Low-Frequency Errors of Thermal Voltage Converters: A Progress Report*

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Abstract

Characteristics of thermal voltage converters (TVC's) and thermal current converters (TCC's) at low frequencies (below 100 Hz) are discussed. This frequency range is the region where the TVC's cease the thermal averaging of the ac input signal. The variation in ac-dc difference as the frequency of the input signal decreases is examined using various devices having differing thermal time constants. The data gathered experimentally using these devices are compared to predictions made using theoretical models of the TVC's at low frequencies and these results discussed. It is expected that this research will lead to improved accuracies for the NIST ac voltage and current calibration service at low frequencies.

Introduction

Ac current and voltage are most accurately measured by comparing an unknown ac signal to a known, stable dc reference using TCC's consisting of either a simple thermoelement (TE) or a TE in parallel with a precision shunt, or TVC's consisting of a TE in series with a range resistor. The thermoelements are composed of one or more thermocouples arrayed along a heater structure. The thermocouples sense the temperature rise along the heater structure, and the user then monitors the thermocouple output while applying ac and both polarities of dc current or voltage in some regular sequence. By comparing the output of the TE with ac applied to the heater to the output of the TE with dc applied, the user may compare the unknown ac signal to the known dc reference.

Since the heater structure has a definite thermal mass, the stability of the output emf from the TE depends on the frequency of the ac applied to the thermal converter. If the frequency of the ac signal is high enough so that the heater structure does not cool significantly between successive peaks, the output of the TE is generally quite stable. If, on the other hand, the frequency is sufficiently low that the heater structure cools appreciably between successive peaks, the output of the TE begins to track the input waveform and may become difficult to measure accurately. In general, the smaller the thermal mass of the heater structure, the shorter the thermal time constant of the device, and the higher the frequency where tracking of the input waveform begins. We will define this point as the critical frequency Γ_c.

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Traditional vacuum-bulb single-junction thermal converters (SJTC's) have time constants of a few seconds and corresponding Γ_c on the order of 20-30 Hz. Recent developments in thermal sensing technology, however[1,2], have produced devices with time constants on the order of a few milliseconds, with a corresponding increase in Γ_c. Using these devices at frequencies below Γ_c requires monitoring the output emf from the TE for a time period long enough to average out the resultant sinusoidal signal[3].

Theoretical models of SJTC's indicate that their ac-dc differences as voltage converters in the frequency range where thermal averaging fails should be inversely proportional to the square of the applied frequency, and should increase with decreasing frequency[4] Their ac-dc differences as current converters, however, should decrease with a much smaller slope. This study was undertaken in order to assess the validity of the theoretical models and to provide a firmer basis for the NIST ac-dc calibration service at frequencies at and below Γ_c.

Devices

A number of TVC's, of different design and fabrication, were tested as voltage and current converters to determine their ac-dc difference characteristics at frequencies below 100 Hz. These devices included:

Single-junction thermal converters

Several SJTC's, designated F_71, T2.5, and FB, were tested at ten-hertz intervals from 10 Hz to 100 Hz, and at 400 Hz and 1 kHz. These devices are representative of SJTC's and have critical frequencies of about 20-30 Hz.

Multiple SJTC's

The NIST working standard for low-frequency ac-dc difference measurements, designated Fe, consists of four 5-mA TEs with the heaters and thermocouple outputs wired in series in a single enclosure. Nominally a two-volt device, Fe is generally operated at one-half rated voltage, so that the temperature rise along the heater is smaller, yielding a much flatter frequency response at low frequencies. A second such device, designated Ru, was constructed for this exercise. Ru consists of six 10-mA TEs connected in series, and is normally operated at about one-twelfth of its rated heater voltage. Since the output emf of Ru at rated voltage is some 60 mV, this TVC is very useful for determining the variation of ac-dc difference with voltage level at low frequencies, and for tests of the TVC's as current converters.

Film multijunction thermal converters (FMJTC's)

Several FMJTC's, fabricated at NIST [5], were measured against Fe and Ru, to determine their low-frequency characteristics. Due to their small dimensions, these devices have extremely short time constants and exhibit "tracking" of the input ac waveform at relatively high frequencies.

Results

The devices indicated above were tested in various combinations to determine their ac-dc differences as both voltage and current converters, and the results compared against the theoretical models. The results of measurements of one of the SJTC's (F_71) taken against multiple SJTC's are presented in figure 1. To check the thoretical models, least-squares fits to the data using both an exponential relationship of the form $\delta = A + Be^{-(C+D/\nu)}$ and the predicted $1/\nu^2$ relationship were performed, and these fitted curves are also shown in figure 1. As can be seen, the exponential fit is generally better than the $1/\nu^2$ fit, although the difference is only a few ppm. Figure 2 presents the voltage converter measurements made using an FMJTC. The short time constant of this device forces the ac-dc difference as a voltage converter to swing sharply positive with decreasing frequency. Again, the exponential fit is better than the $1/\nu^2$ fit. In figure 1, a polynomial of the form δ=A+Bν+Cν^2 is fit to the current converter data.

