Investigation of Two Different Techniques for Accurate Measurements of Sinusoidal Signals

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***Abstract*—In this paper, two different techniques for the determination of the rms value of sinusoidal AC voltage at the range of 2V are practically compared: non-thermoelectric technique (via the direct measurement using a precise high sensitive digital voltmeter, and the comparison method using a precise AC voltage calibrator) and thermoelectric technique (via the null thermoelectric technique, and the algorithmic thermoelectric technique using a calibrated multijunction thermal converter (MJTC)). A series of comparisons between the four methods have been discussed and evaluated at frequencies from 20 Hz to 100 kHz to investigate the level of performance and competitiveness. The comparison results showed that the four applied methods agreed within values of 80μV ± 15μV/V and 68μV ± 11μV/V at frequencies of 20 Hz and 100 kHz, respectively.**

Keywords- AC voltage measurement, AC-DC thermal transfer, uncertainty budget, proficiency test.

I. INTRODUCTION

Recently, the accurate AC voltage measurement in the frequency range up to 100 kHz becomes more important and commercial parameter in electrical metrology laboratories and national calibration services. The past few years have seen an improvement in AC voltage calibrators and voltmeters, which would make them acceptable as standards in their own right except for the very highest accuracy. As a result, the specification for the most accurate ranges (1V to 10V) in the frequency range from 100 Hz to 10 kHz has improved by a factor of two and the frequency range of commercial instruments has been extended up to at least 50 MHz. This gives an annually accuracy of about 20 ppm [1]. This improvement is due to various developments in each of the thermal and non-thermal techniques used for comparing AC and DC voltages and currents.

This paper describes four different methods for the accurate determination of the rms value of 2V at frequencies from 20 Hz to 100 kHz. As all four methods have their advantages and disadvantages, a set of comparisons including the measurement results associated with the expanded uncertainty, the frequency response and the uncertainty budgets of each method is also investigated in this work. In addition, a proficiency testing methodology, to evaluate the compatibility between the four methods, has been applied.

II. NON-THERMOELECTRIC TECHNIQUE

The new generation of AC instrument has increased the demand on accuracy. To meet the demand in the AC voltage measurements, a new generation of the high sensitive and very accurate digital multimeter (DMM) has been developed. DMM is one of the most widely used electrical measurement instruments and provides electrical traceability to many industrial users. However, digital multimeters designers have always had to exert efforts to minimize the parameters contributing into the values of errors and associated uncertainty.

The AC function has the added dimension of frequency. This complicates calibration by introducing additional test points for each amplitude range. In a typical DMM, the AC measurements are made by an AC converter and available with 8½ digit 100 mV ranges with a resolution of 1 nV. Below this level, noise and linearity errors are likely to dominate the reading. The gain of a DMM's AC function varies with frequency. This is called its "Frequency Response" and requires that measurements are made at the cardinal points throughout each amplitude range [2]. An easy way to comply with the conference paper formatting requirements is to use this document as a template and simply type your text into it.

A. *Direct Method of Measurement*

In the technique adopted in this method, a FLUKE 8508A Reference Multimeter is used to measure the rms value of the applied sinusoidal signal in accordance with the corresponding standard [3]. In the 24 hours preceding calibration, the instrument was powered by the mains and placed in the appropriate laboratory conditions. A WAVETEK 9100 Calibration System was used to apply the AC voltage signal for the DMM. During this process, the ambient temperature was controlled at 21 ± 1^{o}C and the relative humidity at 45 ± 5%. Typical ten observations of the supplied signal value from the calibrator is measured, corrected and averaged using the 8½ digit multimeter.

As stated in [4], all measurements are tainted by imperfectly known errors, so the significance associated with the result of a measurement must account for this uncertainty. The uncertainty values were estimated taking into account most known contributing factors to the uncertainty of the undertaken measurement. The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by a coverage factor, k = 2, corresponding to coverage probability of approximately 95% [5]. The standard uncertainty of measurement has been determined in accordance with [4]. During this method, the following contributions are taken into account:

- Uncertainty due to the repeatability of 10 observations (Type A).
- Uncertainty due to the calibration certificate of the DMM.
- Uncertainty due to the display resolution of the DMM.
- Uncertainty due to the drift between two consecutive calibration certificates of the DMM.

The calibration results of 2V using this method associated with the corresponding expanded uncertainty are listed in Table I.

