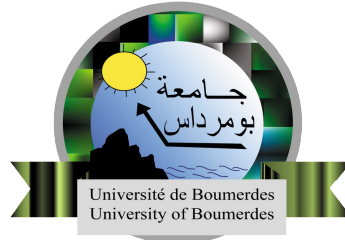


**PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC
RESEARCH**

UNIVERSITY M'HAMED BOUGARA - BOUMERDES



**INSTITUTE OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

PROJECT REPORT PRESENTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS OF THE DEGREE OF:

'MASTER'

IN POWER ENGINEERING

**IMPLEMENTATION OF DIGITAL
MULTIMETERS CALIBRATION TEST**

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Abstract

Electrical calibration is a crucial process that ensures the accuracy and reliability of electrical measuring instruments. This project introduces the importance of electrical calibration and provides an overview of it, a historical review traces its evolution, techniques and their impact on the industry, discussing the accreditation bodies that provide recognition to calibration laboratories. It also highlights the significance of following international guides and standards for calibration procedures and challenges. Different methods of electrical calibration are explored, accompanied by practical examples. The focus is on understanding the materials and equipment used in calibration processes, as well as the concepts of precision, accuracy, and error analysis. The evaluation of uncertainties and methods to analyze and minimize them are also discussed. This paper also delves into the implementation of two distinct calibration tests. The first test explores the direct method calibration conducted in a laboratory setting, emphasizing the meticulous steps involved in calibrating electrical instruments. The second test examines the on-site comparative method, which involves comparing the measurements of the unit under test (UUT) with a reference instrument. The collected calibration data is analyzed and evaluated. The results are compared against the accepted tolerance range to determine compliance. The uncertainties associated with the measurements are also calculated and discussed. Additionally, graphical representations of the data aid in visualizing the calibration results and facilitate a comprehensive understanding.

Dedication

In the name of Allah, the Most Gracious, the Most Merciful.

I would like to begin by expressing my deepest gratitude to Allah, the Almighty, for His blessings, guidance, and mercy throughout this journey.

I extend heartfelt appreciation to my beloved mother, who has been my rock and constant support since the day I was born. Her unwavering love, sacrifices, and dedication have shaped me into the person I am today. My deepest gratitude to my father, whose presence in my life has been a source of strength and inspiration. His guidance, wisdom, and unwavering support have played a significant role in my personal and academic achievements.

Furthermore, I extend my gratitude to my sisters, brother, my LL and all my family members for their love and support. To my friends, whose companionship, laughter, and shared experiences have enriched my life.

To my loved ones. May Allah bless and keep you with me always.

Souhaib Boukabes

Dedication

I dedicate this work to the person who believed in me my mother, to my father who taught me the importance of hard work, to my brothers ,sister and my cousins Redhouane Elhankes, Amine Elboudi and Hamza who always supported me.

To my companion Souhaib who has been a constant source of inspiration and motivation throughout this challenging journey, to my classmates Elhocine, Boulahia, Moh, Hamza Professor, Oussama Bouboun, Amine kakhi ,oussama Dakich, Kamar, Zahia, Amina, Kahina, Soumeya and Skala who provided a nurturing environment for intellectual exchange and camaraderie, to my friends outside the university Samy, Mjld, Achraf, Baziz and Moujeb Westy for their unwavering support and encouragement.

Finally special dedication for Ami Mourad who carried us in the toughest times in our five years Master's journey.

Youssef Mahmoudi

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List of Abbreviations

AC	Alternative Current
ALGERAC	The Algerian Accreditation Organization
ANSI	American National Standards Institute
CAB	Conformity Assessment Bodies
CEN	European Committee for Standardization
Cofrac	Comité Français d'Accréditation
DC	Direct Current
DMM	Digital Multi Meter
EA	European Accreditation
ENIE	Entreprise Nationale des Industries Electroniques
GUM	Guide to the Expression of Uncertainty in Measurement
IEC	The International Electrotechnical Commission
ISO	The International Organization for Standardization
JCGM	Joint Committee for Guides in Metrology
NAB	National Accreditation Bodies
NCSLI	National Conference of Standards Laboratories International
OTC	Optical Test and Calibration
OL	Over Load
RM	Reference Multimeter
SDO	Standards development organizations
UUT	Unit Under Test
UKAS	United Kingdom Accreditation Service

List of Symbols

d	Density	(g/cm^2)
M	Mass	(g)
T	Time	(s)
S	Speed	(m/s)
V	Voltage	(V)
I	Current	(A)
R	Resistance	(Ω)
P	Power	(W)
C	Capacitance	(F)
L	Inductance	(H)
f	Frequency	(Hz)
T	Temperature	(K)
E	Electric Field Strength	(V/m)
B	Magnetic Field Strength	(T)
μ	Permeability	(H/m)
ϵ	Permittivity	(F/m)
Z	Impedance	(Ω)
ω	Angular Frequency	(rad/s)
ρ	Resistivity	$(\Omega \cdot m)$

General Introduction

Metrology is “the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology,”[1]. It establishes a common understanding of units, crucial in linking human activities. It is the foundation for the development of any science, the design of any product, the manufacture of any artifact, and the delivery of any service. It assures the interchangeability of products and services, which is the basis of international trade. It provides a bridge between science and technology.

Calibration, on the other hand, involves comparing a measurement device or system with a traceable standard of known accuracy. Its primary objective is to verify the accuracy and reliability of the measurement system or device being tested. Through calibration, adjustments are made to ensure that the measurement system meets its specified accuracy[2].

Electrical measurement devices are extensively utilized across various sectors, including medical and pharmaceutical, manufacturing, construction, and many others. These industries often demand the highest level of accuracy in their measurement processes. Therefore, it is essential to calibrate and maintain electrical measurement devices periodically to ensure their optimal performance with the utmost precision and reliability.

There are two essential processes types Primary and Secondary electrical calibration, both are important in ensuring accurate and reliable measurements in the field of electrical metrology. These calibration procedures are used to establish and verify the performance of electrical measurement instruments. Primary electrical calibration is the highest level of calibration performed using precise reference standards maintained by national metrology institutes. It involves direct comparison between the instrument under test and these accurate standards. Secondary electrical calibration, on the other hand, is performed by accredited calibration laboratories using equipment calibrated at the primary level. It ensures that instruments meet specified accuracy requirements by validating and adjusting their performance. Both primary and secondary calibration processes are crucial for maintaining accurate measurements and traceability in electrical metrology.

Chapter 1

Introduction to calibration

1.1 Introduction

Calibration is particularly important operation in industries such as manufacturing, healthcare, and transportation, where accuracy and precision are critical for ensuring the quality and safety of products and services. In order to guarantee that, calibration laboratories need to have accreditation by recognized organizations such as The Algerian Accreditation Organization (ALGERAC), United Kingdom Accreditation Service (UKAS), Dubai Accreditation Center (DAC) and many other organizations can help to ensure that a calibration laboratory is meeting internationally recognized standards and guidelines for quality and competence. Accreditation demonstrates that a laboratory has undergone a rigorous assessment of its technical competence and management system, and can provide assurance to customers that the laboratory is capable of producing accurate and reliable calibration results. It is important for organizations to stay up-to-date with the latest standards and guides related to calibration, and to continuously evaluate and improve their calibration processes to ensure that they are meeting the highest standards of quality and accuracy. By following these standards and guides, calibration laboratories can help to ensure the safety of human and equipment and improve the quality and reliability of the products and services they provide.

1.2 A Historical Review

The concept of measurement can be traced back to ancient civilizations where human used to use body parts for measuring length such as the length of a foot, the length of a stride and the breadth of a thumb, which was not a very accurate method to measure due to the differences in body parts for a person to another, this led the Egyptians to develop the cubit rod for linear measurement and many other quantities like the water clock for tracking time.

During the 17th century, the development of modern scientific instruments marked a significant milestone in the history of measurements. Among these advancements, Galileo Galilei invented the thermoscope, which served as a precursor to the modern thermometer. Interestingly, it was during this century that the word "calibrate" first used to describe the process of adjusting a gun's barrel for accurate firing. As the 18th century unfolded, the term "calibration" began to be used more broadly to encompass the adjustment of various measuring instruments to ensure their accuracy. Notably, Pierre-Simon Laplace, a French mathematician

Chapter 1. Introduction to calibration

and physicist, made noteworthy contributions during this period by introducing the concept of error propagation in measurements, highlighting the importance of evaluating and correcting errors to enhance overall accuracy.

The Industrial Revolution in the 19th century led to a greater demand for precise measurements in various fields, including manufacturing and science. Standards and reference materials were developed to establish a consistent basis for measurements. The International Prototype of the Meter (a platinum-iridium bar) was created in 1889 as the standard for length measurement for example. By the 20th century, world witnessed remarkable progress in calibration techniques and practices. The introduction of electronic instruments and devices brought new challenges and requirements for calibration, that is why National metrology institutes were established in many countries to develop and maintain measurement standards.

Today, metrology in general and calibration specifically become an essential part of many industries, including manufacturing, healthcare, and environmental protection. which led to huge advancement in Calibration to ensure that measuring instruments are as accurate and reliable as possible, which is essential for ensuring the quality of products and services.

1.3 Standards development organizations

Standards development organizations (SDOs) are specialized organizations that develop and publish standards and guidelines that establish specifications, guidelines, procedures for products, processes, and services in various industries and technologies. These standards provide a common language, consistent practices, and a framework to guarantee quality, safety, and efficiency. SDOs can be either international, regional, or national in scope, and may function under the aegis of governmental organizations, professional associations, or autonomous bodies. some of the main organizations are:

The international Electrotechnical Commission (IEC)

Founded in 1906, the IEC is the world's leading organization for the preparation and publication of international standards for all electrical, electronic and related technologies. These are known collectively as "electrotechnology"[3].

The International Organization for Standardization (ISO)

ISO is an independent, non-governmental international organization with a membership of 168 national standards bodies. Through its members, it brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges[4].

IEC and ISO are the two most well-known international SDOs, while institutions like the European Committee for Standardization (CEN), the British Standards Institution (BSI), and the American National Standards Institute (ANSI) are examples of regional and national SDOs. Standards development organizations make standards through a consensus-based process that involves input from a variety of stakeholders, including industry experts, government agencies, consumer groups, and other interested parties. They base their standards on a variety of factors, including scientific research, industry best practices, regulatory requirements, and stakeholder input.

1.4 Accreditation Organization

To guarantee high performance and quality of calibration services, laboratories undergo accreditation by recognized accreditation organizations. Having accreditation by those organizations is essential for laboratories, it demonstrates that they are technical proficient, adherence to the highest international standards, delivers accurate and reliable measurements and testing, personnel competent and It improves the reputation of the laboratory.

Most countries around the world have their own accreditation organizations similar to:

Algerian Accreditation Body (ALGERAC)

Ever since 2000 Algeria came to be aware of the need to set up an operational national accreditation body to adjust to the requirements of globalisation. Operating under the authority of the Ministry of Industry, the Algerian Accreditation Body, ALGERAC, was established by Executive Decree No 05-466 of 6 December 2005, and is acknowledged by its peers as the only national organisation to have the power to deliver accreditations- following an evaluation based on international standards- in favour of conformity assessing bodies testifying their technical and organisational competence to provide services relating to testing, analysing, calibration, inspection, or certification. Likewise, ALGERAC is periodically evaluated by its pairs (European Accreditation, EA), and operates with a management system based on

international requirements that are in line with the standard ISO/CEI 17011. It is also committed to observing the three fundamental criteria of impartiality, objectivity, and independence as required in that standard[5].

The European co-operation for Accreditation (EA)

EA, the European co-operation for Accreditation, is a not-for-profit association, registered in the Netherlands. It is formally appointed by the European Commission in Regulation (EC) No 765/2008 to develop and maintain a multilateral agreement of mutual recognition, the EA MLA, based on a harmonized accreditation infrastructure. The EA MLA exists to facilitate fair trade, ensure product and service quality and reduce technical barriers to trade. It currently has 49 Members. The EA Members are National Accreditation Bodies (NAB) that are officially recognized by their national governments to assess and verify – against international standards – organizations that carry out conformity assessment activities such as certification, verification, inspection, testing and calibration[6].

The French accreditation committee (Cofrac)

The French accreditation committee (Cofrac) was created in 1994 at the initiative of the public authorities. We are a not-for-profit association entrusted with a public service mission: that of ensuring the competence and impartiality of conformity assessment bodies (CAB), generally referred to as "inspection" bodies. In 2008, in application of a European regulation, the State designated Cofrac as the sole accreditation body in France [7].

1.5 standards and guidelines

The most well-known reputable and worldwide used by first-class laboratories guidelines are:

ISO / IEC 17025:

ISO 17025 is the world's most common and widely used guideline for calibration laboratories. It was developed by the International Organization for Standardization (ISO) in 1999 and has since been updated in 2015 and 2017, with the latest version being the most up-to-date. Due to its high reliability and ability to ensure the best quality of service, most governments, manufacturers, and Accreditation Organizations such as ALGERAC require laboratories

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to comply with this guideline, it provides a structured framework for organizing and managing laboratory operations, ensuring consistency, reliability, and quality in testing and calibration processes. Key aspects include establishing a robust Quality Management System (QMS) with clear procedures and policies, emphasizing proper documentation control, addressing personnel competence through education and training requirements, mandating the use of calibrated equipment with traceability to recognized standards, emphasizing the selection and validation of appropriate test and calibration methods, and considering measurement uncertainty. By implementing this standard, laboratories align with international best practices, leading to organized and controlled operations that instill confidence in their testing and calibration processes.

ANSI/NCSL Z540

This American National Standard provides requirements for calibration laboratories and calibration systems. It was developed by the American National Standards Institute (ANSI) and the National Conference of Standards Laboratories (NCSL), now known as the National Conference of Standards Laboratories International (NCSLI). It covers various aspects of calibration such as providing guidelines for the development and implementation of effective and traceable calibration procedures. The standard addresses the establishment and maintenance of measurement standards and their traceability to recognized national or international standards. It emphasizes the estimation and reporting of measurement uncertainties associated with calibration results, ensuring accurate and reliable measurements. ANSI/NCSL Z540 also requires the implementation of a quality management system, encompassing document control, equipment maintenance, personnel training, and quality assurance. Additionally, it specifies requirements for equipment control, including identification, labeling, handling, and storage, ensuring proper control and traceability. The standard also outlines the documentation and record-keeping requirements for calibration activities, ensuring the proper recording and reporting of calibration results.

Guide to the Expression of Uncertainty in Measurement

The GUM (Guide to the Expression of Uncertainty in Measurement) is a widely recognized and influential document that provides guidance on evaluating and expressing measurement uncertainties. It was developed by the Joint Committee for Guides in Metrology (JCGM) and is applicable to all fields of measurement.

The GUM outlines a comprehensive framework for estimating and reporting uncertainties associated with measurement results. It provides a systematic approach to analyzing and

quantifying the various sources of uncertainty that can affect a measurement, such as instrument calibration, environmental conditions, and operator skill. The guide emphasizes the importance of considering all relevant sources of uncertainty and combining them mathematically to obtain an overall uncertainty value. In addition, the GUM covers essential concepts and principles related to uncertainty, including the characterization of uncertainties as standard deviations, the use of probability distributions, and the propagation of uncertainties through mathematical equations. It also provides guidance on the reporting of uncertainty, including the use of numerical values and confidence intervals.

It's important to note that the GUM is not a standard itself, but rather a guide that informs the application of uncertainty evaluation in various measurement standards and practices, including ISO/IEC 17025

1.6 Laboratories

ENIE calibration

The National company of electronics (SONELEC) established in 1978 by the Algerian government for electronic equipment production such as televisions. A maintenance and calibration laboratory for electronic equipment and systems was set for internal operations at the start of the production activities. In 1983, SONELEC underwent an organic restructuring, leading to the establishment of ENIE (National Company of Electronic Industries).

In 1985 ENIE decided to develop the maintenance and calibration activity to extend it outwards to the third party. Based on its cumulative experience since 1978 in this field. It considers this activity to be a major and strategic activity. ENIE has clearly indicated its willingness to invest in this area in terms of architectural rehabilitation of the laboratory and the renewal of the stock of standard equipment and equipment measurement standards to comply with ISO / IEC 17025 guide, GUM and other world wide guidelines and standards[8].

Chapter 2

Methods and Materials

2.1 Introduction

In the field of electrical engineering, accurate and reliable measurements are essential for ensuring the proper functioning and safety of electrical systems. The process of electrical calibration involves confirming the precision of the measurement devices employed in these systems. It entails comparing the results of these instruments' measurements to established reference standards. The "Methods and Materials" of electrical calibration focus on the specific techniques, procedures, and equipment used to achieve precise and traceable measurements.

2.2 Methods of Calibration

For electrical systems to provide precise and reliable readings, electrical calibration techniques are essential. These approaches, techniques, and adjustments are applied step-by-step to measurement instruments to correct for mistakes and variances.

There are various methods used in electrical calibration, depending on the specific instrument or system being calibrated. Two commonly used methods are direct calibration and indirect calibration with some popular techniques for electrical calibration are listed below [9]:

- Direct Method
- Indirect Method
- Comparative Method
- Substitution Method
- Null Method

2.2.1 Direct Method

In the direct method measurement, the value of a quantity is obtained directly by comparing the unknown with a reference standard with a known and traceable value. The instrument and the reference standard are connected under the same conditions, and any differences or errors between them are determined. It involves no mathematical calculations to arrive at the results[9].

Examples :

- Measurement of Resistance by Ohms Meter
- Measurement of Voltage using Voltmeter
- Measurement of Length using Vernier Caliper

Practical Example :

Calibrating a digital multimeter using calibrator

In this example the digital multimeter (Fluke 87V Digital Multimeter) is calibrated with reference calibrator (Fluke Calibrator 5522A) using direct method by measuring voltage ,current and resistance values as shown in Figure1.



Figure 1: Calibrating a digital multimeter using reference calibrator [10].

The reading of multimeter is compared by the electrical signal generated from Multi Product Calibrator. The Multi Product Calibrator can simulate almost all the required signal needed to verify the accuracy of multimeter. This procedure is applicable almost to all multimeters whether analog or digital [11].

Measuring directly parameters as ac voltage, dc voltage, ac current, dc current, resistance, capacitance and inductance is which called the direct method of calibration.

The calibration process may vary depending on the specific multimeter and reference calibrator

models. It's crucial to follow the manufacturer's instructions and consult the user manual for detailed guidelines to ensure accurate calibration.

2.2.2 Indirect Method

When direct measurement is not possible, the indirect measurement method is used, direct measurement involves measuring exactly the amount you wish to measure. While indirect measurement involves measuring another quantity and determining the required value through a mathematical relationship [9].

Examples :

- Measurement of Volume by measuring Mass and Density

$$V = M/d \quad (1)$$

- Measurement of Speed by measuring Distance and Time

$$S = D/T \quad (2)$$

- Measurement of DC Current by using shunt(Resistance) using Ohms law

$$I = \frac{V}{R} \quad (3)$$

Practical Example :

Calibrating a digital powermeter using calibrator

In general the reference calibrator does not generate power signal, so indirect method is used for calibration a certain digital powermeter , it is not possible to measure directly the power from the calibrator so instead, current and voltage values are measured and calculating the power values using following equation.

$$P = V \cdot I \quad (4)$$

To calibrate a digital power meter using voltage and current measurements, begin by connecting the powermeter to the calibrator. Next, measure the voltage and current values and record them, then calculate the power by multiplying the measured voltage and current values. Compare the calculated power with the reading displayed on the digital power meter.

2.2.3 Comparative Method

In the comparative measurement method, the quantity to be measured is compared with the known value of the same quantity. It involves comparing the measurements of the device under test with those of a reference standard of known accuracy. The reference standard is usually a highly accurate and traceable instrument that has been calibrated against national or international standards.

Examples :

- Comparing of Multimeter with a reference Multimeter
- Comparing of a Power supply with a reference Power supply

The comparative method is often used for calibrating a wide range of electrical and electronic instruments, such as voltmeters, ammeters, oscilloscopes, and power supplies. It is a versatile method that provides accurate and traceable calibration results [9].

