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Achievement of AC Voltage Traceability and Uncertainty of NIS, Egypt through Capabilities of NIST, USA

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Abstract

This paper describes the methodology used to achieve the AC voltage traceability and the associated uncertainty in National Institute for Standards (NIS), Egypt via the capabilities of National Institute for Standards and Technology (NIST), USA. The methodology includes the use of the thermal voltage converters (TVCs) and micropotentiometers (µPots) via a new automated calibration system for determination of the AC-DC Differences at different frequencies. To confirm the results of this process, a bilateral comparison with NIST was organized through a set of (TVCs) to cover the range from 1 V to 200 V at frequencies of 55 Hz, 1 kHz, 10 kHz and 200 kHz. The comparison results associated with the uncertainty analysis are also discussed in this paper. For low values of AC voltage, new three µPots were fabricated at NIST to establish the traceability from 50 mV to 200 mV at frequencies from 20 Hz to 1 MHz. The converters used in this work are also modeled then simulated using LT-spice/SwCAD III simulator.

Keywords: electrical measurements, thermal voltage converter, micropotentiometer, modelling and electrical simulation, uncertainty analysis, bilateral comparison.

1. Introduction

There is a need for the traceable measurement/sourcing of AC voltage for a variety of applications such as aerospace, automotive, civil engineering, seismology and other areas. The traditional methodology for obtaining AC voltage measurements traceability at a wide-band of different frequencies is using thermal voltage converters (TVCs) which are used to compare the effective heating value of an unknown AC voltage or current to a known DC value. For AC voltage sourcing at the low values, the traceability may be obtained using micropotentiometers (µPots) which are used to produce the traceable AC voltage signal in the range of millivolt with also a wide-band of different frequencies.

As a part of collaboration between NIS and NIST to strengthen scientific and technological capabilities between Egypt and the United States, a set of thermal voltage converters at ranges of 1, 3, 10, 100 and 200 V were compared at frequencies of 55 Hz, 1 kHz, 10 kHz and 20 kHz. Three new micropotentiometers (µpots) were also fabricated at NIST to cover the ranges between 50 mV to 200 mV at frequencies from 20 Hz to 1 MHz. The characteristics of their output voltage levels over these frequencies were also examined in this work. In addition, the equivalent circuit of the these devices is modelled then simulated by using LTspice/SwCAD III simulator to analyze and characterize the important behaviours of the TE such as the frequency dependence and the voltage dependence.

2. Thermal Voltage Converter

AC-DC transfer standards, based on thermal converters, provide the most accurate link between the unknown AC voltage and current and the equivalent DC quantities, which are known with very small uncertainty. So, the root mean square (rms) values of AC voltage are most accurately measured by comparing the heating effect of an unknown AC signal to that of a known, stable and traceable DC signal using thermal voltage converters (TVC's) consisting of one or more thermoelements (TEs), possibly in series with a range resistor [1]. The TE, as shown in Figure 1, is composed of one or more thermocouples arrayed along a heater structure. These thermocouples are used to detect the temperature along the heater structure while applying a timed sequence of an AC signal and both polarities of a DC signal. By comparing the output of the TE, using a high sensitive nanovoltmeter, with AC applied to the average output of the TE when both polarities of DC are applied, the unknown AC quantity may be determined in terms of the known DC quantity. This AC-DC difference is determined using:

$$\delta = \frac{V_a - V_d}{V_d} \tag{1}$$

where δ is the measured AC-DC difference, V_a and V_d are the magnitudes of the AC and DC quantities required to produce the same thermocouple output.

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

$$E = KV^n \tag{2}$$

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.

3. Micropotentiometers (μpots)

The μpot is a standard have been developed worldwide to scale down voltages from the thermal converter level of about 1 V to the mV-level. Figure 2 shows a schematic diagram of the μpot assembly: a type N male coaxial input connector, a UHF-type insulated thermoelement with nominal rated current of 5 mA, and a special low-value radial resistor, which is built into a type N female coaxial output connector. All components are housed in a rectangular aluminium box with a two-pin shielded connector for the output of the TE. The construction of the radial resistor is of prime importance. A special technique must be employed to make its value remain nearly constant throughout the measurement frequency range [3]. If an excitation current provided by an external AC source is maintained constant as indicated by the thermocouple readout, the voltage drop across the radial resistor can serve as a precise low-impedance source of AC voltage, within the specified frequency range. The output voltage is nominally the product of the heater current and the resistance of the disk resistor [4].

