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RECENT IMPROVEMENTS IN AC-DC DIFFERENCE CALIBRATION AND TRACEABILITY ACHIEVEMENT FOR AC VOLTAGE MEASUREMENTS AT KINGDOM OF SAUDI ARABIA

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Abstract: This paper describes a technical survey on the new capabilities in AC-DC Difference calibration services and traceability achievement for AC voltage measurements at National Measurement and Calibration Center (NMCC), KSA. It provides information regarding the arrangement of a new automated calibration system and its operation. In addition, this paper provides instructions for building up calibration system and the associated expanded uncertainty. Although this paper provides a general background to thermal converters and AC-DC Difference measurements, it is really intended to assist the specialists in the everyday operation of the automated calibration systems.

Keywords: AC-DC Difference, Thermal Converters, Thermal Transfer Standards, Automated Calibration Systems, Uncertainty Calculations.

1. Introduction

Presently, ac voltage and current are most accurately measured by comparing the heating effects of the alternating signal to those produced by a known dc signal of a magnitude equivalent to that of the root-mean-square (rms) value of the ac quantity. The devices generally used to make this comparison are thermal voltage and current converters (TVCs and TCCs) which are useful, at various uncertainties, from a few hertz to many hundreds of megahertz. These devices usually consist of a thermoelement (TE) either in series with a resistor (for voltage measurements as a TVC) or in parallel with a shunt resistor (for current measurements as a TCC). A thermoelement is composed of a heater structure, which alternately carries the ac and dc signals to be compared, and from one to several hundred thermocouples spaced along the heater. By applying ac and both polarities of dc in sequence, and measuring the thermocouple output, one can use the conventional definition of ac-dc difference, δ, in parts in 10^6 as:

$$\delta = \left(\frac{Ea - Ed}{Ed}\right) x\ 10^6 \quad (1)$$

Where Ed is that value of DC which, when applied with positive and negative polarities,

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produces the same mean response as the rms AC quantity *Ea* [1].

Present commercially available AC-DC thermal transfer standards are commonly based on either single-junction thermal converters (SJTCs) [2-6] or solid-state transfer standards [7]. The SJTCs have one thermocouple fixed to the heater wire, outputs of 7 mV to 12 mV for full-scale input, and respond in a roughly square-law manner to changes in the input signal. These are existed in a wide range of commercial instruments and are useful from about 10 Hz to about 100 MHz. The best uncertainty for these devices, exclusive of the measurement process and any range or shunt resistors, is a few microvolts- per-volt (μV/V) or better at audio frequency and full-scale input. The uncertainty increases at the extremes of the frequency range and at input levels below about half of full scale [8].

2. NMCC Calibration Service for Thermal Transfer Standards

Currently, NMCC provides calibration services for AC-DC thermal transfer instruments at voltages from 1 V to 1000 V under wide range of frequencies from 10 Hz to 1 MHz. Samples of values of AC-DC Differences, associated with the expanded uncertainty at a confidence level of ≈ 95% (k = 2), are listed in Table 1.

The characterizations of thermal transfer standards of NMCC over the different uncertainties are based on:

- A group of AC measurement standards consists of:

i. A set of Multi-junction Thermal Converters (MJTC), as shown in Figure 1, to cover the range from 1 V – 1000 V @ frequencies from 10 Hz – 1 MHz.

ii. Fluke 792A AC/DC Transfer Standard, as shown in Figure 2, to act as an ultra-high accuracy AC/DC Thermal Transfer Standard and provides a wide voltage range of 2 mV to 1000V, and a wide frequency range of 10 Hz to 1 MHz.

- Range-to-range build-up measurements, as shown in Figure 3 to transfer the accuracy of measurements among the different in-between ranges from 1 V to 1000 V using a new automated calibration system.

A build-up method includes the calibration of the thermal converter at half the nominal voltage (or at its lowest value applicable) by using a basic level Thermal Voltage Converter (TVC), and thereafter use of the calibrated converter in the calibration of the closest lower level TVC at half its nominal voltage (or at its lowest value applicable) [9]. In this way, all converters up to 1000V are calibrated in a chain by using 3 V basic level of thermal converter. The thermal converters used in the voltage range of 1V–3 V are of the basic level, and have been calibrated by TÜBİTAK UME (Turkey) in our case. These converters are compared to each other and rechecked for 3 years period. If the difference between the results and the specified values of certificate are found above the limits stated for the uncertainty in the certificate, TVCs are recalibrated again using the same manner.

