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INVESTIGATING THERMAL VOLTAGE CONVERTERS (TVCS) CORRECTION FACTORS THROUGH ELECTRICAL SIMULATION AND MODELING

[1]Mamdouh S. Saeed, [2]Mamdouh Hermach and [3]Ali Sharaf Elrahman

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Abstract

Thermal voltage converters (TVCs) are essential components in various industries, including power generation, aerospace, and automotive applications, due to their ability to measure AC voltage accurately. However, TVCs are inherently susceptible to errors that can arise from factors such as temperature, frequency, and waveform. Consequently, determining correction factors is imperative to improve the accuracy and reliability of TVC measurements. This study aims to investigate the correction factors for TVCs through electrical simulation and modeling. By employing state-of-the-art electrical simulation tools and advanced modeling techniques, a detailed analysis of the factors affecting TVC performance will be conducted. This analysis will enable the identification of the most significant sources of error in TVC measurements and the development of appropriate correction factors to mitigate these errors. The results of this investigation will have a profound impact on the accuracy and reliability of TVC-based measurements in various industries, ultimately leading to improved efficiency and safety in power generation, aerospace, and automotive applications. Furthermore, the insights gained from this study can be applied to other electrical measurement devices, thereby contributing to the advancement of electrical engineering knowledge and practice.

[1] Sudanese Standards and Metrology Organization P.O. Box 13753, Khartoum, Sudan
[2] Electrical Metrology Department, National Institute of Standards (NIS), Giza, Egypt
[3] Department of Electrical and Electronic Engineering, Faculty of Engineering, University of Khartoum, Sudan

1. Introduction

Thermal voltage converters (TVCs) have been widely used in the measurement of voltage ratios and phase angles in power systems, as well as in calibration laboratories (Klaczak et al., 2017). Despite their broad application, the performance of TVCs can be affected by various factors, including temperature, frequency, and input signal amplitude (Klaczak et al., 2017). As a result, the development of accurate correction factors is crucial to ensure the reliability of TVC measurements.

Previous research on TVC correction factors has primarily focused on temperature-dependent factors, as temperature variations can significantly influence the performance of TVCs (Savary et al., 2016). However, there is limited research on the influence of electrical parameters, such as frequency and input signal amplitude, on the performance of TVCs. Electrical simulation and modeling techniques have recently emerged as powerful tools for investigating the behavior of electronic devices under various operating conditions (Alam et al., 2019).

In this study, we aim to investigate the TVC correction factors through electrical simulation and modeling. By employing advanced simulation techniques, we will explore the influence of frequency and input signal amplitude on the performance of TVCs, complementing the existing knowledge on temperature-dependent correction factors. This research will contribute to the development of more accurate and comprehensive correction factors for TVCs, ultimately enhancing the reliability of TVC measurements in various applications.

2. Principle of AC-DC transfer

In practice, the response of the thermoelement (TE) of the AC-DC Transfer Standards is not ideal, due to the presence of thermoelectric effects, frequency dependent effects and other error sources. This deviation in TE from the same response for AC and DC signals is specified in metrology terms as AC-DC Difference (δ). Furthermore, TE respond differently to positive and negative DC voltages. This behavior causes what is known as DC reversal error [5]. Reversal error is eliminated during the measurements by taking the average of the positive and negative supply voltage. The δ, is usually given in (μV/V) and defined in Eq. (1)

$$\delta = \frac{V_{ac} - V_{dc}}{V_{dc}}\Bigg|_{E_{ac}=E_{dc}} \qquad (1)$$

Where: δ = AC-DC difference for the TE.

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 TE.

In AC-DC Current Transfer Standard, the AC-DC Difference is defined as the ratio of the AC and DC current required to produce the same output on the thermal converter as given in Eq. (2).

$$\delta = \frac{I_{ac} - I_{dc}}{I_{dc}} \qquad (2)$$

The relation between the input AC voltage (or current) and the output of the TE is given as in Eq. (3).

$$E = KV^{n} \qquad (3)$$

where, E is the output (emf) of the TE, V is the applied voltage, K varies 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 for SJTC while equals 2 in MJTC. Therefore, the output (emf) of the TE is used to evaluate the AC-DC Difference using Eq. (4).

$$\delta_{AC-DC} = \frac{E_{AC} - E_{DC}}{nE_{DC}} \qquad (4)$$

3. Electrical Modeling and Simulation

Electrical model is a model in the form of a mathematical description or an electrical equivalent circuit that represents the behavior of an electrical device or a system [6]. The topic of modeling has acquired great importance in engineering education because of astronomical increase in computing power. The simulation of the electrical and optical behavior of devices has been established as an essential tool for both the improvement of existing devices and for the development of new ones. There is no doubt that the role of device modeling will increase in the future. Device modeling involves the numerical solution of a set of equations, which form a mathematical model for device operation, together with models that describe the material properties.