Practical Example :

Calibrating a digital multimeter using another reference multimeter

to calibrate a digital multimeter in lack of precised calibrator (not calibrated) in presence of another precised multimeter (recently calibrated), the multimeter could be calibrated using the comparative method as the example shown in Figure 2

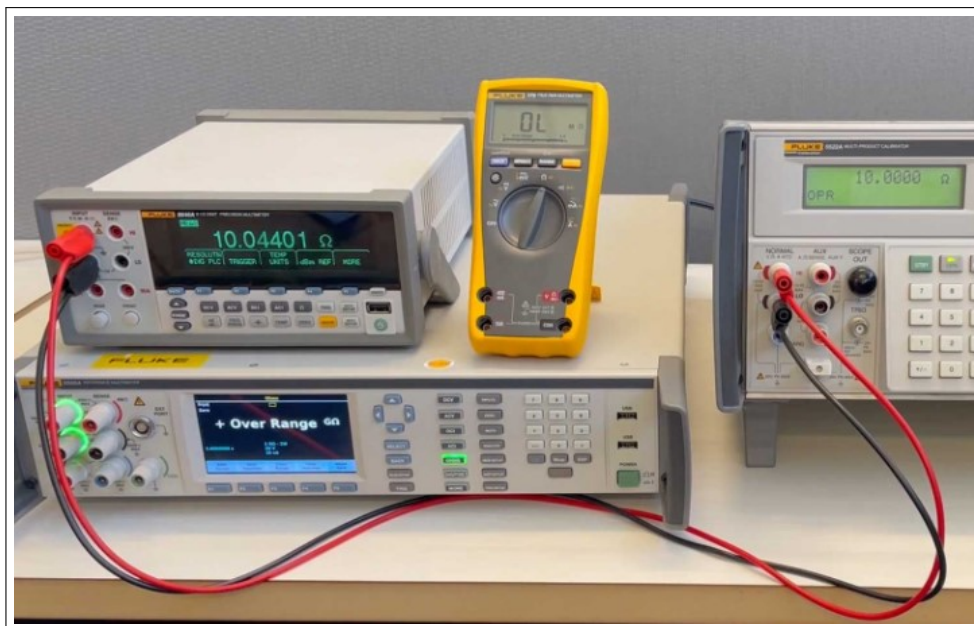


Figure 2: Calibrating Multimeter using another reference multimeter and calibrator [10].

To calibrate a multimeter by using another reference multimeter and a calibrator device. Starting by setting up the reference multimeter and ensuring it is calibrated and functioning correctly. Connect the test leads of the reference multimeter and the multimeter to be calibrated in parallel, ensuring secure and accurate connections. Using the calibrator device, generate a known voltage or current value and measure it simultaneously with both multimeters. Compare the readings between the reference multimeter and the multimeter being calibrated, noting any discrepancies. If there is a significant difference, adjustments may be needed. Repeat the measurement and comparison process with multiple known values to ensure accuracy. Document the calibration values and any adjustments made for future reference. It is crucial to follow proper calibration procedures and use reliable reference equipment to achieve accurate calibration results [9].

2.2.4 Substitution Method

The substitution measurement method involves the replacement of the value of the quantity to be measured with the known value of the same quantity.

In this method, the quantity to be measured is measured by direct comparison on an indicating device by replacing the measuring quantity with some other known quantity that produces the same effect on the indicating device [9].

Examples :

- A simple use of substitution method is calibration of weights by comparing the readings of a weighing instrument with a calibrated reference weight.
- Measurement of Medium Resistances Using substitution method

In this method, first the unknown resistance (R_x) is put into the circuit and note the value of current as shown in the figure below.

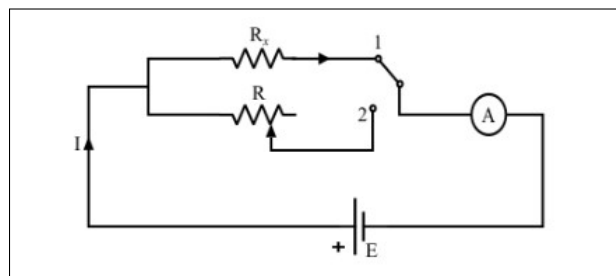


Figure 3: Circuit of measurement of resistances using substitution method (1) [12].

Then the resistance R_x is removed and it is substituted by a known variable resistance R which is varied so that the value of current is same in both the cases. This value of R is equal to the value of unknown resistance [12].

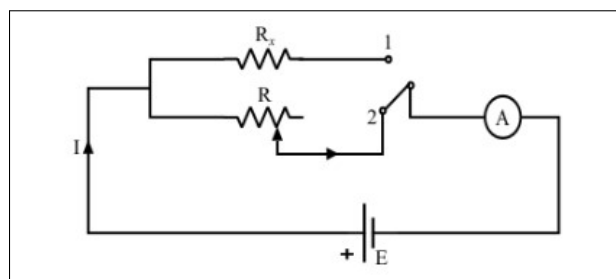


Figure 4: Circuit of measurement of resistances using substitution method (2) [12]

2.2.5 Null Method

In the null measurement method, the quantity to be measured is compared with a known quantity, and the difference between these two is made zero [12].

A known example of using this method is measuring unknown resistance using Wheatstone bridge technique which is explained below.

The Wheatstone Bridge diamond shaped circuit who's concept was developed by Charles Wheatstone can be used to accurately measure unknown resistance values, or as a means of

calibrating measuring instruments, voltmeters, ammeters, etc, by the use of a variable resistance and a simple mathematical formula. Although today digital multimeters provide the simplest way to measure a resistance. The Wheatstone Bridge can be used to compare an unknown resistance to that of a known resistance to determine its value allowing very low values of resistances [13].

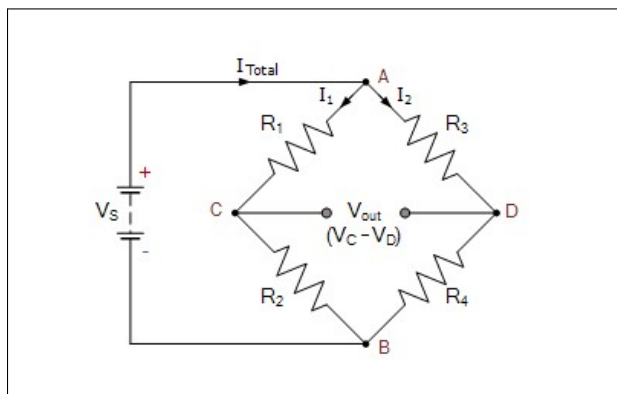


Figure 5: Wheatstone bridge Circuit [13].

When balanced ($V_C - V_D = 0$) voltage., the Wheatstone bridge can be analysed simply as two series strings in parallel. Voltage drop across itself as a consequence of the current flowing through it as defined by Ohms Law.

$$V = R \cdot I \quad (5)$$

the source voltage V_s is divided among the two series resistors in direct proportion to their resistances as :

$$V_S = V_{R1} + V_{R2} \quad (6)$$

$$V_S = V_{R3} + V_{R4} \quad (7)$$

The voltage at point C and D which is also the voltage drop across the lower resistor R2 and R4 Respectively is calculated as :

$$V_{R2} = I_1 \cdot R_2 \quad (8)$$

$$V_{R4} = I_2 \cdot R_4 \quad (9)$$

the source voltage V_s is divided among the two series resistors in direct proportion to their resistances as :

$$V_{R1} = V_s - V_{R2} \quad (10)$$

$$V_{R3} = V_s - V_{R4} \quad (11)$$

As the second series circuit has the same resistive values of the first, the voltage at point D, which is also the voltage drop across resistor R4 will be the same at Point C, with respect to zero, as the voltage is common and the two resistive networks are the same. But something else equally as important is that the voltage difference between point C and point D will be zero volts as both points are at the same value, then the voltage difference is 0 volts. When this happens, both sides of the parallel bridge network are said to be balanced because the voltage at point C is the same value as the voltage at point D with their difference being zero.

Considering what would happen if we reversed the position of the two resistors, R3 and R4 in the second parallel branch with respect to R1 and R2. With resistors, R3 and R4 reversed, the same current flows through the series combination and the voltage at point D, which is also the voltage drop across resistor R4 will be the same as before but different from the the voltage across point C (Only in case of $R1 \neq R2$ and $R3 \neq R4$).

The result of swapping the two resistors is that both sides or “arms” of the parallel network are different as they produce different voltage drops. When this happens the parallel network is said to be unbalanced as the voltage at point C is at a different value to the voltage at point D.

Then the resistance ratio of these two parallel arms, results in a voltage difference between 0 volts (balanced) and the maximum supply voltage (unbalanced), and this is the basic principal of the Wheatstone Bridge Circuit.

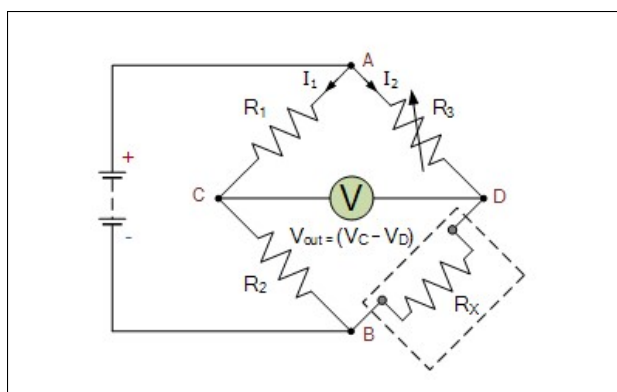


Figure 6: Wheatstone bridge Circuit With Unknown Resistor [13].

Wheatstone bridge circuit can be used to compare an unknown resistance Rx with others of a known value, for example, R1 and R2, have fixed values, and R3 could be variable. If we

connected a voltmeter, ammeter or classically a galvanometer between points C and D, and then varied resistor, R3 until the meters read zero, would result in the two arms being balanced and the value of Rx, (substituting R4) known as shown Figure above.

By replacing R4 above with a resistance of known or unknown value in the sensing arm of the Wheatstone bridge corresponding to Rx and adjusting the opposing resistor, R3 to “balance” the bridge network, will result in a zero voltage output. Then we can see that balance occurs when:

$$\frac{R_1}{R_2} = \frac{R_3}{R_x} = 1 \quad (12)$$

From (11) Rx can be found as :

$$R_x = \frac{R_2 \cdot R_3}{R_1} \quad (13)$$

The Wheatstone Bridge equation required to give the value of the unknown resistance, RX at balance is given as :

$$V_o = (V_C - V_D) = (V_{R2} - V_{RX}) = 0 \quad (14)$$

the Wheatstone Bridge has two input terminals (A-B) and two output terminals (C-D). When the bridge is balanced, the voltage across the output terminals is 0 volts. When the bridge is unbalanced, however, the output voltage may be either positive or negative depending upon the direction of unbalance [13].

2.3 Materials

In order to guarantee the precision and dependability of measurement instruments, electrical calibration depends on the usage of certain materials. Establishing reference values and preserving measurement integrity depend heavily on these materials, which also include calibration standards, measuring tools, and accessories such as cables, connectors, adapters, and calibration software.

2.3.1 Equipment and Instruments

Due to various conditions and time constraints, two experiments were conducted.

The first experiment took place at the ENIE laboratory of calibration in wilaya of Bel Abbes, where the primary objective was to calibrate a digital multimeter using a calibrator

through the direct method. This involved utilizing the calibrator as a reliable reference source to provide known input signals. The measurements obtained from the digital multimeter were then compared to the reference values obtained from the calibrator.

the second experiment was carried out at the institute level due to limitations in available materials. In this experiment, the calibration of the digital multimeter was performed using another reference multimeter and a power supply through the comparative method. The reference multimeter served as a reliable benchmark, while the power supply provided the necessary stable voltages or currents for calibration purposes. By connecting both the digital multimeter and the reference multimeter to the same test signals, the measurements obtained from the digital multimeter were compared against the reference multimeter to evaluate its accuracy and performance.

The instruments used in the two experiments were as follows :

Experiment 1 : Calibrating Digital Multimeter Applying Direct Method

5522A Multi-Product Calibrator

The 5522A Multi-Product Calibrator is a precision calibration instrument manufactured by Fluke Corporation, a leading provider of electronic test and measurement equipment. The 5522A is designed to calibrate a wide range of electrical measurement instruments, including digital multimeters, thermometers, oscilloscopes, clamp meters, and other types of devices. The 5522A is a voltage calibrator, a resistance calibrator, a current calibrator and much more. It sources direct voltage and current, alternating voltage and current with multiple waveforms and harmonics, two simultaneous voltage outputs or voltage and current to simulate dc and ac power with phase control, resistance, capacitance, thermocouples and RTDs. The 5522A can also measure thermocouple temperature, and pressure [10].



Figure 7: fig:5522A Multi-Product Calibrator [10].

Metrix MX24 Digital Multimeter

The Metrix MX24 Digital Multimeter is a handheld device used for measuring electrical parameters. It features a large digital display for easy reading and offers a wide range of measurement functions such as voltage, current, resistance, capacitance, frequency, temperature, and continuity. With its high accuracy and safety features like overload protection, it is suitable for both professional and DIY applications. The MX24 may also include additional features like a built-in flashlight, data hold function, and auto-ranging capabilities. Its durable construction ensures reliability in various environments [14].

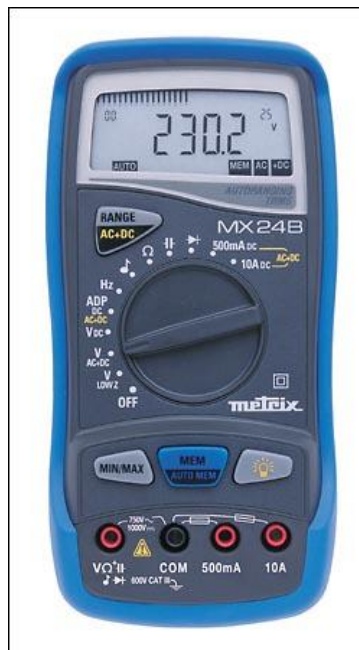


Figure 8: Metrix MX24 Digital Multimeter [14].

Experiment 2 : Calibrating Digital Multimeter Applying Comparative Method

TRUE-RMS RS-232PCLINK DM 500 53000 Bench Digital Multimeter

The Eurotek DM 500 53000 Bench Digital Multimeter is a multi-feature instrument with a dual 5 digit display and 53,000 count measurement for high accuracy and stability. Ten different measurement functions make this model a powerful, versatile performer. With a 30 full screen memory function for saving test data, and display/draw/record software for all test processes, an extremely wide range of applications exist for the multi meter. Its exclusive dynamic scale, which can detect very small changes of parameters, along with its computer interface capabilities, make it ideal for use as a recorder. Safety protection against operator error also makes it perfect for university labs, school technology, industry and research and development[15].



Figure 9: TRUE-RMS RS-232PCLINK DM 500 53000 Bench Digital Multimeter.

DLIN DM 405 Programmable Digital Multimeter

A programmable digital multimeter of 6 digits is a versatile and highly accurate measuring instrument used in electrical applications. With its ability to provide precise measurements of voltage, current, resistance, capacitance, frequency, and more, it offers a wide range of

capabilities. Equipped with a large and clear digital display, it allows for easy reading and interpretation of measurement values with six significant figures. Additionally, this multimeter often offers programmable functions, connectivity options, and safety features such as overvoltage protection. Its durable construction and power source flexibility make it suitable for various environments and applications [16].



Figure 10: DLIN DM 405 Programmable Digital Multimeter.

Metrix power supply ax 3-50

A supply with a voltage range of 0 to 50 volts and adjustable current output is an essential device for electronics and electrical testing. It offers two independent output channels, each capable of delivering a voltage between 0 and 50 volts. The current output can be adjusted to meet the requirements of various devices and circuits. With a clear display panel and precise controls, it allows for accurate and stable power delivery. The power supply incorporates protective features such as overvoltage, overcurrent, and short-circuit protection to ensure the safety of both the power supply and connected devices. Its compact and durable design, along with potential connectivity options for remote control, make it a versatile tool for a wide range of applications [17].



Figure 11: Metrix power supply ax 3-50.

Heath Decade Resistance Model EU-30A

The Variable Resistance is used to limit the current during the calibration process. It does not significantly affect the overall accuracy of the calibration. This is because the values of the current are directly measured from the reference multimeter, and the Variable Resistance primarily serves to control and limit the current flow.



Figure 12: Heath Decade Resistance Model EU-30A.

2.3.2 Accuracy, Range and Resolution of Instruments

Using a multimeter or Calibrator that provides the right measurements is important. Knowing what those measurements mean is even more important. Accuracy and precision ensures the measurements you take will be useful; higher precision enables easier repeatability and higher accuracy means the your readings will be closer to perfect.

Accuracy

Accuracy refers to the largest allowable error that occurs under specific operating conditions. It is expressed as a percentage and indicates how close the measurement displayed is to the actual (standard) value of the signal measured. Accuracy requires a comparison to an accepted industry standard [10].

Example :

A reading of 100.0 V on a digital multimeter with an accuracy of $\pm 2\%$ can range from 98.0 V to 102.0 V. This may be fine for some applications, but unacceptable for more sensitive electronic equipment.

Accuracy may also include a specified amount of digits(counts) added to the basic accuracy rating [10].

Example :

An accuracy of $\pm(2\%+2)$ means that a reading of 100.0 V on the multimeter can be from 97.8 V to 102.2 V. Use of a digital multimeter with higher accuracy allows for a great number of applications.

Resolution

Resolution is the smallest increment a tool can detect and display. it may be listed in a meter's specifications as maximum resolution, which is the smallest value that can be discerned on the meter's lowest range setting.

Range

Digital multimeter range and resolution are related and are sometimes specified in a digital multimeter's specifications. Many multimeters offer an autorange function that automatically selects the appropriate range for the magnitude of the measurement being made. This provides

both a meaningful reading and the best resolution of a measurement. If the measurement is higher than the set range, the multimeter will display OL (overload). The most accurate measurement is obtained at the lowest possible range setting without overloading the multimeter, as shown in following table.

Table 1: Range of Values and Resolutions

Range of Values	Resolution
300.0 mV	0.1 mV (0.0001 V)
3.000 V	1 mV (0.001 V)
30.00 V	10 mV (0.01 V)
1000 V	100 mV (0.1 V)

2.4 Electrical Calibration General Procedure

The procedure for assessing the calibration capability of an instrument involves several steps to ensure the accurate and reliable performance of the instrument being calibrated, it can be separated into three main parts [18]:

2.4.1 Pre Calibration

Switching on and stabilizing the instrument under calibration

This step involves powering on the instrument and allowing it to stabilize in its operational environment. It is essential to ensure that the instrument reaches a stable state before proceeding with the calibration, each instrument needs 30 min run time to be ready for calibration process. The environment, including temperature and humidity, can impact electrical calibration procedures. Changes in temperature can cause material expansion, affect electrical properties, and introduce drift in instruments. High humidity levels can alter electrical characteristics, promote corrosion, and impact insulation properties, generally the guidelines for Electrical Instruments is $23\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ in temperature and $50\% \pm 20\%$ in humidity according to The Recommended Practices (RP) available from NCSLI (National Conference of Standards Laboratories - International) [19].

Instrument initial verification and troubleshooting

Before starting the calibration procedure, an initial verification is performed to ensure that the instrument is functioning correctly. This may involve basic functional checks, verifying indicators or displays, and troubleshooting any issues or anomalies that may affect the calibration process.

Setting operational parameters and interconnection

In this step, the necessary operational parameters and settings are configured on both the instrument under calibration and the calibration equipment or calibrator. This includes setting the appropriate ranges, units, and any necessary interconnections between the instrument and the calibration equipment[20] .

2.4.2 In Calibration

Calibrator adjustment

The calibrator is adjusted or set to generate a known reference signal or value. This adjustment ensures that the calibrator produces an accurate and traceable output that is used for calibration.

Calibrator control

The calibrator's output is controlled and adjusted to match the required calibration values or references. This may involve fine-tuning or adjusting the calibrator's output to align it with the target values specified for the instrument under calibration.

Calibration measurements

With the instrument and calibrator properly configured, calibration measurements are performed. The instrument is subjected to specific inputs or stimuli, and its responses or outputs are measured using calibrated equipment. The measurements are typically taken at multiple points or test conditions, covering the instrument's operating range [20].

Note : It's important to note that the specific steps and procedures may vary depending on the type of instrument, industry standards, and calibration requirements. The mentioned

points provide a general overview of the assessment of calibration capability.

2.4.3 After Calibration Measurements

Quantification of the uncertainty of the results

The uncertainty associated with the calibration measurements is quantified. This involves evaluating and estimating the various sources of uncertainty, such as measurement equipment accuracy, environmental conditions, repeatability, and calibration procedure uncertainties. The goal is to provide an indication of the reliability and confidence level of the calibration results.

Reporting the results and issuing a calibration certificate

Once the calibration measurements and uncertainty analysis are complete, the results are compiled and documented in a calibration report. The report includes the instrument's identification, details of the calibration procedure followed, measurement data, uncertainty analysis, and any observations or recommendations. A calibration certificate is then issued, indicating that the instrument has undergone calibration and meets specified standards or requirements [20].

