HIGH RESISTANCE MEASUREMENTS

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Abstract

This paper describes the accredited calibration methodology used in the Calibration Laboratory operated by Fluke Germany. It is based on the use of a High-Ohms Resistance Bridge made by Measurement International together with appropriate Resistance Standards from 10 kW to 10 MW from Guildline and Russian made Resistance Standards from 100 MW to 1GW.

Indroduction

The calibration of Standard Resistors in the range from 10 kΩ to 1 GΩ is based on the use of a High-Ohms Resistance Bridge, model 6000B, made by Measurement International/Canada (MI) and the use of Standard Resistors from 10 kΩ to 1 GΩ.

The Model 6000B from MI is a binary voltage divider which measures the ratio between the connected known and unknown resistors with very low uncertainty. The ratio follows the following equation:

$$V = \frac{R_X}{R_N} = \frac{V1 - V2}{V3 - V4} = \frac{V1/E - V2/E}{V3/E - V4/E} = \frac{r1 - r2}{r3 - r4}$$

The value of the unknown resistor is calculated as follows:

$$R_X = R_N \bullet V$$

The functionality of the bridge is described later on in this paper, but it functions as shown in figure 1:
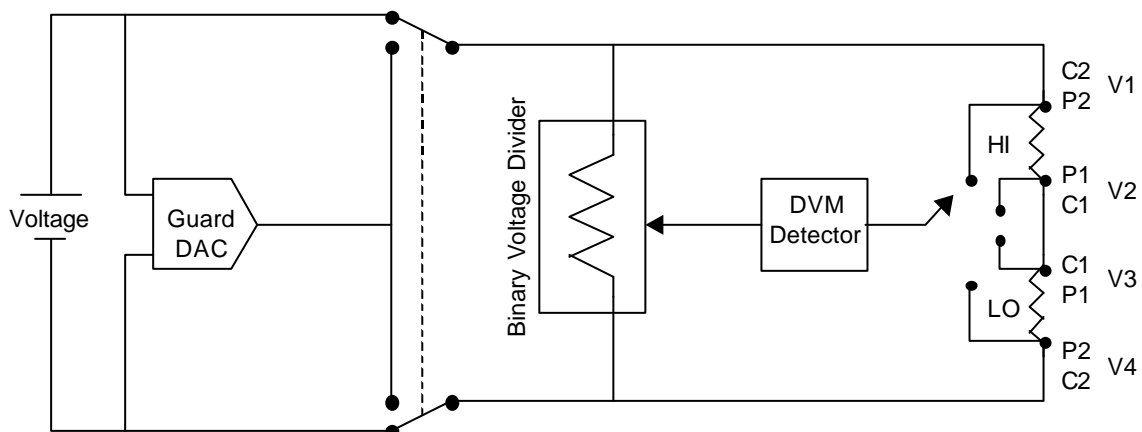

Figure 1: Functional layout for resistance measurements from 10 kΩ bis 1 GΩ mit MI6000B

Technical description of High Ohms resistance Bridge 6000B by Measurement International[i]

The measurement of resistance ratios depends on either of two techniques:
- Passing a current through two or more resistors in series and measuring the ratio of voltages developed across the resistors.
- Passing known ratios of current through each of a pair of resistors until the voltage drop developed across each resistor is the same.

An adaptation of the first technique is to measure voltage ratios by means of a conventional potentiometer or with a DVM. This approach has limited usefulness, being a sequential measurement where the stability of the source voltage is important due to the linearity of the voltage measurement system and the change in range factors. With the introduction of the 25 bit potentiometer, based on the binary voltage divider (BVD), the situation has changed. A single voltage source of 10 volts with a short term stability of a few parts in 10^8 is used to power the potentiometer and the series resistor pair in parallel with a DVM detector.

The direct current comparator (DCC) bridge is an example of the second technique.

In both the BVD method and the DCC method, at balance no current flows in the measuring leads and lead resistance is therefore unimportant when using four terminal connections. In the potentiometric method resolution and accuracy are limited by (and cannot be better than) the stability of the DVM detector. The BVD bridge method suffers from the disadvantage that when scaling resistors in decade steps the same current must be passed through both resistors and the greatest power is dissipated in the largest resistor. This limits the dynamic range for sub ppm

ppm measurements is limited by the current noise of the DCC comparator to 10,000 ohms and less. The DCC method also

25 Bit Potentiometer Basic Operation
The classic circuit of the BVD potentiometer is shown in fig. 1 where a master/slave relationship exists between the BVD and the resistors under test, thus the stability of the common voltage source is not critical as long as it is stable during the time taken to make the four measurements called V_1, V_2, V_3, V_4.

