Calibrations of current-to-voltage transimpedance amplifiers using electrical standards

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Abstract

For photocurrent measurements with low uncertainties, a wide-dynamic range current-to-voltage converter traceable to resistance standards has been developed at the NIST. The design and calibration of the converter standard are described. For validation, the converter standard was compared to the low-current scale of KRISS.

Introduction

In modern radiometry, the basis of the scales for photometric units such as the candela and for radiometric units such as power, radiance or irradiance is the cryogenic electrical-substitution radiometer (ESR). The ESR determines the optical power of the radiation by comparison to the equivalent temperature rise in the receiving cavity produced by the electrical power, and thus, the optical watt is made traceable to the electrical watt. Since the ESR is difficult to use and not easily transported, the optical power responsivity is transferred to photodiodes by substitution calibrations. These photodiodes are operated in photovoltaic mode in a regime where the photocurrent is linearly proportional to the optical power. Since most photometers and radiometers are operated in photovoltaic mode, photocurrent measurement with the lowest possible uncertainty is critical.

Although currents can be directly measured using electrometers, more commonly, the current is converted with current-to-voltage transimpedance amplifiers and the output voltage is measured. If the uncertainty of the current-to-voltage conversion is known, then the difficult current measurements can be changed to routine voltage measurements. This need for accurate current measurements also exists in other fields such as medical dosimetry, testing for material purity and charge mobility.

Previously [1], we developed a current-to-voltage converter standard where the decade feedback resistors (from 10^4 Ω to 10^8 Ω) were calibrated against NIST standard resistors. The current uncertainty at the highest gain was 0.012 % (*k*=2). The photodiode shunt resistance requirements were also discussed to obtain similar uncertainties in both photodiode measurements and electrical calibrations. Test converters using feedback resistors up to 10^{10} Ω were calibrated against the reference converter using direct converter substitution. The converter calibration method was extended to AC.

In this paper, the resistances of the feedback resistors up to 10^{10} Ω are measured in situ, together with the parallel resistances of the circuit board, rotary-gain switch, and feedback capacitors. The reference standards for these calibrations are as well as the resistance elements of the converters are improved-uncertainty 10^9 Ω and 10^{10} Ω resistors that have been used in developing high resistance standards by the NIST Quantum Electrical Metrology Division [2]. The selection criteria of the seven feedback resistors, the design considerations of the improved current-to-voltage converter, and the calibration procedure of the feedback components are described. The current-to-voltage conversion uncertainties are calculated. For validation of the improved NIST current-to-voltage conversion scale, the current measurement uncertainty is compared to the uncertainty of the KRISS reference current source at both 10 pA and 100 pA.

Feedback resistor selections

The resistance elements selected for the feedback were precious-metal oxide (PMO) film type resistors. A heat-treatment process developed for the NIST high resistance standards has been applied to the resistance elements used for the feedback circuit. Groups of resistance elements were measured prior to heat treatment to select those closest to nominal value, and then the elements were heat treated for 250 h at 65 ºC to accelerate the aging and long-term stability. Measurements were made following heat treatment to select the most stable and closest to nominal value resistance elements for the standard. After the resistors are soldered to the printed circuit board, the measurements are repeated.

Reference current-to-voltage converter design

The reference current-to-voltage converter, including all the calibrated feedback resistors, is mounted in an electrically shielded box to avoid 60 Hz and noise pickup by the high-resistance components. Since the gain-switch, the feedback resistors and capacitors, and the printed-circuit-board are seen by the operational amplifier (OA) between its input and output, the resistors are calibrated at these two points with all the above components included in the resistance calibrations. The OA also remains in place but the two gold pin-jumpers built into the circuit board at the OA input and output are removed. To minimize the parallel resistances, a board (Rogers 4003C*) with a minimum surface resistivity of 4.2 x 10^{15} Ω and a minimum volume resistivity of 1.7 x 10^{16} Ω·cm was used. The rotary switch with insulation resistances > 4 x 10^{14} Ω was selected from several different commercially available models. Solder mask was not used on the board to avoid degradation of the board insulation resistance. The size of the board was increased to obtain more spacing between the metal traces and components, thus providing more insulating material between the traces which further separates possible leakage paths. The side of the circuit-

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board with the jumper pins and the rotary switch is shown in Fig. 1. The resistors are mounted on the reverse side of the board.