Work in Progress

Continuing work in this area includes a more mathematically rigorous treatment of the characteristics of TVC's at frequencies below Γ_c. In addition, the frequency response of these devices for input voltages less than the rated input will be studied, as well as new designs for low-frequency thermal converters. It is anticipated that this work will lead to a reduction in the NIST uncertainties for TVC's and TCC's at frequencies below 20 Hz, in addition to a new generation of low-frequency thermal sensors.

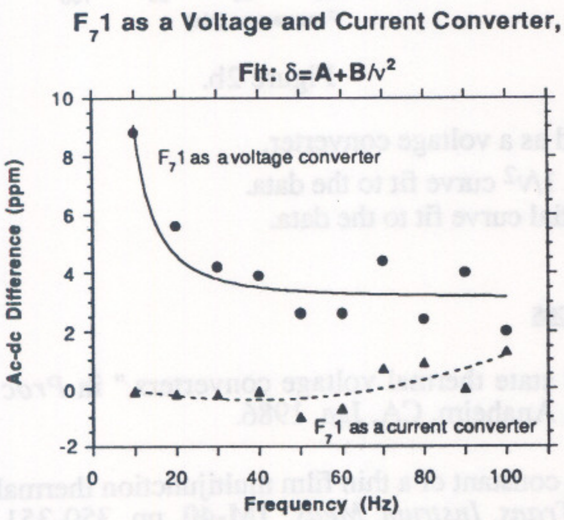

Figure 1a.

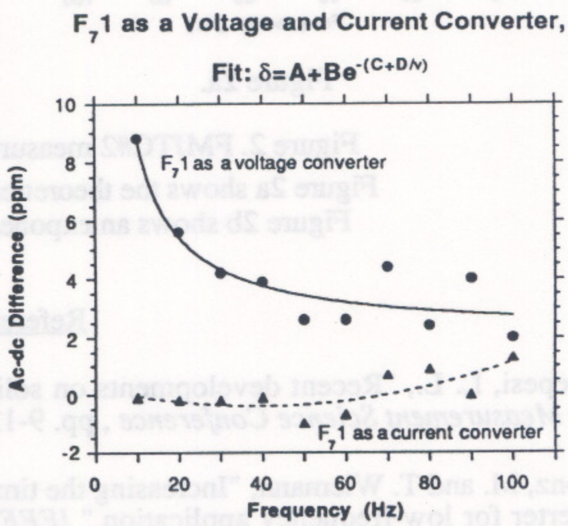

Figure 1b.

Figure 1. $F_7$1 measured as a voltage and current converter.
Figure 1a shows the theoretical $1/\nu^2$ curve fit to the voltage converter data.
Figure 1b shows an exponential curve fit to the voltage converter data.
In both figures a polynomial of the form δ=A+Bν+Cν^2 is fit to the current converter data.

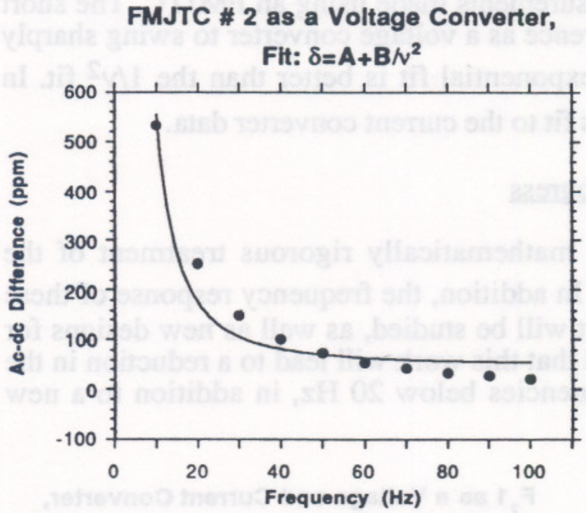

Figure 2a.

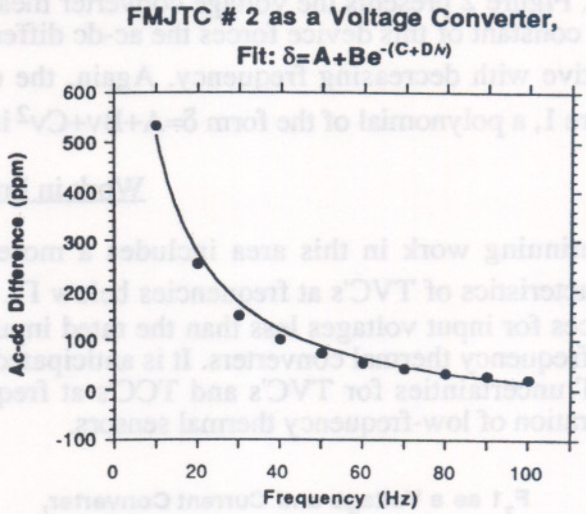

Figure 2b.

Figure 2. FMJTC#2 measured as a voltage converter.
Figure 2a shows the theoretical $1/v^2$ curve fit to the data.
Figure 2b shows an exponential curve fit to the data.

References

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