Table 1: AC-DC Differences & Uncertainties

Voltage	Frequency	AC-DC Diff. (μV/V)	Uncertainty, (μV/V)
1 V	10 Hz	2.1	9.0
	20 Hz	-0.3	7.6
	30 Hz	-0.7	7.6
	40 Hz	0.2	3.7
	500 Hz	0.9	3.5
	1 kHz	-4	3.6
	10 kHz	6.3	3.4
	20 kHz	-3.2	3.5
	50 kHz	6	4.0
	70 kHz	7.8	6.3
	100 kHz	8.9	6.3
	200 kHz	15.8	12
	500 kHz	25.5	16
	700 kHz	34.4	22
	1 MHz	36.5	27

Voltage	Frequency	AC-DC Diff. (μV/V)	Uncertainty, (μV/V)
10 V	10 Hz	0.6	9.2
	20 Hz	0.7	7.6
	30 Hz	1.2	7.6
	40 Hz	1.1	3.3
	500 Hz	-1.5	3.3
	1 kHz	-0.4	3.3
	10 kHz	0.1	3.3
	20 kHz	0.4	3.3
	50 kHz	-2.2	3.3
	70 kHz	-2.1	5.2
	100 kHz	-3.3	5.2
	200 kHz	-13.0	12
	500 kHz	-53.6	16
	700 kHz	-94.3	22
	1 MHz	-185.1	27

Voltage	Frequency	AC-DC Difference, (μV/V)	Uncertainty, (μV/V)
100 V	10 Hz	-5.1	11
	20 Hz	-8.3	9.9
	30 Hz	-5.0	9.9
	40 Hz	-1.0	3.8
	500 Hz	5.1	3.6
	1 kHz	-12.2	3.5
	10 kHz	6.9	3.5
	20 kHz	11.1	3.6
	50 kHz	16.0	3.5
	70 kHz	22.0	5.3
	100 kHz	36.7	5.3
	200 kHz	75.6	13
	500 kHz	82.5	18
	700 kHz	12.0	24
	1 MHz	-189.4	29

Voltage	Frequency	AC-DC Diff. (μV/V)	Uncertainty, (μV/V)
400 V	10 Hz	-0.1	12
	20 Hz	-1.9	11
	30 Hz	2.1	11
	40 Hz	7.3	3.9
	500 Hz	11.2	3.8
	1 kHz	-3.4	3.8
	10 kHz	16.6	3.7
	20 kHz	20.6	3.7
	50 kHz	19.7	3.7
	70 kHz	17.4	5.4
	100 kHz	19.9	5.4
	200 kHz	-9.0	14
	500 kHz	-2.1	18
	700 kHz	-73.6	25
	1 MHz	-275.7	30

Fig. 1: NMCC Thermal Converters (MJTC)

