

AC-DC CURRENT TRANSFER STANDARDS AND CALIBRATIONS AT NRC

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Abstract: This paper describes efforts undertaken to upgrade ac-dc current transfer standards and calibrations at the National Research Council of Canada. The ac-dc current transfer comparator has been redesigned, using guarding techniques most advantageous for the current shunt comparisons. A set of coaxial shunts for currents between 10 mA and 10 A has been built, and characterized up to 100 kHz by a step up procedure. The operating current range was further extended, up to 100 A, by a set of commercial shunts. Furthermore, the fabrication of a set of high current coaxial shunts, with low ac-dc transfer differences, was recently initiated to replace the commercial shunts as the working standards.

1. INTRODUCTION

The most accurate standards of ac-dc transfer difference, multijunction (MJTC) and single junction thermal converters (SJTC), operate on a thermal principle. In such a converter, energy dissipated by an ac current flowing through a heater resistor, raising its temperature above the ambient, is compared to the energy dissipated by a dc current flowing through the same heater. The increase in the temperature of the heater at ac and dc, proportional to the dissipated energy, is measured using a thermocouple or a thermopile. A relative difference between the response of the converter to ac and dc inputs, called *ac-dc transfer difference*, is determined from these two measurements. The thermal standards can be considered as intrinsically current measuring devices, however, traditionally more effort was devoted to ac-dc voltage transfer measurements. For example, while NRC offers calibrations of ac-dc voltage transfer standards from 2 mV to 1000 V and from 10 Hz to 100 MHz, our current calibration capabilities were limited to the currents not exceeding 20 A and frequency up to 20 kHz.

To meet the calibration requirements of new equipment appearing on the market, the NRC ac-dc current transfer standards and calibrations have been recently upgraded, with a goal to extend our current capabilities to 100 A at frequencies up to 100 kHz. Thus far only one National Metrology Institute offers calibrations in these current and frequency ranges, [1]. In support of this effort we have purchased a commercial high current transconductance amplifier and a set of high current shunts, fabricated a new set of standard coaxial

shunts and modified our ac-dc transfer comparator for the current standards comparisons. We have re-evaluated our primary standards of ac-dc transfer difference using a Fast Reversed DC Source and fully characterized our working standards.

2. AC-DC TRANSFER COMPARATOR

A characterization of an ac-dc transfer standard is performed by comparison to a working standard in a measurement setup known as an ac-dc transfer comparator. In the simplest configuration the comparator consists of a dc source, an ac source and two dc voltmeters, measuring outputs of the transfer standards. When ac-dc *voltage* transfer standards are compared, they are connected in parallel so that the same voltage is applied to the input terminals of both instruments. Their guards are connected to the potential of the grounded low terminal of the voltage source.

When two ac-dc *current* transfer standards are compared, they are connected in series so that the same current flows through both standards. However, in this configuration only one of the standards can be at the ground potential. Influence of parasitic impedances, particularly from the standards to the ground, changes with the potential position of the standards and may change the results of the comparison. To minimize this influence, careful attention has to be paid to shielding, guarding and connections of the input/output terminals. Proper connections of the output cables shields and the guards of the output dc meters, will maintain the same potential difference between the ac-dc standard and output meters, independently of the potential position

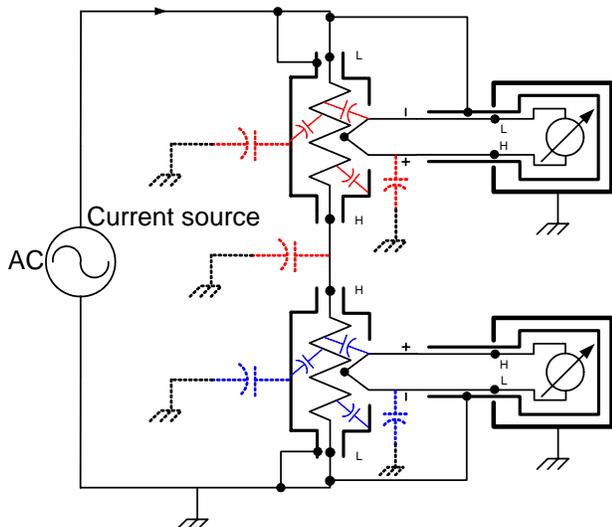


Fig. 1 Comparison of two ac-dc current transfer standards; note connection of the guard circuits and High and Low terminals of shunts and dc voltmeters.

of the standard. This will assure that the standards calibration configuration matches the configuration of a future application.

An example of such connections, for simplicity omitting the dc part of the comparator source circuit, is shown in Fig. 1. The ac-dc current converters are shown schematically as resistors and thermocouples and the parasitic impedances as capacitances.

