Establishment of AC-DC transfer standard at SASO-NMCC

***Abdullah* Alrobaish**[1] ***Ahmed* Aljomaie**[1]

[1](NMCC, SASO, KSA) National Measurement and Calibration Center

Abstract. This paper documents the achievements of traceability and the technical evaluation of the newly established AC-DC Difference calibration service for AC voltage measurements at the NMCC, KSA. It gives details on the establishment and functioning of a new automatic calibrating system. This paper also includes instructions for the expanding uncertainty associated with the calibration system. Nevertheless, this study provides extensive review of heat converters and AC-DC difference measurements. The GULFMET.EM-S3 Supplementary Comparison data show the new system's capabilities, which cover the 2mV to 1000V @ 10Hz to 1MHz range. It also describes the new capabilities of AC-DC difference calibration services and the accomplishment of traceability for AC voltage measurements by the NMCC in Saudi Arabia. It explains the installation and functioning of auto-calibrating system. This paper also guides the construction of calibration systems and the related extended uncertainty. Although it is not very detailed, this document gives an idea of what heat converters and AC-DC difference measurements are all about—the results of the GULFMET.EM-S3 Supplementary Comparisons are used to show what the new system is capable of. These capabilities range from 10 Hz to 1 MHz and 2 mV to 1000 V.

Keywords. Automatic Calibration Systems, Thermal Converters, Thermal Transfer Standards, AC-DC Difference, and Uncertainty Calculations.

1. Introduction

The reference method to measure AC voltage and current is to compare the heating effect of the AC signal to the heating effect of a DC signal. This comparison generally uses thermal voltage and current converters (TVCs and TCCs), which are helpful in different level of uncertainties, from a few hertz to several hundred megahertz. These devices often consist of a thermoelement (TE) connected in series with a resistor for voltage measurements as a TVC or connected in parallel with a shunt resistor for current measurements as a TCC.

From tens to hundreds of thermocouples are connected along a heater structure, alternating the AC and DC signals with a thermoelement. When applying AC and both polarities of DC successively and observing the thermocouple output, the conventional concept of the AC-DC difference can be calculated as in formula (1)

$$\delta = \left(\frac{E_a - E_d}{E_d} \right) x10^6 \tag{1}$$

When used with positive and negative polarities, the mean response from the DC value E_d equals the RMS AC amount E_a[1].

The majority of the present-day commercially available AC-DC thermal transfer standards are realized with the help of single-junction thermal converters (SJTC) [2–6] or solid-state transfer standards [7]. The SJTCs employ a single thermocouple to the heater wire; the output is 7mV to 12mV for full-scale input, and the output responds to the changes in the input signal in a manner proportional to the square of the input signal. These are applied in many commercial applications and are suitable for 10 Hz to 100 MHz frequencies. For all these devices, except range or shunt resistors and the measurement process, the best uncertainty is a few μV/V. The uncertainty rises at input levels below approximately half of the full scale and the frequency range limits. [8].

2. NMCC Thermal Transfer Standards Calibration Service

The characterizations of NMCC's thermal transfer standards across the different uncertainties are based on the following:

Among the standards for measuring AC are:

i. A set of multi-junction thermal converters (MJTC) in the range of 1V-1000V and an operating frequency range of 10Hz to 1MHz, as shown in Figures 1 and 2.

ii. Micro Potentiometers (MPOT) with outputs of 2 mV, 20 mV, 50 mV, 100 mV, and 200 mV and frequencies of 10 Hz, 100 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz as depicted in Figure3.

A build-up technique is calibrating the fundamental level thermal voltage converter (TVC) at half its nominal voltage (or at its lowest value applicable) and then calibrating the closest lower level TVC at half its nominal voltage (or at its lowest value applicable) using the calibrated converter [9]. A chain of converters up to 1000V can be calibrated in this way using a 3V basic-level thermal converter as showed in fig 4. In our case, PTB has calibrated the entry-level thermal converters that are used between 1 and 3 volts. These converters are compared and rechecked every two years. If the deviation of the results from the values indicated in the certificate is greater than the limits of uncertainty displayed in the certificate, the TVCs are adjusted in a similar way.