Electrical simulation is a field that includes both device and circuit simulation techniques, each of which serves a distinct purpose. Device simulation is a higher fidelity approach, in which a single semiconductor device is represented with a set of coupled partial differential equations (PDEs), discretized on a spatial mesh. Device simulation is intended to be accurate, using models for the behavior of the electrical devices that are based on fundamental physics. However, device simulation is often compute-intensive and is not practical for simulation of entire circuits. Thus, transistor-level models (compact models) are derived from these physicsbased simulations that are based on the underlying physics, empirical data (curve-fitting), or tabular data (look-up table). Compact models are much faster to simulate than the original physics-based model and can be integrated into a circuit simulator [7].

3.1 Modeling and Simulation Approach

Indeed, the electrical simulation modeling by using the LT-Spice software [8] has been achieved widely to analyze the physical structure and electrical characteristics of the TE in an effort to better understand the origin of errors in these devices. Another important purpose for using the electrical simulation is performing the building up and building down scaling for the AC-DC Difference measurements. Therefore, the electrical simulation, then, can be used easily to determine the expected AC-DC difference for that device for different values around the rated value at the same frequency. The values from 40 % to 110 % of the rated value of the device are suggested in this review article for obtaining an accurate theoretical determination of the associated AC-DC differences.

The methodology depends entirely on the comparison between the results given by the practical work inside an accredited laboratory and the simulated results given by the virtual system. Many experimental works will be performed through the actual computerized system, while all theoretical results will be predicted through the virtual system based on the electrical modeling and simulation.

According to previous works in this area [9, 10, 11, 12], through the normal use of the SJTVC (the TE itself without any multiplier resistor), the equivalent electrical circuit was imaged as shown in Fig 1. The equivalent circuit parameters of the TE were accurately measured at 55 Hz, for example, by using a very sensitive digital LCR Meter. The typical results of these parameters are listed in Table 1.

