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Publisher's version / Version de l'éditeur:

VIII Semtro (8th International Seminar on Electrical Metrology), 2009-06-30

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APPLICATION OF A CALORIMETRIC THERMAL CONVERTER AS A STANDARD OF AC-DC VOLTAGE AND CURRENT TRANSFER DIFFERENCE

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Abstract: At the National Research Council of Canada (NRC) the primary standard of AC-DC transfer difference at frequencies from 10 kHz to 100 MHz is a Calorimetric Thermal Voltage Converter (CTVC). Because of a simple design, not unlike a coaxial calorimeter for RF power measurements, its frequency characteristic can be estimated theoretically from a number of mechanical and electrical parameters. An internal Tee, integrated into the CTVC, improves calibration accuracy of working standards.

Over the years several of these converters have been manufactured for different operating voltages and with different frequency characteristics, leading to an optimized design with a frequency characteristic practically flat over eight decades of frequency.

The paper describes details of construction of the CTVC. Results of RF-DC voltage transfer difference measurements, AC-DC current transfer difference and uncertainty evaluation of the converter are discussed.

Keywords: AC-DC transfer standard, thermal converter, calorimetric converter, transmission line.

1. INTRODUCTION

AC-DC transfer difference of the highest accuracy primary standards, multijunction thermal voltage converters (MJTC), can be determined theoretically with an uncertainty of a few parts in 10^7 , but only in a limited frequency band. Above approximately 5 kHz to 10 kHz, the calculable, frequency independent, thermoelectric components of the AC-DC transfer difference are dominated by the frequency dependent components. The latter ones, originating in the skin effects and stray reactances in the MJTC physical structure, are difficult to calculate accurately. For this reason, in a higher frequency range, up to 100 MHz and above, less accurate at low frequencies but simpler to evaluate at RF, UHF-type, single junction Thermal Voltage Converters (TVCs) and calculable coaxial resistors, are used as standards by most National Metrology Institutes, [1], [2]. A planar MJTC on a quartz crystal chip is also considered as a possible RF standard, [3].

At NRC, a reference standard of the RF-DC transfer difference in the frequency band above the MJTC range is a Calorimetric Thermal Voltage Converter (CTVC), [4], [5]. The mechanical and electrical design of the CTVC is straightforward, permitting for theoretical calculations of its

frequency characteristic. It is based on a design of a microwave calorimeter. Its AC-DC voltage transfer difference is low, usually below $3 \mu\text{V}/\text{V}$, but not negligible. However, the CTVC AC-DC transfer characteristic is flat in the eight decades of frequency, from 1 Hz to 100 MHz; its typical input voltage range is from 1 V to 2 V.

2. DESCRIPTION OF DESIGN

During an AC-DC transfer voltage calibration of a thermal converter, the tested and reference converters are connected in parallel, attached to two arms of a coaxial “tee” adapter. The calibration voltage reference plane is in the middle of the tee. The length of the coaxial arm of the tee (as well as the matching connector) becomes an integral part of each converter. Thus the design of a reference converter with a calculable frequency characteristic has to take into account parameters of a tee used to transfer reference values to the tested converter. This would require an additional characterization of the tee used at a given calibration. To avoid this extra step, we have therefore decided to increase accuracy of the calculable reference converter by incorporating the tee in its design.

A schematic of the calorimetric thermal voltage converter with a built-in tee is shown in Fig. 1. Fig. 2 shows a photograph of the converter during and after the final assembly.

The input test voltage is applied to the measurement reference plane, the center of the tee, via the side arm type SMA connector. A test converter is connected to the type-N female connector of the test arm of the Tee. The electrical length of this arm was designed to be equal to the electrical length of the arm of a regular type-N Tee, (model UG-107B/U.) The AC-DC difference of the test converter is compared to a calculable AC-DC difference of a reference converter, fabricated at the second, reference, arm of the Tee. The reference arm consists of a short coaxial line, terminated by a miniature microwave rod resistor heater. A thin copper disk electrically completes the heater circuit. The coaxial line thermally insulates the heater resistor from the body of the converter and the input connectors. It is built from two thin-wall stainless steel tubes; the outer surface of the inner tube conductor is copper plated.