2.5 Data Collection and Analysis

Electrical calibration encompasses the process of evaluating and quantifying the accuracy and reliability of electrical measuring instruments and equipment. It helps to ensure that the measurements obtained from these instruments are trustworthy and can be used with confidence in various applications. Here's a brief introduction to error and uncertainty analysis in electrical calibration.

2.5.1 Error Analysis

What is error ?

An error may be defined as the difference between the measured and actual values. For example, if the two operators use the same device or instrument for measurement. It is not necessary that both operators get similar results. The difference between the measurements is referred to as an Error.[21]

Types of error

There are two main types of errors :

(1) **Static Errors**

It is defined as difference between the measured value of the quantity and its true value, it is crucial for assessing the accuracy, precision, and reliability of a measurement instrument in a stable measurement environment and it has three types as shown below.[22]

(a) **Gross Errors**

This category basically takes into account human oversight and other mistakes while reading, recording, and readings. The most common human error in measurement falls under this category of measurement errors. These errors can not be completely eliminated, but it could be minimized by taking proper care while taking readings or recording observations. [21]

(b) **Random Errors**

are statistical fluctuations (in either direction) in the measured data due to the precision limitations of the measurement device. Random errors can be evaluated through statistical analysis and can be reduced by averaging over a large number of observations. These errors are very small in magnitude and follow laws of probability and can be treated mathematically.[21]

(c) **Systematic Errors**

These errors occur due to lack of quality in measuring instruments such are reproducible inaccuracies that are consistently in the same direction. These errors are difficult to detect and cannot be analyzed statistically. If a systematic error is identified when calibrating against a standard, applying a correction or correction factor to compensate for the effect can reduce the bias. Unlike random errors, systematic errors cannot be detected or reduced by increasing the number of observations. It can be divided in three sub groups :

- **Environmental Errors**

This type of error arises in the measurement due to the effect of the external conditions on the measurement. The external condition includes temperature, pressure, and humidity and can also include an external magnetic field. If you

measure your temperature under the armpits and during the measurement, if the electricity goes out and the room gets hot, it will affect your body temperature, affecting the reading.

- **Observational Errors**

These are the errors that arise due to an individual's bias, lack of proper setting of the apparatus, or an individual's carelessness in taking observations. The measurement errors also include wrong readings due to Parallax errors.

- **Instrumental Errors**

These errors arise due to faulty construction and calibration of the measuring instruments. Such errors arise due to the hysteresis of the equipment or due to friction. Lots of the time, the equipment being used is faulty due to misuse or neglect, which changes the reading of the equipment. The zero error is a very common type of error. It can be either positive or negative. Sometimes the scale readings are worn off, which can also lead to a bad reading.[23]

(2) **Dynamic Errors**

It is the difference between true value of quantity changing with time and the value indicated by measurement system if no static error is assumed, which keeps changing with time. [22]

Electrical Calibration Error

When it comes to electrical calibration, both static and dynamic errors play important roles, but they are evaluated in different contexts and serve different purposes.

The reason why static error is often emphasized in electrical calibration is because many calibration procedures and standards are designed to evaluate and minimize the systematic errors and uncertainties associated with the instrument's steady-state performance. Static error analysis helps ensure accurate and reliable measurements in conditions where the signal is relatively stable or slowly changing.[21]

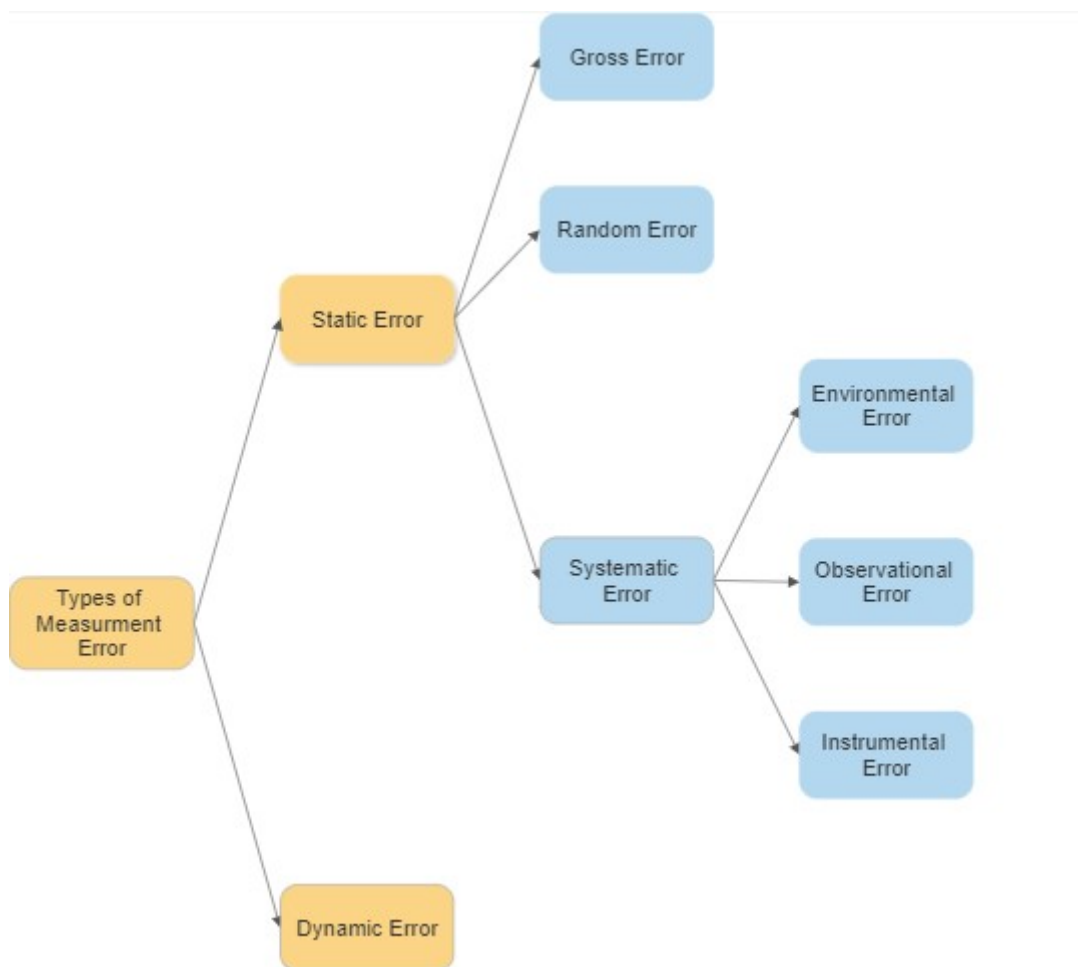


Figure 13: Types of Measurement Errors

Errors Calculation

(1) Static Error

Can be defined as the difference between the measured value of a quantity (by an instrument) V_m and its true or actual value V_a , it is expressed as :

$$E_{\text{Static}} = V_a - V_m \quad (15)$$

Static error can be positive or negative.

(2) Absolute Error

The difference between the measured value of a quantity and its actual value gives the absolute error. It is the variation between the actual values and measured values. It is given by :

$$E_{\text{Absolute}} = |V_a - V_m| \quad (16)$$

(3) **Relative Error**

The ratio of the absolute error to the accepted measurement gives the relative error. The relative error is given by the formula :

$$E_{\text{Relative}} = \frac{E_{\text{Absolute}}}{V_a} \quad (17)$$

(4) **Percent Error**

It is another way of expressing the error in measurement. This calculation allows us to gauge how accurate a measured value is with respect to the true value. Per cent error is given by the formula : [21]

$$E_{\text{Relative}} = \frac{E_{\text{Absolute}}}{V_a} * 100 \quad (18)$$

Note : In general Static Error is the most common used calculation method in analysis and calculations of electrical calibration data and shown in calibration certificate.

2.5.2 Distribution of Measurements

The spread of a set of values can take different forms, or probability distributions.

Normal distribution

In a set of readings, sometimes the values are more likely to fall near the average than further away. This is typical of a normal or Gaussian distribution. You might see this type of distribution if you examined the heights of individuals in a large group of men. Most men are close to average height; few are extremely tall or short.

Figure 14 shows a set of 10 ‘random’ values in an approximately normal distribution. A sketch of a normal distribution is shown in Figure 15 [24].

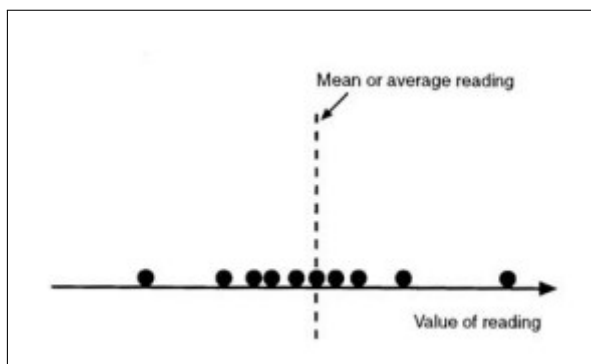


Figure 14: ‘Blob plot’ of a set of values lying in a normal distribution [23].

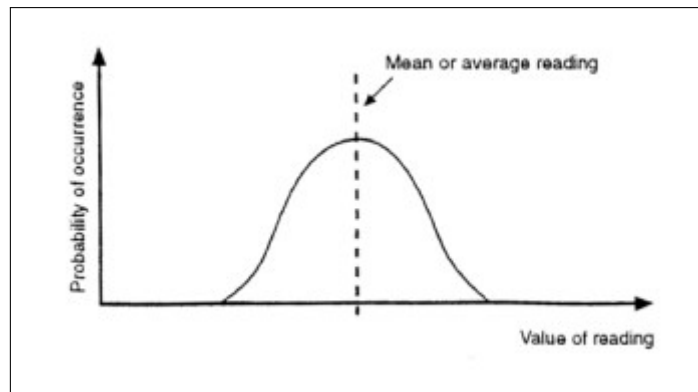


Figure 15: Sketch of a 'normal' distribution [23].

Uniform or rectangular distribution

When the measurements are quite evenly spread between the highest and the lowest values, a rectangular or uniform distribution is produced. This would be seen if you examined how rain drops fall on a thin, straight telephone wire, for example. They would be as likely to fall on any one part as on another.

Figure 16 shows a set of 10 'random' values in an approximately rectangular distribution. A sketch of a rectangular distribution is shown in Figure 17 [24].

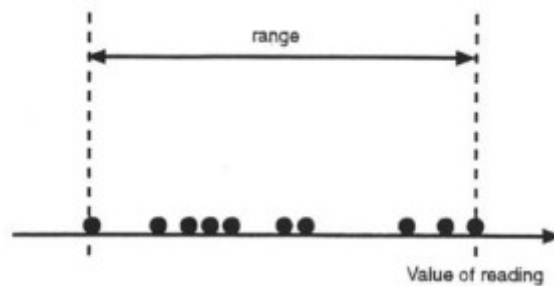


Figure 16: 'Blob plot' of a set of values lying in a rectangular distribution.

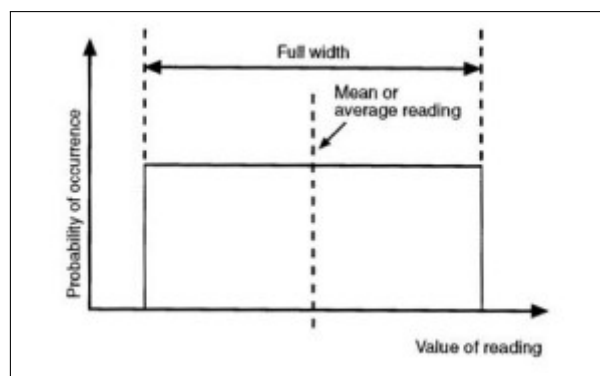


Figure 17: Sketch of a rectangular distribution [23].

Note : Other distributions rarely applied and can have other shapes, for example, triangular, M-shaped (bimodal or two-peaked), or lop-sided (skew).

2.5.3 Uncertainty Analysis

The term “Uncertainty”

The word “uncertainty” means doubt, and thus in its broadest sense “uncertainty of measurement” means doubt about the validity of the result of a measurement. Because of the lack of different words for this general concept of uncertainty and the specific quantities that provide quantitative measures of the concept, for example, the standard deviation, it is necessary to use the word “uncertainty” in these two different senses [25].

Laboratories shall identify the contributions to measurement uncertainty. When evaluating measurement uncertainty, all contributions which are of significance, including those arising from sampling, shall be taken into account using appropriate methods of analysis [26].

Uncertainty of Measurement

Uncertainty is a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand, based on the information used [25].

Uncertainty Calculation

There are three types of uncertainty standard uncertainty (it has two types of evolution Type A and Type B), Combined Uncertainty and Expanded uncertainty. Each type calculation

depend on the previous one, so all types should be calculated in order to find the desired expanded uncertainty.

(1) **Standard Uncertainty (u)**

Standard Uncertainty could be evaluated in 2 methods according to the International Guide of Uncertainty Measurement[25].

Type A evaluation of standard uncertainty

method of evaluation of uncertainty by the statistical analysis of a series of observations.

This method primarily includes random errors.

The uncertainty of a single measurement is limited by the precision and accuracy of the measuring instrument, along with any other factors that might affect the ability of the experimenter to make the measurement. So Whenever possible, repeat a measurement ($X_1, X_2, X_3, \dots, X_N$) several times (N times) and average the results. This average or Mean (μ) is generally the best estimate of the "true" value (unless the data set is skewed by one or more outliers which should be examined to determine if they are bad data points that should be omitted from the average or valid measurements that require further investigation). Generally, the more repetitions you make of a measurement, the better this estimate will be, but be careful to avoid wasting time taking more measurements than is necessary for the precision required. uncertainty of the result of a measurement expressed as a standard deviation [23].

Sum all the measurements and divide by N to get the average, or mean.

$$Mean(\mu) = \frac{X_1 + X_2 + X_3 + \dots + X_N}{N} \quad (19)$$

subtract this average from each of the N measurements to obtain deviations (d) of each measurement.

$$Deviation(d_i) = X_i - \mu \quad (20)$$

Square each of these N deviations and add them all up then Divide this result by ($N - 1$) to obtain The experimental variance of the observations (var).

$$variance(var) = \frac{1}{N - 1} \sum_{i=1}^N (X_i - \mu)^2 \quad (21)$$

This variance (var) and its positive square root termed the experimental standard deviation (s).

$$\text{Standard Deviation}(s) = \sqrt{var} \quad (22)$$

the standard deviation is the most common way to characterize the spread of a data set. The standard deviation is always slightly greater than the average deviation, and is used because of its association with the normal distribution that is frequently encountered in statistical analyses.

Finally to get the standard uncertainty (u) divide the standard deviation by square root of number of measurement (N)[23].

$$\text{Standard Uncertainty}(u) = \frac{s}{\sqrt{N}} \quad (23)$$

Type B evaluation of standard uncertainty

method of evaluation of uncertainty by means other than the statistical analysis of series of observations. This method includes systematic errors and any other uncertainty factors that the experimenter believes are important.

Where the information is more scarce (in some Type B estimates), you might only be able to estimate the upper and lower limits of uncertainty. You may then have to assume the value is equally likely to fall anywhere in between, i.e. a rectangular or uniform distribution. The standard uncertainty for a rectangular distribution is found from:

$$u = \frac{a}{\sqrt{3}} \quad (24)$$

where a is the semi-range (or half-width) between the upper and lower limits.

Some uncertainty components have uniform distribution, Those who have strict upper and lower limits ($-a$ and a) like Display resolution and counter value [27].

Rectangular or uniform distributions occur quite commonly, but if you have good reason to expect some other distribution, then you should base your calculation on that. For example, you can usually assume that uncertainties ‘imported’ from the calibration certificate for a measuring instrument are normally distributed[24].

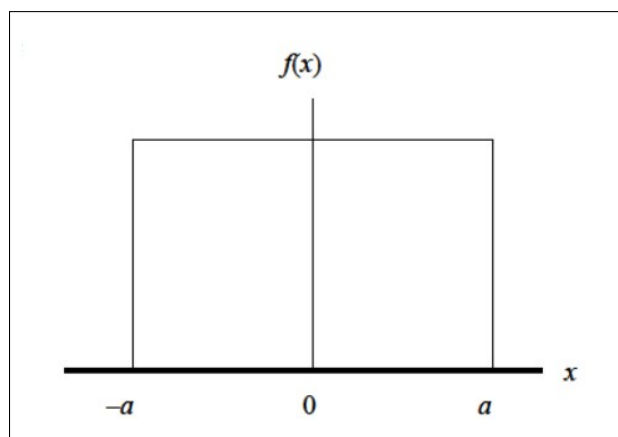


Figure 18: Type B standard uncertainty of a uniform distribution

How to Choose Type A or Type B?

There is a lot of misinformation on type A and type B uncertainty. The VIM definitions are the most accurate[28].

Type A uncertainty is evaluated using statistical means. whereas Type B uncertainty is evaluated using other than statistical means.

The proper use of the pool of available information for a Type B evaluation of standard uncertainty calls for insight based on experience and general knowledge, and is a skill that can be learned with practice. It should be recognized that a Type B evaluation of standard uncertainty can be as reliable as a Type A evaluation, especially in a measurement situation where a Type A evaluation is based on a comparatively small number of statistically independent observations [25].

It is all evaluated by statistical methods. Therefore, the difference is how the data is collected, not how it is evaluated. Type A uncertainty is collected from a series of observations. Type B data is collected from other sources. Although Type B uncertainty found in publications may have been collected from a series of observations, it was not collected by you or the laboratory personnel [18].

(2) Combined Uncertainty (U_c)

Individual standard uncertainties calculated by Type A or Type B evaluations can be combined validly by ‘summation in quadrature’ (also known as ‘root sum of the squares’). The result of this is called the combined standard uncertainty, shown by U_c .

Summation in quadrature is simplest where the result of a measurement is reached by

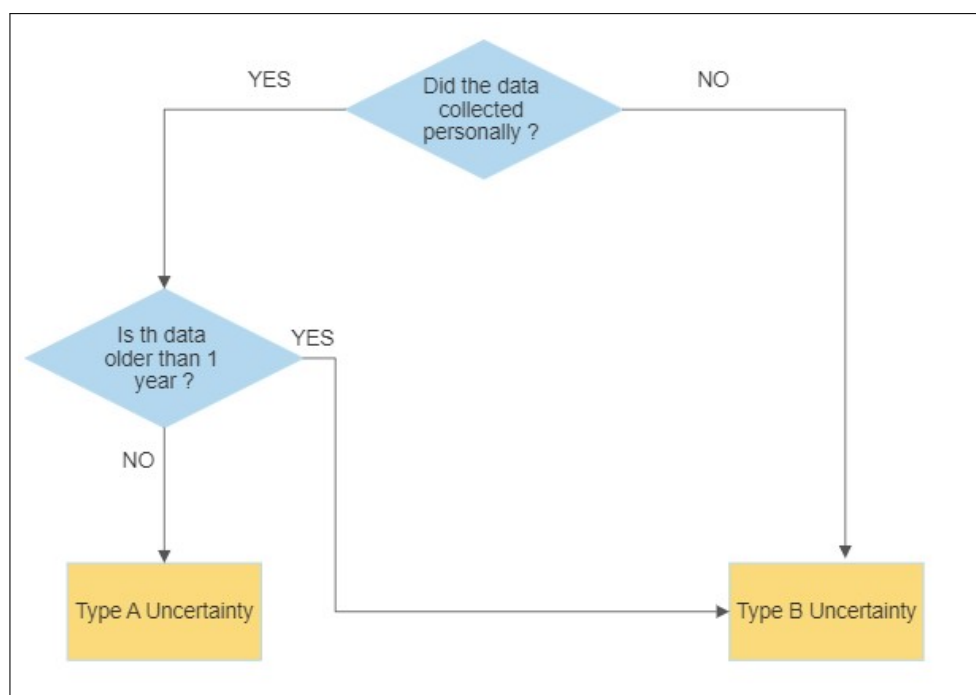


Figure 19: Choosing Standard Uncertainty Type

addition or subtraction. The more complicated cases are also covered below for the multiplication and division of measurements, as well as for other functions.