Fig. 1. Multi-junction Thermal Converters (MJTC)

Fig. 2. Thermal voltage replaced to MJTC

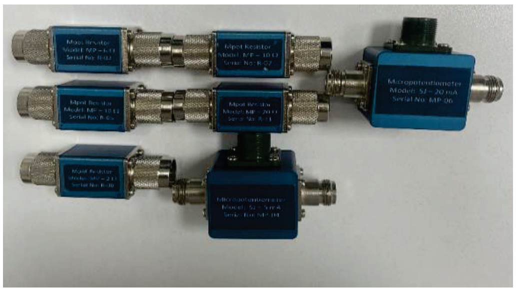


Fig. 3. Set of Micropotentiometer (MPOT)

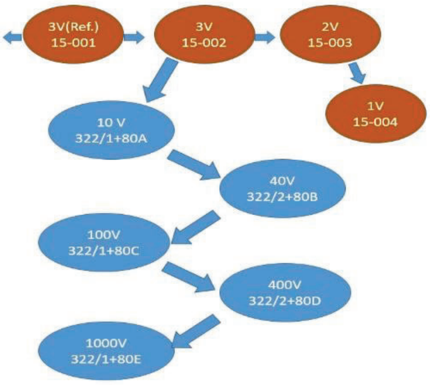


Fig. 4. Range-to-range build-up measurements

3. NMCC's Automated AC-DC Transfer Difference Calibration System

The NMCC has developed a state-of-the-art automated calibration system to facilitate the AC-DC transfer difference calibration process. This system involves a set of precision thermal converters incorporated in an extensive voltage and frequency range. The components comprising this system are:

Thermal Converters: NMCC reference standards include multijunction thermal voltage converters (MJTCs), micro potentiometers, and Fluke 792A. These converters play a significant role in voltage measurements where high accuracy is required. Conventionally, MPOT would represent the lower voltage ranges, and MJTCs would come in at higher voltages, where they would perform with relatively better accuracy and stability.

3.1 Measurement Devices

The system shall be equipped with high accurate nanovoltmeters for the measurements at the output of thermal converters that provide output electromotive forces (EMFs). These devices form the crucial link in establishing an AC-DC difference. In addition, the system shall use a multifunction calibrator to supply stable and precise sources for both AC and DC voltage. Fig 5 illustrate the circuit connection to perform the calibration

The system is designed in such a way that it works fully automatically; a computer with Labware software controls all operations. Consequently, automation allows continuous and exact measurements, decreases human error, and improves the efficiency of the calibration process. The software also allows real-time monitoring and data collection, allowing one to monitor performance and reliability.

3.2 Calibration Process

Each thermal converter is subjected to AC and DC voltages during calibration, and the response is recorded. The system accomplishes a brief AC-DC conversion by transferring a rapid switch that provides the necessary AC and DC alternation and a constant voltage supply to the converters. This makes it easier to measure the AC-DC difference with extremely high precision. To make the calibration information easily accessible to the user, every piece of information is written to the appropriate sections of the screen as fig 6 shows.

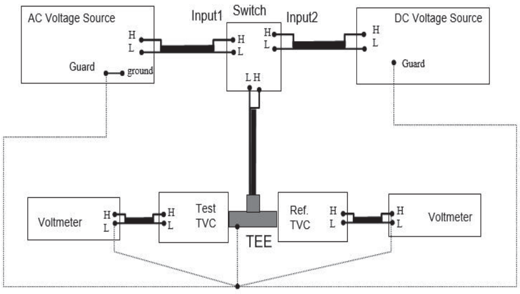
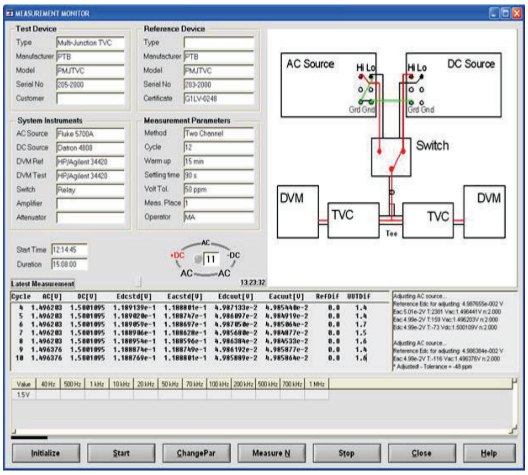


Fig. 5. Step-up procedure of the TVC



Test Device
Type: Multi-Junction TVC
Manufacturer: PTB
Model: PMJTVC
Serial No: 205-2000
Customer:

Reference Device
Type:
Manufacturer: PTB
Model: PMJTVC
Serial No: 203-2000
Certificate: G1LV-0248

System Instruments
AC Source: Fluke 5700A
DC Source: Datron 4808
DVM Ref: HP/Agilent 34420
DVM Test: HP/Agilent 34420
Switch: Relay
Amplifier:
Attenuator:

