AUTOMATIC SYSTEM FOR CALIBRATING ZENER-BASED VOLTAGE STANDARDS

Leonardo Trigo, Heriguati de Souza, Daniel Slomovitz
UTE – LABORATORIO
Paraguay 2358, Montevideo, Uruguay
Tel. +598-21552449, Email: ltrigo@ute.com.uy, dslomo@gmail.com

Abstract: An automatic system was developed to intercompare Zener voltage standards. It comprises a low-emf voltage scanner, a voltmeter, a temperature scanner, an ohmmeter and software. Up to 10 units can be tested at the same time, with a full measurement round of 60 minutes. In this way, the system continuously records around 24 individual measurement values per day for each individual Zener. Typical results are shown.

1. INTRODUCTION

Traditionally, dc voltage standards were maintained by standard cells of 1.018 V. In the past, National Metrology Institutes had banks of many cells with intercomparison routines. In our laboratory, there were three banks of four cells each. To compare each other, with both polarities to avoid stray emfs, a bank of *n* cells required *n*(*n*-1) comparisons. In this case, a complete round required 132 comparisons, which was a very hard work. Other laboratories had more cells, and the comparisons routine was more laborious. In practice, most laboratories divided the bank in several groups reducing the number of comparisons. In [1], a detailed analysis of such comparison was presented, as well as its implementation. Additionally, much care was necessary for this measurement, due to the relative high output impedance and temperature dependence of this kind of device. Most of the work was based on manual operation, so technicians dedicated much of their time to this type of task.

When the first Zener based standard appeared, it seemed that many disadvantages were solved. They have a higher voltage output (10 V) and low impedance (some milliohm), which leads to lower stray-emfs and isolation-resistance influences. Although they kept the old 1.018-V output for compatibility with the standard cells, nowadays this output is generally not used. The advance of electronic scanners together with the low output impedance of the Zener sources, allowed this test to be fully automated.

In the following sections, a detailed description of the automatic system, developed by our laboratory, is shown.

2. INSTRUMENTATION SYSTEM

Figure 1 shows a schematic diagram of the measurement system. It comprises a main scanner (Voltage) and a voltmeter for differential voltage measurements between sources. Additionally, an auxiliary scanner (Resistance) and an ohmmeter measure the resistances of the Zener internal thermistors to compute their internal temperatures. A computer and software process all the data and display statistical results. Only the 10-V outputs of the sources are compared, as the 1.018-V outputs have worse stability and higher impedance. For calibrating the 1-V level, we developed a high precision step-down divider [2], so that Zener low-voltage output calibration was not necessary.

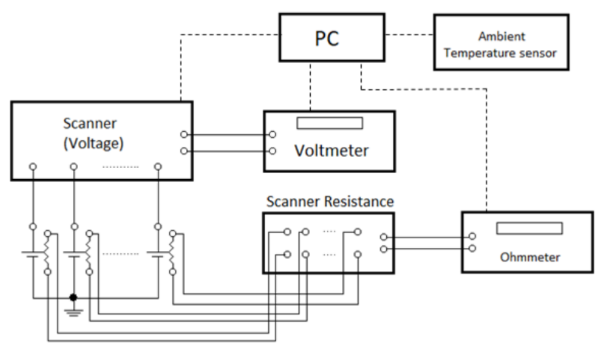

Fig. 1. *Schematic diagram of the measuring system.*

Figures 2 and 3 show photos of the instrumentation. In figure 2, at the top, is the resistance scanner and our Zener Standard Reference [3], both self-developed. In the center are the low-voltage emf scanner (Measurement International 4210B), an Agilent-3458A multimeter used as the differential voltmeter, and the Agilent-34401 multimeter used as the ohmmeter. At the bottom there are several Zener

Fig. 2. Rack containing all the measurement instruments and sources under test.

Standards; some Fluke-732B units and other one, self-developed [4-6]. The latter, like the one at the top of the rack, bases its stabilities on the average of 140 individual Zener diodes. Figure 3 shows the resistance scanner for temperature measurement. It selects the unit under test for measuring the resistance of their internal thermistors.

