Performance of the Single Junction Thermal Voltage Converter at 1 MHz via Equivalent Circuit Simulation

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The physical structure of the single junction thermal voltage converter (SJTVC) can be represented in simulation using an equivalent RLC circuit to investigate the performance and estimate the error sources. This paper describes instruments and techniques that apply 0.6 V thermal converters to achieve this aim. The technique was performed in the department of electrical metrology, National Institute for Standard (NIS), Egypt, to investigate the frequency-dependence of the SJTVC at high frequency. The LTspice/SwCAD III simulator was used to analyze the effect of the physical structure of an SJTVC in an effort to better understand the origin of errors at 100 kHz and 1 MHz. The practical results were first measured at the National Institute for Standard and Technology (NIST), U.S. to validate the simulation model at 100 kHz. The model was then used to estimate the AC-DC transfer error of the SJTVC at 1 MHz. Some of the main error sources such as the changes of the real part of the heater impedance, the effect of thermocouple grounding and the power consumed in the internal resistance of the thermocouple are estimated at 100 kHz and 1 MHz. The expanded uncertainty assigned to the AC-DC automated calibration system of NIS is also described.

1. Introduction

The SI electrical units for current and voltage are defined and realized as DC quantities. Since there is no AC counterpart to the standard cell, the measurement of AC electric quantities presents a special difficulty in that they cannot be determined directly in terms of the derived DC SI units. As a result, measurements of alternating current, voltage, and power are achieved relative to the same DC standards. This process is known as AC-DC transfer [1-3]. The basic standards of AC-DC transfer have a flat and known frequency response and hence may be calibrated on direct current and then used for alternating current measurements precisely. They provide an accurate transfer from direct voltage and current standards to alternating signals measurements [2].

In the last century, technical advances necessitated the introduction of accurate frequency (10 Hz–1 MHz) AC-DC transfer instruments for low-level AC voltage measurements. It was confirmed that high accuracy, low voltage AC-DC transfer calibrations, in the frequency range up to 1 MHz, could be provided by the use of a thermoelement [3]. The essence of electrothermal devices is the use of a resistive element to convert electrical energy into heat and sense the resulting rise in temperature. The root-mean-square (rms) voltage, Vrms, of the AC signal has the same power content as the DC voltage, V_{dc}, when $V_{rms} = V_{dc}$.

These converters are usually called thermal voltage converters, thermal current converters, and thermal millivolt standards–micropotentiometer (μpots) to distinguish them from other types of transfer instruments [2]. They are also used widely by the advanced calibration laboratories to establish the traceability of AC measurements [3]. To assure the traceability for these transfers, they are usually calibrated at the national laboratories or a well-equipped primary laboratory traceable to the national laboratory. In order to achieve the best accuracies, it is necessary to investigate all possible error sources when deducing their AC-DC differences. The difficulties to avoid when performing the measurements, such as the ground impedance, skin effect of the heater, and transmission line effect of the output connector [4], should also be determined.

A method to investigate the error sources of the SJTVC by the means of electrical simulation at 100 kHz and 1 MHz is presented. The method includes a representation of the equivalent circuit in RLC form, summarization of the error sources of the AC-DC transfer, validation of the simulation model at 100 kHz and estimation of the error sources of the SJTVC at 1 MHz. The validation of the model at 100 kHz was achieved using the measured AC-DC transfer errors of this converter that already done in NIST with expanded uncertainty = 8 ppm (k=2) at 100 kHz.

2. Physical Structure of the SJTVC

The use of a single junction thermal voltage converter (SJTVC) for radio frequency (RF) measurements dates back to the early 1940s [3]. Although they are now being replaced by solid-state sensor-based transfer standards,

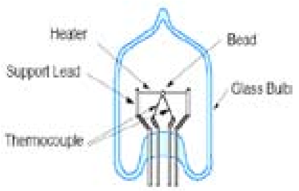

Figure 1. Physical structure of a single junction thermal voltage converter.

thousands of these devices are still deployed in the advanced laboratories around the world. The simplest form of the SJTVC consists of a resistive heater element and a thermocouple attached to its midpoint as shown in Figure 1 [2]. The junction is attached by means of a small insulating glass bead. The thermocouple/resistor assembly is supported on the four lead-in wires (two wires from the resistive heater and two wires from the thermocouple). Thermoelements for currents from 1 mA to 1 A are available with evacuated glass-bulb enclosures to minimize the heat loss and to maximize the sensitivity [2].