Fig. 2: Fluke 792A AC/DC Transfer Standard

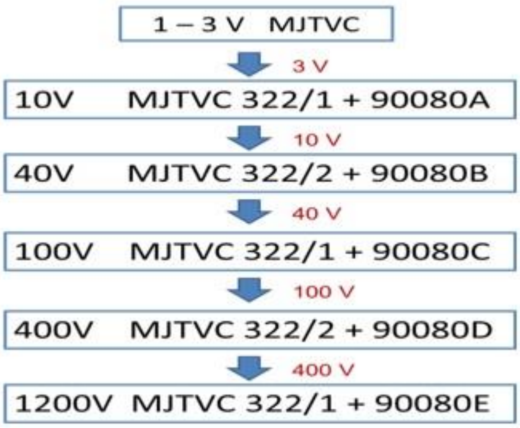


Fig. 3a: Chain of Range-to-range Build-up Measurements

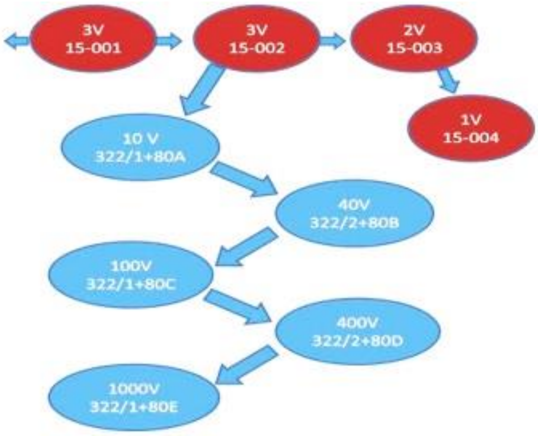
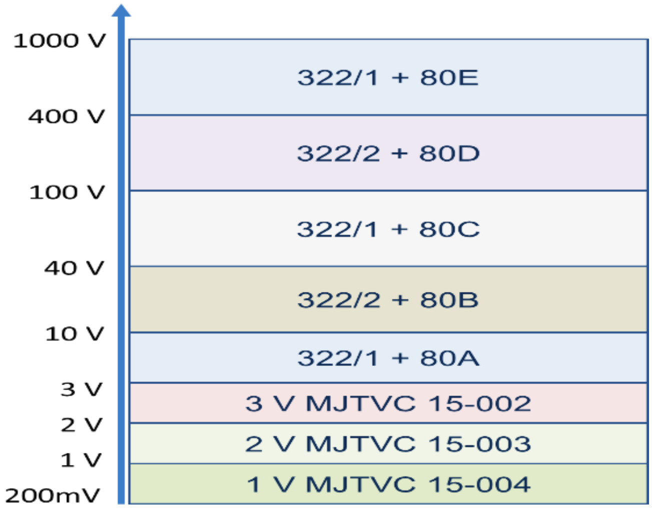


Fig. 3b: Range-to-range build-up measurements

In general, Figure 4 summarizes the AC Standards of NMCC in this area.



Where

- 90080A: Multiplier Resistor for 10 V
- 90080B: Multiplier Resistor for 40 V
- 90080C: Multiplier Resistor for 100 V
- 90080D: Multiplier Resistor for 400 V
- 90080E: Multiplier Resistor for 1200 V

Figure 4: Summarizes the AC Standards of NMCC

3. Automated Calibration System for AC- DC Transfer Difference at NMCC

The NMCC reference standards for AC-DC Difference calibration are a group of Ballantine single-junction thermal converters (SJTCs) and Multijunction Thermal Voltage Converter (MJTVC) to cover a wide range of voltage and frequencies. Those converters composed of single junction thermoelements (or thin film multi junction) which used in series with high precision multiplying resistors for voltages greater than 0.5 V. To confirm the reliability of those standards, NMCC has participated in bilateral comparison with UME, Turkish in the range of 22 mV to 1000 V at frequencies from 20 Hz to 20 kHz.

AC-DC transfer difference is determined by using the AC-DC transfer difference of a reference AC-DC Transfer Standard. Appropriate AC and DC voltages are applied respectively to the reference and test AC-DC transfer standards, which are connected in parallel; AC-DC transfer differences of the test standard are calculated by using DC voltages measured at their outputs, input- output characteristic parameters and transfer differences for the reference standard. The transfer differences are determined at the central point of the Tee connector and in a timed sequence of (AC, DC+, DC-, AC).

The present version of NMCC automated calibration system was assembled and used for routine calibrations beginning in 2016 and in accordance with the agreement of a scientific project between NMCC and UME, Turkish. As shown in Figure 5, this system has very stable and precise sources of AC and DC voltage and a method of monitoring the outputs of the thermal converters with adequate precision. In this system, the AC and DC signals are provided by two separate multifunction calibrators. The measurement signals are then distributed for the two transfers (the standard and the unit under test) by using a tee connector. The millivolt-le vel output electromotive forces (emfs) of the thermal converters are monitored using sensitive, low-noise digital nano-voltmeters.

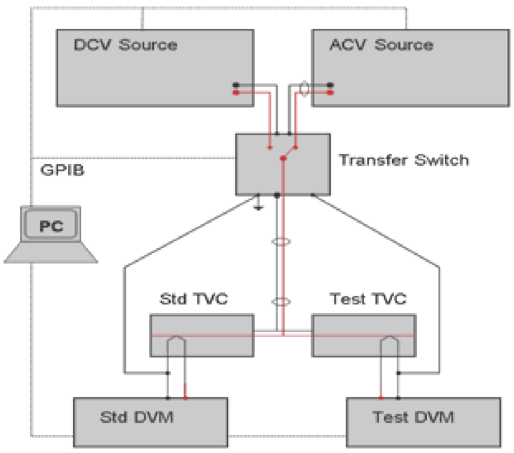
Various arrangements of AC and DC voltmeters and frequency counters are used to monitor the performance of the systems. The calibration system is full automated and controlled by Laptop computer (using LabVIEW environmental), which controls all the operations during the calibration procedure. Final data and results are displayed in a real Excel Sheet program. All data are written to the defined sections of the screen, so that the calibration information is readily available to the user.