The computer continuously runs a software that controls the scanners, the multimeters, and performs all calculations. The values of each Zener Standard are displayed on the screen as well as statistical calculations.

2.1. Scanners

As mentioned, the measuring system has two scanners, the principal one for voltage measurements, and an auxiliary one for temperature measurements. The first one is the main component of the system. It selects the pair of Zener-based sources to be compared. The different parameters that this component must have, have been carefully

***Fig. 3**. Resistance scanner for temperature measurements.*

analyzed. The first one is the number of channels. It must be enough, according to the number of sources. In our case, it has 10 channels. Each channel allows the connection of its inputs to two outputs, A and B, as shown in fig 4.

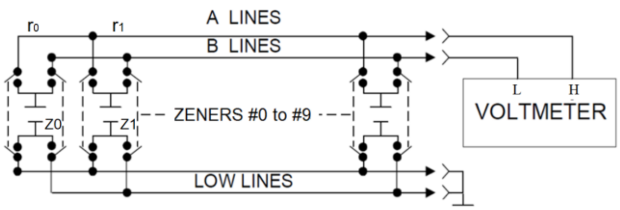

***Fig. 4.** Schematic diagram of the main scanner connections.*

For example, to compare Zener Z0 with Zener Z1 there are two possible configurations, relay r_0 to A with relay r_1 to B, or relay r_0 to B with relay r_1 to A. The average of both measurements eliminates any offset caused by emfs, external to the scanner, and the voltmeter offset.

Other basic requirements for the scanner are to have low thermoelectric emfs, high isolation resistance and low series resistance. The emfs of the scanner are in the order of 50 nV. These emfs mainly come from the thermal environment and the self-heating of the relays. This last point is reduced by using latch relays. They operate by pulses, instead of continues excitation, reducing the energy necessary to maintain the state. Great care was taken with the external connections and thermal isolation, to avoid adding high external emfs. They were limited to 50 nV. In our system, the scanner has factory-installed cables at its inputs and outputs instead of binding post connectors. This eliminates contact problems at the scanner.

Additional characteristics of this scanner are:

Contact resistance: <0.05 Ω
Insulation resistance: >1 TΩ
Number of channels: 10
Interface: IEEE-488 interface

These values are enough to fulfill our requirements, as will be shown in the Uncertainty Section.

The resistance scanner selects the appropriate internal thermistor and connects it to a DMM, an Agilent-34401A, used as ohmmeter. As the thermistor resistances are higher than 2 kΩ, the internal resistance of this scanner plus the cable resistances (0.45 Ω) are appropriate for this measurement. The relative error, for the lowest thermistor value, is 0.02 %, which is reflected in 6 mK of temperature error. The system takes 60 minutes for a complete round, which results in 24 measurements per day for each Zener.

2.2. Multimeters

An Agilent 3458 DMM was selected for measuring the voltage difference between each pair of compared sources. The voltage differences between different sources are lower than some hundred microvolts, so the minimum voltage range that the DMM has (DCV 100-mV), was selected. It has the following specifications.

Resolution: 10 nV. It is equivalent to 0.001 ppm of 10 V.
Accuracy: 9 ppm of reading plus 3 ppm of range. For the 100-mV range, the last one is the principal, equivalent to 0.3 µV.
Aperture time: 4 s, (NPLC 250, for power frequency of 60 Hz).
Effective number of digits: 8 ½
Input impedance: >10 GΩ

The evaluation of the incidence of these parameters on the uncertainty is shown in the Uncertainty Section.

For measuring the thermistor resistances of the internal temperature sensor of the Zeners, an Agilent 34401A DMM is used in the resistance ranges. The thermistor resistance of FLUKE-732 model is around 40 kΩ. The other Zener sources, we have constructed [6], have thermistor resistance of 2 kΩ. Then, ranges of 100 kΩ and 10 kΩ are used. The currents that this DMM applies are 10 µA and 100 µA respectively, so the self-heating is very low, as the powers are 4 µW and 20 µW, respectively.