The heater of this thermoelement is short and straight, thus having minimal reactance, and the insulation of the thermoelement prevents any significant interaction between the AC current and the read-out instrument [2]. The thermoelement is therefore well suited to measurements at audio and higher frequencies. They are also used with series resistors in multirange thermal voltage converters up to 100 kHz on most ranges of voltages and to 1 or 2 MHz at low voltages. The single-range units with carbon or metal film resistors coaxially mounted in tubular forming can also used up to 100 MHz [2].

The output emf of the thermocouple is relatively low (7 to 12 mV); however, heater current differences and differences between AC and DC currents as small as one part-per-million (ppm) can be detected if change in the output are monitored with a sensitive galvanometer or high sensitive microvoltmeter. For operation at higher voltages, resistive networks are used in conjunction with the thermocouple.

The value of the resistor network is usually calculated by the maximum current that the thermoelement can handle, the resistance of the resistive heater (typically 90 Ω) and the magnitude of the applied voltage. The resistive heater of the thermoelement and the resistive network form a voltage divider, which scales the input voltage for a maximum voltage across the thermoelement, in this device 0.6 V.

In the frequency range from 10 Hz to 1 MHz, the AC-DC differences can be reproduced with a best uncertainty of 1 ppm or less. However, due to the different error sources which are estimated and summarized in this work, the values of these differences could become in the level of tens of ppm. The majority of these sources were investigated previously in some details using theoretical and practical means [5].

3. Principle of AC-DC Transfer

In practice, the response of practical thermocouples is not ideal due to the presence of thermoelectric effects and frequency-dependent circuit effects, as well as the equality of outputs on AC and DC, which does not indicate equality of input quantities. This deviation in TCs from the same response for AC and DC signals is specified in metrology terms of an *AC-DC difference*, δ or an *AC-DC transfer error* [2]. Furthermore, TCs respond differently to positive and negative DC voltages. This behavior causes what is known as DC reversal error [1]. Reversal error is eliminated during the measurement by taking the average of the positive and negative supply voltage.

The AC-DC difference, δ, is usually given on the test report of the transfer standard in one of two forms: parts per million (ppm) or (μV/V) and is defined as:

$$\delta = \frac{V_{AC} - V_{DC}}{V_{DC}} \tag{1}$$

where:

δ = AC-DC difference for TC.

V_{AC} = rms value of AC voltage

V_{DC} = average of the absolute values of DC voltage applied in positive and negative direction across the transfer standard.

The relation between the input current of the AC voltage source and its output emf is given by:

$$E = K V^{n} \tag{2}$$

where, E is the output emf of the TE, V is the applied voltage on the heater, K varies somewhat with large changes in heater current but it is constant over a narrow range where nearly equal AC & DC currents are compared and n is usually 1.6 to 1.9 at the rated heater current [6]. The relationship between a small change in TE heater voltage (ΔV) and the corresponding change in output (ΔE) is expressed as:

$$\frac{\Delta V}{V} = \frac{\Delta E}{n.E} \tag{3}$$

From (1), (2) and (3), the AC-DC difference can be defined as:

$$\delta = \frac{E_{ac} - E_{dc}}{n.E_{dc}} \tag{4}$$

where E_{ac} is the mean value of the two outputs of the thermoelement due to the AC voltage and E_{dc} is the average of the two outputs of the thermoelement due to the forward and the reverse DC voltage.

In practice, the standard national laboratory and the traceable test reports state the AC-DC differences at various voltages and frequencies. Then, the converted value of AC-DC difference, δ, is applied to AC-DC transfer as a correction factor in such a way that:

$$V_{AC} = V_{DC}(1 + \delta) \tag{5}$$

4. Error Sources Summarization

AC-DC transfer errors of the SJTVC are caused by various effects that lead to different responses for applying DC and AC signals on the physical structure of the SJTVC including the housing. As discussed in [5], the following are common sources in this type of thermal converters:

1. Error due to series inductance in the leads, support wires and transmission lines. It was found that the effect of these inductances may be up to ≤ 1ppm.
2. Error due to the shunting admittance containing the parasitic capacitances between the live input line and the grounded housing. The typical values for these capacitances were found to be in the level of pF and independent of frequency. Conductance is also assessable, but highly frequency dependant. In general, shunting admittance may offer a few ppm at 1 MHz.
3. Error due to the total skin effect of the present resistances in the structure (heater, tee-connector, housing, leads, etc). It produces a noticeable change in the value of the resistances, hence added dependent-frequency error may reach few tens of ppm at 1 MHz.
4. Error due to stray capacitances across the padding heater resistor. In some cases, this value of capacitance is very small hence gives negligible contribution.
5. Error due to the bead admittance. The admittance was measured at frequencies up to 1 MHz as discussed in [5] and gave capacitance in the levels of pF or nF based on the type of thermal converter and resistance larger than 100 MΩ (≅ 0.5 GΩ). This, in fact, leads to insignificant contribution.
6. Error due to frequency mainly caused by the thermoelectric effects (Thompson, Peltier, etc). These effects were investigated clearly using the fast reversal DC (FRDC) technique as in [7].