The simplest case is where the result is the sum of a series of measured values (either added together or subtracted). For example, you might need to find the total length of a fence made up of different width fence panels. If the standard uncertainty (in metres) in the length of each fence panel was given by a , b , c , etc., then the combined standard uncertainty (in metres) for the whole fence would be found by squaring the uncertainties, adding them all together, and then taking the square root of the total using this formula :

$$\text{Combind Uncertainty}(U_c) = \sqrt{a^2 + b^2 + c^2 + \dots + etc} \quad (25)$$

(3) Expanded Uncertainty (U)

Coverage factor k

Having scaled the components of uncertainty consistently, to find the combined standard uncertainty, we may then want to re-scale the result. The combined standard uncertainty may be thought of as equivalent to 'one standard deviation', but we may wish to have an overall uncertainty stated at another level of confidence, e.g. 95 percent. This re-scaling can be done using a coverage factor, k . Multiplying the combined standard uncertainty

U_c , by a coverage factor gives a result which is called the expanded uncertainty, usually shown by the symbol U .

$$U = k * U_c \quad (26)$$

A particular value of coverage factor gives a particular confidence level for the expanded uncertainty.

Most commonly, we scale the overall uncertainty by using the coverage factor $k = 2$, to give a level of confidence of approximately 95 percent. ($k = 2$ is correct if the combined standard uncertainty is normally distributed. Some other coverage factors (for a normal distribution) are:

$k = 1$ for a confidence level of approximately 68 percent

$k = 2.58$ for a confidence level of 99 percent

$k = 3$ for a confidence level of 99.7 percent

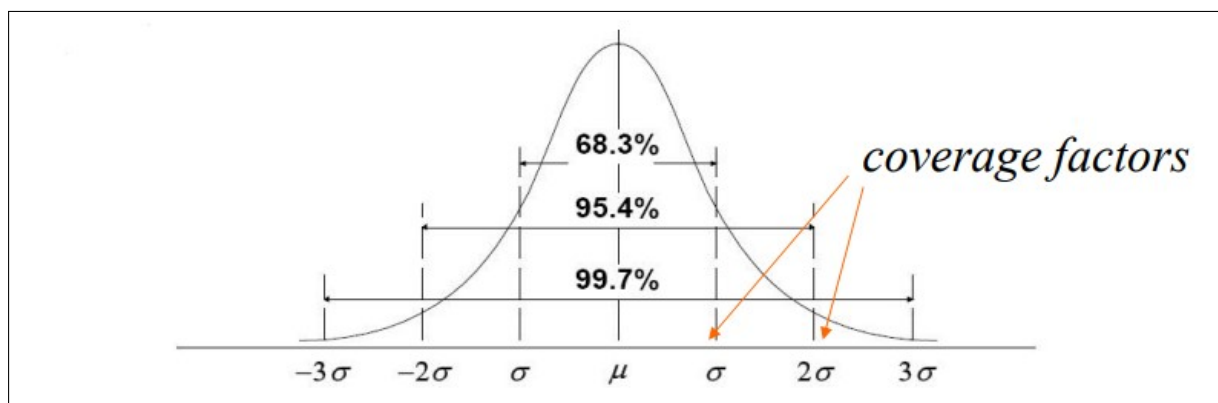


Figure 20: Coverage Factor of Normal Distribution [27]

Note : Other, less common, shapes of distribution have different coverage factors.

Uncertainty and Normal Distribution Formula

Conformity to the specification is proven when the result of a measurement falls within the allowed maximum error limits of the characteristic of a measuring instrument, considering the expanded uncertainty values U . This is referred to as the conformity zone. Beyond the limit values, including the uncertainty, it is the non-conformity zone as shown in figure 21[29].

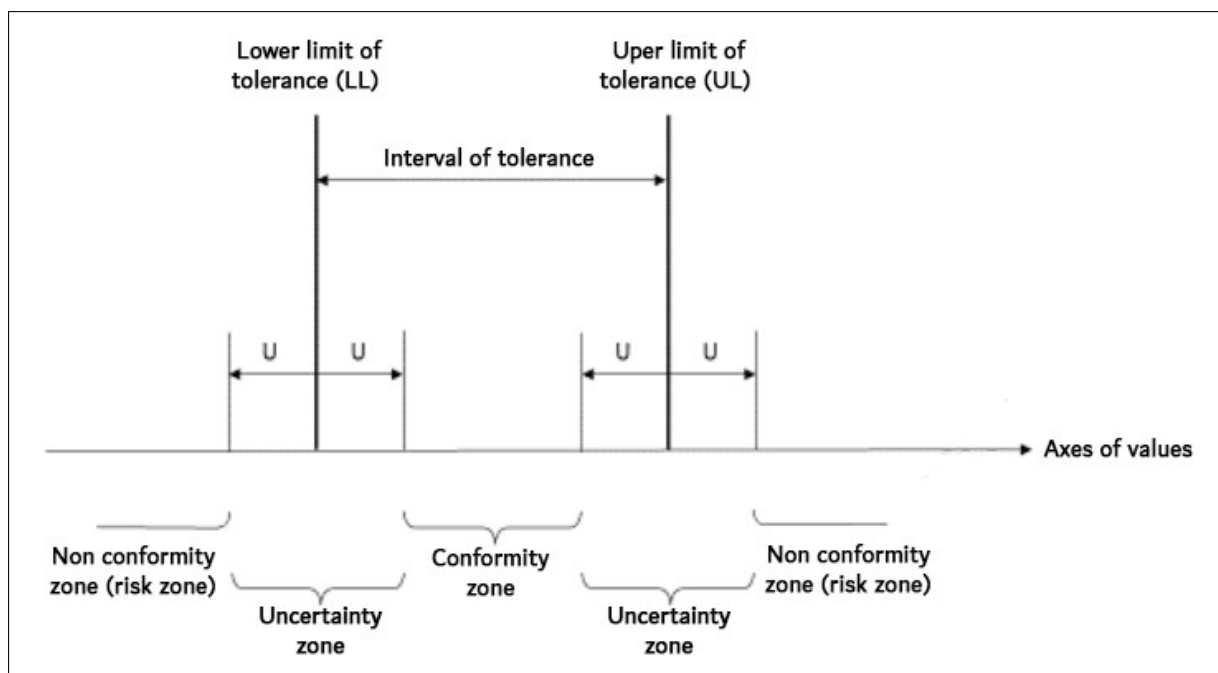


Figure 21: Zones of Conformity

When the result of a measurement falls on both sides of these calculated limit values, a declaration of conformity can still be made but with a varying degree of risk. Moreover, the uncertainty values U are determined by considering a generally assumed "normal" probability distribution. This indicates that an assessment of risk is possible within the range extending from the tolerance limits to the limit deduced from the value of uncertainty U .

When the measured value falls within this range, it is the conformity zone with associated risk, where a non-conforming product can still be declared as conforming.

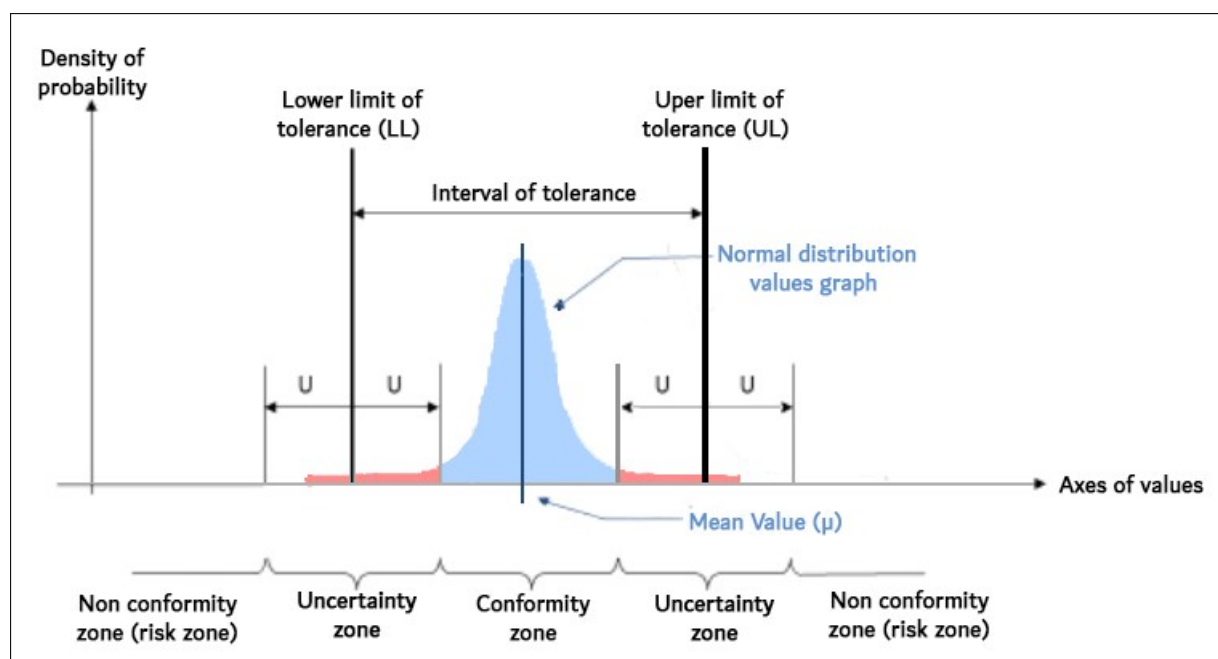


Figure 22: Zones of Conformity and Normal Distribution

When the measured value y , as shown in Figure 22, exceeds one of the tolerance limit values, the risk is too high to declare conformity. This is the non-conformity zone, where there is a risk of declaring a conforming product as non-conforming [29].

Risk Evolution

To calculate the standardized variable in the case where the mean value is close to Lower Limit :

$$z = \frac{(LL \pm U) - \mu}{s} \quad (27)$$

To calculate the standardized variable in the case where the mean value is close to Upper Limit :

$$z = \frac{\mu - (UL \pm U)}{s} \quad (28)$$

Calculation of the probability associated with the risk using the standard normal distribution table as shown in Appendix C.

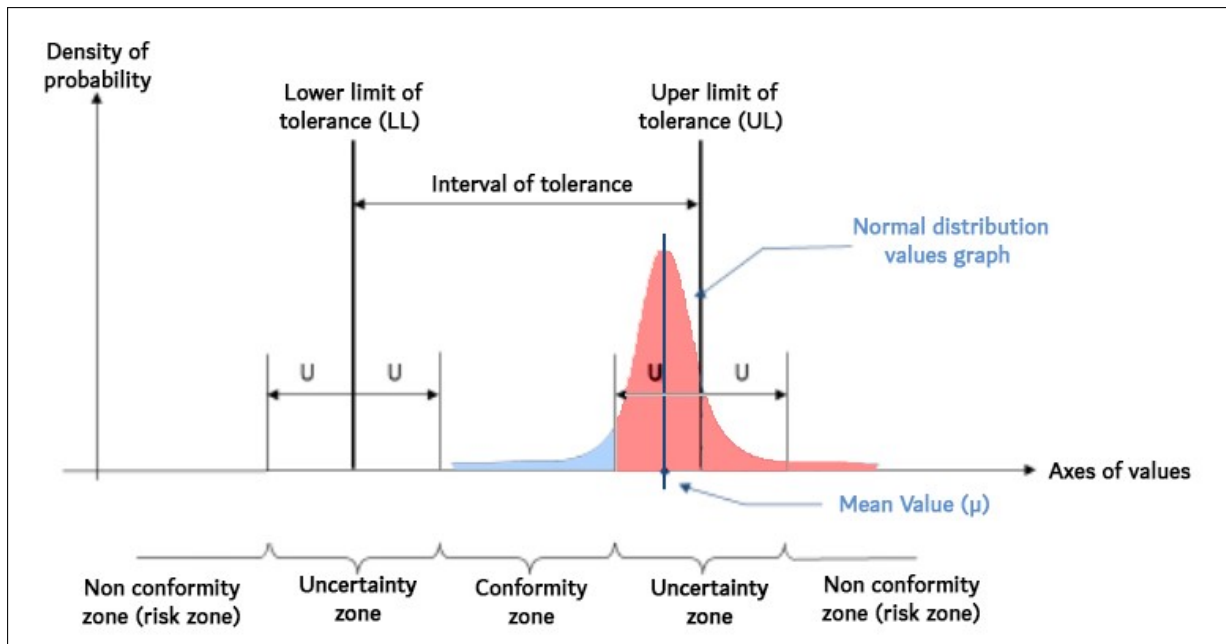


Figure 23: Zones of Conformity and Normal Distribution

Using the normal distribution table to get the percentage of the values contains in conformity zone or in risk zone (uncertainty zone plus non conformity zone), At least of 50% of the normal distribution graph of the instrument measurement must be contains in conformity zone so that the it pass the tests and the instrument could be said accurate but with uncertainty as note in the final certificate.

Chapter 3

Implementation and testing

3.1 introduction

Calibration is a very critic operation that requires precision and professionalism to guarantee quality of measurements and reliability of the results. therefore, it has to be preformed carefully to comply with highest standards.

The operator of calibration must read the user manual of the instrument used to calibrate and the unit under test it self. if the UUT manual is not provided by the customer (owner of the unit under test), the laboratory will make efforts to procure it. Some equipment have a special manual for maintenance and calibration that independent from the user manuals.

3.2 Experiment 1 : Calibrating Digital Multimeter Applying Direct Method

3.2.1 Before starting

The Direct calibration was preformed in ENIE calibration laboratory in sidi bel abbes, algeria. The temperature was 24° C and humidity was 46 %.

- The method used is direct calibration method.
- The instrument used to preform the calibration is Fluke calibrator 5522A.
- The unit under test in this part was a multi-meter MX24B, an instrument that is used to measure AC voltage and current, DC voltage and current, resistance, capacitance and frequency for voltages never exceeding 600V relative to earth.



Figure 24: Metrix MX24 multimeter [14].

The Fluke 5522A calibrator is one of the most advanced pieces of equipment in the field, capable of operating in a wide range of ambient weather conditions. To enhance high performance of the calibrator and maintaining of integrity of the device, the manufacture designated some specifications:

Temperature

Operating	0° C to 50°
Calibration	15° C to 35°
storage	-20° C to 50°

Relative Humidity

Operate	< 80 % to 30° C
	< 70 % to 40° C
	< 40 % to 50° C
Storage	< 95 %

Line power

Line voltage	selectable : 100 V, 120 V, 220 V, 240 V
Line Frequency	47 Hz to 63 Hz
Line Voltage Variation	±10 % of the line voltage setting

All specifications are valid after allowing a warm-up period of twice the time the 5522A

has been turned off, to a maximum of 30 minutes [30].

Unit under test specification

After knowing the calibrators specifications, the operator has to know the UUT specifications

Temperature

Reference temperature	23° ±5 C
Limit range operation	-5° C to 45°
Rated range to use	-10° C to 55°
Storage temperature range	-20° C to 70°

Relative humidity

Humidity	< 80% for 0° C to 35° C < 70% for 35° C to 50° C[14].
----------	--

Once ensuring that all specifications of both the Calibrator and UUT have been met, the calibration process can commence

3.2.2 Calibrating

As mentioned before, the method of calibration is the Direct Calibration method, which is comparing the UUT reading to the reading of the reference calibrator.

Verify that the STBY annunciator appears on the Control Display before making connections. Otherwise, press on the [Reset] button.

After that, the UTT terminals have to be connected with the calibrators appropriate terminals for the function that is being tested.

From the calibrators keyboard, enter the value that the UUT is tested on followed by the unit, entering the unit allows the operator to choose the function to be tested. For example, by pressing the button [V] which means voltage, the calibrator will start generating voltage.

The values that the UUT is tested on are specified by either the manufacture in the manual or the costumers needs. Otherwise, the operator preforms the calibration for one value of each range of the UUT.

DC voltage

For the DC voltage, Calibration was performed for two values: 10V and 15V
 To commence the voltage measurement process, it is necessary to set the rotary switch selector to the "V DC" position, and to choose the appropriate range (50 V) from the range button.

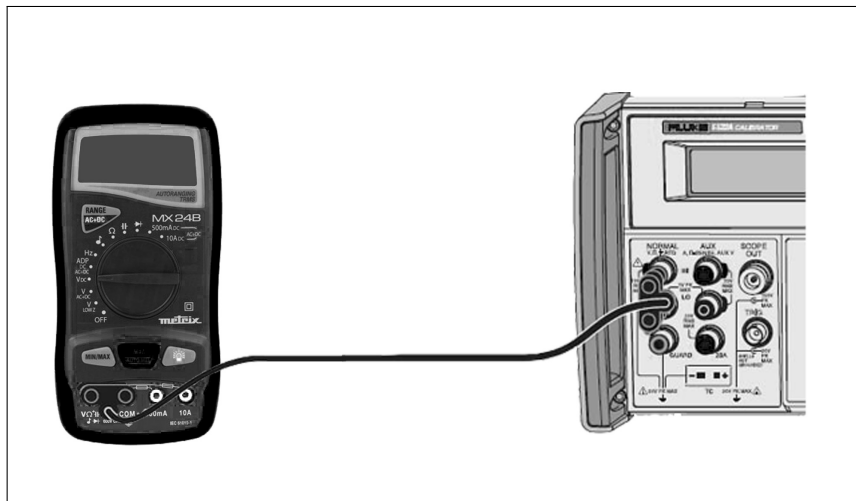


Figure 25: Connection of the calibrator and UUT for DC Voltage test.

The corresponding Tolerance of the instrument in this range is:

$$\text{Tolerance} = 0.3\% R + 2D \quad (29)$$

R: The Reading.

D: Digits.

Example: for the first measure which is 10 V, the reading is 10 and the LCD is second digit after the decimal point. So the tolerance is

$$\text{Tolerance} = \pm \left(0.3 \times \frac{10}{100} + 0.02 \right) = \pm(0.05)$$

So the tolerated error range is: 10 ± 0.05 V

After setting MX24 to measure voltage, the first value of 10 volts (10V) is entered into the Calibrator. This is achieved by sequentially pressing the following buttons on its keyboard: [1], [0], [V], [ENTER], and [OPR] (which signifies "operate"). Pressing [OPR] initiates the

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generation of voltage from the calibrator, allowing the instrument to start the measurement process.

According to the calibration standards, each calibration point should undergo a minimum of 10 tests. After the initial test, the [STBY] button is pressed to switch back to standby mode. After waiting approximately 5 seconds, the [OPR] button is pressed to initiate the second test. This sequence is repeated until a total of 10 values have been obtained and recorded, and their mean is calculated. The calibrator must be set back to the stand by mode by pressing [Set Up] button. The average is calculated using the following equation (19):

$$\text{Average} = \frac{\sum (\text{Measurements})}{10}$$

The error is calculated using the following equation:

$$\text{Error} = \text{CalibratorValue} - \text{MusedValue} \quad (30)$$

Table 1: Results Obtained for Calibration of 10V DC

Results (V)	10.00	9.98	10.01	10.00	9.98	10.00	9.99	9.99	9.98	10.00
Average (V)	9.993									
Error (V)	0.007									

Note: Its noticed that the calibrators Range is set automatically to 33V Range. The same process is repeated for the the value of 15V. By pressing the following buttons sequence on the keyboard: [1], [5], [V], [ENTER], and [OPR], recording the 10 obtained values and their Average using equation 19 and The Error using equation 30. By equation (29), The Tolerated Range is $15 \pm 0.065V$.

Table 2: Results Obtained for Calibration of 15V DC

Results (V)	15.02	15.00	14.98	14.99	14.98	14.98	14.99	15.00	15.01	14.99
Average (V)	14.994									
Error (V)	0.006									

AC voltage

To calibrate the UUT for AC voltage, the selector switch must be rotated to the " V_{lowZ} " position. Keeping the same Range of measuring (50 V).