Measurement Parameters
Method: Two Channel
Cycle: 12
Warm up: 15 min
Settling time: 90 s
Volt Tol.: 50 ppm
Meas. Place: 1
Operator: MA

Start Time: 12:14:45
Duration: 15:08:00

Latest Measurement 13:23:32

```
Cycle   AC[V]     DC[V]      Edcstd[V]     Eacstd[V]     Edcuut[V]     Eacuut[V]    RefDif  UUTDif
  4   1.496203  1.5001095  1.189139e-1  1.188801e-1  4.987133e-2  4.985440e-2    0.0     1.4
  5   1.496203  1.5001095  1.189020e-1  1.188747e-1  4.986097e-2  4.984919e-2    0.0     1.4
  6   1.496203  1.5001095  1.189059e-1  1.188697e-1  4.987050e-2  4.985064e-2    0.0     1.7
  7   1.496203  1.5001095  1.188906e-1  1.188628e-1  4.985680e-2  4.984877e-2    0.0     1.5
  8   1.496203  1.5001095  1.188954e-1  1.188596e-1  4.986384e-2  4.984533e-2    0.0     1.6
  9   1.496376  1.5001095  1.188874e-1  1.188749e-1  4.986192e-2  4.985877e-2    0.0     1.4
 10   1.496376  1.5001095  1.188769e-1  1.188801e-1  4.985889e-2  4.985864e-2    0.0     1.6
```

```
Adjusting AC source...
Reference Edc for adjusting: 4.987655e-002 V
Eac:5.01e-2V T:2301 Vac:1.496441V n:2.000
Eac:4.99e-2V T:159 Vac:1.496203V n:2.000
Edc:4.99e-2V T:-73 Vdc:1.500109V n:2.000

Adjusting AC source...
Reference Edc for adjusting: 4.986384e-002 V
Eac:4.99e-2V T:-116 Vac:1.496376V n:2.000
* Adjusted! - Tolerance = -48 ppm
```

Value	40 Hz	500 Hz	1 kHz	10 kHz	20 kHz	50 kHz	70 kHz	100 kHz	200 kHz	500 kHz	700 kHz	1 MHz
1.5V												

Fig. 6. A new automated calibration system in NMCC

Computers and systems running National Instruments software are in charge of the calibrating systems. During the calibration procedure, a graphics-based system control program called Labware is used as a virtual instrument, or VI, where data and conclusions are presented parallel to the measurements. Comparing this structure to previous language-based systems, it is a significant advance. When using the "virtual instrument" idea, the same screen serves as the system's input and output stages and is often shown for the duration of the calibration run.

As the calibration system is controlled and data is acquired through the IEEE-488 (GPIB) interface, an appropriate device is needed to connect the controller to the GPIB bus. The National Instruments NI-488.2 has successfully implemented the AC-DC calibration program. This application employs a system that toggles input voltage between ordinary and calibrated voltage converters. This calibrated DC source calculates an error of an AC source voltage. A sequence is performed where the first is a measurement of the DC input signal; the second is the switching to the AC signal and taking another measurement back to the DC input signal. Assistance is in recording drifts or signal changes with time to calibrate the voltage of AC accurately.

4. GULFMET.EM-S3 Comparison with Other Metrology Institutes

NMCC validated the performance of its AC-DC transfer standards by participating in the GULFMET.EM-S3 comparison. This comparison evaluated the accuracy and reliability of AC-DC difference measurements among other NMIs. Notable participants included UME (Turkey), NIS (Egypt), NIMSA (South Africa), and SASO-NMCC (Saudi Arabia). The results of this comparison are given in Tables 1 and 2.

Table 1. Results of the comparison of 10 mV @ 1 kHz

NMI	AC-DC Difference (µV/V)	Uncertainty (µV/V)
UME	7	32
NMCC	-3	28
NMIA	-15	49
NIS	-16	41

Table 2. Results of the comparison of 3V@100kHz

NMI	AC-DC Difference (µV/V)	Uncertainty (µV/V)
UME	16.4	5
NMCC	18	10
NMIA	17	10
NIS	19	22

