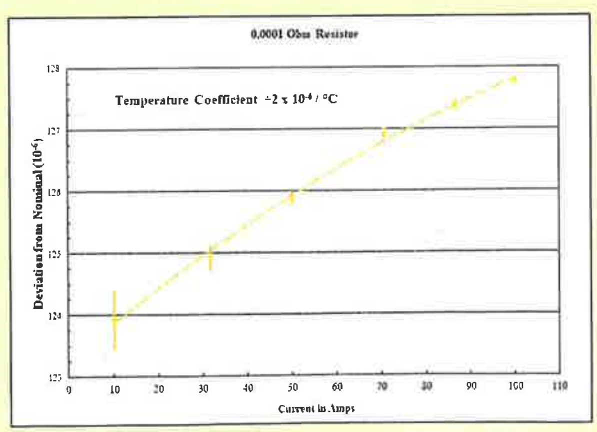

Figure 9. 0.0001 Ω resistor with a temperature coefficient of +2 × 10^{-6} / °C.

Figure 11 shows a 0.0001 Ω resistor with a larger temperature coefficient of +10 × 10^{-6} / °C. The change in the resistors value from 10 A to 100 A is much larger, which agrees with the temperature coefficient.

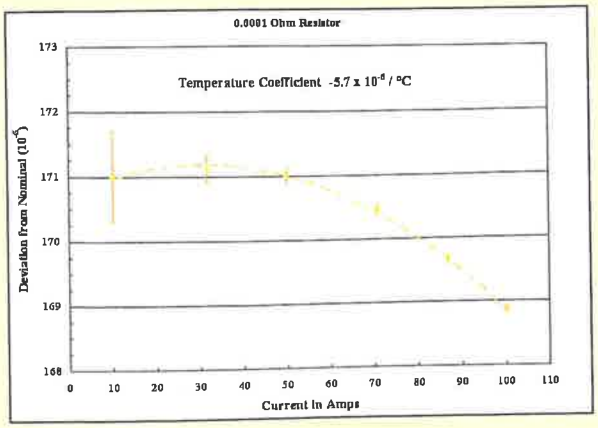

Figure 10. 0.0001 Ω resistor with a temperature coefficient of -5 × 10^{-6} / °C.

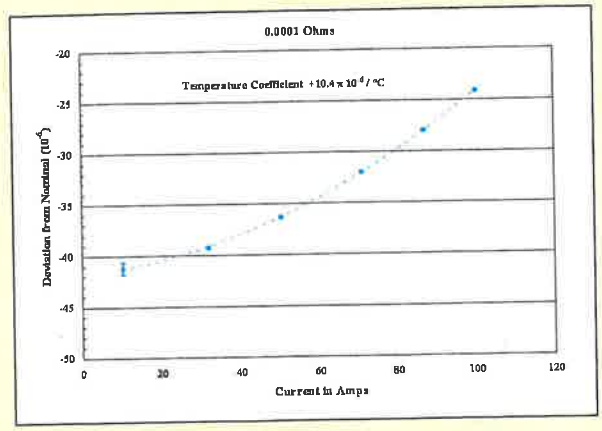

Figure 11. 0.0001 Ω resistor with a temperature coefficient of +10 × 10^{-6} /°C.

4. Summary

As a good metrological practice, DC current comparator range extenders and bridges need to be periodically checked to ensure that results will meet or exceed stated uncertainties. The technique presented here allows you to check the functionality of all ranges of a range extender. Keep in mind that the resistors used in this technique (R_S and R_X), must have an accurate historical drift record, well-known temperature and power characteristics, and must be placed in a constant temperature oil bath maintained at 25.00 ± 0.005 °C to achieve the best possible results. Some of the low value resistors that were discussed in this paper were used in an international low ohm intercomparison with results reported in [6].

5. References

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