The accuracy is 0.01 % of the reading plus 0.001 % of the range. Thermistors temperature-coefficients are around -4 %/K, then, that is equivalent to 2.5 mK, much less than the stability of the ovens.

3. MEASURMENT PROCEDURES

3.1 Sequence

The measurement sequence was designed to discount thermoelectric emfs and non-linear effects of the 3458A multimeter. Polarity reversal was implemented with the voltage scanner. Its inputs are labeled from n=0 to n=9, and its outputs: A and B. These outputs are connected to the High and Low inputs of the 3458A multimeter, respectively. The designed sequence compares each Zener pair (n and n+1), reversing the polarity at the DMM, as:

n-to-A with (n+1)-to-B;
(n+1)-to-A with n-to-B,

with n from n=0 to n=8. Averaging both values, all offsets are discounted.

3.2 Data processing

The measurement system measures only voltage differences between Zeners, so to get absolute values it is needed to assign a reference value to one of these standard units. For this project, we use in this role one of the Zener developed by ourselves [6], which has a drift of less than 0.01 µV/V per year, much lower than commercial Zener Standards.
The first step of the system is to initialize the communication with both scanners and multimeters, and configure them. The 3458A multimeter is configured as explained in chapter 2.2, and the 34401 multimeter is configured as ohmmeter autoranging. Then, the scanners select the two Zener to be compared. To obtain a valid value of the voltage difference, five measurements are made and their average value and standard deviation are calculated. If the standard deviation is less than 1 µV, this set of measurement is taken as valid, otherwise five new measurements are made again. This eliminates stray interferences. After that, the average value is stored in a 10×10 matrix (according to the number of scanner inputs). It is loaded with the forward and the reverse measurements. To

calibrate any of the Zeners under test, the average difference to the reference unit is calculated, and added to the reference voltage value.
After this, the measurement of the temperature of each Zener begins. All Zener have a thermistor so, depending on the resistance value, the temperature is determined. To make these measurements, the temperature scanner and the 34401A multimeter, in the ohmmeter function, are used.

4. SOFTWARE

The program was developed in Labwindows® programming environment. The code was written in *C* programming language. This programming environment was chosen because it has very powerful libraries that make it easy to create user-screens with buttons, controls, graphics, etc. It also has libraries for serial and IEEE 488 (GPIB) communications, to interconnect with scanners and multimeters.

In previous chapters, we have partially commented on the operation of the Zener Standards Monitoring software, now we will complement that information. When the Zener Standard Monitoring Software starts running, it loads the history of each Zener unit, calculates drift, and plots voltage and temperature values against time. At this moment, the user can choose to generate an Excel file with the historical values of all Zeners.

The user must indicate which Zener is connected to each input of both scanners (voltage and resistance). This is very important to have the history of each Zener without mixing measurements from other units. Then, the user can start the automatic measurement system. When starting, the program configures the scanners and multimeters, as mentioned in the previous chapters and starts the measurements.

When a full measurements cycle is completed, the voltage values of each Zener are displayed on the screen, all charts are updated, and all values are saved to a file in the computer's hard drive. This cycle repeats forever, until the user closes the program. One file is created each day with all the measurements of that day. The date is included in the file name. At the end of the day, a copy is made to a flash drive to back up the information.

Figure 5 shows the home screen. In the upper part there are two selection possibilities. One (*Graficos*) is to see the charts with historical values of voltage and temperature of each Zener. The other (*Configuracion*) is for associating the Zener labels to the inputs of the scanners. The last voltage values, the drift of each Zener with respect to the Reference Zener and the days of measurements are displayed.
The user has three buttons: to start (*INICIO*), to end (*FIN*) and one (*EXCEL*) that generates the Excel file with the historical voltage and temperature values of all Zeners.