Other significant error sources and effects are estimated using the equivalent circuit simulation of the SJTVC at 100 kHz and 1 MHz in this paper as in the following section.

5. Simulation Model and Validation

A simple lumped-parameter model for the physical structure of the SJTVC, shown in Figure 2, was prepared to help understand and analyze both the physical structure and electrical characteristics of the measured device in an effort to better understand the origin of errors in these devices.

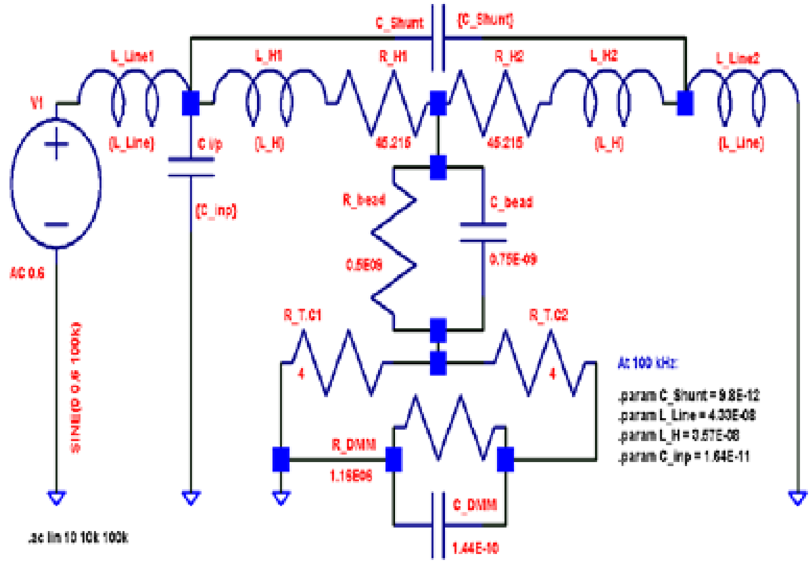

Figure 2. Lumped-parameter model of SJTVC.

In this lumped-parameter, L_input and L_output represent inductances of input and output leads of the tested SJTVC respectively. C_input is the parasitic capacitances across the input terminals of the TE, L_H1 and L_H2 represent the inductances of the two typical parts of the heater. R_H1 and R_H2 represent the resistances of the same two parts of the heater. C_Shunt is the stray capacitance across the voltage drop of the TE heater. C_Bead is the parasitic capacitance across the insulator bead while R_Bead is the high resistance of the insulator bead. R_DMM and C_DMM are the admittance values of the high sensitivity nanovoltmeter attached with the output thermocouple for measuring the output emf. V1 represents the applied rated voltage (AC & DC) of the device, 0.6 V. The values of these parameters were measured at the frequencies of 100 kHz and 1 MHz using a commercial high sensitivity RLC meter. For instance, the typical results of these parameters at 100 kHz are given in Table 1.

The model of the SJTVC was first simulated at 100 kHz by using an "LTspice/SwCAD III" simulator. The LTspice is a high performance Spice III simulator, schematic capture and waveform viewer with enhancements and models for easing the simulation of switching regulators. It allows the user to view waveforms for all components of the schematic in just a few fractions of a second [8].

The estimated value of AC-DC differences (δ_{Sim}) was given by:

$$\delta_{Sim} = \frac{P_{H,ac} - P_{H,dc}}{nP_{H,dc}} \qquad (6)$$

where,

δ_{Sim} is the simulated AC-DC differance

Symbol	Values
L_input and L_output	43.3 nH for each
C_input	16.4 pF
L_H1 and L_H2	35.7 nH for each
R_H1 and R_H2	45.215 Ω for each
C_Shunt	9.8 pF
C_Bead	0.75 nF
R_Bead	0.5 GΩ
R_DMM	1.16 MΩ
C_DMM	144 pF

Table 1. Parameters of the SJTVC at 100 kHz.