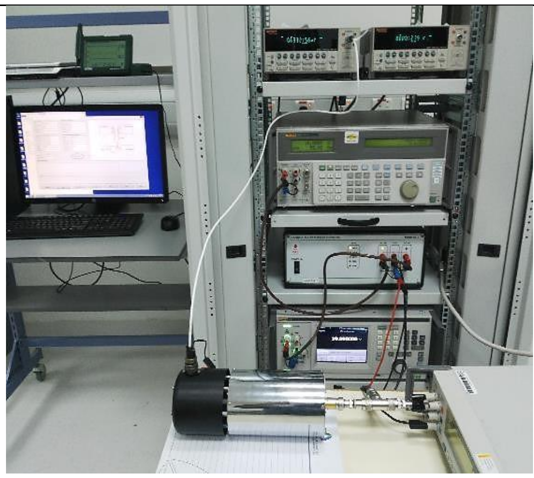
The calibration systems are controlled by computer system running National Instruments' LabVIEW software. LabVIEW is a graphics-oriented system control package, which acts as a “virtual instrument” (VI) during the calibration procedure, displaying data and results in real time as the measurements proceed. This arrangement is a significant improvement over any other language-based systems. With the "virtual instrument" concept, the same screen is displayed for the entire calibration run (in most cases) and acts as both the input and output stages of the system.

Because the calibration system is controlled and data acquired via the IEEE-488 (GPIB) interface, a suitable tool for interfacing the controller with the GPIB bus is required. The AC-DC calibration software has been successfully implemented using the National Instruments NI-488.2 software suite of GPIB drivers controlling the following interfaces:

- National Instruments GPIB-PCI PCI card on Windows computers.
- National Instruments GPIB-USB adapter, on Windows computers

Figure 6 summarizes all the precise equipment used in this system.





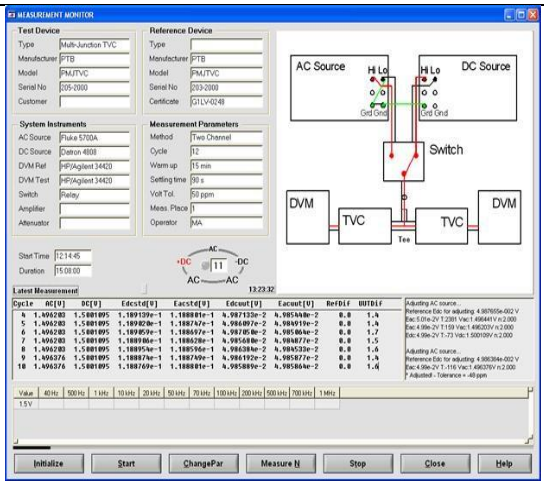


Fig. 5: A new Automated Calibration System in NMCC

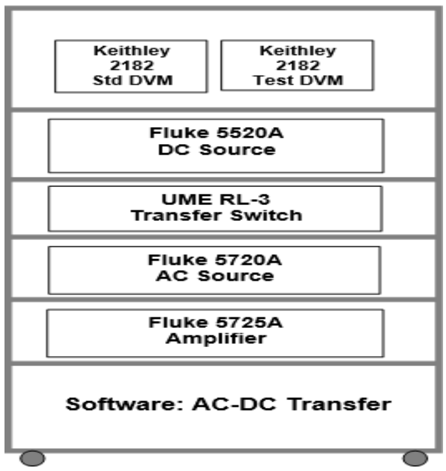


Fig. 6: Equipment Used in Calibration System

4. Technical Applications of the Automated Calibration System

As stated before, high precision AC electrical metrology is organized around devices so called

AC-DC thermal converters. These devices are designed to compare heating effects produced by AC wave and DC voltage on a resistor. Two main type of this standards used widely are vacuum thermocouple and electronic sensor-based converters. The output voltage of a vacuum-junction thermal converter follows a square low via input. General input-output relation of a thermal converter can be expressed as:

$$E = KV^{n} \qquad (2)$$

Where:

- E = output emf of TVC
- K = certain constant
- V = applied voltage on the TVC
- n = characteristic value

The characteristic value n of a thermal converter is used in measurement procedures and should be calculated. Its value can be calculated approximately by using formula:

$$n = (dE.V / E.\ dV) \qquad (3)$$

Where:

- V = Nominal of applied voltage
- dV = Change of the nominal input voltage, usually 1% of the V
- E = Output emf of TVC
- dE = Change of output voltage after changing the input voltage by dV

Typically, characteristic value n is 1.6 – 1.9 for a vacuum-junction thermal converter and 1 for electronic sensor based thermal standards, for example Fluke 792A.