4. Thermoelement Characterization

A new automated calibration system of NIS was used to characterize the thermoelement at 5 mA rated value [5]. The response time of the TE is obtained by measuring the output response when a step of rated DC or AC signal is applied to the TE. The calculated response time, t, is the time taken for output emf to reach 1-(1/e) or about 63% of its final value [6]. The typical results for both AC and DC signals were 6 and 7 seconds respectively. The steady state time of the TE was measured by applying the full rated DC and AC (for example at 55 Hz) suddenly and monitoring the variation of the output electromagnetic force (emf) during about two minutes (the time required to perform one measuring point). It was found that the output emf of the TE, when DC and AC voltage is applied, requires about 32 s and 36 s respectively to reach its rated value and to stop the drift.

An electrical modelling by using LTspice/SwCAD III simulator was also achieved to analyze the physical structure and electrical characteristics of the TE in an effort to better understand the origin of errors in these devices. Based on the traditional using of the TE, the equivalent electrical circuit was imagined and considered as shown in Figure 3. The equivalent circuit parameters of the TE were measured accurately (for example at 55 Hz) by using a high sensitive digital LCR Meter [7].

The comparison results are listed in Table 1 and illustrated in Figure 4 at frequencies of 55 Hz, 1 kHz, 10 kHz and 20 kHz. It has been shown that the agreement between the results was good and reflects the reliability of the suggested modelling. To evaluate the efficiency of the characterization and to determine the simulation error at the different frequencies, a comparison between the theoretical and practical results of the TE AC-DC Difference was performed at the rated value (5 mA). The practical results were evaluated based on the Eq. no. (4). The simulation results were calculated based on the relative different between the heat power (I^2 R) on the TE heater due to the applied DC signal and the real part of the applied AC signal.

With the same manner, the equivalent circuit of the micropotentiometer has been modelled and characterized according to the electrical modelling as shown in Figure 5 [8]. The comparison results are tabulated, for example, at frequencies of 1 kHz, 10 kHz and 20 kHz as in Table 2.

5. Methodology

Because the main goal of this work is achieving the traceability of NIS, Egypt in the field of AC voltage, a bilateral comparison between NIS and NIST in the field of AC-DC transfer measurements and micropotentiometers was organized to confirm this task. This process is also aimed to enhance the capabilities of NIS in that important area. The following artifacts were distributed between the two institutes during this comparison:

- NIST Multijunction AC-DC Transfer standard for 1 V and 3 V.
- NIST-Ballantine TVC for 10 V.
- NIST- Fabricated TVC (F9) for 100 V and 200 V.
- NIST- Fabricated micropotentiometers at ranges of 50, 100 and 200 mV.

The comparison program was implemented using the automated calibration system of NIS [5] and the automated calibration system of NIST [9]. The TVC's were measured, as transfer devices, with under test and standard TVCs connected in parallel to AC and DC voltages in a timed sequence (AC, DC+, DC-, AC) through a tee structure with negligible AC-DC differences at the mentioned frequencies. Since the same voltage was applied to each TVC, the accuracy and the long-term stability of the sources were reduced in importance. The output electromotive forces (emfs) from the TE's, displayed using high-sensitive digital nanovoltmeters, were used to evaluate the AC-DC difference of the TVC under test by using Eq. no. (4).

On the other hand, Figure 5 shows a simplified schematic diagram of using the micropotentiometers. Certain precautions were necessary in order to attain the optimum performance of the circuit. The input resistance of the Digital Voltmeter (DVM) should be reasonably high to avoid loading the μpot. In addition, the DVM's input capacitance should to be very small, throughout the frequency range of interest, to minimize the transmission line effect. Consideration must be also given to fulfil correct grounding connection [10].

Naturally, the input AC source must be capable of accurately delivering the required current to the thermoelement heater, through the entire desired frequency band. Moreover, it must supply the current with the lowest possible distortion. As the TE is a root mean square (rms) responding device, it is essential that a pure sinusoidal signal be fed to the μpot. If the DVM is also an rms responding device, distortion in the supplied current will have negligible effect on the measurement accuracy [10]. Table 3 lists, for example, typical results of the 100 mV micropotentiometer.

6. Uncertainty Calculations

The uncertainties of this work were calculated in accordance with NIST requirements and related to the comparison protocol between NIST and NIS. This manner divides the uncertainty assigned to the measurements into Type A uncertainties (those evaluated by statistical means) and Type B uncertainties (those evaluated by other means) and then combine these uncertainties in a root-sum-of-squares (RSS) fashion. In general, for AC-DC measurements, and for this analysis in particular, the Type B uncertainties are the dominant sources of error. These uncertainties are generally based on estimates of the upper limits of the various contributions of AC-DC difference and the measurement process. A Sample of the uncertainty budget of NIS calculations were determined according to the protocol and listed in Table 4. It has been shown that the contribution of Type B uncertainty was 2.8 ppm while the Type A contribution was only 1.2 ppm. It exhibits good uncertainty agreements with the NIST system and led to quite small corrections for the examined TVCs. These corrections are within the range of about 0.5 and 13 ppm.

