Loading Effects in Resistance Scaling

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Abstract—Reference resistors are affected by the heating of the resistor element caused by the measurement current. The effects of such loading are complex and can change in magnitude as a function of the initial state of the resistor and the external environment. This paper describes a method for determining relative load coefficients by using cryogenic current comparator ratio measurements in a two-step scaling process. Previously undiscovered loading effects are analyzed using a resistance element made from copper, which has an easily measured change of resistance with temperature. The magnitude of loading effects in several types of resistors are listed.

I. INTRODUCTION

A load coefficient of resistance (LCR) indicates the relative change in resistance as a function of electrical power under steady-state measurement conditions [1], and generally is proportional to the resistors temperature coefficient of resistance (TCR). Scaling is the measurement of a resistance value based on a comparison to a reference resistor of a widely different value. Scaling techniques using Hamon devices and cryogenic current comparator (CCC) ratios in bridge measurements between 1 Ω and 10 kΩ have been compared at NIST [2]. The two scaling techniques are in good agreement for reference resistors that have low TCR’s, even though Hamon devices may have significant TCR’s in the range of ±1 × 10⁻⁶ per °C. Scaling with Hamon devices is performed with equal power levels used in the series and parallel configurations to minimize the measurement uncertainty caused by loading. CCC bridges can provide improved resolution in ratio comparisons while dissipating relatively low power in the resistors. However, the CCC scaling method can require that significant power be dissipated in the smaller-valued resistor being compared, e.g., when comparing a 100 Ω resistor at 10 mW to a 10 kΩ resistor at 100 μW.

A measurable load-related resistance change at a power level of 10 mW or less may contribute to differences in the results of international comparisons of resistance where measurements are sometimes made at different power levels in different laboratories. Scaling from the quantized Hall resistance (QHR), which since 1990 has been the international standard of resistance, and resistance scaling for the calculable capacitor experiment [3] also may require determinations of loading effects. Loading effects can be difficult to quantify since the resistance element is subjected to temperature gradients inside a sealed case and the temperature change of the element cannot be accurately measured.

II. COPPER RESISTOR MEASUREMENTS

A copper resistor of approximately 140 Ω was fabricated with the same construction of element and case as certain Evanohm1 10 kΩ, 6453.2 Ω, and 100 Ω resistors used at NIST (Fig. 1). Both types of resistor consist of ten approximately 9.5 m lengths of 0.127 mm diameter wire wound on ten mica cards. This copper resistor has a TCR of about 3.9 × 10⁻⁴ per °C near 25 °C. It was used to study loading effects, based on the assumption that the heat-transfer process that occurs in the copper resistor is similar to that in the Evanohm card-type resistors with a similar design.

One reason for the tests using the copper resistor was to investigate loading effects for resistors measured in air enclosures. Between 1983 and 1992, four 6453.2 Ω transfer resistors in temperature-controlled air enclosures were compared at NIST to the QHR using a potentiometric technique [4] at 25 μA, or about 4 μW load. To facilitate accurate scaling, the transfer resistors were also compared to a Hamon device at a much higher load of 10 mW. These resistance ratios using the Hamon device were recorded as a function of time at 10 mW

1Evanohm is a registered trademark of the Wilbur B. Driver Company. Certain commercial equipment and materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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The least-squares analysis leads us to conclude that exponential behavior is the dominant loading effect in the first hour of measurements at 10 mW for this type of resistor, even for resistors in the air enclosure. The behavior observed in measurements lasting up to 360 min and used to determine loading corrections for 6453.2 Ω transfer resistors from 1987 through 1992 included data dominated by a decay process having a much larger time constant. The loading corrections to the 6453.2 Ω data have been re-calculated, using exponential least-squares fits to the 60-min data segments with a time constant of 24 min. The new values for four dates in 1987 and 1988 are given in Table I. The uncertainty for each value is the same as that given in [4] for that date.