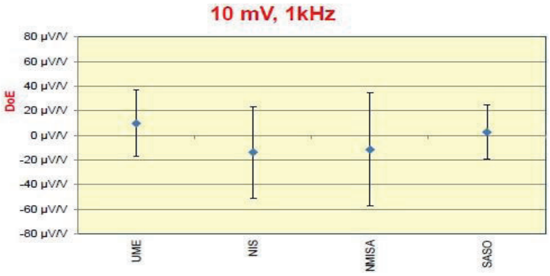


Fig. 7. Degree of Equivalences (DoE) @ 10 mV

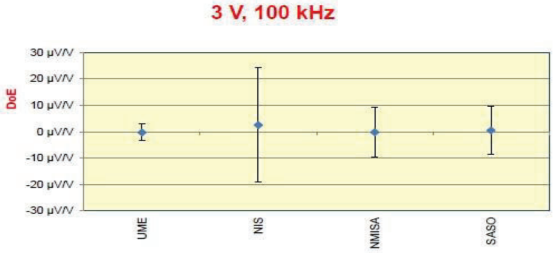


Fig. 8. Degree of Equivalences (DoE) @ 3V

The results showed good agreement among the participating institutes. All of the measurements were within the claimed uncertainties. Specifically, NMCC reported an AC-DC difference of -3 µV/V with an associated uncertainty of 28 µV/V at 10 mV which was the best uncertainty among all participant.

The agreement of these results proves NMCC's interoperability and precision of AC-DC transfer standards. This kind of comparison is critical to mutual recognition of calibration capabilities among NMIs, with a primary meaning only to support consistent and reliable measurements realized in different regions. Table 1 & 2 show some of the comparison results

5. Uncertainty Estimation

The uncertainties of NMCC’s AC-DC Difference Calibration Service are evaluated according to M 3003, the Expression of Uncertainty and Confidence in Measurement, Edition 1, 1997 [10]. The standard uncertainty of the measurement is obtained by summing up the uncertainty components using root-sum-of-squares.

The Type A uncertainty is coming from statistical analysis of a series of measurement. All other uncertainty components are considered as type B uncertainty. These two types are combined using the RSS technique to obtain the combined standard uncertainty. The final or expanded uncertainty provided to the customer or for NMCC standards in a re-characterization is calculated by multiplying the combined standard uncertainty by a coverage factor (K) of 2. This allow a level of confidence of nearly 95 % [11].

The software will determine the uncertainty by including the standard deviations of a result with the Type B components evaluated for a particular type of thermal converter at the voltage and frequency. This will assist in evaluating some of the uncertainties to the measurements made by the automated system. Formula (2) and (3) represent the model function for calculating the delta for 1V to 100V and 100V to 1000V respectively [12]

Table. 3 represent the uncertainty contribution according to model function

$$\delta_x = \delta_{diff} + \delta_{ref} + \delta_{con} + \delta_{con} + \delta_{sys} + \delta_{level}. \quad (2)$$

- For the 100 V–1000 V voltage range

$$\delta_x = \delta_{diff} + \delta_{ref} + \delta_{con} + \delta_{sys} + \delta_{level} + \delta_{equip} \quad (3)$$

Where:

δ_x	The test transfer standard's AC-DC transfer difference
δ_{diff}	The difference between the reference transfer standard and the actual AC-DC transfer test
δ_{ref}	The AC-DC transfer Difference of the reference transfer standard
δ_{con}	Difference in AC-DC transfer from the connectors and connections
δ_{sys}	Difference in AC-DC transfer from the measurement system
δ_{level}	Difference in AC-DC transfer from the thermal converter's voltage dependence
δ_{equip}	Differences in AC-DC transfer from the use of various devices

Table 3. Components of Uncertainty

$u(\delta_{diff})$	The standard deviation repeatability and measurement uncertainty. The distribution is normal.
$u(\delta_{ref})$	Uncertainty of the reference AC-DC transfer standard with normal distribution and k=2.
$u(\delta_{con})$	The uncertainty caused by connections in the system. This uncertainty includes the inaccuracies brought on by using various TEEs and wires. It has a rectangular distribution.
$u(\delta_{sys})$	uncertainty resulting from the measurement system's estimation of the value of "n" which expresses the voltmeters' linearity inaccuracy. It has rectangular distributed.
$u(\delta_{level})$	uncertainty from the voltage dependence in the thermal converters' operating range. It has a rectangular
$u(\delta_{equip})$	uncertainty caused by several equipment. It has a rectangular distribution.

Tables 4 and 5 contains example of the uncertainty budgets for the AC-DC Difference calibration services at 10 mV/55 Hz and 3 V/1 kHz, respectively.

Table 4. The uncertainty budget of 10 mV @ 55 Hz.