The design philosophy used in this automated system software lets us to apply four technical applications in the area of AC Voltage measurements. The following sub- titles will describe these applications briefly:

4.1 Calibration of AC-DC Difference

In this application, the "standard" and the "tested" voltage converters are connected in parallel via proper tee. Outputs of the converters are measured directly with sensitive digital voltmeters. AC and DC voltages are applied to the converters through a fast AC-DC transfer switch to provide continuous voltage signal to the two TVCs. For measurements of voltages higher than 100 V, a power amplifier can be used behind the AC-DC switch to amplify the AC and the DC signals.

As shown in Figure 7, note that the guards of the sources are grounded together with the input and output lows of the voltage converters. If a guarded AC-DC standard is used, (Fluke 792A, for example), its guard also must be connected to the common point. In addition, measurement system should be located in a stable temperature-humidity environment, mechanical vibration should be avoided and all connections should be good tided.

First step of the measurement procedure is determining input-output sensitivity characteristic "n" of both "tested" and "standard" converters at working voltage. At each particular frequency, AC and DC voltage sources are adjusted initially to produce as close outputs as possible on the "tested" converter and then applied in sequence AC, DC+, DC-, AC and output of the converters are measured for each voltage. Output emf of the thermal converters should be measured after at least 60 sec period of changing voltage applied to. Note that several measurement of AC-DC transfer difference should be repeated at each frequency and final result calculated as the mean value of these measurements.

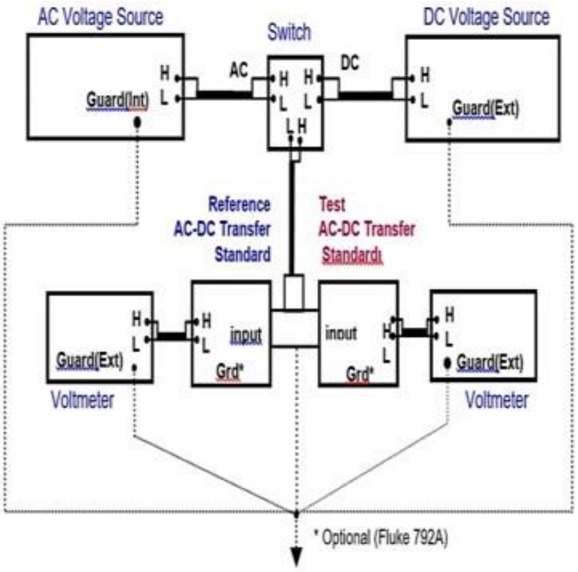


Fig. 7: Set-up of AC-DC Difference Calibration

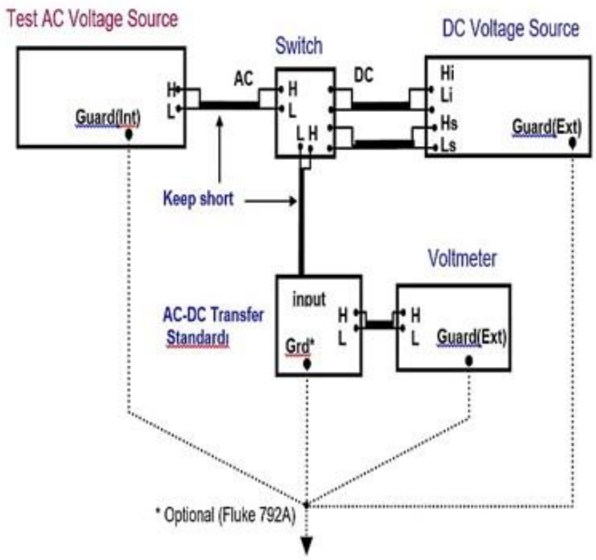


Fig. 8: Set-up of AC Function of Calibrator

Formula used to calculate AC-DC Difference of "tested" TVC is given as:

$$\delta t = \frac{Eas - Eds}{ns \ Eds} + \frac{Eat - Edt}{nt \ Edt} + \delta s \qquad (4)$$

Where:

- δt = AC-DC transfer difference of the "tested" voltage converter.
- δs = AC-DC transfer difference of the "standard" voltage converter.
- Eas, Eds = the output emfs of the "standard" converter when applied AC and DC voltage.
- E_{at}, E_{dt} = output emf of the "tested" converter when applied AC and DC voltage respectively.
- ns, nt = input-output characteristics parameters of "standard" and "tested" converter

respectively.