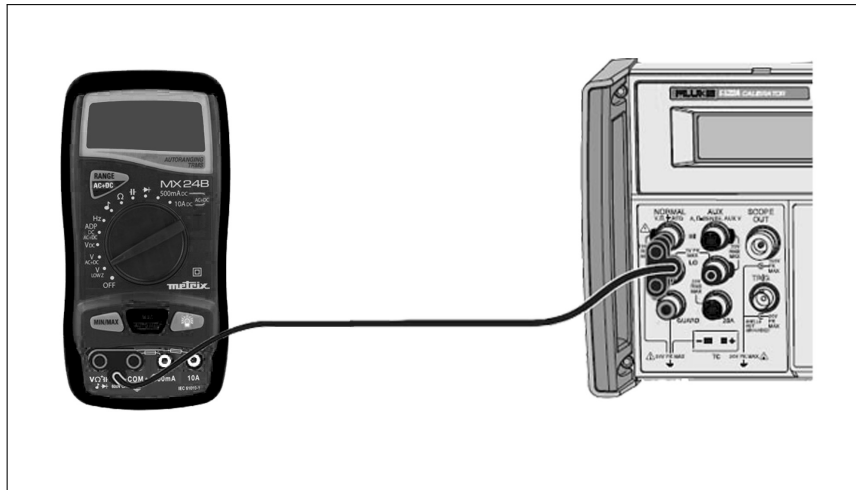


Figure 26: Connection of the calibrator and UUT for AC Voltage test.

the corresponding Tolerance is:

$$\begin{aligned} \text{Tolerance} &= 1\% R + 2 D & (31) \\ \text{Tolerance} &= \frac{1 \times 10}{100} + 0.02 = 0.12 \\ \text{Tolerated Range} &= 10 \pm 0.12V \end{aligned}$$

Calibration steps for fluke 5522A remain the same as DC, with the addition of specifying the frequency after entering the voltage.

for AC voltage, the MX24 was calibrated for two values, 10V and 15V RMS with a frequency of 50HZ. Starting with 10V, the following sequence of buttons are pressed: [1], [0], [V], [5], [0], [Hz], [Enter] and than [OPR] to start the operating. the results, their average and error are recorded in the table bellow:

Table 3: Results Obtained for Calibration of 10V AC

Results (V)	10.02	9.95	9.97	9.94	9.96	9.98	9.97	9.98	9.95	9.99
Average (V)	9.971									
Error (V)	0.029									

After taking the all results for calibration of 10V AC, the [Rest] button is pressed, preparing to the next calibration point.

Repeating the same process for value of 15V AC:

The following sequence of buttons are pressed: [1], [5], [V], [5], [0], [Hz], [Enter] and than [OPR].

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The Measurements tolerated range is calculated using equation (31) since both calibration points 10 V AC and 15 V AC are in the same range, and the result was :

$$\text{Tolerated Range} = 15 \pm 0.17V$$

Table 4: Results Obtained for Calibration of 15V AC

Results	14.95	14.94	14.96	14.98	14.98	14.97	14.94	14.96	14.96	14.95
Average	14.959									
Error	- 0.041									

Resistance

In order to calibrate the resistance measuring function, the same connection is maintained for both the calibrator and the meter, as they both measure voltage and resistance from the same terminals. rotary switch selector is set to "Ω" witch means resistance measuring.

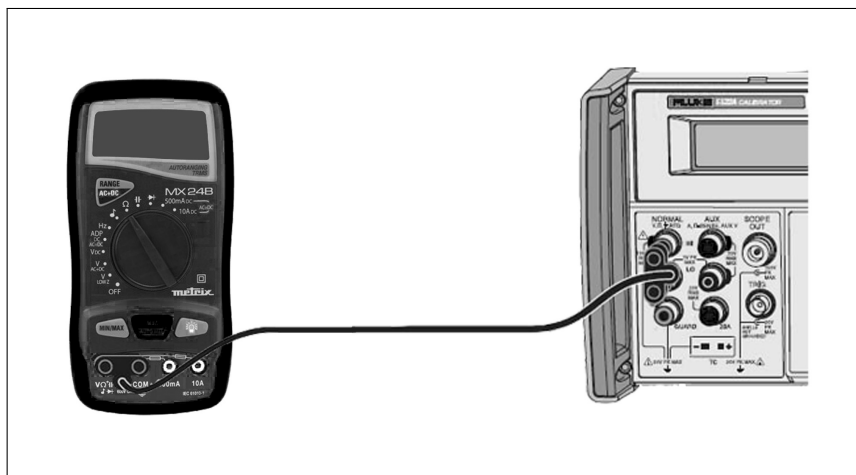


Figure 27: Connection of the calibrator and UUT for Resistance test.

Resistance measuring function was calibrated for two values which are 10 Ω and 10 kΩ. The appropriate scale is chosen by pressing the [RANGE] button on the Multimeter which is

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500Ω range, that has an error tolerance given by:

$$\begin{aligned} \text{Tolerance} &= 0.3\% R + 3 D & (32) \\ \text{Tolerance} &= \frac{0.3 \times 10}{100} + 0.3 = 0.33 \\ \text{Tolerated range} &= 10 \pm 0.33\Omega \end{aligned}$$

To use the fluke 5522A for resistance calibration, the following buttons sequence is pressed: [1], [0], [Ω], [ENTER] and then [OPR]. after calibrating ten times, [RESET] button is pressed. OPR is displayed on the annunciator, results are recorded in the table bellow.

Table 5: Results Obtained for Calibration of 10 Ω

Results (Ω)	10.01	10.03	10.02	10.02	10.01	10.01	9.99	10.00	10.02	10.01
Average (Ω)	10.012									
Error (Ω)	0.012									

In order do the measurements for 10 kΩ the [Range] button is pushed to select the 50kΩ. the following sequence is pressed on the calibrator's keyboarded: [1], [0], [k], [Ω]. [ENTER], [OPR] and after calibrating 10 times [RESET] is pressed. results and average and the error are in the table bellow:

Table 6: Results Obtained for Calibration of 10 kΩ

Results (kΩ)	9.94	9.96	9.95	9.96	9.98	9.97	9.95	9.94	9.95	9.96
Average (kΩ)	9.956									
Error (kΩ)	0.044									

Since the two Ranges have the same Tolerance, The tolerated error range is calculated using equation (32), and it is $10 \pm 0.06k\Omega$

Current under 500 mA

DC current

In order to perform the calibration of the current function on the Unit Under Test, it is necessary to place the connecting wires in the appropriate terminals of both instruments: the calibrator and the Metrix MX24. The calibration of both DC and AC current was done at a specific value of 100 mA, the terminals designated for the 500mA scale on the multimeter are used.

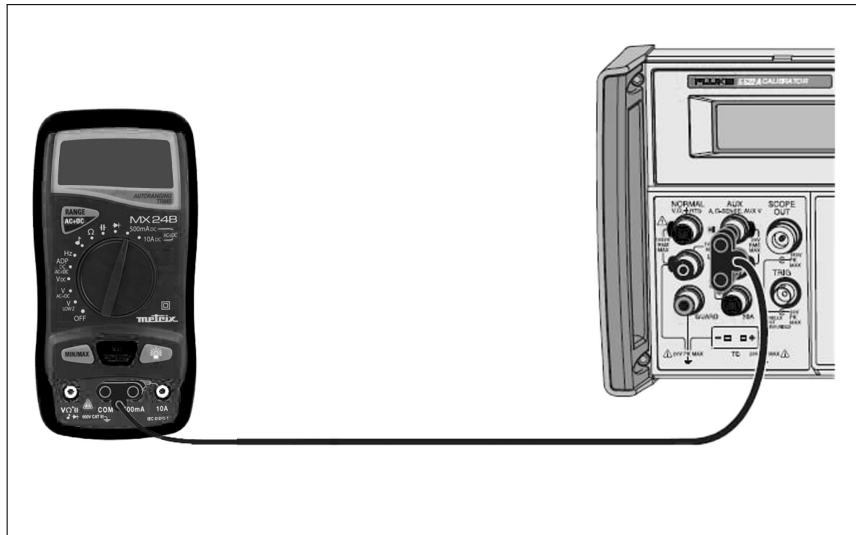


Figure 28: Connection of the calibrator and UUT for DC and AC current under 0.5 A test.

The range was 10A that has a Tolerance of:

$$\text{Tolerance} = 1\% R + 5 D \quad (33)$$

$$\text{Tolerated Range} = 100 \pm 1.5mA$$

To start the calibration the buttons [1], [0], [0], [m], [A], [ENTER] and [OPR] are pressed sequentially. after performing the calibration 10 times, the button [REST] is pressed to put the calibrator on standby mode back. the results gotten, their average and the error are in the table bellow:

Table 7: Results Obtained for Calibration of 100 mA DC

Results (mA)	99.8	99.7	99.5	99.6	99.6	99.8	99.6	99.5	99.6	99.5
Average (mA)	99.62									
Error (mA)	- 0.38									

According to eq 3.2.2, The Tolerated Range is $100 \pm 1.5 \text{ mA}$

AC Current

To calibrate for 100 mA AC, the buttons [1], [0], [0], [m], [A], [5], [0], [Hz], [ENTER], [OPR], after taking ten measures, the button [RESET] is pressed. the results gotten from this process are:

Table 8: Results Obtained for Calibration of 100 mA AC

Results (mA)	99.5	99.6	99.4	99.3	99.5	99.4	99.6	99.3	99.4	99.4
Average (mA)	99.44									
Error (mA)	- 0.56									

Tolerated range is calculated as follows:

$$\text{Tolerance} = 2.5\% R + 5 D = 3\text{mA} \quad (34)$$

$$\text{Tolerated Range} = 100 \pm 3\text{mA}$$

Current above 500 mA

The last test was calibration on 1A DC point, so the connection on the multimeter is moved to the 10A scale terminal, the switch selector is turned to the "10 A" position and the range is adjusted to the 10 A range.

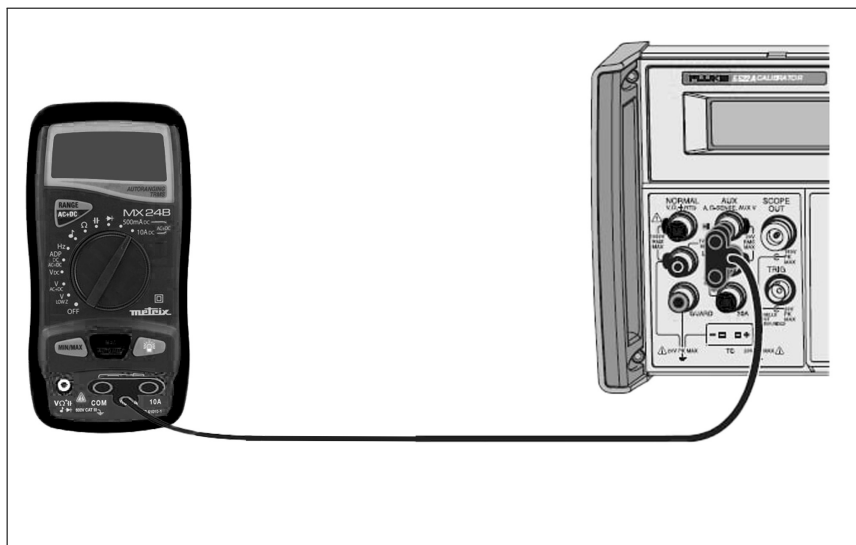


Figure 29: Connection of the calibrator and UUT for 1A DC current.

entering the value by pressing [1], [A], [ENTER], than [OPR]. after testing 10 times the power [RESET] is pressed and than the power button is pushed. the results of this process are shown in the table bellow:

Table 9: Results Obtained for Calibration of 1A DC

Results (A)	1.01	0.99	1.01	1.00	0.98	1.00	1.00	0.99	1.01	0.99
Average (A)	0.998									
Error (A)	- 0.02									

The Tolerated range is Calculated as follows :

$$\text{Tolerance} = 1\% R + 5 D = 0.06 A \quad (35)$$

$$\text{Tolerated Range} = 1 \pm 0.06A$$

3.3 Experiment 2: Calibrating Digital Multimeter Applying Comparative Method

3.3.1 Before starting

The Comparative method of calibration was performed at the Institute of Electrical and Electronic Engineering laboratory. However, due to the inability to control ambient weather conditions and lack of high performance material, the calibration operation is considered as an on-site calibration rather than a laboratory calibration. Performing calibrations on-site presents certain challenges compared to laboratory calibrations. The environmental conditions, such as temperature, humidity, and electrical interference, may vary and can potentially affect the accuracy and reliability of the calibration process.

The Comparative method of calibration is based on comparing the Unit Under Test to a reference instrument. The reference instrument used in this test is the Programmable Digital multiMeret DLIN DM405. The UUT is True Rms RS 232 PCLINK Digital Multimeter.

To preform the operation, an independent power supply such as the Metrix AX 3–50 DC Power Supply was used. During the calibration process, the accuracy of the power supply is neglected. This is due to the fact that the voltage and current values applied are obtained from the reference multimeter, which is assumed to provide accurate measurements. The Operation was preformed under the temperature 22° C and humidity were 65%

Reference Instrument

The Programmable Digital multiMeret DLIN DM405 is not specifically designed to perform calibration procedures. However, if its accuracy has been verified and confirmed by a reputable laboratory or calibration service, it can be utilized as a reference or standard for comparative method calibration. The measurement accuracy of the instrument has been verified by the maintenance laboratory of the Institute of electrical and electronic engineering.

The weather specifications of reference instrument are given in the manual:

Reference multimeter Specifications

Operating

- 0° C to 40° (Relative Humidity 0% to 85%)

Storage

- -20° C to 70° (Relative Humidity < 85%)

Unit Under Test Specifications

Operating

- 5° C to 30° (Relative Humidity 0% to 80%)
- 31° C to 41° (Relative Humidity 0% to 50%)

Storage

- -20° C to 60° (Relative Humidity < 80%)

3.3.2 Calibrating

In the absence of specific calibration point instructions in the manual of the UUT, it becomes necessary to choose the functions and calibration points for the calibration process. This selection should be based on the requirements and intended use of the equipment being calibrated.

To determine the appropriate functions and calibration points, consider the typical range of measurements performed by the equipment and the criticality of those measurements for accurate

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operation. It is essential to cover a representative range of values that are commonly encountered in practical applications.

Dc Voltage

The DC Voltage test was performed for two points, 1 V and 10 V.

1 V DC Voltage

The first step of the calibration process involves connecting the terminals of the power supply to the corresponding terminals of both multimeters. Next, the appropriate range is set on the calibrated multimeter to 5 V and the reference calibrator to range of 2 v as shown in figure 30.

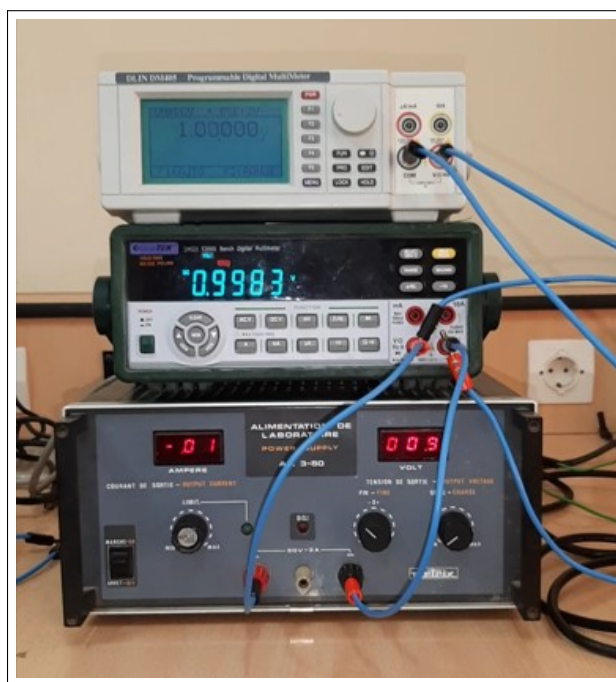


Figure 30: Calibrating Digital Multimeter By Reference Multimeter and Powersupply.

In the second step, the power supply is turned on, and the voltage is adjusted to a value of 1 V, as indicated by the reference multimeter. It is important to note that this voltage value is obtained from the reference multimeter, which is assumed to provide accurate measurements. After obtaining the first measurement, the power supply is turned off and a waiting period of approximately 5 seconds is observed. Subsequently, the power supply is turned on again to take the second measurement. This process is repeated ten times to obtain a total of ten values. The results obtained from the measurements are presented in Table 10, which can be found

below.

Table 10: Results Obtained for Calibration of 1 V DC

RM Reading (V)	UUT Reading (V)	Average (v)	Error (V)
1.00000	0.9983	0.99833	0.00167
	0.9982		
	0.9984		
	0.9982		
	0.9982		
	0.9983		
	0.9982		
	0.9986		
	0.9985		
	0.9984		

Accuracy

The accuracy of the Reference multimeter at range of 2v is calculated as follows:

$$\text{Tolerance} = \pm 0.05\%R + 3 \quad (36)$$

$$\text{Tolerance} = \pm \left(\frac{0.05 \times 1}{100} \right) + 0.00003 = 0.00053V$$

The accuracy of the UUT multimeter at range of 5v is calculated as follows:

$$\text{Tolerance} = \pm 0.03\%R + 6 \quad (37)$$

$$\text{Tolerance} = \pm \left(\frac{0.03 \times 1}{100} \right) + 0.0006 = 0.0009V$$

The Total accuracy limit is the sum of the two Ranges

$$\text{Total Tolerance} = 0.00053 + 0.0009 = 0.00143 V$$

10 V DC Voltage

The same steps as 1V. Starting by step involves connecting the terminals of the power supply to the corresponding terminals of both multimeters. Next, the appropriate range is set on the calibrated multimeter to 50 V and the reference calibrator to range of 20 v .

In the second step, the power supply is turned on, and the voltage is adjusted to a value of 1 V, as indicated by the reference multimeter. It is important to note that this voltage value is

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obtained from the reference multimeter, which is assumed to provide accurate measurements. After obtaining the first measurement, the power supply is turned off and a waiting period of approximately 5 seconds is observed. Subsequently, the power supply is turned on again to take the second measurement. This process is repeated ten times to obtain a total of ten values. The results obtained from the measurements are presented in Table 11, which can be found below.

Table 11: Results Obtained for Calibration of 10 V DC

RM Reading (V)	UUT Reading (V)	Average (V)	Error (V)
10.000	09.987	09.9863	0.0137
	09.987		
	09.988		
	09.984		
	09.985		
	09.983		
	09.986		
	09.987		
	09.989		
	09.987		

Accuracy

The accuracy of the Reference multimeter at range of 20v is calculated as follows:

$$\text{Tolerance} = \pm 0.05\%R + 3 \quad (38)$$

$$\text{Tolerance} = \pm \left(\frac{0.05 \times 10}{100} \right) + 0.0003 = 0.0053V$$

The accuracy of the UUT multimeter at range of 50v is calculated as follows:

$$\text{Tolerance} = \pm 0.03\%R + 6 \quad (39)$$

$$\text{Tolerance} = \pm \left(\frac{0.03 \times 10}{100} \right) + 0.006 = 0.009V$$

$$\text{Total Tolerance} = 0.0053 + 0.009 = 0.0143 V$$

Dc Current

The DC Current test was preformed for two points, 1a and 10.

Variable resistance shown in figure 12 used by connecting it in series with the UUT multimeter, the Reference multimeter and the power supply to avoid over current and short cercuit in the powersupply.

Note : Due to the Excessive use and and the long lifetime of using the UUT multimeter, the ma 500ma fused terminal of measuring the current is disabled, then the only left terminal to use is 10a max fused terminal and the range of 10a only.

1 A DC Current

The first step of the calibration process involves connecting the variable resistance, the UUT multimeter, the Reference multimeter and the power supply . Next, the appropriate range is set on the calibrated multimeter to 10 A and the refrence calibrator to range of 10A .

In the second step, the power supply is turned on, and the Current is adjusted to a value of 1 A, as indicated by the reference multimeter. It is important to note that this Current value is obtained from the reference multimeter, which is assumed to provide accurate measurements. After obtaining the first measurement, the power supply is turned off and a waiting period of approximately 5 seconds is observed. Subsequently, the power supply is turned on again to take the second measurement. This process is repeated ten times to obtain a total of ten values. The results obtained from the measurements are presented in Table 12, which can be found below.

Table 12: Results Obtained for Calibration of 1 A DC

RM Reading (A)	UUT Reading (A)	Average (A)	Error (A)
1.0000	0.9983	0.99774	0.00165
	0.9982		
	0.9984		
	0.9981		
	0.9980		
	0.9986		
	0.9988		
	0.9982		
	0.9984		
	0.9985		

Accuracy

The accuracy of the Reference multimeter at range of 10A is calculated as follows:

$$\text{Tolerance} = \pm 0.1\%R + 5 \quad (40)$$

$$\text{Tolerance} = \pm \left(\frac{0.1 \times 1}{100} \right) + 0.0005 = 0.0015A$$

The accuracy of the UUT multimeter at range of 10A is calculated as follows:

$$\text{Tolerance} = \pm 0.5\%R + 10 \quad (41)$$

$$\text{Tolerance} = \pm \left(\frac{0.5 \times 1}{100} \right) + 0.001 = 0.006A$$

$$\text{Total Tolerance} = 0.0015 + 0.006 = 0.0075 \text{ V}$$

3.4 Conclusion

After completing the calibration process and recording the measurement results, it is crucial to process and analyze the data in order to make informed decisions about the performance of the tested units. The analysis involves various techniques such as statistical calculations, comparison with tolerance limits, and consideration of uncertainties. By examining the processed data, one can determine whether the tested units are performing within the desired specifications or if there are any deviations that need to be addressed.