The ratio of the two resistors is given by:

$$R = \frac{Rx}{Rs} = \frac{V1 - V2}{V3 - V4} = \frac{V1/E - V2/E}{V3/E - V4/E} = \frac{r1 - r2}{r3 - r4}$$

Over the range of 1,000 ohms to 1G Ohm all resistors are measured in a four terminal mode. This eliminates problems associated with lead resistance effects of two wire measurements made with the DCC method above 10,000 ohms.

For the automatic potentiometer, the standard deviation of the measurement is derived from the sensitivity and resolution of the DVM being used as the detector (S_{r1}). For the Fluke Model 8842, the resolution is estimated at ±0.15 ppm and the short-term noise stability of the source is estimated to be less than 0.1 ppm for the time of measurement that is required. Experience with the binary voltage divider suggests that the calibration of the divider is consistent to within 0.02 ppm. When using the Agilent 3458A in the guarded mode, the resolution of the DVM is estimated at <0.1 ppm over the range from 10,000 Ω to 10M Ω and 1 ppm at 1G Ω. The accuracy of the DVM is unimportant as the DVM is only used on the 1.2 millivolt range and is only used as a null detector.
For a typical 1:1 comparison of four terminal resistors the estimated uncertainty of the ratio measurement with E = 10V is = 0.02 ppm.

$$\left(\frac{S_R}{R}\right)^2 = \left(\frac{\left(Sr1\right)^2\left(Sr2\right)^2}{\left(1.0 - 0.5\right)^2} + \frac{\left(Sr3\right)^2\left(Sr4\right)^2}{\left(0.5 - 0.0\right)^2}\right)$$

And for a typical 10:1 ratio measurement of four terminal resistors, r1=1.0, r2=0.09, r3=0.09, r4=0.0, the estimated uncertainty of the ratio measurement with E = 10 volts = 0.035 ppm.

A limit of 10 mW power dissipation has been arbitrarily chosen as the working limit for all resistors. Seven supply voltages have also been considered as follows:

E	R (1:1)	R (N:1)
1 V	> 25 Ω	> 100 Ω
3.2 V	> 250 Ω	> 1000 Ω
10 V	> 2500 Ω	> 10000 Ω
32 V	> 25000 Ω	> 100000 Ω
50 V	> 62500 Ω	> 1000000 Ω
100 V	> 250000 Ω	> 10000000 Ω

Table 1: Constraints due to power dissipation limits

Table 2 has been constructed from a practical point of view using an HP 3458 as the DVM detector and a stable zener voltage with an equivalent internal impedance of 100 milliohms. It will be appreciated that a calibrated voltage is not required; the major requirement is that the source be stable and noise free. Table 2 also illustrates the uncertainties for ratio measurements of 1:1, 10:1, 1:10 and 100:1.

E	(1:1)	(10:1)	(1:10)	(100:1)
0.1 V	1.0	0.5	5.0	20.0
1 V	0.5	0.3	3.0	10.0
5 V	0.25	0.2	1.6	5.0
10 V	0.1	0.1	0.6	3.0
20 V	0.1	0.1	0.33	2.0
50 V	0.1	0.1	0.15	1.0
100 V	0.1	0.1	0.1	0.5

Table 2: Uncertainties (95% Confidence) for Ratio Measurements

Practical use

The MI 6000B together with the software that is supplied to operate the bridge, is generally speaking an easy to use high-precision measurement system. However, the connections of the resistor under test and the standard resistor has to be done carefully as any small mistake in the Grounding and Guarding may have a negative influence on the measurements. The system also requires a Digital-Voltmeter as a detector and an external DC-Source. Care should be taken in the choice of the DVM to be used as a detector. We had used a Datron 1271, but had much better repeatability and consistancy of the result by using a Datron 1281. It seems that Datron 1281 has much better input impedance than the Datron 1271, which maybe due to the better quality parts used in the input circuitry in the Datron 1281. We have not been able to use either an Agilent 3458A nor a Fluke 8842A so far.

The external DC-Source which is required to source voltages from 1 V to 100 V may also be purchased from MI (Model 1000A), but any other source that has similar stability and noise levels may be used as well. However, the MI source is a good source and should be used with the system.

Accreditation of the system

The calibration of Standard Resistors using MI6010B and MI6000B is done under full usage of the „Best Measurement Capabilities" of both systems. The the „BMC" of the systems are given at an ratio of 10:1, meaning the the unknown is 10 times the known resistor. This is reflected in the uncertainty budget.

