Electrical Quantities in Terms of the International System of Units

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Abstract---The electrical International System of Units (SI) are defined and realized as DC electrical quantities. National Institute for Standards (NIS), Egypt maintains the DC voltage unit by using the DC Josephson Voltage Standard (JVS) as a primary standard for DC voltage adding to eight zener diode reference standards as DC voltage secondary standards. The JVS is used to provide traceability of electrical measurements to the SI units. In order to disseminate the DC voltage traceability to the secondary standards, one of the NIS zener diode reference standards has been calibrated via the JVS in 1.018 V and 10 V ranges; then, this traceable zener diode has been used to automatically calibrate the other zener diode reference standards. Accordingly, an automatic system for controlling and calibrating the zener diode reference standards has been specially constructed using the Laboratory Virtual Instrument Engineering Workbench (LabVIEW) software. This automatic calibration system is a consistent construction from the national zener diode reference standards that can disseminate the traceability of all the electrical instruments under calibration. The standard development procedures have been followed in the building of the system software. The software requirement specifications as well as functional specifications are taken into consideration. Design, implementation and testing of the software have been performed. Furthermore, software validation for measurements' uncertainty as well as results' compatibility in both automatic and manual modes has been achieved.

Index Terms---International System of Units, Zener Diode Reference standards, LabVIEW, Software Validation.

I. 1. INTRODUCTION

THE representation of the unit of volt by using the Josephson Effect is bringing about worldwide uniformity in the realization of unit of volt at the primary level. Since about 1990 JVS has been in use in national, industrial and military standards laboratories around the world [1]. JVS systems based on arrays of Superconductor-Insulator-Superconductor (SIS) tunnel junctions are commonly used as primary DC voltage standards [2]. Applying them, secondary voltage standards as well as high precision digital voltmeters can be calibrated with the highest level of accuracy [3]. In the mean time there are approximately 60 JVS systems around the world that use SIS arrays to maintain their national voltage standards and for voltage dissemination [4].

The JVS is used to calibrate the 1.018V and 10V zener diode reference standards, and other measurements such as the linearity of high precision digital voltmeters. NIS DC electrical laboratory has the JVS and a group of zener diode reference standards. This group includes two sets; the first set is the Fluke 734A and the second set is the Fluke 7000.

To disseminate the traceability to all the DC voltage zener diode reference standards, one of the zener diodes' groups has been calibrated via the JVS. Then, the other zener diodes of the group have been automatically calibrated against the traceable one. For this reason, a special programmable calibration system using LabVIEW software has been established. Automatic systems can perform the high quality and time consuming operations required in the calibration activity but the available commercial software is not suitable for the laboratories that work at high levels of accuracy and precision. Therefore the need of software construction arises at the first place in these laboratories.

This paper discusses the establishment of the automatic calibration system. The system hardware and software have been presented in details. Due to the lack of comprehensive validation guidance materials, the importance of software validation becomes one of the main requirements [5]. Accordingly, the validation of the automatic system has been performed. This is demonstrated by calibrating the 10 V outputs of the seven Zener Diodes against the reference unit (traceable zener diode) in automatic as well as in manual mode. Also, the expanded uncertainty of the calibration measurements has been evaluated by testing the system under the same measurements conditions ten times. The 10 V output automatic calibration results combined with their expanded uncertainty of the seven Zener Diode units under calibration have been compared with their manual results.

II. System Setup

The system consists of the DC JVS and two DC zener diode reference standards sets; the first set is the Fluke 734A zener diode standard which includes four 732B separate units and the second set is the Fluke 7000 voltage standard which includes four non separate units in one enclosure with four different output terminals. Adding to the 320A Data Proof low thermal scanner, 8.5 digit HP 3458A highly sensitive recently calibrated digital multimeter (DMM) and a PC controlled by General Purpose Interface Bus (GPIB/IEEE-488).