TABLE I
Calibration Results of Direct Technique

Freq. (kHz)	Actual Value (V)	Deviation (mV)	Exp. Uncert. (μV/V)
0.02	1.996277	3.7233	23
0.055	1.996285	3.7152	18
0.4	1.996432	3.5682	19
1	1.996400	3.6	17
2	1.996334	3.6665	17
10	1.996390	3.61	17
30	1.996187	3.813	19
50	1.995424	4.5759	20
100	1.993153	6.8469	20

*B. **Comparison Method of Measurement***

In this technique, a calibrated FLUKE 5720A Calibrator has been used to provide the reference value of the 2V at the intended frequencies. On the other hand, WAVETEK 9100 Calibration System is used to apply the nominal value of the 2V, to be measured, at the same frequencies and in the same conditions. A FLUKE 8508A Reference Multimeter is then used, as in Fig. 1, to display and compare the two outputs of each calibrator accordingly.

Typical ten observations are also recorded, corrected and averaged associated with the expanded uncertainty (at k=2) as listed in Table II. The following contributions were taken into consideration in this method:

- Uncertainty due to the repeatability of 10 observations of the two readings of the DMM.
- Uncertainty due to the calibration certificate of the 5720A Calibrator.
- Uncertainty due to the display resolution of the DMM.
- Uncertainty due to the drift between two consecutive calibration certificates of the 5720A calibrator.

Since the digital voltmeter is used for comparison only, its display deviation is not relevant. Therefore, the calibration of the DMM did not contribute to the uncertainty budget.

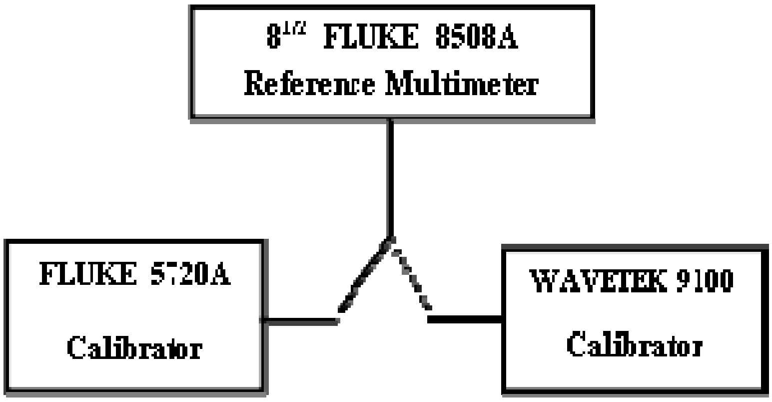

Fig. 1. Comparison Method

TABLE II
Calibration Results of Comparison Technique

Freq. (kHz)	Actual Value (V)	Deviation (mV)	Exp. Uncert. (μV/V)
0.02	1.996249	3.7513	21
0.055	1.99624	3.7603	15
0.4	1.996356	3.644	16
1	1.996419	3.581	12
2	1.996338	3.662	12
10	1.996354	3.6457	12
30	1.996171	3.8288	16
50	1.995476	4.5236	17
100	1.993086	6.9142	17

III. THERMOELECTRIC TECHNIQUE

Indeed, the thermoelectric technique is one of the most precise methods to determine the rms value of an AC voltage in terms of the SI units accurately. To achieve that, it is necessary to use the AC-DC thermal transfers [6]. In this work, a calibrated Multijunction Thermal Converter (MJTC) at the level of 2V was used during two methods to determine the rms value of the 2V at the same range of frequencies. The AC-DC transfer difference (δ) of the MJTVC is known with an uncertainty less than 4 μV/V.

A. Nulling Method

The automated setup of AC measurement using this method is shown in Fig. 2. The automation software [7] developed for this method can produce the calibration results along with standard deviation at each point of measurement.

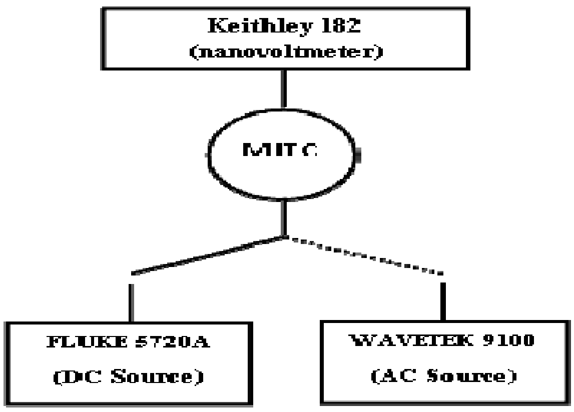

Fig. 2. Nulling Method

In this method, the nominal value of 2V is supplied by the WAVETEK 9100 Calibrator to the MJTC and the corresponding response of 10 typical observations in terms of output emf (E_{ac}) is recorded and averaged by using a Keithley 182 nanovoltmeter. Then DC positive and DC negative voltage of the value of calibrated 2V is applied to produce the same exact value of the emf (E_{ac}) then the corresponding applied voltages V_{dc} positive and V_{dc} negative are recorded and the mean value of V_{dc} is then calculated. The actual value of AC voltage at this frequency is then determined by:

$$V_{ac} = V_{dc}(1 + \delta_s) \tag{1}$$

where δ_s is the AC-DC transfer difference of the MJTC that was already determined in PTB, Germany with values of less than 5.5 µV/V within uncertainty less than 4 µV/V.