The low terminals of the standards and their guard terminals are connected to either the low or the high potential terminal of the source (transconductance amplifier.) The leakage current from the grounded guard is thus eliminated; the leakage current from the guard connected to the high potential terminal loads the source, without entering the measuring circuit.

Internal parasitic impedances between the guard and the converter become an integral part of the standard. Leakage currents flowing through these impedances are the same in both potential positions of the standard.

Leakage current from the connection between the high terminals of the two standards, so called "current Tee," can be limited by the short design of this link.

Leakage current flowing through the dc connection between the standard and the dc voltmeter is limited by placing the cable shield and the meter guard at the guard potential of the measured standard.

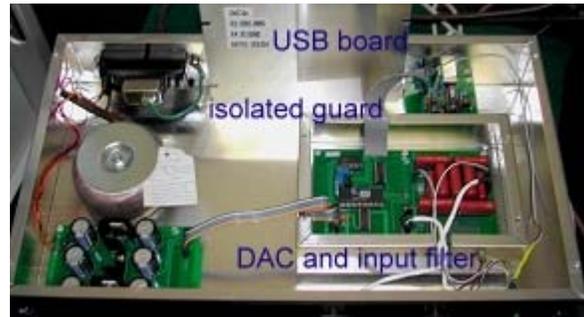


Fig. 2 Photograph of a USB controlled back-off voltage source showing an isolated DAC guard.

The commercially available nanovoltmeters do not have a separate guard, isolated from the ground terminal of the meter, which could be connected to either the low or the high source terminal. However, a nanovoltmeter of an older type, no longer in production, has a guard box, which can be modified to suit this purpose [2]. In the NRC ac-dc current transfer comparator, we are using two such modified nanovoltmeters in addition to the nanovoltmeters of a newer type.

During the tests the outputs of the standards may differ significantly. The two nanovoltmeters are then operating on different ranges, (e.g. 3 mV and 30 mV) with different linearity errors. Additionally, the range of the meter may change during the test, also changing the linearity error. To limit this source of comparison uncertainty, the outputs of the standards are connected in series with a bias (back-off) voltage of opposite polarity (not shown in Fig. 1.) At the beginning of every test point these bias voltages are adjusted to be approximately equal to the outputs of the standards. The nanovoltmeters measure only the remaining small voltage differences, and remain on the lowest ranges. The back-off voltage sources were built at NRC, using 16-bit D/A converters, Fig. 2. An internal floating guard encompassing the DAC can be connected either to the low or the high current source potential.

The NRC ac-dc current transfer comparator is described in more detail in [3].

2.1 USB control of the comparator

The instrumentation of the NRC ac-dc comparator is computer controlled through an IEEE-488 bus (current sources, nanovoltmeters) and through a digital I/O (ac/dc switch, back-off voltage sources.) The control computer is connected to the intranet,

and the comparator can be monitored from a remote location. The IEEE-488 bus signals and the digital I/Os are generated through control cards, plugged into the computer backplane. With every PC operating system change, leading to a control computer change, we were forced to replace the expensive control cards, additionally rendering the control software obsolete. During the current upgrade we decided to switch computer-comparator interface to the universal serial bus (USB.) We have replaced an internal IEEE-488 PC card with an USB-to-IEEE-488 adapter and use USB optoinsulated digital I/O boards, designed at NRC, to control relays and back-off voltages, see Fig.2. We are assuming that the future changes of computer hardware will not obsolete the USB interface.

3. PRIMARY STANDARDS

The NRC primary standard of ac-dc current transfer difference consists of a group of four commercial Guildline Instruments MJTCs with rated current of 20 mA, and heater resistance of 100 Ω. The frequency range of the primary standards was extended from a few kHz to 100 kHz using an NRC calorimetric thermal voltage converter (CTVC). Theoretical calculations, as well as tests of these converters, indicated that the ac-dc current transfer difference of NRC primary standards can be described as equal to $\delta_i = (0.0 \pm 0.4) \mu\text{V/V}$ at 1 kHz, and $\delta_i = (0.0 \pm 0.8) \mu\text{V/V}$ at 100 kHz, [4].