$P_{H,ac}$ is the power dissipated along the heater due to applied AC voltage

$P_{H,dc}$ is the power dissipated along the heater due to applied DC voltage

n is the exponential factor ≅ 1.8

At 100 kHz, the estimated value of the AC-DC transfer error was 79.6 μV/V. The practical value at the same frequency was measured at NIST, U.S. as part of a scientific cooperation between NIST and NIS in 2007. A complete set of these results in frequencies between 10 Hz and 100 kHz are tabulated and plotted in Table 2 and Figure 3 respectively.

Referring to the results in Table 2, the AC-DC difference of that device is 86 μV/V with expanded uncertainty = ± 8 μV/V (k=2) at 100 kHz. The agreement between the estimated and the measured value is only about 6 ppm and the estimated value is located in-between the span of the measured value. This validates the simulation model at 100 kHz. This validation, of course, offers an excellent opportunity to investigate the sources' contributions at 100 kHz and 1 MHz. The model shown in Figure 2 includes the contribution of AC-DC differences arising from:

1. The change of the real part of the heater impedance, Z, with frequency.
2. The effect of heat due to the power loss through the internal resistance of the thermocouple. As a result of the thermocouple and the heater being attached to each other on one side only, 50 % of this power was added.
3. The effect of the additional heat due to the isolated bead on the midpoint of the heater.
4. The effect of the thermocouple grounding.

These contributions to the AC-DC transfer difference were analyzed and their values estimated at 100 kHz as tabulated in Table 3. These tabulated results can be summarized as:

- The grounding of the thermocouple changes the value of AC-DC difference at 1 MHz significantly.

Freq. (kHz)	AC-DC Diff. (μV/V)	Expanded U (μV/V)
0.01	+ 5	13
0.04	- 4	9
0.055	- 4	5
0.1	- 5	5
0.4	- 6	5
1	- 6	5
10	- 5	5
20	- 1	5
50	+ 27	6
100	+ 86	8

Table 2. Measured results of δ.

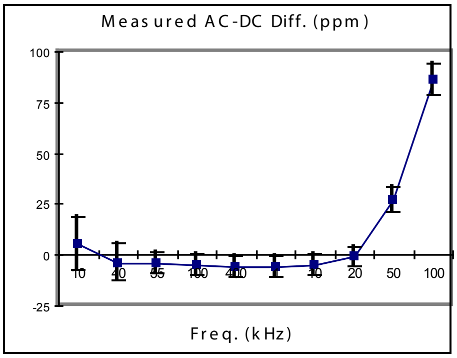

Figure 3. Measured AC-DC difference up to 100 kHz.

- The heater contribution in the transfer error is still dominant (93%).
- With 50 % of the power consumed in the thermocouple, the effect exists (7 %).
- The heat effect of the bead, in all cases, gives negligible contribution in the transfer error.
- The AC-DC transfer error in the case of the ungrounded thermocouple only occurs in the heater.

In the same manner, this model with different parameter values was used to analyze the AC-DC transfer difference of the SJTVC at 1 MHz. It is important to understand and predict the device performance at I MHz due to the lack of practical results at this frequency. A value of 175 ppm was estimated as AC-DC difference at 1 MHz. But as in [9], the practical measured value of the AC-DC difference for this type of thermal converter at 1 MHz is about 110 ppm. A correction factor of (110/175) or 0.63 was used to correct and validate the estimated results of the model at 1 MHz. Table 4 lists these values.

Although similar behavior of this model at 1 MHz was noticed, some additional notes can be remarked as:

- The change in the AC-DC difference due to an ungrounded TC was maximized to about 20 times, hence the importance of making grounding in this type of measurements.

Parameter	δ_{sim}(ppm)
Due to: heater + Bead + TC	79.6 ppm
Due to: heater + Bead	74.1 ppm
Due to: heater+ TC	79.5 ppm
Circuit Impedance Z	90.40 Ω
Heater Contr.	93 %
T.C Contr.	7 %
Bead Contr.	0.03 %

Table 3. Estimated Results of AC-DC difference contributions of grounded SJTVC at 100 kHz.

Parameter	With Grounded T.C	Without Grounded T.C
	δ_{sim}(ppm)	δ_{sim}(ppm)
Due to: heater + Bead + T.C	110 ppm	2200 ppm
Due to: heater +Bead	77 ppm	2200 ppm
Due to: heater + T.C	110 ppm	2200 ppm
Circuit Impedance Z	90.13 Ω	91 Ω
Heater Contr.	70 %	100 %
T.C Contr.	30 %	0 %
Bead Contr.	0.025 %	0 %

Table 4. Estimated Results of AC-DC Difference Contributions at 1 MHz

- For the heater resistance of 90 Ω, the exhibited results in Tables 3 and 4 show the frequency-dependent variation of the impedance, Z of the lumped-parameter model presented in Figure 2.
- The model exhibits inductive behavior. This yields a positive AC-DC transfer difference which increases with frequency.