4.2 Calibration of AC Function of Calibrator

As shown in Figure 8, the tested AC voltage source is firstly applied to the thermal converter, and then DC source is adjusted to produce as close as possible an output on the transfer standard to those produced by the tested AC voltage. When DC source is adjusted to produce output on thermal converter as close as at least 50 ppm to those produced by AC voltage, measurement cycle beginning by applying AC and DC voltages to the transfer standard in sequence: AC, DC-, DC+, AC. At the end of this process, the "Error Value" of the AC voltage source is determined by the following equation:

$$\delta t = \frac{Vdc - Vac}{Vdc} + \frac{Eac - Edc}{n * Edc} + \delta s + Cd \tag{5}$$

Where:

- Vdc, Vac = settings of DC voltage source and tested AC voltage source respectively
- Eac, Edc = output emfs of the "standard" AC-DC transfer standard when applied AC and DC voltage respectively
- n = transfer value of transfer standard
- δs = AC-DC transfer difference of the "standard" transfer standard
- Cd = Correction value of the DC source.

4.3 Calibration of AC Voltage Meter

As shown in Figure 9, AC voltage source is firstly applied to the thermal converter, and then DC source is adjusted to produce as close as possible output on the transfer standard to those produced by the AC voltage. When DC source is adjusted to produce output on transfer standard as close as at least 50 ppm to those produced by AC voltage, measurement cycle beginning by applying AC and DC voltages to the transfer standard and the "tested AC voltmeter" in sequence: AC, DC-, DC+, AC. At the end of this process, the "Error Value" of the AC source is determined by the following equation:

$$\delta_{tc} = \frac{V_{dc} - V_{ac}}{V_{dc}} + \frac{E_{ac} - E_{dc}}{n * E_{dc}} + \delta_s + C_d \tag{6}$$

Where:

- V_{dc}, V_{ac} = settings of DC voltage source and AC voltage source respectively.
- Eac, Edc = output emfs of the reference transfer standard when applied AC and DC voltage respectively

- n = characteristic value of the reference transfer standard
- δs = AC-DC Difference of the reference transfer standard
- Cd = Correction value of to the DC voltage source

At the end of this process, the "Error Value" of the AC Voltmeter is determined by the following equation:

$$\delta tm = \frac{\text{Vmr} - \text{Vac}}{\text{Vac}} \quad (7)$$

Where:

Vmr = Reading of the tested AC Voltmeter, Vac = Applied AC voltage.

Positive error indicates that measured ac voltmeter reads higher than nominal at given voltage/frequency point.

5. Traceability of AC Voltage Measurements

A key concept of measurement technology is that of traceability, which means that all measurements made with a calibrated instrument or device must have a directly traceable link back to the defined quantity. The direct relationship is provided by a traceability chain, each link of which is represented by a calibrated measurement standard. The first link in the chain must be a national standard, such as those held or maintained/provided by National Metrology Institutes (NMIs). All users of traceably calibrated measuring devices or instruments can therefore be quite certain that they really are using the same unit. The chain can be extended to any number of links, although each additional link increases the uncertainty value.

Indeed, one of the difficulties faced by said NMI, is the provision of traceable AC voltage measurements. Therefore, NMCC was keen to achieve a proper traceability in this field using a new set of MJTC. Multijunction Thermal Converters have long been used in many international laboratories as primary standards for AC-DC difference measurements because of their extremely small AC-DC Differences in the audio frequency range. Fortunately, it was a great opportunity for NMCC to take advantage of the scientific project with the Turkish side (UME) in achieving the reliability by completing its capabilities through a set of advanced equipment as well as during a series of successive accredited and traceable calibration. Figure 10 shows the chain of this traceability.