5. Conclusion

An achievement of traceability of NIS capabilities in the AC voltage capabilities was established in accordance with scientific collaboration with NIST, USA. The NIS automated calibration system, set of TVCs and the fabricated micropotentiometers of NIS were confirmed based on the good agreement of the comparison results between the two institutes. The thermoelement of these devices was also characterized by using a powerful electrical simulator to investigate the appropriate modelling of this element. Modelling confirmation was also achieved through the comparison between the simulated and the practical values. The comparison results exhibit good uncertainty agreements with NIST as well as led to quite small corrections for the examined TVCs of the NIS. The needed corrections are only lie between 0.4 ppm to 13.3 ppm.

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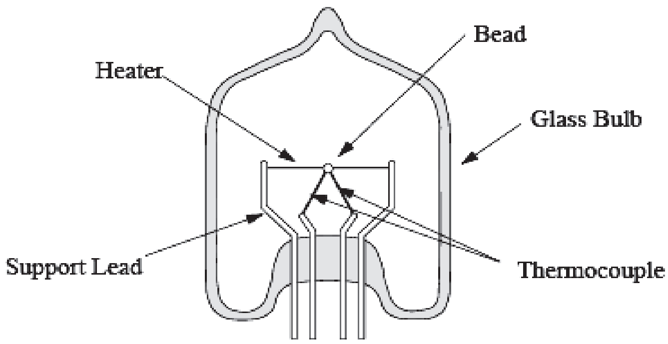

Figure 1. Construction of a typical Thermoelement

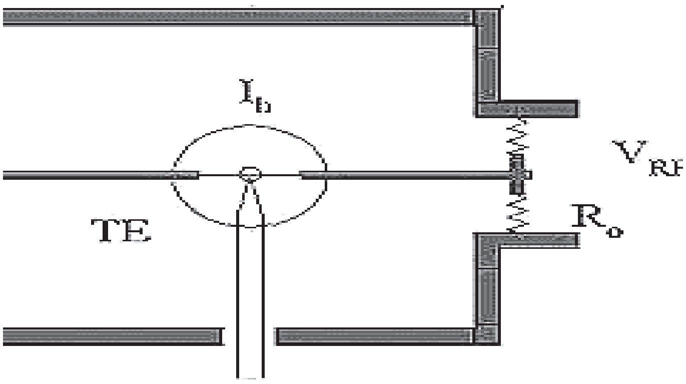

Figure 2. Simple construction of the μpot.