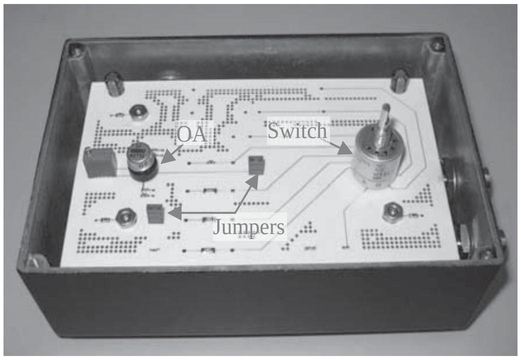

Figure 1. The view of the current-to-voltage converter. The operational amplifier (OA) is on the left with the rotary switch for resistance selection on the right. The jumper plugs isolate the OA when the resistances are measured. The resistors are mounted on the reverse side of the board.

Feedback resistor calibrations

The calibration of a standard resistor requires a defined set of terminals and a screened enclosure that serves as a Faraday cage. The calibration of standard resistors embedded in instrumentation and circuits is challenging and is typically not done with the same level of accuracy as a standard resistor with well-defined terminals. The approach taken here was to design the current-to-voltage amplifier circuit so the standard resistors could be calibrated in situ with the calibration including the standard resistor and other components that form the scaling ratio with the OA. During calibration, the OA is isolated from the other components and the input/output terminals are used as resistor terminals. The resistors, capacitors, circuit board, rotary switch, input/output connectors, and shielded case are treated as a standard resistor and calibrated using the same measurement systems as those used for a traditional standard resistor. The calibration of the on-board standard resistors may be repeated at regular intervals to establish long-term drift rates. NIST standard resistor calibration systems were used in the preliminary testing, demonstrating that the capacitors negligibly effect the calibration of the standard resistors [3].

KRISS current source

The performance of the converter standard in the high-gain range can be verified using a stable low DC current generated on the basis of charging a capacitor by a linearly varying voltage ramp [4]. In conjunction with a set of air capacitors in the range of 1 pF to 1000 pF, the setup can generate DC current in the range of 100 pA to 1 fA with expanded uncertainties of 0.0013 % to 6 % (k=2).

In order to calibrate the current-to-voltage converter standard with the low current, the current from the current source is applied into the converter and then the output voltage of the converter is measured by a digital voltmeter. The input current calculated from the measured output voltage divided by the system feedback resistance in the converter, is compared with the applied input current from the current source. The offset and drift in the output voltage of the converter can be eliminated by changing polarity of the input current and null-current measurement.

Validation inter-comparison

The gain-extended and modified NIST converter design with the improved electrical calibration will enable measurements of low photocurrents with decreased uncertainty and NMI traceability to high resistance measurements. These current measurements will thus reduce uncertainties, of the same order of magnitude as the high resistance measurements. Expanded uncertainties (k = 2) for the 10^7 Ω to 10^{10} Ω standard resistors range from 3μΩ/Ω to 20 μΩ/Ω for optimal test conditions. We estimate that the expanded uncertainties (k = 2) of commercial low level current measurements of 0.15 % (at 100 pA) could be reduced by a factor of 10 to 100 by utilizing the NIST converter design and calibration method. The final total uncertainties of the NIST current-to-voltage converter will need to include factors such as temperature coefficient, voltage coefficient, long-term drift, and transport effects.

References

* Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment are necessarily the best available for the purpose.

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