The DC JVS is a primary voltage standard which uses arrays of Josephson junctions (JJ).
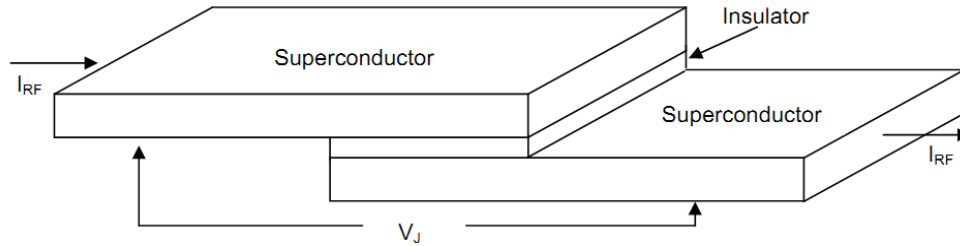
Fig. 1. Superconductor-Insulator-Superconductor (SIS) Josephson Junction (JJ)

These junctions consist of a thin insulating barrier between two superconductors, (SIS) as shown Fig. 1. JVS system based on arrays of SIS tunnel junctions are commonly used as primary DC voltage standards. When Josephson junctions are exposed to electromagnetic radiation of frequency f, the DC voltage across the junction V_J can only assume discrete values given by:

$$V_j = n \times \frac{1}{K_{j90}} \times f \qquad (1)$$

Where n is an integer which identifies a constant voltage step in the current voltage dependence and the value of K_{J90} has been defined since 1990 to be K_{J90} = 483 597.9 GHz/V without any uncertainty. With the equation (1), the voltage will be traced back to a frequency which can be controlled to a very high precision.
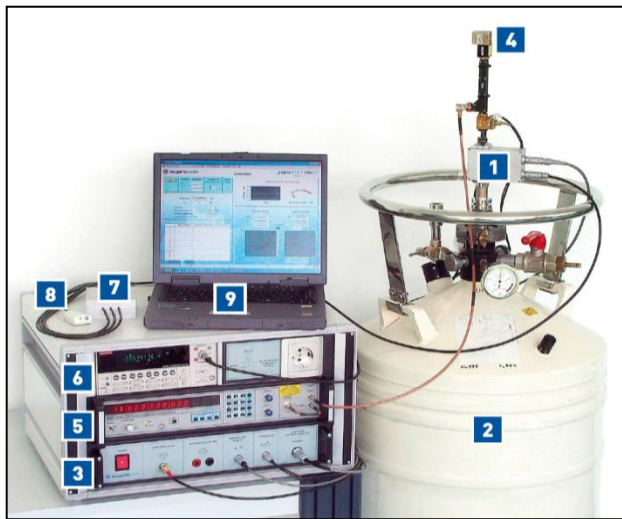

Fig. 2. Josephson voltage standard system

The complete JVS system shown in Fig. 2 consists of the following components:
1. 10 Volt SIS Josephson junction array with cryoprobe
2. Dewar with liquid helium
3. Control electronics
4. 75 GHz microwave electronics
5. EIP 578B source looking counter
6. Keithley 2182A null detector
7. 3-channel polarity reversal switch
8. Sensors for temperature, pressure and humidity
9. Laptop with IEEE interface

One zener diode of the first set (Fluke 732B) has been automatically calibrated via the JVS. Then, it is used as the reference unit (RU) to calibrate the other seven units of zener diodes as units under test (UUT1, UUT2… UUT7). Fig. 3 illustrates the automatic calibration system schematic diagram.

The results of the reference unit have been obtained by applying a linear least-square fit to the data using the following time dependent linear model:

$$U(t_i) = U(\bar{t}) + b \times (t_i - \bar{t}) \qquad (2)$$

Where,

$\bar{t}$: The mean date of the BIPM measurements.

$U(\bar{t})$: The voltage on the mean data

b: A constant drift rate.

The Type A uncertainty, S_U, of the voltage on the mean date is calculated as:

$$S_U^2 = \sum_{i=1}^{n} U_i - U(t_i))^2 / n(n-2) \qquad (3)$$

Where, U_i stands for the measured values and $U(t_i)$ for those computed using the model. n is the total number of measurements. The combined standard uncertainty of the RU for the 10 V is 120 nV, its constant drift rate (b) is 60 nV/day. The voltage in the mean date of the RU from its calibration certificate (at 10 V) is 9.99996702 V. Equation (2) has been used to get the $U(t_i)$ values of the RU. The absolute value of the UUT is obtained by difference method using the high sensitive 3458A DMM through the Data Proof 320A low thermal scanner. The mathematical equation used is [6]:

$$V_{UUT} = V_{RU} + \delta V + \delta V_D + c_{RU}\delta t_{RU} - c_{UUT}\delta t_{UUT} + \delta E \qquad (4)$$
$$\delta V = \delta V_1 + \delta V_2 \qquad (5)$$