### III. 100 Ω Reference Bank

CCC bridges have been used since 1992 at NIST to compare 6453.2 Ω and 12 906.4 Ω QHR plateaus to 100 Ω resistors. CCC measurements are also made between 1 Ω and 100 Ω and between 100 Ω and 1000 Ω. In 1994, NIST began making many of these comparisons using a bank of five 100 Ω resistors that were selected for stability, low TCR’s and low pressure coefficients. The relative first-order TCR’s of these five resistors are between $-0.081 \times 10^{-6}$ per °C and $0.158 \times 10^{-6}$ per °C at 25 °C. The average relative TCR of this bank is $-0.010 \times 10^{-6}$ per °C at 25 °C and the average relative drift is $+0.07 \times 10^{-6}$ per year. These resistors are used at loads up to 10 mW.

CCC measurements were done in early 1995 to determine relative loading coefficients for the five resistors in the 100 Ω bank and three Hamon devices configured as 100 Ω resistors. Each 100 Ω resistor was compared to one 12 906.4 Ω reference with about 6 mW dissipated in the 100 Ω resistor. On the next day each was compared to a 1 Ω reference, with about 0.1 mW dissipated in the 100 Ω resistor. On the following day the comparisons were repeated using the 12 906.4 Ω reference and each 100 Ω resistor, and so on. Calculations yielded values of the 12 906.4 Ω to 1 Ω ratio for each 100 Ω intermediate resistor, and these values are given in Table II for the five 100 Ω bank resistors. The one-standard-deviation uncertainty of the ten calculated values given in the table is approximately $0.0023 \times 10^{-6}$. Much larger differences from this bank average (up to $\pm 0.0200 \times 10^{-6}$) were seen when using the Hamon 100 Ω intermediate resistors, which have TCR’s that are between $+0.4 \times 10^{-6}$ and $+0.7 \times 10^{-6}$ per °C at 25 °C. However, in two cases, the signs of these larger differences did not agree with that predicted from the TCR. Other effects, including thermo-electric effects in the multiple wiring junctions, may contribute to the result for the Hamon devices.

Differences in combined ratios of the type just described may also indicate loading effects in the intermediate resistors.

### Table I

<table>
<thead>
<tr>
<th>Mean date</th>
<th>Value (ref. [4])</th>
<th>Value (new)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 April 1987</td>
<td>$1.8142 \times 10^{-4}$</td>
<td>$1.8245 \times 10^{-4}$</td>
</tr>
<tr>
<td>9 September 1987</td>
<td>$1.8302 \times 10^{-4}$</td>
<td>$1.8362 \times 10^{-4}$</td>
</tr>
<tr>
<td>5 January 1988</td>
<td>$1.8600 \times 10^{-4}$</td>
<td>$1.8632 \times 10^{-4}$</td>
</tr>
<tr>
<td>10 May 1988</td>
<td>$1.8732 \times 10^{-4}$</td>
<td>$1.8760 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
In this case the load on the 100 Ω resistors is greater by approximately 6 mW in the comparisons against 12 906.4 Ω. The 12 906.4 Ω resistor dissipates negligible power and the 1 Ω resistor has a small TCR and is believed to experience negligible loading effects at 10 mW. Loading effects that do occur in either of these resistors should be the same in all of the ratios. The 1 Ω reference used was an unsealed Evanohm resistor made at the CSIRO National Measurement Laboratory in Lindfield, Australia.

In another recent measurement at NIST, the five 100 Ω bank resistors were compared to the 6453.2 Ω plateau of a QHR device with 0.6 mW dissipated in the resistors. A few days later, in comparisons against several 1000 Ω resistors, the 100 Ω resistors were used at a power level of 10 mW. Loading effects that do occur in either of these resistors should be the same in all of the ratios. The 1 Ω reference used was an unsealed Evanohm resistor made at the CSIRO National Measurement Laboratory in Lindfield, Australia.

The new calculations for the 6453.2 Ω transfer-resistor loading corrections result in changes of up to one part in 10⁸ in some values used in the 1988 determination of Ω_{NBS} using the quantum Hall resistance (QHR) [4]. These changes slightly improve the agreement between the new NIST comparison of the QHR and calculable capacitor [3] and that completed in 1988 [4], [5]. NIST QHR measurements and the related scaling are now made using the CCC bridge technique. The uncertainty in these resistance ratio measurements has been reduced by using 100 Ω resistors for which relative loading effects have been determined.

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REFERENCES


Randolph E. Elmquist (M’90), for a photograph and biography, see this issue, p. 267.

Ronald F. Dziuba (M’70–SM’89), for a photograph and biography, see this issue, p. 268.