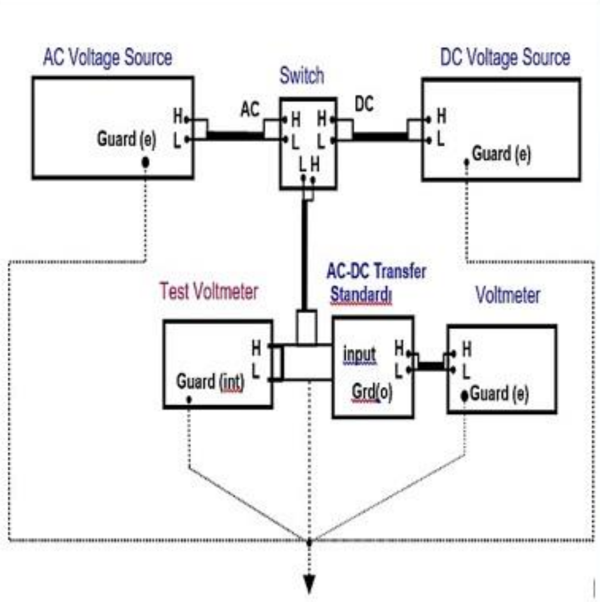


Fig. 9: Set-up of AC Function of Voltmeter

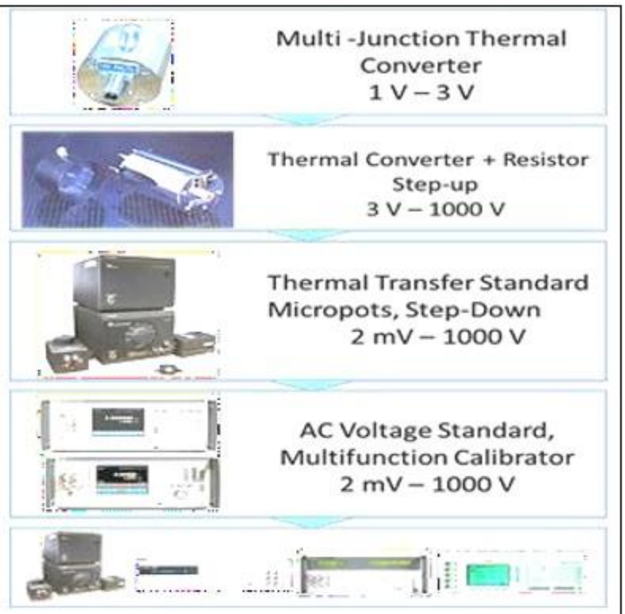


Fig. 10: AC Voltage Traceability in NMCC

7. Uncertainty Estimation

The uncertainties quoted by the NMCC for AC-DC Difference Calibration Service are calculated in accordance with M 3003, the Expression of Uncertainty and Confidence in Measurement, Edition 1, 1997 [10]. The combined standard uncertainty of a measurement is the root-sum-of-squares (RSS) method of combining uncertainty components as standard deviations. These uncertainty components may be evaluated as either Type A or Type B, where the former can be evaluated using statistical means and the latter cannot.

For a determination of AC-DC Difference using a NMCC automated calibration system, the Type A uncertainty is the standard deviation of the points that are averaged to determine the AC-DCDifference. The contributions to the uncertainty arising from the thermal converters themselves and the measurement system are evaluated as Type B components. These two uncertainty components are combined using the RSS method to calculate the combined standard uncertainty. The expanded uncertainty (the "final" uncertainty provided to the customer or forNMCC standards in a re- characterization) is the combined standard uncertainty multiplied by a coverage factor (k) of 2, corresponding to a confidence level of approximately 95 % [11].

To assist in assigning uncertainties to the measurements made by the automated system, the software will automatically calculate the uncertainty by combining the standard deviations of a determination with the Type B components previously evaluated for a particular type of thermal converter at a voltage and frequency combination. Practically, the MODEL

FUNCTION of uncertainty calculations has been estimated as follows [12]:

- For (1 V – 100 V) voltage range

δx = δdiff + δref + δcon+ δsys + δlevel

- For 100 V – 1000 V voltage range

δx = δdiff + δref + δcon+ δsys+ δlevel + δequip

Where:

δx	AC-DC transfer difference of the test transfer standard
δdiff	AC-DC transfer difference between the test and the reference transfer
δref	AC-DC transfer difference of the reference transfer standard
δcon	AC-DC transfer difference due to the connections and connectors
δsys	AC-DC transfer difference due to the measurement system
δlevel	AC-DC transfer difference due to voltage dependence of the thermal converter
δequip	AC-DC transfer difference due to use of different equipment

The components of both Type A and Type B uncertainties are stored in tab-delimited data files as described in Table 2.