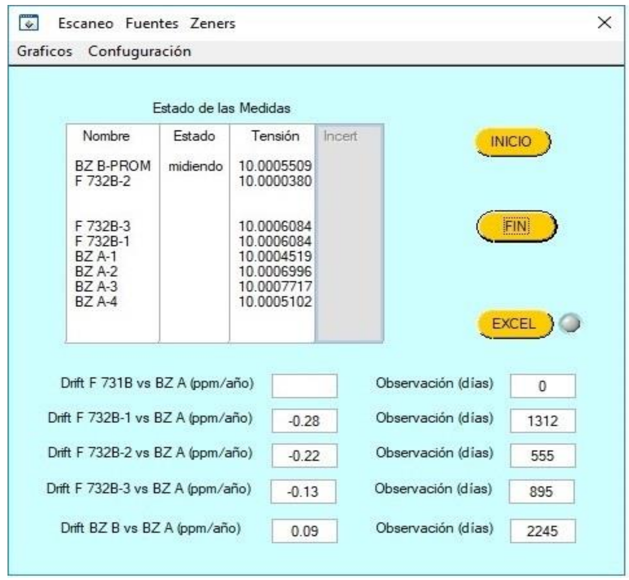

Fig. 5. *Home screen of the measurement system.*

Figures 6 shows the screen with the voltage values of three Fluke-732B during seven years. Figure 7 shows their temperatures calculated from the thermistor resistances. The lack of information in the chats is because in these periods the unit was disconnected from the measurement system.

5. UNCERTAINTY

The uncertainty estimation of the comparison system of a pair of units is analyzed as follows. A partial validation of this calculation was done by an international comparison of voltage at 10-V level [7]. Our Reference Zener was intercompared with a Josephson Standard of the National Metrology Laboratory of Brazil (INMETRO). The traveling standards were two FLUKE 732B, that belong to UTE, compared to our Reference Zener using the described system.