Where,
V_{UUT} = average voltage of the UUT.
V_{RU} = average voltage of the RU
δV_1 = difference in voltage between the RU and the UUT.
δV_2 = linearity deviation of the DMM used for the measurement.
δV_D = drift in the value of the RU.
c_{RU} = temperature coefficient of cells of RU.
δt_{RU} = temperature deviation of RU.
c_{UUT} = temperature coefficient of UUT.
δt_{UUT} = temperature deviation of UUT.
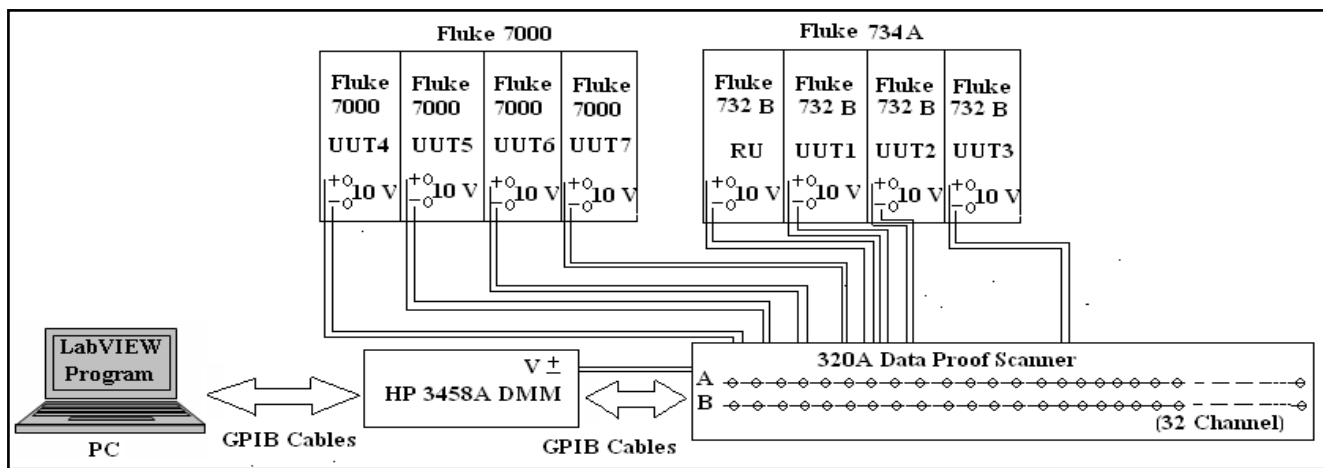δE = thermal emf in calibrating the UUT.

Fig. 3 schematic diagram of the automatic calibration system

The main operative instrument in this system is the low thermal scanner which used for scanning a number of instruments without physically changing the polarity of a device under test [7]. The Data Proof 320A (DP 320A) low thermal scanner with extremely low thermal offsets is ideal for automating precision measurements. It is remotely controlled through the IEEE-488 interface [7]. This versatile dual scanner has 32 input channels and two pairs of output lines (A & B) which makes it suitable for a wide variety of uses. Each unit of the first and the second sets has been connected to the scanner through shielded cables. The output lines A & B of the DP 320A scanner have been connected to the High & Low terminals of the HP 3458A DMM through the same type of shielded cables, where the Low terminals of output lines A & B are shorted together.

In order to calibrate the seven UUTs via the RU, the eight channels of the DP 320A scanner (from channel1 to channel8) have been used. Before using these eight channels in the calibration, they have been checked for their intended purpose. This check has been performed using the third configuration described in [8]. For using this configuration, it requires two input channels at the same time. Therefore, DMM measures effectively the thermal emf difference between these two channels (when their input terminals are shorted) [8]. For the thermal emf measurements of the eight channels, the scanner channel input is shorted through a short copper wire [6]. The gained thermal emf results of the checked eight channels don't exceed 100 nV which are acceptable for the calibration purpose within the DP 320A specifications [9]. The temperature and relative humidity of the calibration laboratory were adjusted and fairly controlled to (23 ±1) °C and (50% ± 10%) respectively.

III. CONSTRUCTION OF THE SYSTEM SOFTWARE

The Zener Diode reference standards calibration system software has been built using LabVIEW graphical language. This software is constructed to control the calibration system, eliminate the operator's errors, allow statistical proceeding of the results in rather short time and generate a complete visual statistical information report from the performed calibration.