6. Automated System Description

At NIS, the AC-DC difference calibration services have been recently determined using a circuit similar to that shown in Figure 4 and as described in [10]. The system has been improved to meet the extended capabilities of the electrical metrology of the electrical department at NIS [11]. Certain precautions are necessary in order to attain the optimum performance of the measuring circuit [12]. For instance, in order to remove effects due to drift in the voltages, a sequence such as "AC, DC+, AC, DC-, AC" is applied.

Technical considerations were also given to fulfill correct grounding connection in this type of measurement [1]. Two devices are usually connected in parallel in this system; the standard one (traceable to NIST) and the thermal converter being measured. As the AC-DC transfer difference of the standard is known, the transfer difference of the other device can be calculated as described in [12].

The system consists of a programmable source, multifunction calibration system Wavetek 9100, for both alternating and direct volts; two thermal voltage converters (TVC); two similar high sensitive digital multimeters (DMM), HP 3458A, connected to the output of each TVC for reading the output emfs; a PC as a GP-IB controller and a printer for printing the resulted sheets. The controller drives the system and records the readings on DMMs via IEEE-488 bus cables.

The flexibility of the system is related to the test software, the software programs have been built in LabVIEW (Laboratory Virtual Instrument Engineering Workbench). The range selection and the frequency for each range are software-controlled.

7. Uncertainty Statement

The expanded uncertainty of this type of measurements was reduced by a ratio of about 1:3 after using the improved automated calibration system [11]. In addition to the calibration of the standard unit, common sources of error in this type of measurements are: the stability of calibrators and multimeters, self-heating, ambient temperature effects, T-connector and drift effects [14, 15, 16]. The contribution of noise to system uncertainty can be reduced by proper grounding and shielding of the system. The uncertainties values of the practical work are calculated in accordance with National Institute of Standards and Technology (NIST) requirements [17].

Obviously, the uncertainty assigned to the measurements is divided into Type A uncertainties (those evaluated by statistical means for 20 similar times) and Type B uncertainties (those evaluated by other means) and then these uncertainties are combined in a form of root-sum of squares (RSS). For AC-DC measurements, the Type B uncertainties generally dominate [14]. The reported values are usually the average of 20 determinations of the transfer standard's AC-DC difference. For instance, the expanded uncertainty of the SJTVC at 55 Hz (k = 2, for 95% confidence level) is given in Table 5.

Conclusion

A method to investigate the causes of the AC-DC transfer errors of a SJTVC has been achieved and evaluated at NIS. It has been demonstrated that it is possible to simulate the SJTVC via an equivalent circuit. This idealized equivalent circuit can offer approximate solutions to understand and estimate the contributions of the error sources on the value of AC-DC transfer errors of the SJTVC. It has been proved that the simulation of the performance of this device via an equivalent circuit is a good alternative to the lack of the

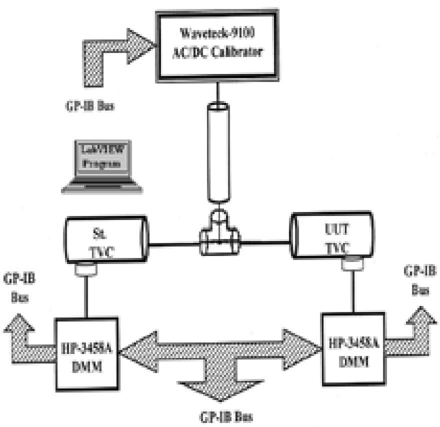

Figure 4. A simplified schematic of the automated measuring system at NIS

Source of Uncertainty	Probability Distribution	Uncertainty Values, ± ppm
Calibration Certificate	Normal (Type B)	2.5
Tee Connector	Rectangular (Type B)	1
Room Temperature Change	Rectangular (Type B)	1
Repeatability (for 20 times)	Normal (Type A)	1.5
Expanded Uncertainty	Normal (k = 2)	6.5

Table 5. Uncertainty Budget at 55Hz.

practical results. From the estimated calculations using the presented simulation model, grounding the thermocouple circuit is very important to providing a pragmatic value of the AC-DC transfer error of the SJTVC. It was found that the heat effect of ceramic bead of the SJTVC contributes negligible value of the transfer errors. In contrast, the thermocouple material may offer additional heat that affects the AC-DC transfer error significantly.

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