Chapter 4

Experiment Data Processing

4.1 Introduction

The analysis of data obtained from the calibration process of a multimeter is a critical step in determining the pass or fail status of the Unit Under Test (UUT). This chapter focuses on the comprehensive examination and evaluation of the calibration results to make informed decisions. By employing a series of data analysis techniques and procedures, the operator can assess the accuracy, precision, and reliability of the multimeter's measurements.

4.2 Experiment 1 : Calibrating Digital Multimeter Applying Direct Method

4.2.1 Verifying Tolerance Compliance

The first step in the analysis involves assessing whether the measured values obtained during calibration align with the predetermined Tolerated Range. The Tolerated Range represents the acceptable limits or specifications defined by the calibration standard or procedure. By comparing the resulting values against these predetermined limits, the operator can ascertain the compliance of the multimeter with the required performance criteria. For the present case,

Table 13: Tolerance Compliance

Function	Calibration point	Lower Limit	Upper Limit	Acceptance Criteria
DC Voltage	10 V	9.95 V	10.05	All In Range
	15 V	14.935 V	15.065	All In Range
AC Voltage	10 V	9.88 V	10.12	All In Range
	15 V	14.83	15.17	All In Range
Resistance	10 Ω	9.67 Ω	10.33 Ω	All In Range
	10 k Ω	9.94 k Ω	10.06 k Ω	All In Range
DC Current	100 mA	98.5	101.5	All In Range
	1 A	0.94 A	1.06 A	All In Range
AC current	100 mA	97 mA	103mA	All In Range

the examination confirms that the obtained values from the calibration process all fall within the Tolerated Range. This outcome signifies that the multimeter's measurements meet the specified criteria and exhibit satisfactory accuracy and precision within the acceptable limits.

4.2.2 Calculating Uncertainty

The second step is to calculate the uncertainty for each calibration point, consider the following three main sources of uncertainty: the standard uncertainty of the measurements (Type A uncertainty), Uncertainty of the calibrator and Uncertainty due to the resolution of the Unit Under Test (UUT).

Note 1: The Uncertainty due to the resolution of the calibrator is not considered in this analysis. This is because the calibration values inputted into the calibrator are highly precise, and the LCD (Liquid Crystal Display) of the calibrator provides a greater level of resolution compared to the Unit Under Test (UUT). Therefore, the uncertainty arising from the resolution of the calibrator can be neglected.

Note 2: The uncertainty due to temperature is neglected in this analysis. This decision is based on the calibration process being performed under optimal ambient weather conditions, where temperature variations are minimized.

The detailed computation of different uncertainties was performed for the first calibration point of 10 V DC. For the other calibration points, the results have been compiled and are presented in table (14) bellow.

Standard Uncertainty u

Since the input quantities (the measurements) are obtained from series of repeated observations, the standard uncertainty is calculated using the Type A evaluation. Using equation (19), the mean of the obtained measurements is calculated:

$$Mean = \frac{10.00 + 9.98 + 10.01 + 10.00 + 9.98 + 10.00 + 9.99 + 9.99 + 9.98 + 10.00}{10} = 9.993V$$

The experimental variance of the observations, which estimates the variance of the probability distribution of measurements is calculated using equation (21):

$$s^2 = \frac{1}{n-1} \sum_{i=1}^N (X_i - \bar{X})^2 = 0.1122mV$$

Using equation (23), The Standard Uncertainty is calculated:

$$u = \frac{s}{\sqrt{N}} = \frac{0.0105924}{\sqrt{10}} = 3.34mV$$

Uncertainty due to the resolution of UUT u_r

Since the maximum error that can happen because of the resolution of the multimeter is half the resolution, and the points have rectangular distribution, the u_r is calculated as follows:

$$u_r = \frac{1}{2} \times \frac{Resolution}{\sqrt{3}} \quad (42)$$

$$u_r = \frac{1}{2} \times \frac{0.01}{\sqrt{3}} = 2.88mV$$

Uncertainty of the calibrator u_{cal}

The calibrator's uncertainty, denoted as u_{cal} , is provided in the manual for each specific range. In the case of the 10 V DC measurement, which falls within the 33 V range, the specified uncertainty is $\pm (12 \text{ ppm} + 20 \mu\text{V})$. This indicates that the uncertainty consists of two components: 12 parts per million (ppm) of the measured value (10 V), and an additional 20 μV . So,

$$u_{cal} = \frac{12 \times 10}{10^6} + 20\mu V = 0.14mV$$

The Combined Uncertainty u_c

The combined uncertainty is calculated with the Root of Sum of Squares (RSS):

$$u_c = \sqrt{u^2 + u_r^2 + u_{cal}^2} = \sqrt{3.34^2 + 2.88^2 + 0.14^2} = 4.41mV$$

Note : Temperature and humidity uncertainties are not included in combined uncertainty because of the environments of experiment satisfy f the requirement conditions range of the experiment (24° C of temperature and 46 % of humidity then $u_{\text{temperature}}$ and u_{humidity} are

neglected)

The Expanded Uncertainty U

The Expanded Uncertainty (U) is determined by multiplying the combined uncertainty (u_c) by a coverage factor (k). The coverage factor (k) is selected based on the desired level of confidence for the interval between $(x - U)$ and $(x + U)$, typically ranging from 2 to 3. A commonly used value for the coverage factor is $k = 2$, which provides an interval with an approximate level of confidence of 95% [25].

For 10 V DC, the Expanded uncertainty is:

$$U = K \times u_c$$

$$U = 2 \times 4.41 = 8.82mV$$

Table 14 bellow shows the uncertainties for all points of calibration.

Table 14: Uncertainty of Measurements of Experiment one

Function	calibration			Calibrator		UUT			u_c	U
	Calibration point	Mean	u	Range	u_{cal}	Range	Resolution	u_r		
DC Voltage	10 V	9.993 V	3.34 mV	< 33 V	0.14 mV	50 V	0.01 mV	2.88 mV	4.41 mV	8.82 mV
	15 V	14.994 V	4.58 mV		2.85 mV				6.12 mV	12.24 mV
AC Voltage	10 V	9.971 V	7.37 mV	3.3 V to 33 V	2.1 mV	50 V	0.01 mV	2.88 mV	8.19 mV	16.38 mV
	15 V	14.959 V	4.26 mV	45 Hz to 10 kHz	0.2 mV				5.14 mV	10.28 mV
Resistance	10 Ω	10.012 Ω	3.59 m Ω	0 Ω to 11 Ω	10.4 m Ω	500 Ω	0.1 Ω	28.87 m Ω	30.89 m Ω	61.79 m Ω
	10 k Ω	9.956 k Ω	4 Ω	3.3 k Ω to 11 k Ω	0.38 Ω	50 k Ω	10 Ω	2.89 Ω	4.94 Ω	9.89 Ω
DC Current	100 mA	99.62 mA	0.036 mA	0 mA to 330 mA	0.010 mA	10 A	10 mA	2.88 mA	2.89 mA	5.78 mA
	1 A	0.998 A	3.26 A	0 A to 1.1 A	0.24 mA				4.36 mA	8.72 mA
AC Current	100 mA	99.44 mA	0.034 mA	33 mA to 330 mA 45 Hz to 1 kHz	0.06 mA	10 A	10 mA	2.88 mA	2.88 mA	5.76 mA

4.2.3 Analyzing Uncertainty Results

The data obtained from the calibration process was analyzed using the PyCharm IDE and the Python programming language. The analysis involved the utilization of two widely

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used libraries: NumPy and Matplotlib.

NumPy is a Python library that provides support for efficient numerical operations and array manipulation, making it suitable for scientific computing tasks. It offers various mathematical functions, statistical operations, and data manipulation capabilities, which were employed to perform calculations and statistical analysis on the calibration data.

Matplotlib, another popular Python library, specializes in generating high-quality visualizations and plots. It enables the creation of a wide range of graphical representations, including line plots, scatter plots, histograms, and more. Matplotlib was utilized to create visualizations of the calibration results, aiding in the interpretation and analysis of the data.

DC voltage

For the first function "The DC Voltage", for both calibration points 10 V and 15 V, the sum of measured points and the uncertainty are on the tolerated limits as it shown in figures 31 and 32 bellow:

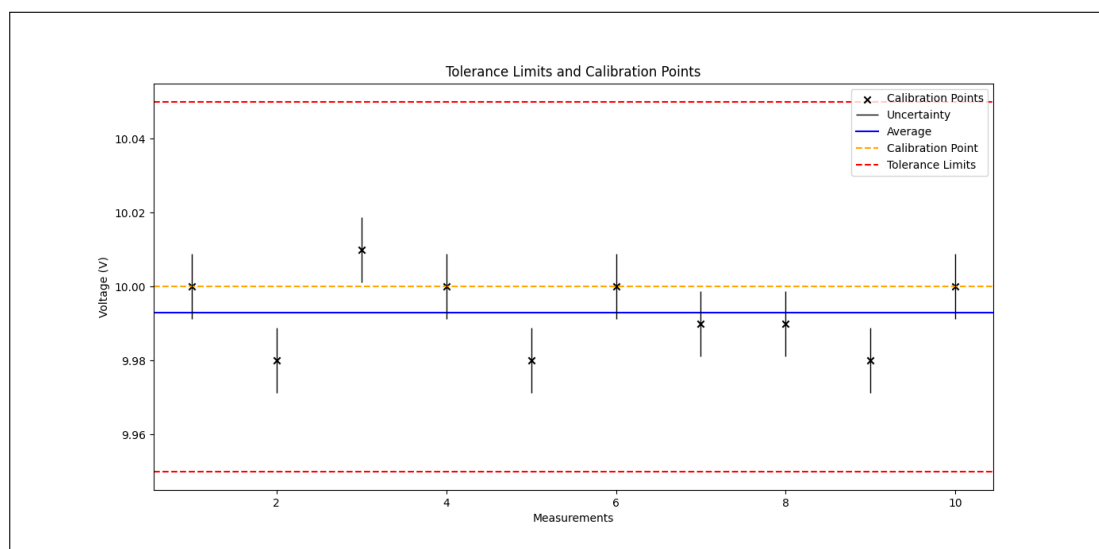


Figure 31: Readings and corresponding Uncertainty of the 10 V DC test.

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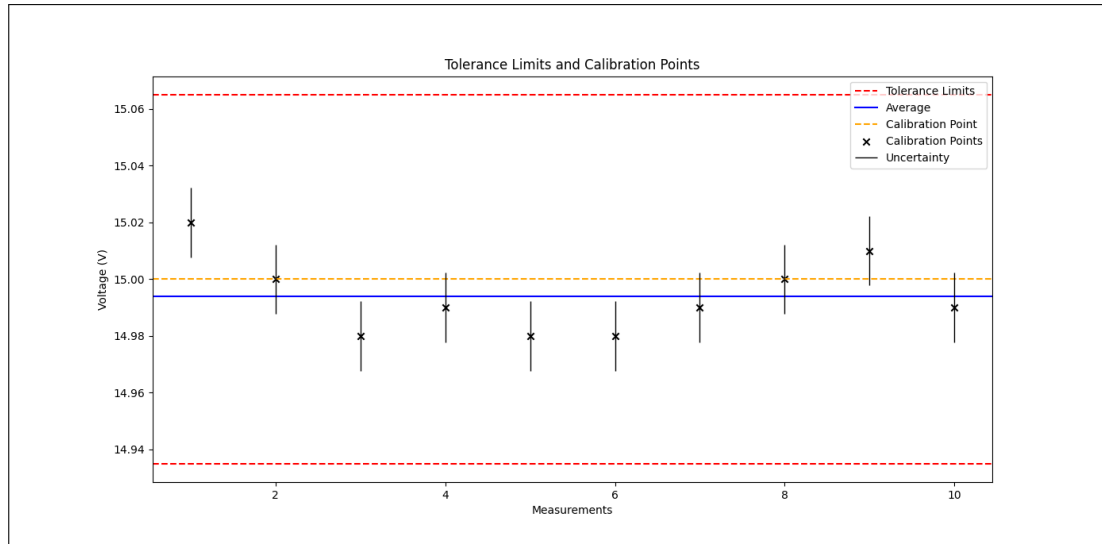


Figure 32: Readings and corresponding Uncertainty of the 15 V DC test.

AC voltage

For the second function "The AC Voltage", the sum of measured points and the uncertainty of both calibration points 10 V and 15 V are on the tolerated Range as it shown in figures 33 and 34 bellow:

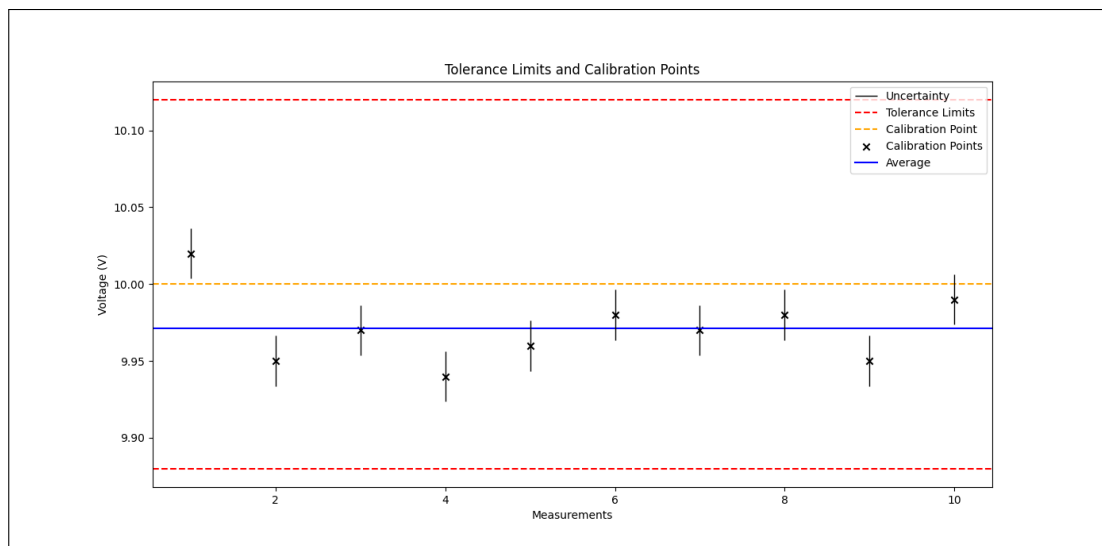


Figure 33: Readings and corresponding Uncertainty of the 10 V AC test.

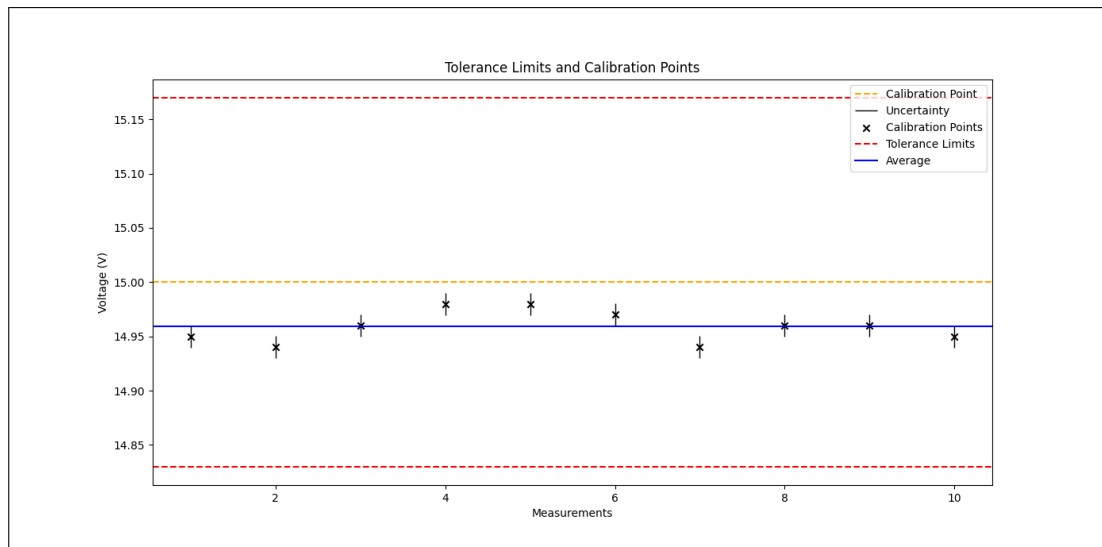


Figure 34: Readings and corresponding Uncertainty of the 15 V AC test.

Resistance

For the resistance function, the measured values obtained during the calibration process for a resistance of $10\ \Omega$, when combined with their corresponding uncertainties, are all within the tolerated range. This is demonstrated in Figure 35 below:

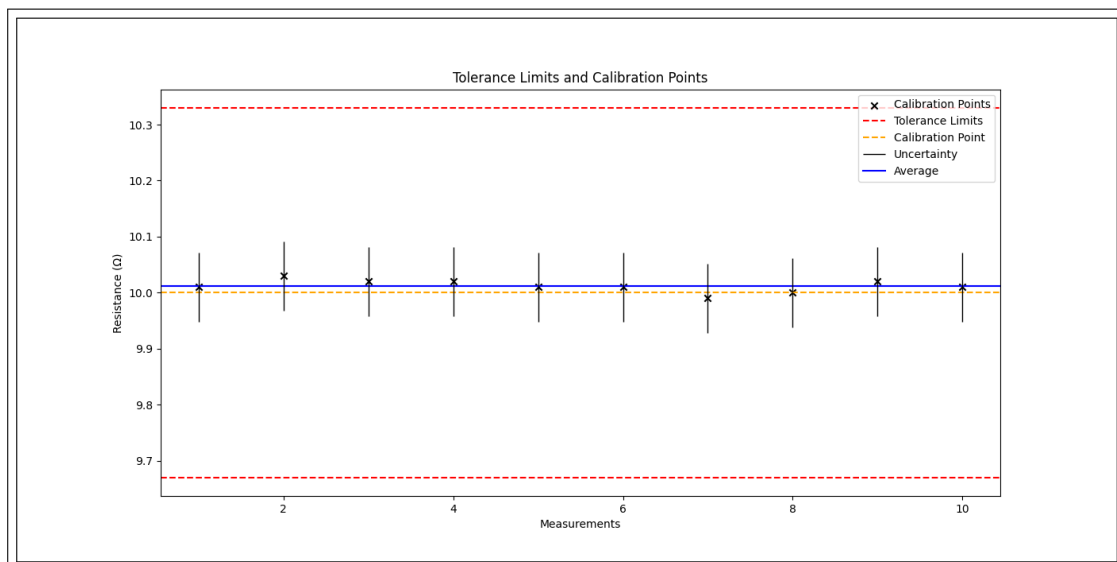


Figure 35: Readings and corresponding Uncertainty of the $10\ \Omega$ test.

For the $10\ \text{k}\Omega$ resistance calibration, eight out of the ten obtained values, when considering their corresponding uncertainties, fall within the tolerated range (conform zone). However, two results were found to be on the lower limit of the tolerated range, with uncertainties exceeding the specified range. This is illustrated in the figure 36 below

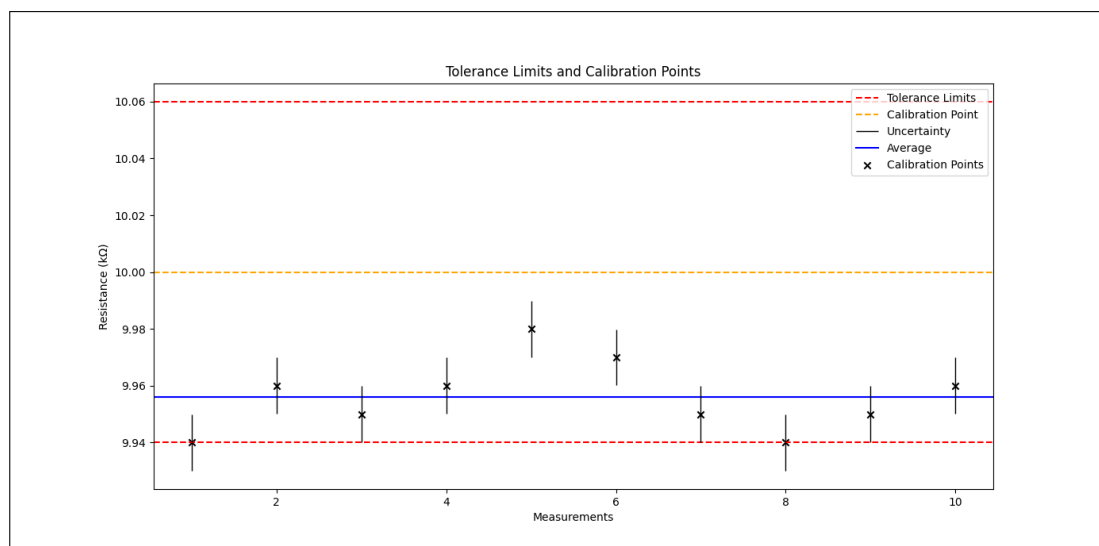


Figure 36: Readings and corresponding Uncertainty of the 10 kΩ test.