The following contributions are taken into consideration to estimate the expanded uncertainty in this method:

- Uncertainty due to the repeatability of 10 observations for each effect of AC and DC.
- Uncertainty due to the calibration certificate of the MJTC and 5720A Calibrator.
- Uncertainty due to the thermal emf effect of the cables used in this method.
- Uncertainty due to the drift between two consecutive calibration certificates of the MJTC and 5720A Calibrator.

The calibration results associated with the corresponding expanded uncertainty (at k = 2), are listed in Table III.

TABLE III
Calibration Results of Nulling Technique

Freq. (kHz)	Actual Value (V)	Deviation (mV)	Exp. Uncert. (µV/V)
0.02	1.996197	3.80338	10
0.055	1.996253	3.7474	9
0.4	1.996361	3.63875	9
1	1.996374	3.6264	9
2	1.996382	3.6179	9
10	1.996394	3.605866	9
30	1.996224	3.775652	9
50	1.995459	5.410847	9
100	1.993153	7.547287	11

B. ***Algorithmic Method***

This technique was developed by Dr. Ilya Budovisky (NMI Australia) [8]. In the principle of AC-DC Transfer, the AC-DC Difference, $\delta_{ac\text{-}dc}$, is usually defined as [7]:

$$\delta_{ac-dc} = \frac{V_{AC} - V_{DC}}{V_{DC}} \tag{2}$$

where: V_{AC} = rms value of AC voltage that produce a certain value of output emf. V_{DC} = average of the absolute values of DC voltage applied in positive and negative polarity to produce the same emf. The relation between the input current of the applied voltage on the MJTC and its output emf is given by:

$$E = K\,V^{n} \tag{3}$$

where K varies somewhat with large changes in heater current but it is constant over a narrow range where nearly equal AC & DC voltage are compared and n is usually 1.6 to 1.9 at the rated heater current [9] (in our case n ≈ 2). The relationship between a small change in TE heater voltage (ΔV) and the corresponding change in output (ΔE) is expressed as:

$$\frac{\Delta V}{V} = \frac{\Delta E}{n \,.\, E} \tag{4}$$

From (2), (3) and (4), the AC-DC difference can be defined as:

$$\delta = \frac{E_{ac} - E_{dc}}{n \,.\, E_{dc}} \tag{5}$$

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. The absolute AC voltage of this signal at this frequency is then determined using the formula:

$$V_{ac} = V_{dc}(1 + \delta_{ac-dc} + \delta_s) \tag{6}$$

where δ_s is the AC-DC transfer difference of the calibrated MJTC.

The following contributions are taken into consideration to estimate the expanded uncertainty in this method:

- Uncertainty due to the repeatability of 10 observations for the effect of AC and DC.
- Uncertainty due to the calibration certificate of the MJTC and 5720A Calibrator.
- Uncertainty due to the thermal emf of the used cables.
- Uncertainty due to the drift between two consecutive calibration certificates of the MJTC and 5720A Calibrator.
- Uncertainty due to the short-term stability of the AC and DC sources (over 3 minutes for both)

The calibration results along with corresponding expanded uncertainty (at k = 2), are listed in Table IV.

TABLE IV
Calibration Results of Algorithmic Technique

Freq. (kHz)	Actual Value (V)	Deviation (mV)	Exp. Uncert. (μV/V)
0.02	1.99622916	3.77084	8
0.055	1.996263021	3.736979	7
0.4	1.996391865	3.608135	7
1	1.99640148	3.59852	7
2	1.996370711	3.629289	8
10	1.996384096	3.615904	8
30	1.996215991	3.784009	8
50	1.995442726	4.557274	8
100	1.99313784	6.86216	9

IV. COMPARISON OF RESULTS

Fig. 3 shows the results of the comparison between the four methods: direct method (M1), comparison method (M2), nulling method (M3), and algorithmic method (M4), by computing the relation between the actual measured values taken using the four methods and the corresponding frequency. This relation also reflects the frequency dependence of the four methods at constant voltage.