Measurement International claims an uncertainty for the ratio over the total range from 1 kΩ to 10 MΩ of the MI6000B which is typical < 0,1 ppm. It was found through comparison with PTB/Braunschweig that this value is at least by a factor of 2 smaller. Since there are 6 steps in the chain from 10 kΩ to 1 GΩ only a sixth of the total uncertainty applies for each step, however, for measurements of a 100 MΩ resistor an 1 GΩ reference measurements are done to the known standard resistor of the same value.

The short term stabilitiy of the standard resistors used in the step chain are very low and the step ups are frequently repeated, the short term stability may be estimated to be 0,01 ppm. See also picture 1 for a sample measurement.
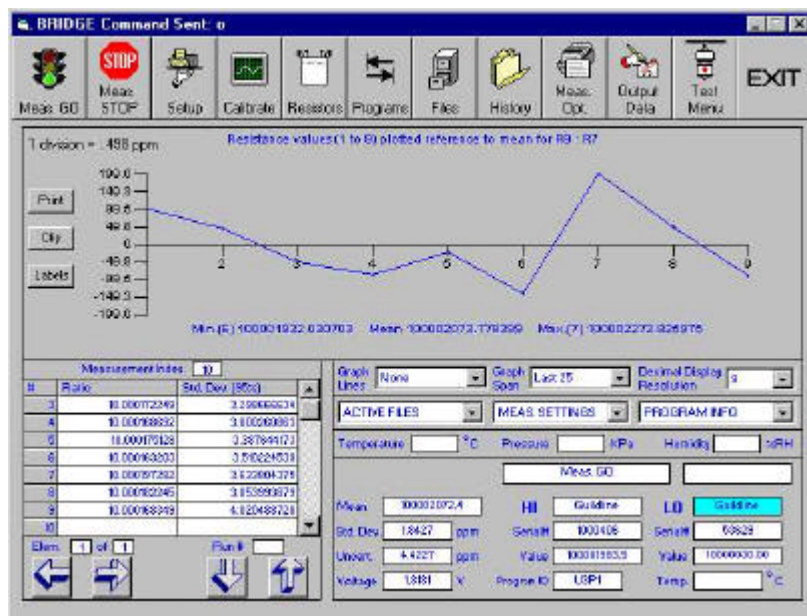
Picture 1: Sample Measurement Screen

Measurement uncertainty Budget

Modelling of the Measurement Process

$$R_X = V \cdot k_V \cdot R_N \cdot k_{(Dt \cdot a)} \cdot k_{DR}$$

Quantity	Unit	Definition
R_X	Ω	Unknown Standard Resistor
R_N	Ω	Unknown Standard Resistor
V		Ratio R_X/R_N
k_V		Transfer factor of the ratio of R_X/R_N
$k_{(Dt \cdot a)}$	Ω	Transfer factor of the Temperaturcoefficient of the Standard Resistors
k_{DR}	Ω	Transfer factor of the drift of R_N

Table 3: List of the effecting quantities

The variance of R_X after partial deduction and division by R_X is :

$$w^2(R_X) = w^2(R_N) + w^2(k_V) + w^2(k_{(Dt \cdot a)}) + w^2(k_{DR})$$

Quantity	Standard uncertainty	Distribution	Type	Degrees of freedom	Sensitivity-coefficient	Uncertainty contribution	Variance
R_{N10kW}	$0,005 \cdot 10^{-6}$	N	B	50	1	$0,005 \cdot 10^{-6}$	$6,25 \cdot 10^{-18}$
$V_{10kW/100kW}$	$0,0125 \cdot 10^{-6}$	N	B	∞	1	$0,0125 \cdot 10^{-6}$	$1,56 \cdot 10^{-16}$
$k_{Dt \cdot a}(10kW)$	$0,02 \cdot 0,2 \cdot 10^{-6}/\sqrt{3}$	R	B	∞	1	$0,02 \cdot 0,2 \cdot 10^{-6}/\sqrt{3}$	$5,35 \cdot 10^{-18}$
$k_{DR}(10\text{-}1kW)$	$0,01 \cdot 10^{-6}/\sqrt{3}$	R	B	∞	1	$0,01 \cdot 10^{-6}/\sqrt{3}$	$3,34 \cdot 10^{-18}$
$k_{DR}(10kW)$	$0,1 \cdot 10^{-6}/\sqrt{3}$	R	B	∞	1	$0,1 \cdot 10^{-6}/\sqrt{3}$	$3,34 \cdot 10^{-15}$