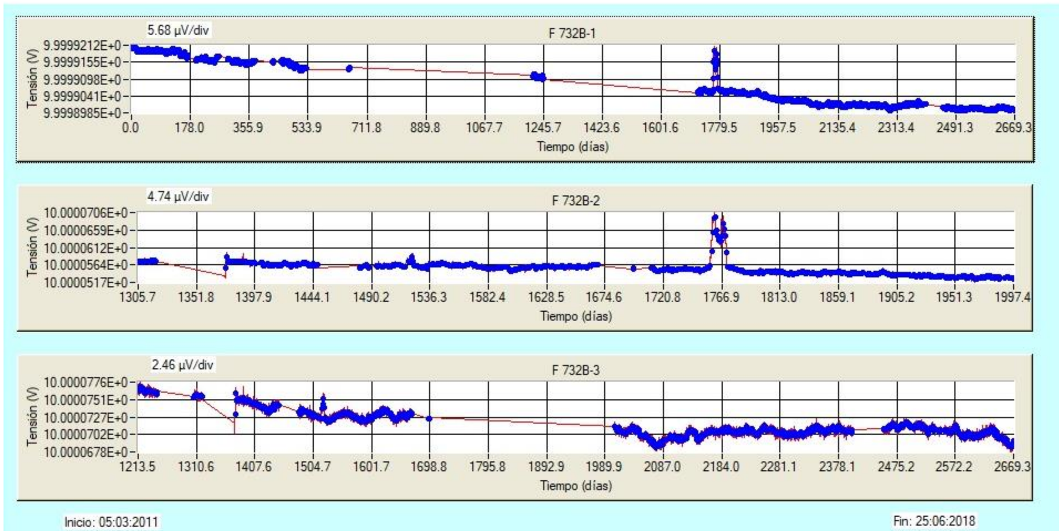

***Fig. 6. V**oltage values of three Fluke-732B, during 7 years.*

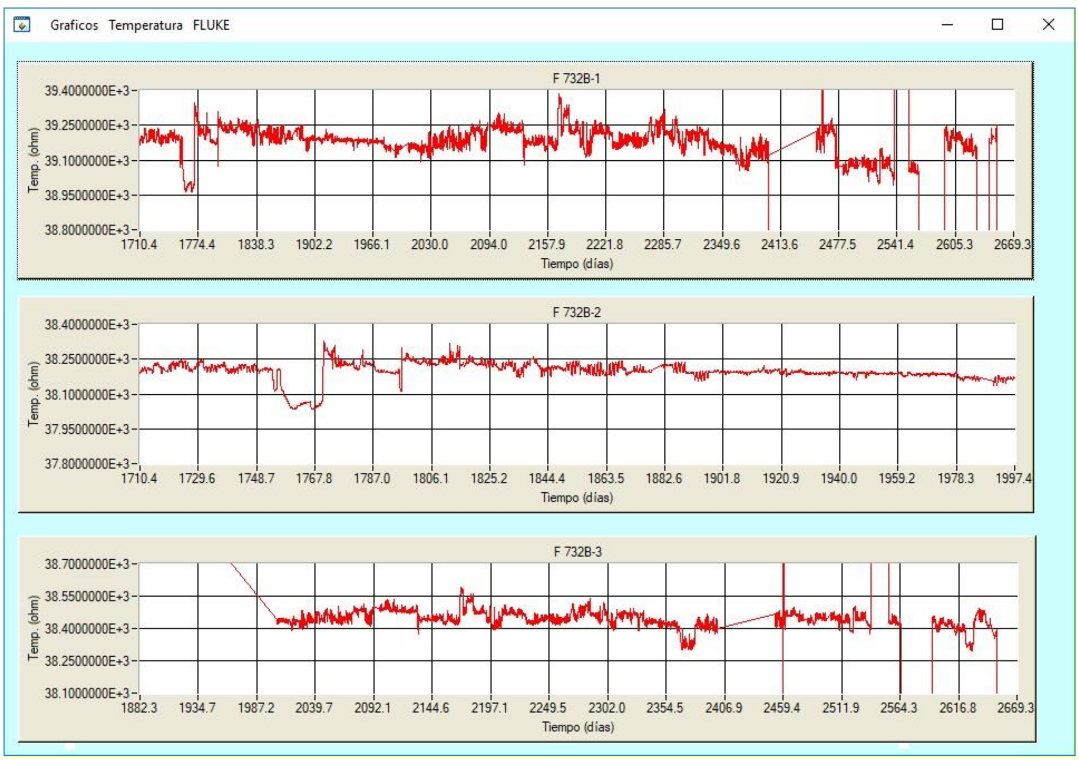

***Fig. 7. T**hermistor resistance values of three Fluke-732B, during 7 years.*

At INMETRO the measurements were carried out with the standards operated with their internal batteries.

To allow the standards to stabilize, battery operated measurements started at least after one hour of disconnection from the ac line power. At UTE, they stayed connected to the ac power. Anyway, studies of the behavior of these two units under ac or battery powered showed agreement of one order lower than UTE uncertainty.

5.1 Uncertainty sources

Several factors were taken into account for the uncertainty calculation of the comparing system. They are: resistance of scanner and connecting cables, isolation, scanner emf, external thermoelectric emfs, and the voltmeter uncertainty sources: accuracy, resolution and input impedance.
The uncertainty of the reference Zener was not included, because the main purpose of this work was only to evaluate the behavior of the automatic comparison system.

5.2 Uncertainty budget

Table 1 shows the calculation of the expanded uncertainty (k=2), for the comparison system. For type A contribution, a Fluke-732B against the Reference Zener was measured. The expanded uncertainty of the entire system is 0.042 µV/V.

Table 1. Uncertainty budget.