The UUT can be considered as passed within uncertainty for the 10 kΩ resistance calibration. The majority of the obtained values were within the specified range, indicating satisfactory performance. While two values exhibited uncertainties that exceeded the specified range, it is important to note that the values themselves still fell within the tolerated range. Indeed, it is important to note any values that deviate from the specified criteria on the calibration certificate. In the case of the 10 kΩ resistance calibration, the two values with uncertainties that exceeded the specified range should be explicitly documented on the certificate.

Current under 500 mA DC and AC

For the 100 mA DC and AC tests, it is important to note that the uncertainty is relatively large when compared to the specified tolerance. This is due to the high resolution of the 10 A Range (10 mA), which is the only range capable of measuring current values above 50 mA. Despite the larger uncertainty, it is significant to highlight that all the measured points fall within the tolerated range. It is important to include this information on the calibration certificate to provide a comprehensive and accurate representation of the calibration results. The results are shown on figures 37 and 38 below:

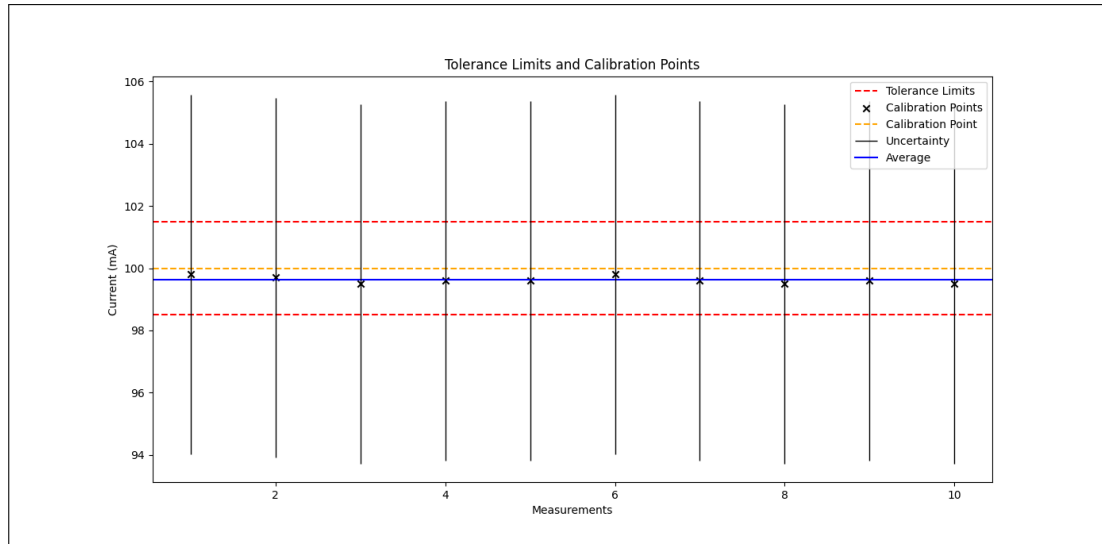


Figure 37: Readings and corresponding Uncertainty of the 100 mA DC test.

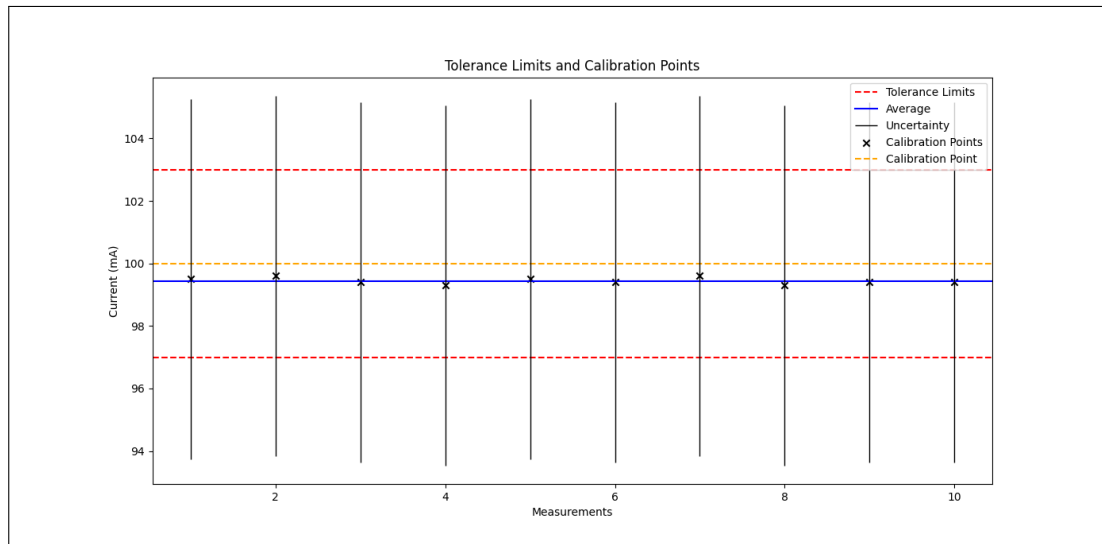


Figure 38: Readings and corresponding Uncertainty of the 100 mA AC test.

The UUT can be considered as passed with uncertainty since all the measured values are within the tolerated range. Despite the presence of uncertainty, the fact that the measured values fall within the acceptable limits indicates that the UUT’s performance meets the required criteria.

Current above 500 mA

For the current measurement above 0.5 A, the calibration was performed at a single point, specifically at 1 A. The resulting values, when combined with their corresponding uncertainties,

all fall perfectly within the tolerated range. This indicates that the UUT's performance for current measurements above 0.5 A is in compliance with the required specifications. The results are illustrated in figure 39.

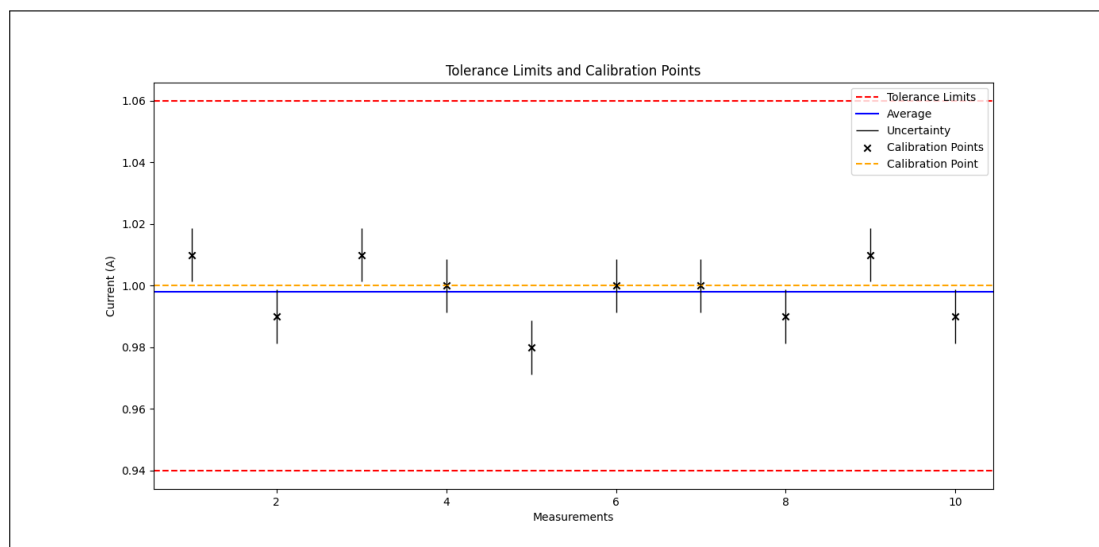


Figure 39: Readings and corresponding Uncertainty of the 1 A DC test.

4.2.4 Conclusion

Based on the calibration test results, it can be concluded that the UUT (Metrix MX 24B) has successfully passed the calibration for most of its functions. However, there are two specific cases that require attention regarding the uncertainty.

For the 10 k Ω resistance point, eight out of ten measured values, when considering their uncertainties, are within the tolerated range. However, two values have uncertainties that exceed the tolerated range. These values should be noted and carefully considered when interpreting the UUT's performance for this specific resistance range.

Similarly, for currents higher than 50 mA and lower than 1 A, the calibration results indicate that all measured values, when combined with their uncertainties, fall within the tolerated range. However, it is important to note that the uncertainty in this range is relatively large due to the high resolution of the 10 A range, which is the only range capable of measuring currents above 50 mA. Despite this, the UUT's performance is still deemed acceptable based on the fact that all measured values are within the tolerated range.

In summary, the UUT (Metrix MX 24B) has passed the calibration test successfully for most of its functions. The uncertainty in the 10 k Ω resistance point and for currents higher

than 50 mA and lower than 1 A should be taken into consideration when evaluating the UUT's performance in these specific ranges. By documenting these results in the calibration certificate, the UUT's compliance with the required specifications can be accurately recorded and referenced in the future. Certificate is shown in Appendix A

4.3 Experiment 2 : Calibrating Digital Multimeter Applying Comparative Method

4.3.1 Verifying Tolerance Compliance

After obtaining the measurements from the calibration operation, the next step is to analyze the results. The first step in this analysis is to verify whether the obtained measurements fall within the tolerance range of the multimeter. By comparing the measured values with the specified tolerance range, one can determine if the multimeter's performance meets the required criteria. It is important to note that during the analysis of the comparative method calibration results, the accuracy and resolution of the reference multimeter is taken into consideration. Unlike the previous experiment where the values were entered based on the calibrator's readings. For the first 1 V DC test, The tolerance of the reference multi meter is $\pm 0.00053V$ and the tolerance of the UUT is $\pm 0.0009V$ Therefore, the total range of tolerance is $\pm 0.00143V$. Based on this tolerance range, the expected values for the calibration should fall within the range of [0.99857 V ; 1.00143V]. However, upon analyzing the obtained values, it is evident that all the measured values are outside of the tolerated range. This discrepancy between the obtained values and the tolerated range indicates a potential deviation or inconsistency in the performance of the calibrated multimeter. Further investigation and analysis are required to identify the uncertainty of our measurements.

4.3.2 Calculating Uncertainty

The second step is to calculate the uncertainty for each calibration point, the main sources of uncertainty are the standard uncertainty of the measurements (Type A uncertainty), Uncertainty due to resolution and accuracy of Reference multimeter, Uncertainty due to resolution of UUT.

Standard Uncertainty u

after calculating the mean of the measurements using equation (19), The Standard Uncertainty is calculated using equations (21) and (23), and it's finale value is :

$$u = 0.0448 \text{ mV}$$

Uncertainty due to the resolution of UUT u_r

Since the maximum error that can happen because of the resolution of the multimeter is half the resolution, and the points have rectangular distribution, the u_r is calculated using equation (42), the obtained value is

$$u_r = 0.0288 \text{ mV.}$$

Uncertainty due to the accuracy and resolution of Reference multimeter

u_{RM}

The accuracy of the reference multimeters affect as same as the resolution since the maximum error that can happen is half the tolerance range and the values are unit distributed so u_{RM} is calculated as follows:

$$u_{RM} = \frac{\text{Accuracy}}{2 \times \sqrt{3}} + \frac{\text{Resolution}}{2 \times \sqrt{3}} \quad (43)$$

$$u_{RM} = \frac{0.00053}{2 \times \sqrt{3}} + \frac{0.00001}{2 \times \sqrt{3}} = 0.1558mV$$

The Combined Uncertainty u_c

The Combined uncertainty is measured using the Root of Sum of Squares of effecting uncertainties.

Note : Temperature and humidity uncertainties are not included in combined uncertainty because of the environments of experiment satisfy f the requirement conditions range of the experiment (22 C of temperature and 65 % of humidity then $u_{\text{temperature}}$ and u_{humidity} are neglected

)

$$u_c = \sqrt{u^2 + u_{RM}^2 + u_r^2}$$

$$u_c = \sqrt{0.0448^2 + 0.1558^2 + 0.0288^2} = 0.1646mV$$

The Expanded Uncertainty U

The Expanded Uncertainty is calculated by multiplying the combined uncertainty times the coverage factor ($k = 2$, which provides an interval with an approximate level of confidence of 95%.)

$$U = k \times u_c = 2 \times 0.1646 = 0.329mV$$

The other Results of uncertainty are shown in table 15 below.

Table 15: Uncertainty of Measurements of Experiment Two

Function	calibration			RM		UUT			u_c	U
	Calibration point	Mean	u	Range	u_{RM}	Range	Resolution	u_r		
DC Voltage	1 V	0.99833 V	0.0448 mV	2 V	0.1558 mV	5 V	0.00001 V	0.0288 mV	0.1646 mV	0.329 mV
	10 V	9.9863 V	0.573 mV	20 V	0.8622 mV	50V	0.0001 V	0.2886 mV	1.0750 mV	2.1499mV
DC Current	1A	0.99774 A	0.0763 mA	10 A	0.3650 mA	10A	0.0001 mA	0.2886 mA	0.4715 mA	0.9430 mA

4.3.3 Analyzing Uncertainty Results

Using PyCharm IDE the uncertainty measurements are represented on the graphs.

DC Voltage

For the 1 V DC test, the resulted values are outside the accuracy range.

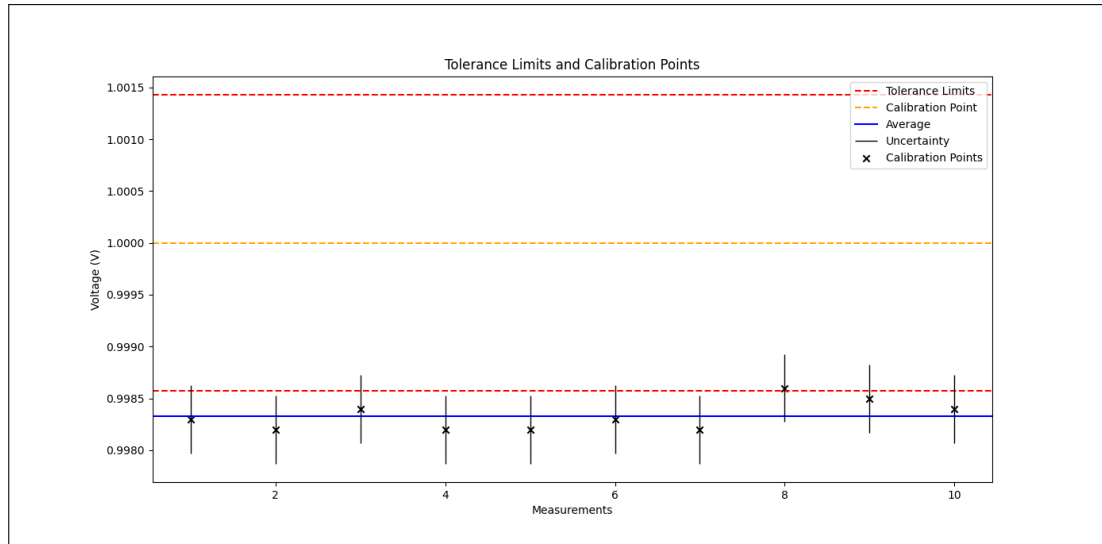


Figure 40: Readings and corresponding Uncertainty of the 1 V DC test.

Declaration of conformity can still be made, but it will carry a greater or lesser degree of risk. to determine the degree of risk, the standardized variable in the case where the average value is close to the lower limit is Calculated using equation (44).

$$z = \frac{x - L}{\delta} \quad (44)$$

$$z = \frac{0.99833 - 0.998899}{0.00013} = -4.38$$

Where:

- x: average
- L: limit of conformity zone (in this case L = Lower limit + uncertainty)
- δ : Standard Deviation

The conversion table of the standard normal distribution shown in appendix C gives us that for $z = -4.38$, the proportion p is Almost 0, which means it is compliant with a probability of almost 0% or compliant with a level of risk of 100% Approximately [29].

Figure (41) below provides graphical illustration of the result

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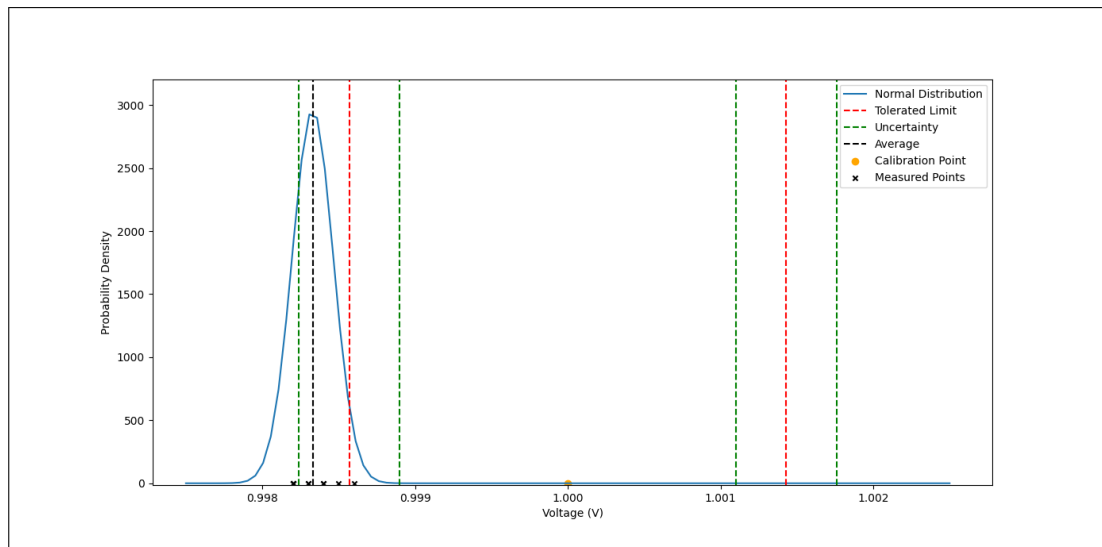


Figure 41: Readings and corresponding Uncertainty of the 10 V DC test.

For the 10V DC calibration, out of the obtained values, 6 fall within the tolerated range when considering their associated uncertainties. However, the remaining four values are outside the range.

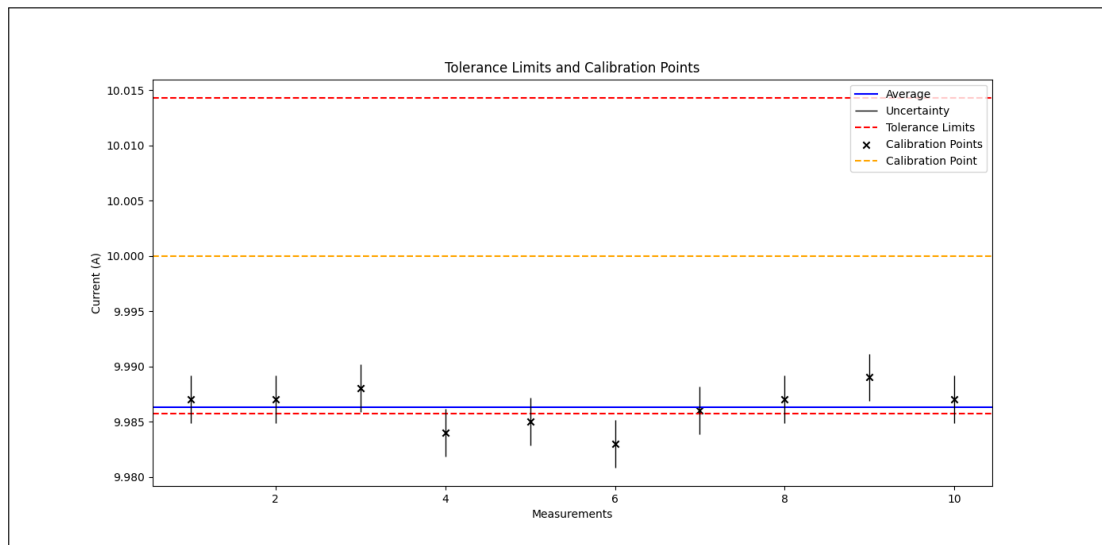


Figure 42: Readings and corresponding Uncertainty of the 10 V DC test.