Symbol	Distribution	Divisor	Contribution
$u(\delta_{diff})$	Normal	1	2.0 µV/V
$u(\delta_{ref})$	Normal	2	23 µV/V
$u(\delta_{con})$	Rectangular	√3	2.0 µV/V
$u(\delta_{sys})$	Rectangular	√3	4.0 µV/V
$u(\delta_{level})$	Rectangular	√3	8.0 µV/V
Total Variance			165 (µV/V)2
Standard Uncertainty			12.5 µV/V
Expanded Uncertainty (K=2)			25.8 µV/V
Declared Uncertainty*			27 µV/V

Table 5. Uncertainty Budget of 3V @ 1 kHz

Symbol	Distribution	Divisor	Contribution
$u(\delta_{diff})$	Normal	1	3.0 µV/V
$u(\delta_{ref})$	Normal	2	30 µV/V
$u(\delta_{con})$	Rectangular	√3	0.2 µV/V
$u(\delta_{sys})$	Rectangular	√3	5.0 µV/V
$u(\delta_{level})$	Rectangular	√3	1.0 µV/V
Total Variance			11.86 (µV/V)2
Standard Uncertainty			3.42 µV/V
Expanded Uncertainty (K=2)			6.83 µV/V

Declared Uncertainty*	7.0 µV/V

Table 6. Extended Uncertainty Value Samples for Various Ranges and Frequencies

Voltage/Range	10 Hz	1 kHz	100 kHz	1 MHz
10mV /22mV	38	28	29	86
3V / 7V	11	7.0	10	28
1000V / 1000V	N/A	17	N/A	N/A

6. Conclusion

Due to the large number of tools and processes needed, a complete calibration system with high precision for AC voltage measurements and their applications is difficult to implement. The new automated calibration approach described in this study and technique recognizes this fact and the difficulty of accurately calibrating any heat transfer reference. This method makes it possible to calibrate the AC voltage with the help of high accurate nanovoltmeter and the AC-DC differences of the transfer standards. Significant high levels of automation provided by the new calibrating system result in great precision and confidence in NMCC and to be at the NMI capability level. This system deals with AC voltage measurements ranging from 2 mV to 1000 V at frequencies of 10 Hz to 1 MHz. the result of this system shows good agreement with the level of the NMIs. The system may achieve uncertainties in the wide range of voltage and frequency, from 6.0 µV/V to 86 µV/V. A chain of certified calibration certifications completed by accredited NMI with KCDB-published CMC has also helped NMCC, KSA to achieve AC voltage traceability.

References

[1] Mamdouh Halawa, A. Hassan, El-Sayed Shehab, El-Sayed Refai, "Integrated Calibration System for Accurate AC Current Measurements up to 100 kHz," *MAPAN, Journal Metrology Society of India*, July 2012.

[2] B. D. Inglis, "Standards for ac-dc transfer," *Metrologia,* 29, pp. 191-199, January 1992.

[3] F. C. Widdis, "Theory of Peltier- and Thomson-effect errors in thermal ac-dc transfer devices," *Proc. Inst. Elec. Eng.*, 109, pt. C (monograph 497 M) pp. 328-334, 1962.

[4] F. L. Hermach and E. S. Williams, "Thermal voltage converters for accurate voltage measurements to 30 megacycles per second," *Trans. AIEE (Comm. and Elec.)*, 79, pt. 1, pp. 200-206, July 1960.

[5] F. L. Hermach and E. S. Williams, "Thermal converters for audio-frequency voltage measurements of high accuracy," *IEEE Trans. Instrum. Meas.* IM-15, No. 4, pp. 260-268, December 1966.

[6] E. S. Williams, "Thermal current converters for accurate AC measurement," *IEEE Trans. Instrum. Meas.,* IM-25, No. 4, pp. 519-523, December 1976.

[7] E. S. Williams, "Thermal voltage converters and comparators for very accurate AC voltage measurements," *J. Res. Nat. Bur. Stand.*, 75C, pp. 145-154, July 1971.

[8] Thomas E. Lipe, "Operation and Reference Manual for the NIST AC-DC Calibration Systems and Software," *Natl. Inst. Stand. Technol*. NIST Special Publication 250-61, May 2004.

[9] Mamdouh Halawa and M. Rahal "A Step-Down Technique to Calibrate AC Current down to 10 µA Using a Precision 10 mA Current Shunt," *MAPAN, Journal Metrology Society of India*, Sept. 2012.

[10] M3003, The Expression of Uncertainty and Confidence in Measurement, Edition 1, December 1997, *UKAS.*

[11] EA-4/02, Expressions of the Uncertainty of Measurements in Calibration (previously EAL-R2), Apr. 1997.

[12] M. M. Halawa and Ahmed Hussein, "Improvement and Confirmation of a New Automatic System for AC-DC Calibration at NIS, Egypt" *Simposio de Metrologia, Mexico* Oct. 2006.