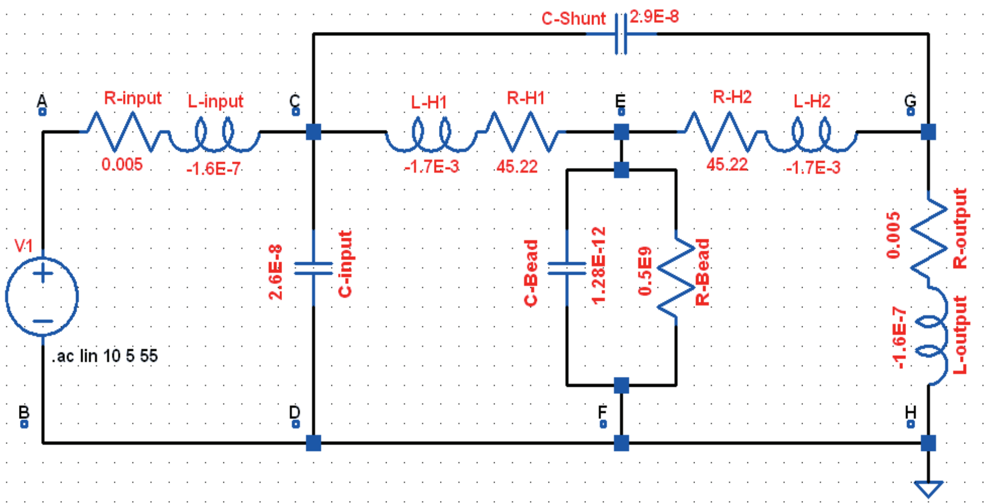

Figure 3. The imaged equivalent circuit of the TE

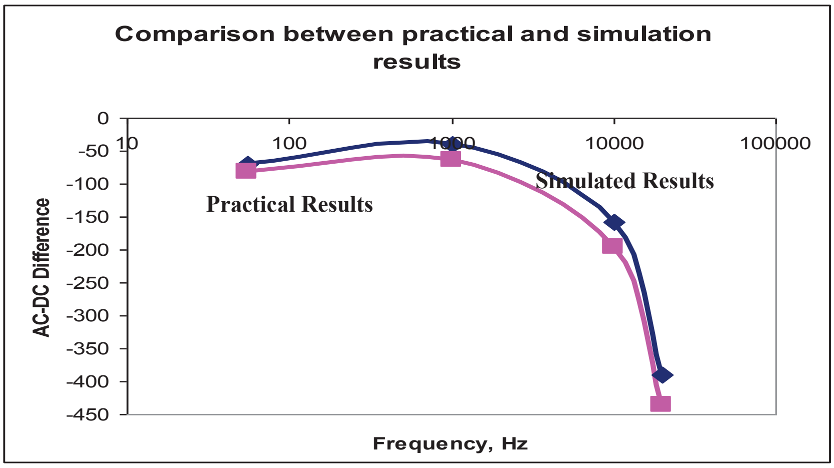

Figure 4. Comparison between Practical and Simulated Results

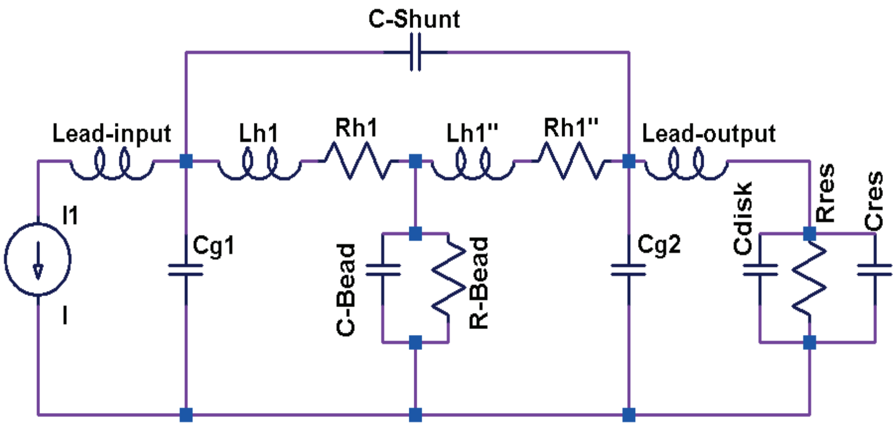

Figure 5. The equivalent electrical circuit of (50 mV) AC voltage source

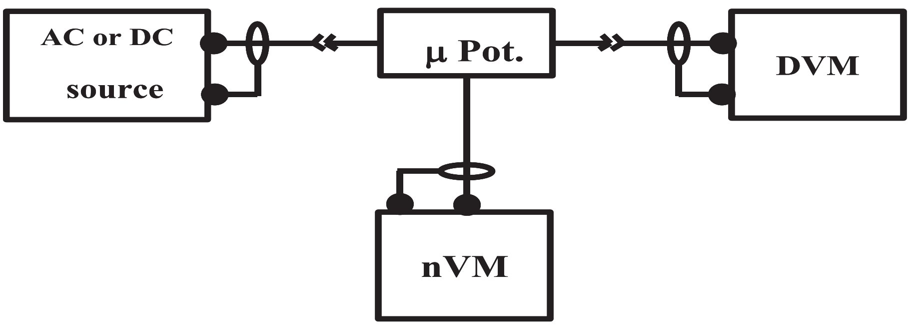

Figure 6. Simplified Measuring Circuit of Micropotentiometer

Table 1. Datasheet of Mock-up Test

Frequency	Practical AC –DC Difference (ppm)	Simulated AC –DC Difference (ppm)	Deviation Magnitude (ppm)
55 Hz	-81	-69	12
1 kHz	-64	-40	24
10 kHz	-196	-168	28
20 kHz	-436	-410	26

Table 2. Comparison between practical and simulated results of micropot @ 50 mV

Frequency	Practical AC –DC Difference (ppm)	Simulated AC –DC Difference (ppm)	Deviation Magnitude (ppm)
1 kHz	-28	-18	10
10kHz	-30	-23	7
20kHz	-24	-21	3

Table 3. Summary results of 100 mV micropot

Parameter	@ 55 (Hz)	@ 1 (kHz)	@ 10 (kHz)	@ 20 (kHz)
AC-DC Difference of the TE (ppm)	3.9	-0.7	12.4	16
Type A uncertainty (ppm)	1.8	3	4	1.5

Table 4. Uncertainty Budget of AC-DC Difference of 3 V at 1000 Hz

Source of Uncertainty	Value, ± (ppm)
Short term DC source stability	0.3
Short term AC source stability	0.6
Thermal emf of the leads	0.6
Ambient temperature change	1
Effect of the T-connector	1.2
Closure of the triangle method	2
Repeatability (for 14 times)	1.2
Combined Standard, UC	3
Expanded Uncertainty (k = 2)	6

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