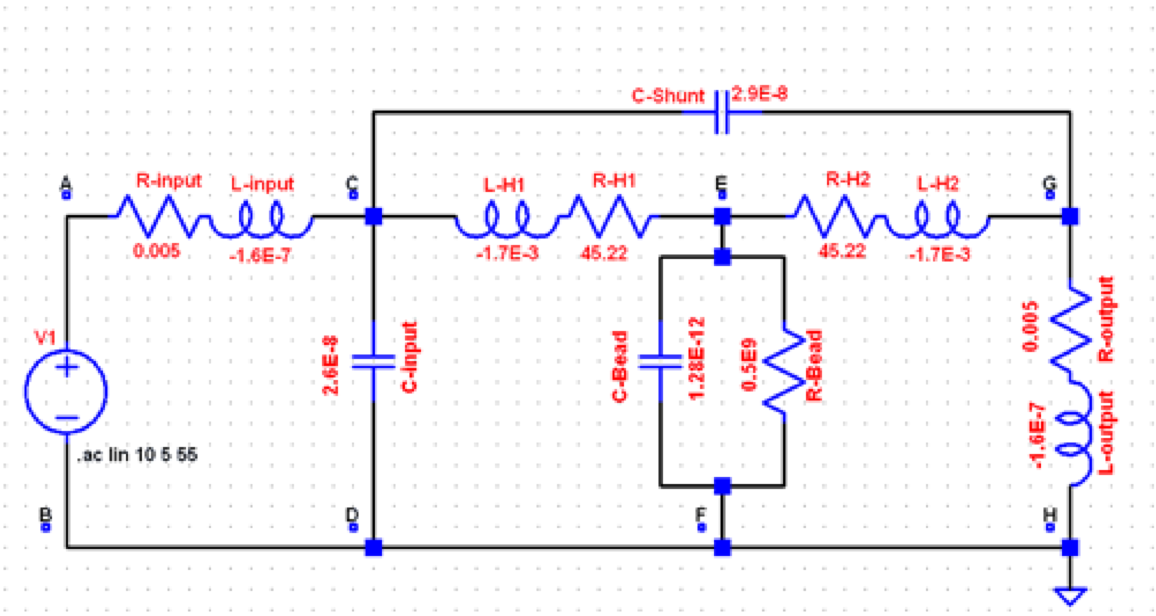

Fig.1: The Suggested Equivalent Circuit of the SJTVC

3.2 Results and Discussion

At the National Institute for Metrology, the thermal converters are characterized or calibrated by the comparison with another converter by the application of dc(+), ac, dc(-) signals in a timed sequence (Fig. 2). In this process, voltage converters are connected in parallel through a coaxial tee, and the current converters or transfer shunts are usually connected in series. This system yields uncertainties range from about 10^{-6} to 7 x 10^{-5} for voltage measurements at 1 MHz [13].

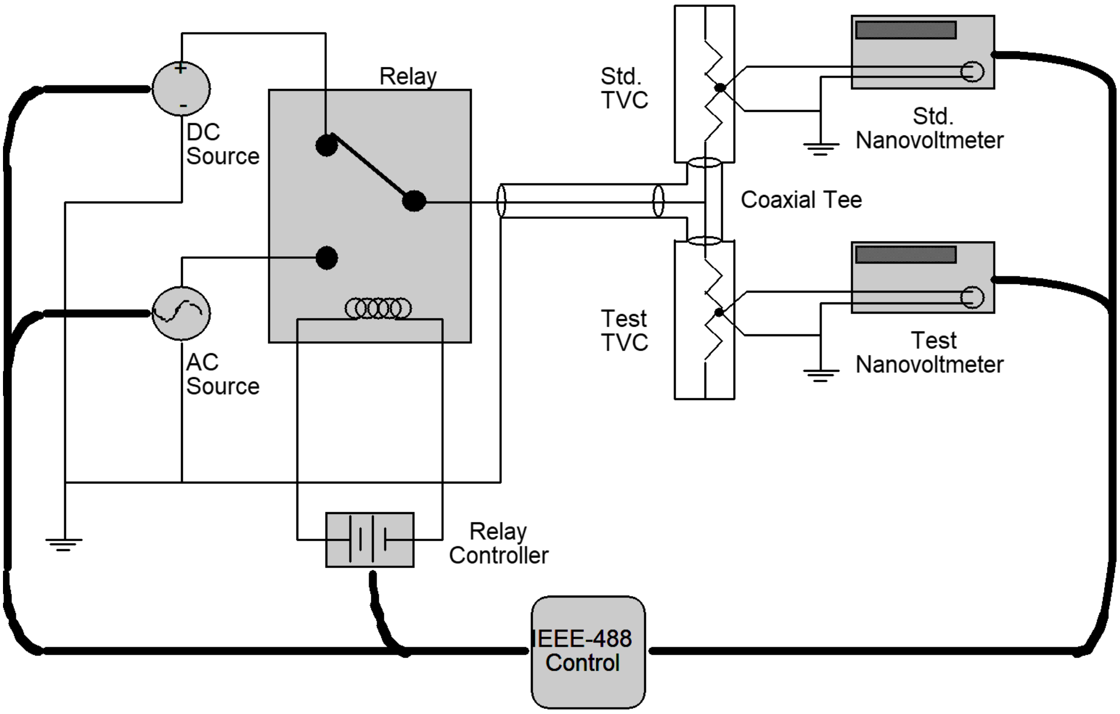

Fig. 2: Block diagram of the automatic ac-dc difference measurement system at NMI

This practical system (computerized or manually) to determine the AC-DC Difference of the Thermal Converters with very small uncertainty at different frequencies. However, many drawbacks were noticed, during this process. The comparison between the results of practical and simulated methods, Fig. 3 and Table 2, at frequencies of 55 Hz, 1 kHz, 10 kHz and 20 kHz, have been analyzed and reflected a good agreement with the results. This, of course, shows the reliability of that method, hence the challenge and motivation