4. COAXIAL SHUNTS

The primary standards are used to calibrate 5 mA working standards of ac-dc current difference, SJTCs. The extension of the current ranges is performed using current shunts. For currents between 10 mA and 10 A we use NRC designed shunts. Shunts for currents (10, 20, 50, 100, 200) mA are built using surface mount resistors (Vishay VSM2110,) soldered in parallel in a star configuration on a small printed circuit board and mounted inside an aluminium box, [3], [5]. For higher currents, (0.5, 1, 2, 5, 10) A, we followed a design used by several other NMIs [6],[7],[8]. Mechanically, a shunt of such a design is built of three plates connected by a number of ribs, Fig. 3, (see also Fig. 5.) The plates and the ribs are cut from double-sided copper clad boards. The shunt resistor consists of a number of metal film resistors (Vishay type S102C,) concentrically mounted between the output and the middle plates, connected in parallel by the copper layers of these plates. The input plate

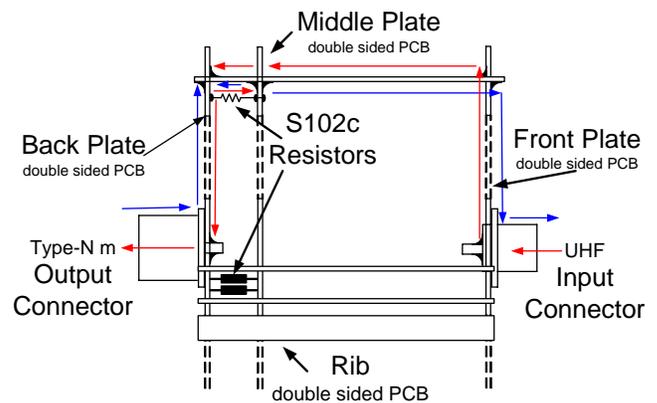


Fig. 3 Schematic diagram of coaxial shunts built for currents 0.5 A to 10 A.

is removed from the two output plates by the length of the ribs. This design minimizes inductive coupling between the input and the output circuits.

For the highest current ranges, (30, 50, 80, 100) A, we rely on a set of commercial coaxial shunts.

4.1. Frequency characteristics of the shunts

Frequency characteristics of the shunts were determined by a step-up procedure in which a higher range shunt is calibrated using a lower range current shunt. The 10 mA shunt/TVC combination was calibrated at 10 mA using primary standards. This shunt/TVC combination was then used to calibrate a 20 mA shunt, which in turn was used to calibrate a 50 mA shunt. In the last step of the step-up the 100 A shunt was calibrated at 80 A using a previously calibrated 80 A shunt. As an example of the final results, Fig. 4 shows frequency characteristics of ac-dc transfer difference of three coaxial shunts, 100 mA, 1 A and 10 A, expressed in $\mu\Omega/\Omega$, i.e. after removal of the components of the ac-dc transfer difference originating in the TVCs.

The high current commercial shunts have much larger ac-dc transfer differences than the NRC fabricated shunts, particularly at frequencies above 10 kHz: up to $-350 \mu\Omega/\Omega$, $-3600 \mu\Omega/\Omega$, $-8400 \mu\Omega/\Omega$ for the 30 A, 80 A and 100 A shunts at 100 kHz and $+770 \mu\Omega/\Omega$ at 20 kHz for the 50 A shunt.

4.2. Uncertainty evaluation

The following uncertainty components were taken into account evaluating shunt uncertainties.

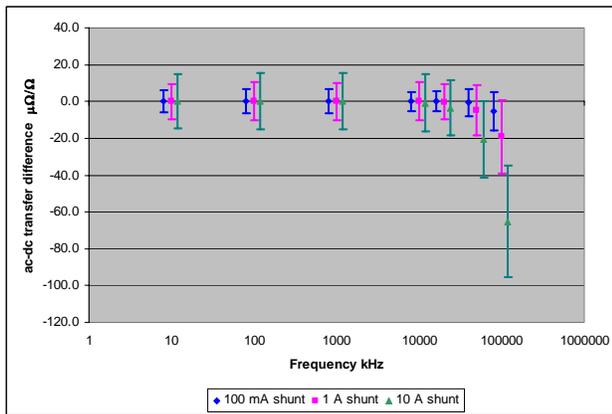


Fig. 4 Ac-dc transfer difference of three coaxial shunts: 100 mA, 1 A and 10 A at (0.01, 0.1, 1, 10, 20, 50, 100) kHz.

Reference standard uncertainty, type A+B, uncertainty of the reference, evaluated at the previous step. Uncertainty of the primary standards used at the first step was evaluated theoretically and experimentally.

Comparison with the reference, type A, pooled standard deviation of the measurements. Typically every test consisted of several test points, each point averaging five ac-dc transfer measurements (*ac-dc_normal-ac-dc_reverse-ac*) performed over approximately 45 minutes. Each test was repeated twice, interchanging the positions of the converters in reference to the transconductance amplifier output low terminal, and the results were averaged. The standard deviation of the measurement was calculated as the standard deviation of the average of the points. It is assumed that this statistically evaluated uncertainty component contains contributions originating in the variations of the ambient conditions and test frequencies during the tests conducted over several days, and the reproducibility of mechanical connections.