Table 4: Uncertainties of the Effecting Quantities

Quantity	Standard uncertainty	Distribution	Type	Degrees of freedom	Sensitivity-coefficient	Uncertainty contribution	Variance
R_{N10kW}	$0,005 \cdot 10^{-6}$	N	B	50	1	$0,016 \cdot 10^{-6}$	$6,25 \cdot 10^{-18}$
$V_{10kW/100kW}$	$0,0125 \cdot 10^{-6}$	N	B	∞	1	$0,0125 \cdot 10^{-6}$	$1,56 \cdot 10^{-16}$
$k_{Dt \cdot a}(10kW)$	$0,02 \cdot 0,2 \cdot 10^{-6}/\sqrt{3}$	R	B	∞	1	$0,02 \cdot 8 \cdot 10^{-6}/\sqrt{3}$	$5,35 \cdot 10^{-18}$
$k_{DR}(10kW)$	$0,1 \cdot 10^{-6}/\sqrt{3}$	R	B	∞	1	$0,1 \cdot 10^{-6}/\sqrt{3}$	$3,34 \cdot 10^{-15}$
Expanded rel. uncertainty with k-factor = 2						$1,19 \cdot 10^{-7}$	

Table 5: Sample calculation of Calibration of a 100 kΩ Standard Resistor

Range	Sum of the variances	Standard-uncertainty $u(R_X)$	Expanded rel. Uncertainty $U(R_X)$
10kΩ bis 100kΩ	$w^2(R_X) = w^2(R_{N10kW}) + w^2(V_{10kW/100kW}) + w^2(Dt \cdot a_{10kW}) + w^2(R_{D10kW})$	$0,59 \cdot 10^{-7}$	$1,18 \cdot 10^{-7}$
100kΩ bis 1MΩ	$w^2(R_X) = w^2(R_{N100kW}) + w^2(V_{100kW/1MW}) + w^2(Dt \cdot a_{100kW}) + w^2(R_{D100kW})$	$0,59 \cdot 10^{-7}$	$1,18 \cdot 10^{-7}$
1MΩ bis 10MΩ	$w^2(R_X) = w^2(R_{N1MW}) + w^2(V_{1MW/10MW}) + w^2(Dt \cdot a_{1MW}) + w^2(R_{D1MW})$	$0,296 \cdot 10^{-6}$	$0,59 \cdot 10^{-6}$
10MΩ bis 100MΩ	$w^2(R_X) = w^2(R_{N10MW}) + w^2(V_{10MW/100MW}) + w^2(Dt \cdot a_{10MW}) + w^2(R_{D10MW})$	$0,48 \cdot 10^{-6}$	$0,97 \cdot 10^{-6}$
100MΩ bis 1GΩ	$w^2(R_X) = w^2(R_{N100W}) + w^2(V_{100MW/1GW}) + w^2(Dt \cdot a_{100MW}) + w^2(R_{D100MW})$	$2,8 \cdot 10^{-6}$	$5,6 \cdot 10^{-6}$

Table 6: Results of the uncertainty budget

Range			*Uncertainty*
10 mΩ	to	100 mΩ	$6 \cdot 10^{-6}$
> 100 mΩ	to	10 kΩ	$3 \cdot 10^{-7}$
> 10 kΩ	to	100 kΩ	$5 \cdot 10^{-7}$
> 100 kΩ	to	1 MΩ	$5 \cdot 10^{-7}$
> 1 MΩ	to	10 MΩ	$2 \cdot 10^{-6}$
> 10 MΩ	to	100 MΩ	$2 \cdot 10^{-6}$
> 100 MΩ	to	1 GΩ	$8 \cdot 10^{-6}$

Table 7: Accredited Measurement Uncertainties (BMC)[ii]

References

DIN ISO/IEC 17025:2000

DIN EN ISO 9001:2000

Calibration: Philosophy in Practice (Second edition) published by Fluke Corporation Everett/WA/USA

EAL-G12; Tracebility of Measuring and Test Equipment to National Standards

DKD-3; Expression of the Uncertainty of Measurement in Calibration

EAL-R2; Expression of the Uncertainty of Measurement in Calibration

High Resistance Ratio Bridge Model 6000B, Operating and Technical Manual

RESISTANCE MEASUREMENT SYSTEMS W/ SUB PPM ACCURACY'S FROM 1uΩ TO 1GΩ Author: Duane Brown

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[i] Courtesy of Duane Brown Measurement International/Canada
[ii] Accreditation of Fluke Germany GmbH under registration DKD-K-00902 by German Calibration Services