The standard procedures for development of software use the V-Model for software life-cycle. This V-Model includes the software requirements specification, functional specification, design specification and implementation [10]. The development principle of V-Model has been followed in the building of the calibration system software. The preparation of the requirements specification is a significant part of the software life-cycle development. In this part, the description of the problem and the approach which will be followed to solve this problem is recognized.

The Requirements Specification is the input to the software design process. Here, the problem which has to be solved by the software development is the performing of the automatic calibration system of the Zener Diode reference standards. The followed approach to solve this problem is outlining the main functions which have to be carried out. The functional specification is more comprehensive than the requirements specification and must include full explanation of each function. It illustrates how each requirement is to be met. Adding together, it should emphasize any inconsistency if complete agreement is not realistic [10, 11].

Finally, the functional specification will cover all the details of how the end-user of the automatic system is to interact with this system. Eventually, each function described will require a test to prove compliance with the specification. Therefore, this document will be used as the input to the functional test. After determination of the problem and declaring of the requirements the software can be designed.

The software design is a record of how the requirements will be implemented. The design document may use state diagrams, flowcharts or formal methods to describe the software design. In this case, LabVIEW is used as the development language. The design document includes the program structure on the base of LabVIEW Virtual Instruments (VI) hierarchy, module (VI) design, LabVIEW coding conventions and LabVIEW tools [12]. Each module defined in this design will require a test to verify compliance with the requirements.

IV. IMPLEMENTATION AND TESTING OF THE SYSTEM SOFTWARE

When the software design is finished the software can be fully implemented. In the implementation step the code is created regarding agreed design of the software.

LabVIEW is a graphical programming language and states transition diagram to follow the coding conversion declared in the design. The module test is executed to prove that each module (VI) requirement in the design document is fulfilled. The excellent test will illustrate that the module achieves the designed function. The functional test is performed as well. This test level is higher than the level of the module test. It tests how the modules work together concerning functions defined in the functional specification. Moreover, it tests the operator interfaces and output results for stability and accuracy.

After module and functional successfully testing, the operational testing is performed by implementing the LabVIEW software in the calibration system. It is preferred to perform the functional tests once more in the final version of the LabVIEW software. Consequently, after applying all the previous standard procedures for software development, NIS LabVIEW software Zener Diode reference standards calibration system has been built.

The LabVIEW is a powerful and flexible instrumentation software system which contains two main components: The front panel and the block diagram. It also contains a comprehensive library for data collection, analysis, presentation and storage. Program execution is determined by the structure of a graphical block diagram on which the programmer connects different function nodes by drawing wires. These wires propagate variables and any node can execute as soon as all its input data become available. The front panel is used to interact with the user when the program is running. User can control the program, change inputs, and see data updated in real time [13, 14]. The front panel and the block diagram of the automatic calibration system for Zener Diode reference standards have been carried out.

The new software has the facility to automatically calculate the estimated uncertainty in the measurements, store the data, record, and plot and report the calibration results. The front panel includes the exact time and date of performing the calibration (automatically taken from the PC) adding to the different (Type B) uncertainty components which contribute in the uncertainty budget.

Ten readings have been automatically taken and transferred to the Excel sheet by the software. The uncertainty of the calibration measurements has been estimated based on the ISO/IEC 17025 [15] and the expanded uncertainty has been reported by the software.

V. VALIDATION OF THE SYSTEM SOFTWARE

The automatic system has been constructed and used for calibrating both the NIS and the customers Zener Diode Reference Standards (1.018 V and 10 V outputs).

By functionality testing of the system hardware and software, it is fairly demonstrated that, the automatic calibration procedures execution is more rapidly than the manual procedures performing.

What is more, in the automatic mode, the operator full attendance is not needed as in the manual mode and a better calibration procedure is guaranteed. In addition to the system functionality test and the importance of achieving the measurements reliability guarantee in metrology science [16], the new system has been validated.

In order to validate the system for its specific purpose, it has been utilized in calibrating the NIS Zener Diode Reference Standards Group at 10V output and the results have been compared with those obtained by their manual calibration.

Then, the calibration measurements uncertainty in both modes has been evaluated and compared by (automatically and manually) testing the system under the same calibration conditions ten times, in five consecutive days. Each day ten observations have been taken to evaluate the average value. The same scanner, DMM, connecting cables and the same environmental conditions of the lab have been used in both manual and automatic calibrations.