The degree of risk is determined to make declaration of conformity. The standardized variable in the case where the average value is close to the lower limit is Calculated using equation (44).

$$z = \frac{9.9863 - 9.98785}{0.0017} = -0.91$$

The conversion table of the standard normal distribution shown in appendix C gives us that

Chapter 4. Experiment Data Processing

for $z = -0.91$, the proportion p is 0.1814, which means it is compliant with a probability of 18.14% or compliant with a level of risk of 81.86% [29].

Figure (43) below provides graphical illustration of the result

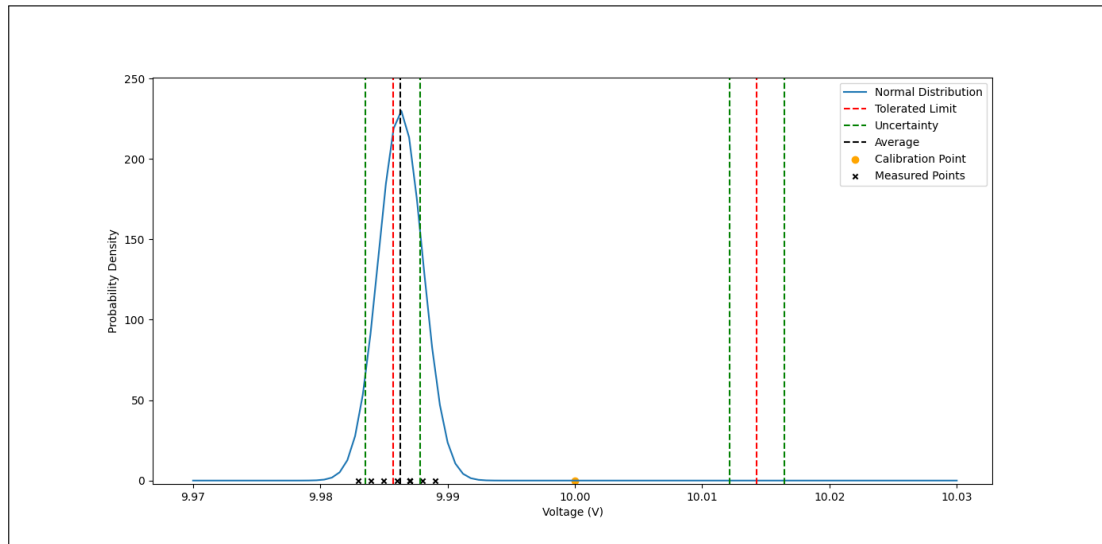


Figure 43: Readings and corresponding Uncertainty of the 10 V DC test.

This observation should be explicitly mentioned and documented in the calibration certificate to provide a comprehensive assessment of the UUT's performance.

DC Current

Based on the graph in figure 44 below, The measurements and their corresponding uncertainties, all the values obtained for the 1 A DC test fall within the tolerated range. Therefore, for the DC Current function, the UUT has passed the test.

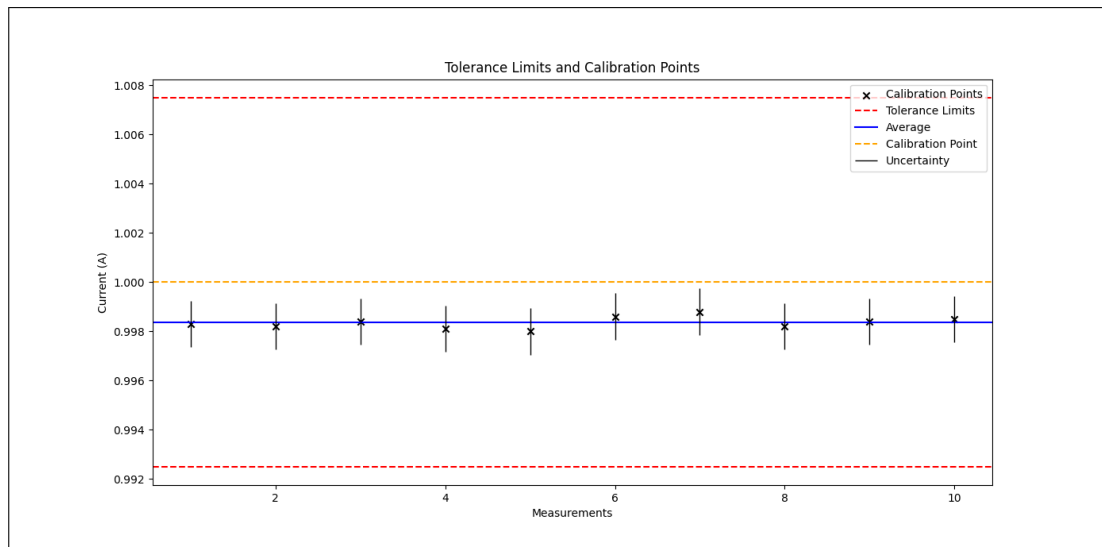


Figure 44: Readings and corresponding Uncertainty of the 1 A DC test.

4.3.4 Conclusion

Based on the results obtained from the comparative method calibration operation, it is evident that the unit under test (UUT) has failed the voltage tests for both the 5 V and 50 V ranges. Although the errors observed are relatively small, the obtained values fall outside the tolerated range, indicating a deviation from the expected accuracy.

On the other hand, for the DC current test, the UUT was tested for a single value of 1 A, which falls within the 5 A range. The measured value for the current was found to be within the tolerated range, indicating that the UUT has passed the test for the DC current function.

Overall, the UUT has failed the voltage tests but has passed the DC current test during the comparative method calibration.

The certificate is in appendix B

General Conclusion

In conclusion, This research on electrical calibration has provided a comprehensive investigation into the principles and implementation of the multiple methods. Which involves comparing the measurements of an instrument under test with those of a reference instrument, has been analyzed and evaluated in terms of its effectiveness and suitability for electrical calibration.

Implementation of the thesis has provided a comprehensive analysis and comparison of two calibration methods for digital multimeters (DMMs), The first experiment involved calibrating the multimeter using a calibrator and applying the direct method. The results of this experiment were favorable, as the multimeter passed all the tests and demonstrated high precision.

However, the second experiment employed a different approach by calibrating the multimeter using another reference multimeter and employing the comparative method. Unfortunately, this experiment did not yield satisfactory results. The multimeter under calibration failed the tests, indicating that it is not precise.

Overall, the research highlights the importance of selecting the appropriate calibration method and reference standards for achieving accurate and reliable calibration results. It emphasizes the effectiveness of the direct method using a calibrator, which proved successful in certifying the precision of the digital multimeter. The contrasting outcomes of the two experiments serve as valuable insights for the calibration process and the significance of reliable reference standards in achieving accurate measurements.

One area for future work is to expand the study of uncertainty sources in electrical calibration. This involves investigating additional factors that contribute to measurement uncertainties, such as environmental conditions, instrument drift, and operator technique. Also a software application can be developed to automate the analysis of calibration results. This software would input the obtained values, instrument under test, and testing instrument, performing comprehensive analysis and decision-making

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Appendix A

Certificate of Calibration

Issued by: S & Y Calibration

Institute of Electrical & Electronic Engineering
ENIE BP 101, Industrial Zone, 22000 Sidi Bel Abbas Algeria
Tel: +213 540 04 42 75 +213 667 31 05 00



Certificate Number: 0000001

Date: 05/04/2023

Client:

Address:

Calibrator: Fluke Calibrator
Model: 8846A
Serial number: 123456
Location: Sidi bel Abbas
Temperature: 23° ±2 C Humidity: 50% ±20

Unit under test

Instrument: multimeter
Manufacturer: Metrix
Model: MX24B
Serial number: 234567

Calibrated: 04/04/2023

Done by:

Signature:

Certificate of Calibration

Issued by: S & Y Calibration

Institute of Electrical & Electronic Engineering

ENIE BP 101, Industrial Zone, 22000 Sidi Bel Abbas Algeria

Tel: +213 540 04 42 75

+213 667 31 05 00



Certificate Number: 0000001

Date: 05/04/2023

Note:

For the 100 mA DC and AC tests, it is important to note that the uncertainty is relatively large when compared to the specified tolerance. This is due to the high resolution of the 10 A Range (10 mA), which is the only range capable of measuring current values above 50 mA. Despite the larger uncertainty, it is significant to highlight that all the measured points fall within the tolerated range.

Certificate of Calibration

Issued by: S & Y Calibration

Institute of Electrical & Electronic Engineering

ENIE BP 101, Industrial Zone, 22000 Sidi Bel Abbes Algeria

Tel: +213 540 04 42 75

+213 667 31 05 00



Certificate Number: 0000001

Date: 05/04/2023

Results:

Function	Range	Applied Value	Real Value	Error	Uncertainty	Result
DC Voltage	50 V	10 V	9.993 V	0.007 V	8.82 mV	PASS
		15 V	14.994 V	0.006 v	12.24 mV	PASS
AC Voltage	50 V	10 V	9.971 V	0.029 V	16.38 mV	PASS
		15 V	14.959 V	0.041 V	10.28 mV	PASS
Resistance	500 Ω	10 Ω	10.012 Ω	-0.012 Ω	61.79 m Ω	PASS
	50 k Ω	10 k Ω	9.956 k Ω	0.044 k Ω	9.89 Ω	PASS
DC Current	10 A	100 mA	99.62 mA	0.38 mA	5.78 mA	PASS
		1 A	0.998 A	0.002 A	8.72mA	PASS
AC Current	10 A	100 mA	99.44 mA	0.56 mA	5.76mA	PASS

Appendix B

Certificate of Calibration

Issued by: S & Y Calibration

Institute of Electrical & Electronic Engineering

AV 1 November 54, Boumerdes, Algeria

Tel: +213 540 04 42 75

+213 667 31 05 00



Certificate Number: 0000002

Date: 25/05/2023

Client:

Address:

Calibrator: Digital Multimeter (Reference Multimeter)

Model: DLIN DM 405

Serial number: 00175

Location: Boumerdes, Algerie

Temperature: 23°±2 C **Humidity:** 50% ±20

Unit under test

Instrument: Bench Digital Multimeter

Manufacturer: EuroTek

Model: TRUE-RMS RS-232PCLINK DM 500 53000

Serial number: 154687

Calibrated: 25/05/2023

Done by:

Signature:

Certificate of Calibration

Issued by: S & Y Calibration

Institute of Electrical & Electronic Engineering

AV 1 November 54, Boumerdes, Algeria

Tel: +213 540 04 42 75

+213 667 31 05 00



Certificate Number: 0000002

Date: 25/05/2023

Notes:

- **1 V DC Voltage :**

the majority of the measured values are outside the accuracy range. As a result, the UUT does not meet the requirements for the 5 V range test and is considered to have failed.

- **10 V DC Voltage :**

out of the obtained values, 6 fall within the tolerated range when considering their associated uncertainties. However, the remaining four values are outside the range, with two of them having uncertainties that also exceed the tolerance. Despite these outliers, the UUT can still be considered as passed with uncertainty because the mean value falls within the tolerated range. This observation should be explicitly mentioned and documented in the calibration certificate to provide a comprehensive assessment of the UUT's performance.

- **1 A DC Current :**

The measurements of the uncertainties, all the values obtained for the 1 A DC test fall within the tolerated range. Therefore, for the DC Current function, the UUT has passed the test.

Certificate of Calibration

Issued by: S & Y Calibration

Institute of Electrical & Electronic Engineering

AV 1 November 54, Boumerdes, Algeria

Tel: +213 540 04 42 75

+213 667 31 05 00



Certificate Number: 0000002

Date: 25/05/2023

Results:

Function	Range	Applied Value	Real Value	Error	Uncertainty	Result
DC Voltage	2 V	1 V	0.9983 V	0.0017 V	0.329 mV	Fail
	20 V	10 V	9.9863 V	0.0137 v	2.150 mV	PASS
DC Current	10 A	1 A	0.9977 A	0.0023 A	0.9430 mA	PASS

Appendix C

STANDARD NORMAL DISTRIBUTION: Table Values Represent AREA to the LEFT of the Z score.

Z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
-3.9	.00005	.00005	.00004	.00004	.00004	.00004	.00004	.00004	.00003	.00003
-3.8	.00007	.00007	.00007	.00006	.00006	.00006	.00006	.00005	.00005	.00005
-3.7	.00011	.00010	.00010	.00010	.00009	.00009	.00008	.00008	.00008	.00008
-3.6	.00016	.00015	.00015	.00014	.00014	.00013	.00013	.00012	.00012	.00011
-3.5	.00023	.00022	.00022	.00021	.00020	.00019	.00019	.00018	.00017	.00017
-3.4	.00034	.00032	.00031	.00030	.00029	.00028	.00027	.00026	.00025	.00024
-3.3	.00048	.00047	.00045	.00043	.00042	.00040	.00039	.00038	.00036	.00035
-3.2	.00069	.00066	.00064	.00062	.00060	.00058	.00056	.00054	.00052	.00050
-3.1	.00097	.00094	.00090	.00087	.00084	.00082	.00079	.00076	.00074	.00071
-3.0	.00135	.00131	.00126	.00122	.00118	.00114	.00111	.00107	.00104	.00100
-2.9	.00187	.00181	.00175	.00169	.00164	.00159	.00154	.00149	.00144	.00139
-2.8	.00256	.00248	.00240	.00233	.00226	.00219	.00212	.00205	.00199	.00193
-2.7	.00347	.00336	.00326	.00317	.00307	.00298	.00289	.00280	.00272	.00264
-2.6	.00466	.00453	.00440	.00427	.00415	.00402	.00391	.00379	.00368	.00357
-2.5	.00621	.00604	.00587	.00570	.00554	.00539	.00523	.00508	.00494	.00480
-2.4	.00820	.00798	.00776	.00755	.00734	.00714	.00695	.00676	.00657	.00639
-2.3	.01072	.01044	.01017	.00990	.00964	.00939	.00914	.00889	.00866	.00842
-2.2	.01390	.01355	.01321	.01287	.01255	.01222	.01191	.01160	.01130	.01101
-2.1	.01786	.01743	.01700	.01659	.01618	.01578	.01539	.01500	.01463	.01426
-2.0	.02275	.02222	.02169	.02118	.02068	.02018	.01970	.01923	.01876	.01831
-1.9	.02872	.02807	.02743	.02680	.02619	.02559	.02500	.02442	.02385	.02330
-1.8	.03593	.03515	.03438	.03362	.03288	.03216	.03144	.03074	.03005	.02938
-1.7	.04457	.04363	.04272	.04182	.04093	.04006	.03920	.03836	.03754	.03673
-1.6	.05480	.05370	.05262	.05155	.05050	.04947	.04846	.04746	.04648	.04551
-1.5	.06681	.06552	.06426	.06301	.06178	.06057	.05938	.05821	.05705	.05592
-1.4	.08076	.07927	.07780	.07636	.07493	.07353	.07215	.07078	.06944	.06811
-1.3	.09680	.09510	.09342	.09176	.09012	.08851	.08691	.08534	.08379	.08226
-1.2	.11507	.11314	.11123	.10935	.10749	.10565	.10383	.10204	.10027	.09853
-1.1	.13567	.13350	.13136	.12924	.12714	.12507	.12302	.12100	.11900	.11702
-1.0	.15866	.15625	.15386	.15151	.14917	.14686	.14457	.14231	.14007	.13786
-0.9	.18406	.18141	.17879	.17619	.17361	.17106	.16853	.16602	.16354	.16109
-0.8	.21186	.20897	.20611	.20327	.20045	.19766	.19489	.19215	.18943	.18673
-0.7	.24196	.23885	.23576	.23270	.22965	.22663	.22363	.22065	.21770	.21476
-0.6	.27425	.27093	.26763	.26435	.26109	.25785	.25463	.25143	.24825	.24510
-0.5	.30854	.30503	.30153	.29806	.29460	.29116	.28774	.28434	.28096	.27760
-0.4	.34458	.34090	.33724	.33360	.32997	.32636	.32276	.31918	.31561	.31207
-0.3	.38209	.37828	.37448	.37070	.36693	.36317	.35942	.35569	.35197	.34827
-0.2	.42074	.41683	.41294	.40905	.40517	.40129	.39743	.39358	.38974	.38591
-0.1	.46017	.45620	.45224	.44828	.44433	.44038	.43644	.43251	.42858	.42465
-0.0	.50000	.49601	.49202	.48803	.48405	.48006	.47608	.47210	.46812	.46414

STANDARD NORMAL DISTRIBUTION: Table Values Represent AREA to the LEFT of the Z score.

Z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.50000	.50399	.50798	.51197	.51595	.51994	.52392	.52790	.53188	.53586
0.1	.53983	.54380	.54776	.55172	.55567	.55962	.56356	.56749	.57142	.57535
0.2	.57926	.58317	.58706	.59095	.59483	.59871	.60257	.60642	.61026	.61409
0.3	.61791	.62172	.62552	.62930	.63307	.63683	.64058	.64431	.64803	.65173
0.4	.65542	.65910	.66276	.66640	.67003	.67364	.67724	.68082	.68439	.68793
0.5	.69146	.69497	.69847	.70194	.70540	.70884	.71226	.71566	.71904	.72240
0.6	.72575	.72907	.73237	.73565	.73891	.74215	.74537	.74857	.75175	.75490
0.7	.75804	.76115	.76424	.76730	.77035	.77337	.77637	.77935	.78230	.78524
0.8	.78814	.79103	.79389	.79673	.79955	.80234	.80511	.80785	.81057	.81327
0.9	.81594	.81859	.82121	.82381	.82639	.82894	.83147	.83398	.83646	.83891
1.0	.84134	.84375	.84614	.84849	.85083	.85314	.85543	.85769	.85993	.86214
1.1	.86433	.86650	.86864	.87076	.87286	.87493	.87698	.87900	.88100	.88298
1.2	.88493	.88686	.88877	.89065	.89251	.89435	.89617	.89796	.89973	.90147
1.3	.90320	.90490	.90658	.90824	.90988	.91149	.91309	.91466	.91621	.91774
1.4	.91924	.92073	.92220	.92364	.92507	.92647	.92785	.92922	.93056	.93189
1.5	.93319	.93448	.93574	.93699	.93822	.93943	.94062	.94179	.94295	.94408
1.6	.94520	.94630	.94738	.94845	.94950	.95053	.95154	.95254	.95352	.95449
1.7	.95543	.95637	.95728	.95818	.95907	.95994	.96080	.96164	.96246	.96327
1.8	.96407	.96485	.96562	.96638	.96712	.96784	.96856	.96926	.96995	.97062
1.9	.97128	.97193	.97257	.97320	.97381	.97441	.97500	.97558	.97615	.97670
2.0	.97725	.97778	.97831	.97882	.97932	.97982	.98030	.98077	.98124	.98169
2.1	.98214	.98257	.98300	.98341	.98382	.98422	.98461	.98500	.98537	.98574
2.2	.98610	.98645	.98679	.98713	.98745	.98778	.98809	.98840	.98870	.98899
2.3	.98928	.98956	.98983	.99010	.99036	.99061	.99086	.99111	.99134	.99158
2.4	.99180	.99202	.99224	.99245	.99266	.99286	.99305	.99324	.99343	.99361
2.5	.99379	.99396	.99413	.99430	.99446	.99461	.99477	.99492	.99506	.99520
2.6	.99534	.99547	.99560	.99573	.99585	.99598	.99609	.99621	.99632	.99643
2.7	.99653	.99664	.99674	.99683	.99693	.99702	.99711	.99720	.99728	.99736
2.8	.99744	.99752	.99760	.99767	.99774	.99781	.99788	.99795	.99801	.99807
2.9	.99813	.99819	.99825	.99831	.99836	.99841	.99846	.99851	.99856	.99861
3.0	.99865	.99869	.99874	.99878	.99882	.99886	.99889	.99893	.99896	.99900
3.1	.99903	.99906	.99910	.99913	.99916	.99918	.99921	.99924	.99926	.99929
3.2	.99931	.99934	.99936	.99938	.99940	.99942	.99944	.99946	.99948	.99950
3.3	.99952	.99953	.99955	.99957	.99958	.99960	.99961	.99962	.99964	.99965
3.4	.99966	.99968	.99969	.99970	.99971	.99972	.99973	.99974	.99975	.99976
3.5	.99977	.99978	.99978	.99979	.99980	.99981	.99981	.99982	.99983	.99983
3.6	.99984	.99985	.99985	.99986	.99986	.99987	.99987	.99988	.99988	.99989
3.7	.99989	.99990	.99990	.99990	.99991	.99991	.99992	.99992	.99992	.99992
3.8	.99993	.99993	.99993	.99994	.99994	.99994	.99994	.99995	.99995	.99995
3.9	.99995	.99995	.99996	.99996	.99996	.99996	.99996	.99996	.99997	.99997