The energy dissipated in the heater resistor raises its temperature above the temperature of the solid copper body of the enclosure. This incremental temperature change is

measured by a thermopile, which consists of approximately 100 junctions, manufactured by partially copper plating a spiral of a constantan wire. The thermopile, wound on a square plexiglas rod, is placed between two electrically insulating thermally conductive beryllium oxide washers. The hot junctions washer is heated by the heater resistor, the cold junctions washer is at the temperature of the copper mass of the enclosure.

The AC-DC transfer difference of the reference arm of the CTVC at a frequency f Hz is calculated from

$$\delta_{CTVC}(f) = \frac{V_{tee}(f)}{V_{tee}(1)} - 1 \quad (1)$$

where $V_{tee}(f)$ and $V_{tee}(1)$ are the AC voltages at the measurement reference plane, that is at the middle of the tee, at the frequencies f and 1 Hz. It is assumed in (1) that the energy dissipated in the heater resistor, as well as the voltage V_l at the resistor end of the coaxial line of the length l , is the same for all frequencies, and that the AC-AC transfer difference, referenced to 1 Hz, is equal to the AC-DC transfer difference.

The relation between the AC voltage V_l applied to the heater resistor terminating the coaxial line, and the voltage V_{tee} at the reference plane of the tee, i.e. the input of the line, can be expressed by the transmission line equation

$$V_{tee} = V_l \left(\cosh \gamma l + \frac{Z_c}{Z_l} \sinh \gamma l \right) \quad (2)$$

where γ is the propagation constant, Z_c is the characteristic impedance of the lossy coaxial line, and Z_l is the impedance of the heater. Details of the calculations of the propagation constant and the characteristic impedance of the CTVC are given in references [4] and [5]. Here it should be noted that the miniature heater is modeled as a non-reactive resistor and that in calculating the coaxial line parameters the skin effect is taken into account.

We have measured the skin effect surface resistance of

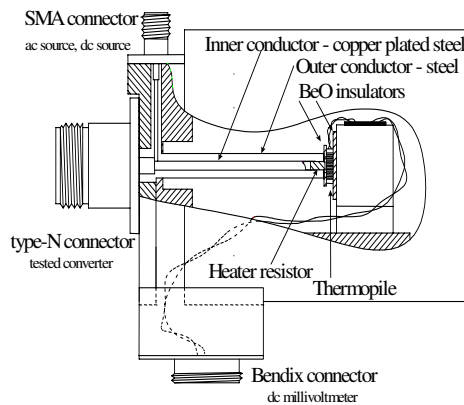


Fig. 2. Simplified diagram of the calorimetric thermal voltage converter.

the stainless tubing experimentally on open circuited resonant coaxial lines, made of long lengths of the inner and outer conductors used in the construction of the CTVC.

The temperature rise of the heater is due not only to the energy dissipated directly in the heater but also to the energy dissipated in the lossy coaxial line, connected to the heater. This effect was taken into consideration by introducing a thermal correction, [4].

The CTVC is mechanically and electrically stable and not easily damaged by overloading. However, it is relatively more difficult to measure than a regular TVC due to its small output voltage, 4.5 mV at 1 V; long time constant, 15 s; and a close coupling of the cold junctions of the thermopile to the enclosure, which increases its sensitivity to the changes of the ambient temperature. The experience of this comparison has shown that it usually requires modifications in the ac-dc automatic comparator software and close attention to a good thermal insulation from the ambient to obtain satisfactory results on the CTVC. Consequently, the standard deviations of typical tests were in the range of a few $\mu\text{V}/\text{V}$, much higher than in tests of a vacuum-junction thermal converter.

The uncertainty budget of the frequency characteristic of the CTVC includes uncertainty of the determination of the mechanical dimensions (coaxial line length and inner and outer diameters), uncertainty of the electrical parameters, radiation losses, uncertainty of the thermal correction, uncertainty associated with the design variations and mechanical assembly. Components of the uncertainty originating in the uncertainty of the mechanical dimensions, were evaluated by recalculating the theoretical frequency characteristic while individually varying the investigated parameter. A change in the characteristic with the change of the parameter was then used to estimate the standard uncertainty of this error source. Other components of the uncertainty were estimated experimentally. The design variation uncertainty was estimated by comparing experimental disagreements between different realizations. Mechanical assembly uncertainty was evaluated by comparing characteristic of a converter before and after reassembly.