Table 2: Uncertainty Components

U (δdiff)	Standard deviation uncertainty of repeated measurements, repeatability. It is normal distribution.
U (δref)	Calibration uncertainty of reference AC-DC transfer standard. Standard is calibrated by UME and the uncertainty of the measurement is stated as standard uncertainty multiplied by the coverage factor k = 2 which for a normal distribution, corresponds to a confidence level of approximately 95%.
U (δcon)	Uncertainty due to the connections in the system. The errors caused by the use of different TEE and cables are included in this uncertainty. Its distribution is rectangular.
U (δsys)	Uncertainty due to determination of the value of "n" caused by the measurement system, the uncertainty expressing the linearity error of voltmeters. Its distribution is rectangular distribution.
U (δlevel)	Uncertainty due to the voltage dependence in the range of which the thermal converters are used. Its
U (δequip)	Uncertainty due to the use of different equipment. Its distribution is rectangular.

For instance, the uncertainty budgets for the Calibration services of AC-DC Difference, at 100 V/200 kHz and 1000 V/10 Hz, are given in "Uncertainty Budget Form" as listed in Table 3 and 4 respectively. Table 5 summarizes samples of the expanded uncertainty declared for this application at different ranges and Frequencies.

Table 3: Uncertainty Budget of 100V @ 200 kHz

Symbol	Distribution	Divisor	Contribution
U (δ_{diff})	Normal	1	9.0 µV/V
U (δ_{ref})	Normal	2	42.3 µV/V
U (δ_{con})	Rectangular	1.732	1.3 µV/V
U (δ_{sys})	Rectangular	1.732	8.3 µV/V
U (δ_{level})	Rectangular	1.732	0.0 µV/V
Total Variance			60.9 (µV/V)^2
Standard Uncertainty			7.8 µV/V
Expanded Uncertainty (K=2)			15.6 µV/V
Declared Uncertainty*			16 µV/V

*(According to ILAC P14:01/2013, uncertainty values should be reported to two significant figures)

Table 4: Uncertainty Budget of 1000 V @ 10 Hz

Symbol	Distribution	Divisor	Contribution
U (δ_{diff})	Normal	1	16.0 µV/V
U (δ_{ref})	Normal	2	72.3 µV/V
U (δ_{con})	Rectangular	1.732	0.3 µV/V
U (δ_{sys})	Rectangular	1.732	5.3 µV/V
U (δ_{level})	Rectangular	1.732	8.3 µV/V
U (δ_{equip})	Rectangular	1.732	8.3 µV/V
Total Variance			110.6 (µV/V)^2
Standard Uncertainty			10.52 µV/V
Expanded Uncertainty (K=2)			21.03 µV/V
Declared Uncertainty			21 µV/V

Table 5: Samples of expanded Uncertainty values for different ranges and Frequencies

Range	10 Hz	100 Hz	100 kHz	1 MHz
0.1 V / 0.2 V	12	5	10	45
0.3 V / 0.5 V	12	5	10	45
0.6 V / 0.7 V	10	5	10	45
1 V	7	3	4	33
2 V / 3 V	7	3	4	33
4 V / 5 V	10	5	5	37
6 V / 7 V	10	5	5	37
10 V	10	5	5	40
20 V	12	5	7	40
30 V	15	6	7	45
40 V / 50 V	15	6	10	NA
60 V / 70 V	20	8	15	NA
100 V	20	10	15	NA
200 V / 300 V	25	10	25	NA
500 V / 600 V	35	15	35	NA
1000 V	35	20	NA	NA

8. Conclusion

The full calibration systems for the services of accurate AC voltage measurements and its applications are challenging due to the big number of equipment and procedures required. The new automated calibration system that described in this work and technique address both this reality and the challenge of accurate calibration of any type of thermal transfer standards. The technique allows for calibration of the AC-DC Differences of the transfer standards, AC function of multi-product calibrator and the AC function of the highly sensitive digital multimeters. The new calibration system, which designed in NMCC to be in the level of NMI capabilities, offers high level of automation results in a high level of accuracy and repeatability. This system covers the applications of AC voltage measurements in the range of 1 – 1000 V at frequencies from 10 Hz – 1 MHz. The expanded uncertainty of this area exhibits good agreement with the NMI's level. The system is capable to yield uncertainties between 3 µV/V and 35 µV/V among the wide range of voltage and frequency. In addition, the AC voltage traceability in KSA has been achieved through a variety of advanced equipment and a chain of accredited calibration certificates performed by the UME, Turkish.

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