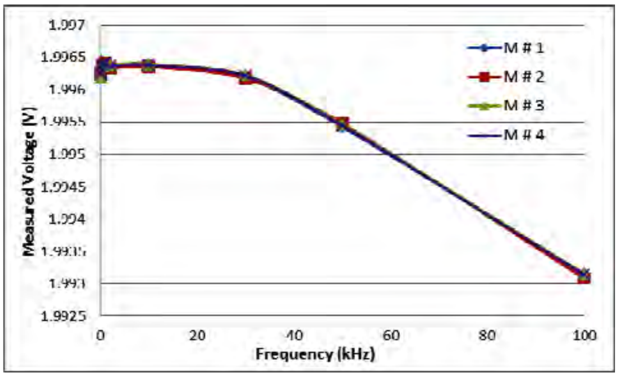

Fig. 3. Frequency dependence of the four methods

As noted in Fig. 3, the frequency response of the four methods has, approximately, the same trend. In this response, results tend to become much less with the increase in the frequency. The least measured value of the 2 V is achieved at 100 kHz. Generally, the calibrated results among the four methods exhibit differences of 80µV and 68µV at 20 Hz and 100 kHz respectively. On the other hand, the results of the measured deviation of the 2V along with expanded uncertainty have been compared (as shown in Figures 4 and 5). Referring to this comparison, it is noticed that the algorithmic method (M4) exhibits the lowest expanded uncertainty compared to other methods. In addition, the methods based on the thermoelectric technique exhibit lower values in comparison to the other methods based on non-thermoelectric technique. As shown in Fig. 6, the two techniques agree within less than 15µV/V and 11µV/V at frequencies of 20 Hz and 100 kHz, respectively.

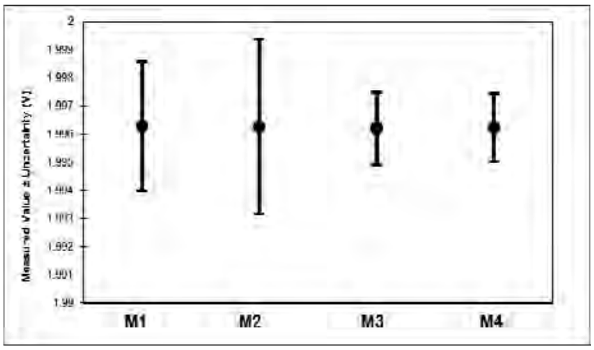

Fig. 4. Comparison of the four methods at 20 Hz

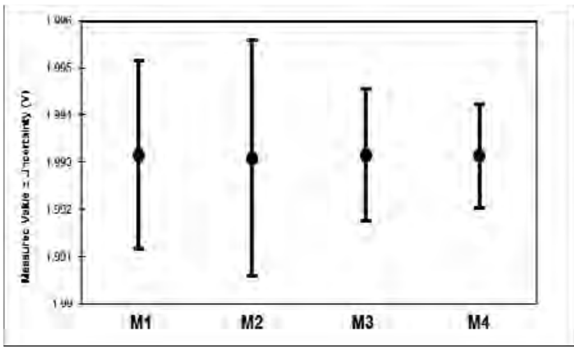

Fig. 5. Comparison of the four methods at 100 kHz

Note: A graph scale of 100:1 for the expanded uncertainty and the deviation respectively was used to represent the values in Figs 4 and 5.

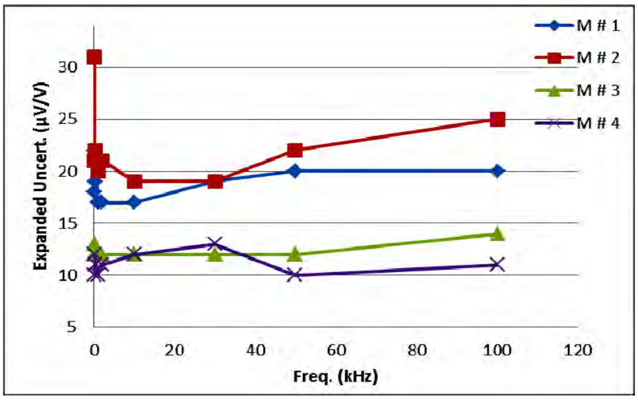

Fig. 6. Expanded Uncertainties of the Four Methods

Despite of the longer time consumed as well as the difficult procedures, it has been observed that the thermoelectric technique (null and algorithmic methods) has a smaller standard deviation for the set of 10 measurements in comparison to the other technique. In addition, the values of the expanded uncertainty in the majority of the measuring points are also smaller. This feature, as a result, recommends the use of thermoelectric technique in the high level of precision measurements.