Magnitude/n-measurement, type B, measurement uncertainty proportional to the magnitude of the ac-dc current transfer difference. This is an uncertainty assigned to the errors originating in the determination of the exponents *n* (sensitivity) of the TVCs, the nonlinearity of the nanovoltmeters and the bias voltage determination. It is usually assumed that it does not exceed 1% of the measured ac-dc difference.

Potential position, type B, high potential/low potential position correction uncertainty. The measured ac-dc current transfer difference of a shunt depends on the

position of the shunt/TVC combination in reference to the transconductance amplifier output low terminal. It is assumed that averaging two sets of measurement determines the ac-dc transfer difference at an 'average' shunt potential. In calculations a value of this uncertainty, the same at every step, was assigned as to be equal to an average measured potential difference for this set of coaxial shunts.

TVC dV/dI correction uncertainty, type B. At every step we compare two artefacts, consisting of a shunt and a TVC. The result of the comparison is equal to the difference of the ac-dc current differences of the two combinations. The ac-dc current difference of each combination is a sum of the ac-dc current difference of the shunt and fractions (different functions of the ratio of shunt resistance and TVC resistance) of the ac-dc voltage transfer difference and the ac-dc current transfer difference of the TVC. Contributions of both TVCs were evaluated at every step and removed from the results of the comparison. However, they are current level dependent and difficult to remove completely, particularly at frequencies below 100 Hz. At these low frequencies the step-up procedure was repeated replacing the TVCs with voltmeters, HP/Agilent model HP3458A. The voltmeters were used in a sampling mode and the measured rms voltage values were calculated using the so-called Swerlein algorithm. The ac-dc current transfer differences of the shunts were derived by combining the results of these two step-up procedures.

Guarding uncertainty, type B. The step-up procedure was repeated three times, using different guarding configurations of the nanovoltmeters. In the first set of measurements, nanovoltmeters guards were connected to either high terminal (guard of the nanovoltmeter measuring output of a TVC positioned at the high potential) or low terminal (TVC at low potential) of the transconductance amplifier output, as in Fig. 1. In the second set of measurements the guarding circuits of both nanovoltmeters were connected to the low terminal of the transconductance amplifier output, configuration required for the new type of nanovoltmeters. In the third configuration guarded bias voltage sources were used, and the guarding circuits of the nanovoltmeters and the bias voltages were connected to either high or low terminal of the transconductance amplifier output. The uncertainty of the effectiveness of the guarding circuit at every current level was evaluated from the differences between these three measurements. It was

assumed to not exceeding the maximum difference between measurements in these three configurations.

Some uncertainty components were not explicitly included in the uncertainty budget assuming that their influence can be neglected in comparison to other uncertainty components (e.g. test frequencies uncertainty, "current Tee" parasitic parameters/leakage.)

For the selected shunts with characteristics shown in Fig. 4 the calculated expanded uncertainties ($k=2$) of the shunts ac-dc differences shown are presented as the error bars.

6. CONCLUSION AND FUTURE WORK

This paper presents the results of the effort to extend NRC ac-dc current transfer calibration capabilities both in current and frequency, in particular by a re-design of the ac-dc transfer comparator and fabrication of the new coaxial shunts for currents up to 10 A. The absolute values of ac-dc transfer difference of commercial shunts, used for currents above 10 A, are relatively high. This can limit their usefulness as highest accuracy working standards. To replace these shunts with shunts of different design we have decided on duplicating the design of BEV, Austria, [9]. We are planning on fabricating shunts for 20 A, 40 A, 80 A and 100 A. We have also acquired a low-inductance high current Tee, manufactured by BEV. Fig. 5 shows the test of a prototype of a BEV-design 20-A shunt, fabricated at NRC. Results of this work will be reported at the conference.

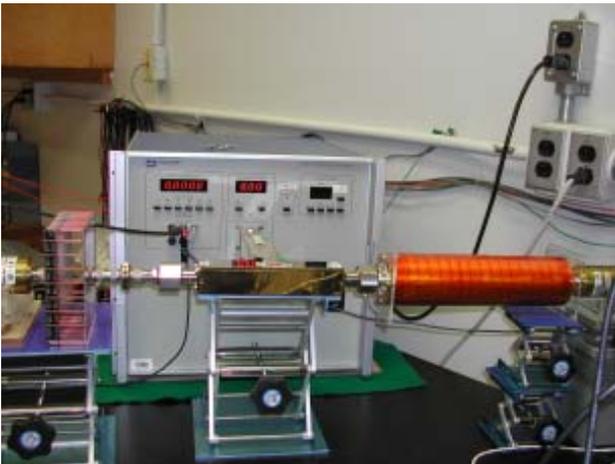


Fig. 5 Comparison of an NRC 10-A coaxial shunt (left) and a 20-A BEV-design shunt (right) using high current BEV Tee.

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