The repeatability evaluated as a 1σ type A uncertainty and in between days variance in voltages has been considered. Table I illustrates the automatic and manual 10 V output calibration results with their expanded uncertainty values (at 95% confidence level, k=2) while, Fig. 4 shows the output DC voltages of the UUT1, UUT2, UUT3, ….UUT7 in the manual (M) mode and automatic (A) mode.

TABLE I
AUTOMATIC AND MANUAL 10 V OUTPUT CALIBRATION
RESULTS WITH THEIR EXPANDED UNCERTAINTY

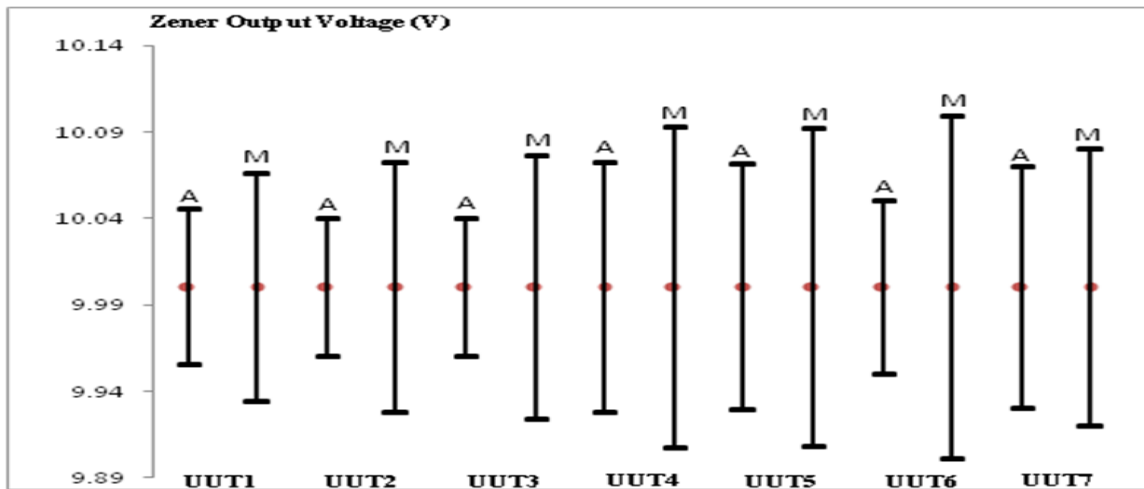| Zener	Automatic Calibration Results of 10 V Output (V)	Manual Calibration Results of 10 V Output (V)
UUT1	10.0000231 ± 0.45E-6	10.0000232 ± 0.66E-6
UUT2	10.0000163 ± 0.40E-6	10.0000162 ± 0.72 E-6
UUT3	10.0000193 ± 0.61E-6	10.0000193 ± 0.76 E-6
UUT4	09.9999481 ± 0.72E-6	09.9999482 ± 0.83 E-6
UUT5	09.9999577 ± 0.71E-6	09.9999576 ± 0.92 E-6
UUT6	10.0000220 ± 0.50E-6	10.0000223 ± 0.99E-6
UUT7	09.9999671 ± 0.70E-6	09.9999674 ± 0.85 E-6

Fig. 4. Output DC voltages of the UUT1, UUT2,…..UUT7 in the manual mode and automatic mode

From the previous results, it is clearly shown that the automatic calibration res ults for the 10 V outputs of the under test seven Zener Diode units are very close to their corresponding manual results. Furthermore, it is quite verified that, the evaluated uncertainty values in automatic mode are smaller than the values manually obtained. As a result, a full compatibility and an improved repeatability have been achieved with measurements made by the automated system.

VI. CONCLUSION

DC JVS is the primary standard for DC voltage which provides traceability of electrical measurements to the SI units. An automatic system has been specially built at NIS using LabVIEW graphical language for calibrating DC Zener Diode reference standards. This system acts as the comprehensive and reliable structure that, from the national electrical standards, disseminates the traceability to all the electrical units under calibration. The new software enables fast and reliable measurement function including statistical proceeding, measurement results visualization on the screen and generation of measurement report. The application of this software in the DC voltage reference standards calibration system significantly improves the measurement process as well as the calibration process.The validation process for the new automated system software and hardware has shown the functionality of the system and a full compatibility with calibration measurements made manually and by the automated system. Adding to, performing rather enhanced uncertainty results in the automatic operation. The new automatic calibration system is now in use for the calibrations of both the NIS and the customer DC Zener Diode reference standards.

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