V. Compatibility and Competitiveness of the Four Methods

To confirm the compatibility of the four methods, and according to the previous comparison, the algorithmic method has been recommended to represent the reference values of this comparison. Table V lists the differences between the measured values using methods 1, 2 and 3 and using method 4 (as the reference value) and coded as Δ1-4, Δ2-4 and Δ3-4, respectively. The results agree within a range of |19.5 to 47.5µV| and |14.8 to 52µV| at 20 Hz and 100 kHz respectively.

On the other hand, Table VI reports the proficiency testing results of this comparison. Proficiency testing is the determination of the performance by means of comparing and evaluating calibrations by two or more methods in accordance with predetermined conditions [10]. The performance of the three methods against the algorithmic method, (as a reference value) is judged using the equation of:

$$E_n = \frac{\lfloor X_L - X_R \rfloor}{\sqrt{U_L^2 + U_R^2}} \qquad (7)$$

where: X_L = the value as measured by the compared method, X_R = the value as measured by the reference method (algorithmic), U_L = the expanded uncertainty of the compared method, U_R = the expanded uncertainty of the reference method.

En ratio (or *En* number) should be between -1 and + 1 (or |*En*| <1), (the value closer to zero is the better.)

TABLE V
Differences from the reference value

Freq. (kHz)	Differences (µV)		
	Δ_{1-4}	Δ_{2-4}	Δ_{3-4}
0.02	47.54	19.54	-32.54
0.055	21.779	-23.321	-10.421
0.4	39.935	-35.865	-30.615
1	-1.48	17.52	-27.88
2	-37.211	-32.711	11.389
10	5.904	-29.796	10.038
30	-28.991	-44.791	8.357
50	-18.626	33.674	16.427
100	15.26	-52.04	14.873

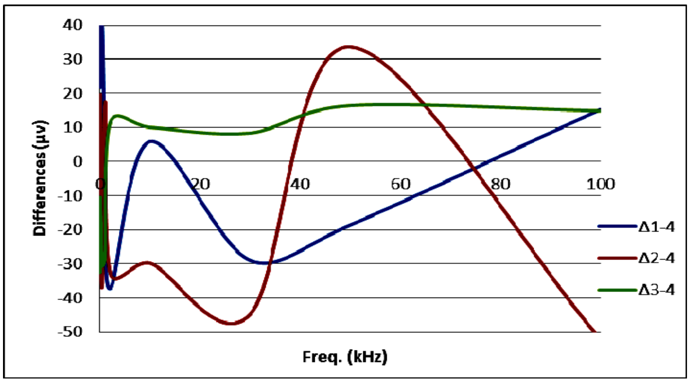

Fig. 7. Differences of M1, M2 and M3 vs M4

TABLE VI
E_n Ratio of the comparison

Freq. (kHz)	**| E_n | Ratio**		
	M 1	**M2**	**M3**
0.02	0.95	0.30	0.92
0.055	0.53	0.51	0.34
0.4	0.91	0.73	0.94
1	0.04	0.40	0.89
2	0.92	0.70	0.35
10	0.15	0.67	0.30
30	0.63	0.97	0.24
50	0.42	0.70	0.53
100	0.34	0.95	0.42

Referring to the values of E_n in Table VI, it can be noticed that E_n values are less than 1 for all the measuring points. This means that all results of the all methods are competent and satisfactory.

VI. CONCLUSION

The calibration results of a precision AC calibrator at level of 2V using two different techniques: non-thermoelectric technique (via Direct and Comparison methods) and thermoelectric technique (via Null and Algorithmic methods) have been practically compared and evaluated at frequencies from 20 Hz to 100 kHz. The four methods agreed within 80μV ± 15μV/V and 68μV ± 11μV/V at 20 Hz and 100 kHz respectively. It has been observed that the thermoelectric technique has comparatively smaller combined uncertainty contribution. Although the thermoelectric technique is time consuming and complex, even in automation calibration, it was more accurate and precise. The standard deviation and the expanded uncertainty of the algorithmic method both were less than the same values of the other methods. The four methods agree within expanded uncertainties less than 15μV/V and 11μV/V at frequencies of 20 Hz and 100 kHz respectively. The algorithmic method was recommended to represent the reference value and to confirm the performance compatibility and reliability of the other three methods via the proficiency testing analysis. The calculated ratio numbers of all results of the three methods were acceptable and satisfied.

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