Uncertainty of the mechanical position of the reference plane was evaluated by building a two-port test fixture,

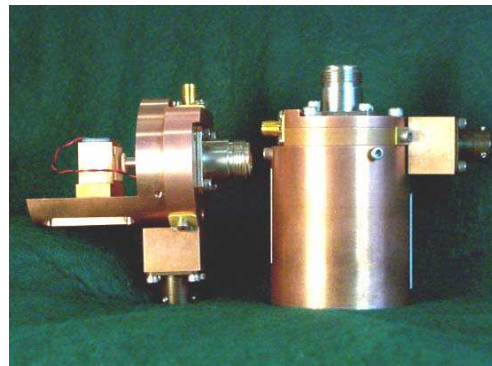


Fig. 3. Calorimetric thermal voltage converter during and after the final assembly.

identical to the CTVC on the type-N connector side but with a SMA-type connector terminating the coaxial line. The electrical length of the N-type side arm was then compared on a Vector Network Analyzer to the electrical length of one arm of a type-N Tee, [6].

The CTVC is not a calculable standard of AC-DC transfer difference. The theoretical determination of the CTVC characteristic takes into account only frequency dependent parameters. Thermoelectric effects are not considered. The frequency independent low frequency AC-DC transfer difference of a CTVC, $\delta_{CTVC}(0)$, has to be determined experimentally, by comparison to a MJTC, an AC-DC transfer standard calculable at low frequency, The AC-DC transfer difference of the CTVC was then obtained as the sum of two parts:

$$\delta_{CTVC} = \delta_{CTVC}(0) + \delta_{CTVC}(f) \quad (3)$$

Starting from this standard, with the AC-DC transfer difference determined at 2 V and frequencies up to 100 MHz, the NRC AC-DC voltage transfer capabilities are extended to higher and lower voltages by following build-up and step-down procedures, using auxiliary standards and the RF-DC Transfer Comparator.

NRC has participated in the CCEM-K6.c Key Comparison of RF-DC Transfer Standards. Results of this comparison have fully confirmed validity of the evaluation of CTVC frequency characteristic and its uncertainty budget, [7].

The CTVC can be also used in the current mode, for the current AC-DC Difference frequency range extension. We used a MJTC as well as a Fast-Reversed-DC Source to characterize the CTVC in the current mode at low frequency. On the basis of these measurements, we have assigned the value of $(0.0 \pm 0.8) \mu\text{A/A}$ to the AC-DC current transfer difference of a CTVC, in the frequency range of 10 Hz - 100 kHz, [8]. Starting from the CTVC used as a standard of a current AC-DC transfer difference, and following a build-up procedure, we were able to extend NRC AC-DC capabilities to currents as high as 100 A at 100 kHz.

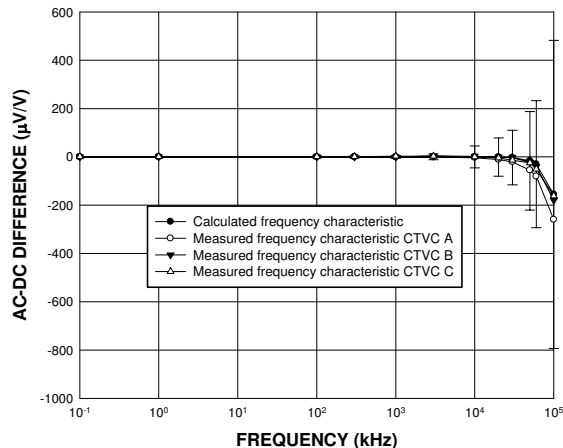


Fig. 3 Calculated and measured frequency characteristic for three different realizations of a CTVC. Error bars show estimated expanded uncertainty ($k=2$).

The CTVC is small, easily transportable and mechanically stable. We have used it as a traveling standard in international comparisons with the National Metrology Institutes of USA, the Netherlands, Germany, [9], and Mexico and Japan.

3. CONCLUSION

The Calorimetric Thermal Converter developed at the National Research Council Canada is a unique, versatile, wide-bandwidth converter that can be used in a voltage and a current mode. At NRC all AC-DC transfer frequency range extensions above 5 kHz are based on the characteristic of this converter. NRC has participated in CCEM-K6c Key Comparison of RF-DC Transfer Standards, as well as in a CCEM-K12 Key Comparison of AC-DC Current Transfer Standards. Results of these comparisons, conducted internationally at the highest levels of uncertainty, fully validate the NRC CTVC design and calculations.

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