Table 1: The Measured Parameters of the TE at 55 Hz

Symbol	Description	Values
L-input and Loutput	Inductance of input and output leads	0.16 µH for each
C-input	Parasitic capacitances across the input terminals of the TE	26 nF
L-H1 and L-H2	The inductances of the two similar parts of the heater	1.7 mH for each
R-H1 and R-H2	The resistances of the two similar parts of the heater	45.22 Ω for each
C-Shunt	The parasitic capacitance across the voltage drop of the TE heater	29 nF
C-Bead	The parasitic capacitance across the insulator bead	1.28 pF
R-Bead	The high resistance of the insulator bead	0.5 GΩ

Table 2: The Comparison between practical and the simulated results

Frequency	**Practical results of the AC-DC Difference, (ppm)**	**Simulation results of the AC-DC Difference, (ppm)**	**The simulation error, (ppm)**
55 Hz	**-81.2**	**-69**	**-12.2**
1 kHz	**-63.7**	**-39.5**	**-24.2**
10 kHz	**-195.5**	**-157.2**	**-38.3**
20 kHz	**-436.3**	**-389.8**	**-46.5**

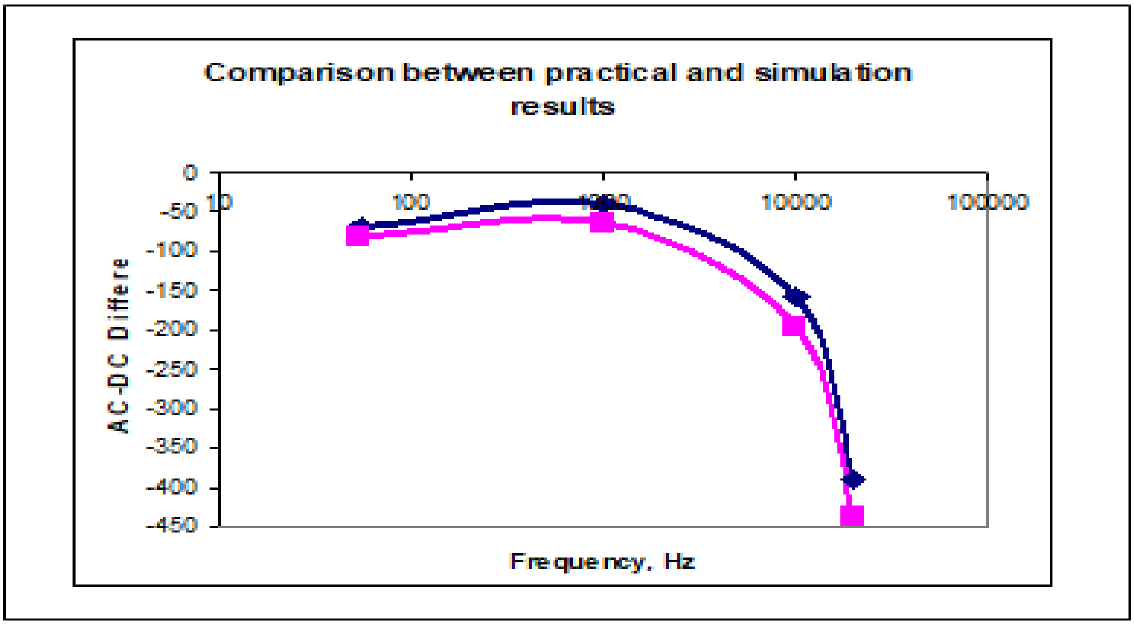

Fig. 3: Comparison between practical and simulated results

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 ACDC Difference was performed at the rated value (5 mA). The practical results were evaluated based on equation (2). 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., as defined in Eq. (5) [5]

$$\delta_{sim} = \frac{P_{H,ac}-P_{H,dc}}{nP_{H,}} \qquad (5)$$

In the same manner, the electrical simulation can be applied and extended by researchers to achieve the calibration process in a more simple way as described in this article.

Conclusion

The results obtained by simulation were in a good agreement with the practical results, this validates the reliability of the new method. Certainly, the new system removed the difficulties accompanying the traditional calibration system. Furthermore, this new method will provide valuable information in predicting the calibration values of these converters in a wide range of frequencies. We are looking forward to repeat the same work for the multi-junction thermal voltage converter (MJTVC) to consider this methodology as a reliable alternative system for the practical one and to overcome all drawbacks of the current systems.

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