Quantity	Value		Standard uncertainty		Sensitivity coefficient		Uncertainty contribution (V)
Scanner emf	0	V	5,00E-08	V	1		5,00E-08
Scanner plus cables resistances	0,5	Ω	0,5	Ω	1,00E-09	V/Ω	5,00E-10
Scanner isolation	1,00E+12	Ω	1,00E+11	Ω	-5,00E-20	V/Ω	-5,00E-09
Thermoelectric emf	0	V	5,00E-08	V	1		5,00E-08
DMM accuracy	0	V	1,73E-07	V	1		1,73E-07
DMM resolution	1,00E-08	V	5,77E-09	V	1		5,77E-09
DMM impedance	1,00E+10	Ω	1,00E+09	Ω	-5,00E-20	V/Ω	-5,00E-11
Type A uncertainty			1,00E-07	V	1		1,00E-07
Combined uncertainty							2,1E-07
Expanded uncertaity							4,2E-07

6. EXAMPLES OF RESULTS

The Reference Standard has 4 sectors. Figure 8 shows the EXCEL result of one sector, observed during several years. The step variation in 2019 is not due to an intrinsic variation of the Zener, but to the variation in the definition of the Unit of volt. Discounting this variation, the stability is better than 0.1 µV/V in three years. Other registers showed that the average value of the four sectors of this standard had varied less than 0.21 µV/V in the last 15 years [6], with a linear trend of 0.013 µV/V/year.

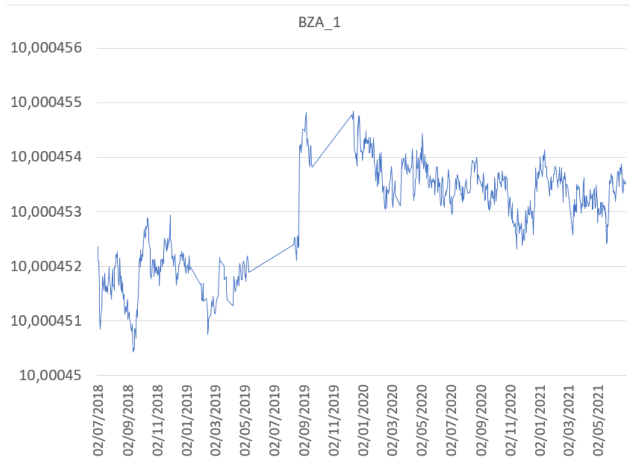

Fig. 8. *Example of data registered by the measuring system.*

7. CONCLUSIONS

An automatic system for calibrating Zener Voltage Standards was described. This system is part of the National Standard of the Uruguayan Volt Unit. The main components are a scanner managed by a software that controls that device, a voltmeter, an auxiliary scanner for temperature measurement and an ohmmeter. High frequency noise generated by the Zeners and the rest of the system is reduced using statistical calculations. The software calculates the value of the unit under test, comparing it against a Reference Zener. Results are shown as chats and tables.

The expanded uncertainty of the entire system is 0.042 µV/V.

REFERENCES

[1] C. A. Pérez, "Nueva instalación del patrón de FEM. Evolución del VOLT-LEM". Revista Electrotécnica, vol. 73, no 5, pp. 187-197, Sep-Oct 1987.

[2] H. de Souza and D. Slomovitz, "Comparison of DC Voltage Standards using a 10:1 divider," IEEE Latin America Transactions, vol. 4, no. 3, pp. 156-159, May 2006.

[3] D. Slomovitz, L. Trigo, H. de Souza, "Fuente patrón de tensión basada en múltiples Zeners". Encuentro de Potencia, Instrumentación y Medidas, EPIM 05. Montevideo, Uruguay, 2005.

[4] D. Slomovitz, L Trigo and H de Souza, "Long term behavior of a multiZener 10 V voltage standard," CPEM 2010, pp. 211-212, 2010.

[5] H. de Souza, L. Trigo, D Slomovitz, "Eleven years of monitoring an ultra-stable 10 V Zener-based voltage standard," Journal of Physics: Conference Series, Volume 733, 2016.

[6] H. De Souza, L. Trigo and D. Slomovitz, "An Ultra Stable Zener Voltage Standard - Fifteen Years of Surveillance," 2021 IEEE URUCON, Uruguay, 2021, pp. 299-302.

[7] D. Slomovitz, R. Landin, H. de Souza, L. Trigo, "Bilateral comparison of dc voltage at 10 V between UTE and INMETRO," METROLOGIA, Brazil, 2021.